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► **To cite this version:**

E Cantin, O Lopez, C Chardonnet, A Amy-Klein, M Rabault, et al. REFIMEVE frequency and time network and applications. *Journal of Physics: Conference Series*, 2024, 2889 (1), pp.012031. 10.1088/1742-6596/2889/1/012031 . hal-04841731

**HAL Id: hal-04841731**

**<https://hal.science/hal-04841731v1>**

Submitted on 16 Dec 2024

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# REFIMEVE frequency and time network and applications

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**Abstract.** We report on the development and current status of the REFIMEVE national research infrastructure, which disseminates time and frequency reference signals generated at LNE-SYRTE to more than 30 research labs all over France. By using mainly the optical fiber backbone of RENATER, the French National Research and Education Network, REFIMEVE is currently providing an optical frequency reference to around 15 labs and to connection points to Germany, UK, Italy and Switzerland. The robustness of the various equipment specially developed for ultrastable frequency transfer and the efficient supervision enable us to demonstrate routinely uptimes of more than 90%. We show the last development we have performed to extend the network to CERN in Switzerland, with a branching link exhibiting residual frequency fluctuations of  $3 \times 10^{-15}$  for 1-s measurement time and a few  $10^{-19}$  at long term. We discuss the issue of data processing for long periods of time and how to mitigate the effects of missing data and obtain a reliable link uncertainty. Thanks to these performances, the REFIMEVE network has been used for the precise comparison of primary and optical clocks in Europe and REFIMEVE optical signal is currently exploited in France by user labs for photonics, laser stabilisation or control and atomic and molecular high-resolution spectroscopy.

## 1. Introduction

When one aims at comparing two distant clocks, a possibility is to move physically one of the two clocks. This is still nowadays a very powerful method, but usually the mobile clock is less performant than the static one [1,2]. Sending a wave that carries the clock information is very attractive for its drastic logistic simplification, and multiple user broadcasting capacity. Therefore since the first transatlantic radio-broadcast by Marconi in 1902, radio-emission based clock comparisons using GNSS, dedicated satellite are the mostly used techniques that effectively enters the computation of the International atomic time (TAI) and Universal coordinated time (UTC) [3,4]. Satellite based methods limit the uncertainty of the comparison at short term, and are not enough performant for optical clocks. Since 2

decades fiber links are explored as a very promising media to achieve the goal of ultra-precise clock comparisons, almost without degradation of the clock performances.

The principle of fiber links is quite simple, and already depicted in the late's 70s and 80s (see for instance [5]). Nowadays, the basic principles are the same, but an ultra-stable laser operated in the C-band feeds a single mode fiber link. It uses strongly imbalanced Michelson interferometry to detect the phase variation of the light that experiences a round-trip in the fiber with respect to the light that experiences a round-trip in the reference arm [6]. In such experiences the light propagates bidirectionally into the fiber. To evaluate the performance of the frequency transfer, a second bidirectional fiber is used to transfer back the laser light to the initial point. One measures the optical phase difference of the transferred light with respect to the ultra-stable laser feeding the link. This so-called end-to-end measurement enables us to give an upper value of the residual frequency fluctuations of the link and of the uncertainty of the frequency transfer [7].

Fiber links has numerous advantages. First of all, the guided propagation allows a low loss transmission, about .2 to .3 dB/km. In addition, there is relatively low noise, and even more importantly with excellent statistical properties: the noise averages very well to zero from 1-s to years of measurement time. The main advantage is the excellent reciprocity of paths for signals travelling forward and backwards the same fiber. It allows to reach a coherent regime, where relative frequency stability scales down as the integration time, or better, which is faster than with satellite method. There are also some limitations. Fundamental limit set by the delay propagation in the fiber limits both the noise rejection amplitude and the bandwidth of the servo-loop which corrects the propagation phase noise [8]. More technical limits are related to the uncontrolled polarisation of the light in single-mode fiber and to instrumental noise floor of the interferometers [8]. The main disadvantage of coherent fiber links is that they are bound to point-to-point or point-to-a-few dissemination [9]. There is also very attractive prospect of using fiber links in uni-directional configuration, but the topic is still little explored so far and debated [8,10,11].

