Time and Frequency Distribution over fibre for Geodesy, Seismology and Industry

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***Abstract*—The Italian Institute of Metrology (INRIM) realized an optical fibre backbone, 1850 km long, for the dissemination of accurate time and frequency standards. Moreover, we implemented a dedicated service for time distribution with traceability to UTC for industrial users. Here we describe techniques, architectures and results.**

Keywords—component, formatting, style, styling, insert (*key words****)***

I. Introduction (*Heading 1*)

The distribution of Time and Frequency (T/F) reference signals over fibre is nowadays the best technique both for achievable performances and for a resilient transfer, even on long hauls, e.g. thousands of kilometres [1][2]. From the perspective of the National Metrological Institutes (NMIs), the realization of optical fibre links was considered initially since they are the only suitable technique to compare the new generation of atomic frequency standards, usually known as optical clocks.

The International Committees of the Metre Convention supported and encouraged the exploitation of the fibre link techniques, in particular through formal recommendations, e.g. from the Consultative Committee for Time and Frequency (CCTF) of the International Committee for Weights and Measurements (CIPM). The Working Group on Advanced Time and Frequency Transfer (WG-ATFT) devotes to the topic particular attention.

The efforts in the development of optical fibre link for T/F are particularly evident in Europe and in Japan [4][5], even if seminal works were developed in U.S., where also promising techniques using free-space optical links was demonstrated [6]. Reliable and accurate fibre link is thought to have a key role in the path towards a possible redefinition of the second. In fact, a crucial point here is to compare optical clocks at different location at an uncertainty level of parts in 10^{18} in terms of relative frequency. So far, commonly used satellite techniques do not support this level of uncertainty to compare atomic clocks, also in the generation of the International Atomic Time (TAI), limiting the uncertainty to few parts in 10^{16} after about one month of continuous measurements.

The basic difference in the performances of optical versus microwave T/F transfer is depicted by the frequency instability at one second. Microwave techniques usually exploited in satellite comparisons can offer a best stability of parts in 10^{10} at 1 second of measurement, whilst optical coherent transfer allows even a stability of 10^{-15} at 1 s over 1000 km. In both cases, the instability lowers with the inverse of the measurement time, hence optical techniques allow a comparison suitable for optical clocks in few hours, whilst microwave techniques are not suited for this the task.

So far, optical fibre techniques suffer of two relevant limitations: they are point-to-point connections, requiring of course the presence of an optical fibre, and NMIs demonstrated only continental. Ideally, this is not a limit since submarine cables link the different continents on Earth: up to 1 million kilometres of fibre are buried at the sea floors for data traffic and the internet world network, as shown in Fig. 1.

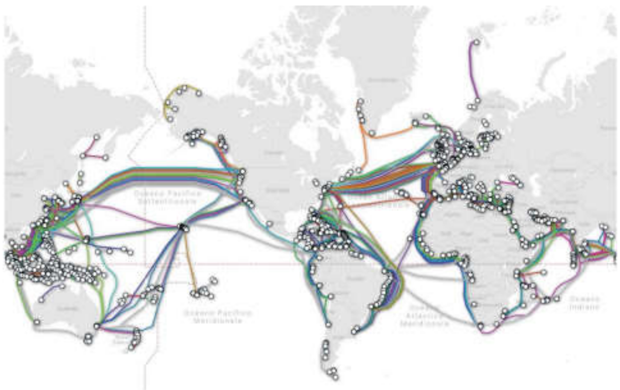

Fig. 1. Submarine cable map (credit: www.submarinecablemap.com)

In this context, the Italian Metrological Institute INRIM developed the project LIFT, a national backbone for T/F distribution over fibre. The aim of this backbone is to develop the techniques and implement the distribution of reliable and ultra-accurate T/F reference signals to stakeholders.

Presently, LIFT connects five different academic research institutions over the entire country, demonstrating the capability of improving the scientific research in different fields, such as space geodesy and radioastronomy [6][21], atomic physics [7], and quantum technologies research like quantum simulation [8] and relativistic geodesy [9].

