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Open Call Deliverable OCL-DS3.2 Final Report (ICOF)

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Abstract

In order to enable optical clock comparisons between the national metrology institutes of the UK and France we have installed bidirectional optical amplifiers in 8 locations of a dark fiber provided by GÉANT, A retroreflector was installed at the output of the amplifier in each location during installation and testing, so that a beat signal could be received at NPL after a round trip. This signal was used to characterize the phase noise of the link. These phase noise measurements have shown that most of the environmentally induced noise arises from the metropolitan areas, in particular the Central London area. The measured noise levels are consistent with what reported for other optical links in Europe and Japan. This link will in future enable clock comparisons between NPL and OBSPARIS.

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1	16-02-15	First draft issued	H. Schnatz
2	02-03-15	Second draft issued	P.-E. Pottie
3	16-03-15	Third draft issued	H. Schnatz
4	19-03-15	final draft issued	H. Schnatz
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Executive Summary

This guide describes:

- Recent results of the Project ICOF, **International *Clock Comparisons via Optical Fibre***

1 Introduction

Objectives:

The aim of ICOF is to establish a stabilized fibre link between NPL and OBSPARIS and to perform a state-of-the-art atomic clock comparison at the level of 10^{-16} or below using the GÉANT long haul dark fibre link between NPL (London) and OBSPARIS (Paris).

Background:

Europe has the highest density worldwide of laboratories in which state-of-the-art atomic clock development is underway. However, Europe's unique position can only be fully exploited if the clocks can be compared internationally at the highest possible level of accuracy.

State-of-the-art atomic clocks located laboratories separated by distances larger than a few hundreds km can currently only be compared at a reduced accuracy by using satellite links. The best accuracy achievable by these free space microwave links is in the order of 10^{-15} after 1 day of integration time and therefore international comparison of atomic clocks cannot be performed at the required level that would enable new advances to be achieved.

Optical fibre links allow for time and frequency comparisons to be performed at a much higher level of accuracy and stability than that currently achievable by more conventional satellite links [1, 2, 3, 4, 5, 6]. The demonstration of a successful clock comparison between remote laboratories will have substantial impact on progress in the time and frequency metrology field as well as contribute to paving the way to further fundamental physics experiment, geodesy and other areas of science.

Introduction:

The comparison of remote clocks via optical fibre requires the cancellation of the environmentally-induced phase noise of the 800 km-long fibre link. This is achieved by applying state-of-the-art frequency transfer techniques. Differently from most telecommunication techniques, where opto-electronic conversion can be used along the link for signal regeneration, an all-optical path was required between the two end laboratories to achieve frequency transfer at the appropriate level of stability and accuracy. The GÉANT long haul dark fibre thus provided an ideal test bed for the clock comparison between NPL and OBSPARIS, using also a dark fiber connecting SYRTE to the third party Laboratoire de Physique des Lasers (LPL).

The frequency transfer over the optical fibre link required the installation of bi-directional optical amplifiers a number of locations along the link, with an average span between amplifiers of 80-100 km. At each end, the frequencies transferred over the fibre link were related to the clock frequencies using an optical frequency comb, combining optical frequency metrology and frequency transfer techniques.

Figure 1: Map of the London-Paris link that has been employed to compare the optical clocks in NPL and OBSPARIS.

2 Project Stucture and Outcomes

Section	Description of Contents
Approach	This section describes the measures take to establish an optical connection between NPL and OBSPARIS
Results	96% of the fibre link has been equipped with remotely-controlled bi-directional optical amplifiers so that a metrological optical carrier sent from NPL was successfully returned back to NPL after a 1600 km round trip. Some technical problems and equipment failures have caused some delays so that a clock comparison could not be achieved within the tight time scale of the project. However, internal funding to extend the link until August 2015 has been secured and comparisons will be performed during this time frame.
Observations	The work done so far has proven invaluable in order to pave the way for international comparisons of optical clocks via optical fibre links, by highlighting the technical challenges and successfully testing of appropriate solutions. The link is an ideal test bed and a showcase for innovation in the area of time and frequency metrology. The progress made to far is the result of a highly collaborative effort between NPL, OBSPARIS and PTB and each laboratory has contributed with their diverse knowledge, skills and equipment.
Recommendations	This work should be continued for its impact on the future of frequency metrology and its applications in science and industry

Table 2.1: Sections and their contents.

