



Publishable Summary for 18SIB06 TiFOON

Advanced time/frequency comparison and dissemination through optical telecommunication networks

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.

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.

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.

Progress beyond the state of the art

In EMRP SIB02 NEAT-FT and EMPIR 15SIB05 OFTEN, technologies for disseminating and comparing ultra-stable optical frequencies over fibre links had been developed and demonstrated. Efforts within EMPIR 15SIB05 OFTEN had focused on optical frequency transfer only.

Few time transfer over fibre techniques achieved performance beyond Global Navigation Satellite Systems (GNSS) and combined time and optical frequency transfer had only been demonstrated in proof-of-principle experiments. This project (**Objective 1**) investigated several approaches to combined time and frequency transfer ranging from immediately applicable solutions to exploratory research, aiming to occupy only a single Dense Wavelength Division Multiplexing (DWDM) channel.

Operating an optical frequency fibre link at the highest level of stability and accuracy required manually adjusting a large number of parameters. In addition, fibre and instrumentation suffered from impairments and were sensitive to environmental fluctuations. This project (**Objective 2**) took up key issues not fully addressed previously and developed solutions for improved phase coherence and automated link management.

Compatibility of time and frequency services with parallel data traffic had been demonstrated in principle in the networks of RENATER (France), PSNC (Poland) and CESNET (Czech Republic). However, there were still reservations among network operators and equipment manufacturers which prevented widespread uptake. In cooperation with stakeholders, this project (**Objective 3**) determined under which conditions the interference-free coexistence of time and frequency services and data traffic could be assured.

Very Long Baseline Interferometry (VLBI) had long been identified as potentially benefitting from optically delivered reference frequencies, although this had not yet been adopted widely. This project (**Objective 4**) focused on the benefits of disseminating time, rather than frequency, to space geodetic facilities, as well as on common clock architectures for improving GNSS data.

Results

Objective 1

Within this project, several 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.

A hybrid RF, time and optical carrier transfer solution based on optical multiplexing [1] was developed and successfully demonstrated. The solution combines ELSTAB technology with a standard optical frequency transfer setup in a bandwidth of just 0.22 nm, the typical pass band of a single 100 GHz channel optical add-drop multiplexer (OADM). The technique is compatible with data traffic in a telecommunication network. It is mature, rigorously tested and fully meets the accuracy targets of this objective.

Several different solutions for integrated optical time and frequency transfer, where the ultra-stable optical carrier is modulated directly, were developed in this project. To exploit synergies, a common hardware platform was used. These techniques currently lack the same maturity and rigour as optical multiplexing, but have the potential to become more precise, more sustainable and more flexible solutions in future. While there is considerable room for improvement, all have been shown to in principle support the accuracy targets.

Looking even beyond, a vision and roadmap towards fully optical time scales, using optical signals, was formulated. Components for the realisation and the comparison of time scales with the potential to reach sub-picosecond accuracy, such as optical flywheels, optical frequency combs and balanced cross-correlators, were considered. While it was found that a sound conceptual and technological basis exists, the lack of known solutions for femtosecond time transfer over long-haul fibre was identified as a critical weakness.

The objective of integrating optical carrier, radio frequency (rf) and time transfer within a single ITU channel and with an accuracy of 1 part in 10^{18} and 100 ps was fully achieved. Although none of the techniques could be implemented in a fibre link between NMIs, one was tested in a national fibre network and the others in laboratory testbeds. The objective of exploring novel concepts with sub-picosecond accuracy was achieved.

Objective 2

An extensive toolbox of technical solutions for improving the reliability and performance of optical fibre links was developed. Highlights include:

- A versatile, accurate, high dynamic range digital phase detector platform built on a commercial FPGA system-on-module. This easily reconfigurable platform enables scientists to implement customised signal processing algorithms helping to avoid cycle slips. The design is freely available, see below.
- A complementary solution [2] combining the simplicity, cost-effectiveness, and well characterised noise properties of analogue electronics with digital supervision and control, helping it deal with cycle slips with minimal disruption and fully autonomously, i.e., no need for human interaction.
- A novel, robust method [3] mitigating the issue of fading due to polarization changes, based on a dual-polarisation coherent receiver. This approach removes a major obstacle in the use of optical links where long measurement times and high reliability are required.
- A monolithic free-space interferometer [manuscript in preparation] with demonstrated uncertainty below 5×10^{-22} , well below the target uncertainty of this objective. This extremely low level of uncertainty renders the interferometer negligible as a source of error in optical frequency comparisons over fibre.
- Novel methods [manuscripts in preparation] allowing automatic balancing of the gains of a chain of optical amplifiers, based on beat signal analysis. Incorrectly set gains are a key driver of cycle slips, and manual optimisation is time consuming, especially in the face of constantly changing environmental conditions.

