Extension of REFIMEVE with a White Rabbit Network

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***Summary*—T-REFIMEVE is a new project funding the infrastructure REFIMEVE, in which one of the objectives is the deployment of a White Rabbit network at the French national scale. Here we report on our current status of the deployment of a White Rabbit network disseminating UTC(OP) to five academic users over a maximum distance of 40 km. We report loop-back measurements and compare results obtained with time transfer and frequency transfer, and discuss the results.**

Keywords—Fiber link, fiber network, time and frequency dissemination

I. INTRODUCTION

Scientific applications concerned either by improved performance or by redundancy and traceability motivate the growing popularity of time and frequency dissemination techniques over fiber as an alternative to GNSS techniques [1-4]. To be considered as a practical solution at a national scale, the level of maturity of the technologies deployed in-field are crucial, both for the effectiveness of the new service and for its implementation on an existing active telecommunication network beyond the framework of a short-term project.

In France, we built over the last decade a national network to disseminate optical frequencies in parallel to the data traffic of active telecommunication networks, under the research program REFIMEVE+ [5-6]. Consolidation and geographical expansion of the network, together with its extension to radio-frequency and time transfer and to new users, are funded within the ESR+ project T-REFIMEVE.

REFIMEVE is a national research infrastructure (RI) acknowledged as such by the French ministry of Education and Research in 2021, aiming at the dissemination of French legal time and of frequency standards to more than 30 research laboratories and RIs all over the metropolitan area of the country [7]. Reference signals originate from LNE-SYRTE and are mainly transported over the optical fiber backbone of RENATER, the French National Research and Education Network.

One of the specific objective of T-REFIMEVE is to provide the scientific community and industrial users with a complete set of timing signals at the best international level that metrology laboratories can provide. It consists in disseminating optical frequencies, radio-frequencies, and time markers, by taking advantage of the exceptional accuracy of optical and microwave atomic clocks and of the French realization of time, UTC(OP). As one element of T-REFIMEVE, we plan to deploy a long-range White Rabbit (WR) network over a unidirectional telecommunication architecture at national scale using xWDM technology [8-9], following our preliminary studies on fiber spools with a 500 km cascaded architecture [10-11]. This is based on pioneering work at VTT Technical Research of Finland and VSL (respectively the Finnish and Dutch metrology institutes), and on work by several National Metrology Institutes in Europe as the National Physical Laboratory (UK), Istituto Nazionale di Ricerca Metrologica (Italy) and RISE (Sweden) [9,12].

II. METHOD

In this paper, we present the status of deployment of our White Rabbit network. By early 2023 the WR network comprises 11 WR modules including 7 WR Switches (WRS), 3 WR ZEN TP (WRZ), and one WR LEN [13-16]. It corresponds to approximately 120 km in total of network spans. There is not a single-type link architecture in our network. In-campus dissemination uses dark fiber, and we use a standard dual wavelength 1310/1490 nm emitter/receiver pair, which is the most popular configuration for short spans [2]. This is the case for instance in our first spans inside the campus of Paris Observatory. We use off-the-shelf CWDM filters for network management, as data traffic and other signals (RF dissemination, optical dissemination) are serviced on the same fibers. Out-of-campus dissemination is on shared fiber with RENATER, using a fiber pair and off-the-shelf CWDM filters. The wavelengths of the emitters vary depending on particular spans, using for example 1310, 1510, 1530, 1541, 1550, and 1560 nm. Five academic laboratories and one company are connected by the WR network : Laboratoire de Physique des

Lasers (LPL, Villetaneuse), Laboratoire de Physique des Hautes Energies (LPNHE, Paris), Thales MIS (Velizy), and Institut des Sciences Moléculaires d'Orsay (ISMO), Laboratoire Aimé Cotton (LAC), and Irène-Joliot-Curie-Laboratory (IJCLab) at Orsay.

In order to evaluate the stability and accuracy of the disseminated time and frequency signals, we loop back the signal to its initial location so that an end-to-end measurement can be made. We present the data acquired for one local in-campus span (range ~ 400 m), and one deployed span reaching a datacenter in Paris (~ 10.1 km). This is illustrated in Figure 1.

Within one span, temporal delay between the final WRZ receiver (R0 and R1) and the initial WRS emitter (GM and M0) is measured on a SR620 time interval counter (TIC) in trigger mode, with a trigger tension of 1 V, using UTC(OP) as a pivot. Single shot resolution is 25 ps. Acquisition rate is 2.8 mHz on the local span, and 0.25 Hz on the deployed one. On the latter, frequency data are acquired too, using a dead-time free frequency counter in Λ-mode, at a rate of 1 Hz. Single-shot resolution is 2-3 ps in a 0.5 Hz bandwidth. TIC and frequency counters are operated in temperature and humidity-controlled environments with continuous monitoring.

