Publishable JRP Summary Report for JRP SIB02 NEAT-FT Accurate time/frequency comparison and dissemination through optical telecommunication networks

Background

The aim of the project NEAT-FT is to investigate new techniques for phase-coherent comparison of remotely located optical clocks, separated by distances of up to 1500 km using optical fibre links. Within the scope of the JRP the equipment necessary for reliable operation of fibre links will be developed and all technological steps towards a full optical link infrastructure demonstrated. Beside frequency dissemination, new techniques for time transfer over optical fibre networks will be investigated in order to provide better timing signals than currently available with GPS receivers. For typical spans of up to 100 km the JRP aims to improve the accuracy down to about 100 ps. Furthermore, the feasibility of a European fibre network connecting optical clocks in Europe will be studied in close collaboration with potential fibre providers.

Leading European National Metrology Institutes (NMIs) and one representative (CESNET) from the National Research and Educational Networks (NREN) have joined to meet the scientific and technical needs for highly stable and accurate reference signals in fundamental physics, GNSS, geodesy, astronomy, and (space-) industry.

Need for the project

The best optical clocks today reach a fractional accuracy of the order of 10^{-17} and this outstanding performance makes them ideal tools for various tests of fundamental physics. Moreover, optical clocks have now surpassed the best caesium-based atomic clocks in both accuracy and stability and 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. Comparison is a vital issue for optical clocks development and to explore their fundamental limitations. However, as conventional satellite-based techniques do not reach the required performance alternatives must be developed.

There is an increasing demand by scientific organisations and universities for accurate links to NMIs for reference to the SI 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 via GPS. 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 such locations will become of central importance. Furthermore, those sites will allow linking the network to other continental networks (USA, Asia, Australia) using relay satellites and optical free space techniques that are being developed today.

Scientific and technical objectives

The JRP addresses the following scientific and technical objectives:

- 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 will be developed.
- “The 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” will be carried out.
- “Applications that require or significantly benefit from remote fibre links” will be identified and considered in close collaboration with stakeholders with the aim of fostering the decision of funding a future European fibre network or bi-directional connections of selected points of presence.

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European Metrology Research Programme
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Expected results and potential impact:

- A prototype of a **high-speed signal monitor** based on that of a digital phase comparator has become available allowing real-time (<200 ns) detection of cycle slips between two signals and detection of signal loss.
- Three fibre **Brillouin amplifier modules** have been installed in the German part of the fibre link between Paris and Braunschweig. First results have been published in Optics Express [1]. Tests of the performance of the link between Braunschweig and Strasburg are currently carried out.
- The prototype **Remote Laser Station** developed by SYRTE and LPL was successfully tested in field. The station acts as "optical tracking filter" to remove excess optical phase noise accumulating along a fibre link. The signal regeneration system has been duplicated four times for the Paris-Braunschweig link. One of the stations will be installed at the cross boarder link in Strasburg in near future.
- Two different system designs of compact **stabilized lasers at 1.54 µm** have been finalized and their performances have been investigated. Compared with the cavity stabilized system the delay-stabilized laser system is simpler, more cost effective and compact; however, it shows a significantly larger drift of up to 10 kHz/s. This system may be used as clean-up laser along fiber links, but is not suitable as reference laser system without further improvement of the long term stability.
- A **multiple user distribution scheme** that allows extraction of a stable reference frequency at several points along a given transmission path has been developed [2,3].
- A **novel time transfer technique** based on the propagation of a pulse train in fibre has been developed and tested over a 50 km spooled fibre demonstrating a timing jitter significantly below 1 ps and a timing accuracy of the absolute delay of 160 ps. The resolution was limited by the time interval counter. These results have been confirmed using 198 km using installed fibre between NPL and Reading in combination with 40 km of spooled fibre. A timing jitter of ≈400 fs at 10 s integration time was achieved.
- Work has continued on the **testing of White Rabbit equipment over long distance**. The main result is the first demonstrated long-term operation of a long-distance. In a 120 day comparison between GPS-PPP time transfer and the 1000-km long link White Rabbit time link in a live DWDM network, the performance and reliability of the fibre link were found to be excellent and the results were limited by the statistics of the GPS–PPP link.
- Work towards the implementation of **three new long haul links** is progressing well. The links are expected to be established before the end of the JRP: Paris-Strasbourg-Paris (2x750 km), Braunschweig-Strasbourg-Braunschweig (2x700 km), London-Paris-London (2x800 km).
- **The Italian link LIFT** has been extended from INRIM to the Italian-French cross-border at the tunnel of Frejus. The link is operational and will support activities within the JRP ITOC by providing the basis for a proof of principle experiment on relativistic geodesy.
- A system for long-distance time and frequency transfer is now ready for field experiments.
- A regenerative amplifier for optical frequency transfer based on optical injection locking has been developed. The portable prototype built with 19-inch rack boxes has been tested. In a proof-of-principle experiment the device was used as a mid-stage amplifier in a bi-directionally operated 292-km long installed dark fiber link (total loss of 86 dB).
- The use of distributed Raman amplification in a coherent frequency transport link involving a 94 km fiber shared with ITU channels carrying data traffic has been investigated. In the shared link experiment, the

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1 S. M. F. Raupach, A. Koczwara and G. Grosche; "Optical frequency transfer via a 660 km underground fiber link using a remote Brillouin amplifier," Opt. Express, **22**, 26537 (2014)

2 G. Grosche; "Eavesdropping time and frequency: phase noise cancellation along a time- varying path, such as an optical fiber," Opt. Lett. **39**, 2545-2548 (2014)

3 A. Bercy, et al., "In-line extraction of an ultra-stable frequency signal over an optical fiber link," J. Opt. Soc. Am.**B** 31, 678-685 (2014)

DRA showed a good compatibility with other ITU data channels lying within the amplifier gain bandwidth. The main advantages of this technique are high gain and feasibility of long fiber spans with a simple apparatus, without degrading the link stability. For the stabilized link a fractional frequency instability of $3 \cdot 10^{-19}$ over 1000 s was achieved at the remote end.

The results of the JRP will enable NMIs to perform better clock comparisons within Europe, and to disseminate highly accurate and stable frequency and timing signals to the user community for groundbreaking science and innovation. Some members of the potential user community are already collaborating with the JRP.

JRP start date and duration:	June 2012, 36 months
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The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union