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1 Executive Summary

Introduction

Optical clocks will provide the next generation accurate time and frequency standards. The aim of this project was to investigate the necessary techniques for the dissemination of time and frequency signals using optical fibres to enable remote comparisons of optical clocks in Europe. It has been demonstrated that frequency transfer over optical fibres has an order-of-magnitude better stability and accuracy than satellite-based methods. It is currently the only long distance transfer technique that meets the requirements of optical clocks. The feasibility of a European fibre network connecting optical clocks in Europe has been studied in close collaboration with fibre providers. Access to reference signals with improved accuracy will have an increasing impact on a possible redefinition of the SI second, for fundamental research and applied science, synchronization of mobile telecommunication networks and navigation.

The Problem

Nowadays optical clocks reach a fractional frequency uncertainty below 10-17 and outperform the best caesium-based atomic clocks in both accuracy and stability. This outstanding performance makes them the most promising candidates for the redefinition of the SI unit of time, the Second, and an ideal tool for various tests of fundamental physics.

However, established techniques for remote clock comparisons based on satellites do not reach the instability and uncertainty required for the comparison of the best optical clocks.

Additionally, there is an increasing demand by scientific organisations, universities and industry for traceability to the SI second. Frequency metrology is also crucial for defence and aerospace engineering, geodesy, high-resolution radio astronomy, navigation, and communication.

The Solution

The demonstrated instability of an optical frequency transmitted over a fibre link is several orders of magnitude more stable than the signal used in satellite transmission systems. Thus, optical fibre links are the sole alternative to satellites for comparing the best clocks and the dissemination of frequency references to end-users with unprecedented instability.

First experiments used dedicated and specially selected fibre routes within national testbeds. To tap into the full potential of optical clocks and optical time and frequency dissemination, however, user-friendly and reliable pan-European fibre links, as well as new time and frequency transfer protocols needed to be developed. The operation of such links required the development of phase-coherent low- noise amplification and detection of optical signals, including remote-controlled bi-direction amplifiers and active noise cancelation, the analysis of the fundamental limitations of the proposed techniques. Within the project the equipment necessary for reliable operation of fibre links has been developed and all technological steps towards a full optical link infrastructure have been demonstrated.

Impact

Almost all technological processes require precise timing or reference frequencies, and improvements in the realisation and dissemination of time and frequency are expected to have widespread impact on innovation, science, and daily life.

Overall, the results of the project have enabled NMIs to perform better clock comparisons within Europe, and to disseminate highly accurate and stable frequency and timing signals to the user community for ground breaking science and innovation.

The ability to compare distant optical clocks at the highest possible accuracy level is the prerequisite for a possible redefinition of the SI second. The project proved the robustness and accuracy of the necessary technology and techniques, and demonstrated improved clock comparisons by at least one order of magnitude.

2 Project context, rationale and objectives

The need for improved time and frequency comparisons has been stressed in the EMRP outline document the "Establishment of novel ways for time and frequency transfer" [1], and the Consultative Committee for Time and Frequency (CCTF) [2]. It is regarded as of supreme importance for a future redefinition of the SI Second and for the sustained development of a European time and frequency infrastructure.

Frequency metrology has developed considerably over the past decades. The best optical clocks today reach a fractional accuracy below 10^{-17} and outperformed the best caesium-based atomic clocks in both accuracy and stability [3,4]. The present challenge consists of accurately comparing the non-portable ultrastable clocks in distant laboratories, with the longer-term goal of dissemination of such standards to the large community of potential user beneficiaries. Such comparison is a vital issue for optical clocks development and to explore their fundamental limitations.

The project was focused on developing methods for comparing optical frequency standards, and dissemination of highly accurate time/frequency signals by using long-distance optical fibre connections.

The project addressed the objectives:

1. Develop novel techniques for frequency comparisons in the ~10^{-18} range at 1 day measurement time using optical fibres and the necessary equipment such as repeater stations, amplification concepts and remote control systems.
2. Development of methods, protocols and techniques for accurate time dissemination and the consideration of different complementary methods and levels of accuracy reaching from a sub-1 nanoseconds (ns) level to the sub-microseconds (sub-µs) level.
3. Identify applications that require, or significantly benefit, from remote fibre links, and consider the next steps fostering the decision of funding a future European fibre network or bi-directional connections of selected points of presence in close collaboration with stakeholders.

This project already supports intercomparisons of the European ensemble of optical atomic clocks at a level only limited by the systematic uncertainties and stabilities of the clocks themselves, enabling optical clocks to enhance the international timescale and support redefinition of the SI second [3].

The project enabled the technological capability to compare clocks within Europe, at the better than 10^{-17} level of stability, and exploited existing optical fibre networks to disseminate highly accurate and stable frequency and timing signals to the user community for ground-breaking science and innovation. With this project Europe has taken the world-leading position in this rapidly-developing area.

3 Research results

3.1. The development of techniques that enable comparisons of the best optical clocks on a relative uncertainty level of about 10^{-18} at one day integration time.

The techniques, tools and equipment necessary to enable reliable operation of long-haul fibre links had to be realized for two alternative link architectures: the use of a pair of d*ark fibres* in a strand of commercially used fibres or a dedicated wavelength channel of a fibre pair carrying telecommunication data in parallel to the optical signal. Even though the two different architectures require dedicated, specialised equipment, the overall design performance requirements are very similar.

The first's research activities have pushed the development towards reliable fibre links that can be operated autonomously on a day-to-day basis and resulted in a versatile tool box that comprises the following equipment:

- For control of remote amplifiers distributed along a fibre link remote control modules needed to be developed. The control devices are based on communication using Universal Mobile Telecommunications System (UMTS), L-Band (long wavelength), or S-Band (short wavelength) communication, or a channel adjacent to the signal channel. Those modules have been implemented in amplification modules and repeater stations to report system status parameters such as system status monitoring for input- and output optical power, pump current, gain level.

