# FINAL PUBLISHABLE REPORT

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# 1 Overview

This project addressed key areas of development to transform fibre-based frequency transfer capabilities in Europe into a universal tool for time and frequency metrology and beyond. Accurate, reliable, and efficient solutions for optical time and frequency over fibre links were developed. By the end of the project, fibre networks supporting time and frequency dissemination had been or were being rolled out in several European states. The technologies and insights developed in this project have made a pan-European fibre network for time and frequency metrology both more feasible and more valuable.

# 2 Need

Time and frequency are at the heart of many everyday applications that we take for granted, such as satellite navigation and telecommunications, and underpin some of the most precise measurements in many areas of research such as fundamental physics, molecular spectroscopy and geodesy.

One of the central challenges of time and frequency metrology at the time was the redefinition of the SI second based on optical frequency standards (also known as optical clocks). The roadmap adopted by the Consultative Committee for Time and Frequency (CCTF) made it clear that remote optical clock comparisons at the highest level of accuracy would be essential for this process. Only fibre links had been shown to achieve the necessary accuracy over distances enabling international clock comparisons. However, the massive effort required for comparison campaigns prevented full utilisation of existing links. Improved automation and higher availability were required both from an economic perspective and in order to achieve long phase-coherent averaging times.

Inclusion of optical frequency standards was shown to lead to more stable international time scales and more accurate local realisations. In addition, many applications in research and industry required synchronisation to a common time scale. Fibre-based time transfer offered performance surpassing satellite-based solutions at that time and had the potential to support fully optical time scales in the future.

Only few of the laboratories developing optical clocks in Europe could afford to have fibre links at the time. To encourage uptake, combined time and frequency services using shared fibre infrastructure were desirable. The compatibility of optical time and frequency transfer with data traffic needed to be further investigated.

Finally, there was a need to engage with the wider scientific community to enable them to utilise the unprecedented performance of optical time and frequency references for their research, as well as to identify novel applications. Applications in geodesy had been identified as likely to benefit from improved synchronisation, utilising time for internal system delay compensation.

# 3 Objectives

The overall goal of the project was to advance pre-existing fibre-based *frequency* transfer capabilities in Europe towards a sustainable, universal tool for *time and frequency* metrology, matching the unprecedented accuracy of modern optical clocks.

The specific objectives of the project were:

1. To sustainably expand existing capabilities for optical fibre frequency transfer towards time transfer. Specifically, this meant integrating optical carrier, radio frequency (rf) and time dissemination and comparison techniques with the aim of limiting spectrum usage to a single International Telecommunication Union (ITU) channel. The target accuracy for the combined service was 1 part in $10^{18}$ for frequency and 100 ps for time, simultaneously. In order to implement such techniques in existing fibre links between NMIs, it would also be necessary to investigate how to extend the compatibility of specialised amplification techniques with rf and time transfer. In addition, novel concepts of time transfer over fibre with the potential of reaching sub-ps accuracy would be explored.

2. To further enhance and develop optical fibre frequency transfer technology, with the aim of human intervention-free operation over several weeks. Also, to identify and address performance-limiting factors, with the aim of achieving 1 part in $10^{18}$ uncertainty within less than one hour for long-distance fibre links, thus matching the expected performance of improved optical clocks.

3. To investigate the compatibility of optical time and frequency transfer with simultaneous data traffic in a laboratory test environment or deployed fibre infrastructure, in order to determine conditions under which they operate mutually disruption-free. Compatibility tests would concentrate on commercial telecommunications equipment deployed in national research and education networks (NREN) and the pan-European network GÉANT.

4. To disseminate ultra-stable frequency and timing signals beyond the NMIs. Particular attention would be paid to identifying the benefits of disseminating time, as opposed to pure frequency. This included demonstrating and facilitating novel applications in geodesy and earth observation. Specifically, essential functionalities for the proper transfer of time between widely spaced geodetic markers would be investigated.

5. To facilitate the take-up of the technology and measurement infrastructure developed in the project by the measurement supply chain (NMIs), standard developing organisations (e.g. ITU-T) and end users (NREN and other fibre network operators, earth science and geodesy communities, calibration laboratories).

The objectives reflected the overall endeavour to create “optical time scales” which harness the superior performance of optical clocks, an ambition that had driven EMRP and EMPIR projects SIB04 Ion Clock, SIB55 ITOC, 15SIB03 OC18 and follow-on projects.

# 4 Results

## *4.1 Objective 1: Optical time transfer*

On their own, optical frequency transfer over fibre and time transfer over fibre were technologically well advanced. By contrast, before this project, there were only few examples of combined optical frequency and time transfer within a single fibre, generally being relatively exploratory and generally occupying relatively large optical bandwidth. In this project, a number of different technological solutions were developed, ranging from conceptually straight-forward optical filtering to coherent optical modulation schemes developed from scratch. In addition, a number of more speculative topics was explored, promising order-of-magnitude improvements over the state-of-the-art in fibre-based time transfer.

### 4.1.1 Optical multiplexing technique for combined optical time and frequency transfer

In this conceptually straight-orward approach developed by AGH, PTB and NPL, all optical signals related to optical frequency, radio frequency (RF) and time dissemination are multiplexed in the optical domain, using a hierarchical structure of ultra-precise optical filters. This solution is fully transparent in terms of methods applied for noise cancellation and causes no undesired interferences between optical frequency dissemination subsystem and RF/time subsystem. The optical coherent carrier remains unmodulated, and the RF and time dissemination is achieved with a second modulated optical carrier.

Forward and backward signals generated by a RF and time dissemination system (such as ELSTAB, or other) are multiplexed with 25/50 GHz interleavers, and then multiplexed with two other signals related to optical frequency transfer, which are located in between the previous ones. Finally, all metrological signals are multiplexed with data traffic occupying the other ITU channels with regular 100 GHz-grid optical add-drop multiplexer (OADM) filters.

In the first step, AGH evaluated the interleavers and OADMs in terms of passband accuracy, isolation and group delay as well as thermal stability. The group delay is changing rapidly with frequency, which might affect the frequency stability and time calibration. Therefore, the proper wavelength location and stabilization of all laser sources is crucial for obtaining good performance of the time and frequency dissemination.

The performance of the system exploiting optical multiplexing scheme was evaluated in a 260 km-long link containing both fibre on spools and sections of fibre deployed in an urban environment. Three bidirectional EDFA amplifiers were used to partially compensate for fibre attenuation. ELSTAB devices with internally incorporated interleavers and additional precise wavelength lockers were used for RF and time transfer, and an optical frequency transfer system with a clean-up laser at the remote side and a standard noise cancellation system at the local side was employed. The obtained transfer stability is very much the same as for both subsystems working separately, without optical multiplexing, which proves that the proposed method is fully appropriate for integration of optical frequency, RF frequency and time dissemination within a single 100 GHz ITU channel, which is the main aim of Objective 1.

The added layer of optical multiplexing leads to an additional contribution to the uncertainty budget of time transfer due to differential group delay, compared to the ELSTAB system alone. Based on specifications and measured group delay characteristics, AGH estimated the extra standard uncertainty at the level of 5 ps. This will have no significant impact on the time transfer accuracy for the ELSTAB system. The total time transfer uncertainty is well below the target value of Objective 1. AGH performed a series of tests to verify time transfer accuracy. The results were fully consistent with the estimated uncertainty budget.

#### 4.1.2 Direct modulation of the optical carrier for combined time and frequency transfer

In the second approach, the consortium pursued several different approaches towards an integrated optical time and frequency transfer technique, where the ultrastable optical carrier is modulated directly. To exploit synergies arising from common functionalities and requirements, CNRS, OBSPARIS, INRIM, METAS, VSL and NPL agreed on a common hardware platform or “generic modem”. The National Instruments ETTUS USRP X310 software defined radio (SDR) was selected because of its built-in synchronisation capability and flexibility regarding transmitter and receiver front ends. The fact that it is also used in two-way satellite time and frequency fransfer (TWSTFT) was another important factor.

