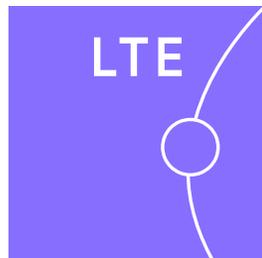




Les avancées du réseau REFIMEVE



Neelam Yadav, Benjamin Pointard, Michel Abgrall, Rodolphe Le Targat, Philip Tuckey, Paul-Eric Pottie

Laboratoire Temps-Espace (formerly SYRTE)

Observatoire de Paris, Université PSL,



Etienne Cantin, Biplab Dutta, Maël Abdelhak, Debanjan Show, Adèle Hilico, Haniffe Mouhamad, Olivier Lopez, Anne Amy-Klein, Christian Chardonnet

Laboratoire de Physique des Lasers
Université Sorbonne Paris Nord, CNRS



Nicolas Quintin,

Laurent Gydé

RENATER

exail

Grégoire Coget, Fabien Verdes, Cédric Majek
Exail Quantum Sensors

Contents

I. REFIMEVE Time and Frequency Service

- Current status
- New extensions



II. Advances on RENATER network



III. Ongoing Research and Development

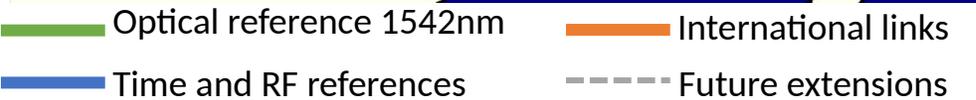
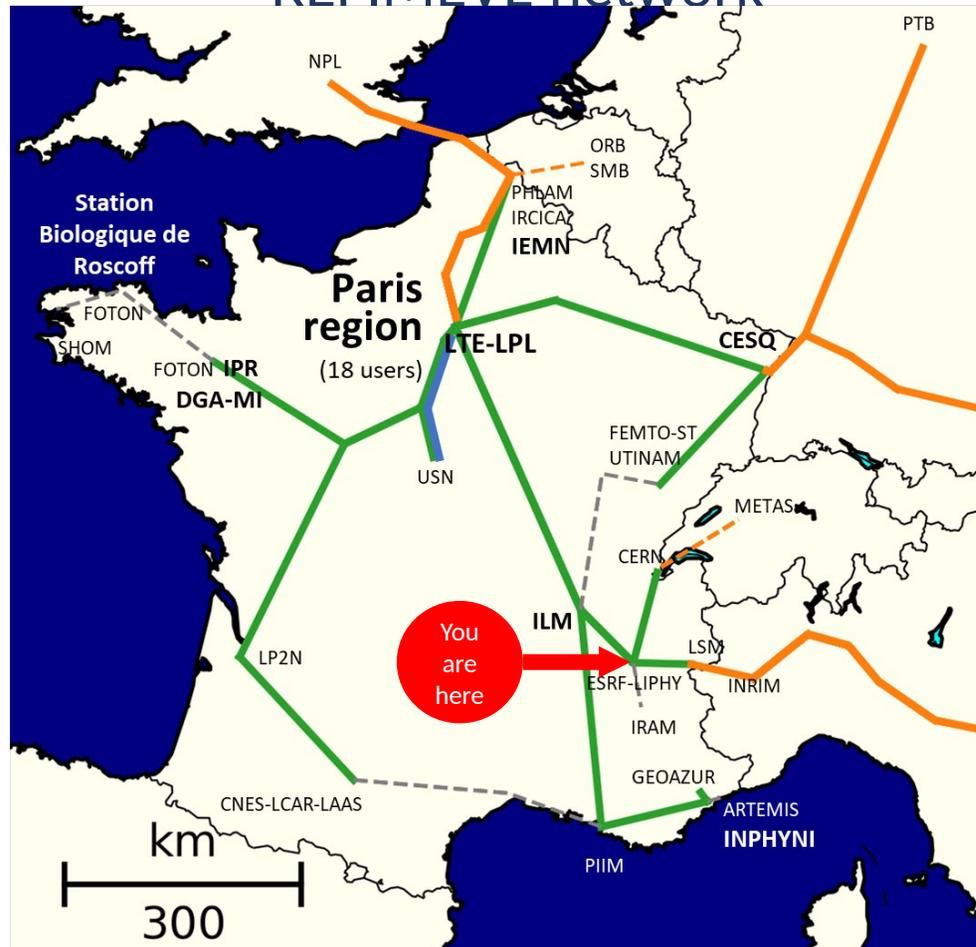


REFIMEVE research infrastructure



A national research infrastructure

REFIMEVE network



→ Transfer of frequency and time references through optical fibers to users

- Collaboration of more than 46 lab users
 - European connection to Germany, England, Italy and Switzerland
- Future connection with Belgium, Netherlands, Switzerland, Spain, Poland...

The network

~9000km of fiber  → Availability of the signal >90%

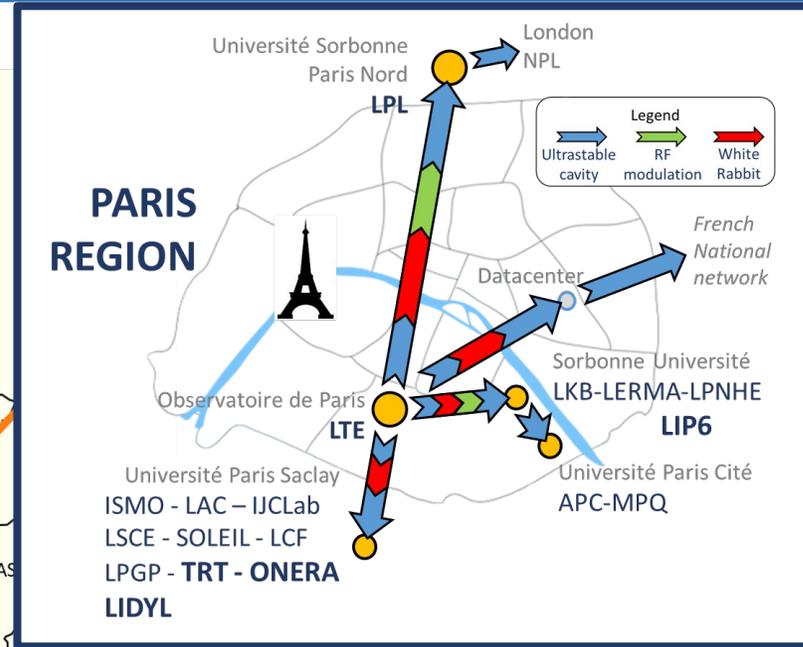
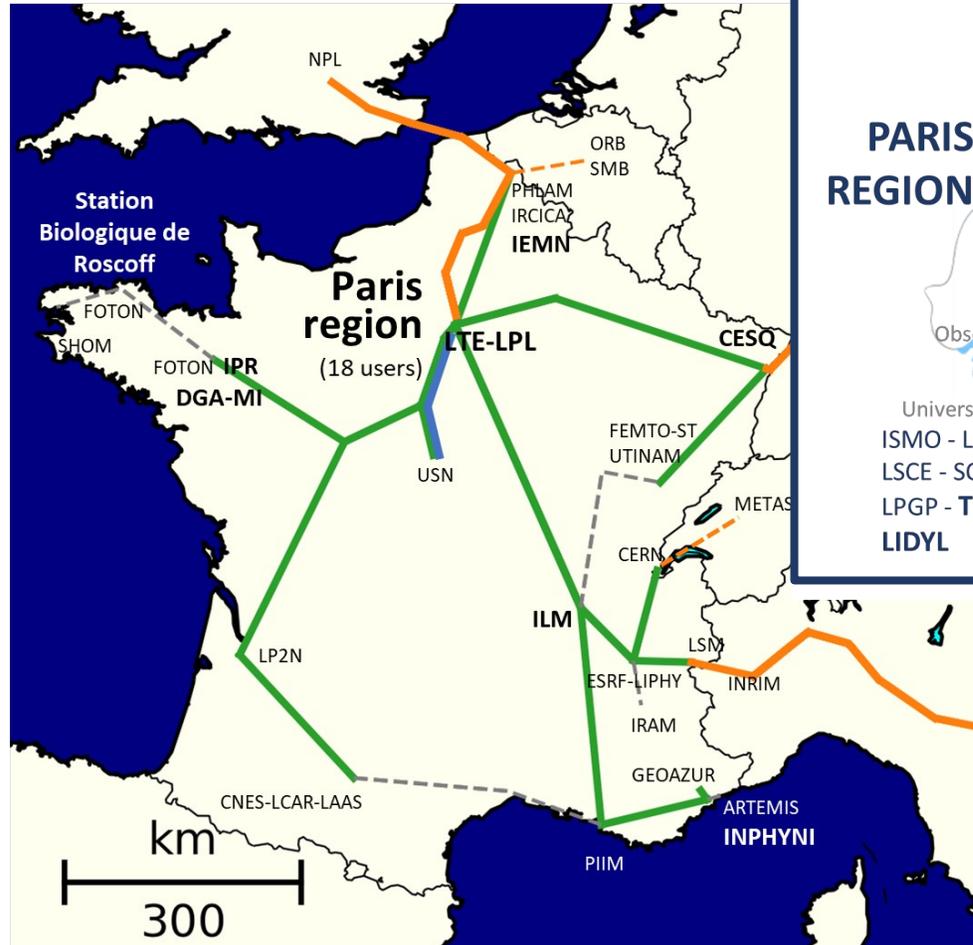
→ ~250 equipment in the field

Strong industrial partnership

- highly mature techniques TRL=9
- Robustness and reliability



REFIMEVE network and users



- Collaboration of more than 46 lab users:
- 30 labs connected!
- 11 new partners of the infrastructure

Welcome to our new partners!!