The ranges of fiber links were extended up to thousands of km, to the point they can be joined and form a concatenation of such links [12,13]. Fiber links reach a high level of technical readiness level [14], and actually the main challenge for fiber links lies in the access to the existing infrastructure designed for high rate data transfer, or alternatively to create an on-purpose designed infrastructure. In term of performances, fiber links outperform satellite-based methods by orders of magnitude. Free-space optical transfer techniques are the only alternative to reach better than  $10^{-18}$  resolution to date [15,16]. This technological breakthrough opens many new scientific opportunities, for clock comparisons [13,17] and chronometric geodesy [1,18], test of special relativity [19], the search for dark matter [20], atomic and molecular spectroscopy [21–24], seismology [25,26] and VLBI [27].

## 2. Current status of REFIMEVE

The REFIMEVE network is a national research infrastructure aiming at disseminating ultrastable time and frequency signals from LNE-SYRTE to academic labs, research institutes and companies all over France, with connections to European National metrological Institutes. It totalizes currently 3800 km of pairs of fiber links, as shown on Figure 1, where the links in operation are displayed with green solid lines and the future links with green dotted lines. It exhibits 4 European connections, to the fiber links of UK, Germany and Italy, and to CERN. REFIMEVE relies on the propagation of ultrastable signals developed at LNE-SYRTE through the fibre network of RENATER. The ultra-stable signals are multiplexed with the digital data from the RENATER network, which is the French National Research and Education Network (NREN). Two signals are currently disseminated on REFIMEVE, an optical frequency reference and a White Rabbit signal, the latter being disseminated only in Paris region up to now.

The optical frequency reference is elaborated from an ultra-stable laser which is actively dedrifted versus either a cryogenic oscillator or a H maser [ref?]. It has a fixed frequency known in a range of 1 Hz when controlled to the cryogenic oscillator, with a stability below  $10^{-15}$  at 1 s averaging time and a routine uncertainty of a few  $10^{-15}$ . For the non-degraded dissemination of this signal with an optical link,

the key issue is the bidirectional light propagation inside the fibre. It is unusual for telecom networks, which are based on the unidirectional propagation of light using two fibres, one for each propagation direction. Thus, every equipment of the telecom network, which is unidirectional, should be bypassed using Optical Add-and-Drop Multiplexers (OADM). The signal is amplified with low-noise bidirectional amplifier, that is a part of the development and knowledge transfer made within REFIMEVE. To build a network on a national scale, we use Repeater Laser Stations (RLS) and Multi-branch Laser stations (MLS) for the signal regeneration and the fibre noise compensation, using a cascaded approach that allows for better propagation noise rejection. These equipment's are commercially available after their knowledge was transferred to Exail [14]. The RLS are placed every 300 to 500 km on the fibre network and include a laser, which is controlled in order that it copies the optical phase of the incoming signal and distributes it to the next optical link. Moreover, a user output enables us to distribute the ultra-stable signal to a local user or to characterize the metrological performance of this signal. MLS are built on the same design but with multiple phase-coherent outputs in order to distribute the signals to multiple links and thus build star-like network configuration [9].

As a national research infrastructure, operating the network also means reducing human intervention as much as possible and controlling the proper frequency transfer, while at the same time achieving the highest possible uptime. To that aim, we develop automated servo loops and nucleate a supervision system. This allows remote operation of the network for parameter tuning and optimization and gives us the possibility to monitor in real-time all the links. More importantly it allows the network operator to always keep the hand on the network and prioritize services. At any time, the lasers and key operating parameters of the metrological network are under control of the Network Operating Center of RENATER. Finally the supervision system includes an automated data processing and management system and the possibility to rise alarms to users.

