Réseaux de fibres optiques terrestres ou sous-marins : Applications géodésiques

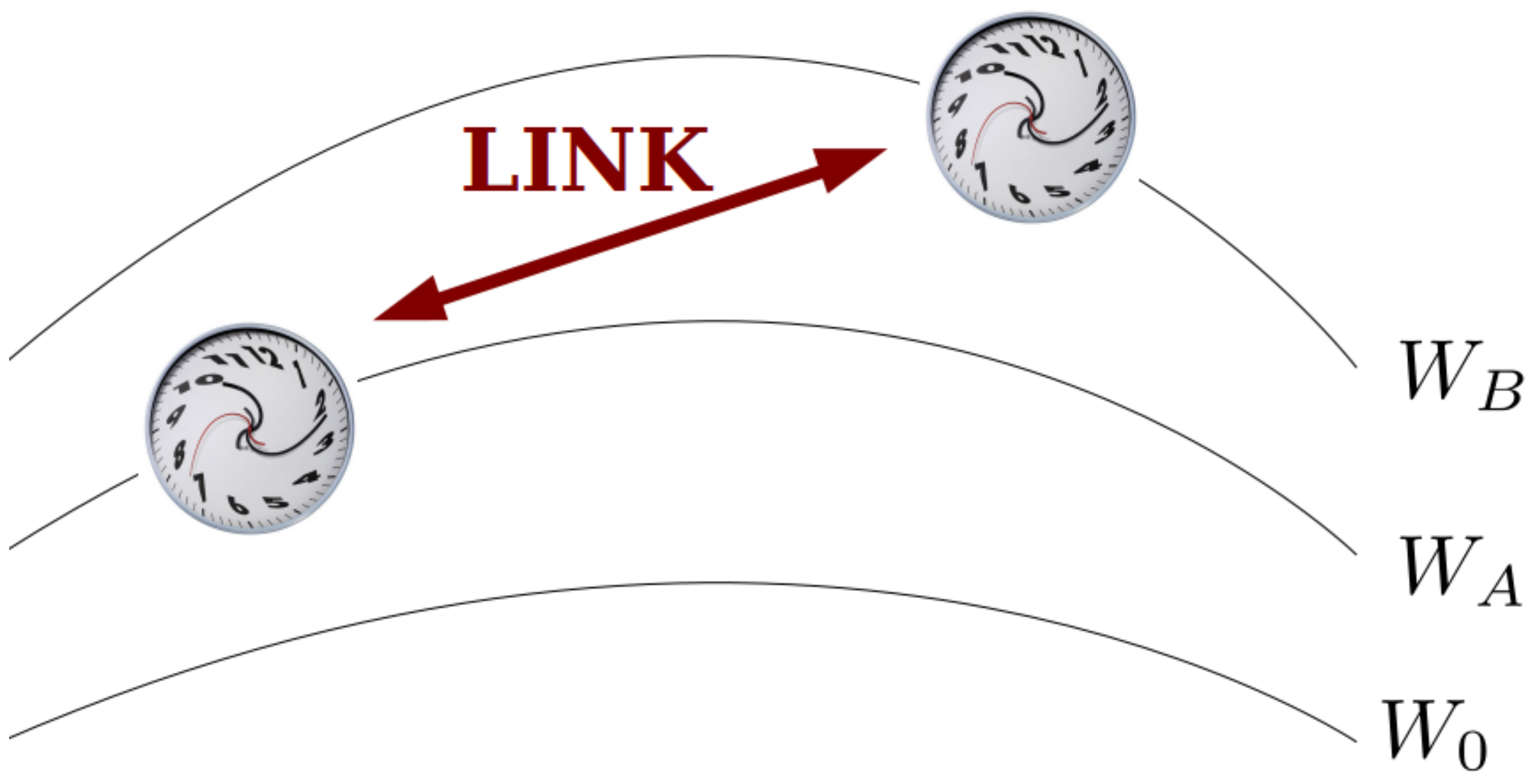
P.-E. Pottie

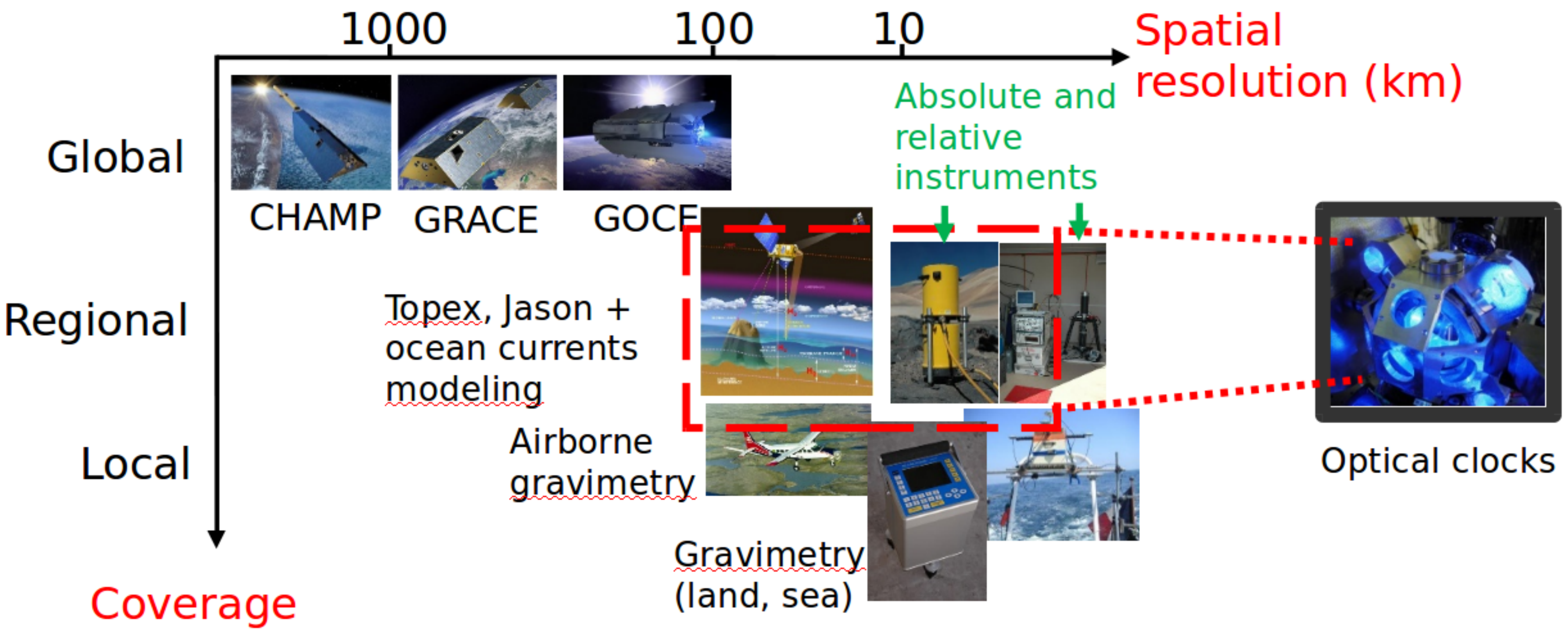
Contents

Chronometric levelling

- Clock rate, when compared to coordinate time, depends on the velocity of the clock and on the space-time metric (which depends on the mass/energy distribution).
- Accuracy of optical clocks starts to be competitive with classical methods: up to a few centimeters for the static potential at high spatial resolution
- Possibilities for technical realisation of a system for measuring potential differences over intercontinental distances using clock comparisons

Gravitational shift ~10^{-16} /m

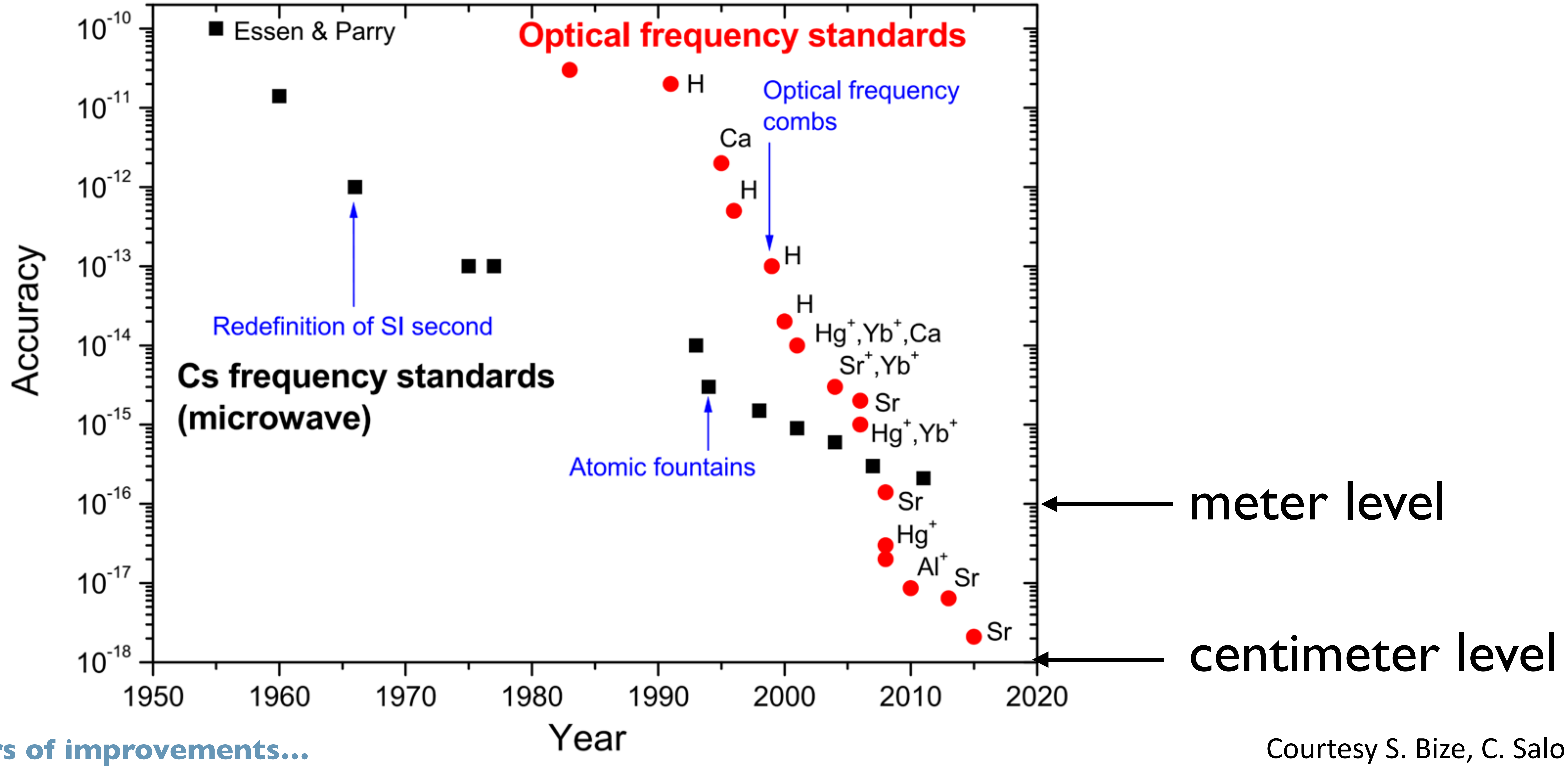




Vermeer, M. (1983). Chronometric Levelling. Finnish Geodetic Institute, Helsinki.
Bjerhammar, A. (1985). Bull. Geodesique 59.3, pp. 207–220. doi: 10.1007/BF02520327.