2.1 Approach

The cancellation of the fibre noise requires an optical carrier from a highly-stable laser to be propagated from NPL to SYRTE for then to be returned back to NPL for comparison with the same optical reference. This requires the installation of bidirectional Erbium-doped optical amplifiers (bi-EDFA) and optical filters in 9 locations along the link. The locations range from main datacentres in busy metropolitan areas to small huts in the countryside or town suburbs. Contrary to standard telecommunication optical links which use only one direction of propagation per fibre, this project requires bidirectional propagation within the same fibre to achieve the best possible symmetry of the environmentally-induced noise in the fibre. Thus, standard optical amplifiers are unsuitable and specially made bidirectional amplifiers have to be employed. However, bidirectional amplifiers are prone to self-oscillations and careful in-situ optimization of the amplifier is required in order to avoid oscillations whilst maintaining a sufficient signal-to-noise. Starting from NPL, the link was progressively extended by adding one amplifier at the time in increasingly distant locations along the link. Testing and optimization was carried out with staff being present at the remote hut as well as NPL.

In addition to the Erbium-doped fibre amplifiers, a high gain fibre Brillouin optical amplifier is required at the intermediary laboratory LPL (43 km away from SYRTE, in fibre length terms) in order to increase the signal to noise ratio of the optical carrier from NPL. A Brillouin amplifier is required as standard EDFAs do not exhibit a sufficiently high gain for the last stretch of fibre from NPL to LPL.

The comparison of the NPL and SYRTE optical clocks is performed by comparing the optical carriers from NPL and SYRTE, which are related to the optical clock transition frequencies using an optical frequency comb at each end, at the intermediate laboratory LPL. The complex optical and radio-frequency experimental setup is shown in Fig.2

The NPL to LPL connection is achieved almost entirely over a dark fibre network, where Internet traffic is present in parallel on the span from InterXion (Aubervilliers) to LPL. The link between SYRTE and LPL is operated over a pair of dark fiber.

