REFIMEVE Fiber Network for Time and Frequency Dissemination and Applications

Etienne Cantin, Olivier Lopez, Nicolas Cahuzac, Yuhao Liu, Mathieu Manceau, Benoît Darquié, Christian Chardonnet, Anne Amy-Klein,
Laboratoire de Physique des Lasers
Université Sorbonne Paris Nord, CNRS,
Villetaneuse, France
amy@univ-paris13.fr

Martin Rabault, Grégoire Coget, Peter Rosenbusch, Vincent Ménoret,
Exail Quantum Sensors (formerly MuQuans)
Talence, France

Nicolas Quintin
RENATER
Paris, France

Mads Tønnes, Benjamin Pointard, Maxime Mazouth, Hector Alvarez-Martinez, Caroline B. Lim, Philip Tuckey, Michel Abgrall, Rodolphe Le Targat, Paul-Eric Pottie,
LNE-SYRTE
Observatoire de Paris, Université PSL, CNRS, Sorbonne Université
Paris, France

***Summary*—We report the performance of REFIMEVE, a national metrological network of optical fiber links, using the academic fiber network. It enables the coherent dissemination of time and/or frequency reference signals from LNE-SYRTE to around 15 labs and more than 30 in the future. We will show the latest extensions of the network in the Paris urban area and all over France, the architecture required for such al network, and the progress in terms of robustness and uptime. We will also present some applications to precision measurements, in particular ultra-high-resolution molecular spectroscopy in the mid-infrared spectral range.**

***Keywords*— optical link, frequency dissemination, fiber network, high-precision molecular spectroscopy**

I. Introduction

REFIMEVE is a national research infrastructure composed of optical fiber links to disseminate time and frequency reference signals from the French National Metrological Institute, LNE-SYRTE, to more than 30 research labs and research infrastructures all over France, over the optical fiber backbone of RENATER, the French National Research and Education Network. Consolidation and expansion of the network, together with its extension to time transfer and new users were recently funded and are currently being implemented. We have the objective to provide the ultra-stable signals with an uptime better than 90% and thus we have developed effective remote control and supervision of all links [1]. Last year the network was extended up to 2x3500 km and it has currently connections to UK, Germany, Italy and Switzerland, as shown in Figure 1.

II. Network extension

The REFIMEVE signal source is an ultra-stable laser whose drift is actively compensated using a continuous comparison to a H-Maser with an operational optical frequency comb. The fiber network uses essentially the academic network of RENATER, thanks to Dense Wavelength Division Multiplexing with data traffic. It is mainly equipped with Repeater Laser Stations, which repeat the ultra-stable signal from one fiber link to another [2], and Multibranch Laser Stations acting as hubs [1]. We have also implemented some industrial-grade Extraction Stations for local use in urban areas [3]. An ensemble of low noise phase-and-frequency recorders, local oscillators and GPS receivers enables remote measurements and clock comparisons at border crossings.

All equipment is remotely controlled and for every link from locations A to B, we implement a second parallel link from B to A in order to assess and trace the proper dissemination of the signal and supervise the network in real time. The link's residual stability is evaluated from the phase