Courtesy Pacome Delva

Clock performances



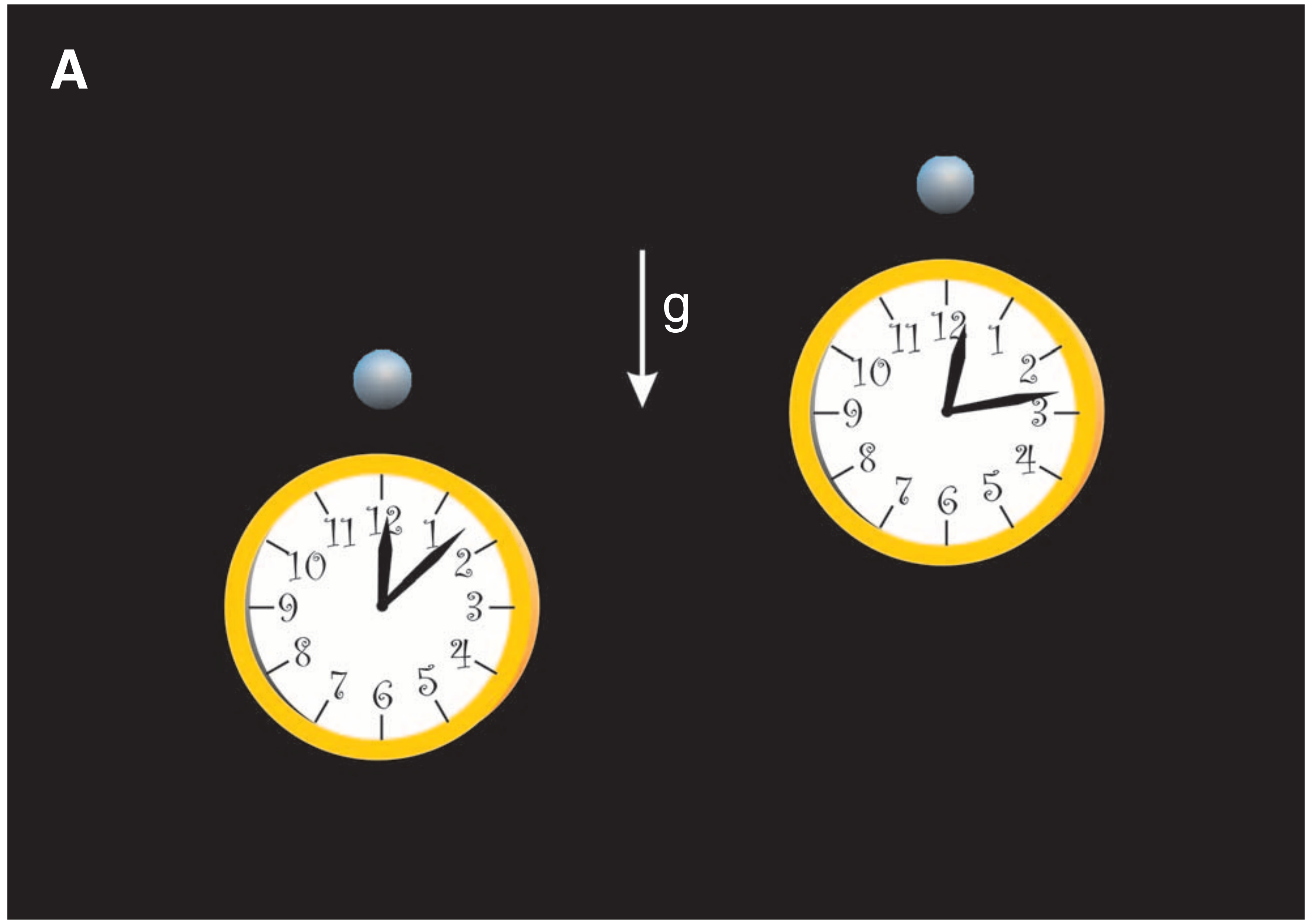
70 years of improvements…

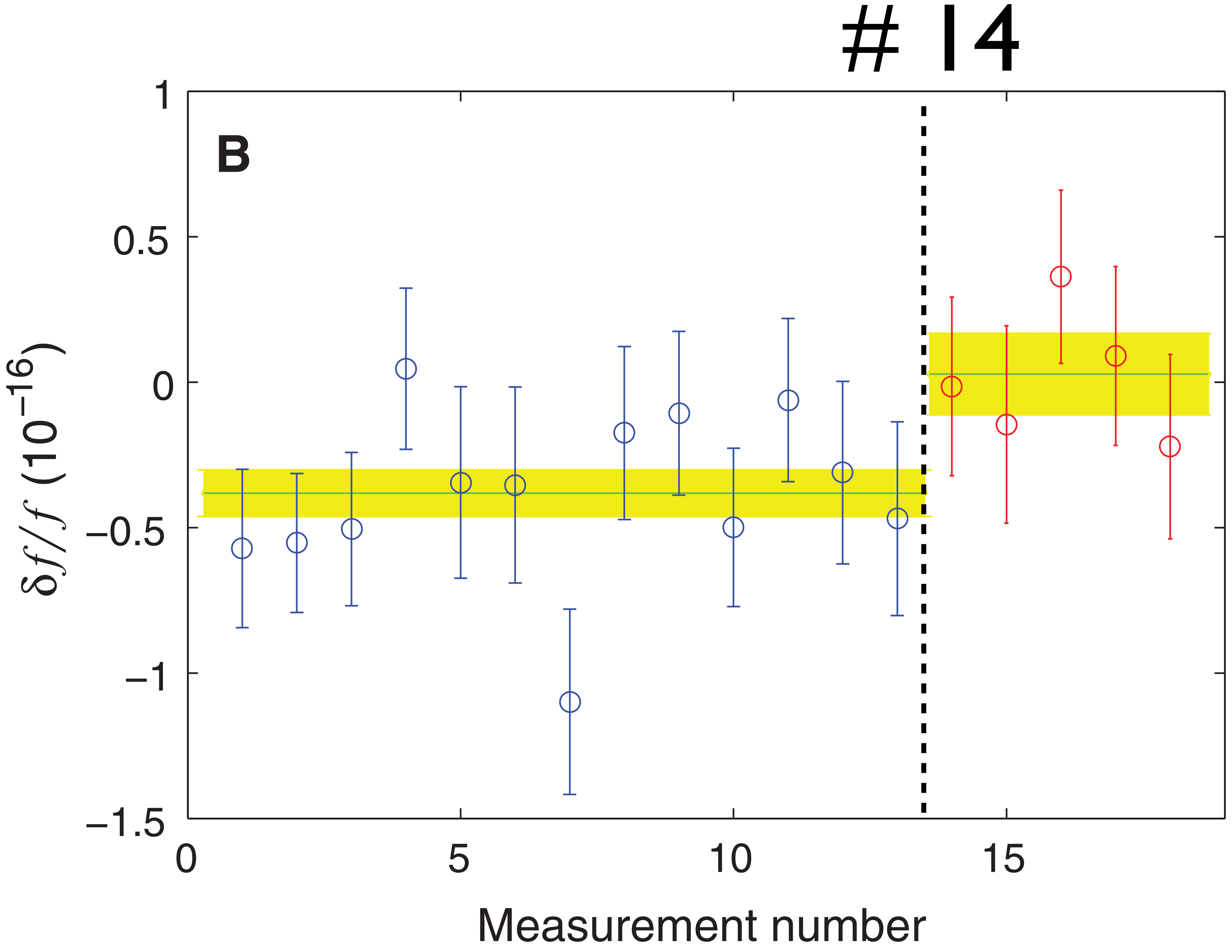
Courtesy S. Bize, C. Salomon

Local clock comparison

NIST

- Experimental demonstration of the dependency of clock frequency with local height with two Al+ optical clocks
- Starting at data point 14, one of the clock is elevated by 33 cm.
- The net relative shift is measured to be $(41 \pm 16) \times 10^{-18}$.

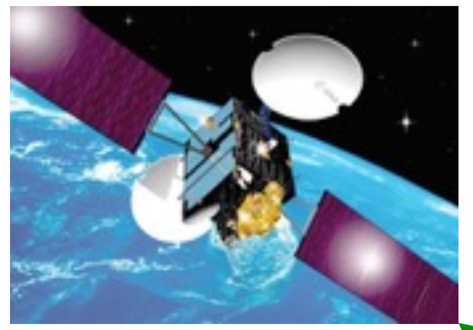




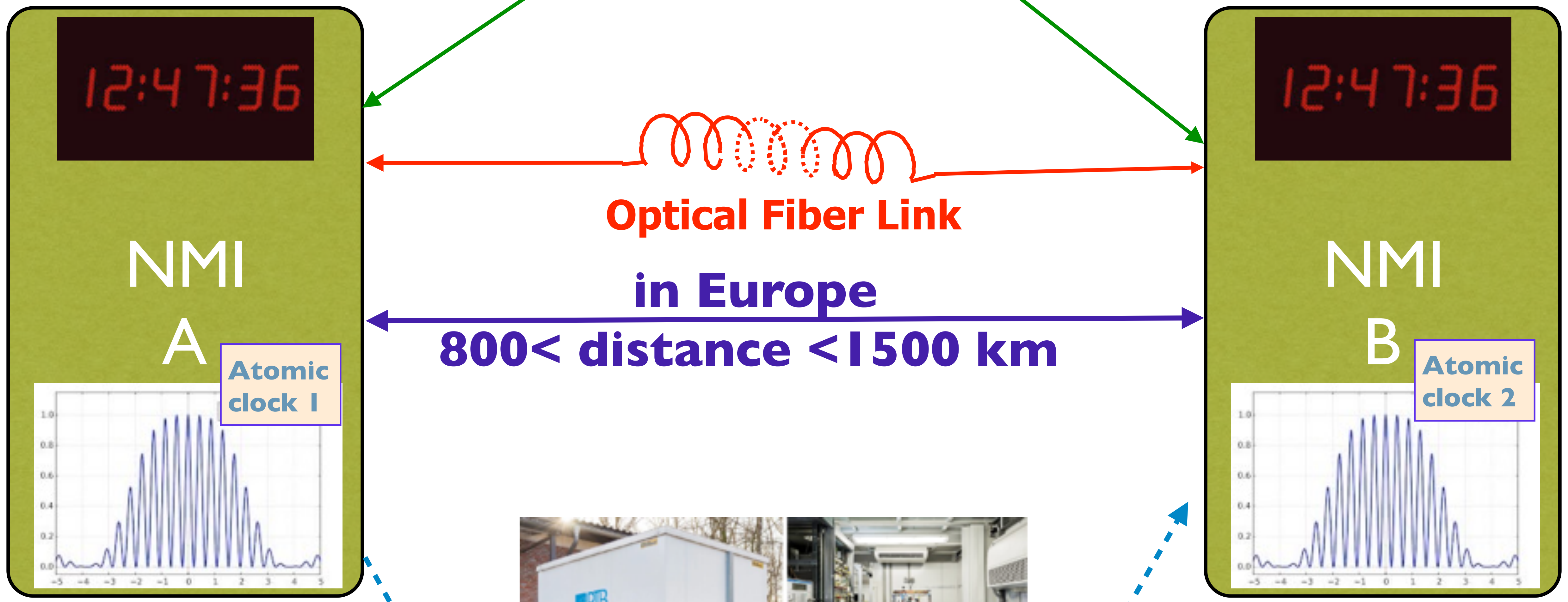
I.Chou *et al.*, Science 329, 5 (2010)

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)

Delay under control…

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

Measuring the propagation delay :

