Operation and supervision of the first industrial-grade coherent optical fiber link for optical frequency dissemination

M. Rabault[1], F. Guillou-Camargo[1], V. Ménoret[1], B. Desruelle[1], A. Amy-Klein[2], E. Cantin[2], O. Lopez[2], C. Chardonnet[2], P.E. Pottie[3], G. Santarelli[4], N. Quintin[5] and E. Camisard[5]

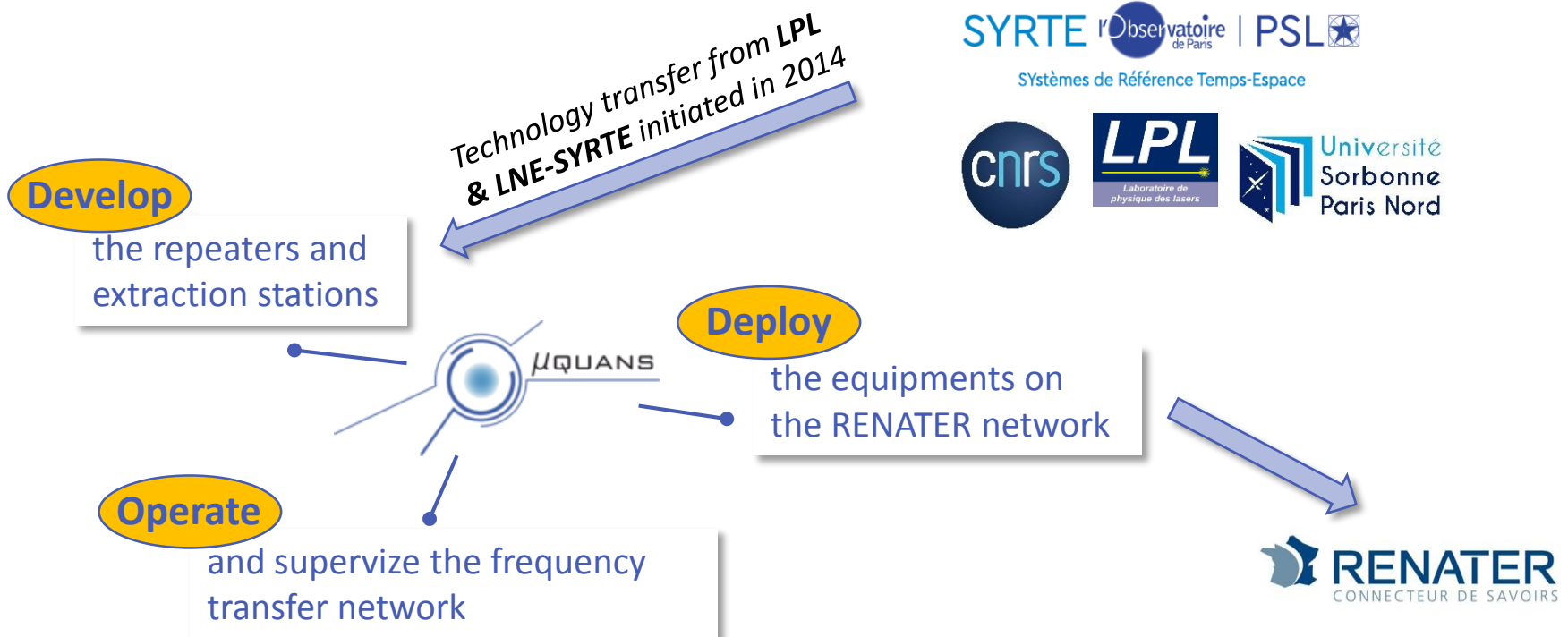*[1]MUQUANS, [2]LPL, [3]SYRTE, [4]LP2N, [5]RENATER*