The frequency transfer performance and reproducibility of a 1400 km long fibre-loop was studied in-depth, before [4] and after implementing improvements developed in this project. These and other [5][6][7] results show that optical fibre links are 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^{-20} level. Within this project, polarisation-mode dispersion (PMD) in the fibre itself

[8][9] as well as polarisation effects in the optical components used for phase stabilisation have been analysed in detail, and the dominance of PMD in the long-term instability was unequivocally confirmed.

While many of the technical improvements still need to be rolled out, the objective of enabling human-interaction free operation over several weeks and 1 part in 10^{18} instability within one hour of averaging was achieved, and such performance was demonstrated.

Objective 3

Tests of unidirectional time and frequency transfer, carried out in a real network, demonstrated the limitations of this approach [10]. On the other hand, the compatibility of bidirectional transfer with data traffic was proven in multiple tests with commercial telecom equipment. Building on experience with the RENATER network, bidirectional optical frequency transfer was successfully implemented in a commercial Dense Wavelength Division Multiplexing (DWDM) network.

Underpinned by extensive tests and analyses performed within this project, a good practise guide for the coexistence of time and frequency signals with data traffic in DWDM networks was produced. The guide highlights situations where care is needed to ensure safe operation of time and frequency transfer and telecommunications equipment and provides advice for designing and operating such systems.

The combination of Raman amplification and bidirectional erbium-doped fibre amplifiers (EDFAs) was identified as critical, and several possible solutions were included in the good practice guide. The tendency of DWDM hardware vendors to integrate Raman with EDFA amplifiers into a single card was found to present additional hurdles for the parallel transfer of data and metrological signals in the C-band. In collaboration with the GÉANT Project GN4-3, solutions for metrological signals in the L-band or C-band were discussed.

The generation of non-linear phase noise was investigated using numerical simulations and was found to not yet impair time and frequency transfer in DWDM systems. The contributed instability was found to be a few orders of magnitude below levels of residual instability observed in pure time and frequency transfer networks.

The objective of demonstrating the compatibility of time and frequency signals with data traffic, and of determining safe operational conditions, was fully achieved. The close collaboration with GÉANT Project GN4-3 and national research and education networks (NREN) was a particular highlight of this project.

Objective 4

In Italy, a 1739-km-long phase-stabilized fibre link was established disseminating an optical frequency reference from the National Metrology Institute (NMI) to two radio telescopes, Medicina and Matera, both part of the International VLBI Service (IVS). The link was successfully used for common-clock very long baseline interferometry (VLBI) [11]. In addition, White Rabbit (WR-PTP) time transfer was designed 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.

In Sweden, the UTC(SP) site in Borås was connected to Onsala Space Observatory (OSO), part of the International GNSS Service (IGS), using the WR-PTP protocol. Hydrogen masers at OSO have participated in the realization of UTC(SP) for many years. The fibre connection enabled an increase in robustness and reliability.

A connection between two further IGS stations, Torino and Paris, was exploited for comparing primary and secondary frequency standards over months [12]. A parallel comparison via geodetic GNSS receivers allowed to observe the differences between the two modes of comparison, similar to a common-clock experiment.

A detailed study identified time coherence as a promising tool to mitigate systematic errors when comparing different space geodetic techniques. The fundamental requirement on phase coherence was identified at the level of less than 3 ps (corresponding to 1 mm). Proof-of-principle experiments performed with the optical delay-compensated timing distribution at Wettzell Observatory confirmed that this level can be achieved.

Multi-user networks with a ring topology, disseminating traceable optical frequency references to academic users, were implemented in the Braunschweig-Hannover region (Germany) and in the Paris area. The ring closure ensured continuous monitoring of the operation and of the accuracy of the disseminated reference.

The objective of disseminating ultra-stable frequency and time signals to non-NMI users was fully achieved with the activities in Italy, France and Germany. The objective of disseminating time, specifically, was achieved

in Sweden and Italy. The objective of investigating proper time transfer between geodetic markers was fully achieved. As another example, intercontinental clock comparison via VLBI is a novel application that arose outside the scope of this project but was inspired by, and builds on, its results.