Considering the industrial stakeholders, LIFT proposes the adoption of a technique such as White Rabbit – Precision Time Protocol PTP-WR [10][11], powerful but still cost effective, that offers high robustness, high integrity levels and a very accurate traceability to UTC(IT), with sub-nanosecond accuracy.

LIFT is part of the efforts to realize a European Network of fibre links, like illustrated in the project H2020-CLONETS [12], following the present developments shown in Fig. 2.

Fig. 2. Present development of European T/F optical fibre links.

II. DEVELOPMENT OF A COHERENT 1850 KM FIBRE LINK

INRIM developed an optical fibre backbone in Italy for T/F and, for the forthcoming future, to implement other quantum technologies. Fig. 3 shows the geographical distribution of the link and the locations of its main connection. Starting form INRIM premises in Turin (A in Fig. 1), the optical link connects Milan (B, fibre haul 279 km), Bologna (C, 550 km), Florence (D, 642 km), Rome (E, 994 km), Naples (G, 1306 km) and Matera (H, 1684 km). LIFT connection to the rest of Europe is from Turin to the French Border in Modane (150 km, not shown in the map). This connection will be part of the link to the French Metrology Institute, scheduled now for 2018-2019.

Another extension is currently ongoing to connect Fucino in centre Italy (F in the map, where there are the premises of the Italian company Telespazio and the Italian Space Agency (ASI), committed within the European GNSS Galileo.

So far, we completed the infrastructure, and impinged the signal from Torino to Matera. The link to Bologna and Florence is already under operation, while the segment Florence-Naple-Matera is under characterization.

The total haul from Modane to Matera is about 1830 km long, and it is equipped with Erbium Doped Fibre Amplifiers (in total, 26 amplifiers).

Our backbone has a 24/7 access to our staff, in all of the 26 housing locations along the country, generally easy to reach, offering a rack to install optical equipment (presently, the amplifiers, with the racks not at their full capacity).

LIFT implements T/F transfer by a coherent technique, and WR-PTP transfer, but the test-bed is ready for experimental developments of other techniques also.

Presently, we implemented the coherent frequency transfer on all the 1830 km, and we are upgrading the optical infrastructure to embed the White Rabbit PTP on all the backbone, too.

A WR-PTP implementation is already operational on a separate fibre from Torino to Milano (see afterwards).

For the coherent frequency transfer, we use our ultra-stable lasers, composed of fibre lasers or extended cavity diode lasers emitting at 1542 nm, stabilized on Fabry-Perot cavities. The stability of the lasers is $<5\times10^{-15}$ in terms of relative frequency, with linewidths <10 Hz and long-term drifts around 1 Hz/s. This laser is usually locked on the long-term on the frequency of a Hydrogen Maser used to generate the international timescale UTC(IT) and/or the Cs fountain clock, the primary frequency reference at INRIM, capable of and accuracy of 2×10^{-16} [13].

Recently, we developed a fully operational Ytterbium optical clock [14], capable of a stability of $2\times10^{-15}/\tau^{1/2}$ and accuracy at 4×10^{-17}, and the 1542 nm will be locked to this frequency reference for dissemination.

The phase noise from the optical fibre is compensated on the fibre link using the Doppler cancellation technique [2]. The link has three separated segments: Turin-Florence, Florence-Naples, and Naples-Matera. Each segment is independently phase-noise compensated. In Florence and Naples there are two regeneration stations, composed of a narrow linewidth laser (few kHz), phase-locked to the incoming reference light from the previous segment (i.e. Turin for Florence and Florence for Matera). Their function is to clean-up the phase noise, hence improving the quality of the link transfer.

Indeed, those regeneration stations serve also as local oscillator for the distribution to different experiments. Such regenerators are placed also in Bologna and Matera, and act as clean-up oscillators and local distributors of the reference signals.