AG Refimeve+ 2020

Muquans in the project

- **REFIMEVE+** : Disseminating an ultra-stable optical frequency standard in the C-band of the ITU-grid over 2 x 4000 km of an operational telecommunication fiber network in France
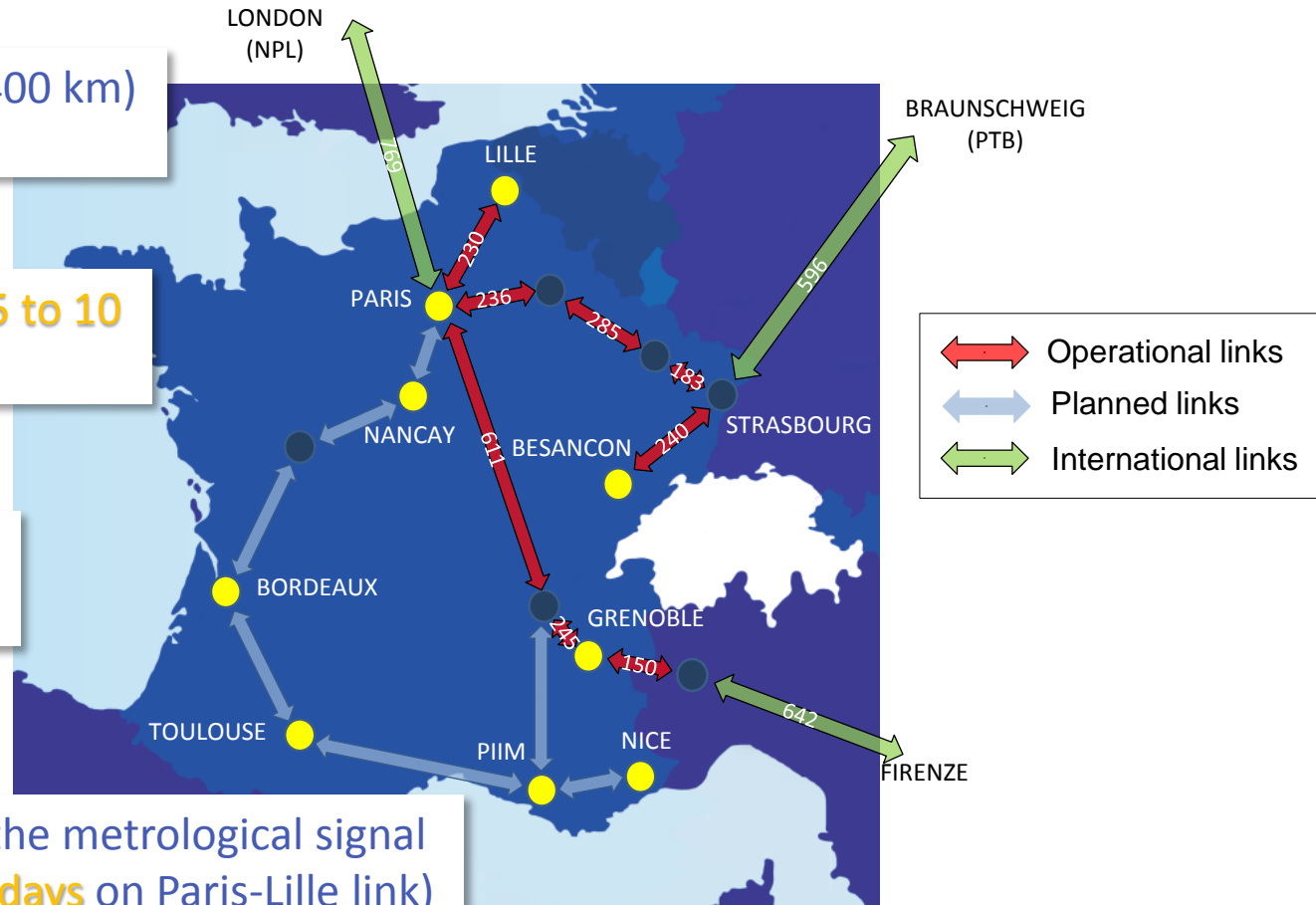
A tight collaboration between several entities

