Réseaux fibrés optiques
Optical Fiber Networks

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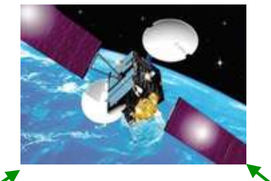
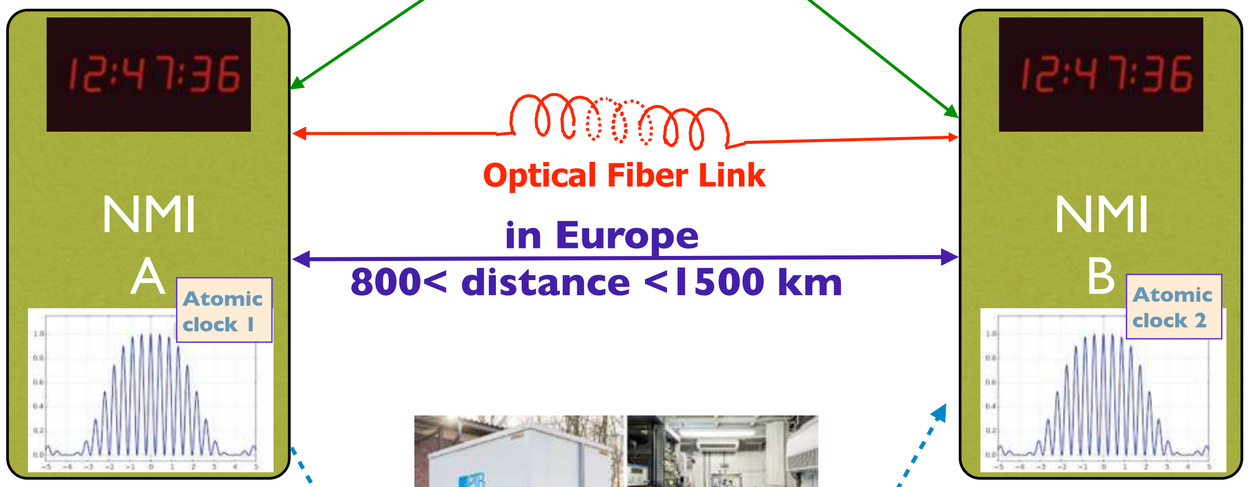
Contents

Means to compare/disseminate clocks at long range

Radio signals and
Satellite Link
10^{-11}(1s)
2×10^{-15}(1d)



Nobel prize 1909
Guglielmo Marconi,
for the 1st trans-atlantic
radio transmission



Stability(1s) $<10^{-13}$
Accuracy $<10^{-16}$

(cf. Belville and *The Greenwich time lady*)

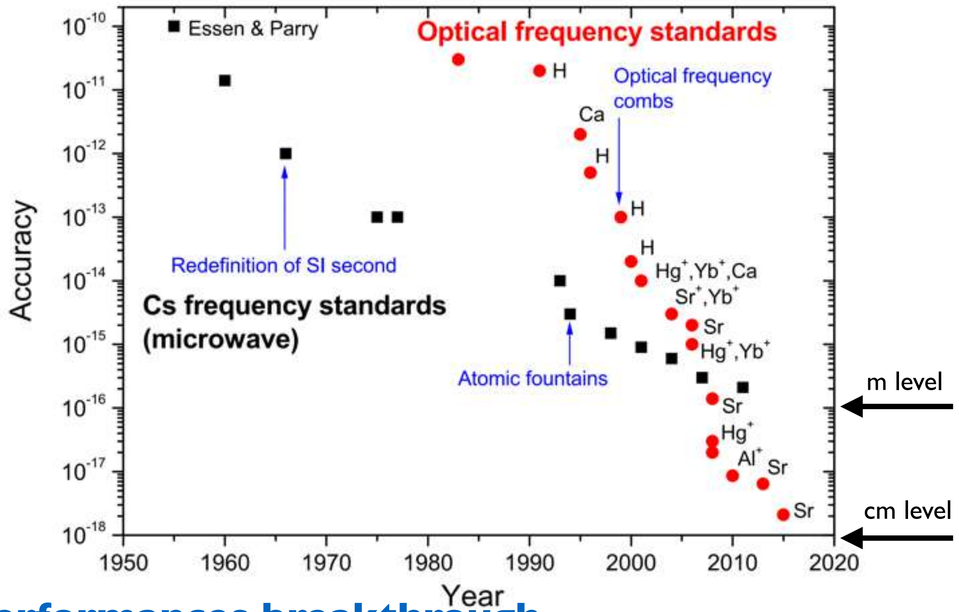
Transportable clock
(Cs, Sr)
Cs : 10^{-13}(1s), 4×10^{-16}(1d)
Sr : 10^{-15}(1s), 10^{-17}(3h)

