l'Observatoire de Paris | SYRTE

Systèmes de Référence Temps-Espace

RENATER
CONNECTEUR DE SAVOIRS

LP2N

LPL
Laboratoire de physique des lasers

Time and Frequency transfer over telecommunication Fiber networks :

a new research infrastructure with applications for geoscience and astro particle physics ?

P.-E. Pottie

cnrs

LABORATOIRE NATIONAL DE MÉTROLOGIE ET D'ESSAIS
LNE

PSL
UNIVERSITÉ PARIS

SCIENCES SORBONNE UNIVERSITÉ

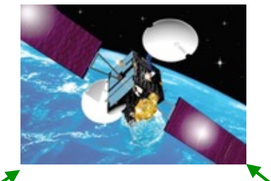
UNIVERSITÉ PARIS 13 NORD

Outline

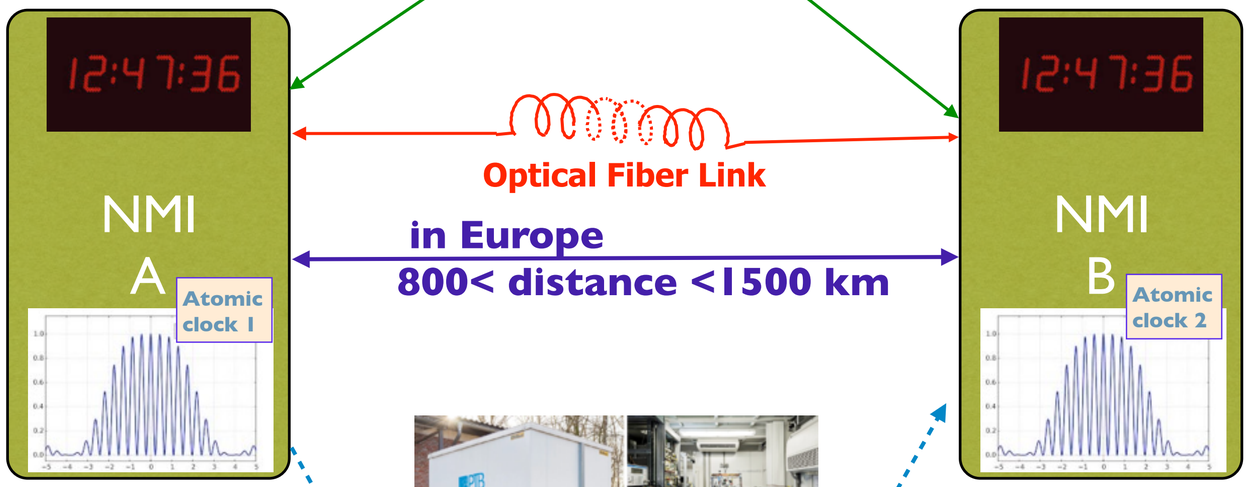
- Introduction to fiber links technology
- Some user-case examples
- REFIMEVE+ : an optical metrology network
- Towards EU research infrastructure
- Proposal in APOGEIA-II

Means to compare/disseminate clocks

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 $<10^{-16}$

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

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

Delay under control…

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

Propagation delay :

Remote measure +	Propagation model Celerity of the waves Spatial coordinates
Local measure +	Reciprocity

Principles

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
Pasadena, California 91109

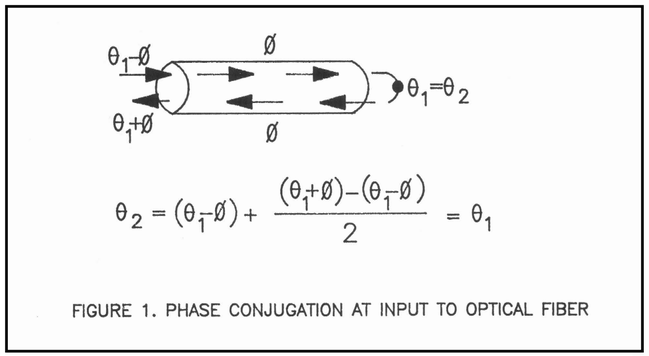


FIGURE 1. PHASE CONJUGATION AT INPUT TO OPTICAL FIBER

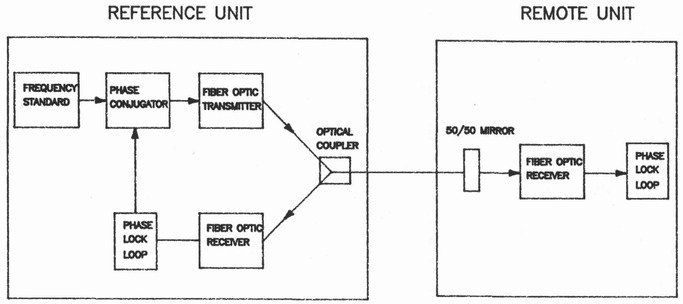
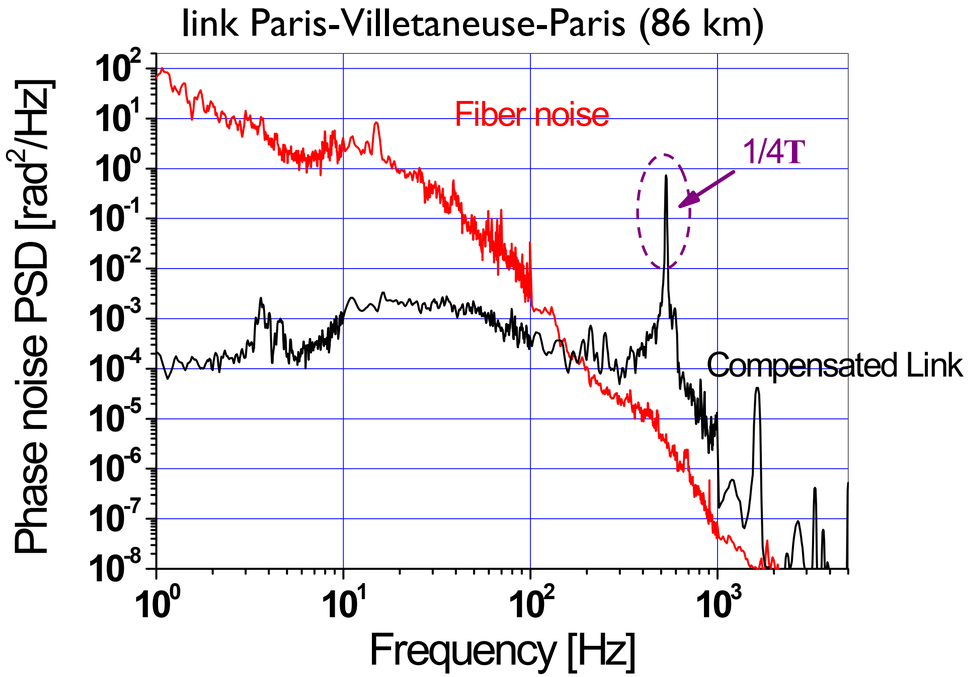


FIGURE 3. FIBER OPTIC FREQUENCY DISTRIBUTION SYSTEM

L. E. Primas *et al.*, Proc. 20th PTTI, Vienna, VA, 29 Nov - 1 Dec 1988(1988)

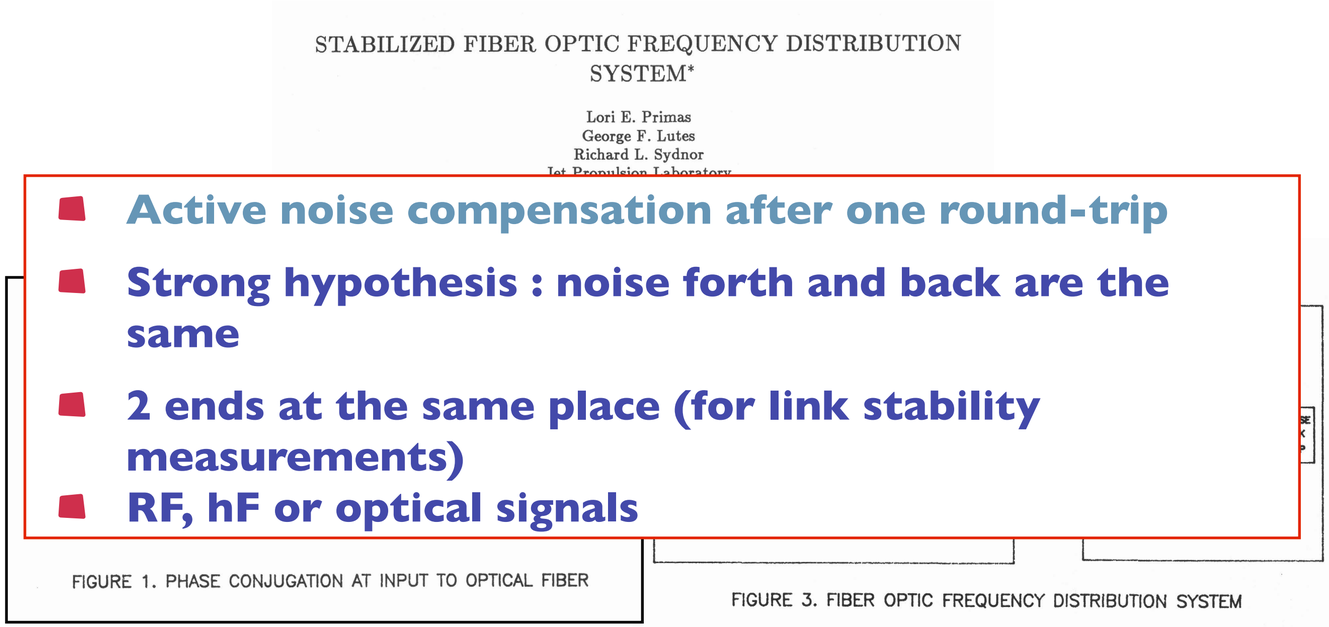


Classes of fiber links

- 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 the correlations)
- Analog or digital (affect the scalability)