- The first implementation of improved remote Erbium doped fibre amplifiers (EDFAs) with GSM (Global System for Mobile Communications) was done successfully, and the equipment was tested on a 540 km link by OBSPARIS and co-workers. The improved EDFAs have been made available commercially.
- Since GSM communication is not available with all fibre providers in Europe, alternative techniques, such as in-band monitoring, have been developed and tested.

* In order to detect and report errors on the signal itself, which occur during frequency transfer, such as signal loss or phase slips signal monitoring devices have been developed that allow for real-time detection of signal failure. Such techniques are now well developed and are available for real fibre links. At PTB an initial version of a high-speed signal monitor based on that of a digital phase comparator has become available allowing real-time (<200 ns) detection of cycle slips between two signals and detection of signal loss. Cycle slip detection is also implemented at OBSPARIS and INRIM with fast analysis of error signals using two other independent techniques.

* Signal amplification on long-haul links is in general very crucial. Moreover, as the optical links considered for time and frequency dissemination require fully bi-directional operation off the shelf amplifiers cannot be used. Thus low-noise, bi-directional signal amplification modules, such as EDFA, fibre Brillouin amplifiers (FBA), Raman amplifiers (RA) and optical injection locking (OIL) had to be developed that are capable of amplification of very weak input signals between 1 nW and 1 µW. Suppression of amplified spontaneous emission (ASE), or parasitic noise, or quasi-unidirectional amplification, different pump configurations, and spectral filtering had to be considered and tested in the novel design for concatenated amplifiers.

  - Brillouin amplifier modules for low noise signal amplification including the communication unit for remote control and automated locking have been developed. The modules bridge fibre spans of more than 200 km [5]. Due to the narrow bandwidth of the Brillouin amplification automatic locking of the FBA frequency to an input signal needed to be developed that guarantees robust tracking and amplification of the input signal. As FBAs had not been operated in serious so far, frequency transmission using at least two FBA modules in series had to be carried out focusing on signal perturbations and parasitic noise. At present three remotely controlled FBA modules are implemented in the German part of the Braunschweig-Paris link (720 km) and are operated in serious over a fibre length of around 1400 km over weeks. Measurements demonstrated an extremely small uncertainty contribution in the 10^{-20} range [6].

  - Distributed Raman amplification (DRA) for the phase coherent transfer of optical frequencies over long-range optical fibre links has been studied by the REG G. Bolognini from CNR. DRA provides high-gain and bi-directional coherent amplification of the optical signal. The performance of DRA with bi-directional pumping frequency dissemination has been implemented, tested and characterised on a link in an urban metro environment. It was shown that a Distributed Raman Amplifier does not add extra noise to the optical link, allowing one to bridge very long fibre spans in bidirectional links without the need of intermediate stations. For the stabilized link a fractional frequency instability of $3\times\cdot10^{-19}$ over 1000 s was achieved at the remote end [7]. Simultaneous combination of DRA and bi-directional EDFA allowed for optical frequency transfer over a multi-node inter-city 180 km long link without intermediate amplification stages. Down to the 10^{-19} level of frequency instability the DRA proves not to affect the spectral purity of the delivered frequency signal [8].

  - Typically, the signal to noise ratio (SNR) of the metrological signal degrades for very long links. Below a certain threshold SNR the phase coherence of the signal can no longer be guaranteed. Therefore **signal regeneration systems or repeater stations** had to be developed that which act as “optical tracking filters” to remove excess optical phase noise accumulating along a fibre link. Such systems are based on ultra-stable cavity stabilised lasers (typically implemented at the endpoint of a link), or fibre-delay-stabilised laser in selected nodes along the fibre link. The repeater station serves to filter and amplify the signal and to exchange signals for the link stabilisation with both the previous and the next station. It comprises cost-effective diode lasers with good passive stability, phase locked loops for robust locking of the station to the incoming metrological signal and full remote control. The prototype **Remote Laser Station** developed by OBSPARIS and the Laboratoire de Physique des Lasers, (LPL) was successfully tested in field. The station acts as "optical tracking filter" to remove excess optical phase noise accumulating along a fibre link. Results over 1480 km of internet fibre were demonstrated. It shows world record relative frequency stability of $7x10^{-16}$ at one second integration time and uncertainty contribution below 10^{-19} [9]. The signal regeneration system has been duplicated six times for the Paris-Braunschweig link. Two stations were installed at the cross border link in Strasbourg.

- o At INRIM two different system designs of compact stabilized lasers at 1.54 µm have been finalized and their performances have been investigated. Compared with the cavity stabilized system the delay-stabilized laser system is simpler, more cost effective and compact; however, it shows a significantly larger drift of up to 10 kHz/s. This system may be used as clean-up laser along fibre links, but is not suitable as reference laser system without further improvement of the long term stability

- Previously existing stabilisation schemes provide a stable frequency output only at the end points. Providing access to a stabilised frequency for a larger number of users located along an existing point-to-point connection is one of the key points for a distribution network. The basic idea of using the optical carrier only had been proposed by Grosche [10]. Based on this approach several simple and robust multiple user distribution schemes that allow extraction of a stable reference frequency at several points along a given transmission path have been developed and tested within the project [11,12]. This included assessment of critical components, a breadboard design for implementation at a user site. With this, users will benefit from a high quality metrological signal, that otherwise is only available at a National Metrology Institute.