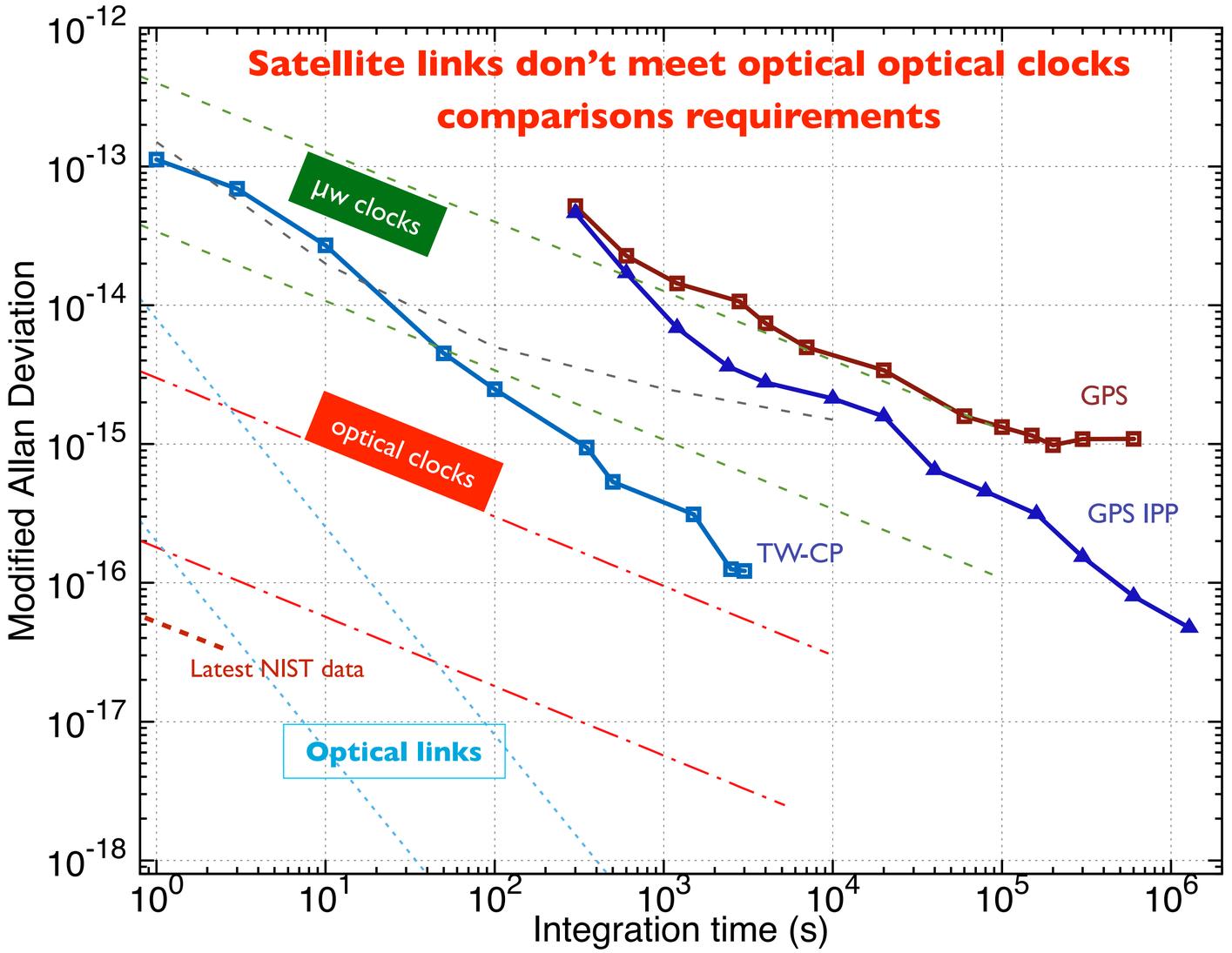
A matter of delay:

Time transfer = mastering delays
- Instrumental delays
- Propagation delays
- Other… (Sagnac effect)

Frequency transfer = mastering delay fluctuations

Motivations





Performances breakthrough

- Atomic clock's accuracy improved by order of magnitudes: particule's motion control, optical frequencies,…
  - reach the low 10^{-18} range
- Means of comparison : Guided propagation + Doppler cancellation, optical frequencies
  - Uncertainties below 10^{-19} range :
  - Enable dissemination without degradation