With an amplitude modulation (AM) modulation format, the signal is recovered as an electrical modulation of the photocurrent at the photodiode at the receiver side. Based on the common hardware platform USRP X310, VSL developed a modem structure designed for accurate time and frequency transfer with Pseudo-Random Noise (PRN) time code modulation and demodulation techniques. The AM scheme developed by VSL is flexible regarding the choice of optical carrier. In the first instance, VSL propose to utilise Coarse Wavelength Division Multiplexing (CWDM) wavelength channels at 1470nm and 1490nm rather than the C-band and L-band Dense Wavelength Division Multiplexing (DWDM) channels commonly used for optical frequency transfer. With co-existing standard CWDM ITU channels, the accuracy and precision of the time transfer can be compared by different techniques.

To achieve an accuracy of time transmission at or below 100 ps, as targeted in Objective 1, VSL developed a new algorithm for joint time synchronization and delay estimation based on two-way message exchange. VSL performed Monte Carlo simulations to show that the target accuracy could be achieved with the proposed set-up, assuming the noise floor of the SDR is below 1 ns. Experiments were performed in the RF domain. Combining the time transfer accuracy estimation results with the SDR noise test confirms the conclusion that the accuracy of the time transfer could achieve below 100 ps.

When using a phase modulation (PM), the modulated signal is not recovered "directly" at the photodiode. Heterodyne techniques, i.e. beating with an unmodulated local oscillator, can be employed. Homodyne self-demodulation is another alternative. The latter approach, based on a Mach-Zehnder interferometer (MZI), is widely used in telecommunications for binary-phase shift keying (BPSK) and was also employed within the project by METAS, CNRS (and linked third party UP13) and OBSPARIS (and linked third party CNRS).

METAS developed a modem for bidirectional time dissemination based on the common hardware platform USRP X310. The modem generates messages composed of a PRN sequence (acting as an identifier key), time stamp and delay information. Conceptually, the aim is to establish a connection between two USRPs A and B, exchanging the generated messages to compare their clock signals under consideration of internal delays and transmission line delays. The principal idea is to use a single 100 GHz ITU-T channel (CH07) for simultaneous dissemination of frequency and timestamps, based on a single phase-stabilized optical carrier, without deteriorating the phase noise compensation. The RF carrier frequency from the USRP acts thereby as an intermediate frequency, shifting the modulation of the time stamps away from the central carrier, onto sidebands at GHz distance.

METAS tested one modem pair (USRP A and USRP B) in a scheme for bidirectional transmission of time using optical phase modulation of a stable optical carrier in a phase-stabilized optical fibre link, consisting of 75 km of fibre spools, with one bidirectional EDFA placed after 50 km, and surrounded by two CH07 OADM filters. Both USRP A and B were referenced to the same 10 MHz signal provided by an active Hydrogen maser. With this setup, METAS validated bidirectional transmission of time stamps with a resolution of 1 µs given by the sampling rate of 1 MS/s. This has potential for improvement by speeding up the data processing and data transfer between USRP and host computer. Alternatively, part of the data processing could be performed directly in the USRP, using the embedded FPGA. The ultimate limit is given by the USRP daughterboards, which provide a maximum sampling of 160 MS/s. The relative stability is further quantified by the phase difference of the transmitted RF carrier with respect to the local RF reference, which is obtained in the USRP.

The measurement of the relative phase of the RF carrier allows the evaluation of the relative stability at a level of tens of picoseconds, meeting the target of Objective 1.

Phase noise cancellation of the optical carrier was fully operational simultaneously to the time dissemination scheme. It should be noted that the way modulation is implemented on the RX side provides non-common-path fibre segments for the return light, which may limit the ultimate stability of the phase noise compensation. Quantification of this effect is still under evaluation.

An alternative scheme was explored by OBSPARIS. Instead of a PRN code, OBSPARIS employed a Barker-13 code. This code is a very simple time code in a finite sequence of logic values (0 and 1), widely used in telecommunication technology, with ideal autocorrelation property. Such a code can be easily synthesized with commercial off-the-shelf synthesizers with low memory capacity. The synthesizer is set in PSK mode, and the pattern is stored in memory. The emission of the pattern is triggered by an external pulse-per-second (PPS) signal. As a receiver, the common hardware platform USRP X310 was employed. Within the project, the focus was on the receiver side and the development of the instrumentation to recover the time code and estimate the propagation delay.

A proof-of-principle experiment performed by OP and CNRS simulated two-way time transfer over 50 km of spooled fibre with a common sender and two independent receivers. It demonstrated reliable determination of the propagation delay and timing offset with a resolution of 8 ns, corresponding to the sample rate of 125 MS/s. The time instability averaged down to the target uncertainty of 100 ps in less than 1000 s.

There is considerable margin for improvement. First, implementation of the sender within the USRP will eliminate delays and associated fluctuations. Second, the processing presented here is only the equivalent of the coarse acquisition techniques used in satellite-based techniques (as in GPS or Galileo). The sample rate is a critical parameter limiting the resolution, however simply increasing it will drive up power consumption, and the required data transmission rate may pose severe problems. A possible mitigation strategy, not implemented in this project, consists of using the dual-mixer time difference technique.

#### 4.1.3 Spread spectrum technique for combined optical time and frequency transfer

The spread spectrum technique described below was first invented at NPL to suppress interference from doubly (or multiply) reflected light and thus improve the optical frequency transfer stability in the London-Paris Link. In this project, NPL further developed the technique to include time transfer capability using Software Defined Radio (SDR) with the common hardware platform USRP X310.

When modulating a BPSK signal on the light signal at one end of a two-way link, the signal spectrum is broadened (spread spectrum signal); modulating the light signal again with the same BPSK signal at the other end will de-spread the signal (reverse modulation) and retrieve the light carrier signal, provided the delay between the two BPSK signals matches the propagation delay of the light. Optimising the carrier recovery thus provides information about the relative timing of the BPSK sequences relative to local clocks at the link ends. The clock offset can be calculated from the optimal BPSK signal period and delay, where the beat signal SNR observed at the link ends is maximal. Optimal values are found by adjusting the BPSK signal period and delay in an automated process. Cable delays and AOM modulation delays must be accounted for by calibration.

NPL tested the technique in a local common-clock experiment with 50 km fibre spool. Based on 13 days of data, with measurements taken every 1 min at 20 MHz sampling rate, a time deviation of 100 ps and 20 ps was achieved in the short ($10^2$ s) and long term ($10^4$ s), respectively, compatible with the target of Objective 1. The time transfer stability can be improved by increasing the sampling rate, and the short-term stability can be further improved by reducing the measurement interval.

#### 4.1.4 Comparative evaluation of combined optical time and frequency techniques

The consortium performed a comparative evaluation of the techniques developed in the project, analysing the potential accuracy, the feasibility and demands to be fulfilled to achieve an absolute time calibration, the foreseeable issues and critical components to be secured.

Optical multiplexing is the most mature technique, with an uncertainty budget below 40 ps for a 500 km-long link. Time transfer accuracy was verified experimentally at 10 ps level for up to 260 km links. The frequency transfer stability obtained experimentally at 260 km-long link was better than 1 part in $10^{18}$ for averaging longer than 100 s, and better than 1 part in $10^{19}$ for averaging longer than 1000 s. This technique fully meets the target of Objective 1.

All SDR-based techniques developed in the project carry time information on modulation sidebands ~GHz off the carrier. The phase-noise cancellation for the optical carrier is unaffected by this, and hence there is no reason to expect worse performance than with optical frequency transfer alone, where an accuracy of 1 part in $10^{18}$ is routinely achieved. A direct verification of this is outstanding.

Direct modulation of an ultra-stable carrier minimises differential delays due to dispersion, which limit the accuracy of optical multiplexing. On the other hand, the SDR platform implies limitations due to digitisation and finite sampling rate. Results obtained within the project indicate that SDR-based techniques can achieve a time transfer accuracy better than 100 ps. This is also supported by experience with SDR-based TWSTFT. Precise determination of the internal delays in the USRP X310 is a critical requirement to achieve this level of accuracy and is yet to be performed.

Whereas optical multiplexing benefits from highly developed commercial technology, the direct-modulation techniques under development still face many challenges, for example around compensation of amplitude and polarisation drifts, a high demand on computational power and long-term stability of SDR characteristics like internal delays. On the other hand, optical multiplexing critically relies on some highly specialised and expensive optical components.