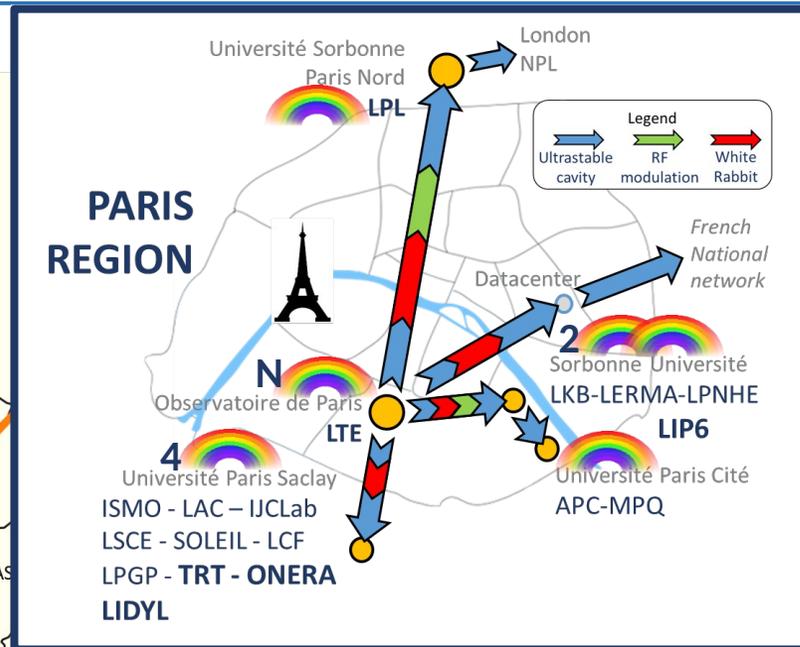
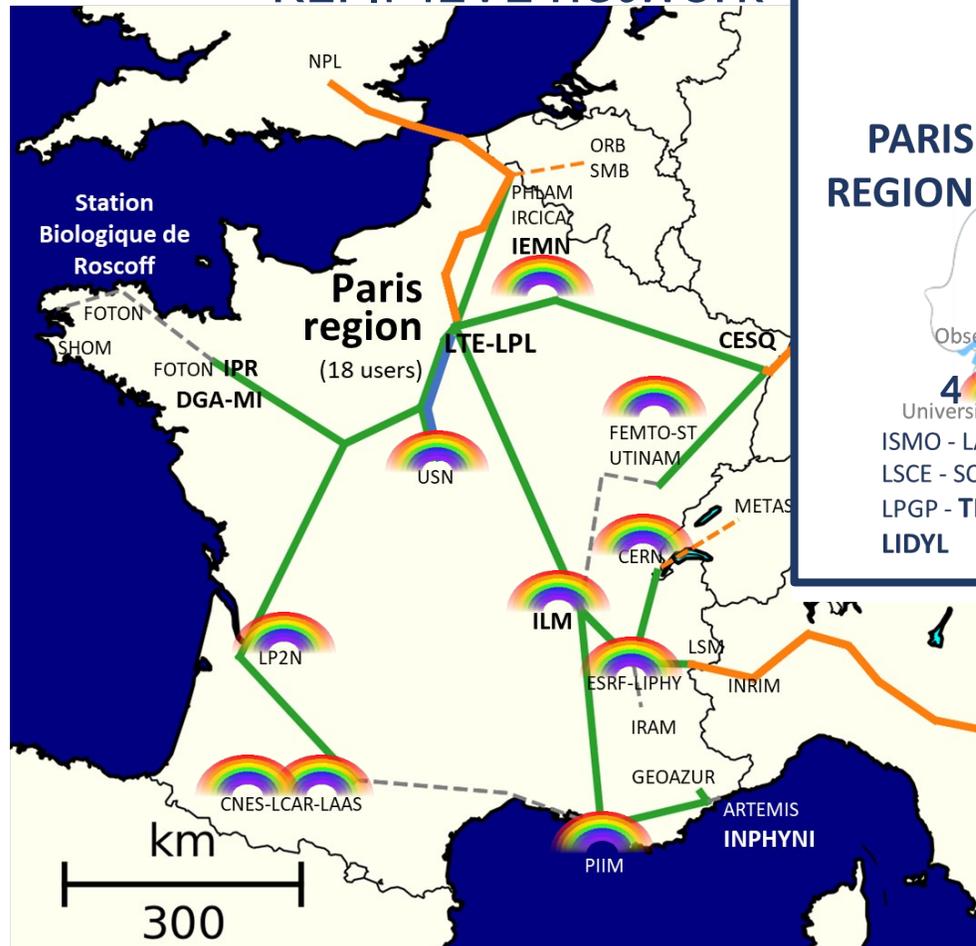
— Optical reference 1542nm — International links
— Time and RF references - - - Future extensions

- | | |
|---|----------------------------|
| 1. Centre Européen de Sciences Quantiques (CESQ), Strasbourg | Cyrille Solaro |
| 2. DGA-Maitrise de l'Information (DGA-MI), Rennes | Jean-Marc Lesage |
| 3. IEMN, Lille | Stefano Barbieri |
| 4. Institut Lumière Matière (ILM), Lyon | Sandrine Galtier |
| 5. Institut de Physique de Nice (INPHYNI), Nice | Olivier Alibart |
| 6. Institut de Physique de Rennes (IPR), Rennes | Lucile Rutkowski |
| 7. Laboratoire d'informatique LIP6, Paris | Eleni Diamanti |
| 8. Laboratoire Interactions, Dynamiques et Lasers (LIDYL), Saclay | David Bresteau |
| 9. ONERA, Palaiseau | Rosa Santagata |
| 10. Station Biologique de Roscoff, Roscoff | Philippe Potin |
| 11. Thales Research & Technology (TRT), Palaiseau | Ghaya Baili, François Guty |

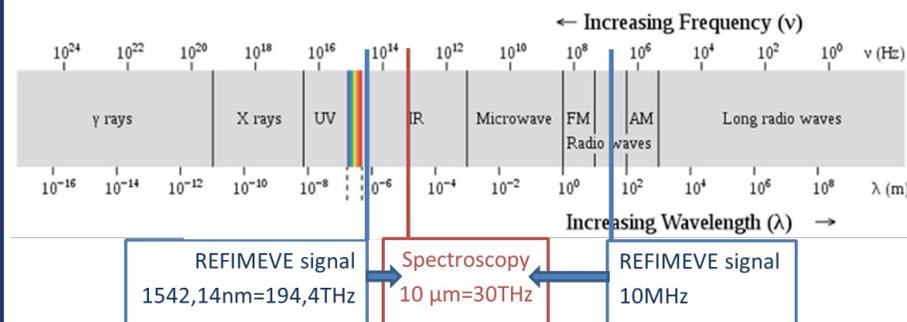
Frequency combs in REFIMEVE



REFIMEVE network



- Frequency comb for spectral transfer purity
- Often necessary for the exploitation of REFIMEVE reference signals



- Alternative: transfer cavity
- ARTEMIS, LPL...

- Currently **22 combs** at the users!

→ partly thanks to the co-funding provided by REFIMEVE. It is a truly successful operation.

- This expertise can benefit everyone

→ contact REFIMEVE team if needed (etienne.cantin@univ-paris13.fr)

→ <https://reseau-femto.cnrs.fr/>

- Optical reference 1542nm
- International links
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- Future extensions

Maintenance of the network



With the **expansion** of the network, maintaining the service requires **more and more resources**

Organization of the maintenance

- Daily monitoring using the network supervision tools
- In case of dysfunction
 - Remote resolution of the issue (~95% of the time), thanks to complete access to the equipment settings
 - Physical interventions needed → Either the **user** resolve/diagnose on-site 😊
→ or the **REFIMEVE team** intervene

The intervention team



Etienne Cantin



Paul Eric Pottie



Maël Abdelhak



Biplab Dutta



Neelam Yadav



Grégoire Coget



Fabien Verdes



This is a full time job
→ Engineer position requested

REFIMEVE information system



REFIMEVE information system in LTE

- Centralize and process scientific data
- Host surveillance software tool + API
- Front end server dedicated to users

→ End-user software to ensure efficient exploitation

Network monitoring software



Full version under development
→ Engineer position requested

Development of a first monitoring
for the signal at user with LIPhy



Monitoring of beatnote power
and status of the stations in the
link to Grenoble

Database requests and visualization

*Yann Le Coq, Samir Kassi and LIPhy
colleagues*

Contents

I. REFIMEVE Time and Frequency Service

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South West - Bordeaux-Toulouse



REFIMEVE network

October 2024

Extension Bordeaux-Toulouse

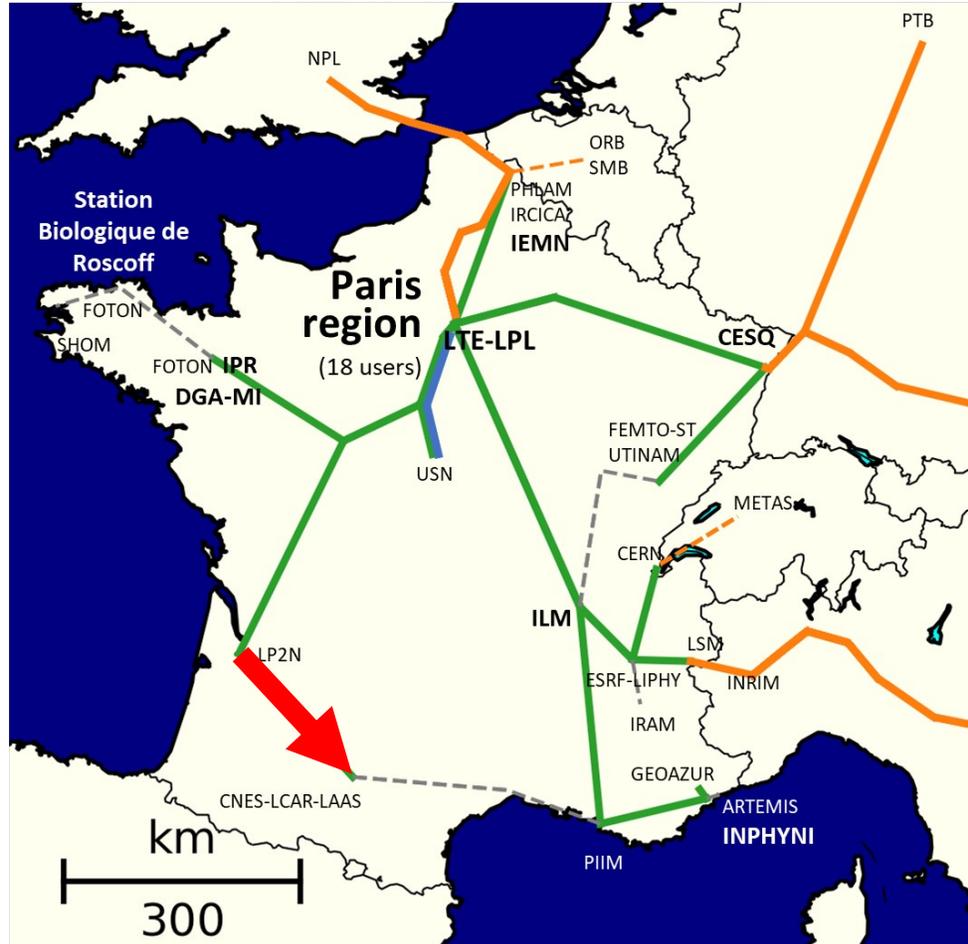
- 3 users: CNES, LCAR and LAAS
- Deployment by Exail (3 days)

