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*Abstract*— **The Italian Institute of Metrology (INRIM) developed an optical fibre backbone for the dissemination of accurate time and frequency standards to several research institutions of the Country. A network of research facilities, involved in areas ranging from atom and molecular spectroscopy to Very Long Baseline Interferometry (VLBI) for geodesy and radioastronomy, has been established. The time transfer over fibre has also been implemented for industrial users. We will describe the status of this 1800 km long facility, the most recent implementations and the research activities where fiber-based frequency dissemination is being exploited.**

***Keywords—optical links, frequency metrology, VLBI, spectroscopy***

## I. Introduction

Optical fibre transfer is nowadays the best technique for the comparison of accurate clocks and for the dissemination of time and frequency standards [1]; in particular it is the only one suitable for optical frequency standards [1]. The Italian National Metrology Institute (INRIM) developed an optical fiber link for the dissemination of accurate time and frequency references to several research institutions across the Country [3]. First, the aim of this infrastructure is of boosting the experimental capabilities of the involved partner institutions and of allowing experiments which could not be performed using the previously available reference signals based on Global Positioning System (GPS) dissemination. In particular, the fibre-baseddissemination of an optical ultra-stable radiation referenced to the national primary frequency standard, which has an accuracy of $2\times10^{-16}$ [4], encompasses by more than four orders of mangnitude GPS dissemination and has been exploited in several applications, ranging from high-resolution spectroscopy of atoms and molecules to geodesy and radio-astronomy based on Very Long Baseline Interferometry (VLBI). Second, we are investigating the possibilities offered by the fibre techniques to industrial users and new services based of time and frequency dissemination over fibre. For these targets, we implemented over our backbone the time transfer using the White Rabbit technique **Errore. L'origine riferimento non è stata trovata.**, that offers high robustness, high integrity levels and a very accurate traceability to UTC(IT), with sub-nanosecond accuracy.

In the following sections, we will illustrate the characteristics of the link and the present applications of this research infrastructure.

## II. Fibre Link Description and Operational Control

Currently, INRIM is connected with permanent links to several strategic locations: the financial district in Milano (279 km), the Institute for Radioastronomy in Medicina (514 km), the European Laboratory for Non-linear Spectroscopy, LENS, in Sesto Fiorentino (642 km), the Italian-French border in Modane, Frejus tunnel (150 km). The link has recently been extended to Roma (994 km) and during 2017, a further extension will reach the National Institute for Optics INO in Arcetri (682 km) and in Napoli (1306 km), the Galileo Precise Time Facility location in Fucino (1150 km), the Space Geodesy Center in Matera (1684 km). Using the cross-border connection in Modane, we plan to link to the French metrological institute LNE-SYRTE in Paris, another key step towards a network of European national metrological institutes.

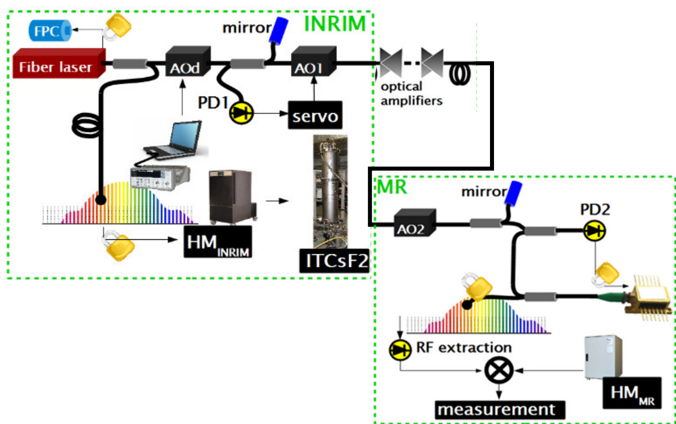


Figure 1. Experimental scheme of the traceability chain from INRIM to the HM of the radiotelescope in Medicina. In Florence, the signal of the link is the reference for an optical comb, and a local ultrastable laser is then locked on the referred comb. FPC: Fabry-Perot Cavity; AO: Acousto Optic Modulator; PD: Photo Diode.