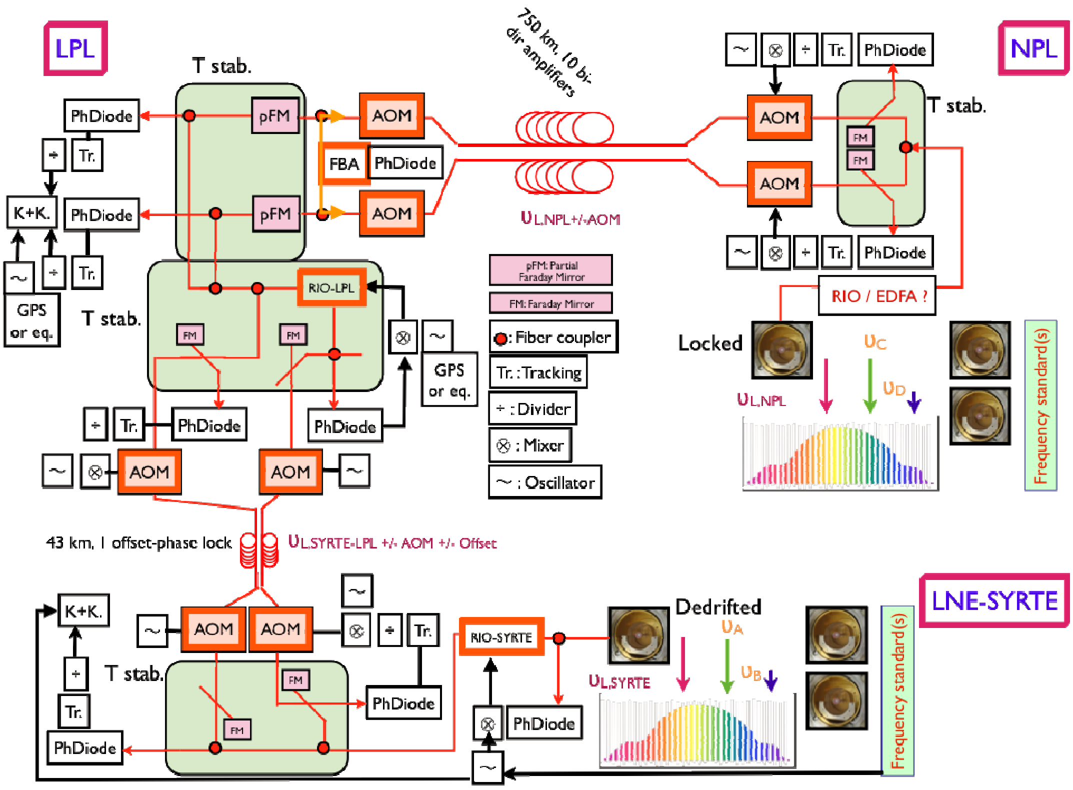

Figure 2: Overall sketch of the experiment NPL-LPL-SYRTE.

2.2 Results

The aim of ICOF was to establish a stabilized fibre link between NPL and OBSPARIS and to perform a state-of-the-art atomic clock comparison at the level of 10^{-16} or below using the GÉANT long haul dark fibre link between NPL (London) and OBSPARIS (Paris).

The following deliverables have been planned:

	Work package title	Type of activity	Person months	Start month	End month
D1	Establishing a stabilized fibre link between London and Paris	RTD	12,2	10/13	06/14
D2	Performing clock comparisons at the level of 10^{-16} or below between National Metrology Institutes.	RTD	8,5	07/14	03/15
D3	Impact	other	0,9	03/15	06/15
D4	Management	MGT	0,4	10/13	06/15

For deliverables 1 – 4 we have performed the following tasks:

D1.1 **Installation of equipment along the link**: Bi-directional optical amplifiers were installed in 8 out of 9 locations, with the last remaining amplifier to be installed in Paris Gateway (GWY), in the outskirts of Paris (Figure 3). A number of logistic and technical challenges had to be overcome, such as missing or excessively lossy connections in a number of locations. Due to a failure of amplifiers in UK and delay to get funded and delivered for in France, measurements for the full link have been delayed. The delay was partly compensated in France by swapping the work plan schedule between task 2 and task 1. Alternative techniques were investigated, as uni-directional operation. The outcome of the research was published in Phys. Rev. A. [7] (Phys. Rev. A 90, 061802(R)), with explicit mention of the GN3+ funding support.

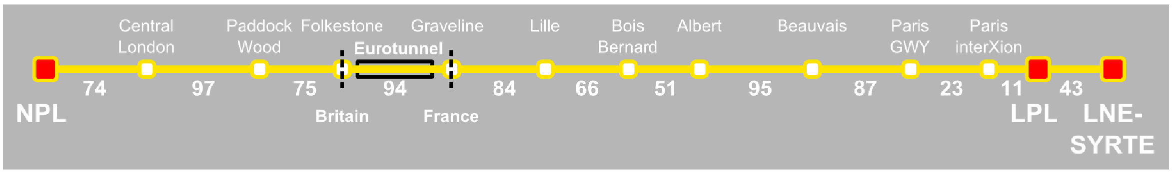

Figure 3: Huts and distances (in km) along the London-Paris link, including connections from the GEANT PoPs to NPL and LPL respectively.

A typical setup is shown in Figure 4. The bi-EDFA amplifiers are remotely controlled by GSM signals except for Central London where a wired internet connection was available. A novel, more reliable communication system based on control signals transmitted through the fibre rather than GSM has been developed and tested. The data link is established over the same dark fibre pair as the metrological signal using wavelength multiplexing.