*Technology transfer from **LPL** & **LNE-SYRTE** initiated in 2014*

Develop
the repeaters and extraction stations

Deploy
the equipments on the RENATER network

Operate
and supervize the frequency transfer network

SYRTE l'Observatoire de Paris | PSL
SYstèmes de Référence Temps-Espace

cnrs

LPL
Laboratoire de physique des lasers

Université Sorbonne Paris Nord

μQUANS

RENATER
CONNECTEUR DE SAVOIRS

An industrial-grade network

① 4 links deployed (2 x 2400 km)
→ 3 by Muquans

② Fast deployment : **5 to 10 days** for 1 link

③ Efficient optimization : **< 20 days**

④ High availability of the metrological signal (ex : **> 99% over 43 days** on Paris-Lille link)

LONDON (NPL)

BRAUNSCHWEIG (PTB)

LILLE

PARIS

NANCAY

BESANCON

STRASBOURG

BORDEAUX

GRENOBLE

TOULOUSE

PIIM

NICE

FIRENZE

139

230

236

285

183

240

611

245

150

596

642

Operational links

Planned links

International links

➡ Fully **autonomous** equipments (embedded intelligence)

A big technology challenge

- ## Equipment:

  ✓ High-performance level and good reproducibility: **50 state-of-the-art RLS**

  ✓ Reliability and robustness

  ✓ Cost and delay control: **6 months of production**

  ✓ Remote control and autonomy

- ## Network supervision:

  ✓ More than 150 equipment to monitor (EDFA, RLS, frequency counters)

  ✓ Save and analyse large amount of data

The Repeater Laser Station

- <u>Main features :</u>

② Uses narrow-linewidth local laser diode (< 5 kHz)

① Works in the C-band, channel #44 (1542.14 nm)

⑥ Automatic polarization optimization

③ Low-noise heterodyne detection

⑤ Thermally controlled interferometer : sensitivity < 1 fs/K

④ Needs very low input optical power level (few nW)

Low-noise electronics developped by **Syrlinks** ⟨⟩

Industrial certification process

- A test bench to validate the production:

  - ✓ Electrical and optical qualification process of each RLS (optical losses, thermal sensitivity, …)

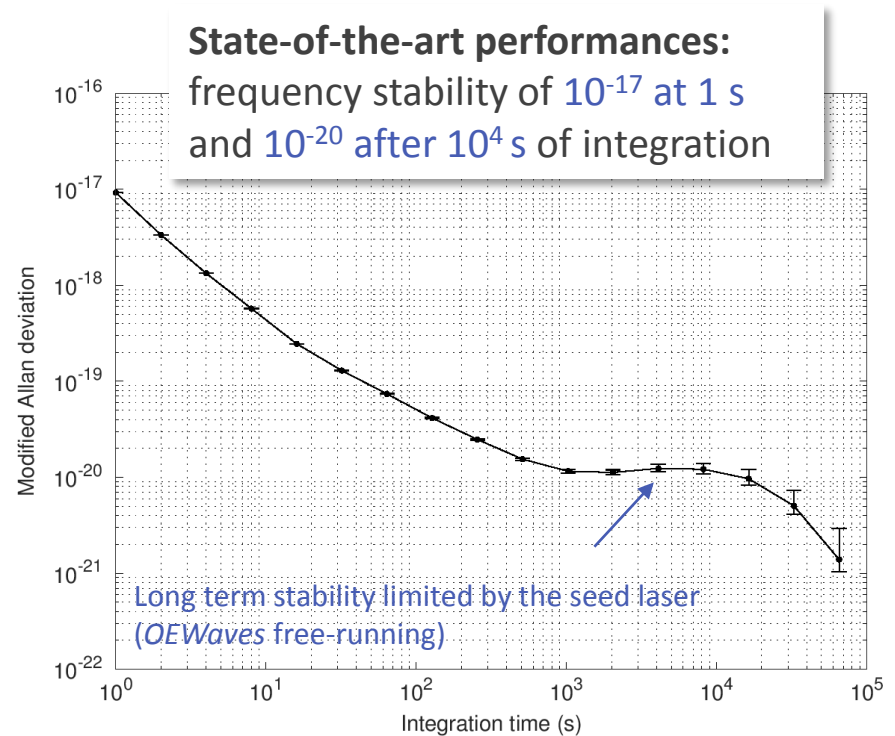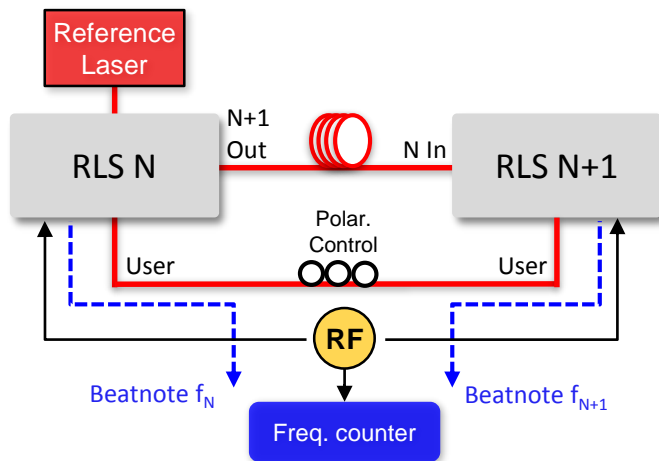 - ✓ Real link configuration: OADM, bi-dir EDFA, **500 km** of fiber spools, …