Principles

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



STABILIZED FIBER OPTIC FREQUENCY DISTRIBUTION SYSTEM*

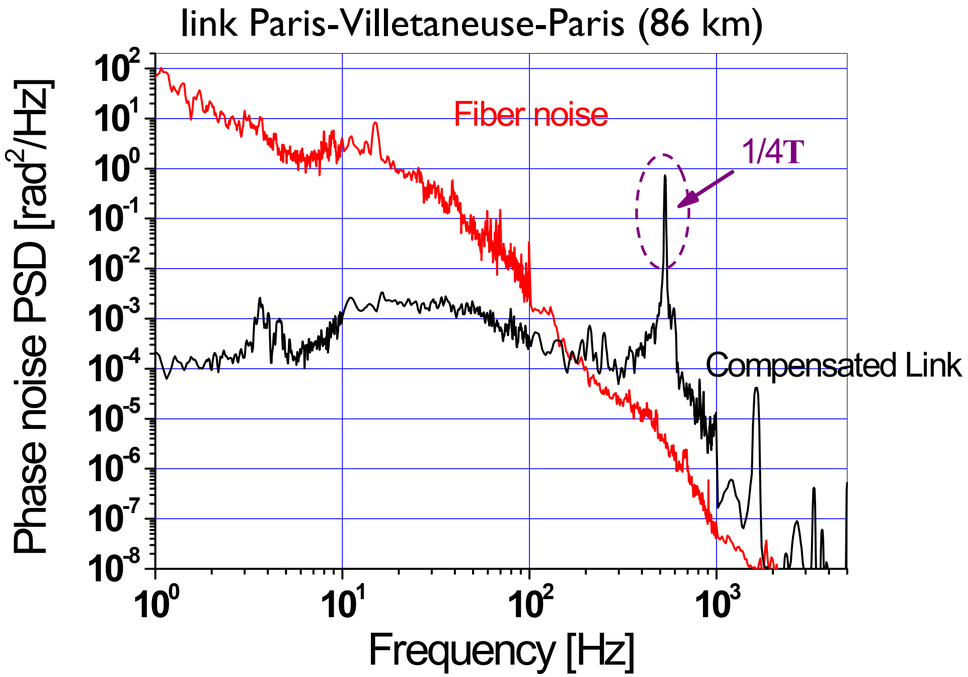
Lori E. Primas
George F. Lutes
Richard L. Sydnor
Jet Propulsion Laboratory

- **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**

FIGURE 1. PHASE CONJUGATION AT INPUT TO OPTICAL FIBER

FIGURE 3. FIBER OPTIC FREQUENCY DISTRIBUTION SYSTEM

L. E. Primas *et al.*, Proc. 20th PTTI, Vienna, VA, 29 Nov - 1 Dec 1988(1988)



Classes of fiber links

- Two-way : Stabilized / Post-processed
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- One way: Unstabilized (affects stability and accuracy)
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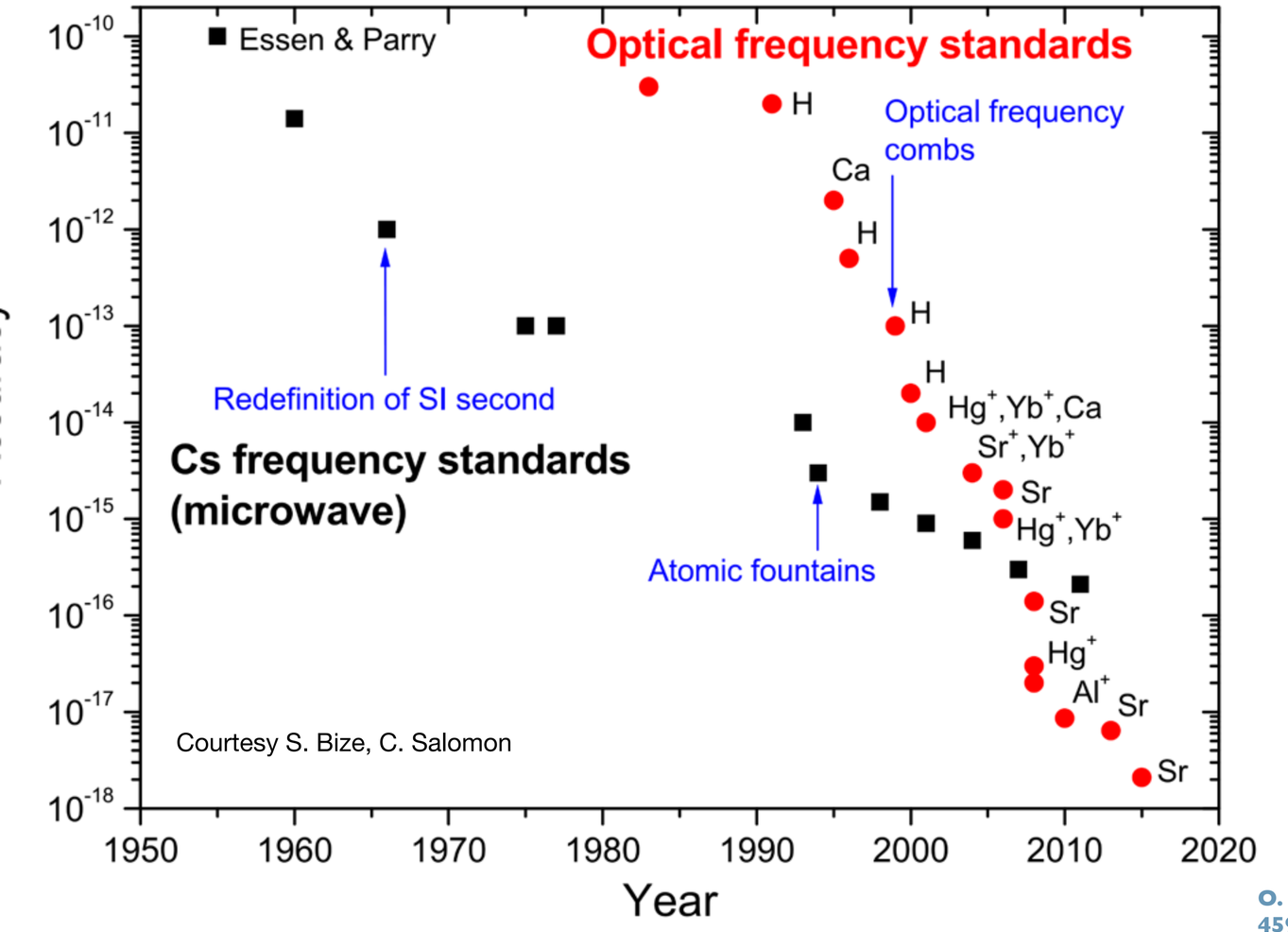
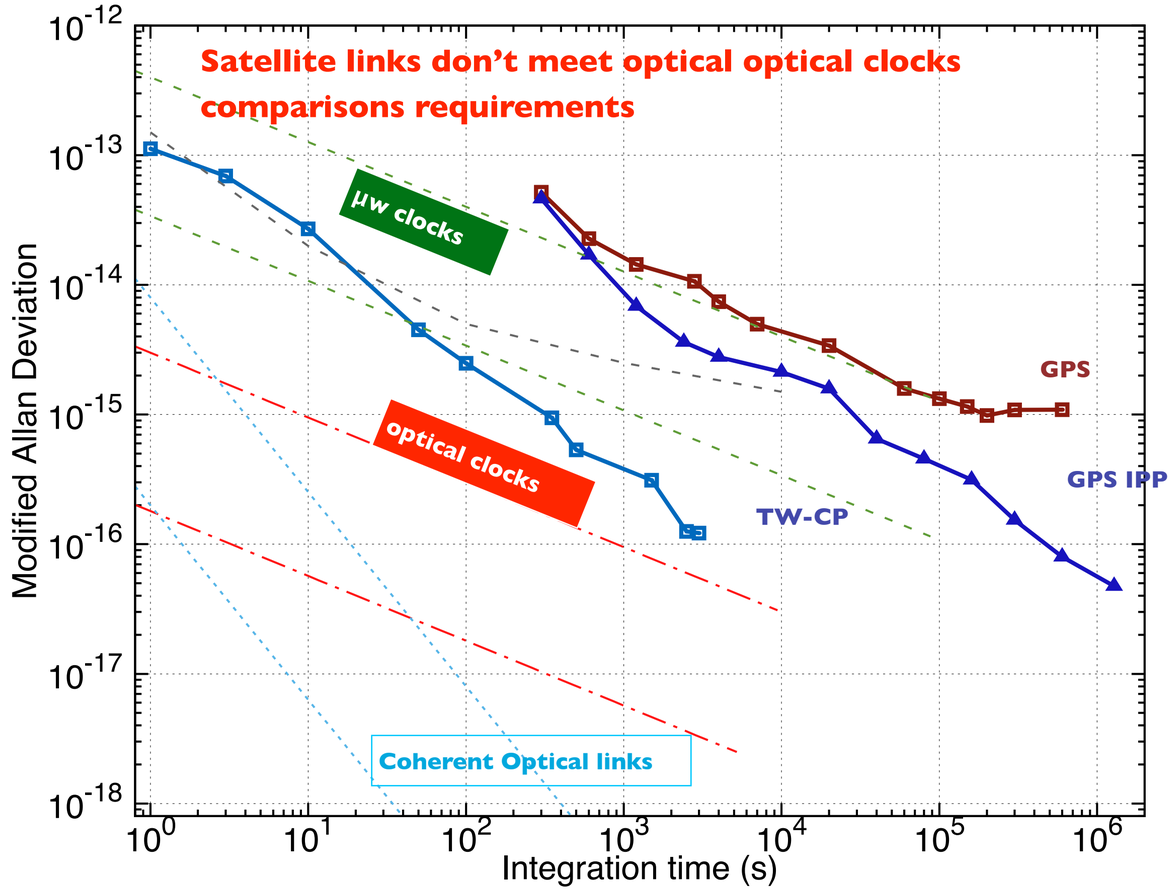
- Analog or digital (affect the scalability)