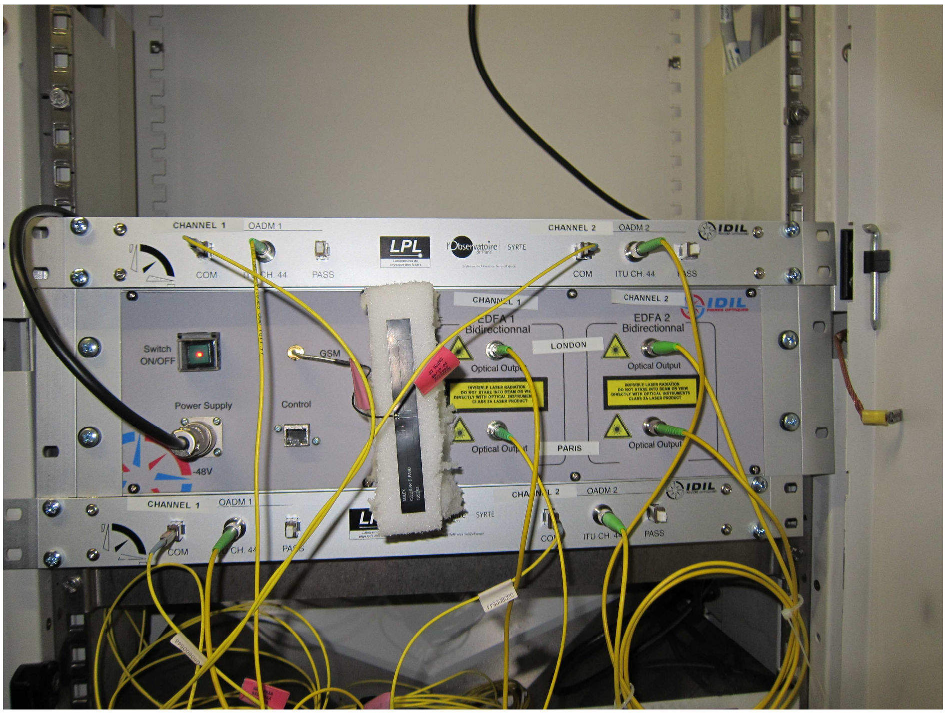

Figure 4 :Sketch and picture of the setup as realized in Lille-Bois Grenier. At the bottom and the lower part sits the optical Add/Drop Modules (OADMs) The double bi-directional amplifier (centre) is sandwiched between optical Add/Drop Modules (OADMs), used to restrict amplification and spontaneous emission to only the relevant ITU channel. The GSM antenna is visible at the front (vertical black strip).

D1.2 **Development of the fibre link stabilization system:** Interferometric stabilization systems (see Figure 5) were built to actively compensate the phase fluctuations accumulated along the link. Such systems including optical interferometers have been assembled and tested at PTB, NPL and OBSPARIS with support of third party LPL.

D1.3 **Development of the laser stabilization system:** An ultra-stable laser source, with coherence length greatly exceeding the NPL-LPL-NPL round trip distance, was developed at NPL. The ultra-stable source is required in order for the phase of the optical carrier to be constant during its propagation over the link. The stabilization of the laser source was implemented using a robust technique employing a fs-frequency comb to transfer the stability of a highly-stable frequency reference (at 1064 nm) to the telecommunication wavelength used over the link (approximately 1543 nm). The ultra-stable laser source at SYRTE is a fiber-laser stabilized on an ultra-stable cavity using the Pound-Drever Hall technique. The frequency stability of the laser source is about 1E-15 at 1 second integration time.

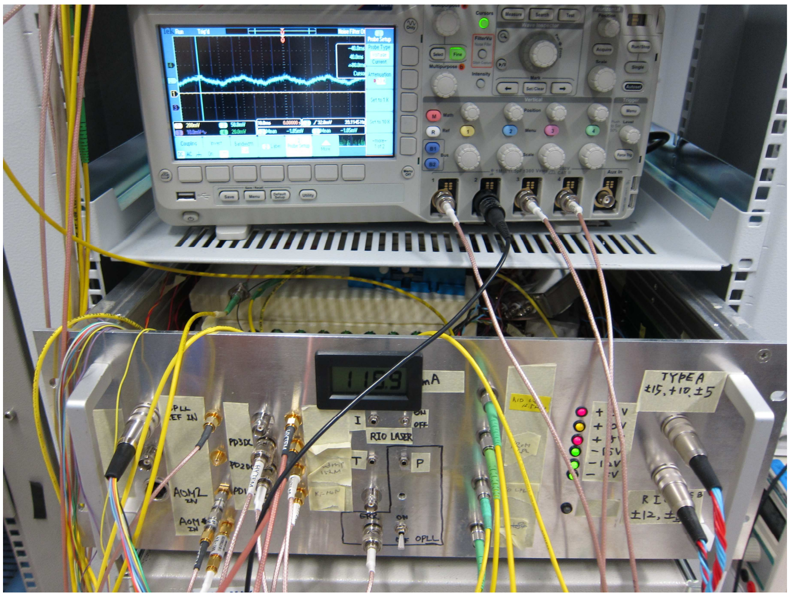

Figure 5 : Picture of the Laser station setup at SYRTE, containing the NIR laser source and the interferometric setup, shielded in a polyurethan box, and part of the stabilisation electronics.