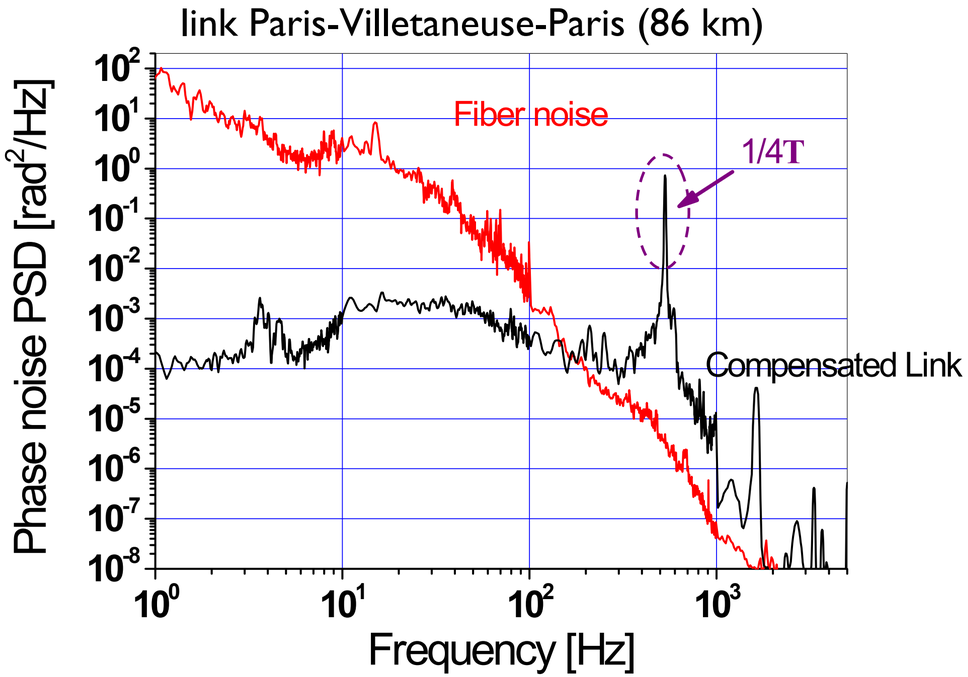
Principles of operation of fiber links

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

STABILIZED FIBER OPTIC FREQUENCY DISTRIBUTION SYSTEM*

Lori E. Primas
George F. Lutes
Richard L. Sydnor
Jet Propulsion Laboratory

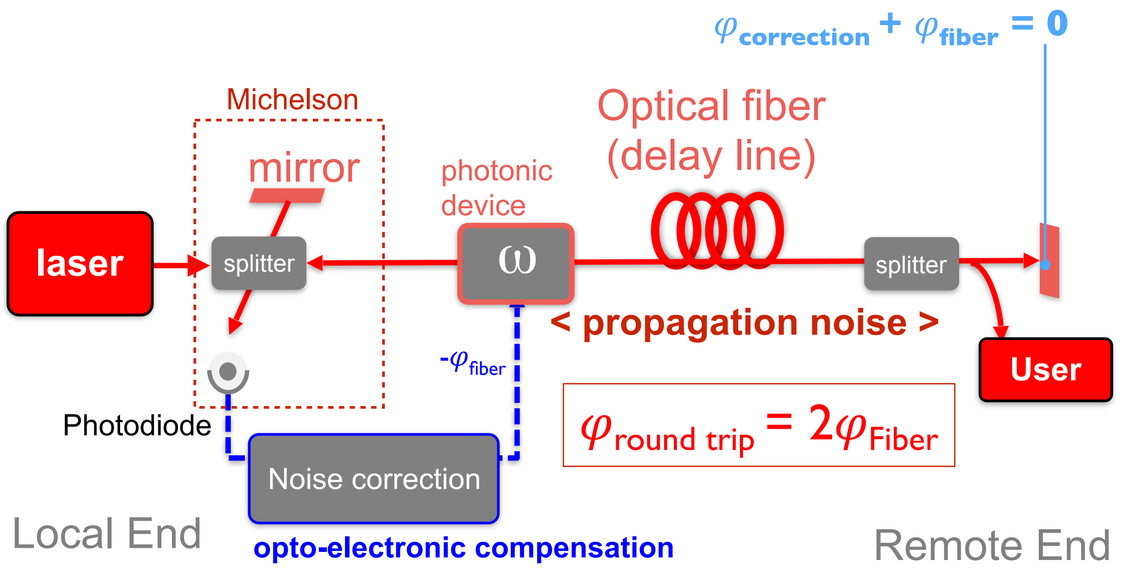
- **Active noise compensation after one round-trip**
- **Strong hypothesis : noise forth and back are the same**
- **2 ends at the same place (for link stability measurements)**
- **RF, hF or optical signals**
- **Technical challenges:**
  - **Long haul : more noise, less signal…**
  - **Automation, remote control**



- Two-way : Stabilized / Post-processed
  - Post-processed techniques used for comparison purposes
- One way: Unstabilized (affects stability and accuracy)

- Bi-directional or uni-directional (affects noise **correlations**)
- Analog or digital (affect the scalability)

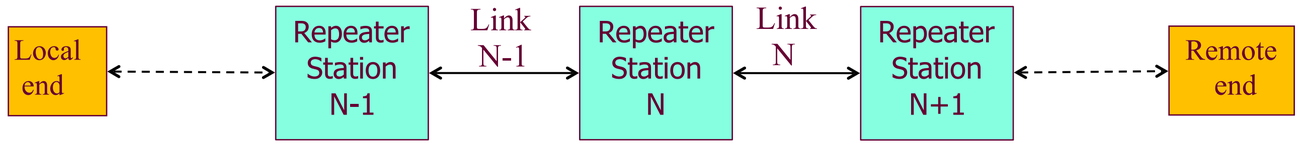
Optical frequency transfer : key elements



- Fully bi-directional. A 2nd link transfers back the signal
- Unbalanced Michelson interferometer
- Heterodyne detection: eliminates mutli-path
- Guided propagation: ensure paths reciprocity
- Assumption : Forward noise = ½ Round-trip noise
- → 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



Repeater laser station (RLS) functionalities :

- sends back signal to station N-1,
- corrects the noise of next link N,
- provides a user output

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

O. Lopez, *et al.*. OE **18**, 16849–16857 (2010).

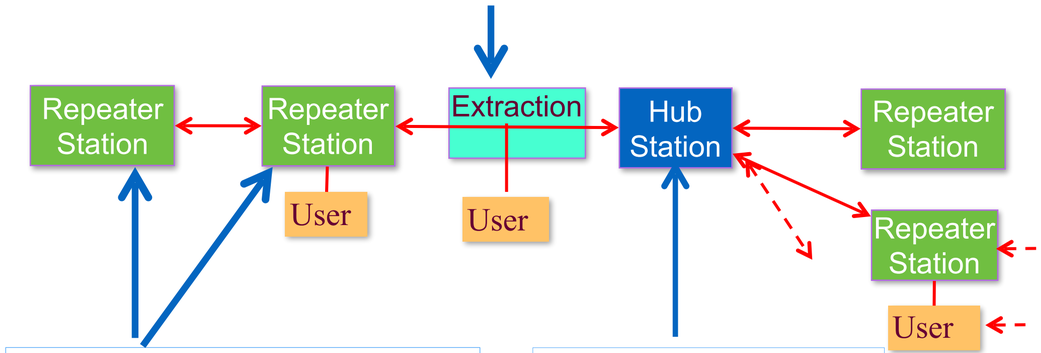
Hub station (multi-branches RLS)

can correct the noise of several (~5) links

E.Cantin *et al.* New J. Phys. **23**, 053027 (2021).