exail

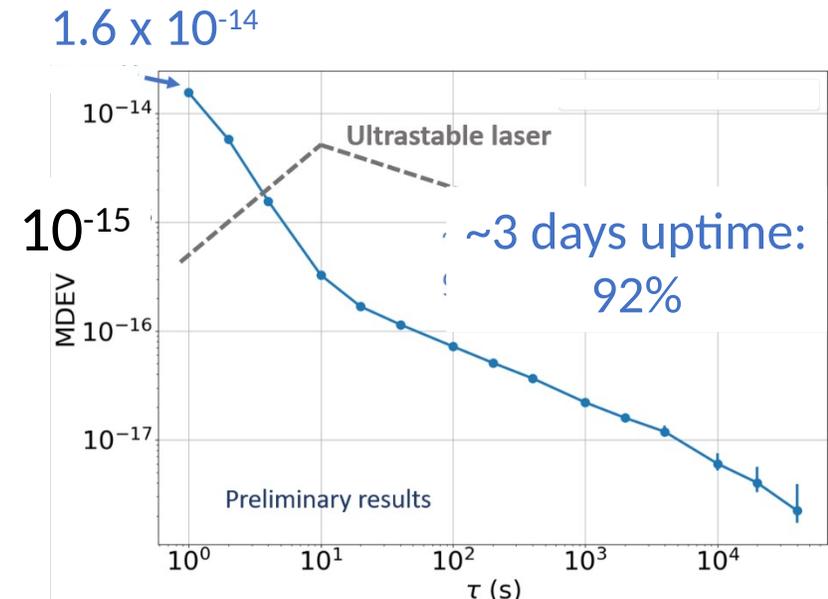
→ Paris-Toulouse: longest and most cascaded link

Setting of the link (power, loop gains...) is tricky.

Link still to be optimized (technical noise limitation)



Optical reference 1542nm
Time and RF references
International links
Future extensions



Uncertainty on transferred frequency: $1.9 \pm 3.2 \times 10^{-18}$

South East – Marseille-Calern



REFIMEVE network

December 2024

Extension Marseille-Calern

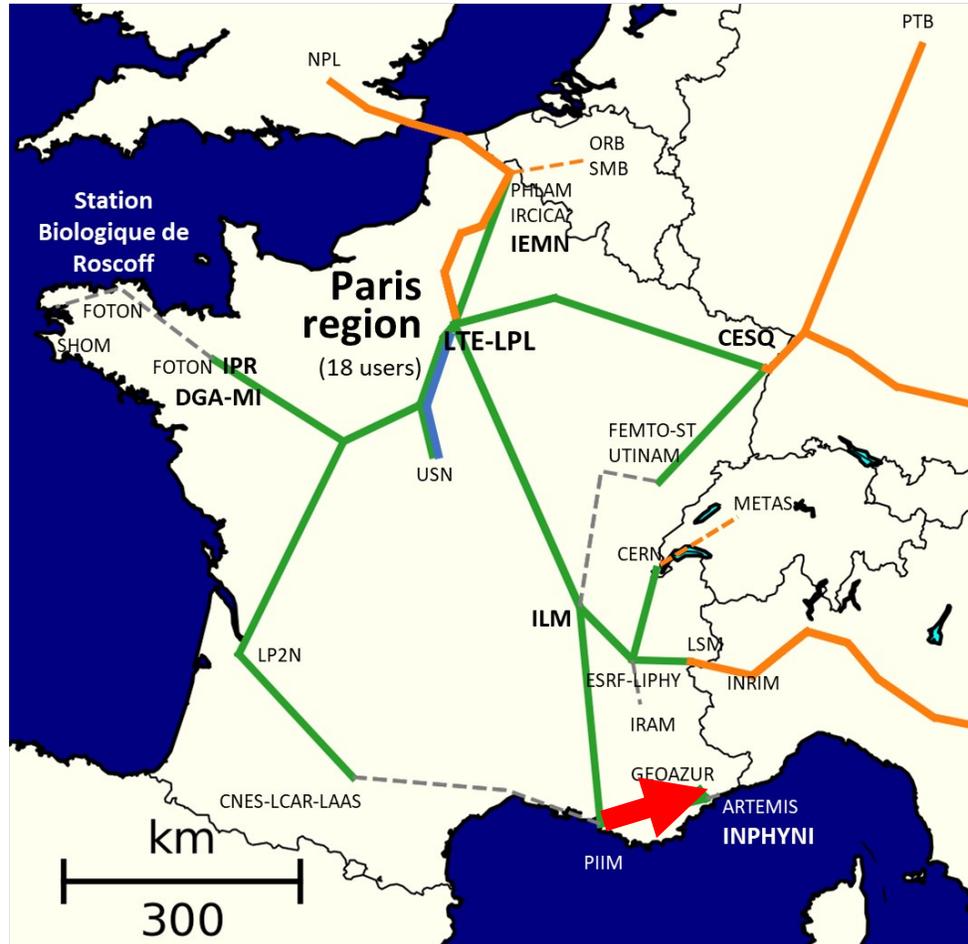
- User: GeoAzur - Observatoire de la Côte d'Azur - Calern
- Deployment by Exail (4 days) **exail**

➔ **RENATER fibers + 60km Orange fibers**

Thanks to the users and IT service of univ and labs (PIIM, GeoAzur)

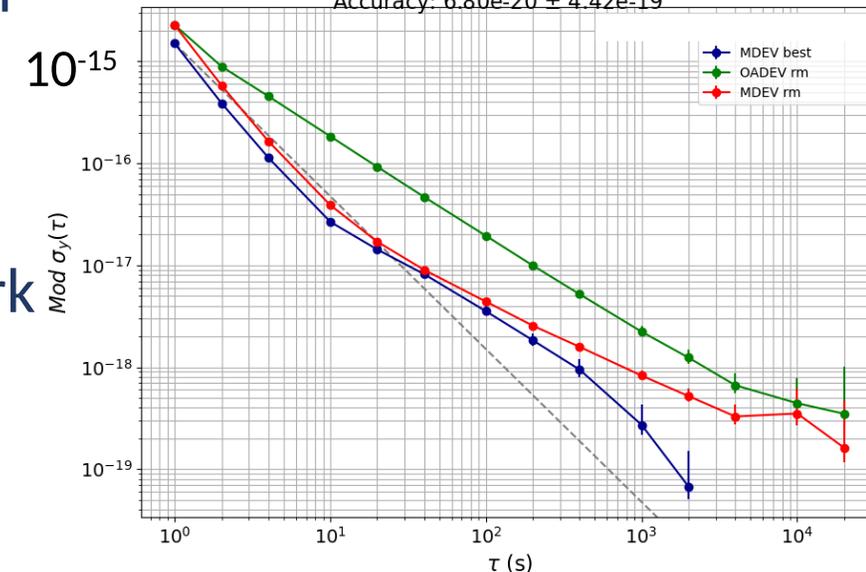
REFIMEVE towards quantum telecom network in Nice

Extensions for fiber sensing activities, KM3NET,...



— Optical reference 1542nm
— International links
— Time and RF references
- - - Future extensions

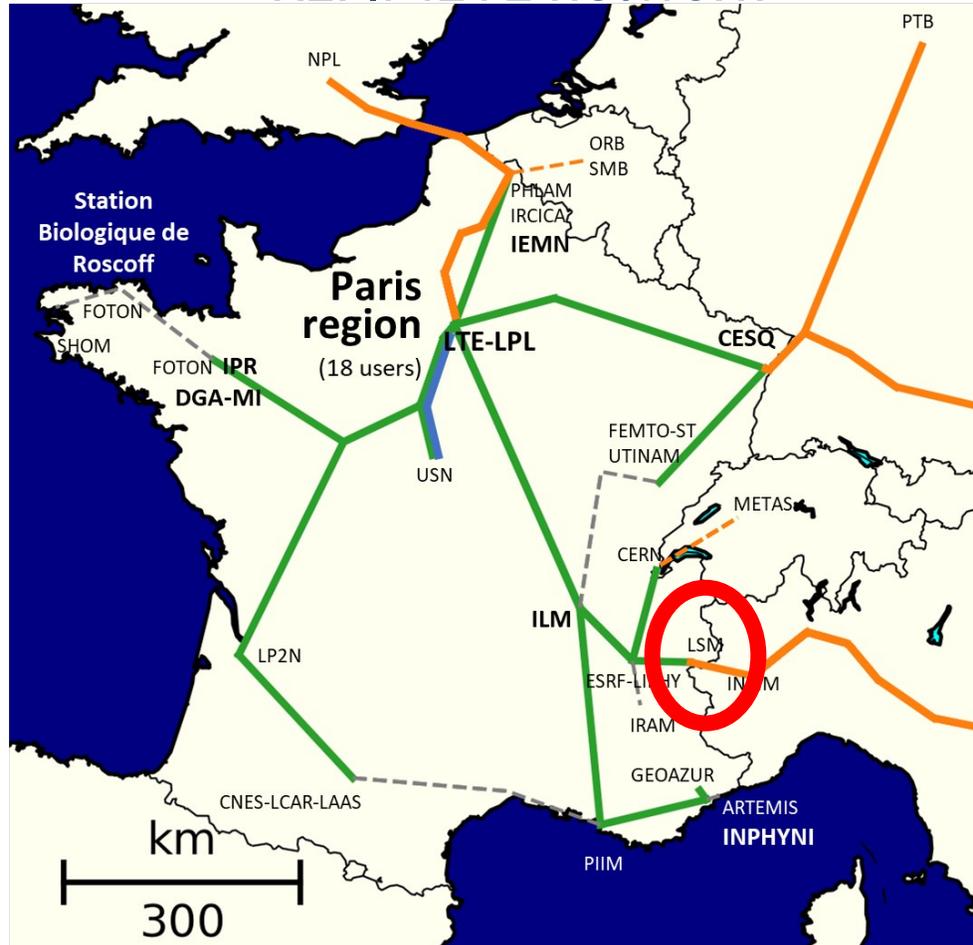
2×10^{-15}
 16/01/2025 - 17/01/2025
 Accuracy: $6.80e-20 + 4.42e-19$