### 3. Performance of REFIMEVE

#### 3.1. Robustness of REFIMEVE network

Figure 2 shows an example of the operation of 4 national links and 1 regional link of REFIMEVE during 73 days in fall 2022. Each graph displays the residual frequency fluctuations of the forward and backward links with an averaging time of 1 s. The links lengths range from  $2 \times 50$  km to  $2 \times 900$  km and exhibit residual fluctuations which increase with this length and range from a few  $10^{-15}$  to a few  $10^{-14}$ . Note that the link Lyon-Marseille (red trace) is a branching link on the main link Paris-Modane (as depicted in Fig. 3 a)), it picks up part of the residual noise of this main link and thus exhibits an enhanced noise.

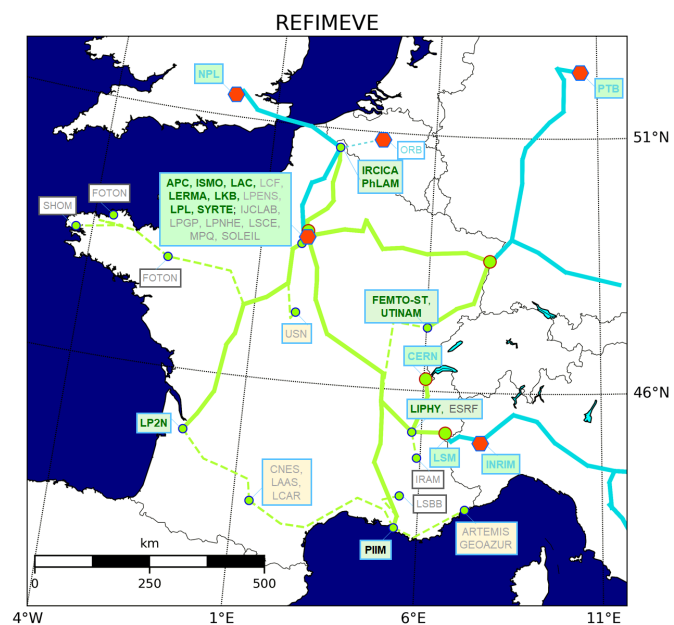


Figure 1 : current status of REFIMEVE research infrastructure. Continuous green lines: operational links, dotted green lines: future links, blue lines: European links to which REFIMEVE is connected, blue dotted line: future European link. French connected labs are indicated in green, links which will be connected in the future in grey.

Thanks to the supervision and remote control of the network equipments, and the maintenance of the fiber network by RENATER, the uptime of the links is quite high, ranging from 73% to 91%. Each interruption has been analyzed in order to improve the operation. For instance, the long interruption on the link Paris-Modane (green trace) is due to unusual noise, undoubtedly attributed to works along the fibre route. Some interruptions occurred on all the 4 or 5 links and are attributed to a failure of one of the master MLS of the network at SYRTE or in the main datacenter in Paris. Finally the main interruptions on the Lyon-Marseille link (red trace) (a short and a long one) and on the Paris-Orsay link (purple trace) are due to a failure of the end-to-end instability characterisation but the signal was still disseminated to the remote labs and used there.

These traces show the robustness of the REFIMEVE network, that we are continuing to improve with the aim of an uptime of more than 90% on all the links, and more than 99% during dedicated periods.