We compare the results obtained using the time data and the frequency data, and discuss their consistency.

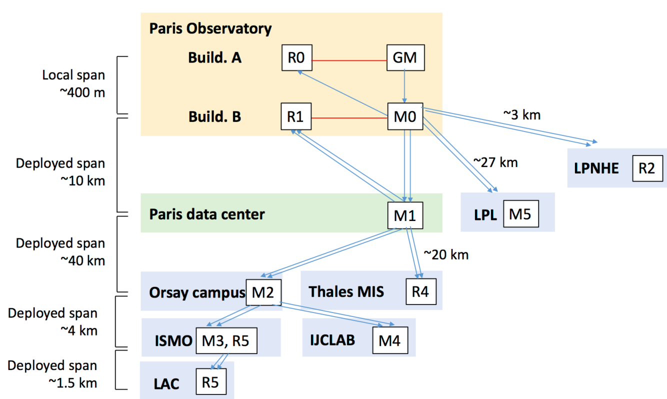

Figure 1: Schematic of the local and deployed spans architecture. Blue arrows represent the transmitted time and frequency signals. Red lines indicate the end-to-end measurements. GM: Grand Master, M: Master, R: Receiver.

III. RESULTS AND DISCUSSION

Figure 2a shows the time delay for the local span derived from time data over 3 months. R0 reproduces the GM timing with an agreement of 200 ps, which is assigned to link asymmetry. Peak-peak fluctuation is below 100 ps. As a result, the WR link achieves referencing to UTC(OP) within a 100 ps uncertainty continuously over 3 months. Correlation between the emitted and received traces is very strong, more than 80% beyond 5 days of integration, showing overall a very good control of the M0 WRS. In terms of stability, Figure 3a shows the temporal Allan deviation (TDEV) for the emitted and for the emitted-transmitted signals. Single-shot resolution is 10 ps, limited by the TIC, but compatible with future timescales comparisons at such resolutions. Long integrations reach a 2 ps floor noise level, compatible with geodesy applications.

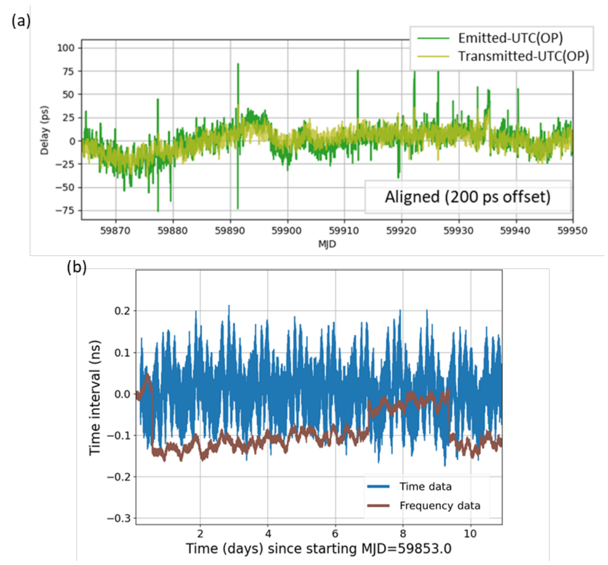

Figure 2: a) Time delays with regards to UTC(OP), over 3 months on a local span, for the emitted and transmitted signals. b) Time error between emitted and transmitted signals, over 10 consecutive days on a 10.1-km deployed span (20.2 km round trip), derived from frequency (brown) and time data (blue).

Figure 2b shows the time error between emitted (M0) and received (R1) signals, over 10 days for the deployed 10.1-km span, derived from the time and frequency data. The uncompensated distributed maser at the basis of UTC(OP) is used as a pivot. Measured time intervals do not exceed 200 ps in absolute value, which is in agreement with the WR expected accuracy. Short-term standard deviation of the time data is 28 times larger than that of frequency data, which is consistent with the acquisition procedure. TDEV are presented in Figure 3a) and show that time data stability is dominated by the TIC white phase noise at short integration time, with a $\tau^{-1/2}$ power law, and by night/day temperature fluctuation cycles, clearly seeable as a bump with the TDEV plot. This is consistent with the periodic daily fluctuations visible on the temporal trace of Figure 2b. Frequency data stability is dominated by flicker phase noise at first, which is expected. Beyond 100 s of integration, the TDEV increases dramatically, which is due to the cycle slips and missing data not being addressed in our processing. Strategies will have to be deployed to overcome this and enable to reach the targeted 10^{-15} stability levels, as proposed in [17] for example.

