REFIMEVE: Etat d'avancement et quelques cas d'applications

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Outline

• Motivations
• Introduction to fiber links
• From fiber links to fiber networks
  • update of the REFIMEVE fiber network
• Optical clocks network
• On-going projects and outlook
Motivations for time and frequency dissemination

Dissemination of Time and Frequency from standards (atomic clocks, timescales)
for industry / society: Telecom and network synchronisation, smart grids, finance, manufacturing...

Timing+syntonisation:
ms-ns, 1e-11-1e-15
Traceability

Sensing/Defense:
Positioning, Navigation and Timing

Large instruments, array of detectors
astronomy, astro particle, geoscience
multi-messenger astronomy

Timing+syntonisation:
ns-ps, 1e-16

Resiliency

Fundamental Scientific Applications
Definition & Variations in fundamental constants

Tests of Special & General Relativity

Earth Science and climate change
geodesy, chronometric leveling

Timing+syntonisation:
ns-ps, 1e-18 and better!
Comparisons

Illustrations: courtesy N. Newbury, NIST
Passive stabilization of fiber optic transmission links, such as burial of the cable, is not sufficient for maintaining stabilities in the range required for many applications. When stabilities higher than a part in $10^{15}$ are required the link must be actively stabilized.

Fiber links: seminal works (Primas et al., 1988)

- Active noise compensation after one round-trip
- Strong hypothesis: noise forth and back are the same
- 2 ends at the same place (for link stability measurements)
- RF, hF or optical signals

Coherent optical fiber links

Fiber links: pro and contra

- Guided propagation:
  - Low noise
  - No interferences
  - Low optical losses
  - Excellent reciprocity
- Major drawback
  - Point to point

Goal for SI-s re-definition

Coherent optical links are the only technique to date to enable optical clocks comparisons at continental scale

CCTF task force at BIPM for the redefinition of the SI-s:
Optical frequency transfer: key elements

- Unbalanced Michelson interferometer
- Heterodyne detection: eliminates multi-path
- Fully bi-directional. A 2nd link transfers back the signal
- Guided propagation: ensure paths reciprocity
- Assumption: Forward noise = $\frac{1}{2}$ Round-trip noise
  - $\rightarrow$ corrects only reciprocal noise
- Coherent regime if coherence length > 2L (need ultra-stable laser!)
- Fundamental limits set at short term by the finite velocity of light in media

**A second set-up on a second fiber transfers back the signal:** « End-to-end » measurement, out of loop.

**Multi-segment approach**

- Shorter delay, larger bandwidth
- Signal regeneration with a narrow laser (a few kHz at 1 Hz bandwidth, free running)

**Repeater laser station (RLS) functionalities:**
- sends back signal to station N-1,
- corrects the noise of next link N,
- provides a user output

**Multi-branches Laser Station (Hub station)** can correct the noise of several (~5) links


Optical frequency transfer: noise floor

Design of low-temperature sensitivity multi-branches Michelson interferometers

RLS: 3-branches > 2 input/output (back, next) and one user output

MLS: 2x6 input/output to seed up to 6 branches and their link back for traceability

- temperature sensitivity:
  1st lab prototypes: 7fs / K
  RLS industrial grade: < 1 fs / K
  MLS industrial grade: < 0.04 fs / K

3 designs:
- MLS1: Free-space, starting point design
- MLS2: Free-space, man-in-the-middle design
- MLS3: Fibered, end-point design

see also work on spools and mid-haul fiber links:
Aim
- Wide dissemination to academic labs, that covers wide scientific applications
- Link between National Metrological Institutes (in Europe)

Technical issues
- Signal generation
- Remote control (for installation in telecom hubs)
- Compatibility with non-metrological environment (no stable RF, no GPS…)
- Robustness
- Assessment of the accuracy and stability of the disseminated signal
From fiber links to a metrological network

- **Availability of the fiber**
  - Dedicated frequency channel aka “dark channel”: parallel transmission of ultra-stable signal and data traffic in the same fiber on different frequency channels using dense wavelength division multiplexing (DWDM)