Remote measure + Propagation model, Celerity of the waves, Spatial coordinates

Local measure + path reciprocity

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
Pasadena, California 91109

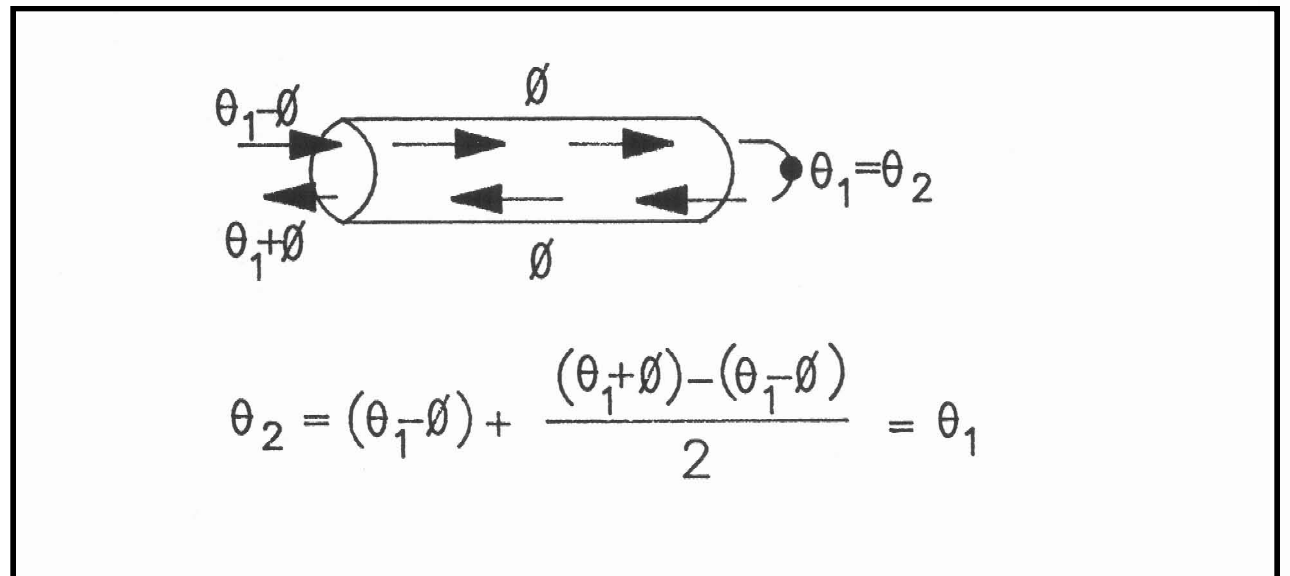


FIGURE 1. PHASE CONJUGATION AT INPUT TO OPTICAL FIBER

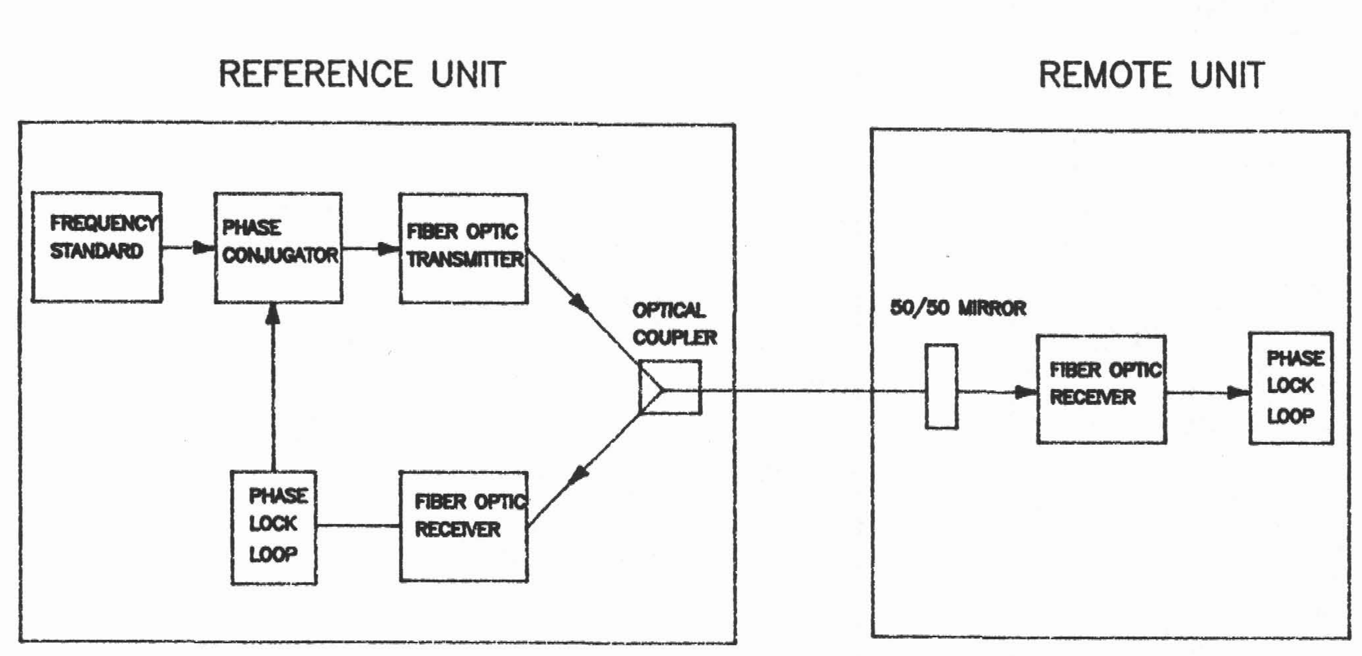
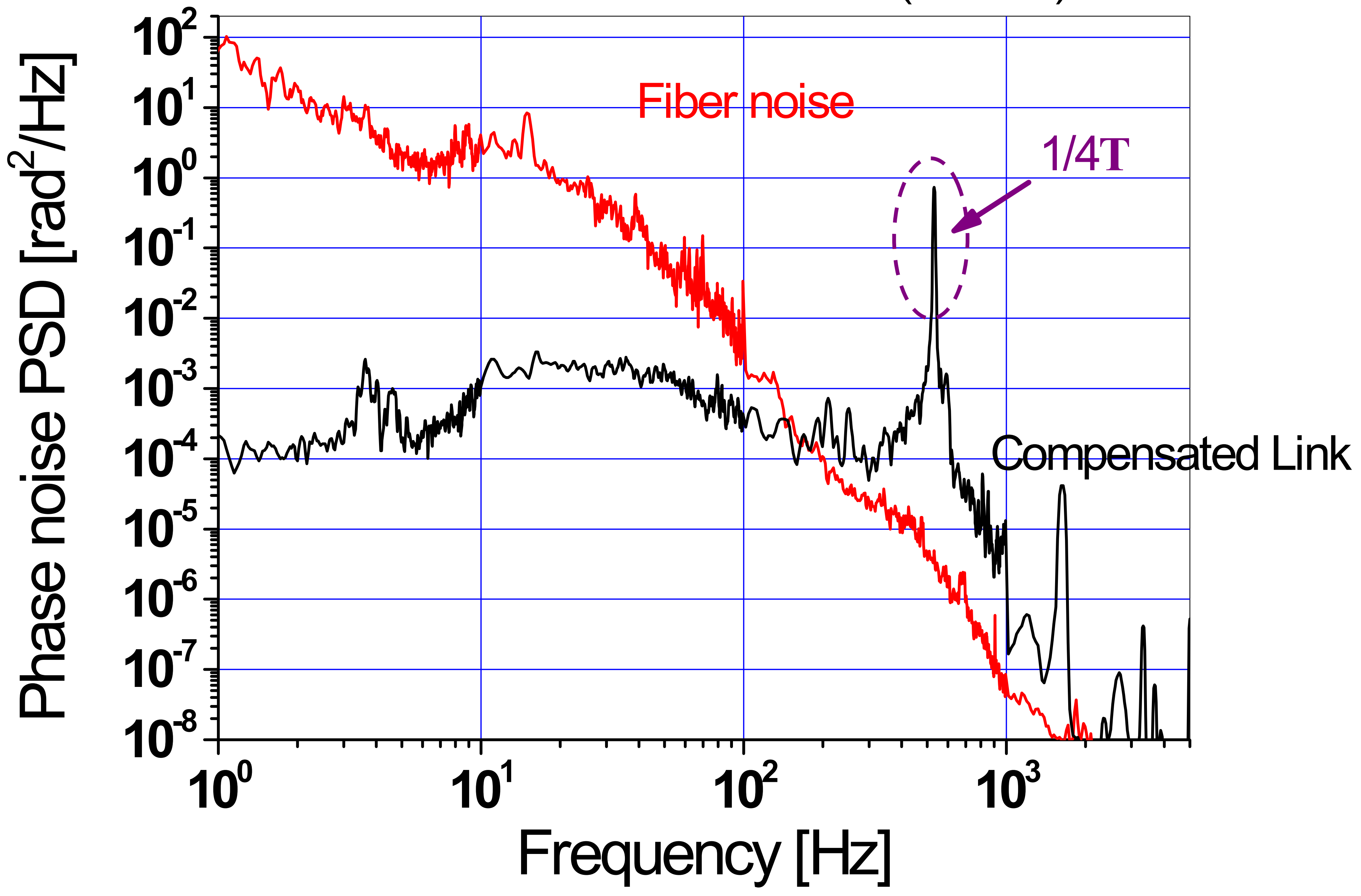


FIGURE 3. FIBER OPTIC FREQUENCY DISTRIBUTION SYSTEM

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

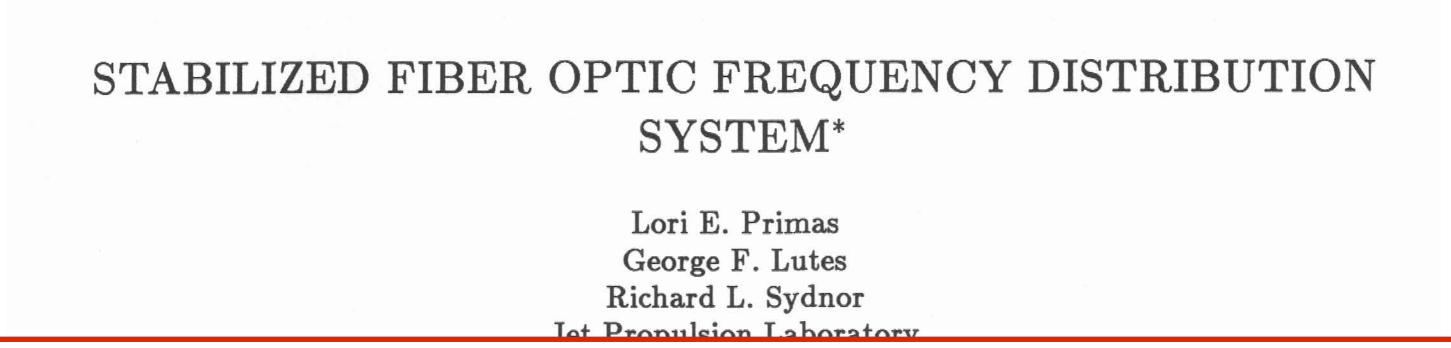


Classes of fiber links

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

Principles of operation of fiber links

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



STABILIZED FIBER OPTIC FREQUENCY DISTRIBUTION SYSTEM*

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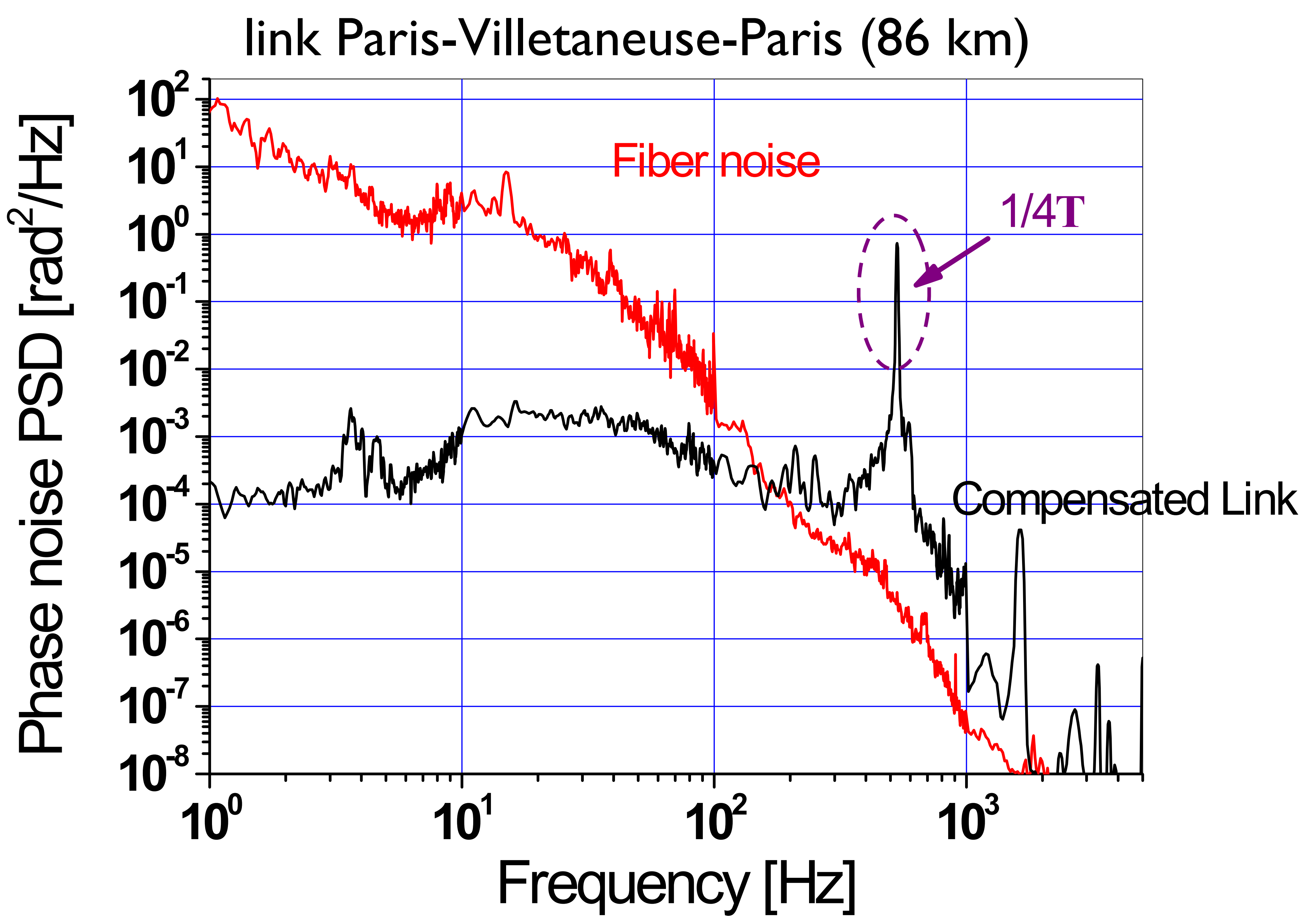
- **Active noise compensation after one round-trip**
- **Strong hypothesis : noise forth and back are the same**
- **2 ends at the same place (for link stability measurements)**
- **RF, hF or optical signals**
- **Technical challenges:**
  - **Long haul : more noise, less signal…**
  - **Automation,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