- In the French network RENATER ITU channel 44 is currently dedicated for metrological applications. Considering that very little background information on the availability of dark channels from other fibre providers exist, and only another (adjacent) channel might be available when switching from one provider to another. In collaboration with the REG from UoS we have investigated methods and devices for reliable cost effective coherent wavelength shift between ITU channels. This involved a passive frequency comb and OIL that allows bridging of ITU channels by means of a microwave signal applied to an electro-optical modulator in a resonant optical cavity. The performance of a diode laser when injection locked to low power input signals has been investigated and a regenerative amplifier based on optical injection locking was developed. The portable prototype built with 19-inch rack boxes has been tested at PTB over several weeks. In a proof-of-principle experiment the device was used as a mid-stage amplifier in a bi-directionally operated 292-km long installed dark fibre link (total loss of 86 dB) [13]. Additionally a wavelength converter based on an optical frequency comb generator, OFC, was developed. The wavelength converter covers a frequency band of 1.2 THz (9.6 nm) with a net gain of 32 dB.

These results open the way to accurate and high-resolution frequency comparison of optical clocks over intercontinental fibre networks.

In addition to the development of a versatile toolbox for optical signal conditioning we have focused on two different approaches for long-haul ultra-stable frequency comparison and distribution; one based on dedicated dark fibres and the other on a dark wavelength channel in a shared public telecommunication network. For both approaches we have demonstrated long distant fibre link capability at continental distance that allows optical clock comparisons with an uncertainty limited only by the frequency standards (clocks) at the remote ends.

- In addition to the activities described above SYRTE implement a real-time frequency comparison over a uni-directional telecommunication network of 100 km using a pair of parallel fibres with simultaneous digital data transfer [14]. The relative frequency stability is 10^{-15} at 1-s integration time and reaches 2×10^{-17} at 40 000 s, three orders of magnitude below the one-way fibre instability. Ultrahigh-resolution comparison of optical frequencies with a bidirectional scheme using a single fibre showed that the relative stability at 1-s integration time is 7×10^{-18} and scales down to 5×10^{-21}. The same level of performance was reached when an optical link was implemented with an active compensation of the fibre noise. The fractional uncertainty of the frequency comparisons was evaluated for the best case to 2×10^{-20}.

- At INRIM a novel technique based on two-way remote optical phase comparison was developed and tested [15]. In this case two optical frequency signals were launched in opposite directions in an optical fibre and their phases were simultaneously measured at the other end. In this technique, the fibre noise is passively cancelled, and the two optical frequencies were compared at the ultimate 10^{-21} stability level. The experiment was performed on a 47 km fibre that was part of the metropolitan network for Internet traffic. The technique relies on the synchronous measurement of the optical phases at the two ends of the link. This scheme offers some advantages with respect to active noise cancellation schemes, as the light travels only once in the fibre. Two-times better stability than actively compensated system could be demonstrated.

- We have extended the distance between local and remote end up to 2000 km by implementing tools developed in fibre links becoming available within the last three years. We have characterized those links in terms of link instability, frequency noise, frequency offset, robustness and reliability; e.g. for a dark fibre link of nearly 2000 km length, between the Max-Planck-Institute for Quantum Optics (MPQ) and PTB, the relative frequency instability of the link expressed as modified Allan deviation (ModADEV) dropped below 10^{-18} at 100 seconds integration time [16]. Fundamental limits of fibre links were investigated and sources of noise degrading the performances at medium range of integration were identified and eliminated [17] allowing for a relative frequency stability in 1-Hz bandwidth at the 10^{-20} range.
- As fibre links between optical clocks in NMIs in Europe were not in place at the beginning of the project, we have investigated the prospect and explored routes to enable international optical clock comparisons over very long distances such international comparisons. This task required collaboration with National Research and Educational Networks, NREN, such as RENATER (France), DFN (Germany), or GARR (Italy) and the European counterpart GÉANT. NRENs in collaboration with GÉANT could in future possibly provide a network for sustainable international frequency comparisons (see Figure 1).