#### 4.1.5 Remote synchronisation of optical frequency combs

Pioneering work at NIST has shown the great capacities of optical frequency combs to transfer time with unprecedented accuracy at the fs level over a free-space link. To synchronize two remote optical frequency combs over fibre, ISI chose a solution based on transferring one or two selected comb teeth over a stabilized fibre link. This approach is suitable especially where telecom traffic allows only specific CW laser wavelengths (instead of a continuous part of the comb spectrum) to be transferred.

Two independent phase-coherent optical frequency transfer setups operating at 1540.6 nm and 1542.14 nm were installed and operated over a 438 km in-field fibre loop set up by ISI and CESNET. First results show that the fractional repetition rate stability of a slave comb synchronized over the long-haul fibre can reach the $10^{-14}$ range after 10 seconds. This is first step towards comb synchronisation with potentially femtosecond precision across long-haul fibre links.

#### 4.1.6 Towards time dissemination through Fibre Brillouin Amplifiers (FBA)

One bottleneck for long-haul time dissemination is the limited range of fully bi-directional links. Amplification based on stimulated Brillouin scattering (Fibre Brillouin Amplifier, FBA) has proven a valuable tool for optical frequency transfer, but its narrow-band nature poses a challenge for accurate time transfer.

PTB explored the transmission of modulated signals over an FBA-based fibre link using numerical simulations of the electric fields of a BPSK-modulated signal wave and a continuous pump wave. BPSK modulation is used in TWSTFT as well as some optical time transfer techniques. The results imply that chip rates comparable to the current standard for TWSTFT links contributing to UTC are feasible. However, asymmetric phase shifts can result in a delay uncertainty in the few nanoseconds range under realistic conditions. This poses a serious challenge to the use of FBAs for time transfer.

#### 4.1.7 Ultra-broadband technologies (≥100 Gbit/s)

The fast evolution of the telecom network opens the prospect of large-scale dissemination if the capabilities offered by modern coherent ultra-broad band techniques can be utilised for accurate time transfer. INRIM and POLITO set out to extend IEEE 1588 PTP-WR (“White Rabbit”) to 100 Gbps and further increase its time transfer sensitivity and stability. White Rabbit usually operates at 1.25 Gbps.

A survey of legacy optical transmission products was carried out, searching for a component capable of sustaining a PTP protocol at 100 Gbps. The Whitebox Cassini (Edgecore AS7716-24SC) was selected. However, testing ultimately had to be suspended due to unsolved problems in implementing the PTP profile. Feedback from the vendor was not enough to fix the issues. This experience illustrates the challenges arising from a perception by vendors that time transfer is still a research area.

#### 4.1.8 Towards fully optical time scales with sub-ps accuracy

Physical realisations of time scales such as UTC(PTB) generally rely on electronic signals, for example PPS pulses. The precision to which such signals can define events in time is fundamentally limited by the available bandwidth. For electronic signals, the bandwidth is generally on the order of a few GHz at most, implying the shortest discernible feature in the time domain is on the order of a nanosecond. Additional difficulties arise as a result of dispersion and nonlinearity in cables. Achieving picosecond, let alone sub-picosecond, precision timing with electronic signals must be considered very challenging.

The inherent advantage of optical signals over electronic ones is widely recognised in the context of optical clocks. It seems obvious to extend this advantage to the realisation of time scales. With this in mind, NPL, OP and PTB developed a tentative roadmap towards fully optical time scales, where all the core functionalities are implemented using optical technologies. A review of relevant optical technologies was carried out. It was found that there is a well-developed technological and conceptual basis for all-optical time scales in principle.

Of all the functionalities required, optical time transfer was identified as the least developed. Techniques for optical time transfer at the femtosecond level have been demonstrated, but do not yet cover the entire range of distances required. For medium and long distances beyond a few kilometres, free-space optical two-way time and frequency transfer (OTWTFT) is currently the only proven technique for femtosecond-level time transfer. However, a fibre-based solution would be required for resilience and reliability. This need has been partially addressed in this project but remains a weakness in our vision of all-optical time scales.

Femtosecond lasers and/or optical frequency combs play a crucial role in this vision. Miniaturisation and production at scale of these light sources is therefore likely to become the critical path towards wide-spread adoption of all-optical timing. Alternative approaches may emerge, for example from the field of coherent optical communications, and may ultimately prove more scalable albeit possibly at a cost in terms of precision.

#### 4.1.9 Summary

Within this project, a number of different technological solutions addressing combined time and frequency transfer over fibre links were developed, ranging from conceptually straight-forward optical filtering to coherent optical modulation schemes developed from scratch. The technique for combined time and frequency transfer based on optical multiplexing developed in this project is mature, rigorously tested and fully meets the accuracy targets of Objective 1 – including calibration. Techniques based on direct modulation of the optical carrier which were also addressed in this project currently lack the same maturity and rigour but have the potential to become more precise, more sustainable and more flexible solutions in future.

Looking towards sub-picosecond optical timing, fibre-based transfer techniques cannot currently match free-space OTWTFT in terms of performance. Due to the reliability advantage of fibre, this has been identified as an area needing development in a vision of fully optical time scales.

Overall, Objective 1 has been fully achieved.

### *4.2 Objective 2: Reliable optical frequency transfer*

At the start of this project, despite progress made in previous EMRP and EMPIR projects, techniques for optical frequency dissemination over fibre had not yet achieved a technological readiness level sufficient for human intervention-free operation over extended periods. In addition, it had been observed that one of the main drivers of medium-term instability are cycle slips, which destroy the coherence of the frequency transfer. Cycle slips occur as a result of the response of feedback loops, phase detectors etc. to amplitude and phase noise. They can be minimised by carefully tuning parameters such as loop bandwidth, but any instrumentation capable of human intervention-free operation must be able to detect and deal with residual cycle slips.

This project took a multi-pronged approach to attack these issues, developing a range of technical solutions. In the following, we summarise the achieved improvements in the phase coherence of fibre based optical frequency transfer and progress achieved towards automated global management and human-intervention-free operation of fibre links.

#### 4.2.1 Improved phase-locking electronics

ISI and NPL with support from PTB developed a versatile, accurate, high dynamic range phase detector platform. The platform is based on the National Instruments sbRIO9651 FPGA System-on-module, an analogue/digital converter (ADC) / digital-analogue converter (DAC) board including high precision clock generation developed by ISI, and a custom carrier board developed by NPL that fits into existing electronics racks. The FPGA module is programmable in LabVIEW, lowering the threshold for scientists to engage and enabling them to develop innovative signal processing and control algorithms. Applications include tracking of low-SNR beat notes and complete phase-noise cancellations servos for fibre links. The tracking loop achieves a bandwidth of 200 kHz.

This easily reconfigurable platform enables scientists to implement customised signal processing algorithms, such as digital phase-locked loops (PLLs) with a finely adjustable bandwidth and with a high resilience to fast transients, helping to avoid cycle slips. The design files for the carrier board, the ADC/DAC board and the clock module, along with programming examples, are freely available on Zenodo.

In addition, PTB studied the accuracy of another FPGA-based phase-stabilisation solution, confirming no negative impact or limitation from the FPGA at an uncertainty level of $2\times10^{-21}$.

AGH developed a digitally enhanced solution active cancellation of fibre phase noise, where a charge pump is added for pulling the PLL used to track the beat note towards locking condition. The charge pump is steered by a microcontroller measuring simultaneously two frequencies, the tracker frequency and the frequency driving the acousto-optic modulator. Analysing both frequencies, the locked and unlocked states may be distinguished, and the required integrator pulling may be determined.

This complementary solution combines the simplicity, cost-effectiveness and well characterised noise properties of analogue electronics with digital supervision and control. The digital features of this high-TRL solution help it deal with cycle slips with minimal disruption and fully autonomously, i.e., no need for human interaction.

### 4.2.2 Improved interferometer optics

The general aim of accurate and stable dissemination of optical frequencies via interferometric fibre links (IFLs) requires an interferometric reference with low spurious fluctuations. For out-of-loop (OOL) characterisations, the disseminated optical frequency is typically returned to the sender site in a looped IFL configuration. This can be accomplished either as a true fibre loop or by concatenating two individually stabilized IFLs. The OOL characterisation is performed by comparing the output of this IFL loop against the input optical frequency. The significance of OOL characterisations is limited by the fluctuations induced on the connection between IFL loop output and input and by (anti-)correlated fibre noise on different OOL paths that may cancel the effect to be characterized. At PTB, two different strategies to tackle the task of improved frequency disseminations and OOL characterisations have been tested.