France-Italy - Modane



REFIMEVE network

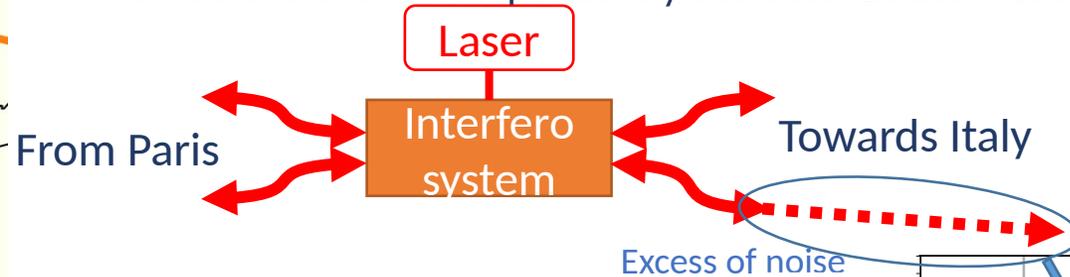


— Optical reference 1542nm
— International links
— Time and RF references
- - - Future extensions

Feb+March 2025

Enhancement in Modane

- Link to Italy (clock comparison)
- Development of a custom low-noise interferometric system
 → To transfer and independently characterize the French and Italian links

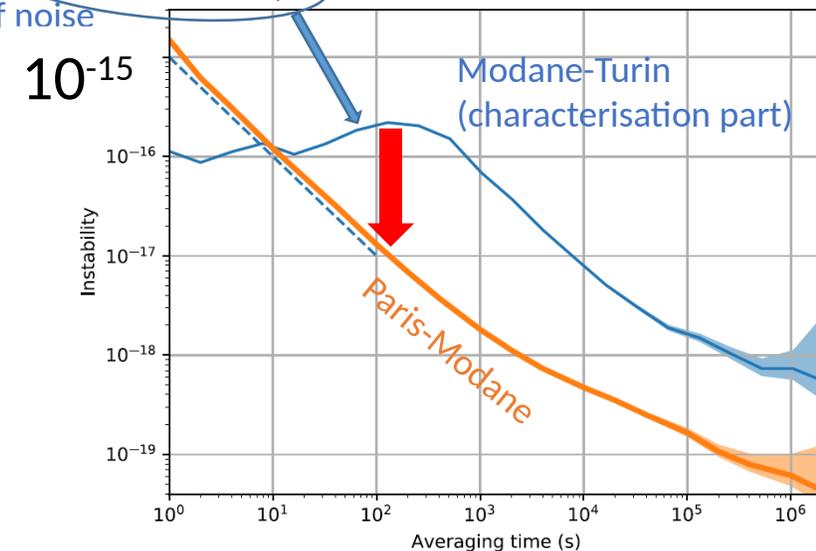


Clivati *et al.*, « Coherent Optical-Fiber Link Across Italy and France », *Phys. Rev. Appl.*, vol. 18, n° 5

→ Clocks comparison campaign

→ Sébastien BIZE's talk

Future use of REFIMEVE for experiments in LSM

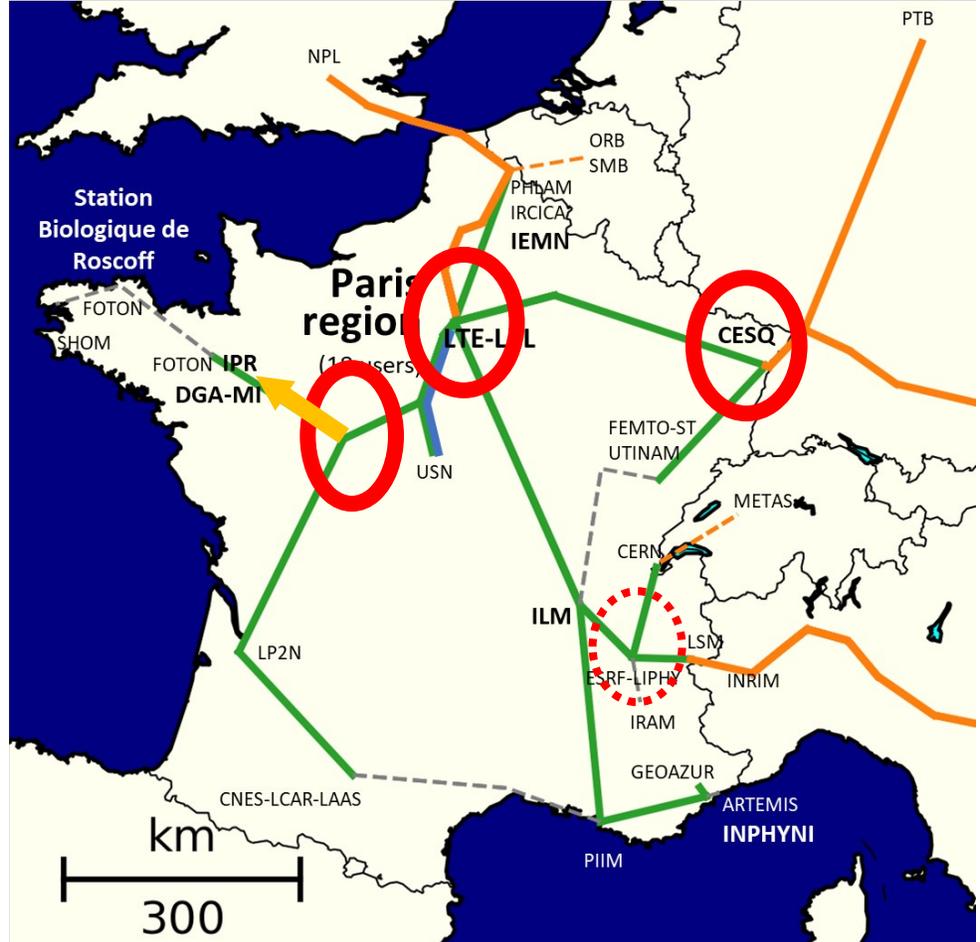


Network development - MLS



REFIMEVE network

2025



— Optical reference 1542nm — International links
— Time and RF references - - - Future extensions

Installation of Multibranch Laser Stations

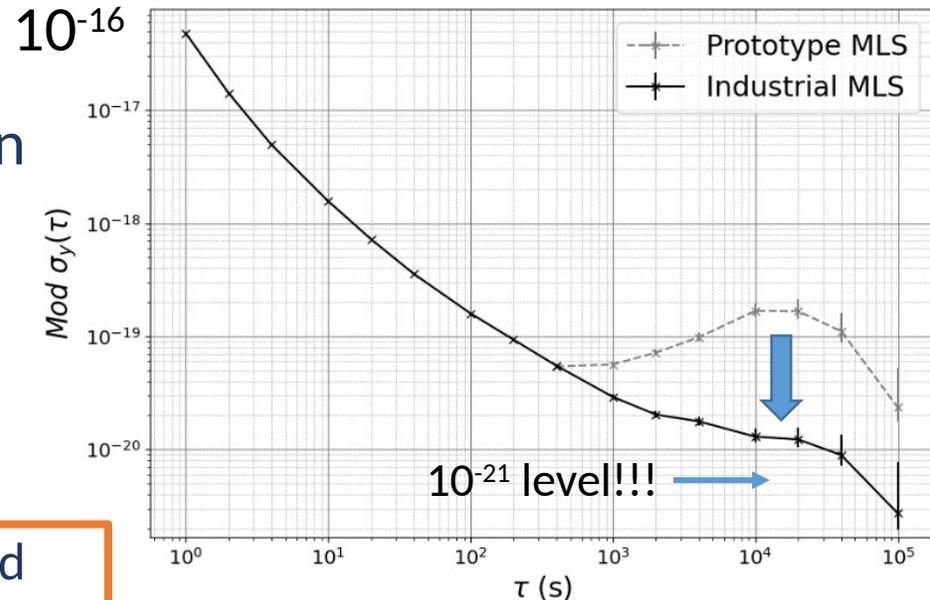
- Network resizing and long term performances enhancement
- Knowledge transfer and industrialisation by **exail**

Allow a node of 6 links
 Better assessment and settings of the link (span by span)
 → more to be installed

→ Biplab DUTTA's talk

Tours-Rennes is deployed
(but link not in operation yet)