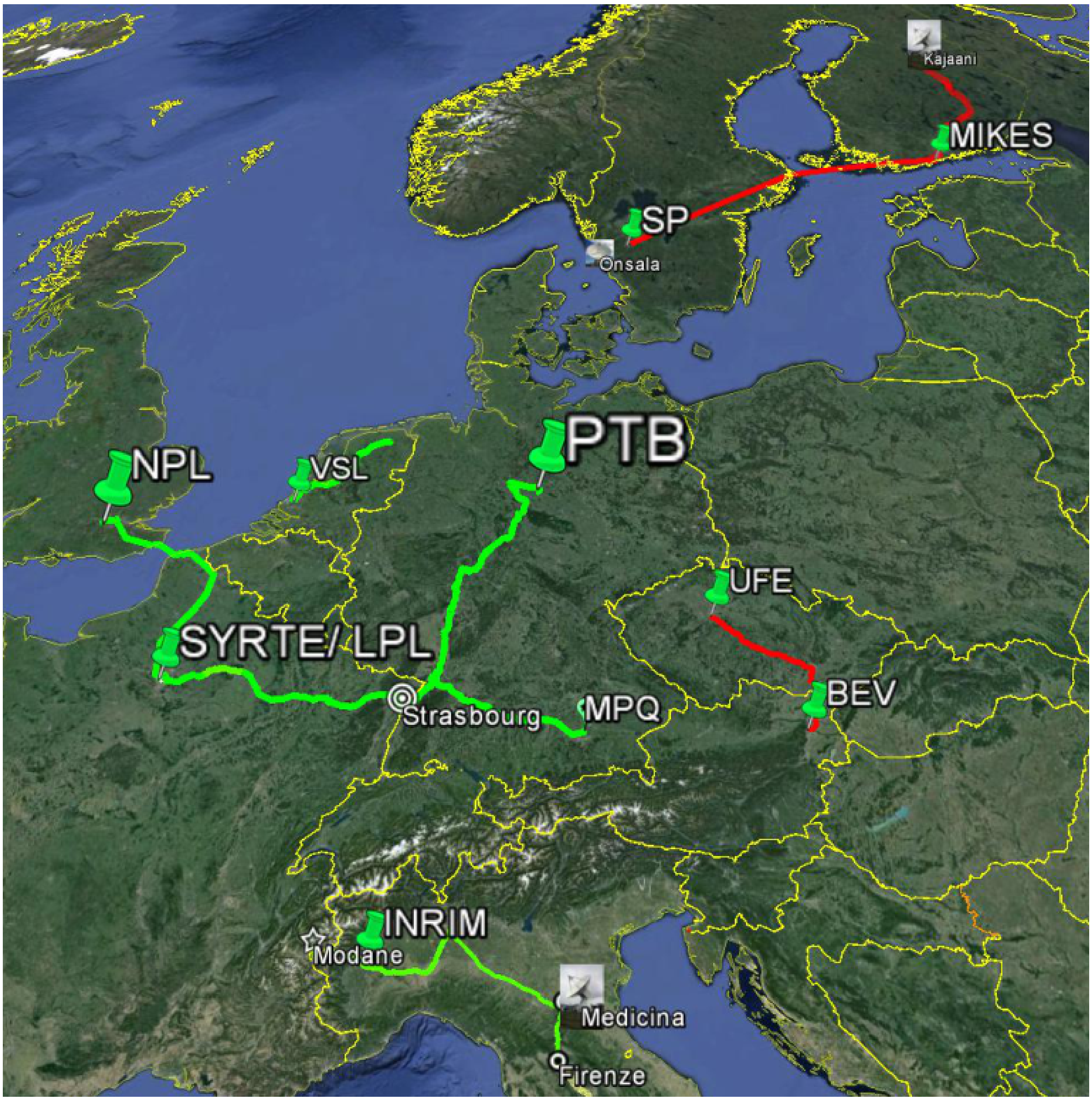

Figure 1: European fibre link projects referred to in the text (green) and previously existing timing links (red) with an extension from Espoo to Kajaani in Finland using White Rabbit technology.

- In Germany a direct fibre link between Braunschweig and Kehl/ Strasbourg was established in 2013. This link branches in Karlsruhe towards MPQ Garching and replaces the previously existing link between PTB and MPQ via Erlangen. Via a cross border link of RENATER and DFN in Kehl the first international fibre route for optical clock comparisons between two European NMIs became feasible.
- In parallel the French colleagues from OBSPARIS and LPL extended their previously existing link via Nancy towards Strasbourg. Both links are now interconnected at the computing center of the University of Strasbourg and undergo evaluation and are used for a first international frequency comparison of Sr (Strontium) lattice clocks.
- With support from LPL, OBSPARIS and PTB extended their national links from Paris and Braunschweig to Strasbourg. The cross border link at the University of Strasbourg was established in October 2014. The interconnection between the French and German stabilized links was realized in February 2015.

- The Italian project LIFT (Link ottico nazionale per la Frequenza e il Tempo) now connects INRIM in Torino with the European Laboratory for Non-Linear Spectroscopy (LENS) in Firenze via Milano and the Radio-astronomical Centre in Bologna (VLBI station). The link is 640 km long, and was equipped with the improved remote EDFAs, now available as commercial product. As LIFT has been extended from INRIM to Modane underground laboratory at the Italian-French cross-border at the tunnel of Frejus. This link will eventually be extended towards France. Moreover, close collaboration with the EMRP project ITOC (International Timescales with Optical Clocks) allowed for a first proof of principle experiment on relativistic geodesy between clocks at INRIM and a mobile clock at Modane underground laboratory.
- As a result of a workshop for stakeholders in Hoofddorp, The Netherlands, the project received support from GÉANT representatives. Within the iteration GN3plus of the GÉANT Project**,** GN3+ an open call of the EU has been issued, making available a fibre route between two GÉANT Points of Presence (PoP) in Paris and London (GÉANT project ICOF - International Clock Comparisons via Optical Fiber). In this way an international fibre link between NPL and OBSPARIS via LPL has been established in 2015. The implementation of the link was supported by RMG1-IMBiH. The link is now available for frequency comparisons of optical clocks. This link complements the link between PTB and OBSPARIS.
- Overall, five new long haul links have been be established before the end of the project: Paris-Strasbourg-Paris (2x 750 km), Braunschweig-Strasbourg-Braunschweig (2x 700 km), Torino-Florence-Torino (2x 640 km), London-Paris-London (2x 800 km) and Torino-Modane-Torino (2x 90 km). This will allow for future clock comparisons at the highest level of accuracy. Together with the activities and links mentioned above, this is another breakthrough towards a European scientific network.
- Using the Paris- Braunschweig link a first international comparison of Sr lattice clocks of PTB and SYRTE has already been carried out in 2015 [3].

Overall, these activities paved the way to perform the first international clock comparisons via optical fibres and to novel applications of optical clocks in the field of relativistic geodesy.

3.2. Development of methods, protocols and techniques for accurate time dissemination and the consideration of different complementary methods and levels of accuracy reaching from a sub-1 ns level to the sub-µs level.

Besides frequency dissemination, new techniques for time transfer over optical fibre networks had to be developed to meet the second objective. The issue of time dissemination has been addressed in the subsequent research. Here we give a short overview of the status of time transfer over optical fibre prior to the start of the research project:

Standard GPS receivers achieve about 100 ns timing accuracy, whereas state-of-the-art GPS time transfer (operated in commonview mode) achieves about 5 ns absolute timing accuracy. This is only surpassed by dedicated international clock-comparison links employing two-way satellite time and frequency transfer (TWSTFT), providing around 1 ns timing uncertainty [18]. Tests of fully fibre-optical two-way time transfer (TWTT) methods on relatively short (1–2 km) links have demonstrated timing accuracy at the 100-ps level using TWTT by bidirectional transmission on a dedicated optical fibre [19]. TWTT over Dense Wavelength Division Multiplexing(DWDM) wavelength channels has demonstrated the potential of achieving nanosecond timing accuracy, using unidirectional fiber pairs of 740 km total length with known path delay asymmetry [20]. Similar accuracy is achieved using fiber-based TWTT over active Synchronous Digital Hierarchy (SDH) / Synchronous Optical Network (SONET) networks using a ‘piggy-back’ technique, where the start sequence of each data frame is detected in both ends [21]. In Sweden, a prototype setup has been in operation since 2008 between Borås and Stockholm, a distance of 560 km, and it has been verified that the uncertainty introduced by the time transfer is comparable to the presently-used Global Navigation Satellite System (GNSS) techniques (~1 ns). One-way time transfer through optical fibres at the level of 10-100 ns has been shown to be possible by making use of a ‘dual-wavelength’ technique [22].