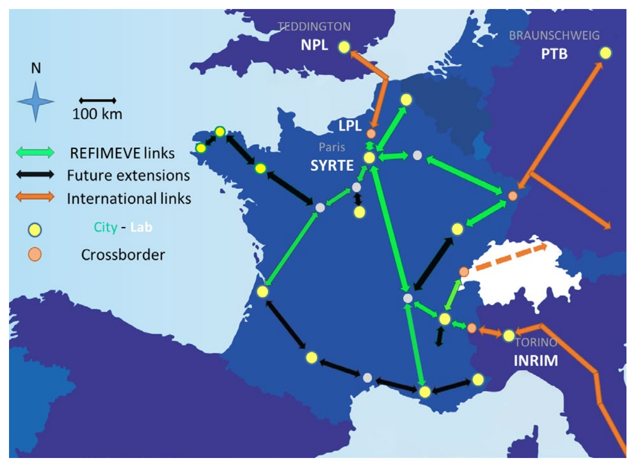

Figure 1: schematic of the REFIMEVE network

comparison of the signal injected in a link and the signal after dissemination from A to B and back to A. Figure 2 displays the residual frequency fluctuations of such an end-to-end phase comparison for four REFIMEVE links during 5 months. The link's length ranges from 2x340 to 2x900 km. The uptime of the links varies between 71 and 85%. The residual frequency fluctuations are typically 10^{-17} or below for an integration time of 1000 s, enabling precise clocks comparison within less than one hour. Figure 3 displays the corresponding end-to-end stabilities, calculated with the modified Allan deviation. The short-term instability is typically below 10^{-15} at 1-s averaging time and the long-term instability at a level of 10^{-19} or below. We also checked that the bias of the transmitted frequency is compatible with zero within an uncertainty of respectively 4×10^{-20}, 6×10^{-20}, 1×10^{-19} and 2×10^{-19} for the four links (a) to (d) considered in Figures 2 and 3.

Due to the missing data in long-term measurements, the estimation of the link stabilities is not straightforward. We either concatenated the data or replaced the missing data with simulated data of the same statistical properties. This last approach enables us to mitigate the effects of missing data as

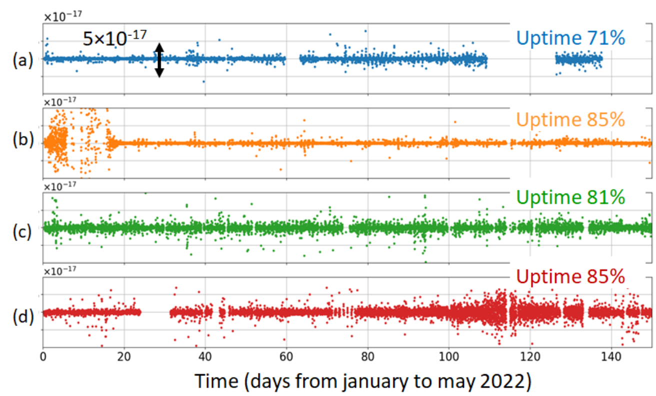

Figure 2: Relative frequency fluctuations (1000s/point) with time of 4 REFIMEVE links, during 5 months a) Paris-Lille-Paris (2x340 km); b) Paris-Strasbourg-Paris (2x650 km); c) Paris-Lyon-Modane-Lyon-Paris (2x900 km) ; d) Lyon-Marseille-Lyon (2x440 km).

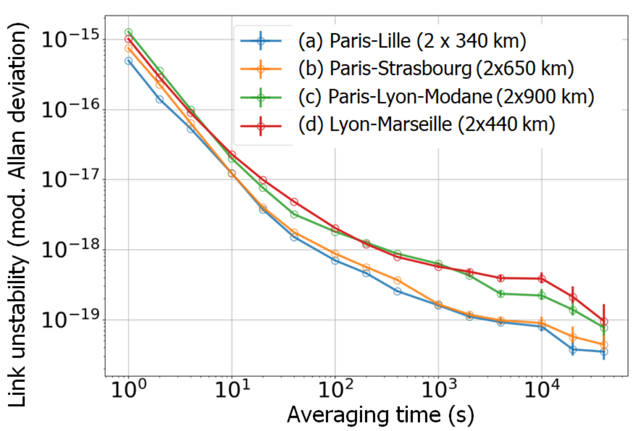

Figure 3: End-to-end stability (modified Allan deviation) for the 4 REFIMEVE links of Fig. 2.