Performances

60 years of improvements…



30 years of improvements

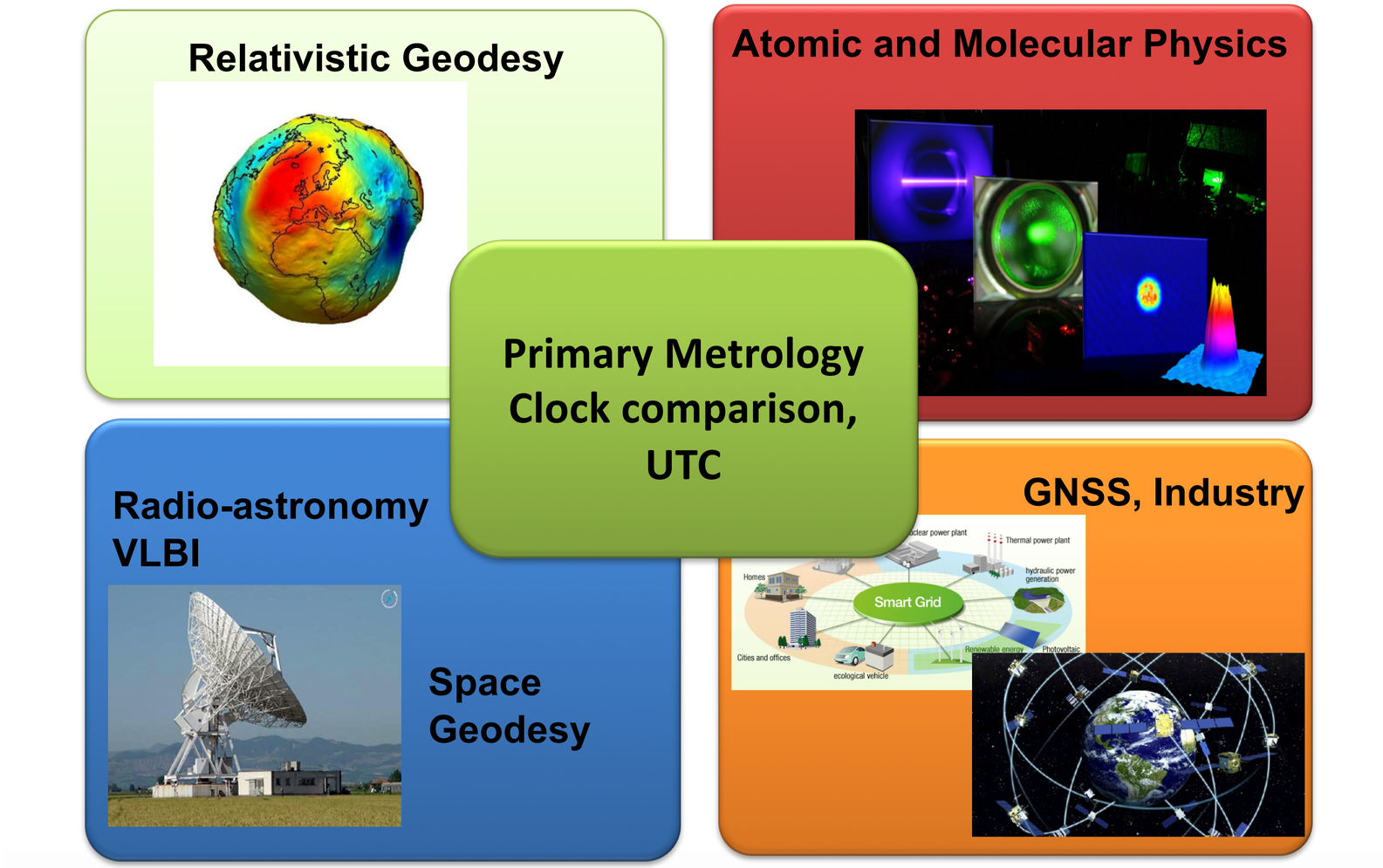


O. Lopez *et al.*, «F&T transfer for metrology and beyond (...)», Comptes Rendus Physique, 16 (5), pp. 459-586 (2015) (2015)

Applications area

Optical methods

RF+time methods



Courtesy of Davide Calonico (on behalf BIPM)

Scientific cases

PAPER · **OPEN ACCESS**

First international comparison of fountain primary frequency standards via a long distance optical fiber link

To cite this article: J Guéna *et al* 2017 *Metrologia* **54** 348

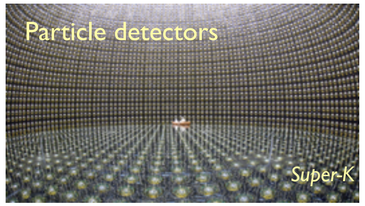
White Rabbit 'ecosystem'

SKA

CTA

Asterics
Astronomy ESFRI & Research Infrastructure Cluster

KM3Net



NEBuLA

ARTICLE

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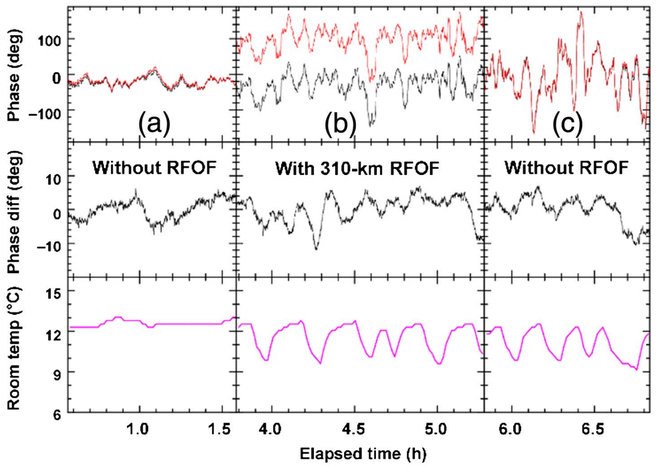
DOI: 10.1038/ncomms12443 OPEN

A clock network for geodesy and fundamental science

C. Lisdat[1], G. Grosche[1], N. Quintin[2], C. Shi[3], S.M.F. Raupach[1], C. Grebing[1], D. Nicolodi[3], F. Stefani[2,3], A. Al-Masoudi[1], S. Dörscher[1], S. Häfner[1], J.-L. Robyr[3], N. Chiodo[2], S. Bilicki[3], E. Bookjans[3], A. Koczwara[1], S. Koke[1], A. Kuhl[1], F. Wiotte[2], F. Meynadier[3], E. Camisard[4], M. Abgrall[3], M. Lours[3], T. Legero[1], H. Schnatz[1], U. Sterr[1], H. Denker[5], C. Chardonnet[2], Y. Le Coq[3], G. Santarelli[6], A. Amy-Klein[2], R. Le Targat[3], J. Lodewyck[3], O. Lopez[2] & P.-E. Pottie[3]

VLBI



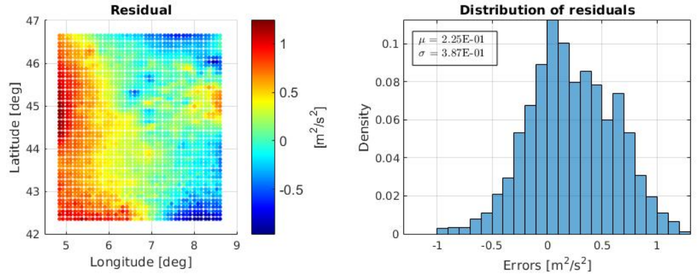
Y He et al., Optica, **5**, 138–146 (2018).

see also :
C. Clivati et al., IEEE Trans. on UFFC **62**, 1907–1912 (2015).