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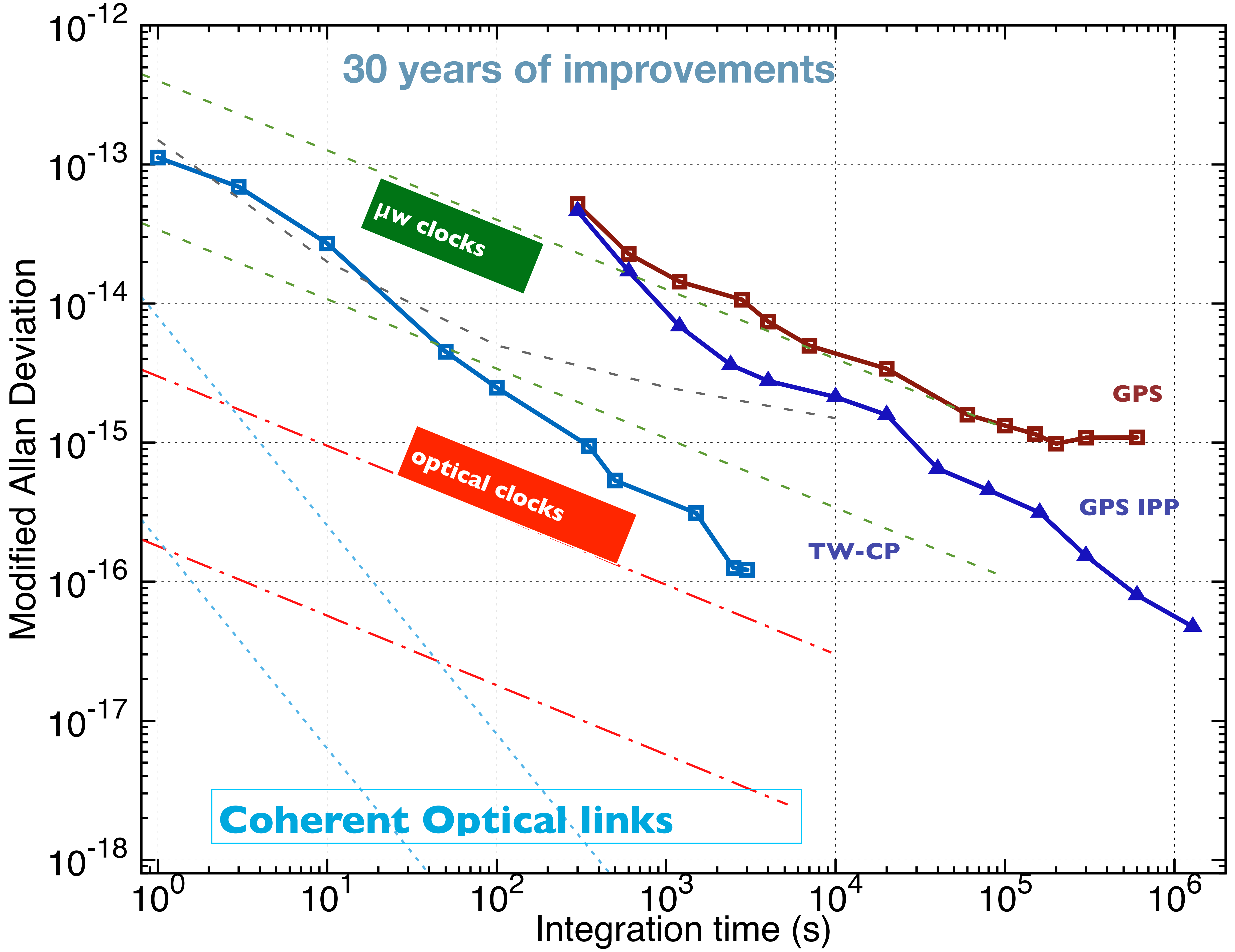
Performances of means of comparison



Satellite links don't meet optical optical clocks comparisons requirements

Coherent Optical links:

- Frequency comparison with inaccuracy ~10^{-19}
- Range ~ a few 1000 km
- >10 years of development
  - Matured technology
  - **knowledge transfer to industry mostly done**
  - **Commercially available**

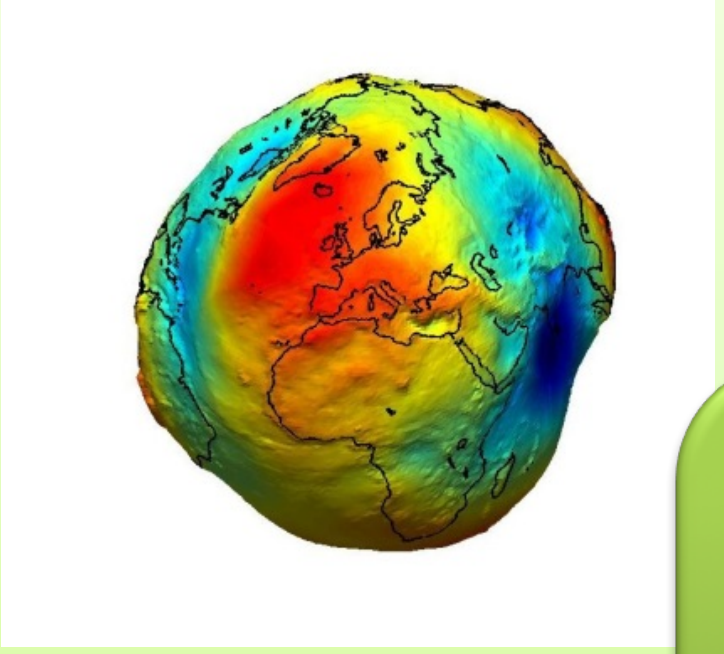
O. Lopez *et al.*, Comptes Rendus Physique, 16 (5), pp. 459-586 (2015) (2015)