The laser is then sent through the fiber, which is stabilised through the standard Doppler noise cancellation technique. The total loss experienced between INRIM and LENS (Florence) is 194 dB, partly compensated by a chain of 10 bidirectional Erbium Doped Fibre Amplifier (EDFA). The total number will amount to 30 for the whole project, and full optical regeneration is planned in Florence and Napoli. The amount of instrumentation placed along the fiber-haul poses the need of efficient remote monitoring and control capabilities. In particular, the EDFA gain proved to be extremely sensitive to the environmental temperature and has to be frequently adjusted. Figure 1 reports the gain of some of the EDFAs located on the link from Torino to the radioantenna in Medicina. Such features result inup to 10 dB variations on the peak power of the beatnote used to phase-stabilize the optical link. The large fluctuations shown in Figure 1 cause the unlock of the active compensation, reducing the uptimes of the link. To overcome the problem, we have implemented a control using one of the amplifier as actuator, notably the first one of the chain that offers the largest gain dynamics. Figure 2 illustrates the result of a simple control loop on the EDFA actuator, in particular 7 days of continuous operation keeping the roundtrip beatnote amplitude constant within 1 dB. Few exception are shown, due to a clipping condition set on the minimum current of the amplifier, but they have not generated any unlock.

The remote control of the EDFA exploits the same fiber as the metrological dissemination for Ethernet-based communication to the devices. This approach guarantees reliable communication and short latency time, which are mandatory to enhance the infrastructure robustness. Figure 3 reports the cycle slips rate observed during the data taking, monitored with a double track oscillator technique. The total number of glitches was 377 and during the all 7 days, also the regeneration station at Medicina was continously locked to the signal incoming from the link, using a polarization control to compensate for the polarization rotation induced by the fibre.

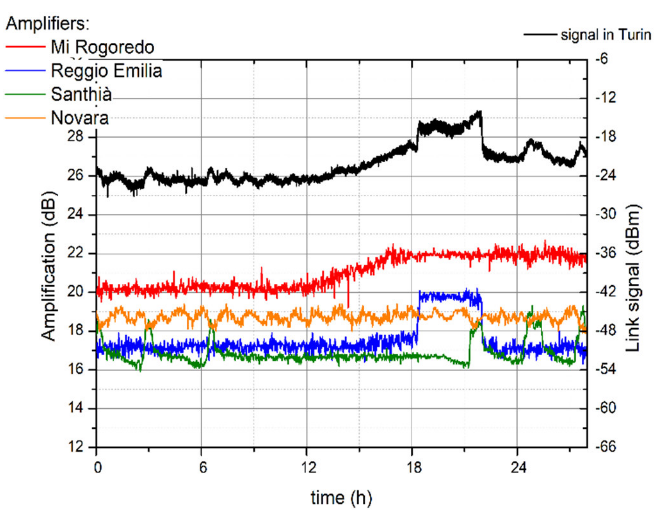


Figure 1: Monitor of the link before the implemntation of the active control of the amplifiers gain over one day: (upper black curve) Link signal reference, i.e. the amplitude of the beatnote between the ultrastable laser radiation and the roundtrip signal reflected back from the remote end of the fibre; (other lines) Gain of four main EDFAs along the fibre. The variation of the link signal due to the change of the gain for the EDFA in the sites of Mi-Rogoredo and Reggio Emilia is very close to the maximum dynamics of the active noise compensation electronics.

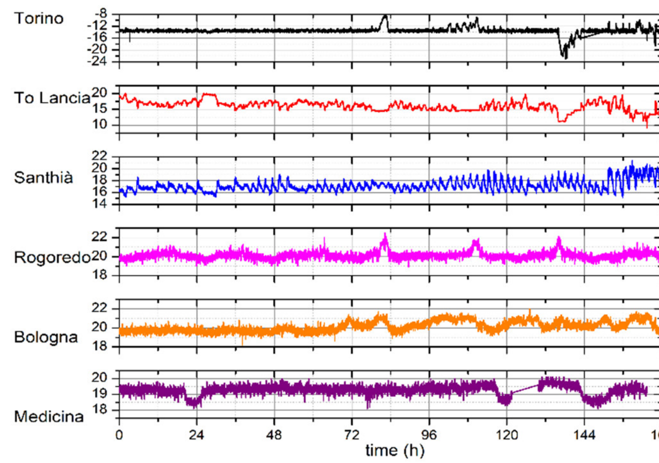


Figure 2: Link monitoring over 7 days of continuous operations, after the active control of the gain for the EDFA located in To-Lancia: (upper curve) amplitude of the beatnote between the laser and the radiation reflected back form the remote end of the link, exhibiting an overall stability at 1 dB level, with few exceptions; (second curve) gain of the EDFA located in To-Lancia, that acts as the actuator to control the link dynamics; (other curve) gain of amplifiers at selcted locations, where there are some relevant variations, in particular in Santhià.