In the first approach, a compact, all-dielectric free-space interferometer assembly was set up, with the aim of minimizing all involved paths and, therefore, minimizing the sensitivity to external disturbances. Using this compact assembly, the reference arm length for the in-loop interferometer was reduced to about 5 mm. Employing an inline retroreflector and dielectric materials only, the potential for cancellation of temperature fluctuation in the OOL characterisation was completely avoided. Based on the properties of the materials involved, environmental temperature and pressure sensitivity of the OOL characterisation was estimated to of $\gamma_{T,OOL} = 0.69$ fs/K and $\gamma_{p,OOL} = 4.01$ as/hPa. The measured instability averages down to below the $10^{-21}$-range. Comparison with the predicted instability derived from measured environmental parameters and estimated sensitivities suggests that the achievable performance is limited by the residual impact of temperature fluctuations above averaging times of $\approx10^3$ s. Compensating the temperature fluctuations in post-processing reduces the typical frequency transfer uncertainties from $\approx2\times10^{-21}$ to $\approx5\times10^{-22}$. With active temperature stabilisation, sub-$10^{-21}$ OOL frequency transfer characterisation should be possible in future.

In a second approach, standard temperature shielded fibre interferometers were used and the impact of the output-input connecting fibre was mitigated by implementing a two-way scheme between the two points. The measured instability of this set-up demonstrates an order of magnitude improvement, reaching the low $10^{-21}$ range after already $\approx$5000 s. The corresponding relative frequency offset is also below $10^{-21}$.

Both experiments achieve the target of Objective 2, namely OOL characterisation with an instability below $10^{-20}$ after one hour of integration and with an accuracy of better than $10^{-20}$. In future, both approaches will help to characterize non-reciprocal frequency transfer uncertainty contributions in greater detail and will also serve applications such as chronometric levelling experiments with two in-field clocks.

### 4.2.3 Improved signal and data processing

The standard feedback-loop design used in interferometric fibre links, which is based on a phase-locked loop with PI controller, suffers from a large phase lag due to signal delay. In a collaboration of PTB with the group of Prof. Dr. Schumacher from Technical University Braunschweig, a thorough analysis of the feedback-loop was performed, with the aim of achieving the best possible rejection bandwidth despite the delay. It turned out that a Smith Predictor, often used to cancel dead times in industrial applications, is of no help in fibre link stabilisation. In any case it is important to realise that in the low-frequency limit, the phase noise at the remote end cannot be improved below the fundamental limit, irrespective of how well the round-trip phase is compensated.

Nevertheless, an approach was found to adapt the feedback loop design such that the high-frequency noise rejection within the feedback bandwidth can be enhanced by a factor of approximately two. While only a modest improvement, a twofold reduction of the link instability can make a big difference for detecting cycle slips, due to the exponential suppression of large random deviations of the phase.

In optical clock comparisons, cycle-slips in PLLs used to stabilize different components along the measurement chain lead to frequency transfer errors. In interferometric fibre links, one typically observes those cycle-slips as occasional, quasi-instantaneous disturbances. PTB and NPL investigated strategies to detect and post-correct these cycle-slips in a continuous wave frequency transfer measurement chain based on a comparison of ultra-stable optical cavities at both ends, instead of separate out-of-loop monitoring. This method captures the entire measurement chain on the one hand, and on the other hand avoids unnecessary phase noise from a second fibre link. Both features are critical for detecting the presence (or absence) of a cycle slip with certainty, and hence for the accuracy of the comparison.

A mathematical description linking instability (modified Allan deviation) and cycle slip detection probability was formulated. Based on data from published measurements, it was estimated that cycle slip detection should be possible in a window between 100 ms and 100 s averaging time with acceptable rates of false positives and false negatives. In addition, a novel averaging method was developed that is better adapted to typical fibre link phase noise and could enhance the margin between cycle slips and instability by a factor of two.

#### 4.2.4 Management of amplifier chains

Two different solutions were found for the long-standing problem of balancing gains in a chain of bidirectional EDFAs. At the core of these solutions are two novel metrics, developed by AGH and CESNET, that can be used together with an optimisation algorithm for automatically setting the gains. Both metrics are derived from the (in-loop) beat note of the optical frequency transfer system. The Link Quality Metric (LQI), proposed by CESNET, was designed primarily to evaluate appearance of frequency components linked to parasitic lasing and for early/pre-lasing detection and avoidance. The metric, essentially the slope of noise near the centre of the beat note, was identified heuristically. It is calculated from a digitally acquired beat spectrum. A second metric, proposed by AGH, is based on a dedicated two-channel noise detector, which allows to independently measure the noise contributions related to insufficient (wideband component) and exaggerated (close-to-carrier component) gains of the amplifiers. Both metrics, together with suitable optimisation algorithms, have been successfully tested with chains of 3 or 4 amplifiers in realistic fibre links several 100 km long, achieving stable operation without human intervention.

A method to deterministically control the gain of a bidirectional EDFA was developed by NPL. The all-optical gain-clamped EDFA (AOGC-EDFA) uses optical feedback where amplified spontaneous emission (ASE) noise is injected back into the EDFA thereby clamping the gain. Initial results suggest that all-optical gain clamping effectively reduces gain and power variation and has no negative influence on the signal to noise ratio (SNR). Good gain clamping was achieved over a wider dynamic range as compared to conventional EDFA operation.

PTB developed and implemented a signal-to-noise ratio (SNR) monitoring tool for the interconnection point between the German and the French network in Strasbourg. The tool enables monitoring of the relevant beat signals from both the French side and the German side. This is helpful for localizing faults and provides an insight into the complexity of signal propagation in the heterogeneous amplifier chain.

The accumulation of noise and, hence the degradation of SNR in cascades of FBA was studied by PTB using numerical simulations. The noise level was found to be strongly dependent on signal power. This means that the overall SNR can be improved by placing more FBAs in short intervals for a given link length, circumventing a potential limitation on the total length of a single-span link based on FBAs.

#### 4.2.5 Mitigating polarisation effects

A fundamental limit to the performance of fibre links arises from the hypothesis of reciprocity in the paths of the light travelling forward and backward in the fibre. Non-reciprocal noise arises from technical sources, for example set-up asymmetry induced by the optical interferometers, and fundamentally from the Sagnac effect when the fibre link encloses a non-zero area.

OBSPARIS and CNRS studied very carefully the phase noise and frequency stability contributions based on multi-channel synchronous measurements in the case of coherent optical frequency transfer in a fully bi-directional fibre links. They developed a physical model, verified substantially by the experiment, that predicts the dominant noise mechanism at low Fourier frequencies to be polarization asymmetry induced by temperature and relative humidity variations. The flicker noise floor due to the non-reciprocal noise arising from polarization mode dispersion was evidenced. With a fibre spool set of 2x25 km, a time error of about 8 fs after 5 days of measurement was obtained. The extrapolation to long-haul fibre links is yet to be done.

INRIM and POLITO developed a new and robust method that overcomes the issue of fading due to polarization changes, based on a dual-polarization coherent receiver and a dedicated signal processing on a field programmable gated array (FPGA). The method allows analysis of polarization-induced phase noise from a theoretical and experimental point of view and endless tracking of the optical phase. This removes a major obstacle in the use of optical links for those physical experiments where long measurement times and high reliability are required.

INRIM performed a series of tests aimed at assessing the performances of the optical hybrid and compared the results achieved with this device to those of a traditional detection scheme based on a single photodiode in a real-field environment including 50 km of in-field fibre. The lock performed with the optical hybrid remained stable and cycle-slip-free even as fibre birefringence was varied randomly. This is an evident experimental proof of the advantage of the proposed solution over the traditional single-photodiode approach.