Applications area

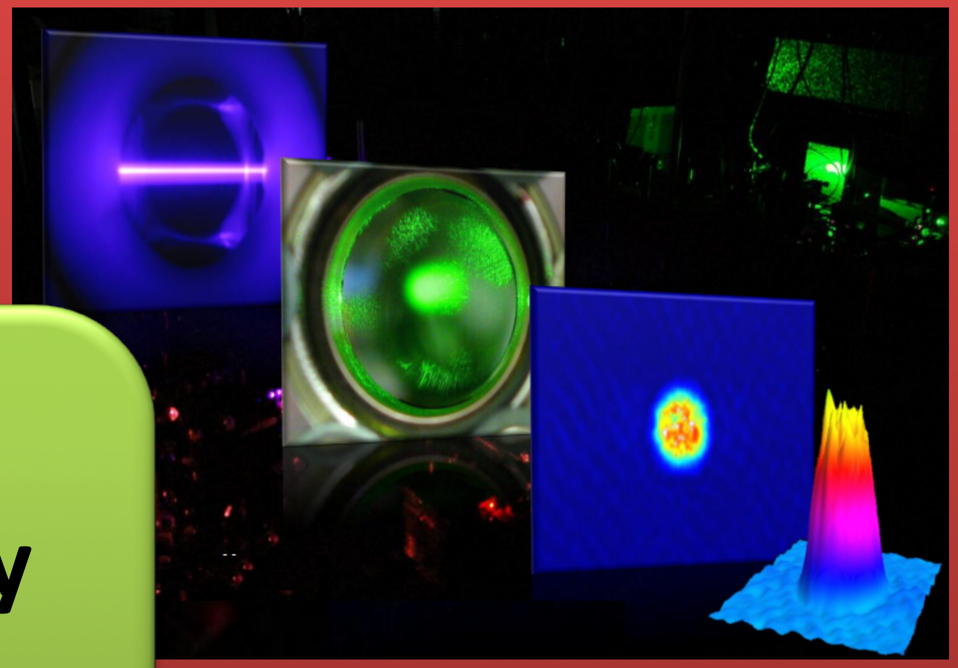
Optical methods

RF+time methods

Relativistic Geodesy



Atomic and Molecular Physics

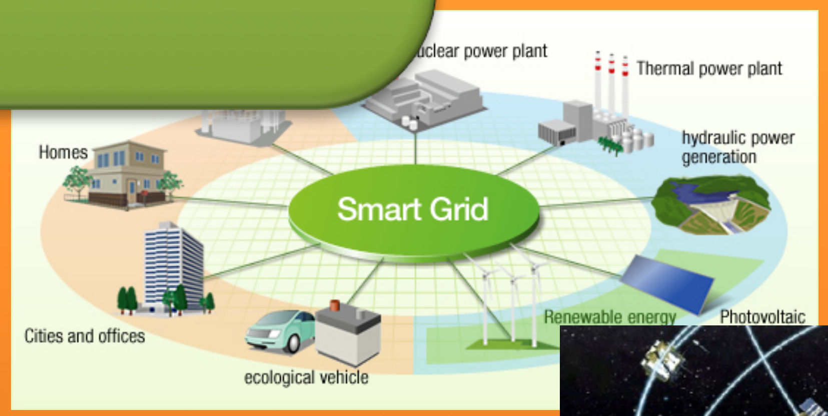


Primary Metrology Clock comparison, UTC

Radio-astronomy VLBI

Space Geodesy

GNSS, Industry

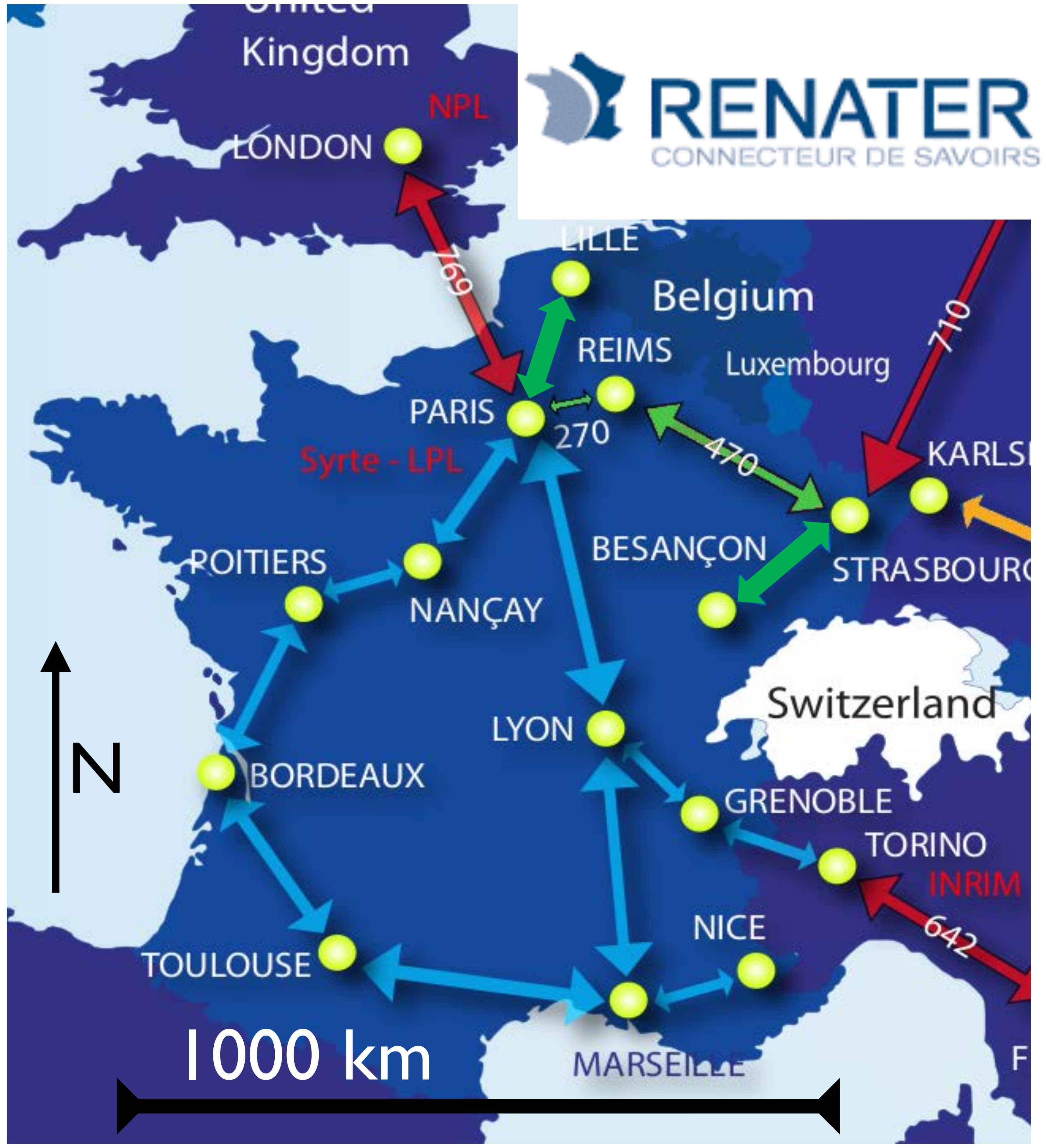


this talk now focus on optical frequency transfer

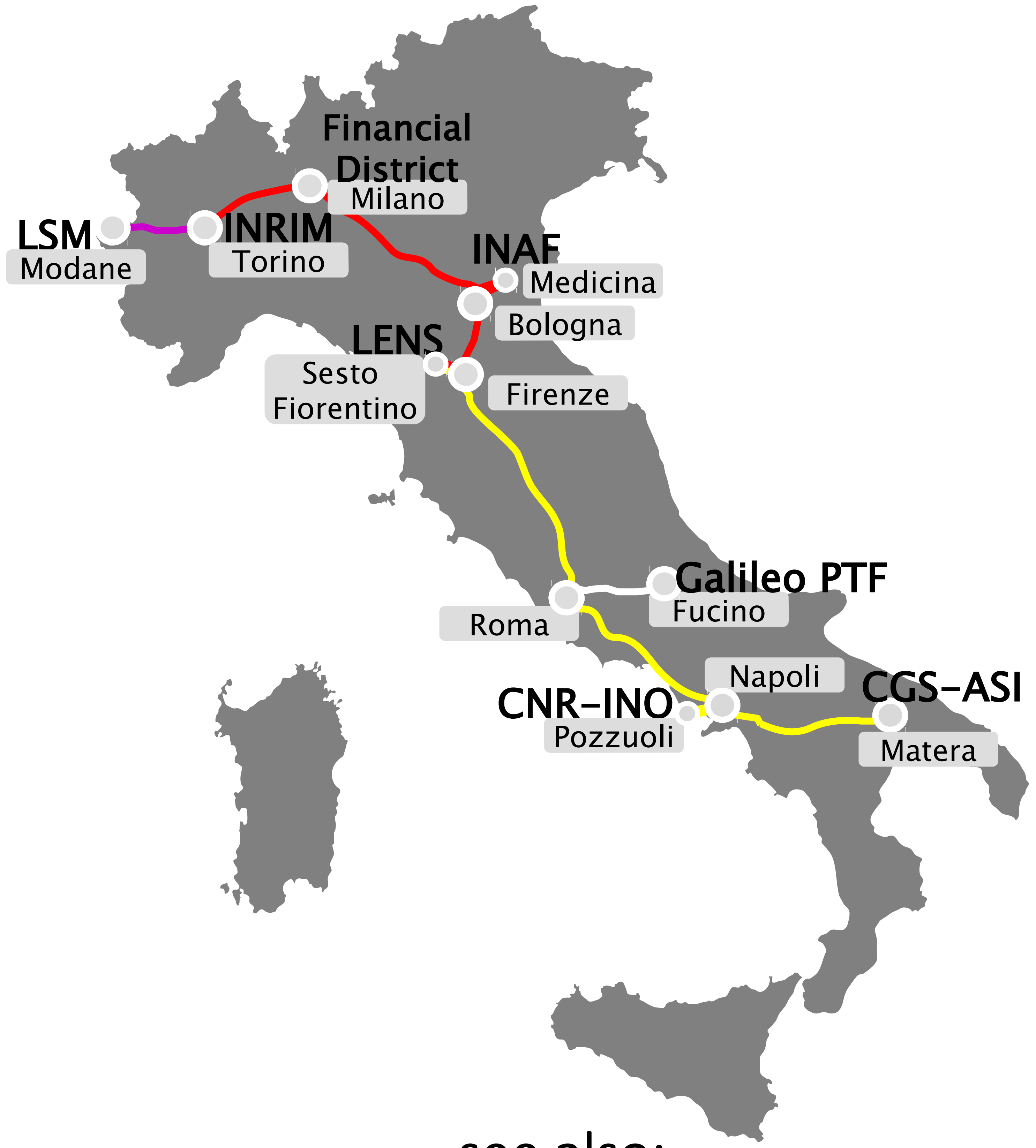
Courtesy Davide Calonico

Fiber networks

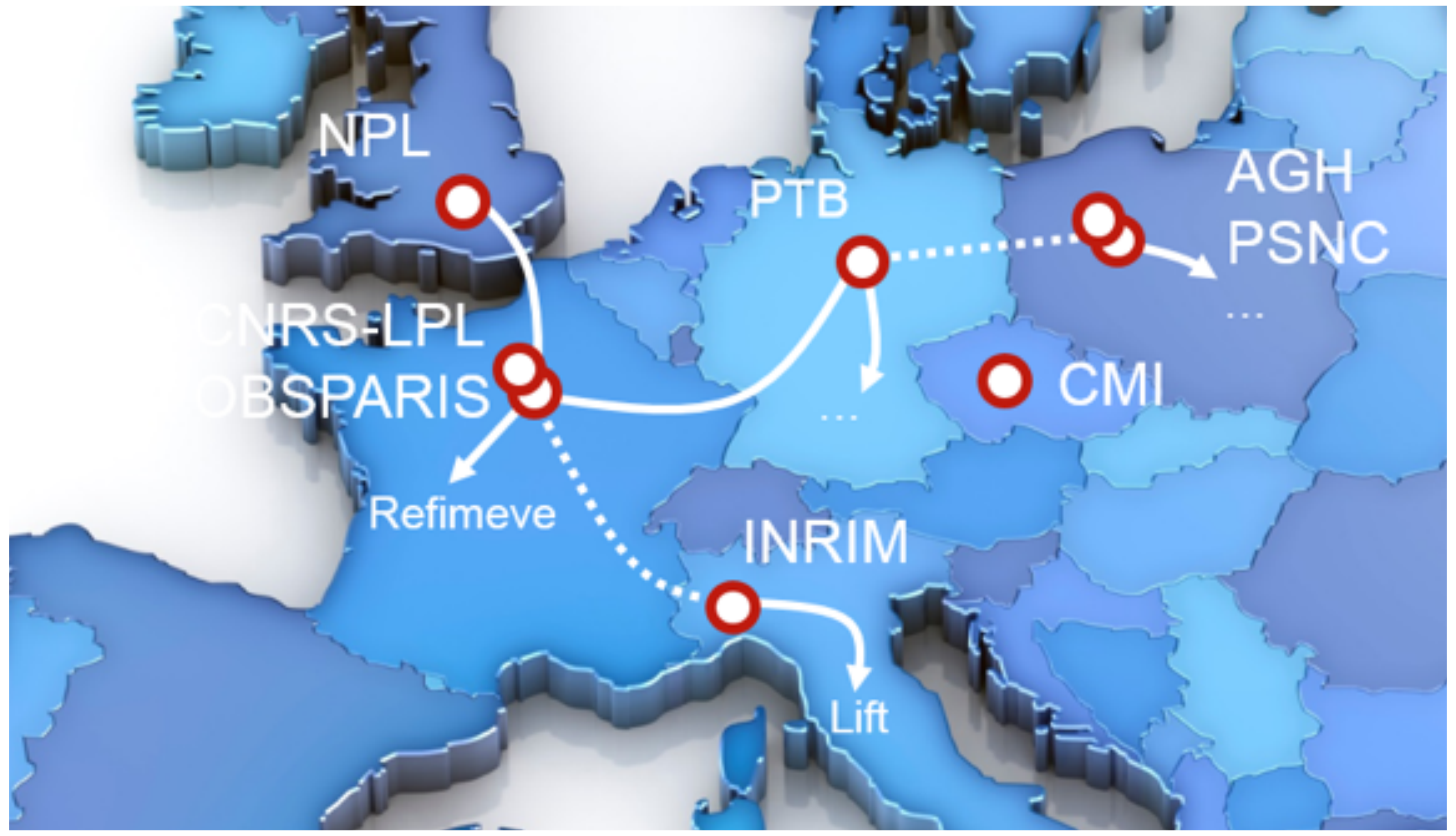
REFIMEVE (France) ~ 1300 km



LIFT (Italy) ~2000 km



NPL, PTB, SYRTE connected
INRIM scheduled for 2019

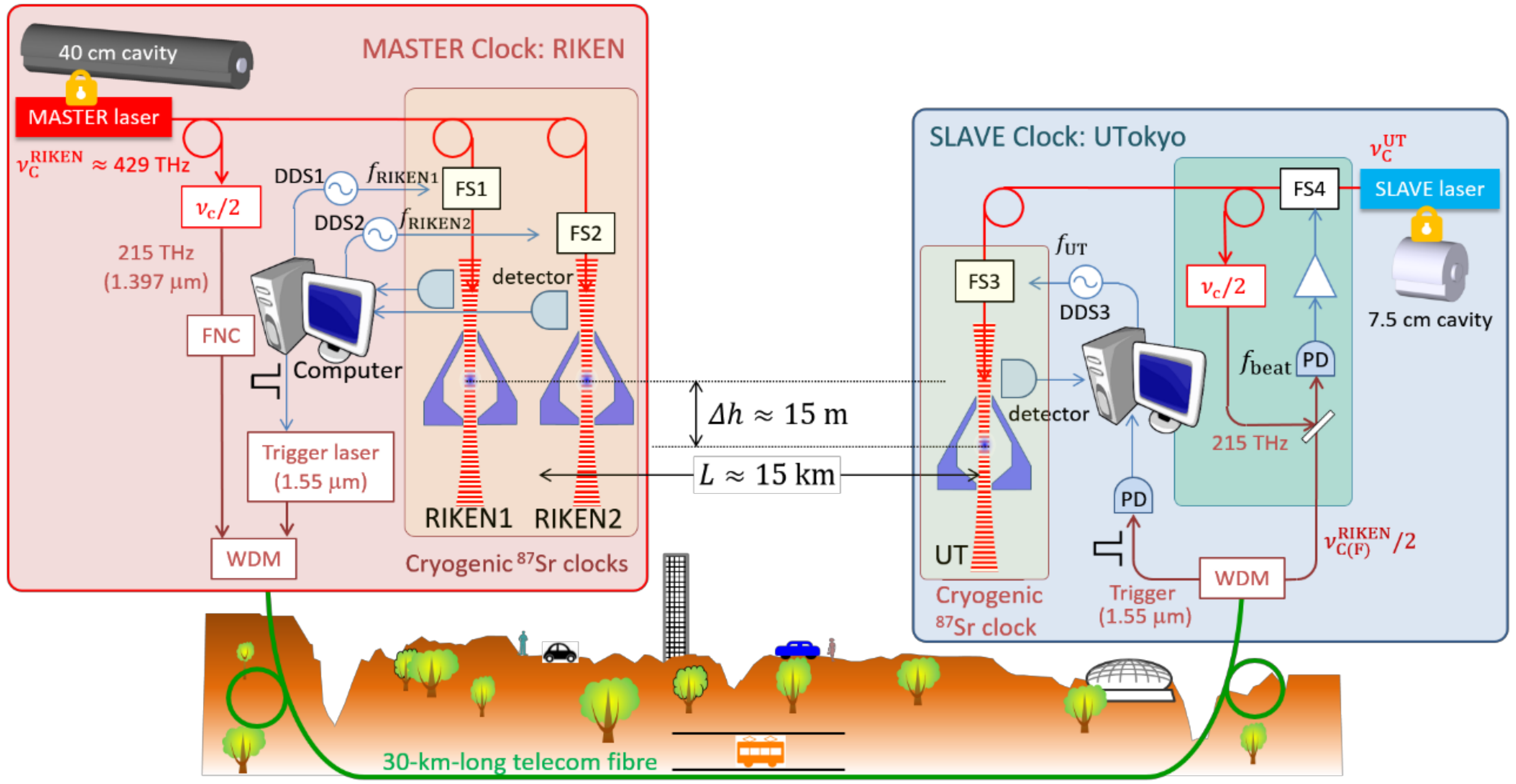


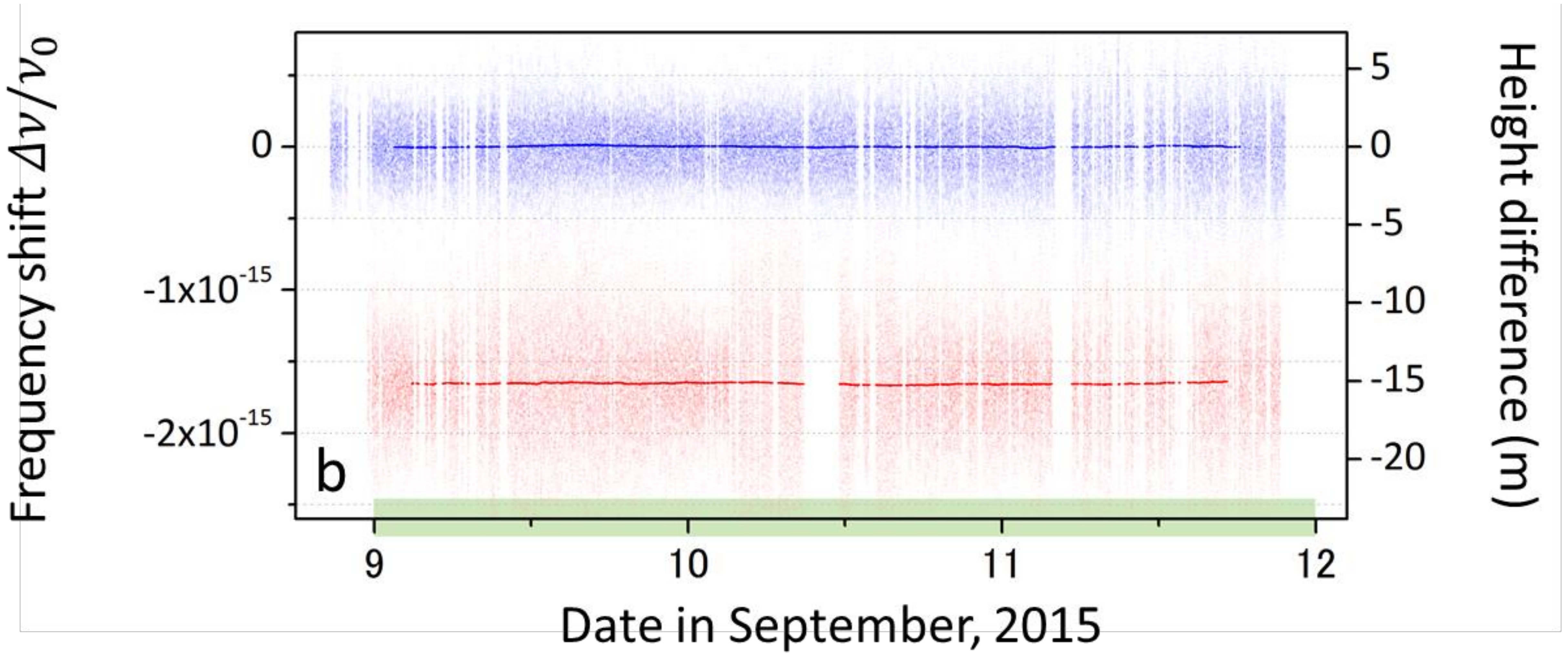
A fiber network of about 6000 km in EU enabling bi-directional, coherent, optical frequency transfer