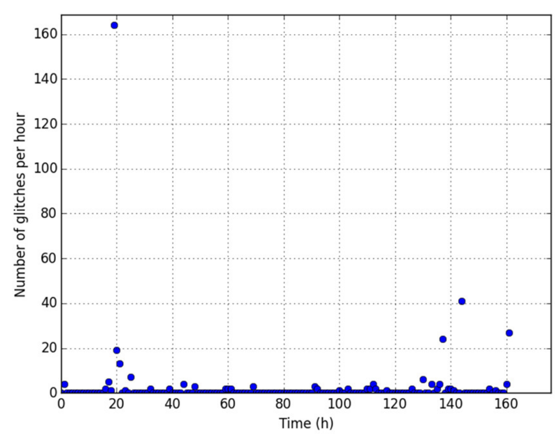


Figure 3: Cycle Slips per hour on the fibre link in 7 days of continous operations, measured with two Tracking Voltage Controlled Oscillators.

## III. T/F Fiber Dissemination for Ultracold Atoms spectroscopy, molecular spectroscopy and Quantum Simulation

At the Laboratory for Non Linear Spectroscopy, in Sesto Fiorentino, the traceability to the primary standard has been transferred to the visible domain around 578 nm and this allowed the currently most precise measurement of the clock transition of $^{173}$Yb, at the 2x10$^{-14}$ uncertainty level (limited by systematics), which could not be attained with the previously-available GPS-rferenced Rb oscillator [4]. This setup is also enabling the simulation of quantum phenomena such as topological phases, through the measurement of Spin-Orbit Coupling on the cold Yb sample, continuously addressed by a fiber-link-referenced probe laser [7]. The long-term, resolved spectroscopy on the atom ensemble is performed through an extremely efficient interrogation scheme, which exploits the low frequency-instability (<$10^{-14}$ on timescales of 10s of seconds) of the fiber-disseminated signal. The spectral purity of the fiber-disseminated radiation has also been transferred 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 [8].

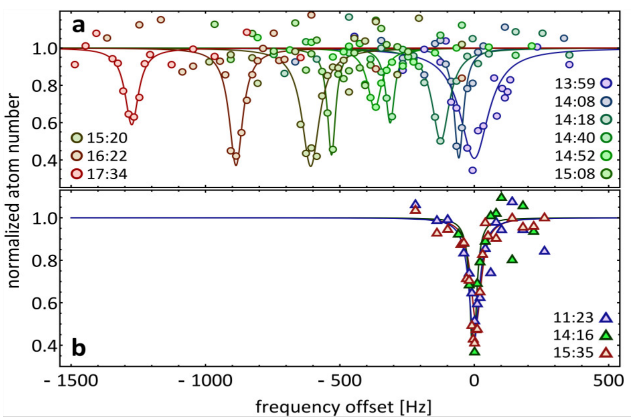


Figure 4: Fibre link dissemination at Florence, as reported in [6]. a) ultracold Ytterbium clock spectroscopic measured with the clock laser referred to a Rubidium clock signal (disciplined to GPS). Each line corresponds to a different epoch of the acquisition, within 4 ours of measurement: the data spread does not allow an average of the acquisitions. b) Spectroscopy within 4 hours locking the clock laser on the link reference signal. The data spread is now limited to few tens of Hz by the linewidth of the clock laser.