Fiber spools
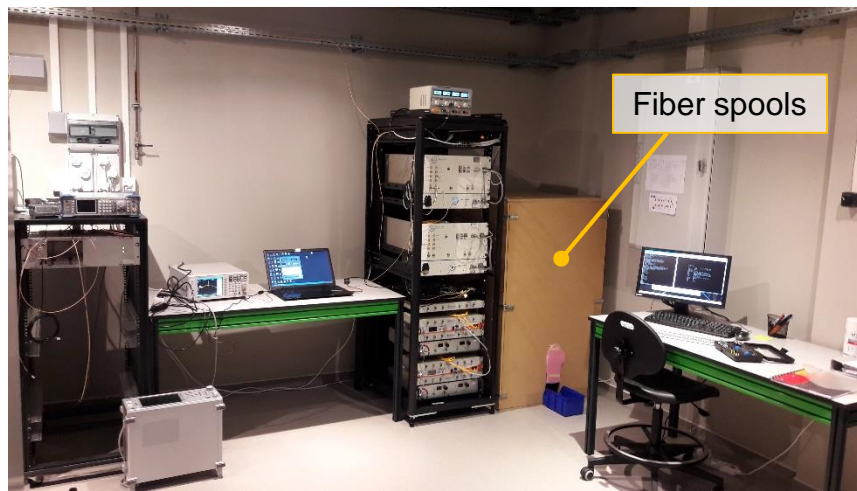
- Configurable for R&D experiments