D1.4 **Development of the narrowband fibre Brillouin amplifier:** A fibre Brillouin amplifier (FBA) was built at PTB. This special amplifier is required at the LPL receiving end (from NPL) because the bidirectional amplifiers do not exhibit sufficiently high gain. The design (see Figure 6) comprises a compact narrow linewidth laser module, driver electronics and a phase locked loop (PLL)-based system that allows for stabilizing the frequency of the FBA pumping frequency by means of a fs-comb.

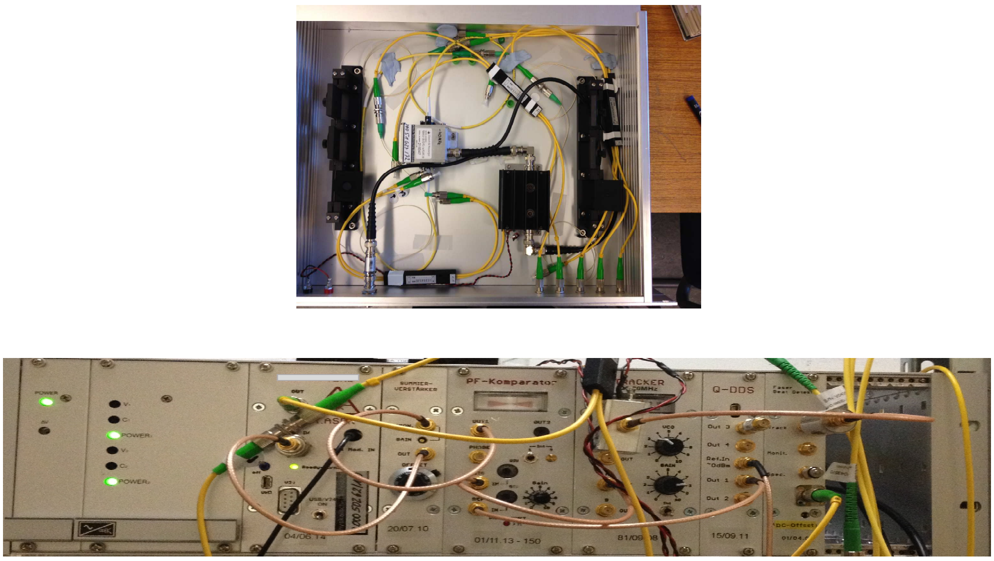

Figure 6 : Picture of the FBA module and driver electronics constructed by PTB.

D1.5 **Measurement of phase noise of the link:** Bidirectional amplifiers were installed in 8 locations, both in the UK (London, Paddock Wood, Folkestone) and France (Gravelines, Lille, Bois Bernard, Albert, Beavais). A retroreflector was installed at the output of the amplifier in each location during installation and testing, so that a beat signal could be received at NPL after a round trip. This signal was used to characterize the phase noise of the link. These phase noise measurements (Figure 7) have shown that most of the environmentally-induced noise arises from the metropolitan areas, in particular the Central London area. The measured noise levels are consistent with what reported for other optical links in Europe and Japan.