From fiber links to fiber network

In-line *extraction* station *§
noise detection/correction at extraction point



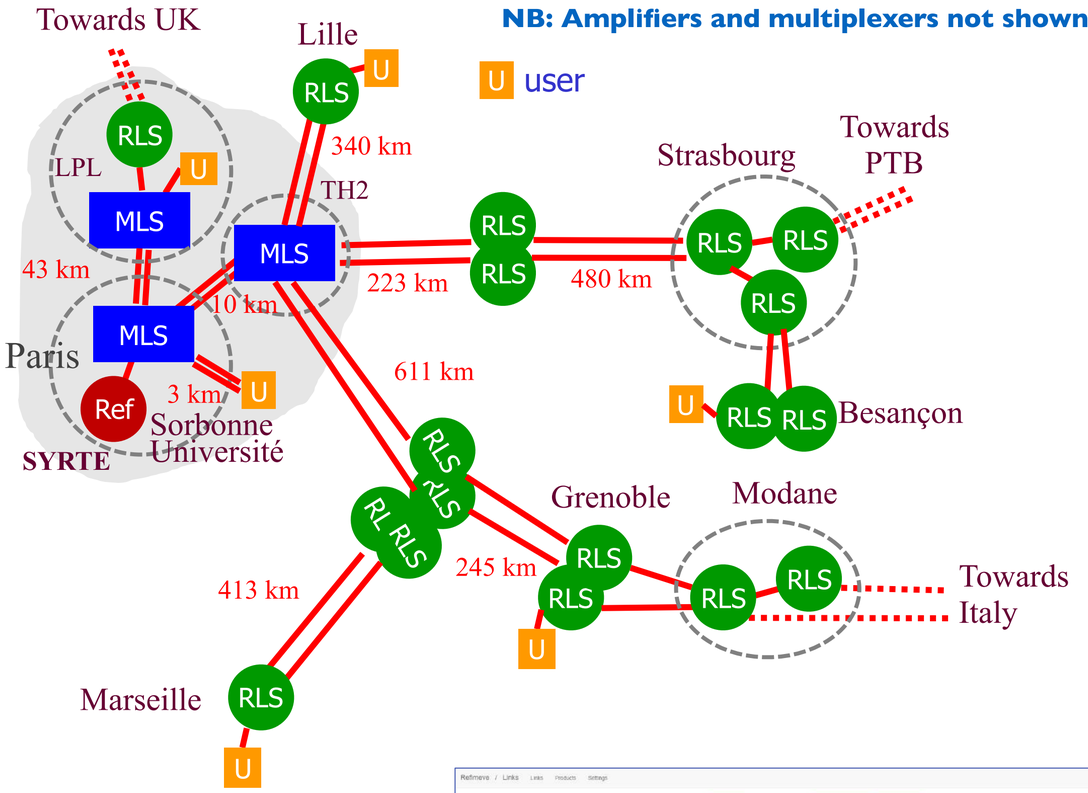
Repeater station *§

Hub station *

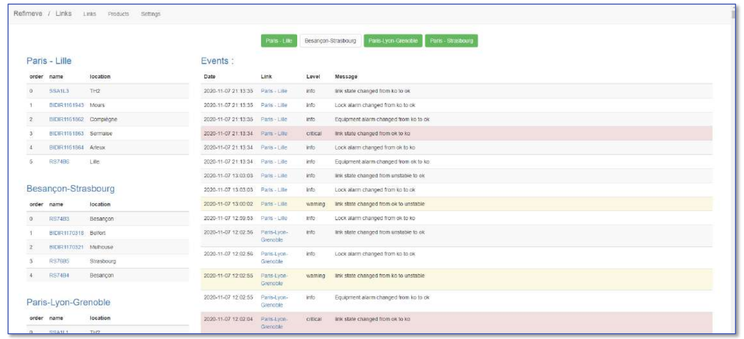
* Autonomous - Remotely controlled

§ Commercially available – Can be installed in telecom hub

F.Guillou-Camargo *et al.* AO **57**, 7203 (2018).



with remote control and supervision

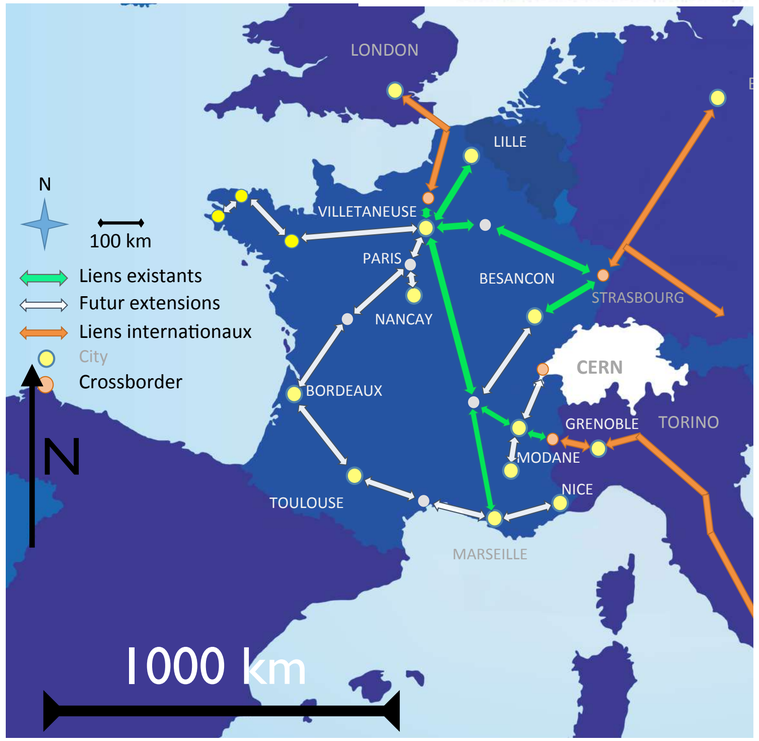


https://www.muquans.com/products/time-and-frequency-transfer/

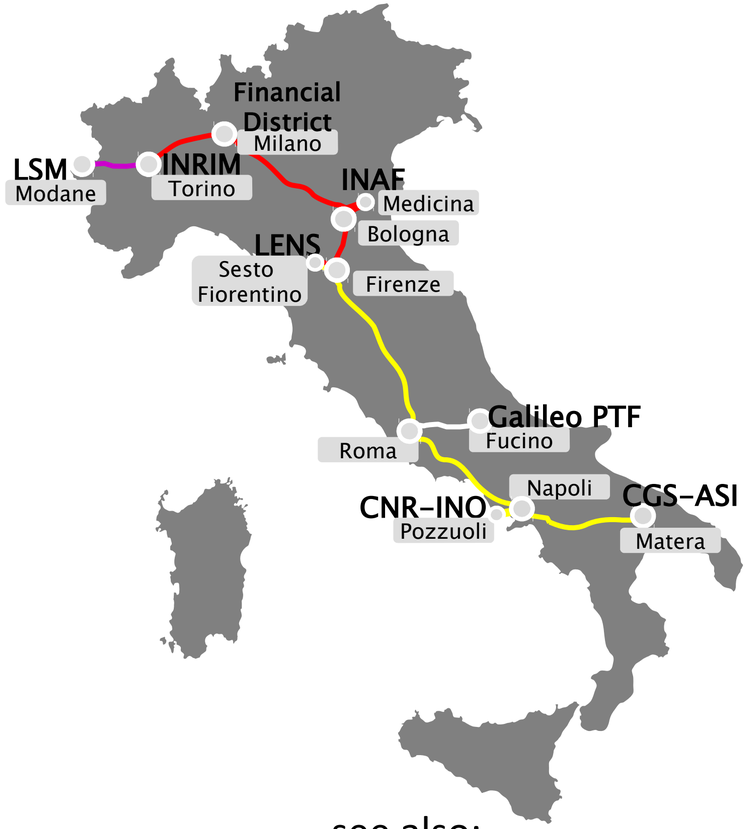
Fiber networks : Optical frequencies networks