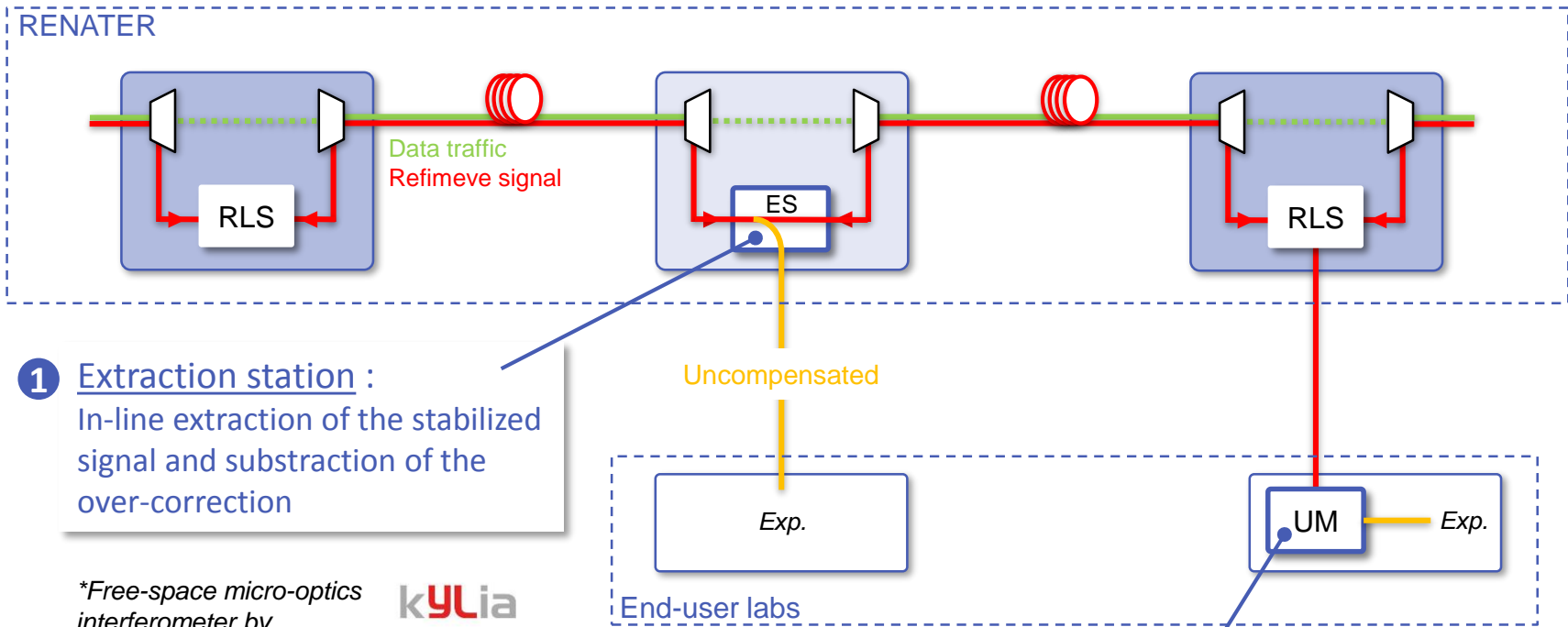# RLS performances

- ## Measurement of repeater station noise floor :

✓ Two-way between 2 RLS → very short link : 1 m

✓ Out-of-loop end-to-end measurement

State-of-the-art performances: frequency stability of 10^{-17} at 1 s and 10^{-20} after 10^4 s of integration

Long term stability limited by the seed laser (*OEWaves* free-running)

F. Camargo-Guillou et al, *Characterization of an industrial-grade fiber link for optical reference dissemination*, Appl Optics Vol. 57, Issue 25, pp. 7203-7210 (2018)

Other products for fiber links

- Extraction station (ES) and user module (UM)

RENATER

Data traffic
Refimeve signal

RLS

ES

RLS

1 Extraction station :
In-line extraction of the stabilized signal and substraction of the over-correction

Free-space micro-optics interferometer by **kYLia**

Uncompensated

Exp.

End-user labs

UM — Exp.