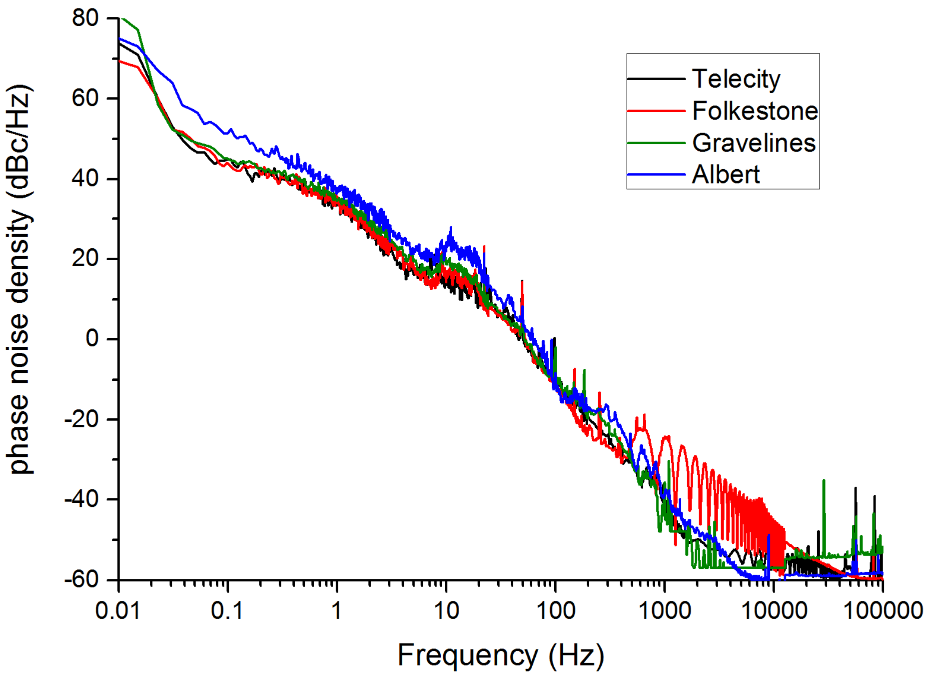

Figure 7: Phase noise accumulated over the round trip from NPL to four different locations along the link and back.

D2.1 **Performing clock comparisons:** This deliverable is delayed. Several failures of previously tested equipment were experienced and several fibre routing and logistic problems had to be resolved, slowing down progress towards completion of the stabilized link. However, the link is currently 96% completed with only approximately 30 km currently remaining to be tested. We will complete the link characterization and clock comparison after the actual end of the project in March 15. Funding from NPL was secured in order to extend the existing fibre rental until August 2015. A purchase order has been already submitted.

Measurement of the phase noise and frequency stability of the link OBSPARIS-LPL and uncertainty evaluation: A full opto-electronic set up has been set up in OBSPARIS to stabilize the link

OBSPARIS to LPL, and to monitor its frequency stability. The system has proven to be extremely robust, successfully stabilizing the link for 24 hours a day, 7 days a week almost uninterruptedly. The transfer stability of the SYRTE-LPL link is shown in Figure 8 and Figure 9.

We demonstrate our ability to measure at LPL an optical frequency with a relative frequency stability of 5E-16 at 1 second integration time (full bandwidth, about 70 kHz). For a frequency comparison performed by Lambda-counting in a 1 Hz bandwidth the stability is 6E-17 at 1 second integration time. The noise floor is 2E-20 at 4000 s integration time, and is due to the interferometer noise. The relative uncertainty of the transferred optical reference is conservatively set to 1E-19 (note that statistical uncertainty reaches 5E-20). These results greatly exceed the required stability for a successful comparison of the NPL-SYRTE clocks.

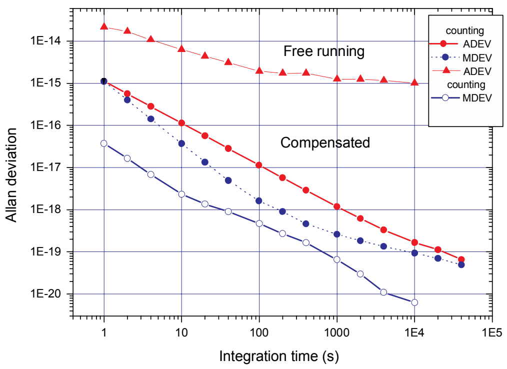

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Figure 8: Relative frequency stability of the link SYRTE-LPL-SYRTE Plain symbol: PI-counting data. Open symbols: Lambda-counting data.

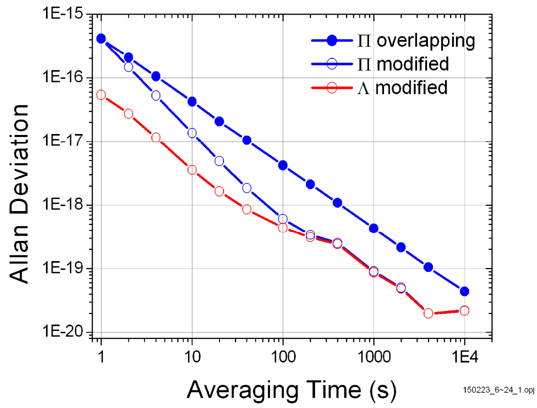

Figure 9: Relative frequency stability of the cascaded link SYRTE-LPL + LPL-SYRTE with extraction at LPL.