Polarization variations over time are important when the detection includes heterodyne optical mixing, as this process is highly polarization sensitive. The links connecting the RISE campus show substantial polarization variations, covering full circles on the Poincaré sphere, induced by 50 Hz from the electrical power grid. This effect is caused by long sections of fibre (100s of meters) installed parallel and across electrical cables. The result of measurements performed by RISE indicate that the deterioration caused by polarization variations could be largely compensated using a dual channel detection technique of both polarizations combined with post-processing, like the one developed by INRIM.

The influence of polarisation was also seen in time transfer between RISE in Borås and Onsala Space Observatory, based on White Rabbit. Even though this transmission is not polarization sensitive at the receiver, it is a result of polarization-to-timing conversion in the optical components. The external fibre transmission from RISE is supported by the Swedish University Network, SUNET, who operates a network with fibres both buried and aerial along the power grid. The polarization changes are more induced by mechanical movement than by electromagnetic influence, however the details are under investigation.

Meanwhile, PTB worked on describing formerly unconsidered aspects of the varying fibre birefringence and estimated the order of magnitude of these effects, taking into account the impact of the state-of-polarization (SOP) dependent fused fibre couplers and non-ideal Faraday rotator mirrors (FRM). The fractional frequency uncertainty contribution from SOP dependence of the fibre coupler was estimated as $\leq 5\times10^{-22}$ for a $\approx$700 km long IFL. The impact of the non-ideal FRM was estimated as $\leq 3\times10^{-23}$. This shows that both effects will probably only play a role when the impact of polarization mode dispersion of the fibre and resulting phase shift after beating with the local oscillator at the remote end are mitigated.

Following the patented easily automated polarisation optimizable, low-insertion-loss FBA design, PTB manufactured and installed FBA modules (FBAMs) for all three amplifier sites at the PTB-Strasbourg IFL. Using these FBAMs, continuous and human intervention-free operation has been achieved, even in cases of severe polarization rotation as encountered in a measurement campaign in the spring 2022.

NPL developed an automatic polarisation controller based on Nelder-Mead optimisation. The polarisation controller consists of four polarisation actuators, a logarithmic RF power meter and an Arduino microcontroller implementing a simple state machine. The controller is capable of autonomously tracking and, when needed, re-optimising the RF power of the in-loop beat note of an IFL, thus reliably mitigating fibre birefringence fluctuations even in the presence of power fluctuations due to other reasons. The polarisation controller has been implemented in the London-Paris fibre link.

Finally, OBSPARIS and CNRS demonstrated that polarisation scrambling can mitigate the effect of polarisation mode dispersion, which dominates the phase noise observed in uncompensated fibre links. As shown above, polarization variations in optical fibres are complex to manage. Here another mitigation strategy employing polarization scrambling was tested, where polarization variations in the optical fibre are averaged and the phase perturbations are minimized. The experimental challenge was to scramble the polarization while keeping the amplitude of the beat note constant. To solve this issue, a phase conjugation technique was employed to achieve self-demodulation of the scrambling. The result was a drastic reduction of the free-running noise with scrambling, and improvement also for the compensated fibre noise.

#### 4.2.6 Link supervision and management

Field deployed fibre is subject to environmental influences that introduced noise of various origin. Such noise is directly added to the optical signal carried by the fibre due to the Doppler effect. The whole frequency stabilization system behaves as a distributed fibre sensor and analysis of the observed noise or correction signal can provide information about vibration or stress applied to the fibre. One of the possible applications is checking fibre integrity, for example identifying construction work near the fibre or even an attempt to tap the fibre.

CESNET designed an experiment to show how the Doppler signal can be used record the disturbances in fibre proximity, using the link between Prague and Brno with a total fibre length of 267 km. Manual knocking on a patchcord was clearly visible, but displayed a higher noise level than state-of-polarisation (SOP) monitoring. The impact of a magnitude 5.4 earthquake in Croatia (epicentre distance 400—500 km) was also recorded. In conclusion, the Doppler signal could be used for fibre protection and detection of different events in fibre proximity or even far earthquakes.

With the growing complexity of metrological network such as the REFIMEVE network, supervision is a key to maintain a high-level service to the users. OBSPARIS and CNRS have been working towards a supervision system that integrates various equipment providers. As part of the project, OBSPARIS and CNRS reported on their progress, focussing on the laser source and the generation of the REFIMEVE signal, and on the synchronicity of the measurement taken remotely in-field.

Data acquired over the network is periodically retrieved into a centralised server and processed. The outcome is accessible to REFIMEVE operators through an Application Programming Interface. This tool enables the operational supervision, subcontracted to the leading industrial partner of REFIMEVE, to interoperate with the supervision of the laser source that feeds the network. In the REFIMEVE network, frequency measurements are time stamped according to the clock of the acquiring computer. The time of the remote computers in the network is synchronized using NTP. This mechanism has also proven valuable for spotting or cross-check malfunctions.

#### 4.2.7 Future clock comparisons at the $10^{-19}$ level

Several of the improvements described above were implemented in the fibre link between PTB and Strasbourg. PTB performed tests both on a 2×330 km-long subsection of the fibre link with only a single FBA as well as on the full link to Strasbourg with a combination of FBAs and a repeater laser station (RLS). In both cases, the instability reaches sub-$10^{-19}$ levels after an integration time of around 10 minutes. The impact of technical improvements is clearly seen in the short link, although it is masked by higher residual phase noise in the long link. The accuracy of all measurement runs scatter in the low $10^{-20}$ range for both configurations. Hence, future clock comparisons at the $10^{-19}$ level are supported.

The comparison with the estimated impact of PMD fluctuation assuming the highest literature value of PMD coefficient shows nearly a match with the measured instability curves for longer averaging times. This may indicate that in future, a further frequency transfer uncertainty reduction may be achieved by implementing means to mitigate the impact of PMD, including those demonstrated within the project.

#### 4.2.8 Summary

Within this project, decisive solutions to several key issues affecting the reliability and performance of optical fibre links have been developed, alongside a large toolbox of specific technical solutions. One highlight is the development of metrics suitable for automated balancing of amplifier gains. Incorrectly set gains in a long chain of amplifiers are a key driver of cycle slips, as well as potentially affecting data transmission in shared fibre. Manually optimising the gains is notoriously time consuming and hardly adequate for tracking the constantly changing environmental conditions of an in-field link.

Optical fibre links have been shown to be ready for next-generation optical clock comparisons at the $10^{-19}$ level. On the other hand, polarisation-mode dispersion is now widely seen as the next big challenge in pushing performance beyond the $10^{-21}$ level.

Objective 2 of the project has been fully met.

### 4.3 *Objective 3: Telecom infrastructure sharing*

As one of the most prominent outputs of this project, a good practice guide for the coexistence of time and frequency signals with data traffic in DWDM network was produced. Underpinning the recommendations provided in this guide, summarised below, are analyses and tests performed by PTB, OBSPARIS, INRIM, AGH, CESNET, CNRS, iXblue (formerly Muquans), POLITO and PSNC. Specifically, CESNET and PSNC carried out a paper study to assess the prospects and compatibility of time and frequency (T/F) signal distribution in DWDM systems, where the focus was on bidirectional T/F transmission in unidirectional telecommunication systems. POLITO and INRIM carried out theoretical analysis and numerical simulations of the interaction between T/F and data signals propagating in the same fibre. PSNC, AGH with the support of PTB tested an optically multiplexed time and frequency transfer technique developed with this project in a laboratory DWDM system together with coherent 100G signals. iXblue (formerly Muquans), CNRS and OBSPARIS performed laboratory tests of the compatibility of telecommunication systems and optical carrier dissemination systems, focusing on bidirectional EDFAs as a potential source of interference and drawing on their experience with the REFIMEVE network in France. AGH and PSNC performed stress tests to determine the resilience of telecommunication networks to T/F signals exceeding acceptable limits. In this context, a novel approach of minimizing interference between Raman and bidirectional erbium doped fibre amplifiers was developed. Tests with in-field telecommunication infrastructure were performed by CESNET, RISE, ISI, PSNC and AGH. Much of the research was coordinated with the OTFN group of GÉANT, set up to evaluate the possibility of including T/F services in future iterations of the GÉANT pan-European network, and actively communicated to other NREN. Complementing these activities, IMBIH (RMG1, hosted by INRIM) investigated the asymmetry of long-haul DWDM T/F links based on the White Rabbit protocol (WR-PTP).