2 User module (AOM+FM) :
Bring the metrological signal as close to the experiment as possible
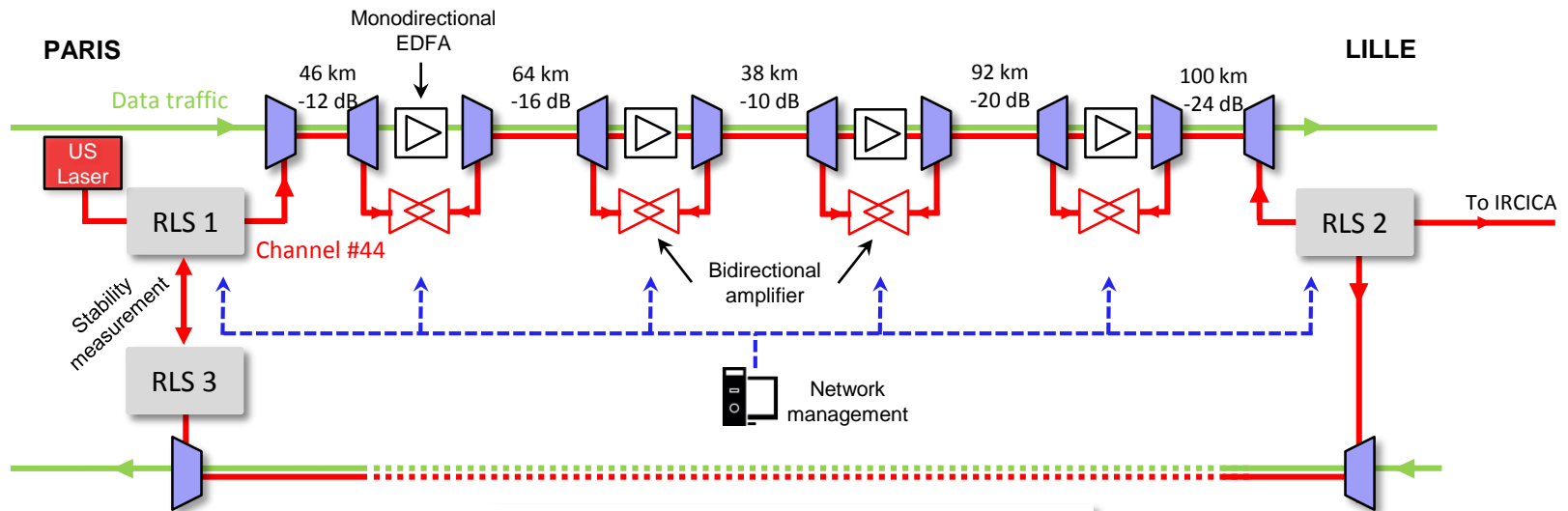
- Adaptable solutions to end-user needs

Real link configuration

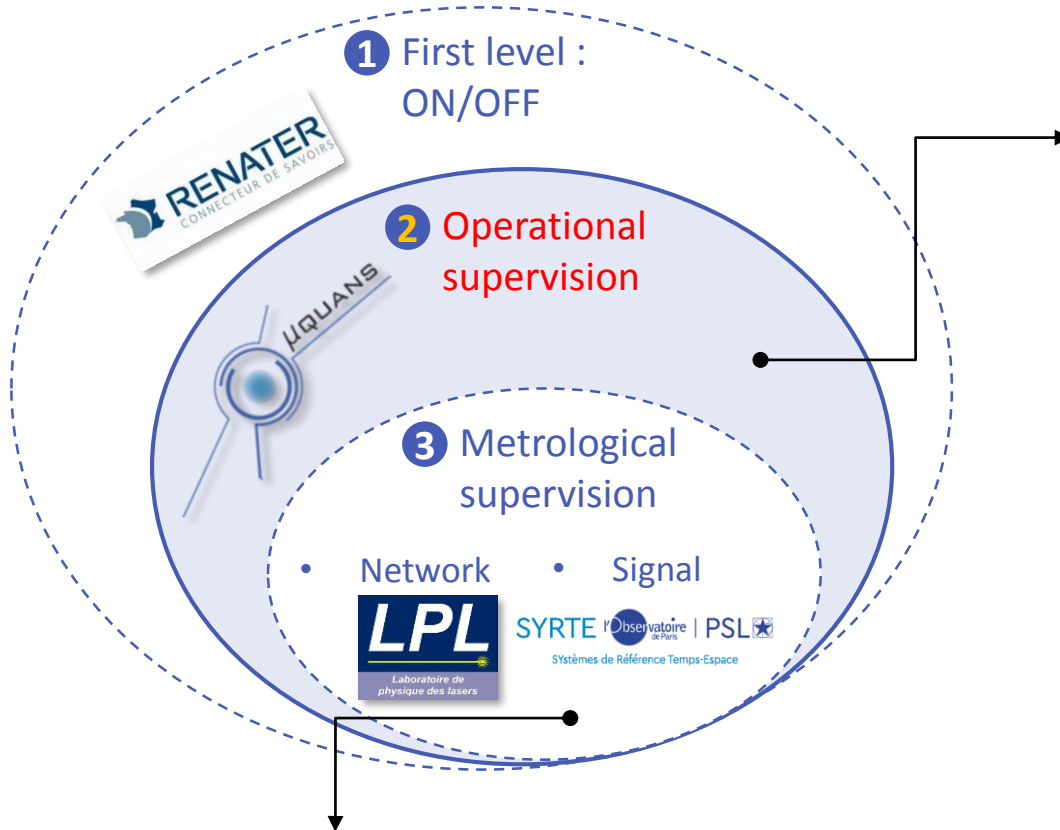- Ex : **Paris-Lille** (**2 x 340 km**)