REFIMEVE (France) ~ 2x2800 km built
2x 4500 km after completion

RENATER
CONNECTEUR DE SAVOIRS



LIFT (Italy) ~2000 km



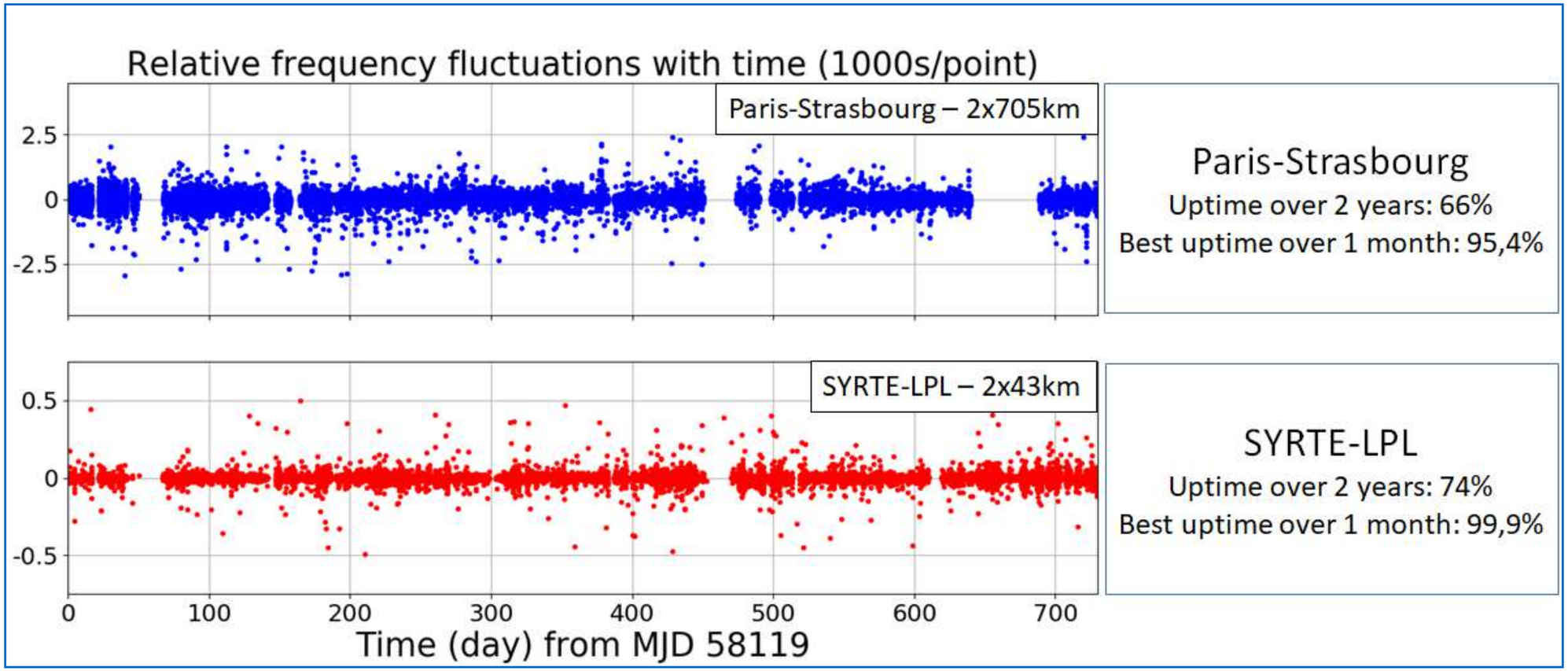
NPL, PTB, SYRTE connected
INRIM achieved in 2020

A fiber network of about 6000 km in EU enabling bi-directional, coherent, optical frequency transfer

Germany : ~2000 km, UK ~1000 km

see also:
Relativistic Geodesy and Gravimetry with Quantum Sensors (geo-Q)
https://www.geoq.uni-hannover.de/

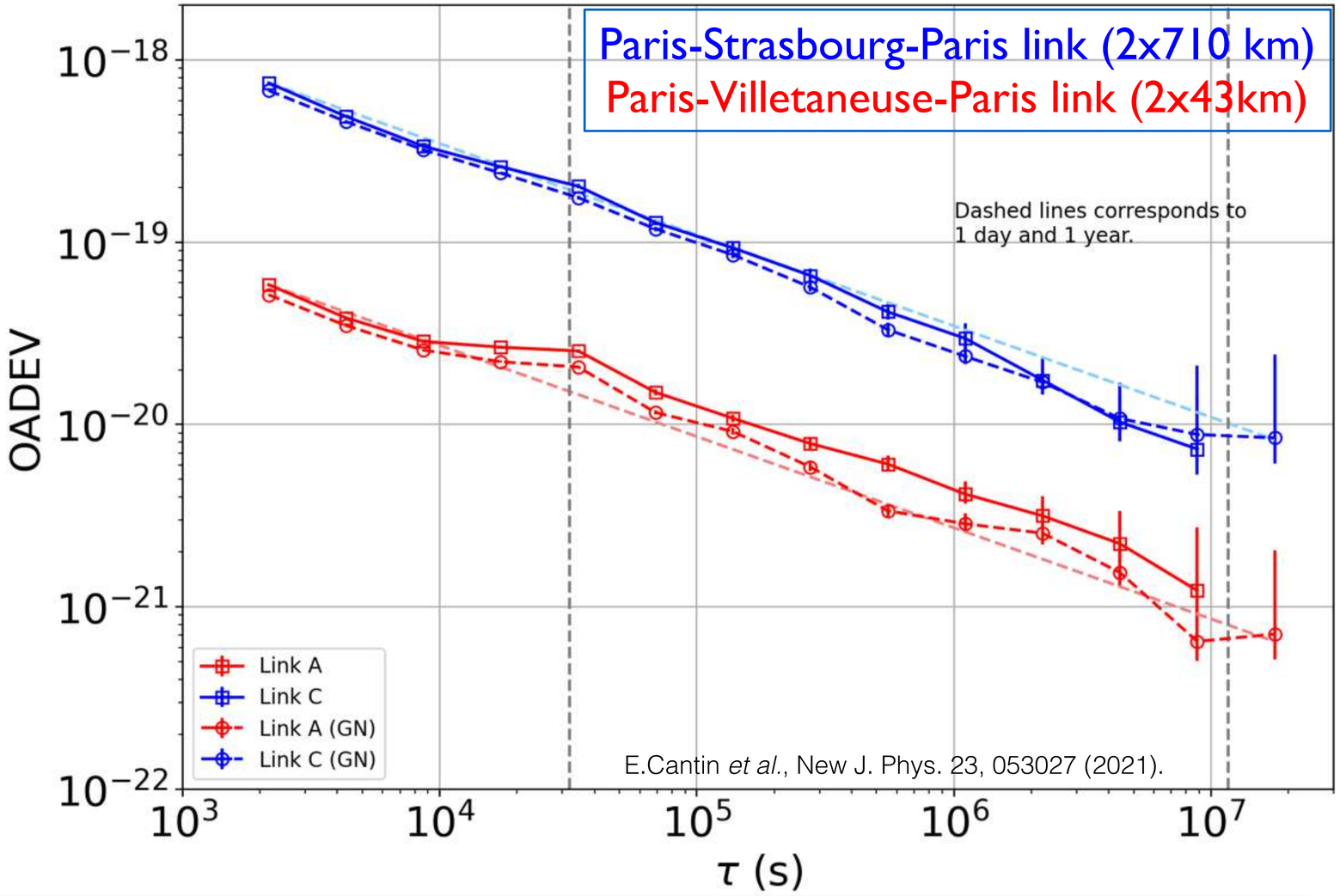
REFIMEVE: towards a highly available signal