#### 4.3.1 Unidirectional T/F transfer

The primary way of transmitting telecommunication signals in DWDM networks is uni-directional transmission. This means that the opposite directions of transmission are physically separated and use individual fibres and independent optical signal amplifier modules. Some DWDM network operators allow transmission of “foreign” signals in separated optical spectrum. This spectrum can also be used to transfer a reference frequency, however this signal (similarly to telecommunication data signals) is transmitted over a pair of optical fibres and amplified using existing DWDM system modules. The great advantage of this solution is that there is no requirement to modify the DWDM system, and the willingness of operators to provide such a service.

Unfortunately, this solution violates the desired symmetry of the propagation delay changes in the forward and backward directions, which causes deterioration of the stability of the transmitted reference signals. Moreover, time transfer is problematic in this solution. An extensive analysis of time transfer stability and accuracy in this approach was carried out by PSNC and AGH, clearly highlighting the limitations.

Nevertheless, research by IMBIH (RMG1, hosted by INRIM) shows that transfer of time, frequency, and data signals on the same fibre link in a unidirectional scheme is possible without mutual interference and maintaining an accuracy <1 ns even during stress tests. In this example, time and frequency transfer was implemented using White Rabbit (WR-PTB) equipment and standard DWDM multiplexers.

#### 4.3.2 Bidirectional T/F transfer

The second solution for time and frequency reference signal transfer in a DWDM network is based on "extracting" these signals in each network node, bi-directional amplification and then multiplexing with telecommunication signals. In practice, this means that the T/F signals are transmitted bi-directionally in a single fibre, while the remaining signals (telecommunications data) are transmitted in the same way as before, that is, unidirectionally, using a pair of optical fibres. This solution guarantees the stability of the reference signal transfer, comparable with the situation in dark fibre, and enables absolute time calibration to be performed without the necessity of using external calibration systems.

The experiments and analysis conducted within the project confirm the feasibility of implementing bidirectional time and frequency (T/F) transfer in current DWDM telecommunication networks. However, persons designing and maintaining such networks require extensive engineering knowledge, especially in the field of bidirectional transmission in a single fibre. The basic guideline that greatly simplifies the design of such networks is the recommendation to avoid fibre optic plane connectors (called Physical Contact - PC connectors) along the path in which bidirectional signals are transmitted. In practice, this applies to all optical fibre connectors linking devices to the line cable, as well as patch connections inside the data centre. This also applies to connectors in the OADM filter (except for one port where DWDM equipment is attached - the reflect port). The above recommendation is often feasible at relatively low cost, while significantly reducing reflections from such connectors. The use of Angled Physical Contact (APC) connectors increases the safe amplification threshold of bidirectional amplifiers since reflections cause instability and lasing.

For optical carrier (OC) metrology signals and those generated by the ELSTAB system, PSNC and AGH did not observe any negative effects on the quality of data transmission due to the lack of guard bands. However, it should be noted that thin-film filters (used in OADM modules) for single, four or eight DWDM channels (with a grid of 100 GHz) are now widely available. Narrower filters are difficult to achieve, very expensive and in practice not used to build OADM modules.

For the transfer of spectrally narrow signals (which most current T/F signals are), the issue of stimulated Brillouin scattering (SBS) is also important, as observed by CESNET and in the REFIMEVE network. In long-haul links, the bidirectional path should be significantly undercompensated - the gain should be much lower than the attenuation - otherwise the thresholds for SBS and for amplifier instability become lower for longer links. It should be noted that using Raman amplifiers reduces the maximum acceptable level of the metrological signals. The impact of the SBS problem can be reduced in future by 'artificially' broadening the transmitted signal spectrum (this applies in particular to Optical Carrier (OC) signals). The first experimental work in this area is currently being carried out.

The nature of Raman amplifiers (they are distributed amplifiers, which amplify an optical signal in a fibre optic line) means that they amplify both metrological and data signals simultaneously. Therefore, changing their gain may require changing the gain of the bidirectional amplifiers (dedicated to the metrology signals) as well. Unfortunately, there is currently no dedicated protocol for the automated exchange of information about such events between DWDM devices and devices dedicated to T/F signal transfer. In some networks, for example REFIMEVE, an attenuator is used to suppress the metrological signals co-propagating with the Raman light by a value equal to the maximum gain of the Raman amplifier. This solution guarantees high security of the transmitted data signals, preventing the phenomena known as SBS-based comb generation and instability (lasing) of cascaded bidirectional amplifiers, but significantly reduces the power budget of the metrological signals and may lead to a complete interruption of the transmission of these signals if the Raman gain is significantly reduced, whether intentional or resulting from an emergency. As an option, “hardware-limited” bi-directional EDFA amplifiers (with a short Erbium fibre) can be used instead of an attenuator. This will significantly improve the SNR of the metrological signals.

DWDM systems without Raman amplifiers have significantly fewer problems. Nevertheless, in very long links (hundreds of kilometres) containing many nodes, the problem of backscattered signals (due to both Rayleigh and Brillouin backscattering) and back-reflected signals that can build up along the whole link, make the link much more vulnerable to destructive effects. The preliminary recommendation is that at least 5 dB of under-compensation is needed per 100 km of link length.

Simulations conducted by INRIM and POLTIO have shown that the non-linear phase noise generation due to the Kerr effect can be expected not yet to impair the transmission of T/F signals in DWDM networks. Interestingly, though, the contributed instability is only a few orders of magnitude lower than typical results obtained on operating T/F networks, and may already be detectable in some dedicated testbeds, configured specifically for testing purposes. Thus, investigation of this problem from an experimental point of view, while being beyond the scope of the present work, may deserve future developments.

Since data transmission systems are mainly unidirectional solutions while T/F signal distribution systems use bidirectional transmission, the combination of these two technologies within a single network undoubtedly requires specialist knowledge and skills among those managing the infrastructure. Some networks (such as REFIMEVE) have decided to separate the competences of the persons (and institutions) managing the T/F distribution system from those managing data transmission, despite both tasks being implemented within the same DWDM network. This situation requires very close cooperation between the two teams. Unfortunately, the lack of standards and protocols for automatic exchange of information between the two systems (T/F distribution and data transmission) makes it difficult to separate the competences of these two teams, requiring the development of procedures for responding to sudden failures and setting priorities for individual services. In practice, data transfer services are most often treated with higher priority (the network management centre requires permission to shut down the T/F transfer service if a fault is detected).

Given the lack of standardised protocols for the exchange of information between T/F and data transfer systems, the integration of the competences of both groups of operators in a single network management centre seems highly advisable. This is particularly relevant for DWDM networks containing Raman amplifiers. As shown above, a change in amplifier gain affects both transmission systems, and gain correction of the “metrological” amplifiers (bi-directional EDFAs) is necessary to maintain optimum optical power levels. Combining the competences of these two teams will allow faster identification of failures, more effective responses to events, and an improvement in the service level agreement (SLA) for the T/F transfer system. In the future, it would be desirable to develop a suitable protocol for the automatic exchange of control information between metrological signal transfer systems and data transmission systems.

An issue independent of the allocation of responsibilities between the different management teams is the need to accurately determine the current gain of individual amplifiers and to precisely monitor their output power. In the currently deployed bidirectional EDFA amplifiers, automatic gain control for OC signals (unmodulated signals) is not possible. The solution adopted is manual setting of the amplifier pump current to a fixed value. This in turn means that it is only possible to determine an approximate value for the gain, which is not stabilized against changing amplifier operating conditions. It is desirable to use solutions that guarantee automatic gain control regardless of the type of transmitted signal, such as the one developed in this project. It seems likely that commercial solutions will emerge in time.

Also related to the above issue is the development of dedicated algorithms to automatically optimise the gain of the entire chain of bidirectional amplifiers. Due to the high complexity of the various dependencies affecting the quality of metrological signal transfer, such an algorithm would be very helpful in maintaining this type of network. Preliminary solutions have been proposed within the project.

For efficient management of the combined data and T/F transfer network, access to the software management of its individual components must be available regardless of the state of the network itself (e.g. when a failure occurs). A complete shutdown of the bidirectional EDFA pumps can be crucial, for instance to re-initialise the Raman amplifiers.