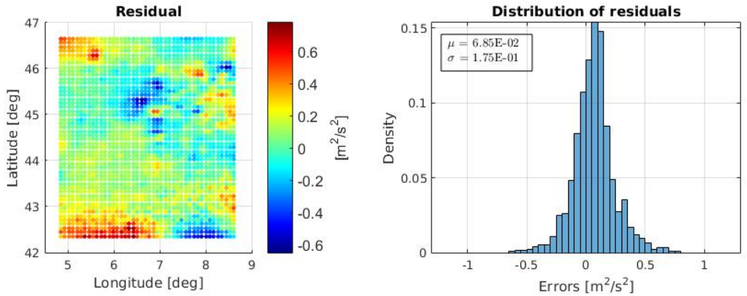
Determination of a high spatial resolution geopotential model using atomic clock comparisons

G. Lion*[1,2], I. Panet[2], P. Wolf[1], C. Guerlin[1,3], S. Bize[1] and P. Delva[1]

[1]LNE-SYRTE, Observatoire de Paris, PSL Research University, CNRS, Sorbonne Universités, UPMC Univ. Paris 06, 61 avenue de l'Observatoire, F-75014 Paris, France
[2]LASTIG LAREG, IGN, ENSG, Univ Paris Diderot, Sorbonne Paris Cité, 35 rue Hélène Brion, 75013 Paris, France
[3]Laboratoire Kastler Brossel, ENS-PSL Research University, CNRS, UPMC-Sorbonne Universités, Collège de France, 24 rue Lhomond, 75005 Paris, France



(a) Without clock data.

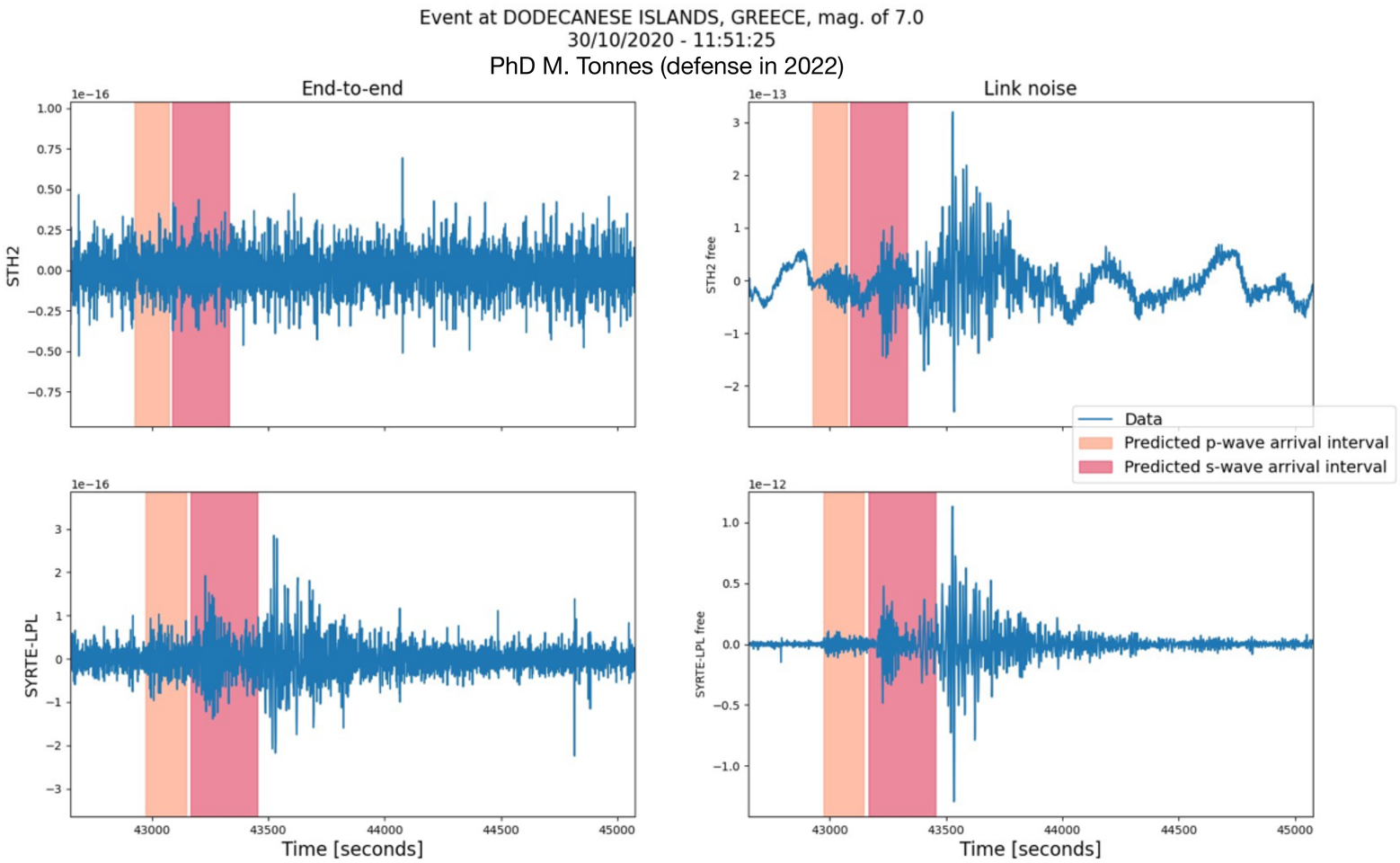


(b) With clock data.

see also :
T. E. Mehlstäubler et al., Atomic clocks for geodesy. Rep. Progress in Physics **81**, 064401 (2018).

Seismic detection

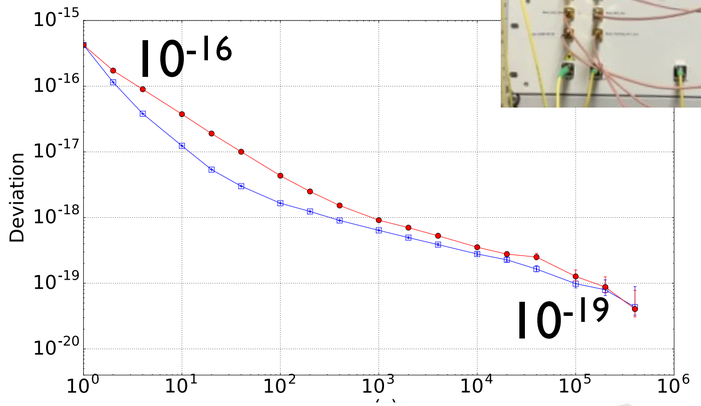
- Detection os seisms with fiber links
  - Acoustic noise seen in propagation delay fluctuation and residuals after compensation
  - Detection in a fiber network not yet done
- Determination of propagation velocities
- Localisation ? Early warning ?
- Optimal parameters :
  - Fiber length
  - Sampling rate
  - …
- Work under progresses at SYRTE and LPL…



see seminal work at INRIM and NPL: G.Marra *et al.* Science eaat4458 (2018) doi:10.1126/science.aat4458.