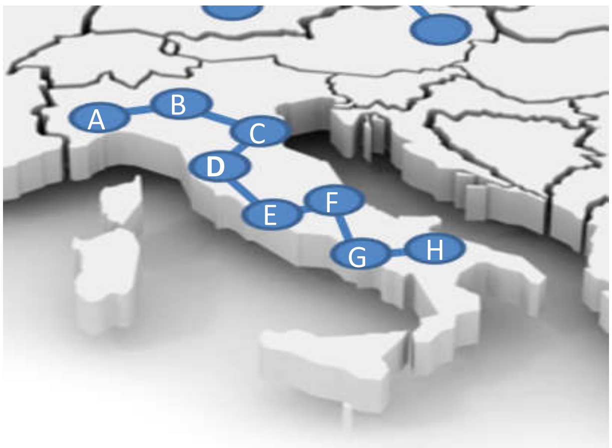

Fig. 3. The optical fibre backbone for T/F in Italy.

Fig. 4 shows the phase noise of the three segment, with and without cancellation, while Fig. 5 illustrates the evolution of the fibre noise on our link with respect to the fibre length. The infrastructure needs an efficient remote monitoring and control. For example, the EDFA gain proved to be sensitive to the environment temperature and needs an adjustment time to time. Fig. 6 shows the gain of some of the EDFAs, the gain of an amplifier used as a servo-loop actuator, and the resulting beat note for the Doppler cancellation with and without implementing the servo.

We achieved with this servo up to 7 days of continuous operation keeping the amplitude of the roundtrip beat note constant within 1 dB.

The remote control of the EDFA and of the regeneration stations uses the same fibre as the metrological transfer by an Ethernet-based communication, reliable and with short latency, mandatory for the robustness.
We monitor the cycle slips limiting the accuracy of the link with a double track oscillator technique. They can be as low as few hundreds/a week on the Turin to Florence link; the Florence to Matera segment is currently under characterization.

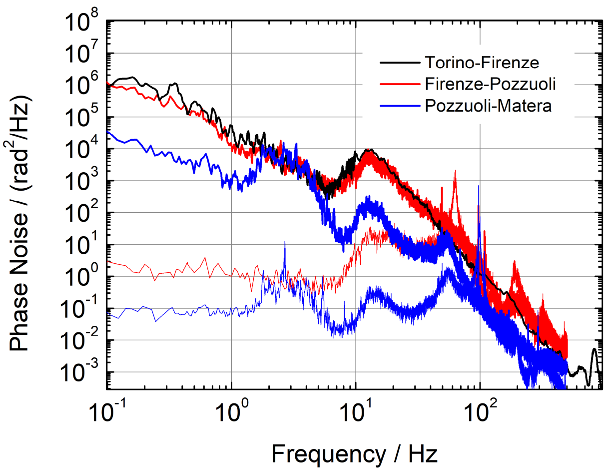

Fig. 4. Phase noise of the three segment Turin-Florence, Florence-Naples, and Naples-Matera, with and without the noise active Dopler cancellation.

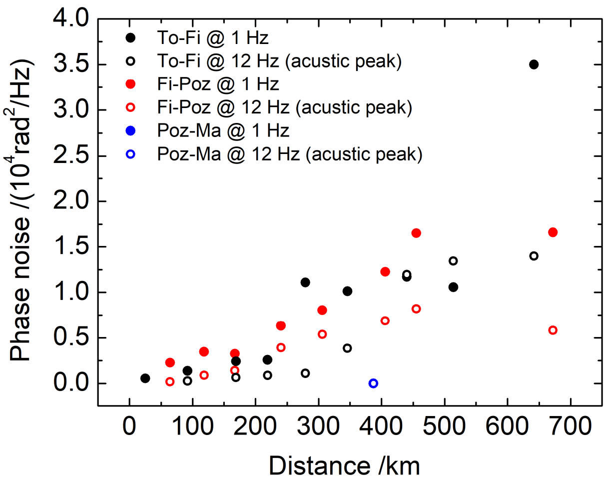

Fig. 5. Evolution of the fibre noise on the Turin-Matera link with respect to the fibre length, on the different segments (To=Tutin; Fi=Flotrence; Poz=Naples, Ma=Matera).