- **Knowledge transfers:**
  - System vision, production, installation, & operation

- **Network supervision:** operational + scientific

- **Data** availability & usability (FAIR), documentation, archives, live monitoring, community management…
**Key concepts**

- Mutualisation
  - Time and frequency reference systems
  - Fiber networks (national, regional,…) for education and research
- T/F as a service
  - To date: ~30 academic research laboratories. 19 physically connected as of 10/2023
  - 6 research infrastructures: SOLEIL, ESRF, IRAM, LOFAR, LSM, + CERN
- Industrial partnership & societal impact
- Open access (FAIR)
Refimeve network map (2023)

• 3 international connections (DE, UK, IT)
  • New: CERN connected March 2023
  • New: Belgium-France cross-connection planned
• Clocks (microwave and optical) at INRIM, PTB, NPL, and SYRTE are connected with fiber network
• REFIMEVE connects, by 10/2023: PhLAM, IRCICA, FEMTO-ST, UTINAM, LIPHY, LSM, PIIM, APC, IJCLAB, ISMO, LAC, LERMA, LKB, LPGP, LPNHE, MPQ, LP2N, SYRTE, LPL
• FIRST-TF (Research federation) acts for the scientific animation of the French users connected by the fiber network
• EURAMET: 5 EU projects to develop technology, + run optical clock comparisons,…
The signal source + network monitoring and supervision

- Optical and microwave sources are compared with an optical comb (femto-second laser)
- REFIMEVE signal copies the stability of the laser at short term, and the one of the (flywheel) maser at long term.
- Enable comparisons with satellites links (GNSS, TWSTF, ACES...)
- Source uptime since Dec. 2019: 95%
- REFIMEVE signal frequency:
  - 194 400 121 000 000 +/- 2 Hz
  - No He > stop cryogenic oscillator
  - 194 400 121 000 000 +/- 25 Hz

- Signal generation monitoring example:
- Link performance monitoring example:
**Industrial grade fiber links**

**First industrial link:**
Paris - Lille - Paris (2x 330 km)

Optical amplifiers:

Repeater laser stations

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**Tech. readiness level:** from 5 in 2012 to 8-9 by 2018

**up-time for 1 month:** 99%

**F. Camargo** et al., *57* (25), 2018, doi.org/10.1364/AO.57.007203

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**SPECIFICATIONS**

**Optical specifications (all optical specifications given at 25°C except if notified)**

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Symb.</th>
<th>Min.</th>
<th>Typ.</th>
<th>Max.</th>
<th>Units</th>
<th>Notes / conditions</th>
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</thead>
<tbody>
<tr>
<td>Mode of operation</td>
<td>MofO</td>
<td>CW</td>
<td>by design</td>
<td></td>
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<tr>
<td>Operating wavelength</td>
<td>OW</td>
<td>- 1542,14</td>
<td>ITU44 by design</td>
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<tr>
<td>Saturation Power</td>
<td>(P_{\text{sat}})</td>
<td>- 5 dBm</td>
<td>4,1 dBm and 4,0 dBm</td>
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<tr>
<td>Input power range</td>
<td>(P_{\text{in}})</td>
<td>-45 - -16 dBm</td>
<td>by design</td>
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<tr>
<td>Total gain</td>
<td>(G)</td>
<td>12 - 21 dB</td>
<td>Adjustable gain by step &lt; 1dB</td>
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<tr>
<td>Noise Figure</td>
<td>(\text{NF})</td>
<td>&lt;5 dB</td>
<td>&lt; 5 dBm for (I &gt;90) mA</td>
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<td>Optical polarization</td>
<td>(\text{Pol})</td>
<td>random</td>
<td>by design</td>
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<tr>
<td>Output power tunability</td>
<td>OPT</td>
<td>10-100 %</td>
<td>verified</td>
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<td>Output power stability</td>
<td>OPS</td>
<td>- 0,3 %</td>
<td>0,29 % and 0,30 %</td>
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<td>Input monitoring</td>
<td>IM</td>
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<tr>
<td>Output monitoring</td>
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<td>Input fiber</td>
<td>IF</td>
<td>SMF</td>
<td>by design</td>
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<td>Input connector</td>
<td>IC</td>
<td>FC/APC</td>
<td>by design</td>
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<td>Output fiber</td>
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<td>SMF</td>
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<td>Output termination</td>
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**Electrical specifications**