Germany : ~2000 km, UK ~1000 km

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

Geopotential measurements with linked optical lattice clocks





- 3 optical clocks in Tokyo area, Japan; ~30 km fiber link
- Height difference ~ 15 m ⇒ Gravitational redshift ~ 1.5x10^{-15}
- Consistent with geodetic measurements
- NB: Clocks @ NIST, RIKEN : cm level @ 1 hour integration time

First remote comparison of optical clocks :

A. Yamaguchi *et al.* Applied Physics Express 4, 082203 (2011)

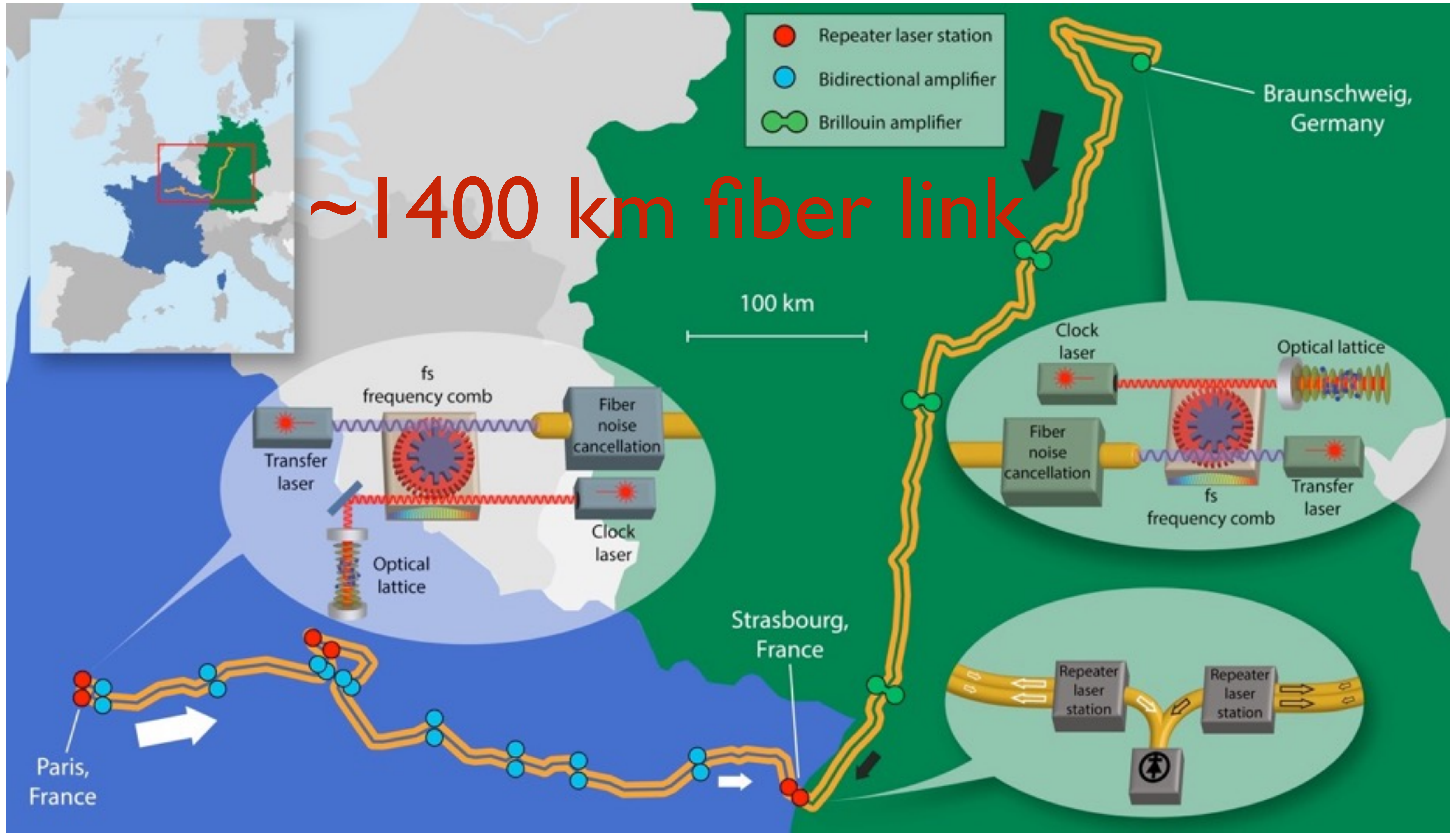
Geopotential measurement with synchronized clocks:

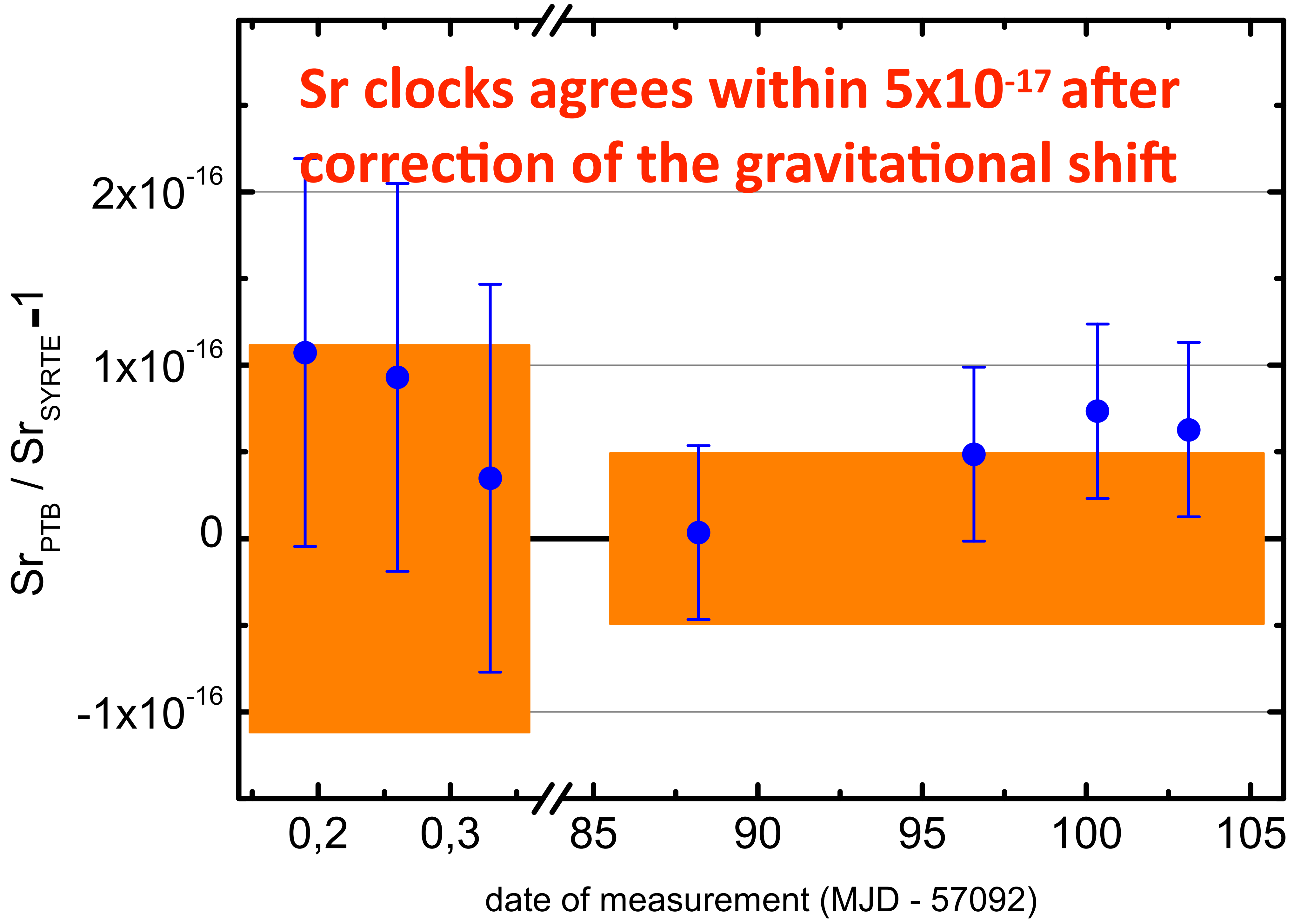
T.Takano *et al.*, Nature Photonics 10 (2016)

see also :

E.Oelker *et al.*, arXiv:1902.02741 (2019).