Furthermore, if the correlation between the two data sets is strong within the scale of 1h of acquisition, it does not necessarily hold over a few days. Reminding that the time and frequency signals are in common mode, exploiting and understanding the correlations and combination of both data could constitute a powerful tool for analysis. As a first step, Figure 4 shows the data autocorrelations. For frequency data, we obtain a typical autocorrelation peak, but for time data, the autocorrelation is dominated by periodic fluctuations, assigned to day/night temperature fluctuations in the lab. As a result, it appears that the TIC is much more sensitive to such effect than the frequency counters. In the future, we will need to identify further such instrumental issues. Overall, by exploiting the time and frequency data acquired continuously over several months, our goal is to understand the phenomena inducing these behaviors, and eventually to use them as tools to assess and improve the time and frequency transfer performance.

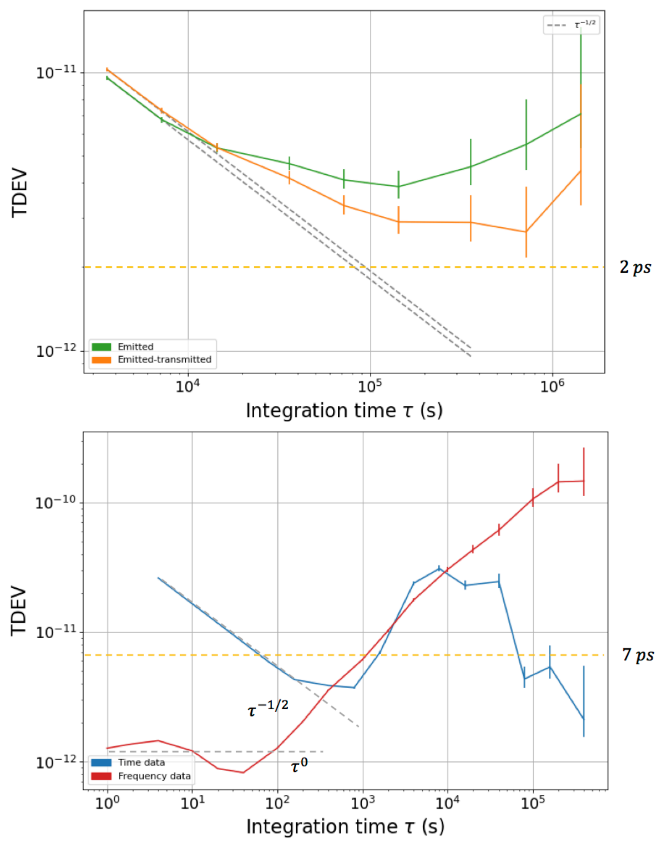

Figure 3: a) Stability of the emitted (green) and emitted-transmitted (orange) signals on the local span. b) Stability of the emitted-transmitted signal on the deployed span, derived from time (blue) and frequency (red) data.

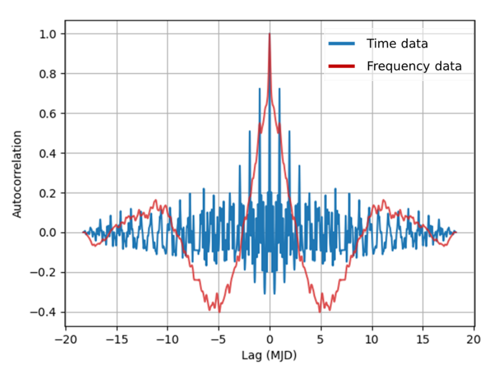

Figure 4: Autocorrelation of the emitted-transmitted time (blue) and frequency (red) measurements on the deployed span.

IV. Conclusions

We report on the current deployment status of a WR national scale network within the new research infrastructure REFIMEVE. We assess the time and frequency transfer performance over two short- and mid- range spans of our WR network currently under deployment. The end-to-end measurements of stabilities and time errors, as well as the correlations between the disseminated time and frequency signals are analyzed. Very good preliminary results were obtained on the short baseline, with uncertainty levels below 100 ps hold continuously over 3 months, and 2 ps long term stabilities. On longer baselines, instrumental issues need to be identified, especially related to temperature fluctuations and link asymmetry. Our approach for future work is to perform combined time and frequency transfer and to exploit comparisons of transfer techniques. These are critical steps towards the future implementation of this WR network over several thousands of km of optical fiber for the dissemination of UTC(OP) with sub-ns statistical uncertainty at a national scale.

Acknowledgments

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