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<th>Units</th>
<th>Notes / conditions</th>
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<tbody>
<tr>
<td>Control mode</td>
<td>CM</td>
<td>Supply voltages, diodes (T°), rack (T°)</td>
<td>remote control by USB port</td>
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<tr>
<td>Interface</td>
<td>INT</td>
<td>Front panel</td>
<td>Diodes currents, diodes (T°), board (T°), status alarm</td>
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<td>SSH</td>
<td>IP</td>
<td>Communication by port RJ-45</td>
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<td>SNMP V2</td>
<td>MIB designed</td>
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<td>Supply voltage (VDC)</td>
<td>SV</td>
<td>-40 - 48 - 64 V</td>
<td>by design</td>
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<tr>
<td>Power Consumption</td>
<td>PC</td>
<td>- 8 15 W</td>
<td>Max 15 W</td>
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</table>

**Mechanical & environmental specifications**

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<th>Units</th>
<th>Notes / conditions</th>
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<tbody>
<tr>
<td>Housing</td>
<td>Hg</td>
<td>442 x 250 x 44 mm</td>
<td>2 amplifiers per rack</td>
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<td></td>
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<tr>
<td>Cooling</td>
<td>Cg</td>
<td>Air fans</td>
<td>by design</td>
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<tr>
<td>Operating temperature</td>
<td>TO</td>
<td>15 - 35 °C  &lt;1 dB variation verified</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Storage temperature</td>
<td>TS</td>
<td>-20 - 55 °C verified</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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[iXblue](https://www.muquans.com/products/time-and-frequency-transfer/)
https://www.keopsys.com/portfolio/bi-directional-fiber-amplifier/
Towards a highly available signal

Relative frequency fluctuations vs time (days)
1000 s / point

Paris-Lille-Paris
(2 x 340 km)
Uptime 71%

Paris-Strasbourg-Paris
(2x650 km)
Uptime 85%

Paris-Lyon-Modane-Lyon-Paris
(2x900 km)
Uptime 81%

Lyon-Marseille-Lyon (2x440 km)
Uptime 85%

4 links: {340,650,900,440} km x2 = 2x2330 km
>70% / 1/2 year (2022)
>90% uptime for several months
next objective: 90% / year
Simultaneous optical frequency transfer to several users

- 4 simultaneous transfer (links A to D)
- Central node in Paris (11 km)
- Villeteaneuse (43 km)
- Lille (340 km)
- Strasbourg (705 km)
- Relative frequency instability
- $<1\times10^{-18}$ after a few $100$ s
- 2200-km stabilized fiber link in total

By 2023:
- 7 links operated in parallel
- 2x3800 km
- Data analysis over years meas. time


Accuracy of the optical frequency transfer

Statistical contributions
Example link SYRTE-Uni Strasbourg (>PTB)

Systematic contributions
Sources of systematic error:
- Inaccuracy of the 10 MHz signal provided to the counter by GNSS
- Desynchronisation of the measurement
- Time error of the data time stamps (> NTP)
- Mean offset of the stabilized link