During the project we have investigated fibre based techniques for time broadcasting, two-way time transfer over future high capacity links, and dark fibre solutions in order to provide better timing signals than currently available with GPS receivers. For typical spans up to 100 km the project aimed to improve the accuracy down to about 100 ps by using the methods developed for frequency transfer. This involved measuring the delay/optical path length with optical techniques and cancelling the environmentally-induced changes of the optical path length/delay in the optical link.

While frequency transmission over fibre requires the stabilization of the optical carrier frequency only, time dissemination additionally requires traceability and unambiguous marking of the optical phase (time of day). Standard techniques typically transmit one pulse per second (pps) in parallel with e.g. a 10 MHz or 100 MHz reference frequency. This pps signal has a calibrated phase offset from UTC (Coordinated Universal Time) and can be used to reference a remote time scale to the local time scale of a UTC laboratory once the link delay has been calibrated.

Generation of a signal similar to the pps signal from an optical carrier requires some effort. In a first approach a fs-frequency comb was used that emits a pulse train in the time domain and at the same time millions of “optical carriers (modes)” in the frequency domain.

We have successfully developed a novel technique for the simultaneous dissemination of time and frequency signals propagating over a single ITU channel. Contrary to other existing techniques the technique is based on the propagation of a pulse train derived from a fs-frequency comb. Unambiguous labelling of fs-comb-pulses using a Mach-Zehnder modulator enabled time stamping by marking a single optical pulse from a 100 MHz pulse train. The timing stability of the 80th harmonic of the repetition rate delivered at the remote end was measured against that at the local end by means of a microwave phase detector. The event marker scheme has been tested successfully over a 50 km spooled fibre demonstrating a timing jitter significantly below 1 ps and a timing accuracy of the absolute delay of 160 ps. A timing jitter of ≈400 fs at 10 s integration time was achieved, greatly exceeding the 100 ps target.

We originally had planned to investigate the simultaneous transmission of two optical carriers separated by a frequency offset of several tens of MHz up to 1 GHz where the fibre noise is cancelled using existing optical carrier transfer techniques. However, given the need to establish the fibre link between London and Paris within a short period of only 15 months (GÉANT Project ICOF), the necessity of have been reconsidered and found to be obsolete. Additionally, different approaches to generate a microwave signal based on two optical carriers have already been described in literature. Moreover, this technique has been investigated by the University of Tshingua and has recently been implemented in the Square Kilometer Array (SKA) distribution system [23]. Considering the published results, the achievements the consortium obtained with the WR links in Finland and the Netherlands, and the upcoming need to additionally support the implementaion of the new fiber link between London and Paris on short notice we did not continue further investigations of this technique and shifted activities towards the London – Paris link.

The main achievements are listed in the subsequent paragraphs.

To demonstrate the feasibility of the dual carrier approach the transmission of two optical carriers with frequency differences between 60 MHz and 400 MHz has been investigated using a 5 km fibre spool and an unstabilized fibre link between PTB and LUH (Leibniz Universität Hannover). The two fibres were patched at LUH forming a single span of 146 km with sender and receiver in the same lab. However due do the fact that additional amplifiers at LUH and PTB were not available, the following measurements were performed without phase stabilization of the link.

- For the 5 km fibre spool a short term frequency instability was limited by the counter resolution; for longer averaging time a modified Allan deviation, ModADEV, of $8 \times 10^{-11}/\tau^{3/2}$ was achieved.
- Over the unstabilized link from PTB to LUH and back a relative frequency instability of ModADEV=1×10^{-11} at 1 s integration time was achieved reaching a flicker floor of a few 10^{-15} after 10000 s. The short term instability (TDEV 10 ps at 1s) was limited by the signal to noise ratio of the beat signal. Over 4 days a differential delay of < 2 ns was observed. During this period the air temperature outside varied by about 15 K.

In order to demonstrate the benefit of optical links for classical time and frequency transfer a GPS carrier-phase frequency transfer link along a baseline of 540 km was established and characterised by comparing it to a phase-stabilized optical fibre link of 920 km length, established between the two endpoints, the Max-Planck-Institut für Quantenoptik in Garching and PTB in Braunschweig [24].

In addition to work planned for the second objective, a novel technique for synchronisation and time transfer via coherent frequency transfer was developed and demonstrated in a proof-of-principle experiment at PTB [25] and OBSPARIS [26, 27], respectively. While absolute calibration of such links will require further investigations these preliminary show that the targeted timing accuracy of 100 ps can definitely be achieved.

As planned we evaluated the physical capabilities and limitations for fibre based, continuous time transfer using different techniques and studied the feasibility of a robust European time transfer network connecting European NMIs.

Different national and bi-national effort was spent during last few years, including two-way transfer between Prague and Vienna using a dark channel and cost-effective opto-electronic transceivers, and two-way transfer based on a novel "piggy-back" technique on top of a communication link between Espoo and Borås via Stockholm. In these relatively small experiments it was shown that sub-ns performance can be achieved with high reliability, but know-how and equipment needed for long-distance time and frequency links in existing optical fibre networks as well as a single solution addressing all end-user needs was lacking.