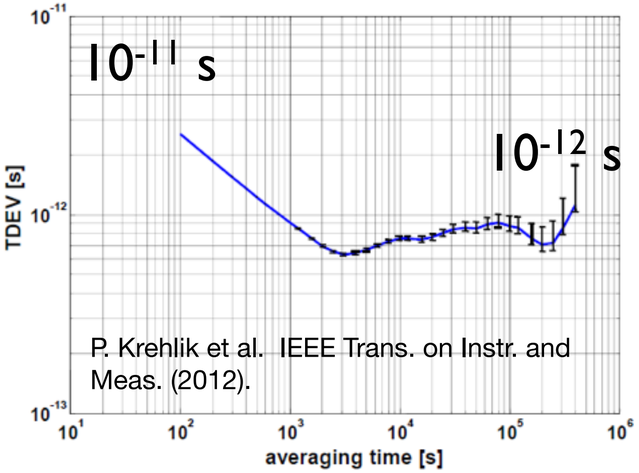
Technical solutions (non exhaustive)

optical carrier // Data

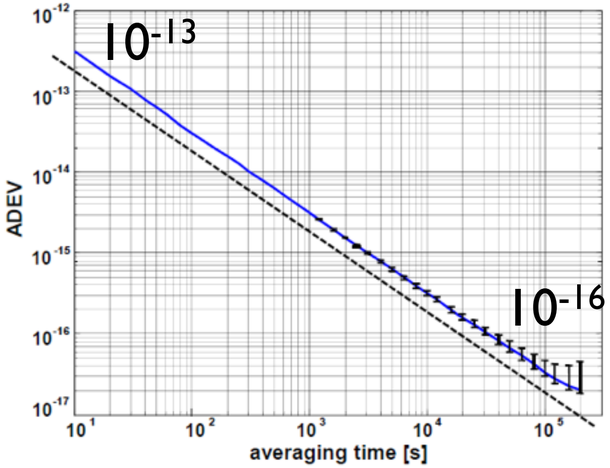


1Gb/s

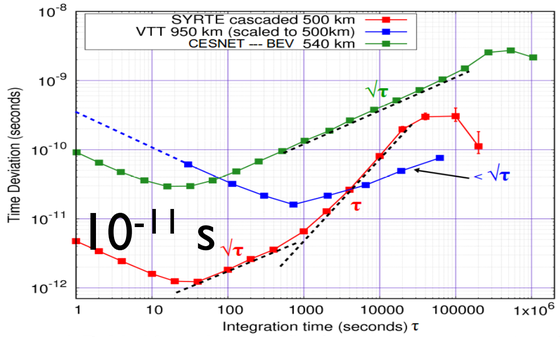
RF+time



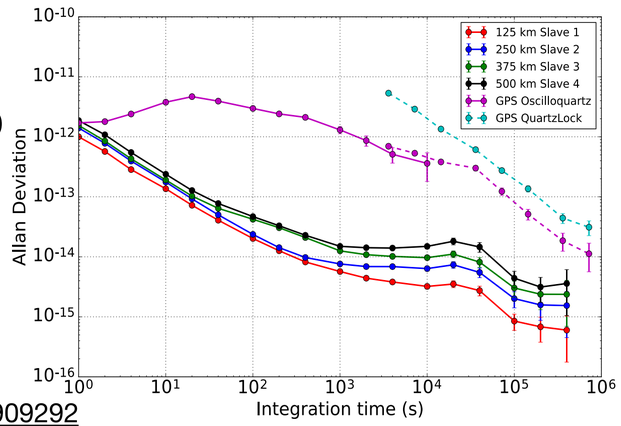
P. Krehlik et al. IEEE Trans. on Instr. and Meas. (2012).



RF+time+data



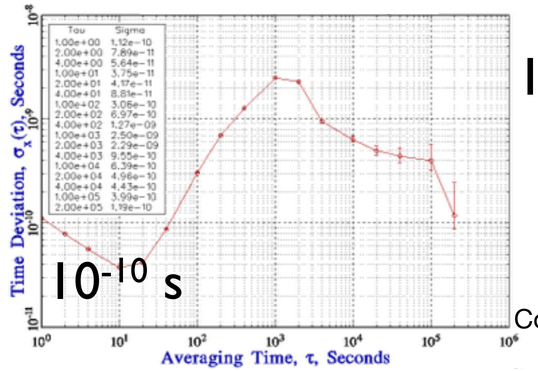
10-10



0-14

phD N. Kaur https://hal.archives-ouvertes.fr/tel-01909292

time+data



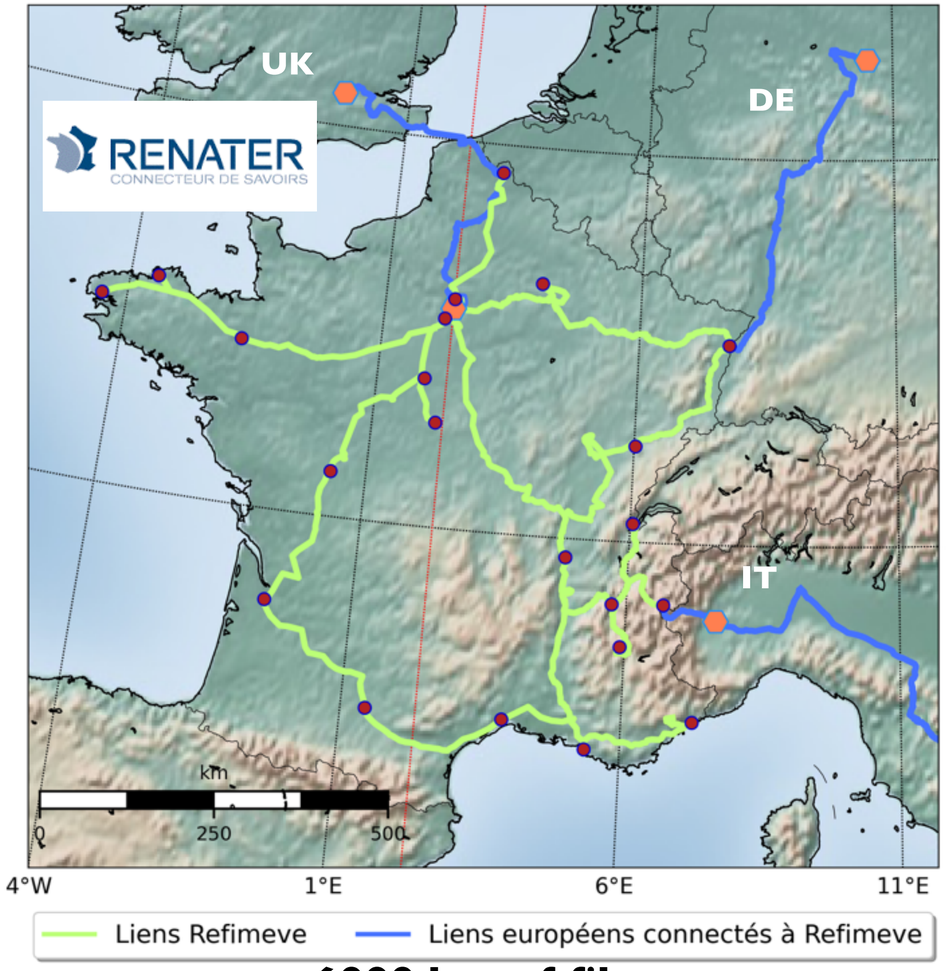
10-9 s

1-10Gb/s

Courtesy E. Laier-English (NPL)

REFIMEVE: REFIMEVE+ and T-REFIMEVE

Listed as National Research Infrastructure in 2021



~6000 km of fibers

~35 partners

Kernel

Industrials

Users

+FOTON, IRCICA, IEMN, SHOM, IJCLAB, LPNHE IRAM, ESRF, SOLEIL (CERN)

REFIMEVE: REFIMEVE+ and T-REFIMEVE

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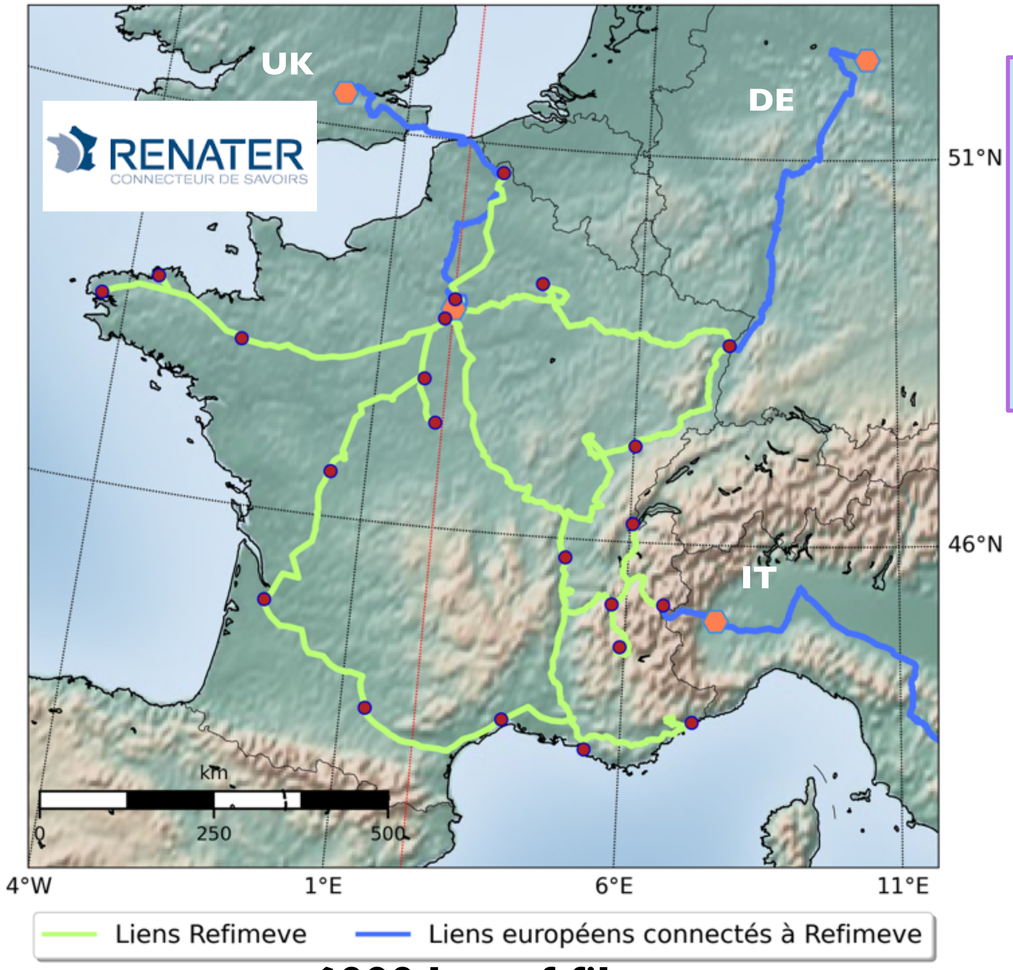