>80% / 1 year (2018)
>90% uptime for several months
up to 99.5% over 1 month
<u>next objective: 90 % / year</u>

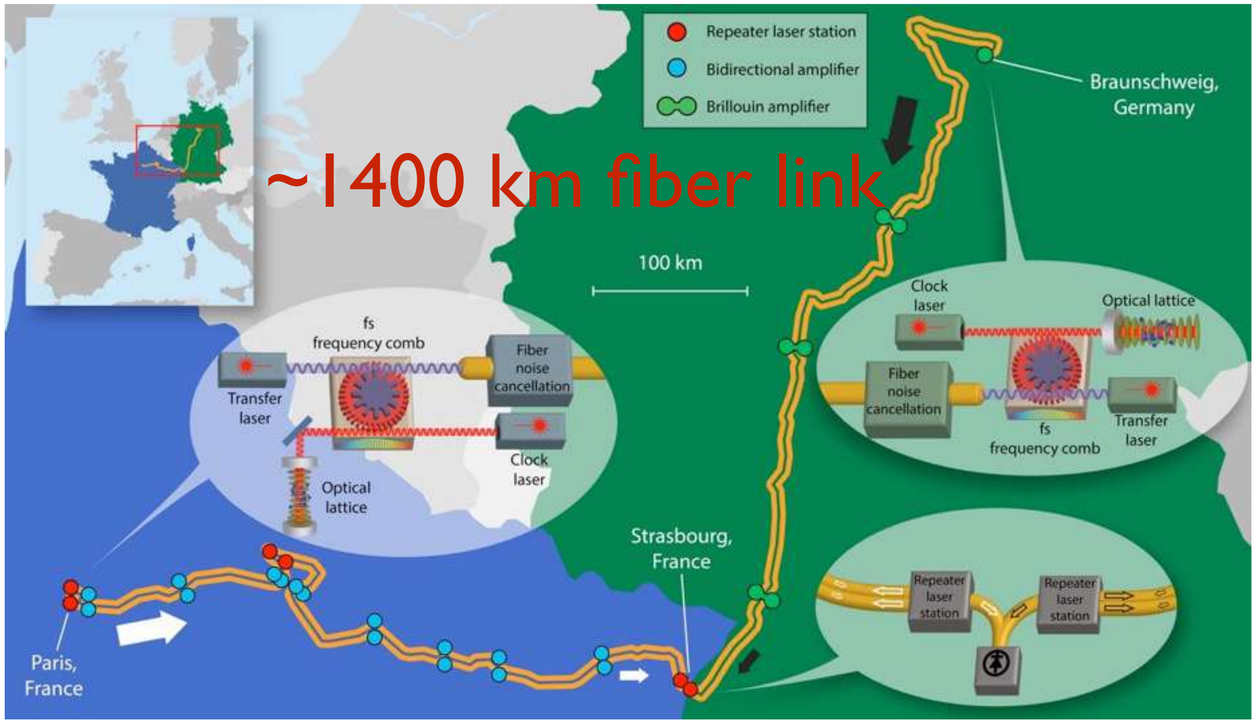
REFIMEVE: Long term performances

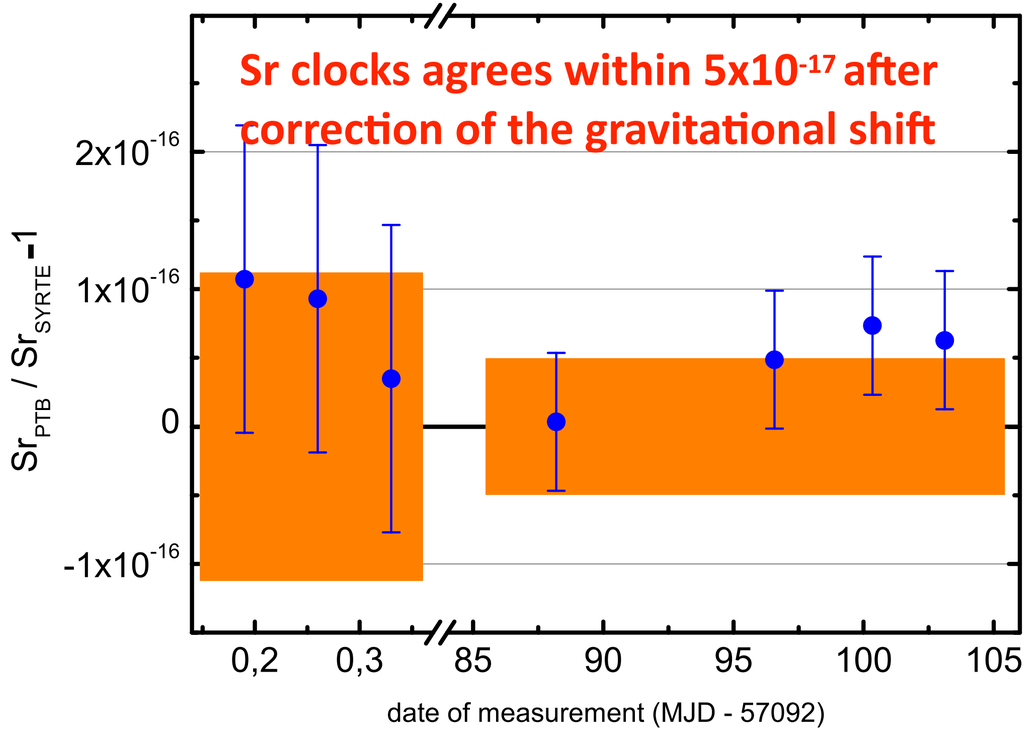
- Data processing to be handled with missing data
  - Concatenation (full lines)
  - Noise model: Gaussian noise for White Frequency Noise, dashed lines
- Accuracy:
  - A: $(-3\pm2)\times10^{-21}$
  - C: $(-0.5\pm1)\times10\text{-}20$