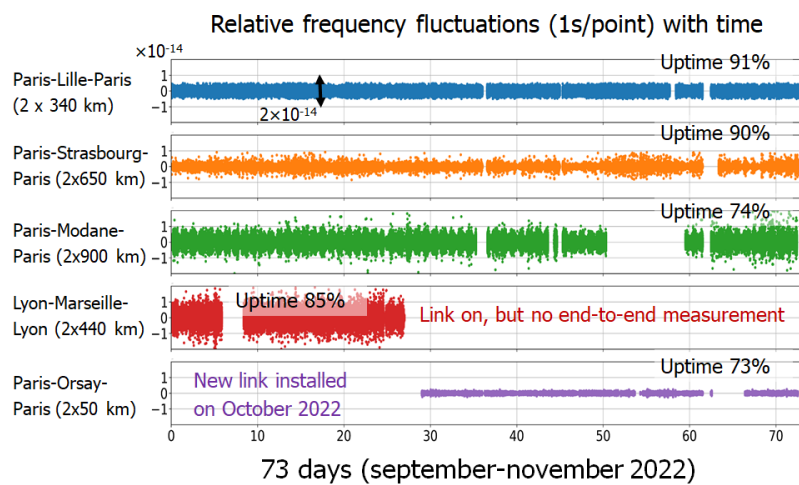


Figure 2 : relative frequency fluctuations of 5 links versus time during 73 days in 2022, with their uptimes. Averaging time: 1s/point.

### 3.2. Example of SYRTE-CERN link

In this part, we focus on the last link implemented on REFIMEVE network, connecting SYRTE (Paris) to CERN (Geneva, Switzerland). It is a branching link of 200 km along the long cascaded link of 1000 km between Paris and Italy, as showed on Figure 3 a). The residual instability of the link to CERN and back (2×200 km) is displayed on Figure 3 b) for a data set of 5 days with an uptime of 97 %, showing that the link is quite robust. It is  $3 \times 10^{-15}$  at one second averaging time, reaches the  $10^{-18}$  level in less than 2 hours, and  $3 \times 10^{-19}$  at  $10^5$  seconds.

This residual instability is higher than with other links of

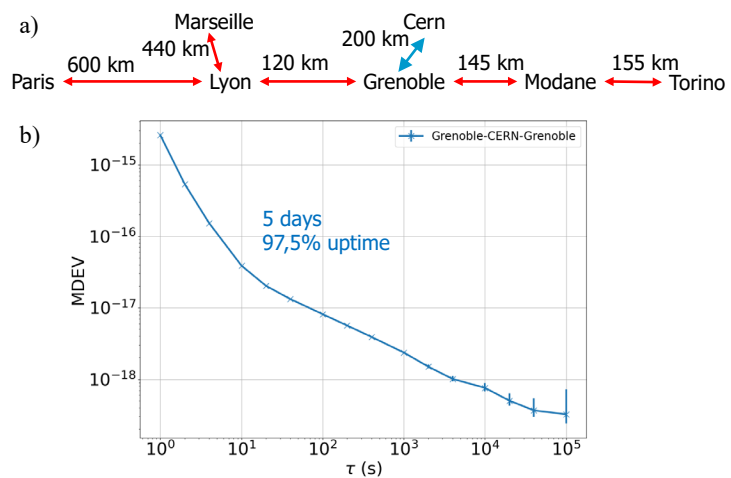


Figure 3 : a) schematic of the link from Paris (SYRTE) to Geneva (CERN); b) residual instability (modified Allan deviation) of the link from Grenoble to CERN and back.

similar length of the REFIMEVE network. The noise is indeed increased by the residual noise of the previous segments of the main link, this residual noise being quite high since it is increasing with the link' length. This stability could be improved in the future with a better signal regeneration in Grenoble, using for instance an ultra-stable laser as a regeneration laser instead of a low-noise laser diode. The uncertainty on the transferred frequency is estimated from the mean relative frequency and the long-term instability to be  $1,4 \pm 4.2 \times 10^{-19}$ .

### 3.3. Noise study at yearly scale

We have taken advantage that a REFIMEVE link of 700 km, connecting SYRTE to the German border, is operated since 2015 to study the noise statistics on a very long period [28,29]. For such a study, we face the issue of missing data along times, since the link was not operated all the time, due to fiber replacement or other interruptions. The basic data processing consists in concatenating the data but in that case the time scale is lost, especially for long interruption. Another possibility is to analyse the link during a long operation period without interruption, and fit the noise parameters. This enables us to simulate the noise and replace missing data by simulated noise in the data set. These various processing methods were used and the mean relative frequency offsets of the processed data are displayed on Figure 4, together with the corresponding modified Allan deviations. The lower uncertainty is obtained when missing data are replaced with simulated data, and the offset is compatible with the one obtained with concatenated data. Similarly, when replacing the data, we obtain a stability which is compatible with the short-term stability, and which is better than with the concatenation. Finally this study gives a long-term stability below  $10^{-20}$  at  $10^7$  s, whatever the processing methods is used, and in the low  $10^{-21}$  for a time averaging of one year, when missing data are replaced with simulated noise. As far as we know, this is the longer averaging time ever probed with optical links.