~6000 km of fibers

~35 partners

Collaboration with RENATER

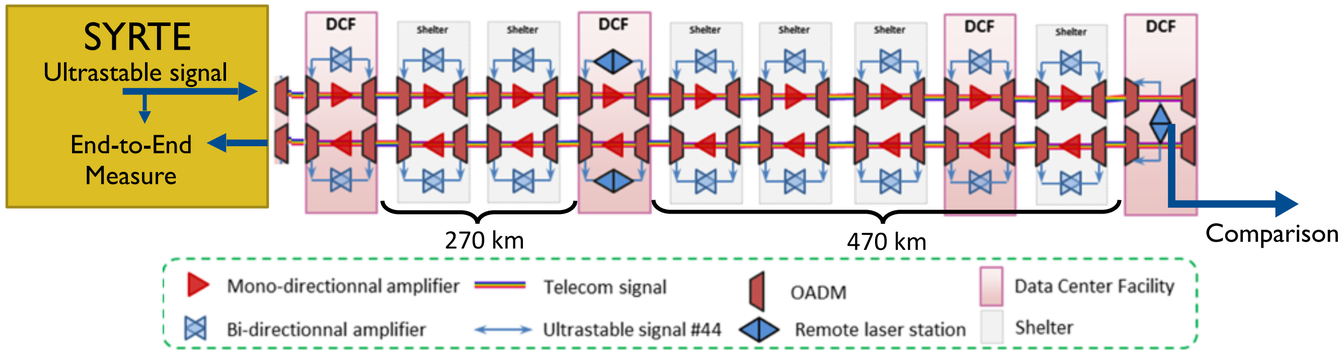
*Signal in **parallel of data traffic***

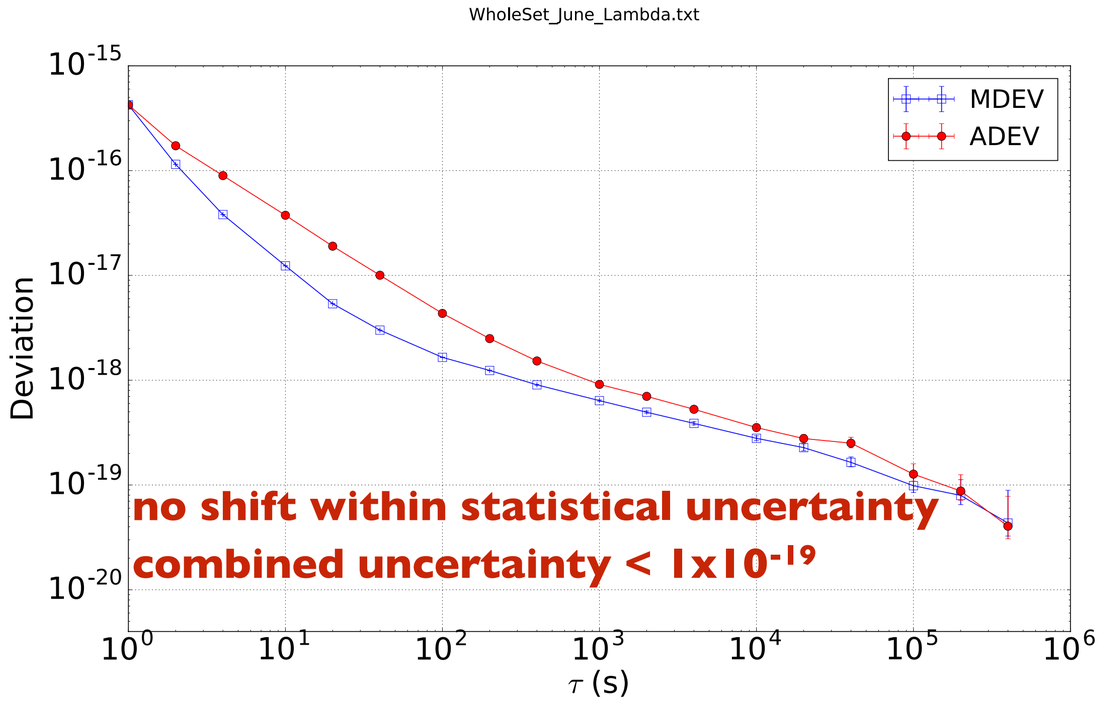
- **Sustainability**
  - Dedicated Fiber ≈ **200€ / km**
  - Fiber sharing : ≈ **cost / 10**
    - Supervision embedded in a **Network Operation Center**

Users

+FOTON, IRCICA, IEMN, SHOM, IJCLAB, LPNHE IRAM, ESRF, SOLEIL (CERN)

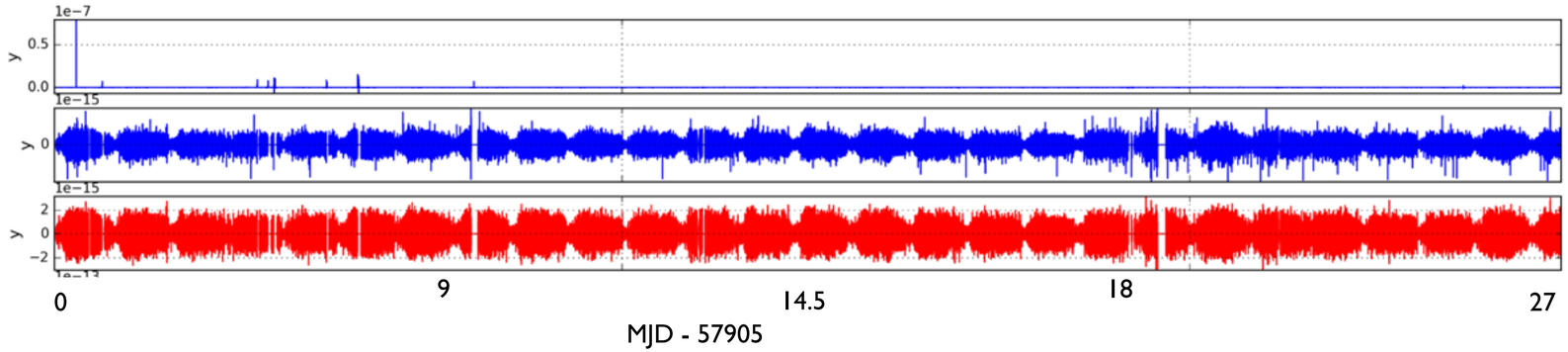
REFIMEVE+ : Performances over 1 month

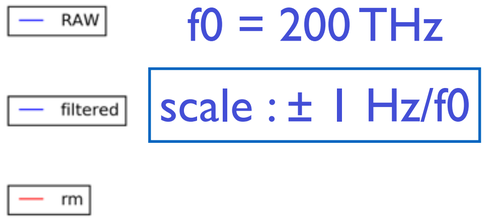




Link summary

- 2x205 dB attenuation
- Parallel data traffic
- 16 EDFA
- 32 OADM
- 5 Repeater laser stations
- ~ 1400 km