In the following several approaches to realize time transfer over optical fiber at the sub-ns level are described. We analysed the influence of modulation formats, especially on time transfer utilizing transmission of a signal derived from a fs-frequency comb, 100 Gbit/s communication techniques, formats and protocols. This included the analysis of the clock stability specifications and detection solutions, as well as cost analysis of necessary equipment.

- A novel time transfer technique based on the propagation of a pulse train in fibre has been developed. Unambiguous labelling of fs-comb-pulses using a Mach-Zehnder modulator enabled time stamping by marking a single optical pulse from a 100 MHz pulse train. The e*vent marker* scheme has been tested successfully over a 50 km spooled fibre demonstrating a timing jitter significantly below 1 ps and a timing accuracy of the absolute delay of 160 ps. The resolution was limited by the time interval counter. These results have been confirmed using 198 km using installed fibre between NPL and Reading in combination with 40 km of spooled fibre. A timing jitter of ≈400 fs at 10 s integration time was achieved [28].

- Time Transfer by Passive Listening as realized between the UTC realizations UTC(SP) and UTC(MIKE) uses the data signal from commercial routers (Synchronous Digital Hiearchy Protocol, SDH (STM-64)) in a 10 Gb/s optical data networks to carry the synchronization between Cesium clocks or Hydrogen Masers. A transmission system in lab environment has been assembled by SP to demonstrate time transfer on an active communication fibre link. For this, an experimental fibre link has been established between SP Technical Research Institute of Sweden in Borås and Chalmers University of Gothenburg in Sweden. The one way fibre length is about 60 km and implemented in SUNET (Swedish University Network). The signal quality was evaluated when sending a stable optical frequency utilizing a wavelength in a DWDM) system fibre pair. The experiment uses a channel in the DWDM with the wavelength of 1542.14 nm. In contrast to other distribution systems the approach used here utilizes a pair of fibres; one for the forward, the other for the return path, thus introducing a delay asymmetry that affects the fractional frequency instability of the connection. However, for a fibre link based on unidirectional light signals in parallel fibres a free-running, fractional frequency stability of approximately $3\text{x}10^{-13}$ at τ = 10 s and almost $1\text{x}10^{-14}$ at 10^5 s could be achieved [29].

- We have developed a two-way optical transfer method and equipment for sub-200 ps measurement accuracy as a more accurate alternative to current satellite techniques for mid-range distances. ÚFE and CESNET successfully developed instrumentation for two-way optical time transfer using DWDM channels arranged by CESNET either in a pair of optical fibres or within a single fibre. This instrumentation has been tested on an optical link between ÚFE and BEV/PTP. The achieved link stability was approximately 30 ps in terms of TDEV at 1-s averaging interval. The achieved uncertainty is approx. 5 ns (*k*=1) was in agreement with measurements performed by means of GNSS time transfer [30,31]. As a result, time transfer between ÚFE and BEV now runs continuously and the results are regularly reported to the International Bureau of Weights and Measures (BIPM).

- REG AGH from the Akademia Gorniczo-Hutnicza im. Stanislawa Staszica w Krakowie (AGH), Poland, developed alternative techniques for frequency and time transfer in the RF domain including multiple user distribution [32]. This included a novel technique for delay stabilization which was tested and evaluated using the existing fibre link between PTB in Braunschweig and Leibniz University (LUH) in Hanover [33]. This system has been upgraded for long-distance time and frequency transfer and is now used in field experiments in Poland and Germany. Stable operation of the full system over weeks has been achieved. This system achieves a relative instability below 1ps and a timing accuracy at the 10 ps level.

- As mentioned above and in addition to the experiments performed by ÚFE and BEV on time transfer first experiments performing simultaneous optical frequency and accurate timing transfer have been demonstrated by OBSPARIS & co-workers from LPL, achieving less than 20 ps for any measurement time up to one day and 250 ps accuracy over internet fibre with parallel data traffic between two remote sites [27]. The time transfer signals were provided by a pair of two-way satellite time-transfer modems (TimeTech-SATRE). The principle of the time measurement is to relate the phase of a pseudorandom noise code (PRN), carried by a radio frequency carrier signal, to the one-pulse-per-second (1PPS) and a 10 MHz reference signal from a common clock. The modem correlates the signal received from the remote end with a local replica of the expected signal. This gives the time of arrival of the received signal with respect to the local clock. Finally, the time-of-arrival datasets from the two modems are collected by a computer, which calculated the differential time delays.

During the course of the project we had to merge activities addressing the evaluation of fundamental accuracy limits of the time transfer in optical fibres and the development of cost-efficient methods for dissemination of UTC with accuracy better than state-of-the-art satellite-based methods using some one-way transfer technique.

We evaluated three different existing methods, based on the experience of CESNET, SP, and a system based on an extension of the precise time protocol PTP.

- From a technical point of view, it would be possible to make a design for a one-way transmitter and receivers that, in the end, costs a few hundred Euros or even less. However, we found that it would be difficult to implement any new one-way time dissemination protocol in an existing optical network, in a way that it would have better performance than existing protocols in all-copper networks.
- To implement efficient one-way time dissemination in an optical fibre network would require a serious change in the structure of the network; especially at connection nodes in the network. It is not impossible, but since fibre providers wouldn't have any benefit from such a change, it is very unlikely to happen. For this reason the consortium decided in agreement with the MSU and the advisory board that it didn't make sense to continue the work on one-way time dissemination.
- Following a recommendation of the Internatioanl Advisory Board, IAB, the possibility to construct a time link between radio-observatories at Metsähovi (Finland) and Onsala (Sweden) has been investigated. For this a study on suitability of a standard uni-directional network for long-haul timing dissemination using PTP-WR (Precision time Protocol- White Rabbit (WR), developed at CERN [34] was initiated by MIKES. WR is a two-way synchronization protocol designed in a way that it can be fully integrated with other (Ethernet) data traffic. This makes this alternative much more likely to be integrated in existing optical fibre networks. Moreover, for this technology, hardware was already available.