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.

List of publications

- [1] P. Krehlik, Ł. Śliwczyński, Ł. Buczek, H. Schnatz, and J. Kronjäger, ‘Optical multiplexing of metrological time and frequency signals in a single 100 GHz-grid optical channel’, *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, pp. 1–1, 2021, <https://doi.org/10.1109/TUFFC.2021.3053430>.
- [2] P. Włodarczyk, P. Krehlik, and Ł. Śliwczyński, ‘A maintenance-free solution for optical frequency transfer’, *Metrology and Measurement Systems*, vol. 27, no. No 3, pp. 441–450, Oct. 2020, <https://doi.org/10.24425/mms.2020.134586>.
- [3] C. Clivati *et al.*, ‘Robust optical frequency dissemination with a dual-polarization coherent receiver’, *Opt. Express, OE*, vol. 28, no. 6, pp. 8494–8511, Mar. 2020, <https://doi.org/10.1364/OE.378602>.
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- [5] M. Schioppo *et al.*, ‘Comparing ultrastable lasers at 7×10^{-17} fractional frequency instability through a 2220 km optical fibre network’, *Nature Communications* vol. 13, p. 212, 2022. <https://doi.org/10.1038/s41467-021-27884-3>
- [6] M. B. K. Tønnes *et al.*, ‘Coherent fiber links operated for years: effect of missing data’, *Metrologia*, vol. 59, p. 065004, 2022. <https://doi.org/10.1088/1681-7575/ac938e>

- [7] S. Koke, E. Benkler, A. Kuhl and G. Grosche, 'Validating frequency transfer via interferometric fiber links for optical clock comparisons', *New Journal of Physics*, vol. 23, p. 093024, 2021. <https://doi.org/10.1088/1367-2630/ac21a0>
- [8] D. Xu, O. Lopez, A. Amy-Klein and P.-E. Pottie, 'Non-reciprocity in optical fiber links: experimental evidence', *Optics Express*, vol. 29, no. 11, pp. 17476-17490 (2021). <https://doi.org/10.1364/OE.420661>
- [9] D. Xu, O. Lopez, A. Amy-Klein and P.-E. Pottie, 'Polarization Scramblers to Solve Practical Limitations of Frequency Transfer', *Journal of Lightwave Technology*, vol. 39, no. 10, pp. 3106 – 3111, May 2021. <https://doi.org/10.1109/JLT.2021.3057804>
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- [11] C. Clivati *et al.*, 'Common-clock very long baseline interferometry using a coherent optical fiber link', *Optica, OPTICA*, vol. 7, no. 8, pp. 1031–1037, Aug. 2020, <https://doi.org/10.1364/OPTICA.393356>.
- [12] C. Clivati *et al.*, 'Coherent Optical-Fiber Link Across Italy and France', *Physical Review Applied*, vol. 18, no. 5, p. 054009, Nov. 2022. <https://doi.org/10.1103/PhysRevApplied.18.054009>
- [13] P. Krehlik, Ł. Śliwczyński, and Ł. Buczek, 'Electrical regeneration for long-haul fiber-optic time and frequency distribution systems', *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, pp. 1–1, 2020, <https://doi.org/10.1109/TUFFC.2020.3016610>.
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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/>

Project start date and duration:		1 st June 2019 36 Months (extended to 42 Months)
Coordinator: Jochen Kronjäger, PTB		Tel: +49 531 592 4341
Project website address: http://empir.npl.co.uk/tifoon/project/		E-mail: jochen.kronjaeger@ptb.de
Internal Funded Partners:	External Funded Partners:	Unfunded Partners:
1. PTB, Germany	7. AGH, Poland	16. METAS, Switzerland
2. INRIM, Italy	8. CESNET, Czech Republic	
3. OBSPARIS, France	9. CNRS, France	
4. NPL, UK	10. ISI, Czech Republic	
5. RISE, Sweden	11. Muquans, France (ceased to exist on 31/07/2021)	
6. VSL, Netherlands	12. POLITO, Italy	
	13. PSNC, Poland	
	14. TUM, Germany	
	15. iXblue, France (participation from 1 st December 2020)	
Linked Third Parties:		
17. CNRS, France (linked to OBSPARIS)		
18. UP13, France (linked to CNRS)		
RMG01: INRIM, Italy (Employing organisation); IMBiH, Bosnia and Herzegovina (Guestworking organisation)		