Final Publishable JRP Summary for JRP SIB02 NEAT-FT
Network for European Time and Frequency Transfer

Overview

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

Need for the project

Frequency metrology: Optical clocks have now surpassed the best caesium-based atomic clocks in both accuracy and stability; they are the most promising candidates for the expected redefinition of the SI unit of time, the second. However, adequate means to compare distant clocks at the highest level of accuracy are missing, but such a comparison is a vital issue for optical clock development and for the exploration of their fundamental limitations. The best optical clocks today reach a fractional accuracy of the order of 10^{-17} or better and this outstanding performance makes them ideal tools for various tests of fundamental physics. Optical fibres are now the preferred alternative to conventional satellite techniques for time transfer between optical clocks, but it is necessary to demonstrate the techniques and technology are in place for the expected redefinition of the SI second by means of an optical clock.

Dissemination of reference frequencies and timing signals to the scientific community: There is an increasing demand by scientific organisations and universities for accurate links to National Measurement Institutes for reference to the SI (International System) second. In typical research laboratories, high-resolution optical frequency measurement is limited by the accuracy of commonly-used rubidium clocks, which are referenced to UTC (Coordinated Universal Time) via GPS (Global Position System). In the longer term, it is likely that some of the most advanced applications of future atomic clocks will be space based, and their operation will require ground stations with access to ultra-stable frequency references linked to the best available ground clocks. In this respect optical fibre links to these ground stations will become crucially important.

Industrial and technological needs: In addition to these scientific developments, high performance frequency metrology is also at the heart of a number of industrial and technological applications, such as defence and aerospace engineering, geodesy, navigation, electronic transactions, communication systems (Internet, mobile telecommunications and electronic financial transactions). It is envisaged that the need for improved time and frequency transfer methods will grow once the SI second is redefined in terms of an optical atomic transition, and optical clock systems are spread all over Europe.

Scientific and technical objectives

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

The project addressed the objectives:

1. Develop novel techniques for frequency comparisons in the ~10^{-18} range at 1 day measurement time using optical fibres and the necessary equipment such as repeater stations, amplification concepts and remote control systems.
2. Development of methods, protocols and techniques for accurate time dissemination and the consideration of different complementary methods and levels of accuracy reaching from a sub-1 nanoseconds (ns) level to the sub-microseconds (sub-µs) level.

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

Results

The project has achieved all its objectives, and demonstrated the equipment and technology necessary to move to optical clock technology. Testing was more extensive and comprehensive than originally proposed, as there was more access to fibres, both dedicated and commercially available.

This project is the fundamental breakthrough towards a European scientific network which will allow for optical clock comparisons at the highest level of accuracy. This is already demonstrated by the world's first international direct clock comparison performed between Strontium lattice clocks located at PTB, OBSPARIS and NPL. The necessary equipment has been developed, tested and found to be fit for purpose.

Objective 1: Develop novel techniques for frequency comparisons in the ~10^{-18} range at 1 day measurement time using optical fibres and the necessary equipment such as repeater stations, amplification concepts and remote control systems.

Remote control of equipment installed along a fibre link is essential for long term operation, error detection and trouble shooting. Remote monitoring techniques were developed and are now available for real fibre links. A prototype of a high-speed signal monitor, based on that of a digital phase comparator, has been developed allowing real-time (<200 ns) detection of cycle slips between two signals and detection of signal loss. Two other techniques for fast analysis of error signals have been developed.

Improved Erbium Doped Fibre Amplifiers, with reduced noise and remote control, were developed and made available commercially. Remote laser stations and fibre Brillouin amplifiers have been developed and tested over more than 1000 kilometres. Measurements over a fibre length of around 1400 km demonstrated an extremely small uncertainty contribution in the 10^{-20} range [[1]].

The prototype Remote Laser Station was successfully tested in the field [[2]] and regenerates the optical signal and removes excess optical phase noise accumulating along a fibre link. Results over 1480 km of internet fibre were demonstrated and showed relative frequency stability of $7x10^{-16}$ at one second integration time and uncertainty contribution below 10^{-19} [[3,3]].