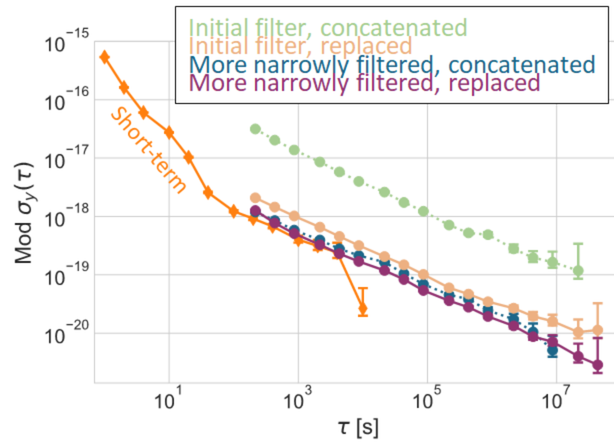

Figure 4: End-to-end stability (modified Allan deviation) for the Paris-Strasbourg-Paris link along 5 years of data. Missing data are taken into account either by concatenating the data or by replacing missing data with simulated data having the same statistical properties.

shown in [4]. We applied both approaches to a very long data set of 5 years of operation of the Paris-Strasbourg link, with 44% uptime, as displayed on Fig. 4. The graph shows that the stability obtained when missing data are replaced with simulated data (violet) is fully compatible with the stability calculated from a data set without any missing data at short-term (orange), and with concatenated data when the minimal duration of a data subset exceeds the statistical coherence time. Without a proper set of filtering parameters, a concatenated approach can lead to erroneous evaluation of the relative frequency stability and introduce frequency biases (green curve). Furthermore, with this processing method we were able to assess the link residual instability at 1-year averaging time and the link uncertainty at a level of a few 10^{-21}.

III. Recent development

We have recently extended the REFIMEVE network both in Paris region and on a national scale, to the south-west part of France and to CERN in Switzerland, which is a major European interconnection point for academic networks and GÉANT.

A schematic of the current network in Paris region is shown on Fig. 5. It disseminates the optical signal and a White Rabbit time signal to all the main universities in north, center and south of Paris in a star network configuration. All the links depart from LNE-SYRTE where a multibranch station enables us to coherently disseminate the optical reference to all the users [1]. Extraction stations are used at Sorbonne Université and Université Paris-Saclay to drop the signal to the user labs [3].

The link to CERN is a branching link of length 200 km along the main link between Paris and Italy, as displayed on Fig. 6. Its stability is limited by the residual noise of the previous segments of the link, which totalize a length of 720 km. However its stability reaches the 10^{-18} scale in less than 2 hours, and a few 10^{-19} at 1-day averaging time. This performance could be improved in the future with a better filtering of the accumulated noise at the branching node.

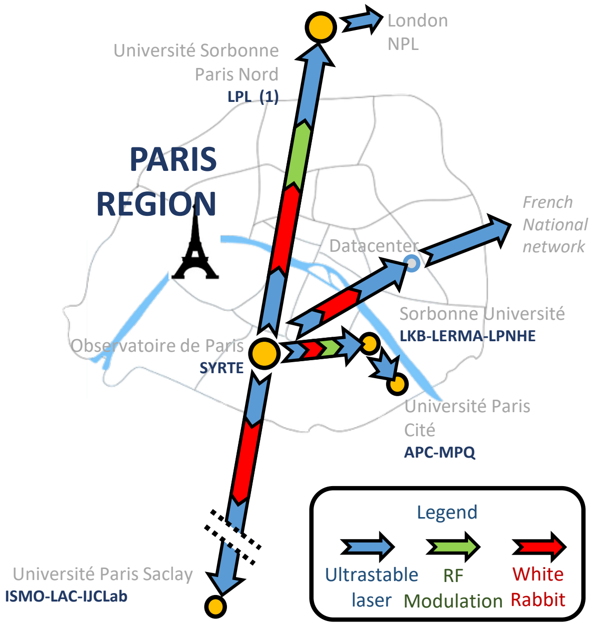

Figure 5: schematic of the REFIMEVE regional network in Paris.