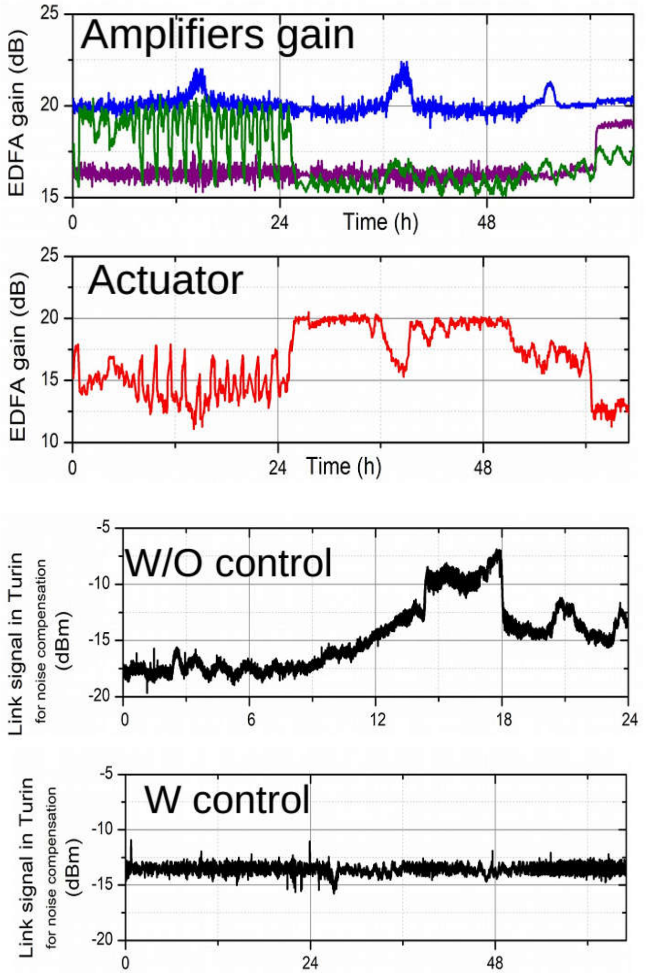

Fig. 6. Gain of some of the EDFAs along the fibre link (first graph); gain of an amplifer used as a servo-loop actuator (second); resulting beat note for the Doppler cancellation with (third graph) and without (fourth) implementing the servo.

To improve the performance of the link in term of phase noise, and reducing the dependency of regeneration station, we tested in the past another strategy in. In particular, interesting results were demonstrated using Raman amplification on our link, reported in [15]. From those experiments, the Raman amplification result fully compatible with ultra-stable frequency dissemination, offering some advantages in terms of noise because it does not introduce the amplifier spontaneous emission in the same DWDM channel of the signal. We recall here the set-up demonstrated in [15], shown in Fig. 7 and the data on the back scattering in Fig. 8. They show why we consider the introduction of a hybrid amplification infrastructure to improve the backbone, mixing the use of EDFA and Raman amplifiers. This will also relieve the role of the clean-up oscillator, still maintaining their role of local oscillator because of the local distribution.

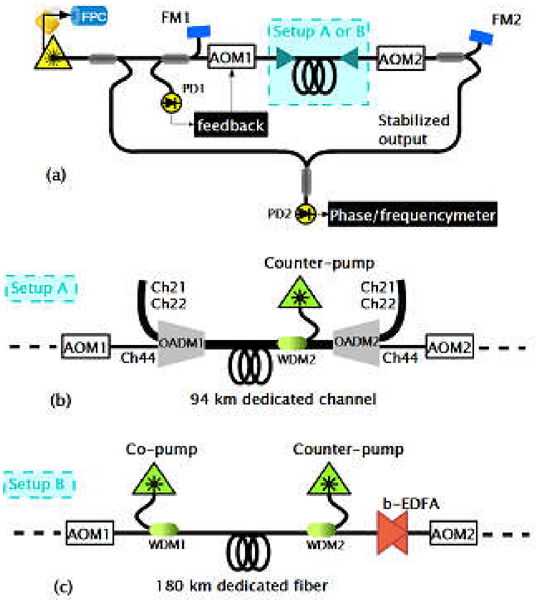

Fig. 7. Different set-up implemented on the link to test Raman and hybrid Raman/EDFA amplification. These set-up are considered beneficial for an infrastructure upgrade reducing the phace noise of the link.