Improvement of Long-term Round-trip Stability

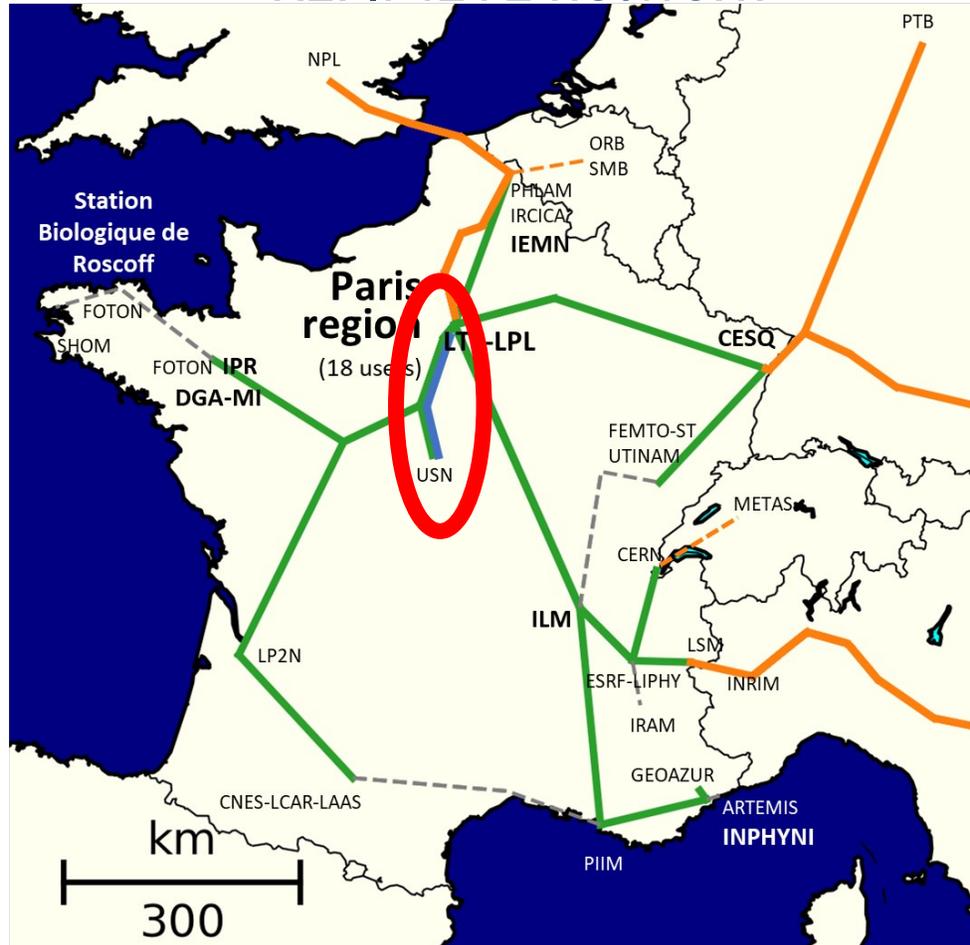


Cantin et al., « An accurate and robust metrological network for coherent optical frequency dissemination », New J. Phys., 2021,

Center – Orléans-Nançay



REFIMEVE network



- Optical reference 1542nm
- International links
- Time and RF references
- - - Future extensions

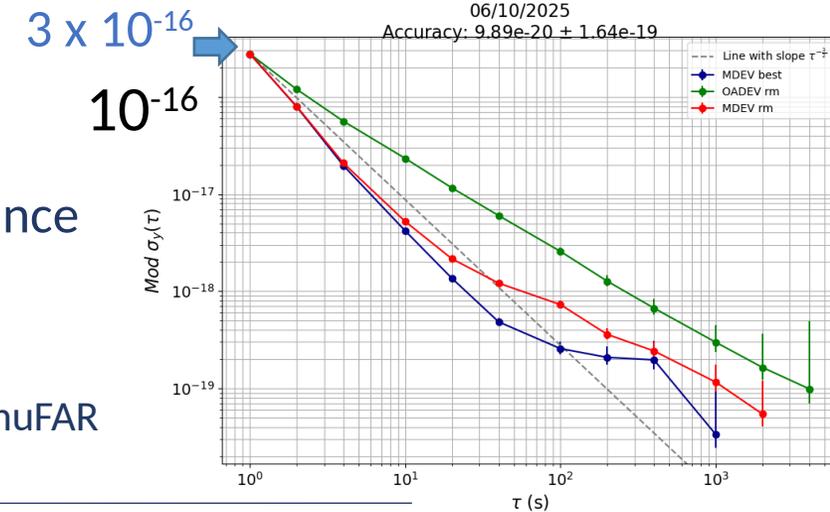
Sept 2025

Observatoire de Nançay

→ Optical reference 1542nm: problem solved on the fiber network for the dissemination

→ Time transfer (White Rabbit): characterisation of the long distance time transfer and on-site measurements

→ perspectives for LOFAR/nenuFAR and EPTA (Pulsar timing array)



White Rabbit Network

- Deployed in Paris region
- Long-distance pilot link to Nançay

Neelam
YADAV
Post-doc



talk

RENATER

Nicolas Quintin

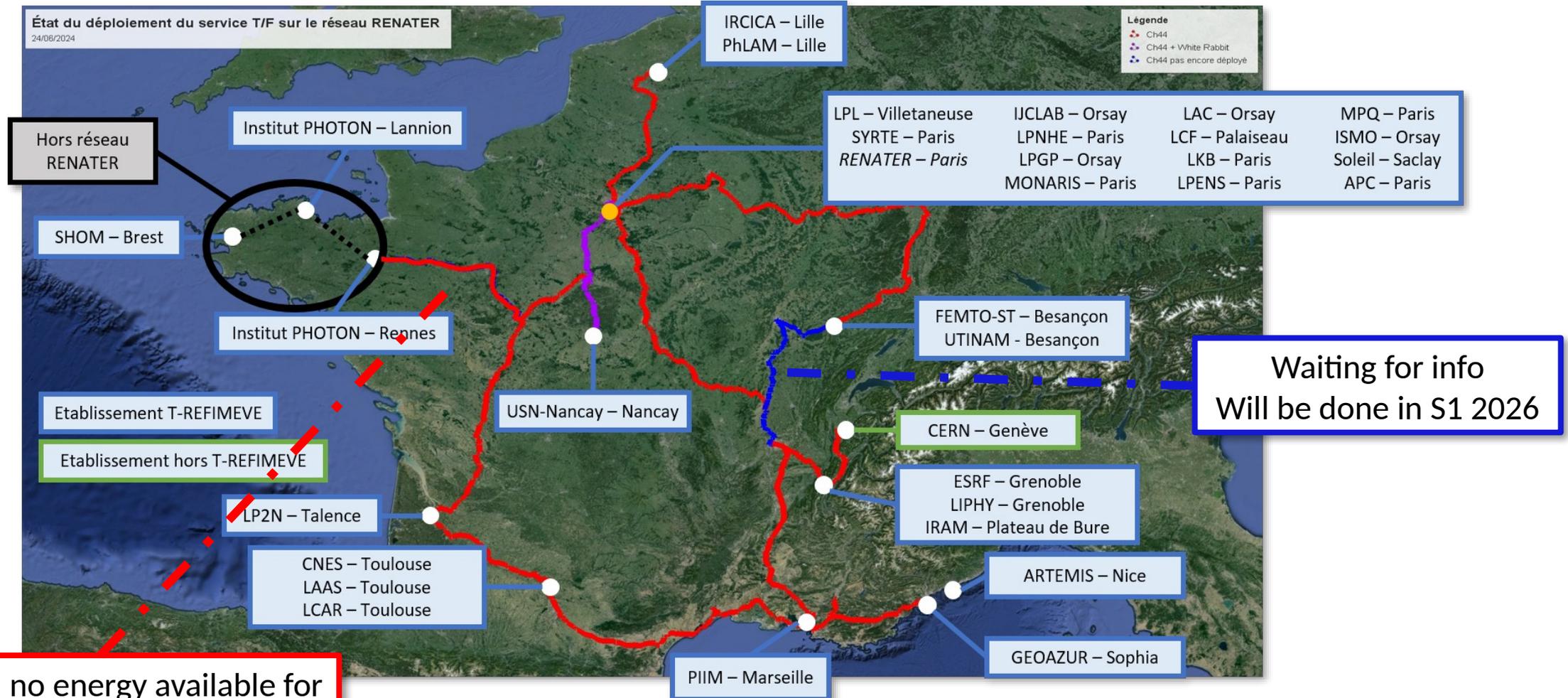
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Snapshot of OADM's in RENATER BB **RENATER** CONNECTEUR DE SAVOIRS



**Warning: no energy available for T/F equipment.
To be fixed in december 2025**

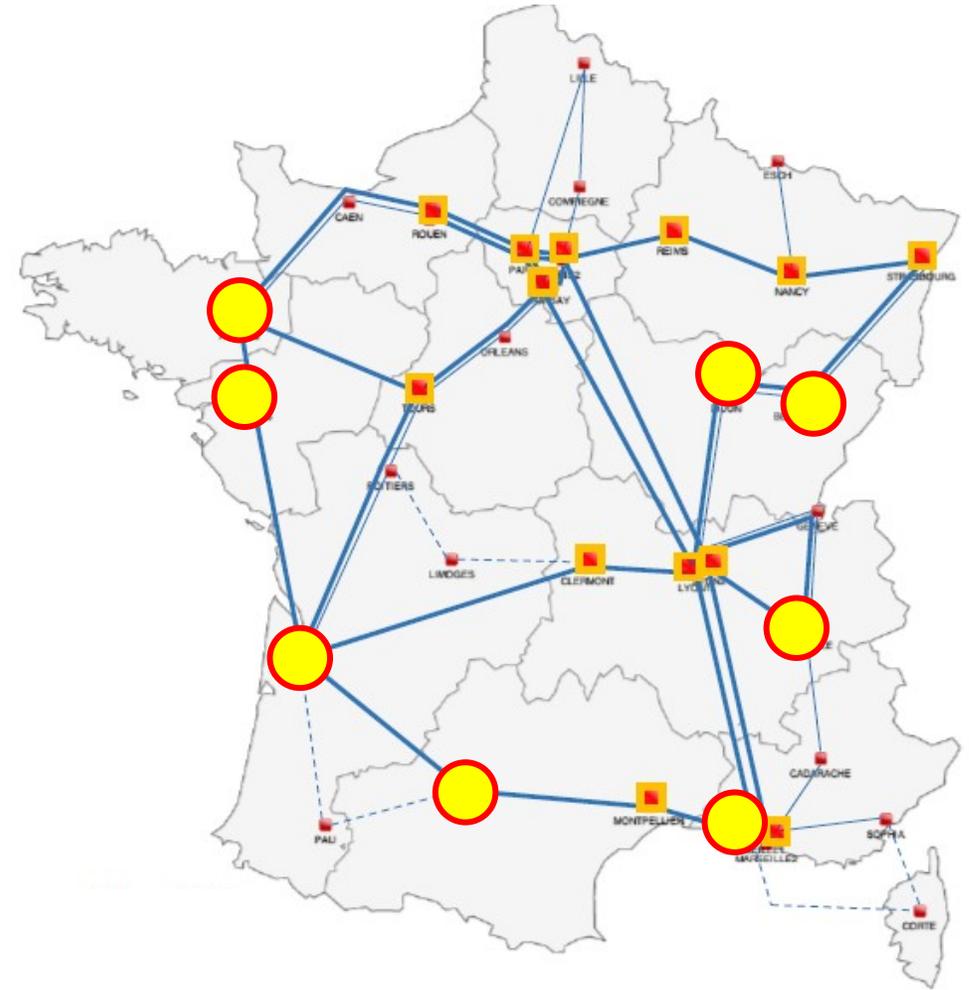
AG T-REFIMEVE 2024&2025 (no changes)