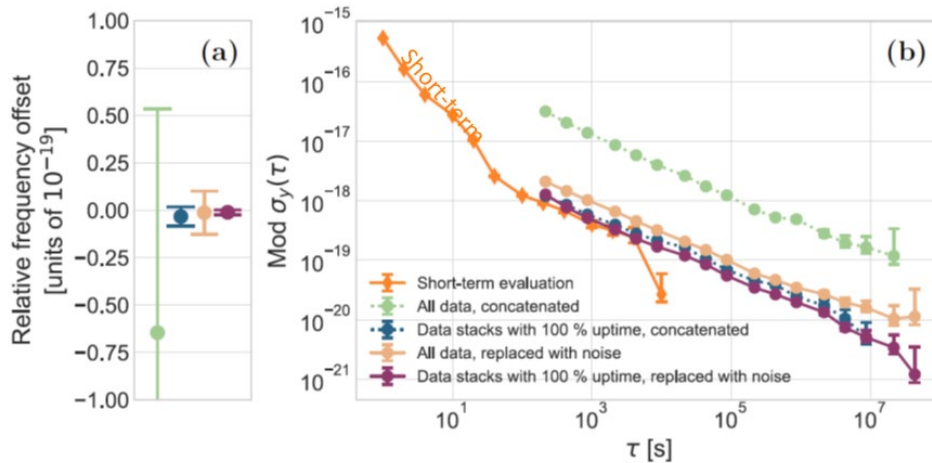


Figure 4: (a): Relative frequency offsets and (b): modified Allan deviations (MDEVs) of Paris-Strasbourg link (2x700 km) over 5 years, calculated in 4 different ways: from all data stacks (green), only data stacks with 100 % uptime (blue), all data stacks where missing data is replaced with simulated noise (light brown), and only data stacks with 100 % uptime where missing data is replaced with simulated noise (purple) (from [29]).

## 4. Applications of REFIMEVE

With its connection to 3 neighbouring European links, REFIMEVE enables European clocks to be compared with the best possible uncertainty, which is definitely below  $10^{-18}$  as recommended by the BIPM [30]. The first european clocks comparison by optical fiber link occurred in 2015 and gave the possibility to compare the Sr optical clocks of SYRTE and PTB through a 1400-km link [17]. The clocks frequencies agreed with an uncertainty of  $(4.7 \pm 5) \times 10^{-17}$  after the gravity potential correction has been

considered. The comparison uncertainty was not limited by the link residual fluctuations, which contribute to only  $2 \times 10^{-19}$ . This seminal clocks' comparison was followed by multiple comparison campaigns, mainly in the frame of the EURAMET projects OFTEN and ROCIT (see for instance [13]). These campaigns rely on the star network between SYRTE and NPL, PTB and INRIM and on the technology of the RLS developed in the frame of REFIMEVE, using for instance two-way frequency comparison of the RLS user outputs. These comparison campaigns are essential for T&F metrology and the future redefinition of the second [30]. Moreover they enable to perform some fundamental test of physics and for instance search for dark matter [20] or test special relativity [19]. For these comparisons, it is very important that the residual instability and uncertainty of optical links are below that of the clocks, and this is the case, uncertainty is in the low  $10^{-19}$  range for all REFIMEVE links.