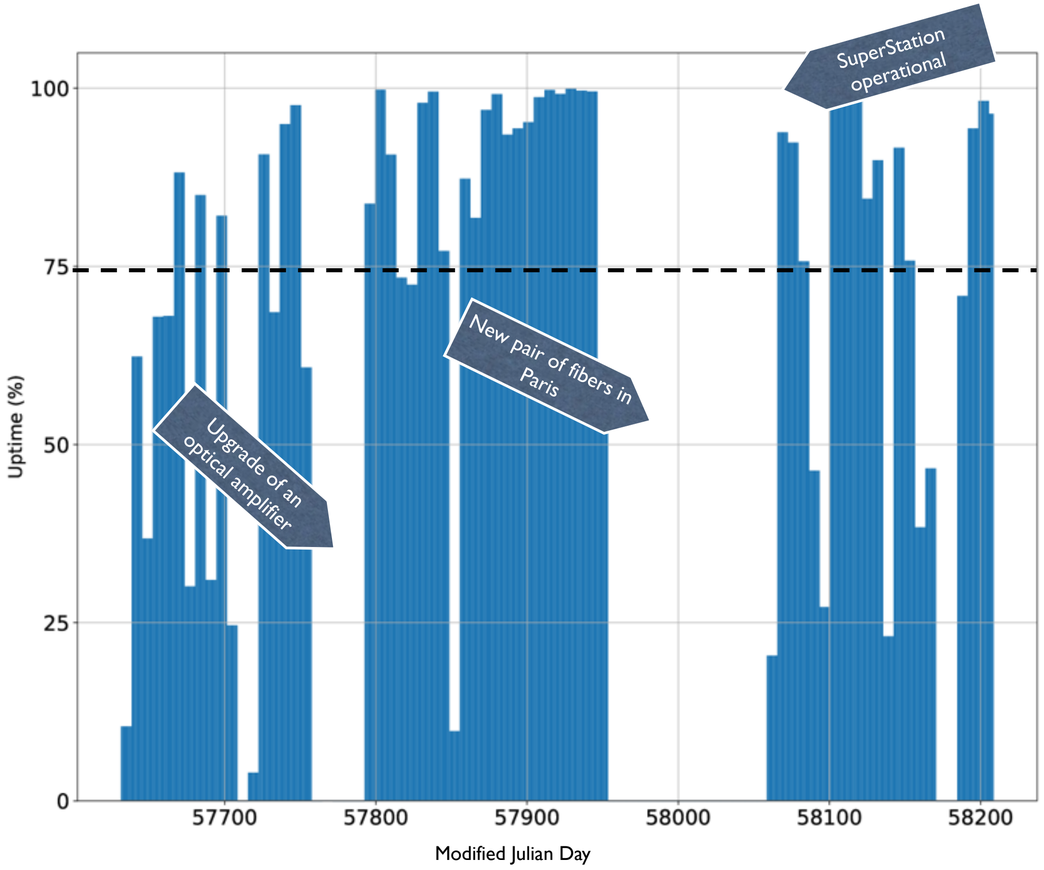


f0 = 200 THz

scale : ± 1 Hz/f0

REFIMEVE+ : uptime

Operation of a link / 19 months

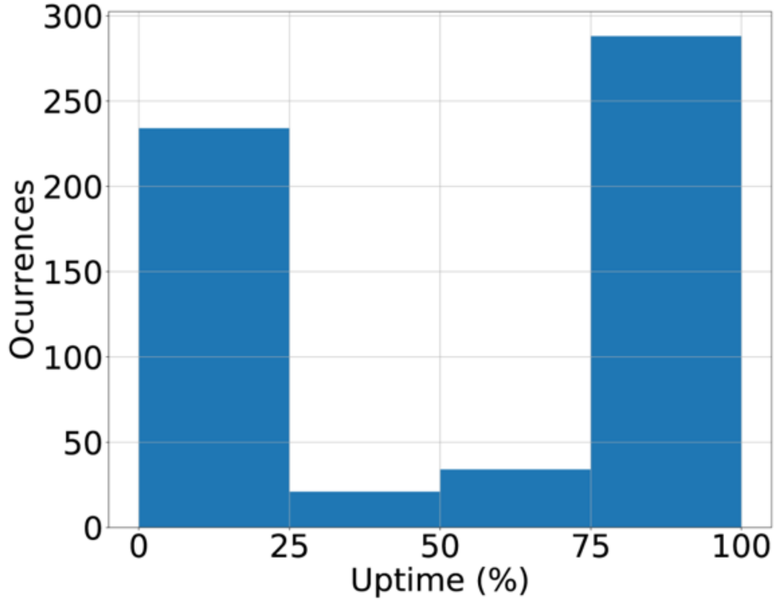


link Paris-Strasbourg-Paris

19 months = 576 days = 49'766'400s

- Total Uptime = 54.5%
- Selection criterium
  Frequency < 10 Hz = $5x10^{-14}$

- <u>All the system involved</u>
  (Ultra-stable Laser + Comb + Link)



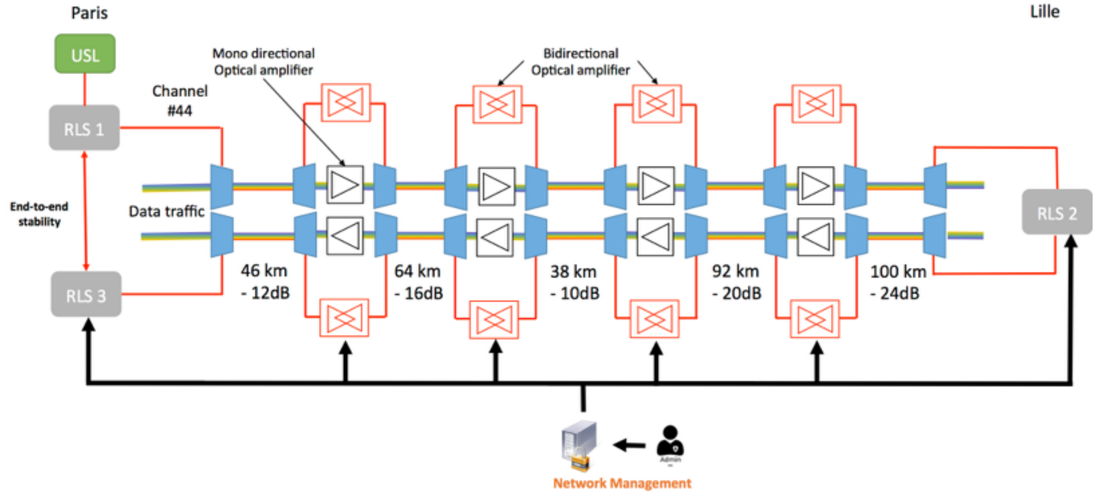
E.Cantin *et al.* New J. Phys. 23, 053027 (2021).