REFIMEVE applies for the acknowledgement as a National Research Infrastructure by MESRI in 2021

The first international optical clock comparison



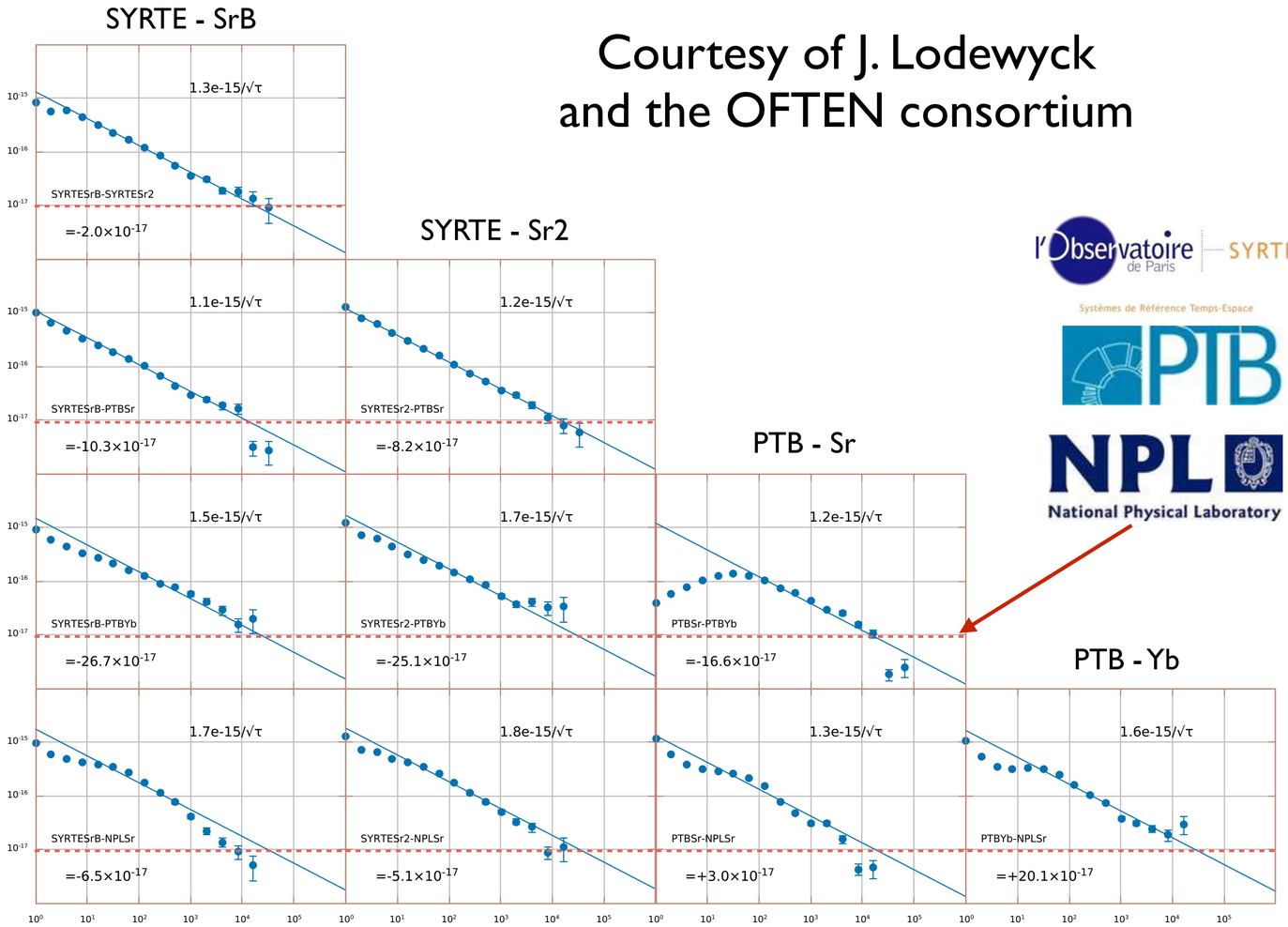


- Leveling campaign was performed prior to the comparison (IGN, IfE, LUH; Delva *et al.*, 2018)
- Confirms accuracy of Sr clocks SYRTE/PTB
- Confirms capabilities of long haul coherent fiber links

Absolute frequency difference without SI-Hz

C.Lisdat *et al.*, ncomms. 7, (2016)

An EU optical clock network : NPL-SYRTE-PTB-INRIM



Courtesy of J. Lodewyck
and the OFTEN consortium

l'Observatoire de Paris — SYRTE
Systèmes de Référence Temps-Espace

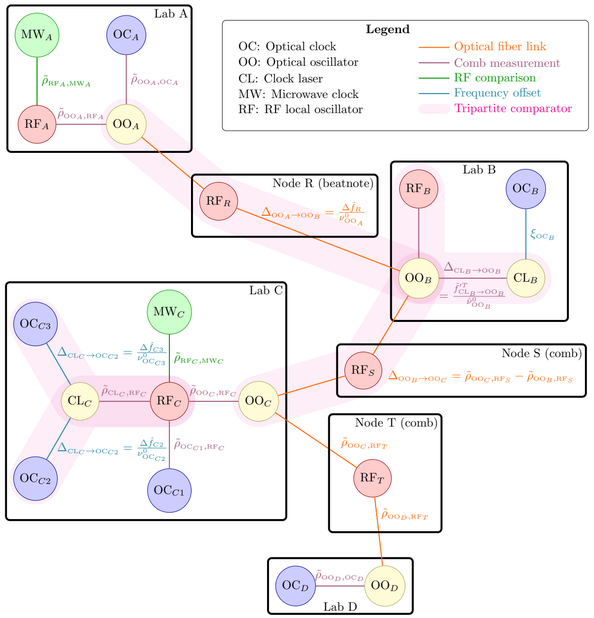
PTB

NPL National Physical Laboratory

NB: 2018 data. INRIM connected since 2020.