1 3 RLS installed in the Renater nodes

2 4 bi-directional EDFA installed in the telecom shelters with 10 OADM on each span

PARIS

Data traffic

Monodirectional EDFA

LILLE

46 km -12 dB

64 km -16 dB

38 km -10 dB

92 km -20 dB

100 km -24 dB

US Laser

RLS 1

Channel #44

To IRCICA

RLS 2

Bidirectional amplifier

Stability measurement

RLS 3

Network management

3 Total optical attenuation : **160 dB**

➡ Full remote access to all the equipment (RLS, ES, UM, EDFA) via a **Renater VPN**

Optical links supervision

1 First level : ON/OFF

2 Operational supervision

3 Metrological supervision

- Network
- Signal

- Metrological data processing
- Accuracy calculation
- Ultra-stable source management

Components of the global supervision:

- ✓ **Supervision software:** monitor and control the REFIMEVE+ performances

- ✓ **Database:** store all the information useful to the network management

- ✓ **Human-machine interface:** for final users, academic teams and the network manager

The supervision software

- ## The role of the supervision software is to:

1 Monitor the proper functioning and **remotely control** the equipment parameters in **real-time**.

```
REFIMEVE_STM32
adc          516  2552 2537 2460 3538 3120 458  2048
             1689 4008 4012 982  2525 342  4003 4008
aom_user     active
board_type   even
board_user   off
board_state  on  off on  on  on  on
ctrl         on  on  on  on  on  on  on
dac          2446 3787 1210 2435 1190 2380 1170 2510
dds          np1:1000 user:300
ftw          858993 858993 859650 860300 860400 859850
limit        off off
ofs          98 136 99 137
polar:       11
pot          150 150 150 150 150 150 10 150
sm_mode      semi-auto
sm_state     2 6 3 3
tcxo         on
temp         47.19
vco          off off
vga          7 6 4
```