#### 4.3.3 Summary

The compatibility of bidirectional time and frequency signals with data traffic was demonstrated in multiple constellations involving various time and frequency transfer and commercial telecommunications equipment. Situations where particular care is needed were identified and safe operating conditions determined. The work was performed in close collaboration with GÉANT Project GN4-3 and national research and education networks (NREN). The results have been written up as a comprehensive “Good practice guide for the coexistence of time and frequency signals with data traffic in DWDM networks”, which is expected to become publicly available as a Euramet Technical Guide.

Objective 3 of the project has been fully met.

### *4.4 Objective 4: Applications beyond metrology*

At the start of the project, there were only few examples of T/F dissemination to institutions other than National Metrology Institutes (NMI) with documented results. Examples include the fibre connections in Italy, Poland and Sweden between an NMI and a VLBI/geodetic radio astronomical facility. Beyond radio astronomy, some non-NMI users in France, Italy and Germany were already exploiting fibre links for atomic and molecular spectroscopy. These links provided frequency rather than time transfer.

With the overarching aim of expanding the use and the usefulness of ultra-accurate time and frequency references for non-NMI users, the focus of the project has been on space geodetic applications and facilities on the one hand, and on regional multi-user networks on the other hand. In this context, particular attention has been paid to the benefit of time transfer as opposed to frequency transfer only.

#### 4.4.1 Space geodesy

In the framework of this project, we have described how optical fibre links disseminating time and frequency references would impact the study of geodesy in the field of radio astrometry and imaging, geodetic VLBI, relativistic geodesy and Satellite Laser Ranging. Initial theoretical analysis was complemented by experimental realizations in different countries (Germany, by TUM; Italy, by INRIM; Sweden, by RISE), each offering results at the state of the art in the field.

The role of accurate time transfer in the optical ground to space time transfer for space missions like ACES was analysed by OBSPARIS. It was found that the ground-to-ground segment, eventually using an optical fibre network, should be designed to reach at least a time deviation below 7 ps after one day of integration. It was shown that the time and frequency transfer from a UTC(k) to a ground station terminal, set hundreds of meters away, experimentally fulfils such stringent requirements.

Space geodesy is a scientific case that requires highly precise time and stable reference frequencies. Satellite laser ranging (SLR) is an optical two-way measurement technique that fulfils these needs (among other) and that is operated for example at the Geodetic Observatory Wettzell (Germany). It requires tight control of all possible signal delays in the ranging process. TUM identified time coherence locally and between geodetic fundamental stations as a promising tool to mitigate systematic errors, which map into the clock. To illustrate this by an example, TUM compared two remote masers, one in Wettzell (Germany) and the other one in Matera (Italy), by GNSS and through VLBI. The result showed a variable offset on the order of 1 ns over the course of two weeks, demonstrating the need for improved local timing distribution. The fundamental requirement on phase coherence of tick marks was identified at the level of less than 3 ps (corresponding to 1 mm).

Delay control of small and variable system delays is achieved at Wettzell Observatory through an optical delay-compensated timing distribution, resulting in an end-to-end time stability of about 2 ps over the duration of ~110 days. Under some assumptions, this may enable time comparison between the ground and the ACES space segment with a single shot resolution of 25 ps and 3 ps after 100 s integration time (for each measured satellite pass). It provides an independent and comparable approach for the interrogation of the ACES space clock with an unprecedented resolution. Physical height differences are expected to be observable with an initial resolution of approximately 20 cm from the result. It also provides a unique way of performing closure measurements. To illustrate an example for a SLR system, TUM implemented an optical event timer relating the SLR signal arrival directly to the clock markers of their new optical delay-compensated timing distribution. The results demonstrate that a long-term stable optical event timer can be realised with a remaining instability at the few ps level.

In Italy, INRIM disseminated an optical frequency reference from a Metrology Institute to two distant radio telescopes, Medicina and Matera, using a 1739-km-long phase-stabilized fibre link. Medicina and Matera, separated by a baseline of 600 km, are both part of the International VLBI Service for Geodesy and Astrometry (IVS). A microwave signal was synthesized at each telescope site using an optical frequency comb and could be used to feed the VLBI synthesis chain or be compared to a local active Hydrogen Maser or a geodetic GNSS receiver.

The described infrastructure allows the dissemination of microwave and optical frequency standards to multiple sites, with up to two orders of magnitude improvement in accuracy and stability as compared to local hydrogen masers or fibre-based RF dissemination. As a proof-of-concept experiment, INRIM used this infrastructure in a 24 h geodetic VLBI campaign where the two Italian telescopes shared a common fibre-delivered clock signal. These experiments demonstrate the feasibility of this approach and open the possibility of more advanced studies on VLBI limiting effects.

In addition, INRIM designed time transfer using the White Rabbit PTP technique on the Italian Quantum Backbone for SLR experiments at Matera. Within the duration of the project, the implementation reached Fucino, near Rome, where the Primary Time Facility for GALILEO is located. Time signals disseminated over this 1000 km long link were compared with GPS geodetic receiver signals, both in real time and in post-processing. Time transfer results in a time deviation of <400 ps from 300 s to 40000 s measurement time.

In Sweden, using the infrastructure of Swedish University Network, SUNET, the UTC(SP) site at RISE in Borås was connected to the clock room at Onsala Space Observatory (OSO). OSO is part of the International GNSS Service (IGS) global network of stations. The commercial time equipment used implements the White Rabbit (WR-PTP) protocol. For evaluation, the 1 PPS output on each site was connected to a Time Interval Counter (TIC) and thus referenced to a local Hydrogen maser. The masers are part of the present system, using GNSS Common View (CV) with a Precise Point Positioning (PPP) solution for monitoring. At RISE, the TIC was connected to HM6, which is one of the masers supporting the UTC(SP) realization and also reported to BIPM for UTC. At OSO, the TIC was connected to HM2, the maser used as main reference for VLBI observations as well as for the IGS. The measurements were monitored with reference to the starting conditions. We observed clear daily variation, caused by temperature variations in the two fibres, and the difference in the sensitivity of this variation in the two fibres. However, there is a correlation in the measured Round-Trip Time (RTT) of the WR-PTP link, and future work might look at correcting these deviations based on RTT. Hydrogen masers at OSO have been monitored and have participated in the realization of UTC(SP) for many years. This project enabled an increase in robustness and reliability through a fibre-based connection.

A connection between two further IGS stations, Torino and Paris, was operated and exploited by INRIM in Italy and CNRS and OBSPARIS in France. Torino and Paris are linked through an interconnect between the Italian Quantum Backbone and the French REFIMEVE network. Both fibre networks disseminate and compare optical signals referenced to an ensemble of microwave and optical clocks. The optical link between Torino and Paris was operated for months. The clocks involved in the network were the French fountains FO2-Rb and FO2-Cs, the Italian Cs fountain ITCsF2, and the Italian Ytterbium optical lattice frequency standard IT-Yb1. The primary clock comparisons showed a very good result, with relative statistical uncertainty of $2\times10^{-15}$ at 1000 s integration time. The clock comparison campaigns were used to compare the optical frequency transfer by fibre links with the RF frequency transfer via geodetic GNSS receivers. The results were cross compared to the frequency report published within the Circular T (BIPM) and by geodetic GNSS receivers using the integer ambiguity resolution and precise point positioning. The data are still under investigation as small differences between the modes of comparison were discovered.

### 4.4.2 Multi-user dissemination

Beyond the present exploitation of time and frequency transfer, the project aimed at using fibre links more widely to provide time and frequency references to users at regional non-NMI locations. To serve simultaneously many users within regional locations with optical reference frequencies while maintaining traceability, fibre links in a ring topology were developed. Pilot schemes were implemented in the Braunschweig-Hannover region (Germany) and in the Paris area (France).

In the Paris area, the performance of a ring topology network (a sub-network of REFIMEVE) was investigated by CNRS with the help of OBSPARIS. Users were located about 3 km apart, at the centre of Paris and at the East of Paris, at Sorbonne Université and Université Paris Cité. The service provides users with a SI-traceable optical frequency reference with a demonstrated instability below $10^{-15}$ (1s). Currently the SI-traceable optical signal is used to stabilise optical frequency combs at Laboratoire Kastler-Brossel for spectroscopy of $H_2^+$ for Quantum Electro-Dynamics tests, fundamental constant (namely proton to electron mass ratio) determination and fine structure constant determination, and at LERMA for molecular spectroscopy for atmospheric and astrophysical applications.