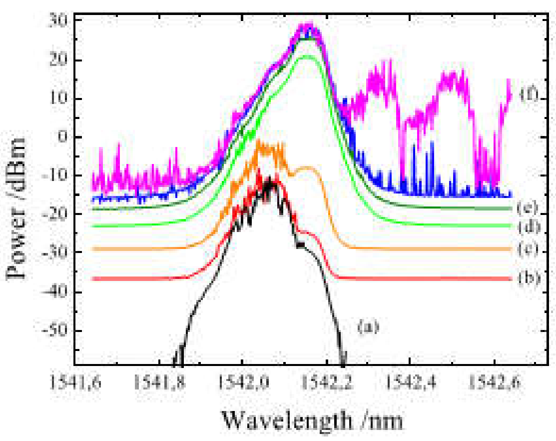

Fig. 8. Optical spectrum of the backscattered radiation in the characterization of the Raman amplification for T/F cohrent transfer from [15]. (a) Pump off; (b) pump power at 0.2 w; (c) 0.6 W; (d) 1 W, (e) 1.3 W; (1.5 W; (g) 1.6 W. Just the last power level shows the comparison of detrimental effects, setitng an upper limit on usable the pump power.

III. RESULTS OVERVIEW: SCIENTIFIC CASES

The LIFT project has already contributed to different scientific experiments, enabled by the frequency dissemination of an ultra-stable and ultra-accurate optical reference. In particular, we illustrate here five main results, concerning quantum simulation [8], molecular spectroscopy [16], radioastronomy [6]**Errore. L'origine riferimento non è stata trovata.**, relativistic geodesy [9], and seismologic detection [17], the two latter published this year.

By the distribution of INRIM signal to the Laboratory for Non Linear Spectroscopy, in Sesto Fiorentino, we exploited the presence of an experiment based on ^{173}Yb quantum gas. INRIM set a complete metrological chain, from the Cs fountain to the Yb sample, composed of the Cs fountain, the comb to lock the 1542 nm laser, the optical link and an optical comb in Florence. This latter is used to lock the laser at 578 nm of the local Yb experiment to the 1542 nm radiation coming from INRIM. After measuring the clock transition of ^{173}Yb, at the 2×10^{-14} uncertainty level (limited by systematics, still now the most accurate measurement of this transition), INRIM's set-up enabled the simulation of quantum phenomena (e.g. topological phases) by measuring the Spin-Orbit Coupling on cold Yb sample, addressed by a fibre-link-referenced probe laser [8].

In Sesto Fiorentino, INRIM's link has served also for to transfer the spectral purity of the fibre-disseminated radiation to a quantum cascade lasers emitting in the mid-infrared, the molecular fingerprint region, which is extremely interesting for some of the most challenging experiments, such as the search for variations of fundamental constants and the measurement of the electron dipole moment [18]. We achieved the first absolute measurement of a molecular transition in Carbon Oxide, using a metrological chain similar to one used for Ytterbium [16].

In Bologna, LIFT served for the investigation of possible improvements in space geodesy and radioastronomy VLBI. The possibility to replace the local frequency reference with fibre-disseminated frequency standards is seen as beneficial as it might open new scenarios with a common clock distributed to multiple antennas, hence with the full rejection of its noise. We demonstrated tow pioneering results in European VLBI campaigns involving the Medicina Radiotelescope of the Italian Astrophysical Institute (INAF) [6]; now, we look for to the extension to the Space Geodesy Centre of the Italian Space Agency (ASI), in Matera.

The perspectives for the fibre link distribution is to add a time distribution, initially based on WR-PTP technique, to offer to the radiotelescope both timing and frequency at the best possible level today. A further evolution will try to unify time and frequency transfer using the same optical cw carrier. In Europe, there are several radioastronomical premises, and some of them are already close to the fibre link network for T/F in development, as shown in Fig. 9.

Fig. 9. European locations of radioastronomical antennas, together with the hauls of T/F fiber links currently operational or in development.