## IV. T/F Remote reference for Radioastronomy

Another field of high relevance where state-of-the art frequency dissemination can be exploited is the investigation of the ultimate limits of spatial geodesy and radioastronomy based on VLBI. This technique is based on the correlation of measurements collected by a network of distant radiotelescopes, all equipped with high-quality local oscillators [9]. We are investigating the possibility of replacing the currently used H-masers with fiber-disseminated reference signals [10]. This allows the distribution of clock references of superior quality and opens completely new scenarios where the same clock can be delivered to multiple locations, thus allowing the full rejection of its contribution. We already exploited the fiber-based frequency dissemination in European VLBI campaigns involving the Medicina Radiotelescope [10], and we are now extending the link to the Space Geodesy Centre in Matera, southern Italy. Figure 5 shows a map of Italy with the indication of the main sites with radioastronomical or space facility. Figure 6 reports the first experimental fringes obtained in an international VLBI campaign involving 7 European observatories, among which Medicina used a remote HM reference transferred via a coherent fibre link. The fringes are the correlation of the radioastronomical signals measured at the radioantennas of Medicina and Wetzell, Germany. To fully benefit from the fibre link, the geodetic VLBI technique is high demanding in terms of the resilice of the frequency trasnfer. In fact, each geodetic campaign lasts 24 hours, and it is required an uptime of 100% for the frequency reference. The improvement on the link control has demonstrated to be adequate for this achievement, even if more test and mesurements have to be done.


Figure 5. Map and the fibre link, with the main locations for radioastronomical and space premises in Italy.

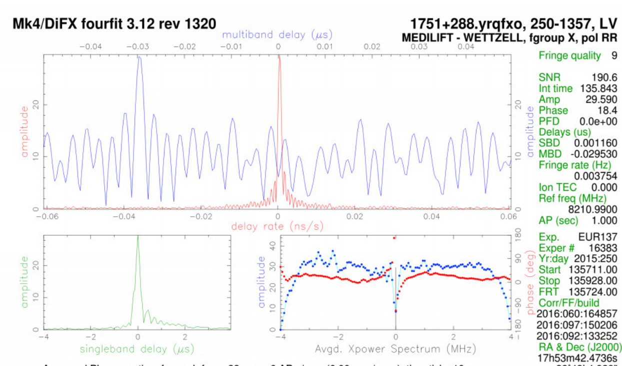


Figure 7: Interference fringes from a real VLBI campaign in 2015, whose results are reported in [11]. The fringes come from the interferometry beteen Medicina an the telescope in Wetzell, Germany. The Medicina radioantenna used the HM at INRIM disseminated by the fibre.(Courtesy of M. Negusini, INAF)

## V. CHRONOMETRIC GEODESY

The Doppler-stabilised link to the Laboratoire Souterraine de Modane (LSM), inside the Frejus tunnel on the Italy-France border, has been used for a proof-of-principle experiment in relativistic geodesy, with the aim of demonstrating that optical clocks can be used as probes for the gravitational redshift [12, 13]. The ratio between a Yb clock and a transportable Sr clock was measured when they were co-located at INRIM and after one of them was transported to LSM, using the fiber-disseminated signal at 1.5 μm as a spectral bridge. This kind of experiments will significanlty change the paradigm in relativistic geodesy, allowing the investigation of changes of the gravitational potential at the cm level, and on timescales of hundreds of seconds, faster than those measured with classical instruments [12]. The connection to LSM is also the first span in the forthcoming link to the French Metrology Institute, planned for 2017.

## VI. INDUSTRIAL USERS: THE FINANCIAL SECTOR USE CASE

Last, time transfer using White Rabbit is now permanently implemented on an independent link from INRIM to the financial district of Milano (279 km) [15]. This will be a suitable option for the UTC traceability of financial markets, as requested by a new regulation (2018) from the European Security and Markets Authority, named MiFIDII **Errore. L'origine riferimento non è stata trovata.**. The regulation asks for a traceability level depending on the financial activity, but in the most stringent case the required accuracy is 100 μs and sensibility 1 μs.

## VII. CONCLUSION

We developed a national fiber backbone between several research institutions in Italy for the accurate dissemination of the national primary frequency standard: the present haul is 1800 km long and spans from the French border to Matera; 800 km are fully operational, disseminating our INRIM references, while the remainder will be implemented by 2017.

We are strongly focused on the exploitation of this facility in fields outside the core frequency metrology, and target the realization of distributed research facilities of continental scale, which could lead to novel, high-impact ways of doing research. The synchronization of the radiotelescopes in Medicina and Matera will build a thousand-km wide interferometer, whereas the connection of spectroscopy laboratories such as LENS and INO allows for the simultaneous monitoring of atomic and molecular transitions with unprecedented accuracy. The measurement capability of the single institute will be empowered, resulting in an extremely useful tool to probe Physics as we know it today. On the other hand, time transfer over fiber is a technique already mature for industrial user, and we started the implementation of permanent fibre links devoted to this target.

## ACKNOWLEDGMENT

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