Alternative techniques for signal regeneration and wavelength switching were investigated. Raman amplification of signals derived from ultra-stable lasers was investigated and it was demonstrated that a Distributed Raman Amplifier does not add extra noise to the optical link, allowing very long fibre spans to be bridged without the need of intermediate stations[[4]].

Two-way techniques were developed and used to achieve long-haul optical frequency comparisons over multiplexed fibre networks in an urban area [,]. Two-times better stability than actively compensated system were demonstrated.

Fundamental limits of fibre links were investigated and sources of noise degrading the performances at medium range of integration were identified and eliminated [[5]]. The systematic uncertainty of a fibre link was carefully evaluated [[2]], and the relative frequency stability in 1-Hz bandwidth at the 10^{-20} range was demonstrated [2-4, 6-7].

The demonstrated length of a stabilised link has been extended up to nearly 2000km using a dedicated fibre in Germany in a loop configuration [[6]]. The demonstrated length of a stabilised link on an active internet network has been extended to nearly 1500 km using optical regeneration.

Objective 2: Development of methods, protocols and techniques for accurate time dissemination and the consideration of different complementary methods and levels of accuracy reaching from a sub-1 ns level to the sub-µs level.

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1 S. M. F. Raupach, *et al.*, Phys. Rev. A, 92, 021801(R) (2015)
2 O. Lopez *et al.*, Comptes Rendus Physique, 16 (5), pp. 459-586 (2015)
3 Chiodo *et al.*, in prep. (2015)
4 G. Bolognini, *et al.* IEEE Photonic Conference 2014, p.1-3 (ISBN 978-1-4577-1504-4)
5 F. Stefani *et al.*, J. Opt. Soc. Am. B, Vol. 32, No. 5 p. 787 (2015)
6 S. Droste *et al.*,PRL 111, 110801 (2013)

Time transfer over optical fibre now provides a superior alternative to GNSS based time transfer. There have been several independent demonstrations of a timing instability significantly below 100ps and a timing uncertainty well below 1ns.

Experiments performing simultaneous optical frequency and accurate timing transfer have been demonstrated, achieving 6ps timing stability and 250ps accuracy over internet fibre with parallel data traffic between two remote sites [7].This was the first demonstration that it is possible to transfer simultaneously an ultra-stable optical frequency and precise and accurate timing over optical fibres with sub-ns accuracy.

Additionally, a novel time transfer technique based on the propagation of a pulse train in fibre has been developed. A timing jitter of ≈400 fs at 10 s integration time was achieved.

An alternative technique for synchronisation and time transfer via coherent frequency transfer was developed and demonstrated in a proof-of-principle experiment [8].

A GPS carrier-phase frequency transfer link along a baseline of 450 km has been established and is characterised by comparing it to a phase-stabilised optical fibre link of 920 km length, established between the two endpoints [9].

Alternative techniques for frequency and time transfer in the RF domain were developed including multiple user distribution [10]. This system has been upgraded for long-distance time and frequency transfer and is now being used in field experiments in Poland and Germany [11]. This system achieves a relative instability below 1ps, a timing accuracy at the 10ps level and has been operated continuously over months.

A study on feasibility of a standard uni-directional network for long-haul timing dissemination using Precision time Protocol - White Rabbit was initiated. The performance and reliability of the fibre link were found to be excellent, but the results were limited by the statistics of the GPS–PPP link.

Objective 3: Identify applications that require or significantly benefit from remote fibre links and consider the next steps fostering the decision of funding a future European fibre network or bi-directional connections of selected points of presence in close collaboration with stakeholders.

The fibre links established while this project was running have enabled it to go far beyond the original planned activities. Bi-directional fibre links have been established between prominent NMIs or stakeholders from academia, and the first international comparison of optical clocks has been performed [12].

Multiple user distribution schemes that allow extraction of a stable reference frequency at several points along a given link have been developed [13,14], demonstrating that the second-user signal can be even better than the main user signal. Three new long haul links (up to 1840 km) have been characterised, stabilised and evaluated. The links are now ready to perform for frequency comparisons of optical clocks between European NMIs.