Using the fibre link between Turin and Modane, we realized the first proof of principle of chronometric levelling [9], a technique within the larger category of relativistic geodesy. The basic concept is that the atomic clock, affected by the general relativity time dilation, can be used as sensor of gravity potential if their accuracy is at a proper level. Indeed, in the Earth potential field, a clock is affected by a frequency shift, the so-called gravitational redshift of about 1×10^{-16} per metre in height over the Geoid. The new generation of atomic clocks, the optical clocks, offers a sensitivity to potential difference beyond the possibilities of other techniques, such as satellite methods, and look for time changes in the potential in the short-medium term (e.g. hours to days). This is achieved comparing two optical clocks frequency in different location, using a fibre link.

In an international collaboration (EMPIR-ITOC project) INRIM set up a link between its clocks (the Cs fountain and the Yb clock) located in Turin at ~240 m on the Geoid level, and a transportable Sr clock located inside the Frejus tunnel, on the Italy-France border, at ~1300 m on the Geoid. Hence, the frequency difference induced by General Relativity is $\sim1\times10^{-13}$. This measurement paves the way of new campaigns for a better map of gravity potential and possibly a monitor of its stability in time, exploiting the network of clocks/fibre links.

Last, this year we published the results of the use of T/F dissemination over fibre links for Earthquake detections [17]. The basic concept relies on the fact that seismic events shake the fibre and hence this vibrations are imprinted on the phase of the distributed laser. It was not obvious how sensitive was the coherent T/F tecnique with respect to earthquakes, but a sereis of experiments has shown that the sensitivity is adequate with close and far events, large and small magnituteds, and the signals are comparable to classical seismometers. We have still to fully understand to which extent the signal from the fibre technique, that is a distributed sensor, can be compared or can be complementary to classical sesimometers. On the other hand, this technique is extremely powerful if we consider the submarine earthquakes. In this case, a network of seismometer is not present on the sea-floor, and the earthquakes are usually detected by the network on land. This fact has two main consequnces: the impossibility to detect small events and the delay with respect to the event due to the time necessary for the sesimic wave to propagate form the epicentre to land.

In an international collaboration with the National Physical Laboratory (NMI in UK) and the University of Malta, we set a submarine fibre link between Malta and Sicily, 120 km long, on a sea-floor at ~200 m depth. We were able to demnostrate that the phase noise on the submarine cable is lower than at land, by a factor 10000, and that the signal-to-noise for earthdetection is quite good. Fig. 10 shows an example of submarine earthquake detection from our link and from an ordinary seismometer at land.

This observation open two possibilities. First, we can think of using the international network of submarine cables for internet to develop a network for submarin seismic detection, with a sustainable cost. Second, we demonstated that the phase noise on the seafloor is compativble with the trasmission of metrological T/F signals over ultra-long hauls, i.e. tranoceanic links. This would be of the outmost importance to set up links between Europe, america and Asia in view of the comparisons of optical cloks that are necessary for the redefiniotion of the second and that requires a level of accuracy at parts in 10^{-18}.

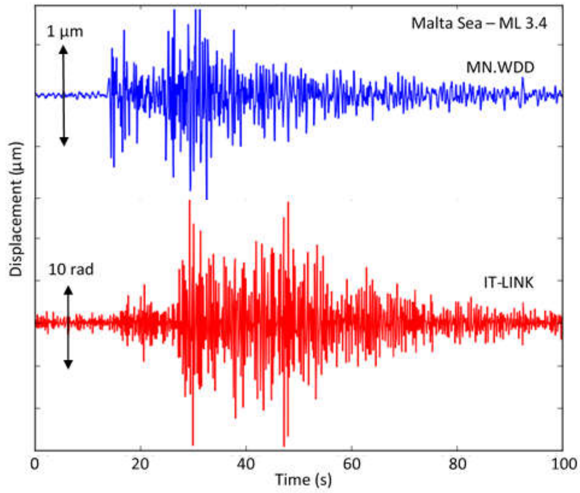

Fig. 10. Signals from the submarine earthquake detection experiment on a submarince cable between Sicily and Malta. Upper curve: the seismic event seen by an ordinary seismometer at land; lower graph: the same event detected buyt the T/F fibre link.