Forecasted NR moves

NR that might have to be moved in the next years:

- Rennes
- Nantes
- Bordeaux
- Marseille 1
- Toulouse
- Dijon
- Besançon
- Grenoble

To be precised in February 2026



Ideas for RENATER 7 photonic layer

F-OADM (RENATER 6)

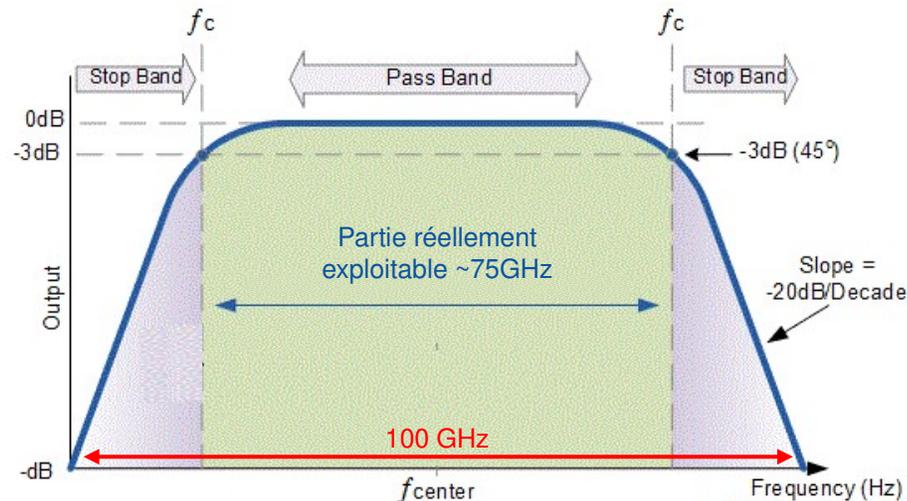
Fixed optical add/drop multiplexer

- Passive equipment
- Up to 40 100 GHz channels in the fiber
- 1 channel = 1 lambda up to 400 Gbit/s maximum
- Maximum occupancy (L1 <> L2) = 12 channels or 1,200 GHz used but actual spectrum occupancy on this link = 537 GHz

R-OADM (RENATER 7)

Reconfigurable optical add/drop multiplexer

- R-OADM technology allowing to generate filters with the desired spectral-width
- Compatible with all baud rates aka symbol rate (even those not yet developed)
- Active equipment = susceptible to failures + energy dependent
- Higher operational complexity than F-OADM



Year	Capacity per lambda
2013	100 Gbit/s
2015	200 Gbit/s
2016	400 Gbit/s
2018	600 Gbit/s
2020	800 Gbit/s

Shannon–Hartley theorem

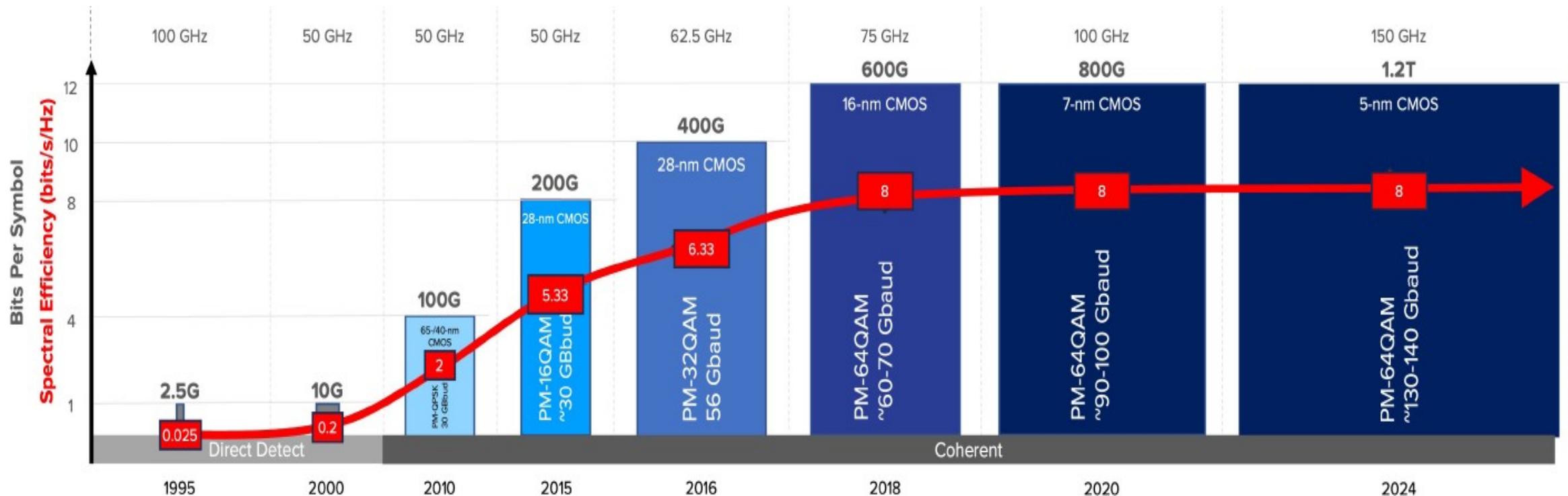
$$C = B \log_2(1 + SNR)$$

$$\frac{C}{B} = \log_2(1 + SNR)$$

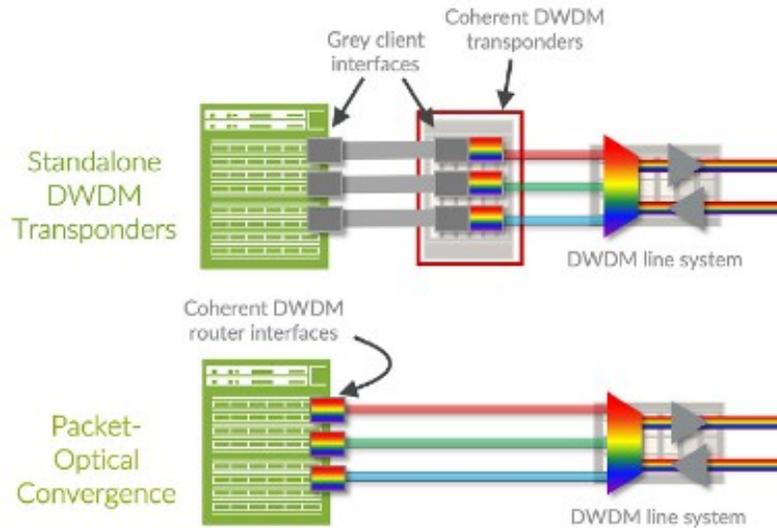
C: Maximal capacity in (en bit/s)

B: Spectral bandwidth(en Hz)

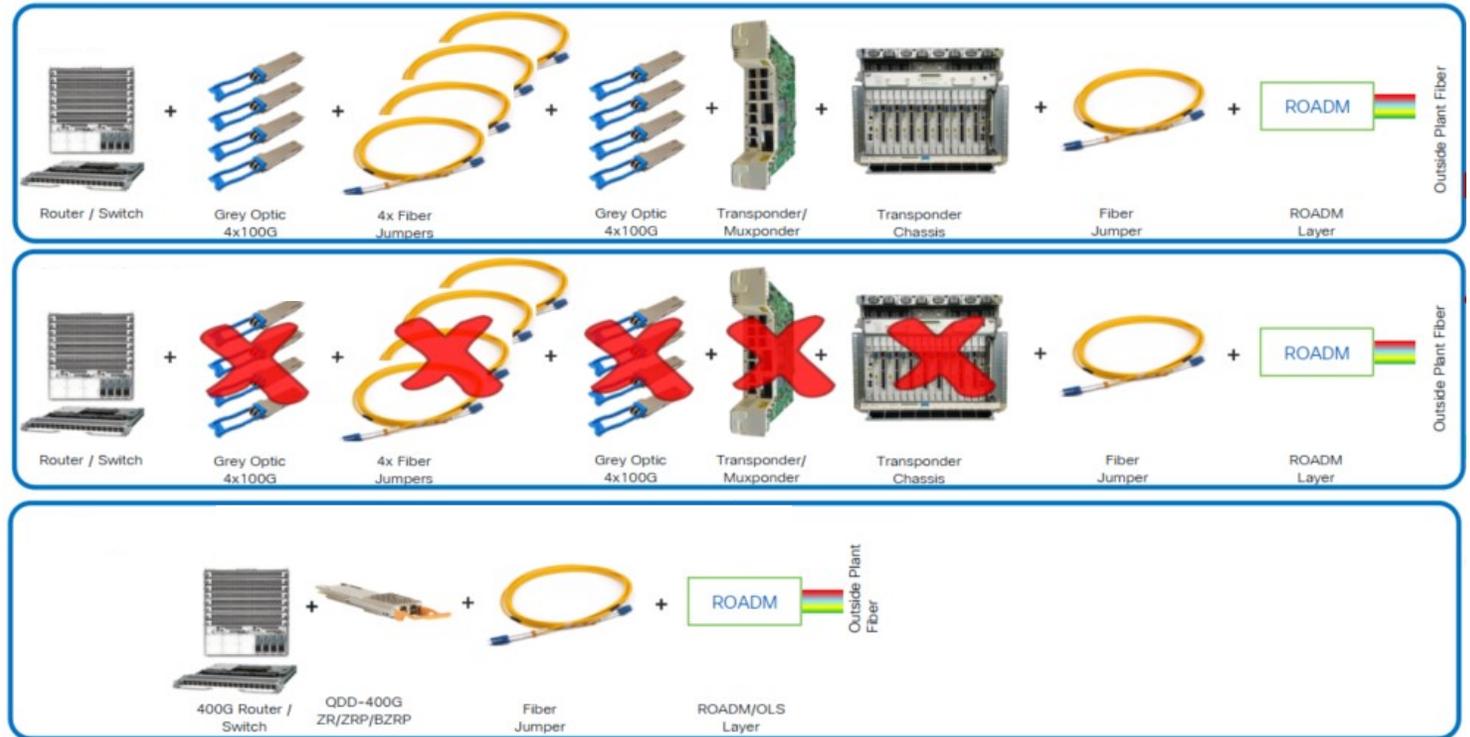
SNR: Signal to Noise Ratio



IPoDWDM in RENATER 6.5



Classical and IPoDWDM architectures



Pros:

- Convergence and simplification : IP routing replaces OTN features.
- Less material : Reduces clutter, energy consumption and maintenance.
- Faster deployments : Easier lambdas provisioning because only in endpoint routers

Cons:

- Higher skills: master both optics (DWDM management, amplification, OSNR, FEC) and IP/MPLS + SR routing.
- Visibility and optical telemetry to be adapted: need to develop tools to measure the optical quality (OSNR, estimated BER) of modules located in third party routers.

First trials

04/2024

Cisco NCS router (lent) Nokia photonic layer	Paris 1 – Marseille 1 879 km
F-OADM	Modules 400 ZR+ Cisco/Ciena/Infinera/Nokia

It proved the ability to deploy 400 Gbit/s services through the F-OADM RENATER 6 and the supervision via Solarwinds of the NOC RENATER.

01/2025

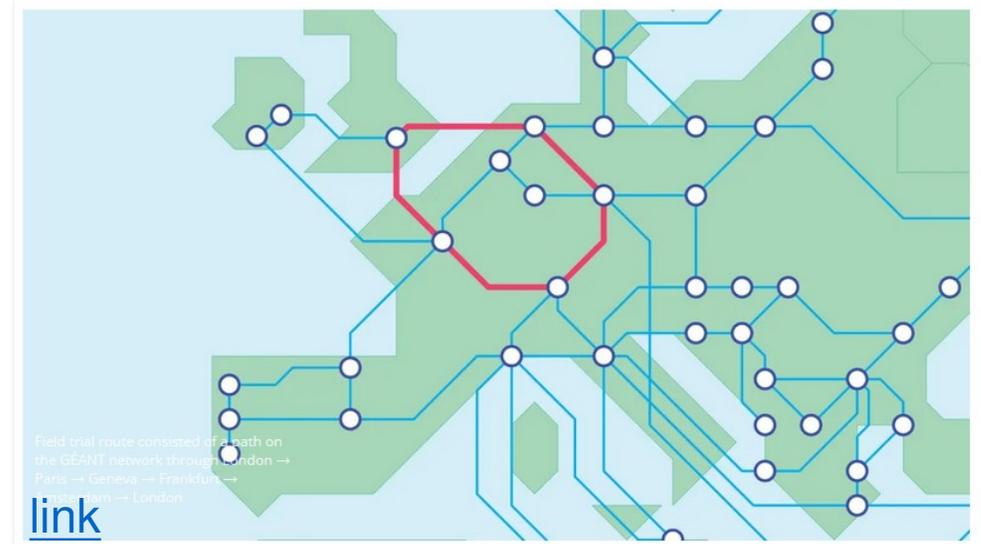
Cisco NCS router (lent) Nokia photonic layer	Tours – Rennes 289 km
F-OADM	Modules 100G ZR Cisco

It demonstrated the ability to quickly deploy additional capacity by directly deploying this type of module in routers. IPoDWDM soon to be in production in RENATER 6

POCs RENATER

06/2025

Nokia routers Photonic layer Nokia	3 403 km
R-OADM	Module « Cisco » 400G Ultra Long Haul (ULH)



Field trial GEANT

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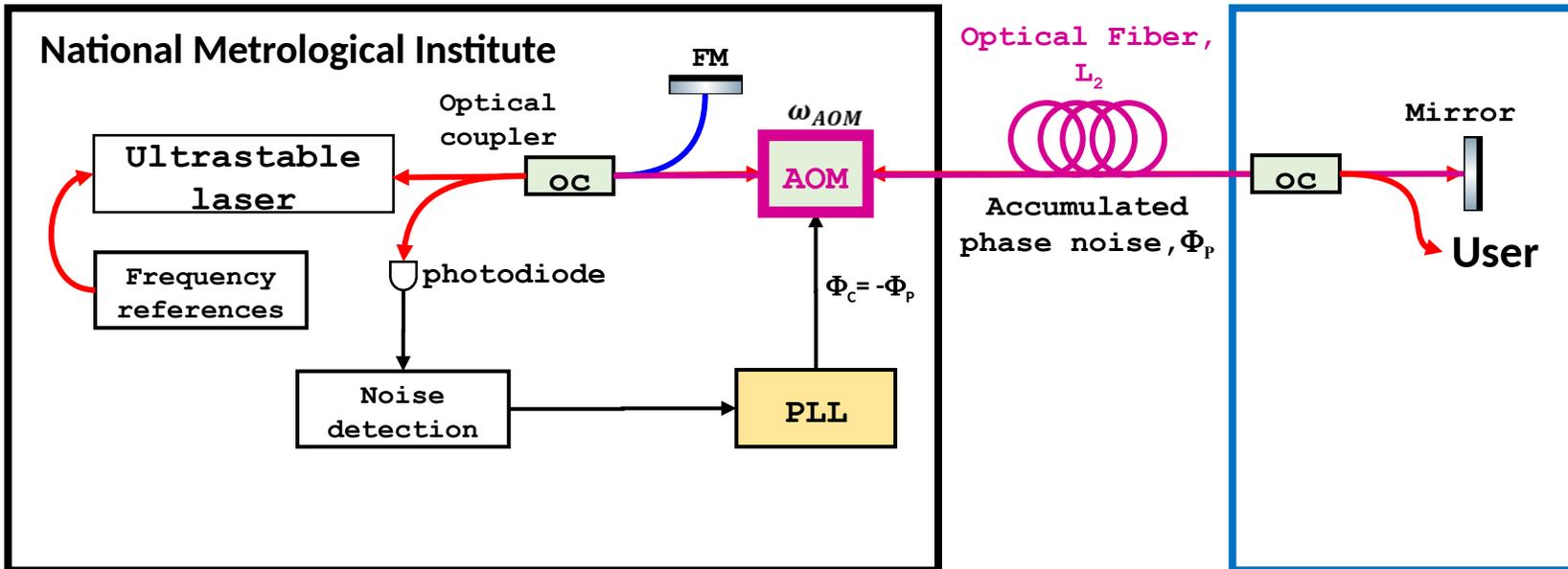
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Frequency transfer technique