  Being originally designed for synchronisation of local area networks up to 10 kilometres, the consortium decided that resources would be likely better used by advancing existing WR technology towards a long-distance PTP-White Rabbit (WR) version. With initial performance tests in the laboratory followed by field tests on long distance links the range of PTP-WR has been extended towards 1000 km within the project. The time transfer on this link was compared (after initial calibration) against a clock comparison by GPS precise point positioning (GPS-PPP). The agreement between the two methods remained within ±2 ns over 3 months of measurements.

  MIKES and VSL continued work on testing of White Rabbit equipment over long distance. Between Delft and Amsterdam, the Netherlands, a roundtrip was created by cascading two links of 137 km each. In this case the WR links were realized as bidirectional paths in single fibres. The measured time offset after the round trip was within 5 ns with an uncertainty of 8 ns, mainly due to the estimated delay asymmetry caused by chromatic dispersion. The main result is the first demonstrated long-term operation of a long-distance. In a 120 day comparison between GPS-PPP time transfer and the 1000-km long link White Rabbit time link in a live DWDM network, the performance and reliability of the fibre link were found to be excellent and the results were limited by the statistics of the GPS–PPP link [35].

To our knowledge, this is the first time PTP-WR has been applied to a long haul system.

Overall, these activities pave the way towards opportunities for new services such as accurate and traceable time and frequency directly available to many users.

3.3. Identify applications that require or significantly benefit from remote fibre links and consider the next steps fostering the decision of funding a future European fibre network or bi-directional connections of selected points of presence in close collaboration with stakeholders.

The project brought together the long standing expertise of nine leading European National Metrology Institutes (NMI) and one representative from the National Research and Educational Networks (NREN) to meet the scientific and technical needs for highly stable and accurate reference signals in fundamental physics, Global Navigation Satellite System (GNSS), geodesy, astronomy, and (space-) industry. The joint activities of the project partners have provided an alternative to established satellite based time and frequency methods that now allows improving clock comparisons by at least one order of magnitude and opens the possibility to provide time and frequency references to European industry suitable to meet most current and planned objectives and missions.

In the following we give some examples highlighting applications that benefit from the major achievements of the project:

- Based on the technology developed by AGH a collaboration between PTB, AGH, and German Telekom (DTAG) was initiated that aims to continuously compare UTC(DTAG) with UTC(PTB) via optical fibre in order to provide supervision of the mobile network of DTAG.

- A fibre link that delivers UTC(MIKE) to the time-stamping authority in Finland according to ITU-T recommendation TF.1876 “Trusted time source for Time Stamp Authority” has been implemented in Finland using the long-haul version of the PTP-WR (Precision time Protocol- White Rabbit) developped in the project. Within the new EMPIR SIP project TIMEFUNC (Time Synchronisation Impact Enabling Future Network Communication, 2015), the knowledge and experience on WR-PTP from the project will be disseminated to industrial organizations for applications in telecom networks.

- In a proof of concept the EMRP project ITOC has performed a clock comparison between the local Sr lattice clock at INRIM and a transportable clock developed by PTB. The transportable clock has been moved to the Modane underground laboratory in the Frejus tunnel at the Italian / French border. The frequency comparison was carried out using the fibre link established within the project.

In addition to the activities originally planned several steps towards establishing a future European fibre network have been undertaken:

- The interaction with the research and education networks is also well established; both at the national (NREN) and international level (GÉANT). The project directly benefitted from the contact with DANTE (Delivery of Advanced Network Technology to Europe) management and other NRENs such as DFN, RENATER, GARR or CESNET. In addition contacts with industry on behalf White Rabbit Technology, amplifier development and stable laser development are in place.

- Within the iteration GN3+ an open call was issued and a fibre route between two GÉANT sites in Paris and London was made available. In this way an international fibre link between NPL and OBSPARIS via LPL could be established in 2015. The link is now available for frequency comparisons of optical clocks. This second link for optical frequency comparisons complements the link between PTB and OBSPARIS.

- The consortium has been interacting with the EURAMET TC-TF (Technical Committee for Time and Frequency), the CCTF Two-Way Satellite Time and Frequency Transfer (WGTWSTFT) and the Working Group on Coordination of the Development of Advanced Time and Frequency Transfer Techniques (WG ATFT). Status and achievements of the project have been presented at the regular meetings of the WGs. Four members of the project are contributing to the task group on fibre links under the CCTF WGAFTF.

- With support from the Laboratoire de Physique des Lasers (LPL), OBSPARIS and PTB extended their national links from Paris and Braunschweig to Strasbourg. The cross border link at the University of Strasbourg was established in October 2014. The interconnection between the French and German stabilized links was realized in February 2015. Subsequently, the world's first international direct clock comparison has been performed between Strontium lattice clocks located at OBSPARIS and PTB [1]. PTB and OBSPARIS demonstrated relative frequency stability in 1-Hz bandwidth at the 10^{-20} range.

- In Germany the collaborative research center Geo-Q has been established aiming to track the motion of test masses in the gravitational field with nanometer accuracy, to develop atomic gravity sensors, and to establish the quantum metrology of long-distance frequency comparisons to observe the gravitational frequency redshift with optical atomic clocks.

- In Italy the first radio-astronomical station in Bologna is now linked to the primary clocks at INRIM. Using the fibre link to INRIM first measurements of the performance of the local reference clock, Hydrogen-maser (H maser) at the level of its statistical uncertainty have been carried out. Improved VLBI is also of interest to the Time and Frequency metrology community, as it is used to monitor the rotation of the Earth with respect to TAI (International Atomic Time).