Clock comparison formalism: Lodewyck et al., Phys. Rev. Research 2, 043269 (2020).

Clock comparison formalism



NPL -

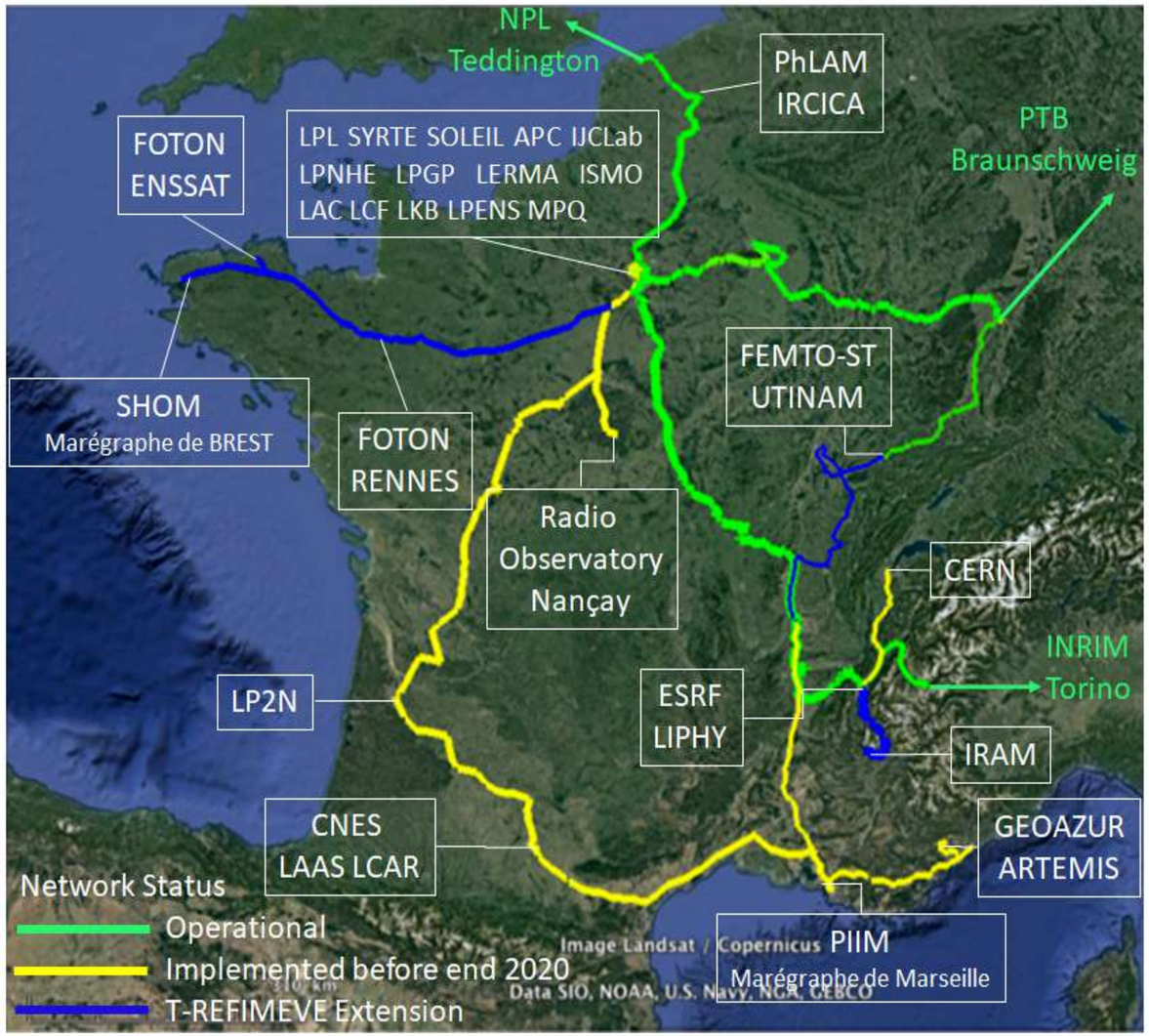
- Scale : 1s - 1e6 s; 1e-14 - 1e-18
- Ensemble of 5 optical clocks
  - typ. statistical uncertainty <1e-17
  - repeated 8 times over 6 years
- Major step towards the SI-s re definition

T-REFIMEVE

- 2020 – T-REFIMEVE, projet ESR/EQUIPEX+ was selected within PIA3
  - Investissement of 9,85 M€ / 8 years
    - Network equipment upgrade, knowledge transfer to industrial partners
  - Add new signals :
    - High-performance radiofrequency and time transfer (fully bi-directional)
    - radiofrequency and time transfer with « white rabbit » all over the network (mono-directional)
  - Co-funding for optical frequency combs
  - **Mobile platform** to ease the scientific exploitation
- Geographical and application science case extension
  - > 30 lab. users, including 3 research infrastructures (SOLEIL, IRAM, ESRF)
  - ~160 researchers
- One major scientific goal : sea level monitoring with chronometric leveling (collaboration with SHOM – tide gauges at Brest, Marseille, Dunkerque): see Rodolphe's presentation !

T-REFIMEVE (2020-2028)

- REFIMEVE+ : PIA (2011)
- T-REFIMEVE: PIA 3 (2020)
  - Extension to Brest
  - Extension to 15 new users
  - RF (1GHz) and time signal on the optical carrier (bi-directional, highest performance)
  - WR: 10 MHz and time signal, additional channel, mono-directional
- Mobile platform (transportable combs, transportable optical clocks, + precise instrumentations)



Outlook

- Fiber links : a new technology for T/F transfer, capabilities beyond GNSS solutions :

  1e-15@1s to 1e-19@1day;

  - Optical metrological networks: REFIMEVE, LIFT
  - REFIMEVE demonstrates reliable optical frequency dissemination at year scale
  - EU clock network: NPL+SYRTE+PTB+INRIM
- Next challenges and open questions:
  - Fiber network as a distributed (quantum) sensor
  - Submarine links for transcontinental comparisons
  - Accurate time transfer over long range
- Towards EU research infrastructure, RI integration

Refimeve+ Réseau fibré métrologique à vocation européenne

https://www.refimeve.fr

https://www.clonets.eu/

https://clonets-ds.eu/

Thank for your attention !

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