<table>
<thead>
<tr>
<th>Source of Error</th>
<th>Shift (x 10^{-18})</th>
<th>Statistical (x 10^{-18})</th>
<th>Systematic (x 10^{-18})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Remote RF frequency reference at comparison point</td>
<td>1.7</td>
<td>.1</td>
<td>-</td>
</tr>
<tr>
<td>Instruments desynchronisation</td>
<td>2.9 x 10^{-4}</td>
<td>2.6 x 10^{-12}</td>
<td></td>
</tr>
<tr>
<td>Data timestamping</td>
<td>2.4 x 10^{-6}</td>
<td>3.6 x 10^{-6}</td>
<td>3.7 x 10^{-14}</td>
</tr>
<tr>
<td>Optical frequency transfer, 705-km link</td>
<td>.17</td>
<td>.45</td>
<td>&lt; .1</td>
</tr>
<tr>
<td>Optical frequency transfer, 10-km link</td>
<td>.11</td>
<td>.14</td>
<td>&lt; .1</td>
</tr>
<tr>
<td>Total</td>
<td>1.7</td>
<td>1.1</td>
<td>&lt; .14</td>
</tr>
</tbody>
</table>

Note: scaling factor Optical / GNSS ~ 1e6


5.1. An international network of NMIs

so far, only possible continental. As with the specific European connections shown in figure 5.1, this can, and probably will, be more complex in the future, including several other European NMIs or other metrology laboratories. Such a complex network must be able to compare any number of different clocks, oscillators, or lasers, all operating at, in principle, arbitrary frequencies. Naturally, this requires vastly different hardware, as well as different means of comparison, as the fundamental and technical challenges differ greatly depending on the nominal oscillator frequency, stability and accuracy. In that frame a universal formalism was developed and reported [85], enabling clock comparisons of any kind with sufficiently low uncertainty.

In the following I will describe the principles of remote clock comparisons as performed by SYRTE and the European partner NMIs. A case study of a comparison between SYRTE and PTB will be shown. I will describe the setup used in the comparison between the two NMIs at UoS in Strasbourg. The general scheme of the frequency chain of the remote comparison is illustrated in figure 5.2: a clock laser is measured against the transfer laser at 1542 nm using an optical frequency comb. The transfer laser is locked to an ultra-stable cavity, which is actively dedrifted by an H-maser. The ultra-stable signal is disseminated through the REFIMEVE network, being amplified and regenerated as described in chapter 2.2. At the comparison site, the signal from the partner NMI arrives as well. A beat-note between the two transferred signals is generated. The beat-note is amplified and filtered, and its frequency is measured with a remote dead-time free frequency counter. The counter is referenced on short term by an oven-controlled crystal oscillator (OXCO), which is referenced by a GNSS signal, removing the long-term drift, which will be present for the quartz oscillator. This provides an accurate enough 10 MHz reference, which is detailed in M. Tønnes PhD Thesis.

Links lengths:
To Germany: ~1400 km
To UK: ~900 km
To Italy: ~1200 km
(in total)

Real-time ultra-stable laser comparisons: example SYRTE-PTB

International clock comparisons: a world first in 2015

Frequency instability $\text{Sr}^{\text{PTB}} - \text{Sr}^{\text{SYRTE}}$
$2 \times 10^{-17}$ (@5000 and 50,000 s)

Accuracy: $\text{Sr}^{\text{PTB}} - \text{Sr}^{\text{SYRTE}}$ agreement
$(4.7 \pm 5) \times 10^{-17}$

Run I: March 2015
Run II: June 2015

Combined link contribution

Red shift $\sim 10^{-16}$/m
Comparisons require precise clock levelling to take into account the clock height difference!

Chapter 5. International comparisons with a fiber network

Villetaneuse (North of Paris), in Strasbourg, and in Modane, ensures connections to the European partner NMIs NPL, PTB, and INRIM. This is illustrated in the map in figure 5.1.

Figure 5.1: Map of fiber links operated by the EU consortium ROCIT during international optical clock comparisons, spanning from 2018 to 2022. The relevant REFIMEVE links are highlighted with red continuous lines, and other REFIMEVE links are shown as dashed lines. Blue lines indicate international links, operated by partner NMIs, and orange hexagons show the locations of the four partner NMIs.

In the frame of the European project Robust optical clocks for international timescales (ROCIT), clock comparisons with IPPP and TWSTFT have been performed between the Paris Observatory, Valtion Teknillinen Tutkimuskeskus (National Technical Research Centre) (VTT) in Finland, NPL in England, and Uniwersytet Mikołaja Kopernika w Toruniu (UMK) and Space Research Centre of Polish Academy of Sciences (SRC PAS) in Poland. Furthermore, a high number of institutes are connected with satellite techniques, for a potentially even more complex comparison network.