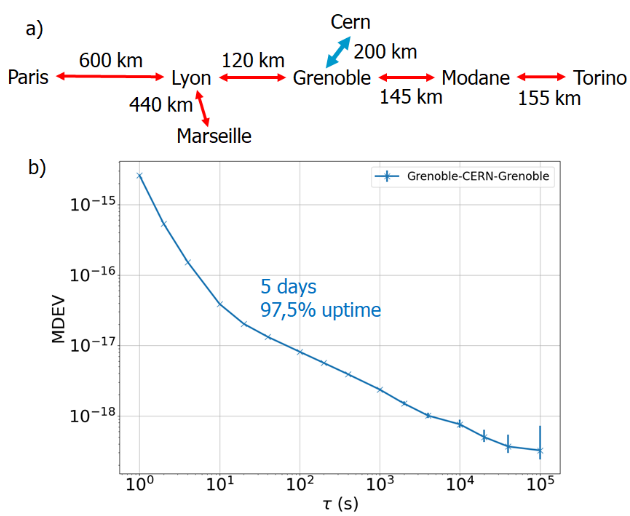

Figure 6: End-to-end stability (modified Allan deviation) of the Grenoble-CERN-Grenoble link of 2x200 km.

IV. Current applications

The ultra-stable frequency signal disseminated with REFIMEVE has been used for more than 10 years for precision measurements in the Paris regional area, mainly at LKB and LPL [5]. It is disseminated to a few laboratories in Besançon, Lille, Grenoble [6], Marseille and Paris, where current applications of REFIMEVE concern photonics, laser stabilisation or control, atomic and molecular spectroscopy. Current developments are very active in precision molecular spectroscopy in the mid-infrared spectral range around 10 µm, with molecules of interest for atmospheric and astrophysics studies [5, 6] or for test of fundamental physics [7]. At LPL,

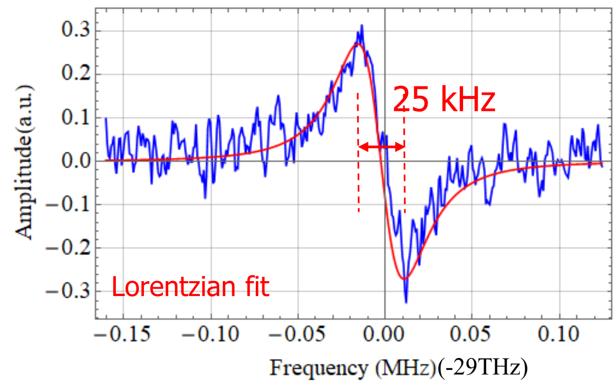

Figure 7: saturated absorption spectrum of the line P(E,co,0,2,33) of methanol at a pressure of 0,05 Pa, around 29 THz (10 µm), with 1s/point. The signal is detected in transmission of a Fabry-Perot cavity with a Quantum Cascade Laser stabilised to the REFIMEVE signal.

molecules are probed with Quantum Cascade Lasers stabilised to the REFIMEVE optical reference, through an optical frequency comb. Fig. 7 shows a saturated absorption spectrum of the line P(E,co,0,2,33) of methanol, a molecule involved in numerous atmospheric reactions, and present in the interstellar medium. The spectrum is recorded in transmission of a Fabry-Perot cavity, with a resolution around 25 kHz limited by the pressure broadening. A Lorentzian fit enables us to determine the line center with an uncertainty around 600 Hz.

V. Conclusions and Perspectives

The REFIMEVE network is mature and enables more and more labs to benefit from an ultra-stable and accurate frequency signal for their precision experiments. Moreover, thanks to its European connection, it gives the opportunity to compare the best atomic clocks in Europe, as performed with Italy during 4 months in 2021-2022 [8] or through a two-months measurement campaign within Europe in 2022. It is also very interesting for applications to chronometric geodesy, using these clocks comparison campaigns [9] or with the planned development of a mobile platform which can be placed at the output end of any links providing transportable comb and clock for clock comparisons.

REFIMEVE contributes to the roadmap towards a pan-European fiber network, as actively prepared through the project CLONETS-DS. The development of such networks is also in progress in other EU countries and all around the world, for instance in China and Japan [10, 11]. Interconnection and combination with free-space techniques, such as the well-established radio-communication Two-Way Satellite Time and Frequency Transfer (TWSTFT) and more-ground breaking techniques such as optical TWSTFT, is a challenge to be faced to enable world-wide multi-technique optical timescale comparisons.

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