The first international optical clock comparison



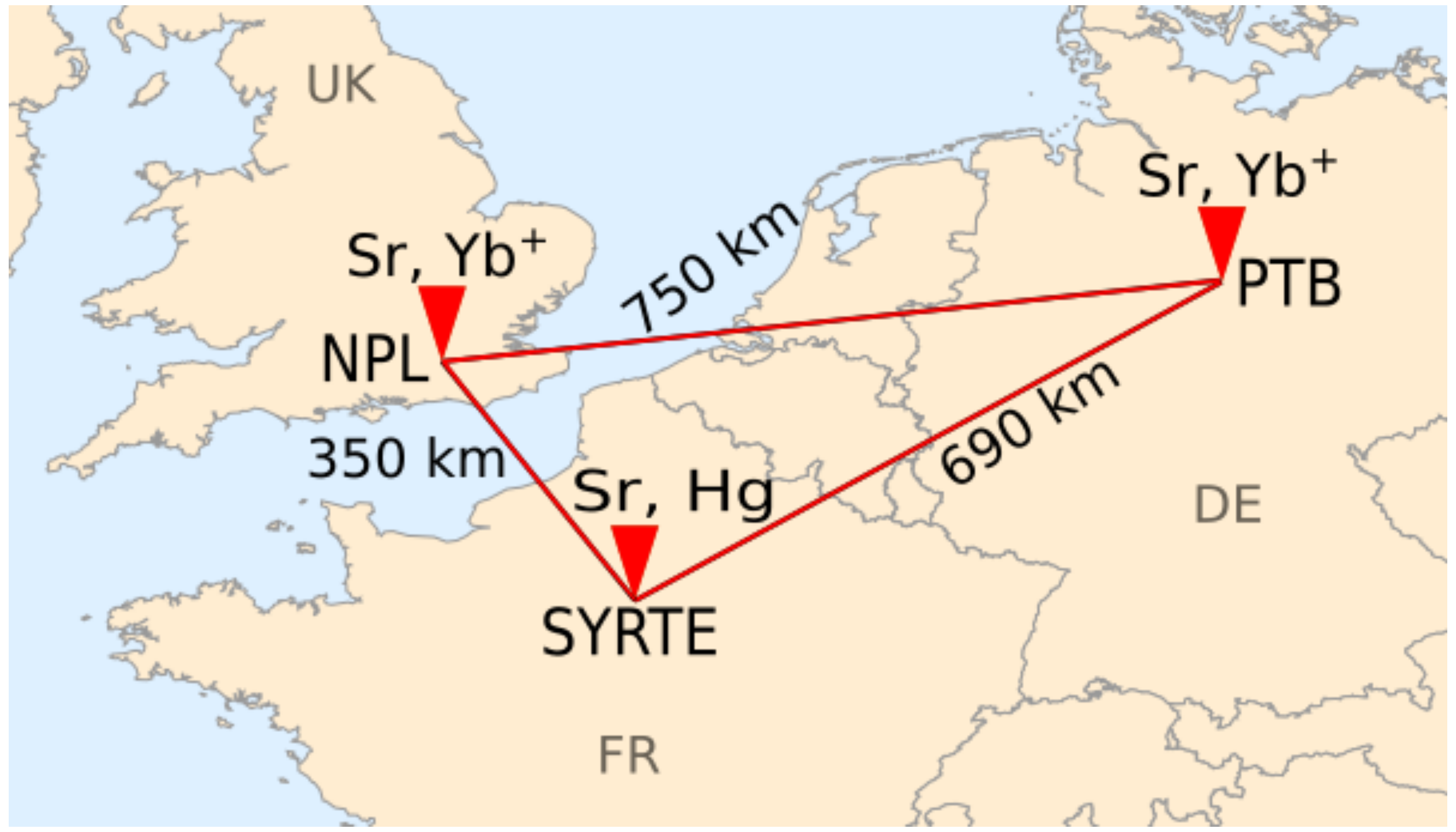


- Leveling campaign was performed prior to the comparison (IGN, IfE, LUH; Delva *et al.*, 2018)
- Confirms accuracy of Sr clocks SYRTE/PTB
- Confirms capabilities of long haul coherent fiber links

Absolute frequency difference without SI-Hz

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

Clock comparisons through a fiber network



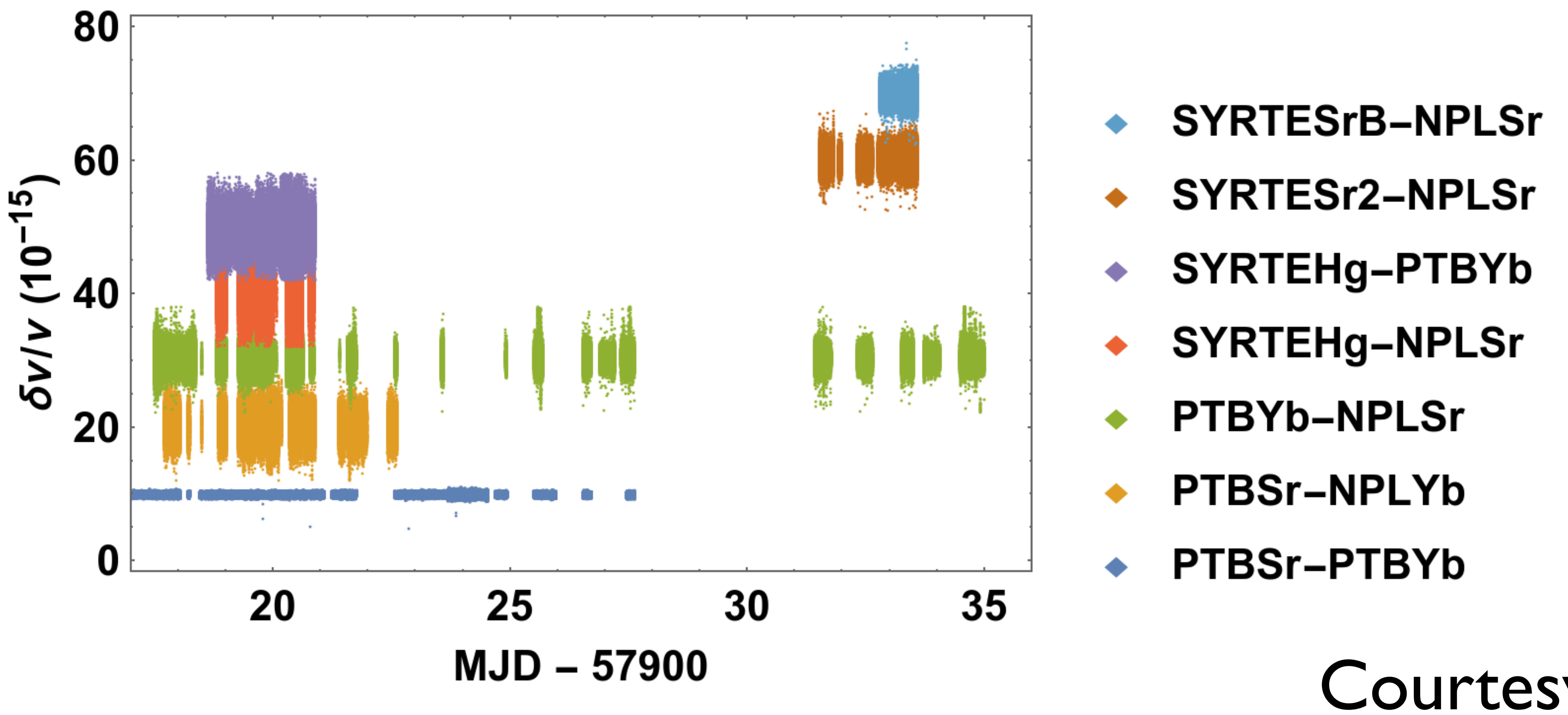
~2300 km fiber link

- Sensitivity: ✓ $(\delta\alpha, \Lambda)$
  limited only by clocks: Sr-Sr: $\delta\omega/\omega \sim 3 \times 10^{-17}$ at 1000s
- Long observation time: ✓ $(\mathcal{T})$
- Long-term stability: ✓ (d)

Fibre network

- High-accuracy long-distance clock comparisons
- Different clocks: $Hg/Sr/Yb^{+}$

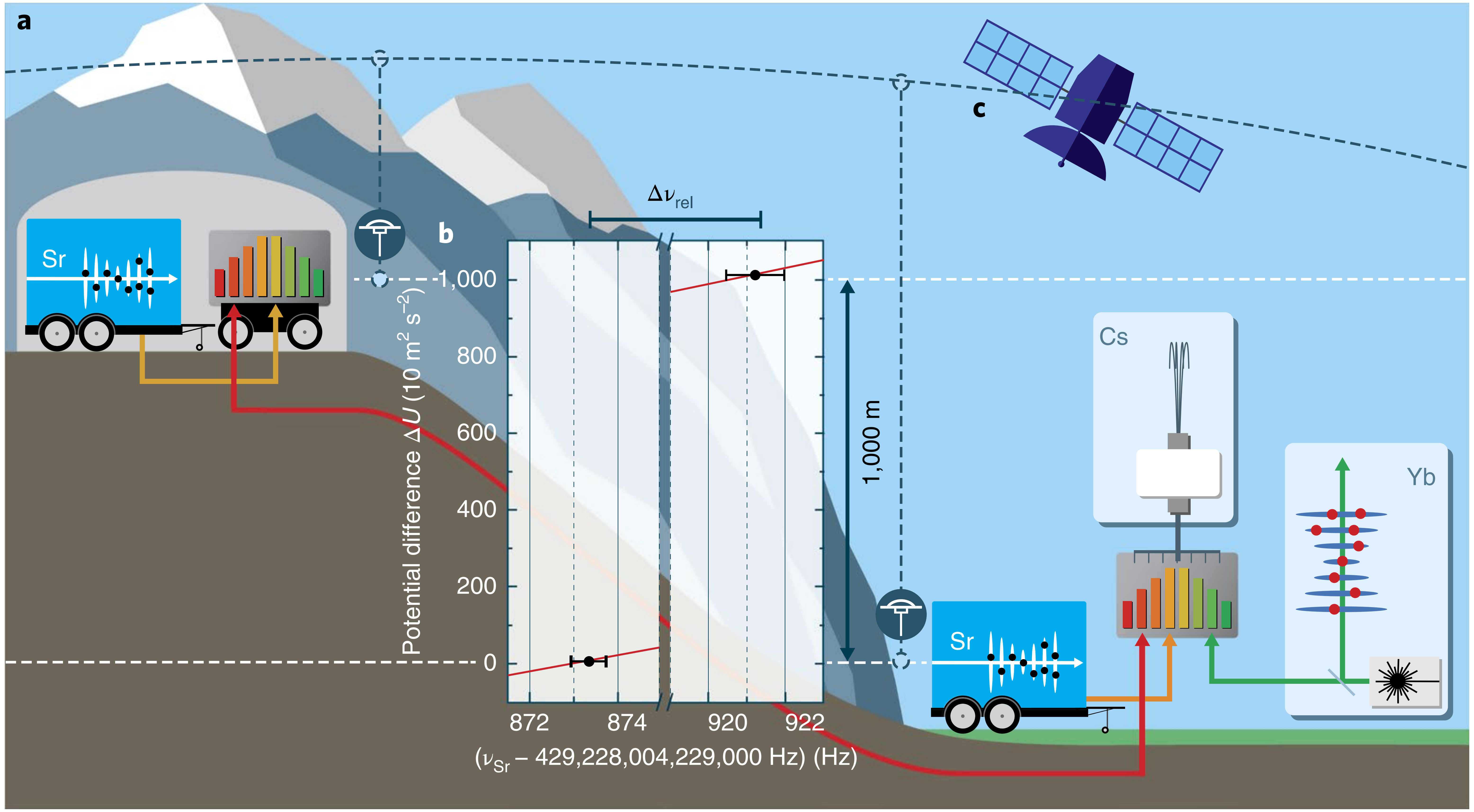
5 weeks campaign, June 2017



Courtesy Pacome Delva
Jérome Lodewyck

Geodesy with a transportable optical clock

A transportable optical clock is moved from Laboratoire Souterrain de Modane (French Alps) to INRIM, and compare to static clocks operated @INRIM through ~150 km fiber link



- Height difference ~ 1 km ⇒

  Gravitational redshift ~ 10^{-13}
- relativistic redshift of 47.92(83) Hz
- gravity potential difference is 10 034(174) m^2s^{-2}
- Consistent with geodetic measurements