In Germany, in the Braunschweig-Hannover region, PTB implemented a fibre link providing multiple users with an ultra-stable reference frequency that can be traced back to the local implementation of the SI second at PTB. Measurements demonstrated a residual fractional frequency instability of the extracted frequency well below $10^{-16}$ after 1 s of averaging time and below $10^{-19}$ after ~100 s of averaging time. The ring closure, from the ultra-stable laser through the ring-shaped link back to the laser, ensures a continuous monitoring of the correct functioning of all relevant systems and correct frequency referencing to the SI-units.

### 4.4.3 Data availability

Phase noise data routinely collected when operating a fibre link may contain information useful for other scientific communities and areas of science, for example on seismic noise. In this project, steps were taken towards sharing this data with the wider scientific community. The work carried out was two-fold, covering software aspects on the one hand and legal and ethical aspects on the other hand.

An exchange format was adopted by PTB, NPL, INRIM, OBSPARIS and CNRS. Data processing procedures were developed by each institute, to eliminate as much as possible bugs, and the scripts were shared. This background served as a template to share phase noise data from their respective links available for analysis by the wider scientific community. A pilot study was set up with data from the REFIMEVE network by OBSPARIS and CNRS. Data of the operational supervision were linked to the data obtained from the supervision of the signal source and a set of end-to-end measurements. This was done by enabling an application programming interface (API) between servers.

It was found that there is no legal obstacle in sharing with scientists the noise measured with the fibre links, and probably other measurement data recorded in the network. Data sharing is first subject to the constraints of the legal institutions that administrate the infrastructure and take place in a general policy given by the European commission who encourage open science. The data can then be made available after an embargo time of typically 6 months to one year, but details on physical fibre path, the information system, its structure and protocols are considered sensitive and must be protected.

### 4.4.4 Summary

Ultrastable optical frequency references were disseminated to multiple academic users in the Braunschweig-Hannover and Paris regions, as well as to two radio telescopes in Italy. Particular highlights include the proof-of-concept geodetic VLBI experiment in which the two radio telescopes, separated by a 600 km baseline, were supplied with a common clock reference that was optically disseminated from the Italian NMI, and the first measurement with a newly created 1023-km-long fibre link between the NMIs of Italy and France. The benefits of utilising time for internal system delay compensation were shown at the example of the geodetic observatory Wettzell. A novel approach to address clock-related issues in VLBI was demonstrated by utilising a common clock reference disseminated via fibre,

Objective 4 of the project was fully met.

# 5 Impact

Outputs from the project were accepted for presentation at several national and international conferences. The major European conference in the field, the European Frequency and Time Forum (EFTF), accepted 19 contributions over the project duration (including those transferred to IFCS-ISAF 2020). Roughly the same number again were presented at a variety of other conferences and workshops. The project has generated 14 peer-reviewed publications, of which 5 have resulted from international collaborations, with a further 2 manuscripts submitted and 1 drafted.

A 2-day virtual stakeholder workshop on “Time and frequency dissemination over optical fibre networks” was held on 9-10 February 2021. More than 100 participants from a broad range of backgrounds heard an informative series of presentations from experts in industry, academia and research. A discussion session at the end of each day collected feedback and ideas from the participants that have contributed to the direction of activities in the field.

Highlights of the project close to completion were presented to more than 200 participants from around the globe at the international workshop “Optical clocks for international timekeeping”, hosted by the ROCIT project in October 2022. The session organised by our project also included a contribution by a representative of H2020 CLONETS-DS, “Time and frequency services via optical fibre networks for European science”, thus bringing together for the first time in a dedicated event three major lines of European projects concerned with optical time and frequency dissemination.

*Impact on industrial and other user communities*

Hardware and software developed within this project, such as the auto-locking tracking filter [2], the combined optical phase and polarisation tracker [3] and the Optical-Electrical-Optical (OEO) regeneration technique [13], will be incorporated, over time, into commercial products. Commercial systems, sub-systems and components resulting from outputs of this project will, in turn, facilitate the uptake of time and frequency services by the metrological and wider scientific community. The benefits of optical time transfer in supporting 5G networks have been highlighted in IEEE Communications Magazine [14].

To facilitate uptake, three specific outputs of this project have been designated “open hardware”. For the FPGA-based signal processing platform already mentioned, full design files for the custom circuit boards developed within this project, as well as programming examples, have been published on Zenodo (https://www.zenodo.org/record/7565427). For the digitally-enhanced analogue solution and the dual-polarization coherent receiver, the peer-reviewed publications was complemented with technical note published on Zenodo (https://www.zenodo.org/record/7459866 and https://www.zenodo.org/record/7503161, respectively),

Best practices regarding the compatibility of time and frequency services and data traffic have been communicated to network operators (specifically NREN) and equipment manufacturers and will enable new fibre links being implemented. Our cooperation with GÉANT, Europe's leading collaboration on e-infrastructure and services for research and education, is an example of such activity. The good practice guide for the coexistence of time and frequency signals with data traffic in DWDM networks produced within this project was submitted to the Euramet secretariat and is expected to be published as a Euramet Technical Guide.

*Impact on the metrology and scientific communities*

Improvements to the ability to inter-compare optical frequency standards were made available to the existing core network NPL-SYRTE-PTB-INRIM, which was utilised for an international optical clock comparison campaign in spring 2022 (as part of the EMPIR project ROCIT).

The project investigated the feasibility of adding time transfer capability to these links, which would enable connected NMIs to inter-compare their time scales with higher accuracy and more rapidly. Know-how of optically multiplexed combined time and frequency transfer fed into the design of at least one national fibre network under development.

Benefits of fibre-based synchronisation identified in this project were made available to a number of space-geodetic facilities including Matera and Medicina observatories, where a first experimental demonstration was performed [11]. Chronometric levelling and other scientific applications will benefit from enhanced reliability and automation. The developments in the project leading towards always-on fibre links and an "open data" approach have the potential to transform the way tests of fundamental physics are performed.

Multiple training events targeting relevant scientific communities, such as molecular physics or optical networking, were held to raise awareness of and promote insight into the opportunities optical time and frequency dissemination over fibre, both at the national and international level. The metrological community in Europe was kept abreast through regular presentations at the Euramet Technical Committee for Time and Frequency (TC-TF).

*Impact on relevant standards*

An overview of project activities and results was presented at each of the annual meetings of the EURAMET Technical Committee for Time and Frequency (TC-TF) from 2020 to 2023. The good practice guide for the coexistence of time and frequency signals with data traffic in DWDM networks produced within the project was presented to the TC-TF at its annual meeting in 2023. In addition, representatives of partner organisations within the project actively participated in the Consultative Committee for Time and Frequency (CCTF) working group for the redefinition of the SI Second.

*Longer-term economic, social and environmental impacts*

Time and frequency dissemination technology developed within this project, along with optical frequency standards, will contribute to an improved international time scale UTC, with applications in monitoring telecommunication networks and GNSS ground clocks, such as the Galileo Precision Timing Facility. Fibre optic delivery of secure, traceable timing could also help increase the resilience of critical infrastructure otherwise reliant on GNSS synchronisation. Improvements in geodetic and gravimetric measurement capability resulting from this project could contribute to tackling environmental challenges related to e.g. terrestrial water storage, ice mass changes and sea level variability. Chronometric levelling can provide long-term stable fix points for height grids leading to the unification of European height systems.

The high density of inter-connected (or inter-connectable) clocks puts Europe in a unique position to play a leading role in the redefinition of the SI second. It also facilitates large-scale dissemination of time and frequency references that otherwise would only be available at a few laboratories, to scientific or industrial end users. This project has taken another step towards a pan-European fibre network for time and frequency dissemination, and it has helped to ensure that European businesses and society will be the first to benefit from optical timing.

# 6 List of publications


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This list is also available here: https://www.euramet.org/repository/research-publications-repository-link/

All publications are available in the TiFOON community on Zenodo: https://zenodo.org/communities/tifoon/

# 7 Contact details

Not applicable.