D3.1 **Impact:** Talks and posters about the project have been given at the European Time and Frequency Forum in Neuchatel and at the Photon 14 in London. One peer-review paper in the high-impact factor review Physical Review A : Phys. Rev. A 90, 061802(R).

D4.1 **Management:** The ICOF Project report for Annual GEANT Report was provided.

D4.2

Milestone/ deliverable code	Milestone/ deliverable name	Due Date	Delivery Date	Achieved Yes/No	% complete	Comments
D1	Establishing a stabilized fibre link between London and Paris	10/13	03/15	partially	90	Link equipped with EDFA final testing delayed
D2	Performing clock comparisons at the level of 10^{-16} or below between National Metrology Institutes.	07/14	06/15	No	0	Link not yet fully operational
D3	Impact	03/15	06/15	Yes	100	The project has been presented at several meetings with VLBI people, and on international conferences. One peer-review paper has been published
D4	Management	10/13	06/15	Yes	100	

2.3 Observations

ICOF will substantially impact the time and frequency metrology fields, geodesy and other areas of science, as well as change the way we conduct fundamental physics experiments. For example:

- By increasing the capabilities of the National Measurement Institute by several orders of magnitude, previously impossible levels of stability and uncertainty can be reached when comparing frequencies between remote clocks.
- The fundamental laws of physics – "are they really constants, or do they vary in space or time?" The high precision of atomic clocks, now reaching relative uncertainties at the level of 10^{-17} can help us to answer this question; by putting stringent limits on variations of fundamental constants.
- European space missions such as GNSS Galileo, ESA Cosmic Vision program and ACES, rely on the availability of highly accurate and ultrastable frequencies or timing signals.
- Many industrial and technological applications will benefit, for instance: defence and aerospace engineering, geodesy, high-resolution radio astronomy, navigation, communication systems (internet, mobile telecommunications, and electronic financial transactions).

2.4 Recommendations

As the fibre link between NPL and OBSPARIS is a unique opportunity to further enhance time & frequency metrology beyond the current state of the art in Europe it is highly desirable to continue this joint effort. The results of ICOF will keep the metrology institutes busy for many years to come. As mentioned above this project has outreach into different fields evolving from pure to applied science and from leading edge development to industrial products.

This particular link should be used in future

- To support the ACES mission of the European Space Agency.
- To demonstrate relativistic geodesy with optical clocks leading to a new definition of the Geoid.
- To unify high systems in Europe and to observe varying gravitational potential e.g. due to tides.
- To support the redefinition of the SI-Second within the new SI.

3 Conclusions

ICOF will substantially impact the time and frequency metrology fields, geodesy and other areas of science, as well as change the way we conduct fundamental physics experiments. For example:

- Using optical fibre networks the frequency of distantly located optical clocks can be compared at an unprecedented level of stability and uncertainty.
- The fundamental laws of physics - are they really constants, or do they vary in space or time? The high precision of atomic clocks, now reaching relative uncertainties at the level of 10^{-17} can help us to answer this question by putting stringent limits on variations of fundamental constants.
- European space missions such as GNSS Galileo, ESA Cosmic Vision program and ACES, rely on the availability of highly accurate and ultrastable frequencies or timing signals.
- Many industrial and technological applications will benefit, for instance: defence and aerospace engineering, geodesy, high-resolution radio astronomy, navigation, communication systems (internet, mobile telecommunications, and electronic financial transactions).

This is a great example of how the GÉANT network can support novel research with potentially huge implications to the wider scientific and engineering landscape, and the results of ICOF are likely to keep the metrology institutes busy for many years to come.

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Glossary

GNSS	Global Navigation Satellite System
GALILEO	Name of European GNSS
ESA	European Space Agency
bi-EDFA	bi-directional Erbium Doped Fibre Amplifier
OADM	Optical Add and Drop Module
GSM	Global System for Mobile Communications
FBA	Fibre Brillouin Amplifier

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7 A. Bercy, F. Stefani, O. Lopez, C. Chardonnet, P.-E. Pottie and A. Amy-Klein
Two-way optical frequency comparisons at 5×10^{-21} relative stability over 100-km telecommunication network fibers; *Phys. Rev.* ***A*** **90**, 061802 (2014)