- In a proof of concept the EMRP project ITOC has performed a clock comparison between the local Sr lattice clock at INRIM and a transportable clock developed by PTB. The transportable clock has been moved to the Modane underground laboratory in the Frejus tunnel at the Italian / French border. The frequency comparison was carried out using the fibre link established within the project.

- Within the new EMPIR SIP project Time Synchronisation IMpact Enabling FUture Network Communication, TIMEFUNC (15SIP04), the project's knowledge and experience on time dissemination over optical fibre in general and on WR-PTP provided by VSL, UFE, BEV, SP and MIKES will be disseminated to industrial organizations for applications in telecom networks.

- With the new EMPIR project OFTEN (Optical frequency transfer - a European network 2015) the achievements of the project will continue to allow more accurate and efficient dissemination of the SI second to end users and to provide impact in various fields reaching from fundamental science to variety of novel applications.

➢ The fibre links between participating NMIs developed within the project has paved the way for the realization of a comprehensive test of the Atomic Clocks Ensemble in Space (ACES) clock comparison system at the highest possible level using a dedicated microwave link (MWL) with a specified performance at the 10^{-17} level and at a global scale. The ACES system is expected to fly onboard the International Space Station (ISS) in 2018. Since the performance of a fibre link is expected to outperform that of the MWL, the limitations to this MWL will be readily observed so that the evaluation can be completed during the mission. We have laid the basis for a significant contribution to the scientific added value of the ACES mission.

The following steps for a sustainable European fibre network have been undertaken:

- In April 2015 we introduced the achievements of the project, the vision behind, and the possible benefits of a metrological backbone to members of the Directorate General DG Connect, Referat C1, in Brussels

[1] C. Lisdat et al., Nature Comm. (2016), in press

expressing our strong interest in the network infrastructure provided by European NRENs including GÉANT and asked to

- consider the needs for high precision timing in the on-going next generation network definition,
- to discuss a provision of dedicated fiber links between European NMIs,
- to support a consortium of European NMIs and academic partners to lay the foundations of a future European optical metrology network for precise time and frequency dissemination by facilitating access to existing fiber infrastructure.

- During the meeting DG Connect encouraged the consortium to participate in an upcoming call for European infrastructure in 2016 (INFRAINNOV 2016). In response members of the consortium participated in this call. The project proposal was selected for funding in September 2016.
- In addition M. Inguscio, president of INRIM, introduced the vision of a European Fiber Backbone for Time and Frequency at a meeting with Comisioneer G. Öttinger in Oktober 2015.
- European activities have been complemented by several national activities asking for support at the national government level or national funding agencies.

3.4. Conclusions

Within the project we have developed the necessary equipment to implement optical fibre links and demonstrated that optical fibres are the sole alternative for frequency comparisons of the most advanced optical clocks. We have investigated several methods, protocols and techniques for accurate time dissemination; some of them allowing an accuracy level substantially below 1 ns.

In close collaboration with stakeholders and our partners from academia we have identified applications benefitting from optical fibers and considered the next steps fostering the decision of funding a future European fibre network.

Overall, this project goes far beyond the original planned activities and is the fundamental breakthrough towards a European scientific network which will allow for optical clock comparisons at the highest level of accuracy, novel applications of optical clocks in the field of relativistic geodesy, or opportunities for new services such as accurate and traceable time and frequency directly available to many users.

4 Actual and potential impact

Actual and potential impact

Overall, the results of the project have enabled NMIs to perform better clock comparisons within Europe, and to disseminate highly accurate and stable frequency and timing signals to the user community for ground breaking science and innovation.

Dissemination of results

The achievements of this project have been presented at more than ten international conferences and several workshops. Five individuals have received training from members of the consortium, and between 50 and 100 people have been trained at a training workshop.

Early impact

The ability to compare distant optical clocks at the highest possible accuracy level is the prerequisite for a possible redefinition of the SI second. The project proved the robustness and accuracy of the necessary technology and techniques, and demonstrated improved clock comparisons by at least one order of magnitude. The fibre links between participating NMIs have paved the way for the realisation of a comprehensive test of the clock comparison system of the Atomic Clocks Ensemble in Space (ACES) at the highest possible level using a dedicated microwave link between ground and space with a specified performance at the 10^{-17} level and at a global scale. The project demonstrated the ability to provide time and frequency references to European industry to meet most current and planned objectives and missions, with the required level of confidence. The ACES system is expected to fly onboard the ISS in 2018. Since the performance of a fibre link is expected to outperform that of the existing microwave link (MWL), the limitations to this MWL will be readily observed so that the evaluation can be completed during the mission. This will pave the way towards intercontinental clock comparisons at a so far unprecedented level of performance.

Potential future impact

This work has three potential areas of impact:

- The results of the project have enabled NMIs to perform better clock comparisons within Europe, and to disseminate highly accurate and stable frequency and timing signals to the user community. This project is the fundamental breakthrough towards a European scientific network which will allow for optical clock comparisons at the highest level of accuracy.
- Optical fibre links now provide an optical reference frequency for fundamental research with an uncertainty and stability that today is only locally available at NMIs and a small number of other dedicated laboratories. This makes SI traceability easier wherever the laboratory is. This work will allow countries that do not possess primary frequency standards (optical or microwave) to have easy access to accurate time and frequency signals from the best clocks in Europe.
- Accurate and reliable timing signals can be used for local-area augmentation systems that allow more accurate and much faster navigation than by currently available GNSS. Possible applications would be in air-traffic control near airports to assist in automatic landing of aircraft, or efficient control of traffic flows consisting of autonomous vehicles. Using the synchronisation at the 10-16 level at two distant stations, such as the PTS (Precise Timing Stations) of the GALILEO ground segment, a test of the accuracy and stability of the GPS/GALILEO system can be performed with significantly higher precision. Other industries likely to benefit include telecommunications, finance and the Internet where dissemination of Coordinated Universal Time (UTC) through optical fibre can also provide a secure backup for GPS timing in vital systems.

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