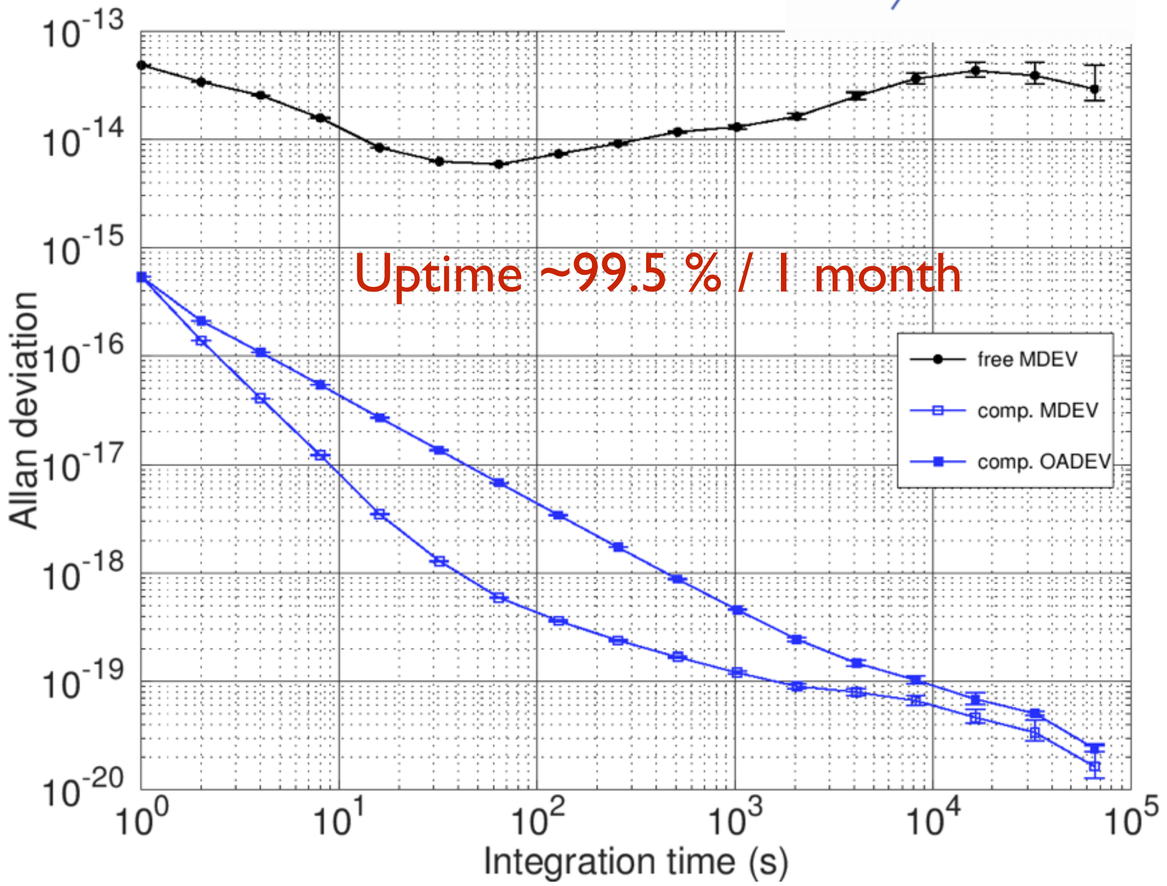
REFIMEVE+ : industrial partnership

Industrial grade fiber links

Link summary

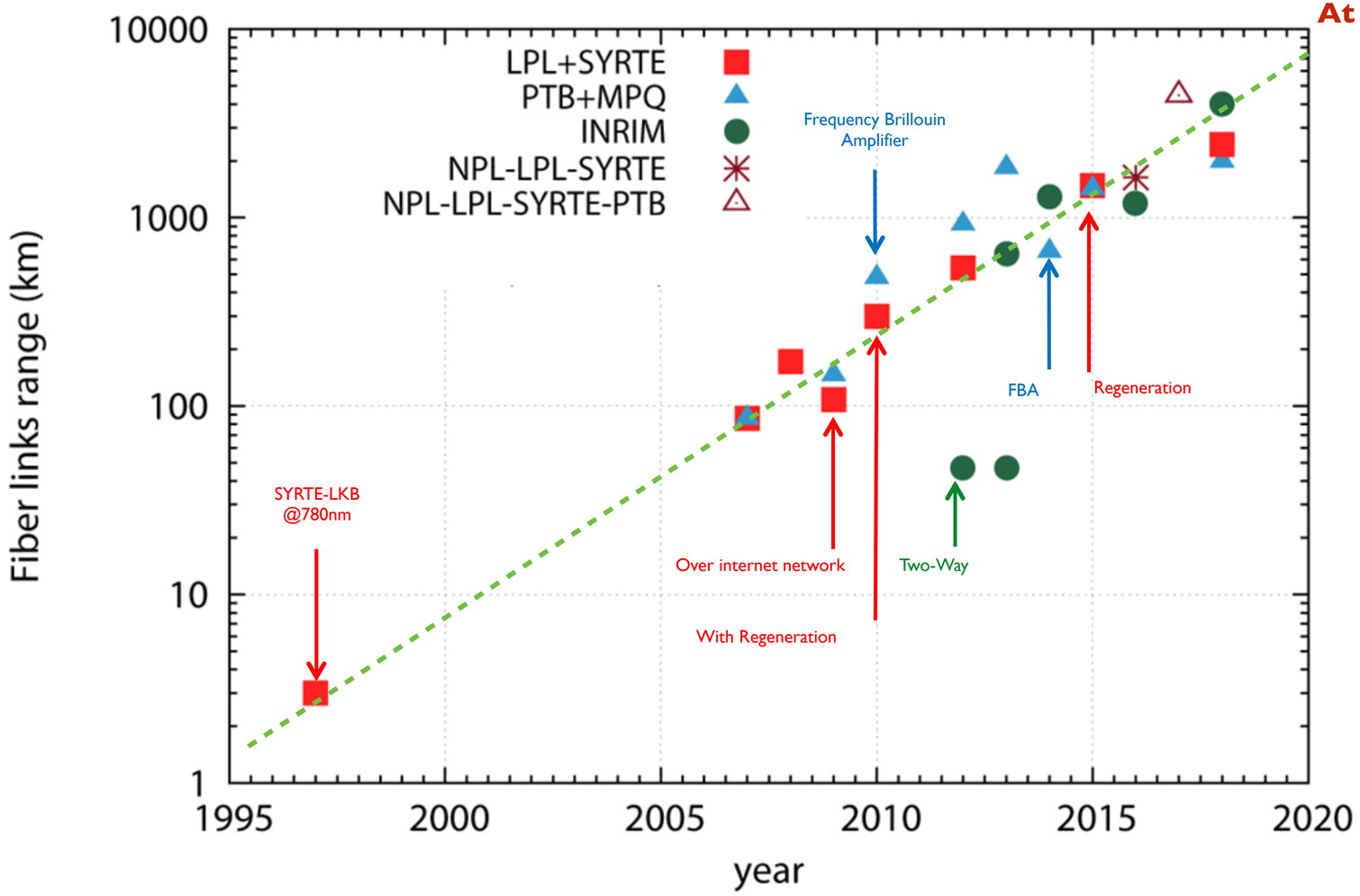
- 2x80 dB attenuation
- Parallel data traffic
- 10 EDFA
- 20 OADM
- 3 Repeater laser stations
- ~ 680 km





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

CLONETS : towards EU-Research Infrastructures



At horizon 2020 : 8000 km

https://www.clonets.eu/

https://clonets-ds.eu/

Towards a large research infrastructure ?

GÉANT
connect • communicate • collaborate

RENATER, CESNET, PSNC, GARR JISC/JANET, DFN, SURFNET, NORDUNET…

CLONETS : a paper study

https://www.clonets.eu/

16 partners from 3 areas

- Work with Network for Education and Research Industry to make the technology available
- Ways to access the network
- Compatibility with TelCo

Surveys and reviews

- 2 surveys, 1 market study : research infrastructures, industry, society…
- Technology reviews
  - T/F service parallel to data traffic
  - Guide for best practice
  - Emerging technologies

Current work

- Overall vision
- Strategic roadmaps
- Technology roadmaps

Project CLONETS involved 16 partners from 7 European countries. Partners represent 4 main areas:

- National Measurement Institutes: OBS PARIS (FR), NPL (UK), PTB (DE), INRIM (IT)
- National Research and Education Network: RENATER (FR), CESNET (CZ), PSNC (PL), GARR* (IT),
- Academic Laboratories: AGH (PL), UP13 (FR), UCL (UK), ISI (CZ), CNRS* (FR)
- Industrial: MUQUANS (FR), MENLO (DE), PIKTIME (PL), SEVEN SOL (SP), OPTOKON (CZ), TOP-IX* (IT)

* Third-party member

1 **FRANCE**
- OBSERVATOIRE DE PARIS
- GIP RENATER
- UNIVERSITE PARIS 13 - LPL
- MUQUANS
- CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE

2 **ITALY**
- INSTITUTO NAZIONALE DI RICERCA METROLOGICA
- CONSORTIUM GARR
- CONSORZIO TOP-IX

3 **GERMANY**
- PHYSIKALISCH-TECHNISCHE BUNDESANSTALT
- MENLO SYSTEMS GmbH

4 **UNITED KINGDOM**
- NPL MANAGEMENT LIMITED
- UNIVERSITY COLLEGE LONDON

5 **CZECH REPUBLIC**
- CESNET, z.s.p.o.
- USTAV PRISTROJOVE TECHNIKY AV CR, v.v.i.
- OPTOKON

6 **POLAND**
- POZNANSKIE CENTRUM SUPERKOMPUTEROWO-SIECIOWE
- PIKTIME SYSTEMS sp. z o. o.
- AKADEMIA GORNICZO-HUTNICZA IM. STANISLAWA STASZICA W KRAKOWIE

7 **SPAIN**
- SEVEN SOLUTIONS S.L.

Proposal in APOGEIA

- A1: Noise compensation <-> Noise understanding
  - Link to WP Fiber (DAS): How DAS and T/F can help each other
  - Specific case of undersea fibers: Mediterranean see, Atlantic ocean
- A2: Synchronisation and syntonisation to observatory for multi-messenger astronomy
- A3: Array of quantum networks (clocks, absolute gravimeters): spatial and temporal variation of gravity
  - Proof of principle at SYRTE: Common reference for two distant AQG
  - Implementation at Laboratoire Souterrain de Madone (AQG, +clocks +.. ?)
  - Benefit of Mobile Platform (REFIMEVE), transportable clocks, transportable absolute gravimeter.
  - Link to WP underground, Gravi and Clocks

Outlook

- Fiber links : a new technology for T/F transfer
  - Beyond GNSS solutions : 1e-15@1s to 1e-19@1day
  - Complement GNSS solutions
- REFIMEVE+ : fully optical metrological network https://www.refimeve.fr
  - Optical reference signal disseminated in France
  - Partnership with RENATER (NREN) and industrial consortium
  - Deployment is still under way
- Towards EU research infrastructure building a clock service

https://www.clonets-ds.eu/

Thank you for your attention

A non-exhaustive review:

Hyper-frequency:

O. Lopez, et al. Applied Physics B **98**, 723–727 (2010).
F. Yin, F. et al. Optics Express 22, 878 (2014).
X. Chen, X. et al. Optics Letters 40, 371 (2015).
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Radio-frequency:

C. Daussy et al. Physical Review Letters **94**, (2005).
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M. Fujieda et al., IEEE T-IM **58**, 1223–1228 (2009).
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