Applications that significantly benefit from this project range from low-level laser frequency calibration, length interferometry, and remote wavelength standard calibration, over the synchronisation and timing of accelerator facilities or mobile telecommunication networks, the validation and improvement of GNSS, to high-end applications in geodesy and fundamental research.

Actual and potential impact

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

Dissemination of results

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

7 O. Lopez *et al.,* Comptes Rendus Physique, 16 (5), pp. 459-586 (2015)
8 Raupach et al.,Proceedings EFTF 2013
9 S. Droste, *et al.*; New J. Phys. **17**, 083044 (2015)
10 Ł. Śliwczyński, P. Krehlik; IEEE Transactions on UFFC, **62**, pp. 412-420, (2015)
11 P. Krehlik *et al.,* European Frequency and Time Forum (EFTF) 2013
12 C. Lisdat et al., Nature Comm. (2016), in press
13 G. Grosche, Opt. Lett. **39**, 2545-2548 (2014)
14 A. Bercy, et al., J. Opt. Soc. Am.**B** 31, 678-685 (2014)

Early impact

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

Potential future impact

This work has three potential areas of impact:

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

List of publications:

1. S. M. F. Raupach, *et al.*; *"Subhertz-linewidth infrared frequency source with a long-term instability below 5 times 10^{-15}",* Appl. Phys. **B 110**, 465 (2013)
2. S. Droste, *et al.*; *"Optical-Frequency Transfer over a Single-Span 1840 km Fiber Link",* Phys. Rev. Lett. **111**, 110801 (2013)
3. S. M. F. Raupach and G. Grosche; *"Chirped Frequency Transfer with an accuracy of 10^{-18} and its Application to the Remote Synchronisation of Timescales",* IEEE Transactions on UFFC **61**, 920-929, (2014)
4. G. Grosche; "Eavesdropping time and frequency: phase noise cancellation along atime-varying path, such as an optical fiber", Opt. Lett. **39**, 2545 (2014)
5. S. M. F. Raupach, A. Koczwara and G. Grosche; *Optical frequency transfer via a 660 km underground fiber link using a remote Brillouin amplifier,* Optics Express, **22**, 26537-26547 (2014)
6. S. M. F. Raupach, A. Koczwara, and G. Grosche; *Brillouin amplification suports $1{\times}10^{-20}$ uncertainty in optical frequency transfer over 1400 km of underground fiber,* Phys. Rev. A, 92, 021801(R) (2015)
7. S. Droste, *et al.*; Characterization of a 450-km Baseline GPS Carrier-Phase Link using an Optical Fiber Link, New J. Phys. **17,** 083044 (2015)
8. C. Clivati, *et al.; "Distributed Raman optical amplification in phase coherent transfer of optical frequencies",* Photonics Technology Letters, IEEE , **25**, 1711 (2013)

9. C. Clivati, G. Bolognini, D. Calonico, S. Faralli, F. Levi, A. Mura, and N. Poli; *Distributed Raman optical amplification in phase coherent transfer of optical frequencies,* IEEE Photonics Technology Letters, **25**, 1711-1714, (2013)
10. C. E. Calosso, *et al.; "Frequency transfer via a two-way optical phase comparison on a multiplexed fiber network",* Opt. Lett. **39**, 1177- 1180 (2014)
11. D. Calonico et al., "*High accuracy coherent optical frequency transfer over a doubled 642 km fiber link"* Applied Physics B, **117**, pp 979-986 (2014)
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14. D. Calonico, M. Inguscio, F. Levi, "*Light and the distribution of time"*, European Physics Letters **110** 4000 (2015)
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18. P. Krehlik, Ł. Śliwczyński, Ł. Buczek, J. Kołodziej, M. Lipiński; *Ultrastable long-distance fiber-optic time transfer: Active compensation over a wide range of delays,* Metrologia, **52** , pp. 82-88, (2015)
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23. J. Kim, R. Slavik, H. Schnatz, D. S. Wu, D. J. Richardson; *Optical injection locking based amplification in phase coherent transfer of optical frequencies,* Optics Letters Vol. **40**, No. 18. pp. 4198, (2015)
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