Transfer of an optical ultrastable and accurate laser, without degradation

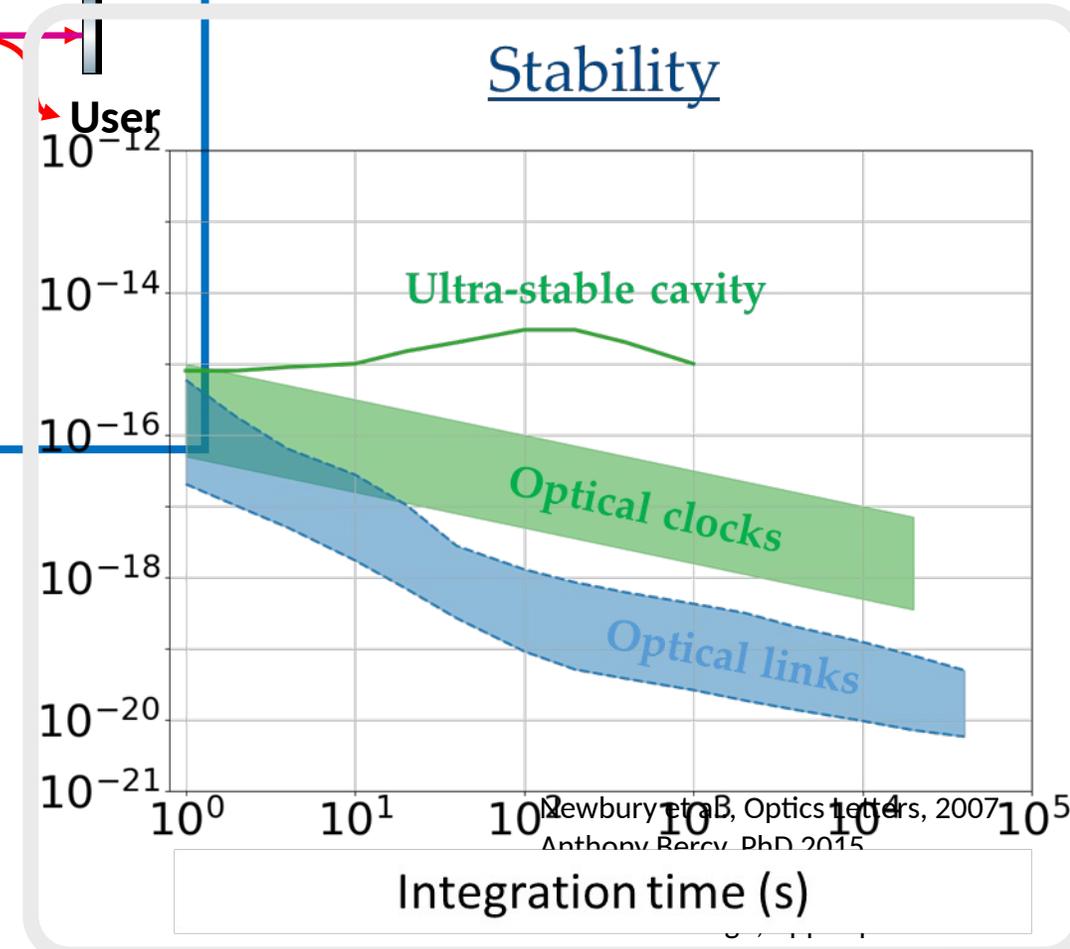
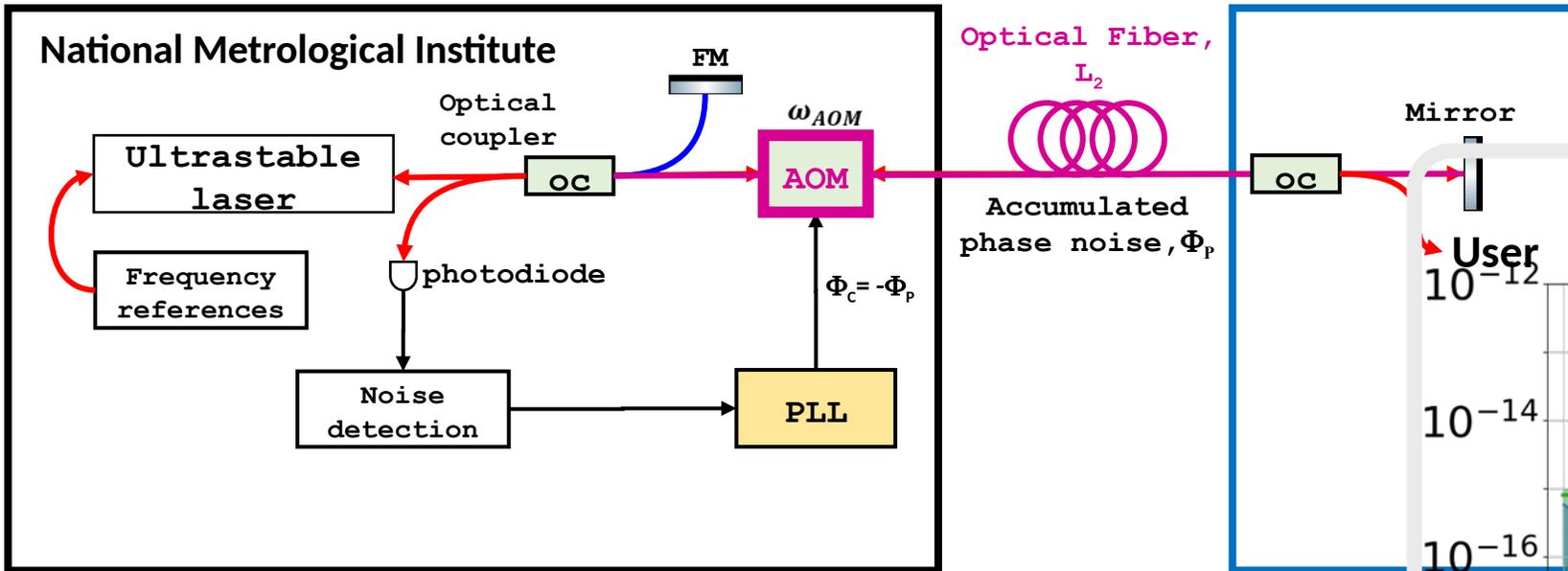


- **Noise detection** with a **strongly unbalanced Michelson interferometer**
 - Long arm = fiber to the user
 - Short arm = reference arm
- **Heterodyne detection** between the reference signal and the reflected signal

Frequency transfer technique



Transfer of an optical ultrastable and accurate laser, without degradation



- **Noise detection** with a **strongly unbalanced Michelson interferometer**
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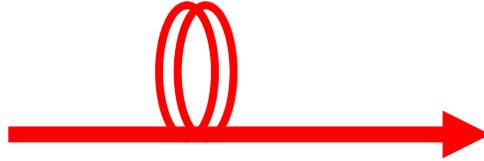
Clean-up oscillators for REFIMEVE



Linewidth broadening of the REFIMEVE signal > 100km

Source laser linewidth at LTE

→ around 1 Hz



Residual phase noise during the transfer (correction is limited)

Linewidth broadening ~1kHz

(depends on link length and noise)

→ Samir KASSI's talk

→ Mathieu COLLOMBON's talk

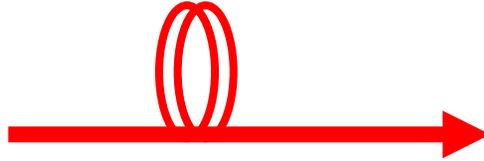
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Installation of cavities in the network

1 Hz Laser system



Biplab
Dutta
IR cdd



Talk

Alternative: ultra-narrow linewidth laser

Developed by FOTON, now commercial

Adèle
Hilico
MCF



Poster



Slimliner (produit SilentSys)

Uptime improvement: to infinity and the 100%!



Enhance the robustness, reliability of the network and the uptime of the REFIMEVE signal at user

1 - Unexpected counter shutdown (25% of the downtime!)

- Test of other counter types
- Realisation of a new K+K counter control system

2 - Automatic relock not always optimal

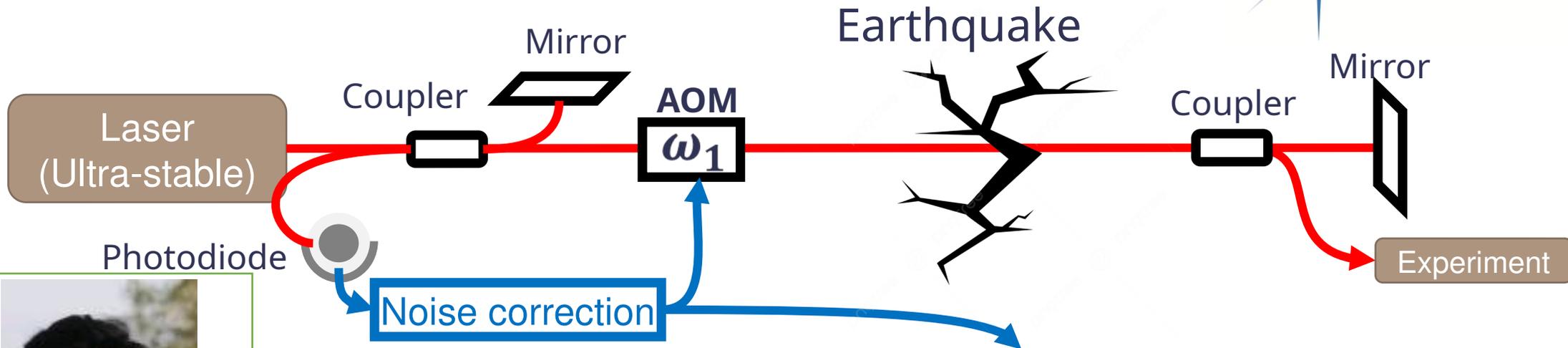
- improve the automation routine of a link
- Thanks to the REFIMEVE IT system developed

3 - Unavailability due to polarisation adjustments

- Adjustment to maximize the optical beatnote
 - Polarisation insensitive detection under development



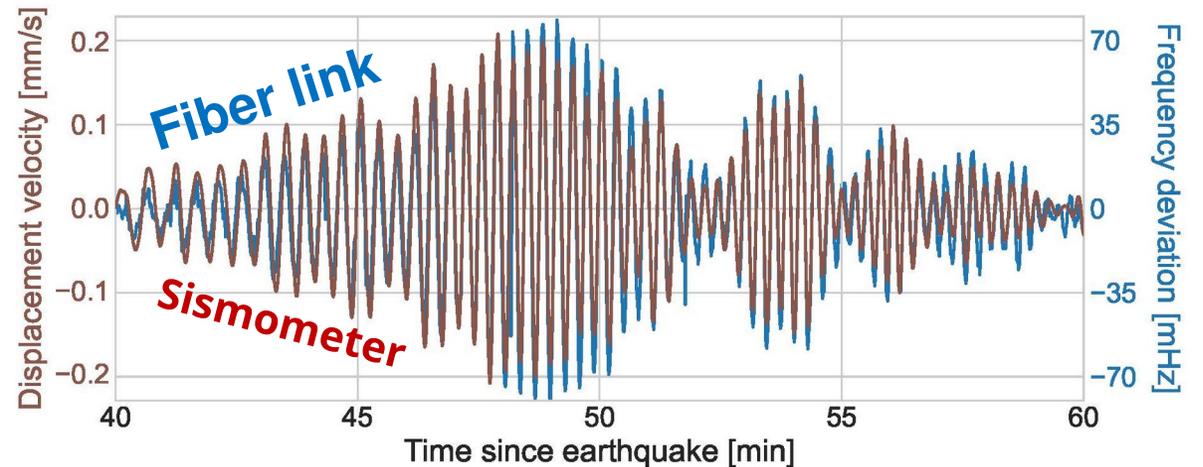
Fiber sensing



Debanjan Show IR cdd



Poster



→ Cecilia CLIVATI's talk

European SENSEI project:

senseiproject.eu

PhD Thesis, Mads Tønnes

→ Mutualize existing fiber network for environment sensing

S. Donadello et al., *Commun Earth Environ*, vol. 5, n° 1, 2024,

Perspectives and conclusions



- Extensions of the network (Laser stations and White Rabbit)
 - ~90% of the expected T-REFIMEVE network is constructed
 - Extensions to Nice, Bretagne, Dijon, new partners
 - and to European network: extensions to ORB (Belgium), ROA (Spain), switzerland... and towards a european access point at CERN

- REFIMEVE service strengthening (maintenance, operation...)

- Research and developments:
 - RF and time transfer on the current optical carrier
 - Mobile platform for ultra-precise measurement
 - Fiber sensing in the network

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**Thanks for
your
attention!!**