2 Detect and manage **bugs and alarms** (cycle slips, polarization optimizations, …)

Admin

Visualize ↑↓ Manage

Renater server

Request
Upload

Database

Notify ↓↑ Supervise

RLS N — EDFA — EDFA — RLS N+1

IP protocol, secure access

3 Upload the information collected on the field and store in the database (alarm, events, …)

4 Administrate and troubleshoot system configurations

2 outliers rejected from 172702 points : Uptime 100.0%
Time link has been down : 0 s
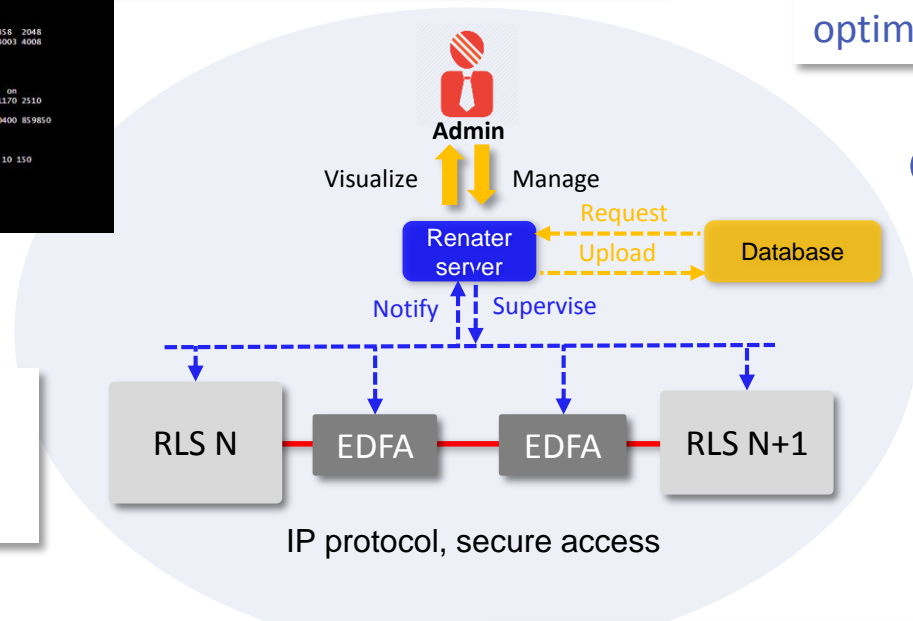
5 **Data pre-processing:** outliers detection, Mdev calculation, …
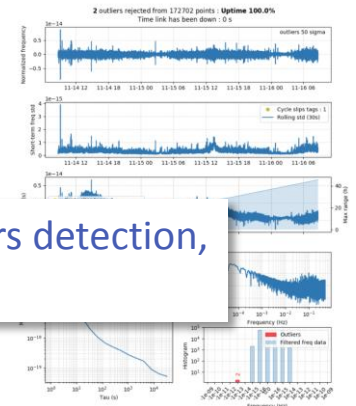
Software and database hosted on a Renater server

End-user service

- A dedicated interface for the end-users under development with Syrte/LPL

  - ✓ Based on the supervision software

  - ✓ Webpage interface

  - ✓ Sort the useful information for users : link status, frequency data, …

  - ✓ In progress …
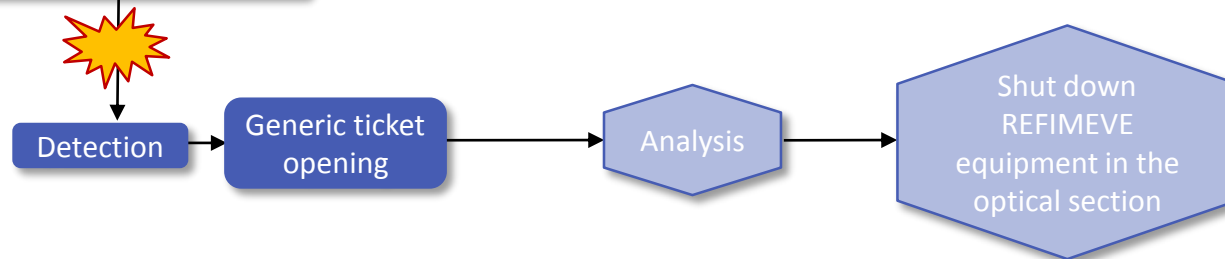
Web interface

Demonstration !

Conclusion

- **First industry-grade frequency transfer link operational**

  - ❑ 2 x 2400 km already deployed

  - ❑ State-of-the-art performances (frequency stability < 10^{-18} long term)

  - ❑ High availability (> **99%**)

  - ❑ Fast and efficient deployement/optimization of a link

- **Deployment of the REFIMEVE+ network under way**

- **Efficient supervision tool to manage the network**

Incidents management

Incident in the network

Detection → Generic ticket opening → Analysis → Shut down REFIMEVE equipment in the optical section

Renater Working hours

T&F ticket opening → ✉ → T&F ticket closing

REFIMEVE+ Working hours

INCIDENT report sent to REFIMEVE+ mailing list

✉ → T&F service is shut down → Analysis → Route cause found → Allow to turn back on REFIMEVE equipment

Back to operational state