IV. Results overview: industrial cases

We will implement the time transfer over the LIFT fibre backbone using the White Rabbit PTP technology. We will develop as well further research activity to test other approaches, but as a first step, we are convinced that White Rabbit will offer the best solution, at an effective cost, with proper level of stability and accuracy for most scientific and industrial users. Last, but relevant aspect, the WR-PTP is very close to the standard IEEE-1588, hence it is reasonable to expect in the forthcoming years an upgrade of the standard that will include WR features. Offering a platform equipped with a technique close to a standard is considered a plus for our metrological institute.

While working on the implementation of WR-PTP for the entire 1830 km of lift, we have tested WR-PTP time transfer over the test-bed from Turin to Modane, within the project H2020 Demetra [19]. The successful test has pushed us to offer WR-PTP as a service for industrial users.

In June 2018, also the project WRITE (White Rabbit Industrial Timing Enhancement) has started, coordinated by INRIM within the program EMPIR of Euramet. The objective of WRITE is to improve the WR-PTP capabilities and to facilitate the take up at the industrial level. To achieve these goals, a team of 10 institutions, NMIs, companies and academia, will develop new calibration techniques, new hardware and new in-field test involving industrial users.

At the same time, in collaboration with Consortium TOP-IX [20], INRIM implemented a service fibre link between INRIM and the financial district in Milan, where there is the colocation for the companies operating on the Italian Stock Exchange. This service link, that is separated from the LIFT backbone, offer a service of timing, accurate and resilient, to accomplish for the requirements of the new European regulation MifiD-II. This regulation requires for any company operating on the stock exchange a time-stamping of the financial negotiation traceable to UTC and with a level of accuracy down to 100 microseconds and a sensibility of 1 microsecond.

The request of traceability, resilience, safety and accuracy has convinced INRIM to offer a service based on fibre transfer. Fig. 11 shows one of the first data taking for this WR-PTP link. The set up consisted in a fibre loop over the telecommunication network used by TOP-IX, completely blind to the metrological institute; the signal is impinged from INRIM, reaches a terminal in Milano and then comes back on a different, redundancy fibre to INRIM. The fluctuations have never been larger than 2-3 ns peak-to-peak, and the accuracy has been always kept below 10 ns, without interruptions and without intervention on the network infrastructure, that of course is still used for the internet data traffic. The infrastructure implements DWDM and the metrological signal is on a dedicated channel, to provide full control for the certification of traceability to UTC(IT).

The total length for control and characterization is 400 km. After the trials, the service is now operational for users.

It is worth to stress the satisfactory robustness of the system and the capability to offer a full-compliant accuracy continuously. We know that we can push accuracy well beyond 1 ns, but this is not the goal of the service, that on the other hand requires complete reliability and close operation with the telecommunication operator.

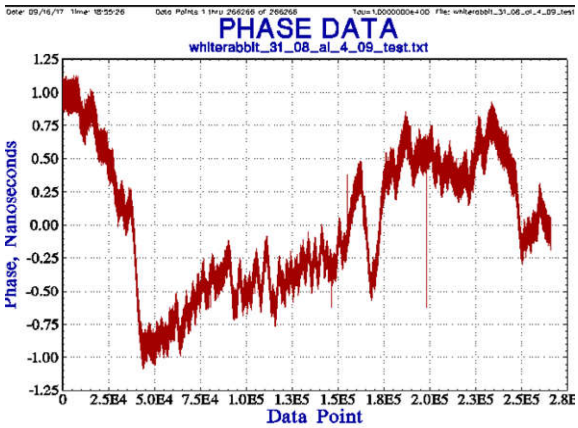

Fig. 11. Time offset between UTC(IT) and the WR-PTP signal after 400 km over a fibre network used for internet data traffic.

V. Conclusions

The implementation of a European fibre Network for T/F is advancing. The impact of the wide spreading technology is affecting not only National Primary Metrology and their institutional roles, but it is offering a new platform for Time and Frequency distribution, both at an academic and industrial level.

INRIM demonstrated different architectures, different techniques and different uses, and they have in common outperforming performances and the highest resiliency.

The possibility of compare remote optical clocks over different continents is no longer a remote far issue, and recent achievements demonstrate that submarine cables can support this goal. The use of optical fibre networks for quantum technologies and T/F related sensing is opening a new venue for science, whilst the possibility of a powerful dissemination technique for industry is currently under early exploitation.

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