Beyond clocks comparison, REFIMEVE has enabled the partner labs to perform a wide range of precision measurements, from high-resolution molecular spectroscopy [31–33] to photonics and noise

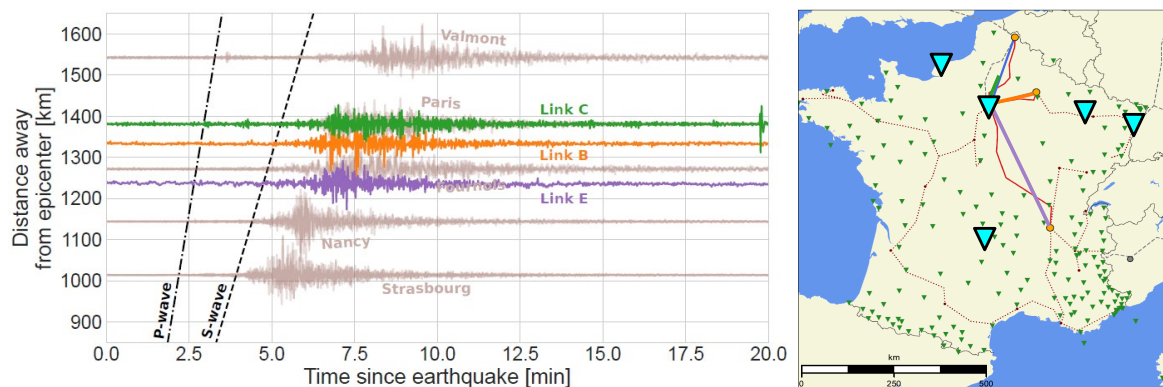


Figure 5 : example of earthquake sensing with 3 links of REFIMEVE network and comparison with standard seismometers. The links and the seismometers positions are shown on the map on the right. (from [29])

characterization (see for instance [34]). Moreover the network itself can be exploited as a giant and distributed noise sensor, both for sensing seismic noise [25,29] or tiny Earth rotation fluctuations through the Sagnac effect [35]. Figure 5 gives an example of the detection of an Earthquake arising in Bosnia and of magnitude 5.7 with three links of REFIMEVE network : the detected signals compare very well with that of low-noise broadband seismometers (as trillium compact), with similar sensitivity or lower at 0.5 Hz bandwidth in the best case.

## 5. Conclusion

To conclude, the REFIMEVE research infrastructure is currently connecting 15 labs all around France, together with cross-connections to 4 European countries, enabling clocks comparison with UK, Germany and Italy. The network will be soon extended to south and west of France and new European connections are planned, for instance with the Belgium National Metrological Institute (BOOSTED project).

The current development concerns also the upgrade of the network, which will be equipped with MLS at each node of the network, in order to simplify the multi-user dissemination. Ultrastable lasers could be also set-up in key nodes of the network in order to better regenerate the signal.

The service provided by REFIMEVE is being extended to RF and time transfer, using the White Rabbit technology. Currently all Paris region already benefits from a White Rabbit signal, and this coverage will extend soon to a radio-observatory in the center of France.

Beyond fundamental metrology, the applications of REFIMEVE are very wide. Most of them are concerning currently some tests of fundamental physics as for instance the search for fundamental constants variation or for dark matter, and high-precision spectroscopy. In the future, we anticipate

extensive applications to sea level monitoring with chronometric levelling, to Earthquake sensing, and to synchronization for astrophysics or high-energy physics.

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## Funding

The authors have received financial support from Agence Nationale de la Recherche ANR T-REFIMEVE (ANR-21-ESRE-0029), REFIMEVE+ (ANR-11-EQPX-0039), Labex First-TF (ANR-10-LABX-48-01), Idex PSL (ANR-10-IDEX-0001-02 PSL), LNE, Conseil Régional Bourgogne-Franche-Comté, Conseil Régional Ile de-France (DIM SIRTEQ), the European Metrology Programme for Innovation and Research (EMPIR) in project 15SIB05 (OFTEN) and 18SIB05 (ROCIT). The EMPIR is jointly funded by the EMPIR participating countries within EURAMET and the European Union.

## Acknowledgements

We acknowledge the strong support of RENATER, and especially Emilie Camisard and Laurent Gydé. We are grateful to Samir Kassi and co-workers (LIPHY) for their commitment in hosting the equipment for the Grenoble-CERN link.