5.1.1 Continental clock comparisons

A continental clock comparison is conceptually the same as a worldwide comparison, with the sole difference that a comparison through optical fibers are, in chapter 5.3. For a full comparison between the two atomic references, the full frequency chain is monitored at all times. The frequency differences between each link in the chain is continuously recorded, and is validated by the responsible scientist(s). The validation of each measurement is different between any subsystems.

5.2 Palantir: the software backbone

Historically, a comparison of atomic clocks could only be performed in two ways: either by physically moving a clock from one place to another, or remote comparisons through GNSS links, which are still being used to this day. An ensemble of links connecting several remote clocks is called a clock network, and an illustration of such a clock network is shown in figure 5.3.

Optical clocks (12):
SYRTE: Sr2, SrB, Hg
PTB: Yb+, Sr (static), Sr (transportable), In+
NPL: Yb+, Sr+, Sr
INRIM: Yb, Sr

Microwave clocks (9):
SYRTE: FO1, FO2-Cs, FO2-Rb, FOM
PTB: CSF1, CSF2
NPL: Cs-F1, Cs-F2
INRIM: CsF2

REFIMEVE connects many clocks contributing to TAI

https://webtai.bipm.org/database/show_psfs.html
An optical clock network


Example OFTEN campaign SYRTE-PTB-NPL

- Scale: 1s - 1e6 s; 1e-14 - 1e-18
- Ensemble of 4 optical clocks
- Typ. statistical uncertainty <1e-17
- Repeated 10 times over 7 years
- Major step towards the SI-s re-definition
Recent clock comparisons campaign: 4 months-long comparisons

Call for more work to compare means of comparisons
Application: Chronometric geodesy

Gravitational (red) shift $\sim 10^{-16}$ /m


G. Lion et al., J Geod 115 (2017)

- Adding $\sim 30$ clocks are sufficient to obtain centimeter-level standard deviations and **1-2 order of magnitude improvements in the bias**.
- Clocks can also contribute to the unification of height systems realizations
- **3 tide gauges in France can be connected to REFIMEVE**
- On going projects (ROYMAGE):
  - Evaluating the contribution of optical clocks for the determination of the geopotential at high spatial resolution
  - Find the best locations to put optical clocks to improve the determination of the geopotential
  - Need complementary optical frequency transfer in free-space


see also:
A wide fields of applications

- Clocks and cavities comparisons
  - C. Lisdat et al., Nat. Comm., 7, (2016),
  - Schioppo et al., Nat. Comm 13, 1(2022)
- Test of general relativity
- Chronometric geodesy
  - G. Lion et al., J Geod, 91, 6, (2017)
- Search for Dark Matter
  - High-precision atomic and molecular spectroscopy
- VLBI, GW, QKD, Seismic sensing...

see also


Seismic detection by a fiber network

M.Tønnes et al., in prep
T- REFIMEVE (2021-2029)

- Extension to Brest, IRAM, CERN; +14 new users
- RF (1 GHz) and time signal on the optical carrier (bi-directional, highest performance)
- WR: 10 MHz and time signal, additional channel, mono-directional
- Mobile platform:
  - A test facility for the REFIMEVE users and exploration of chronometric geodesy
  - Extraction of the REFIMEVE signal
  - Transportable shelter with ultra-stable cavity, comb, and room to host a transportable clock or a transportable quantum sensor
Fundings

LIOM, REMIF, REFIMEVE+, T-REFIMEVE, FIRST-FT

LOFIC

JRP: NEAT FT, OFTEN, WRiTE, TIFOON
ITOC, ROCIT (clock comparisons)
H2020: ICOF

EU Research infrastructure

CLONETS
CLONETS-DS

INSU
GRAM

ROME, LICORNE, TORTUE, (…)

TOCUP, ONSEPA, (…)
Thank you for your attention