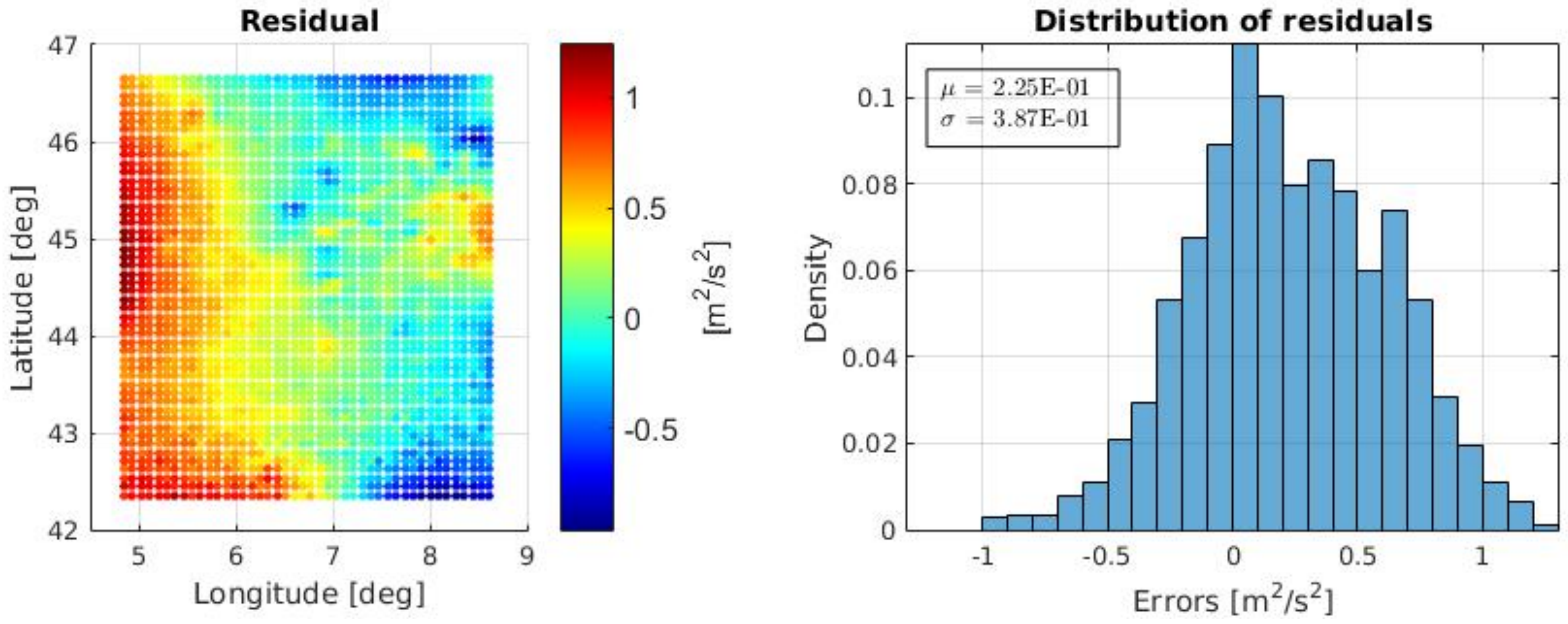
INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA

PTB

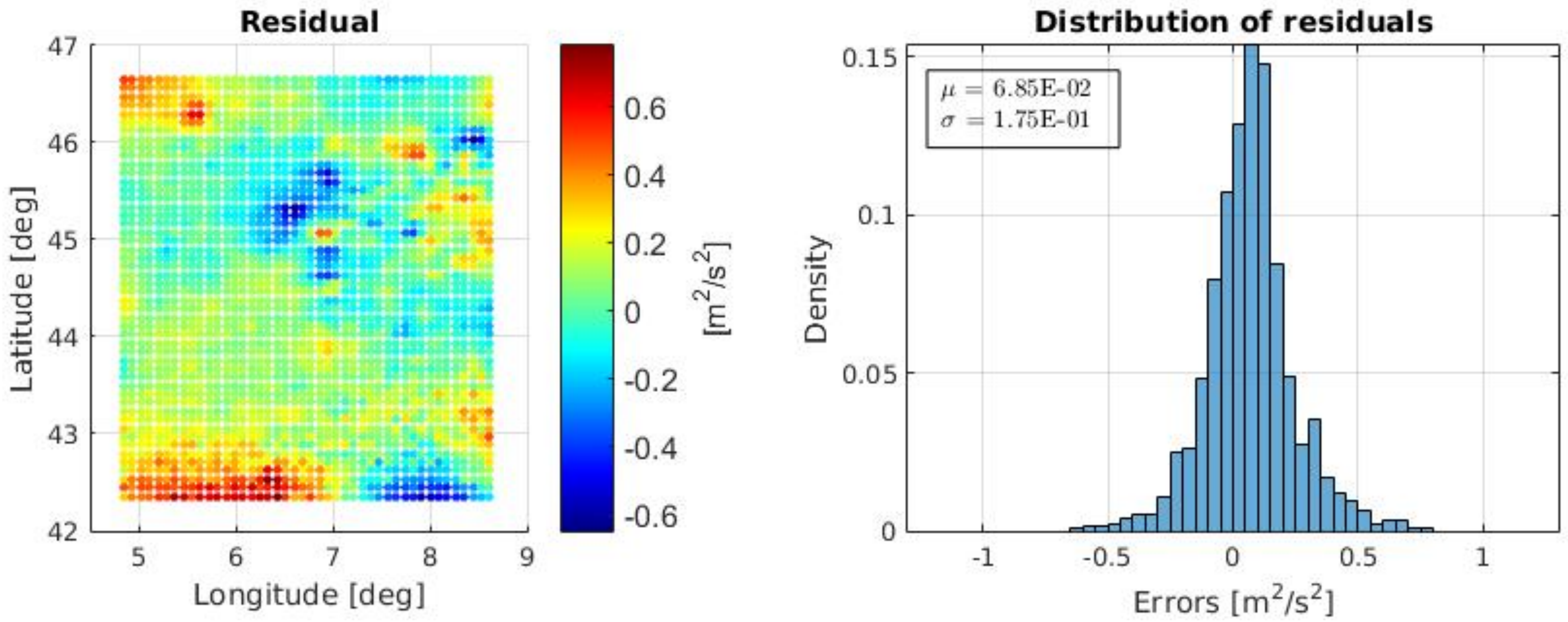
NPL National Physical Laboratory

J.Grotti *et al.*, Nature Physics 1 (2018). doi: 10.1038/s41567-017-0042-3

Chronometric geodesy for high resolution geopotential



(a) Without clock data.



(b) With clock data.

- SYRTE/Obs.Paris, LAREG/IGN and LKB collab.
- Goals :
  - 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
- Adding ~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

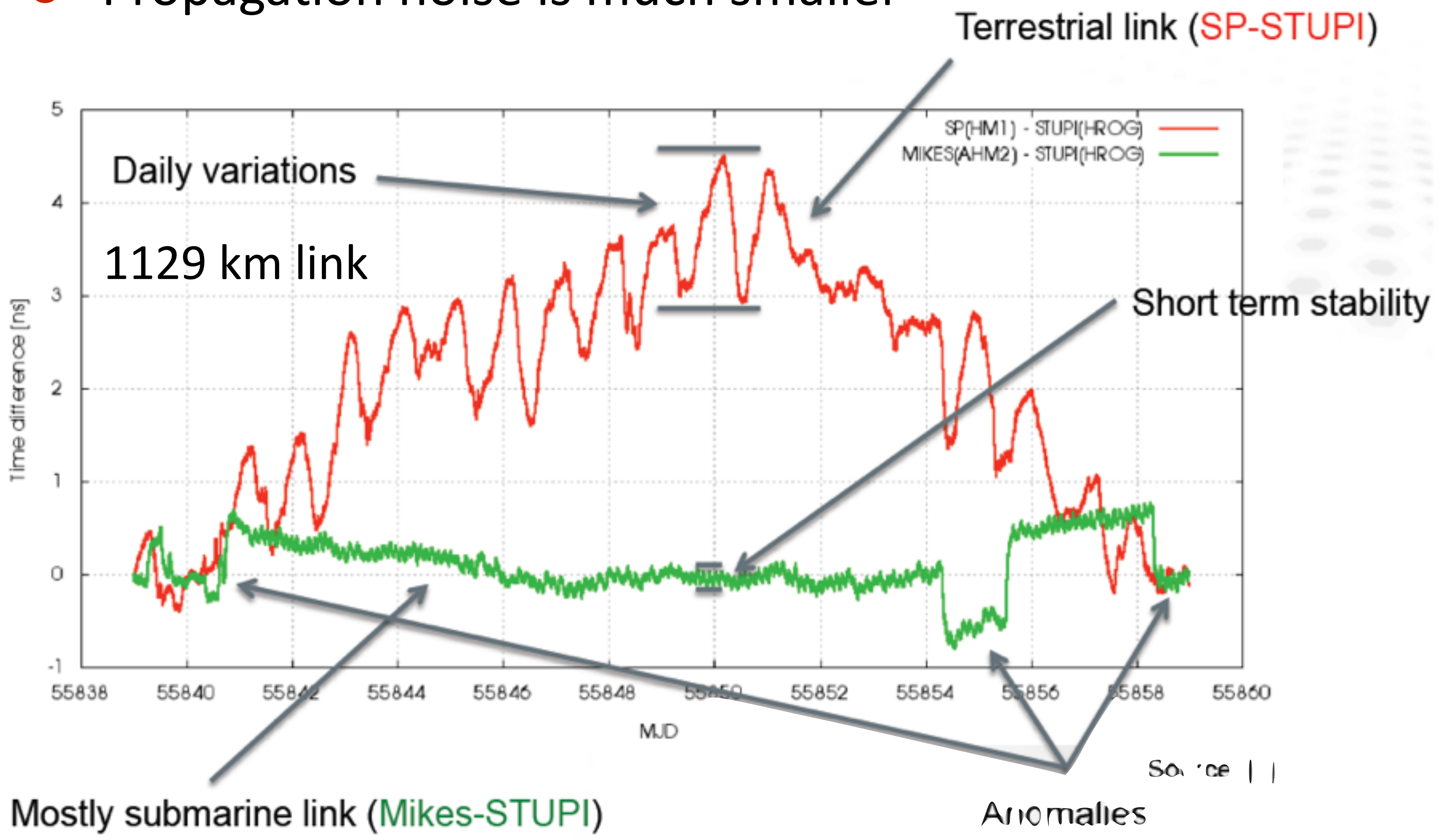
G. Lion *et al.*, J Geod 115 (2017)

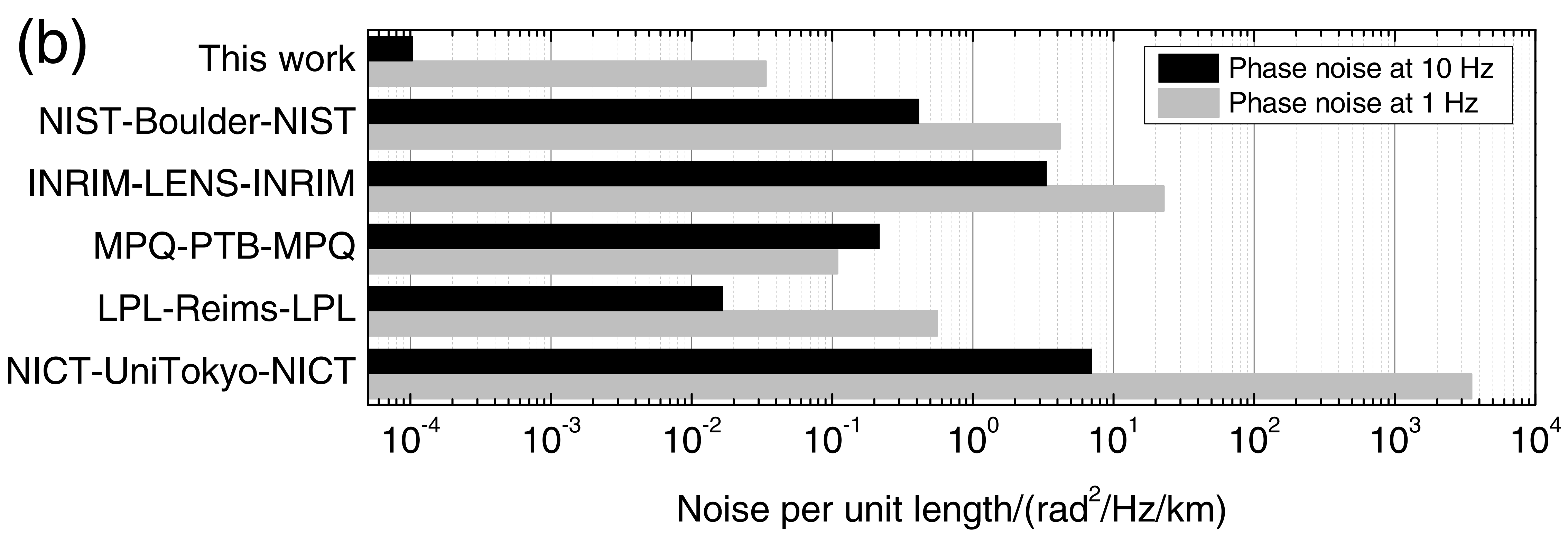
see also :

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

Submarine links

- Not possible to by-pass uni-directional submarine amplifiers : bi-directional links are probably not doable!
- Link accuracy limited to ~10^{-17}
- Propagation noise is much smaller





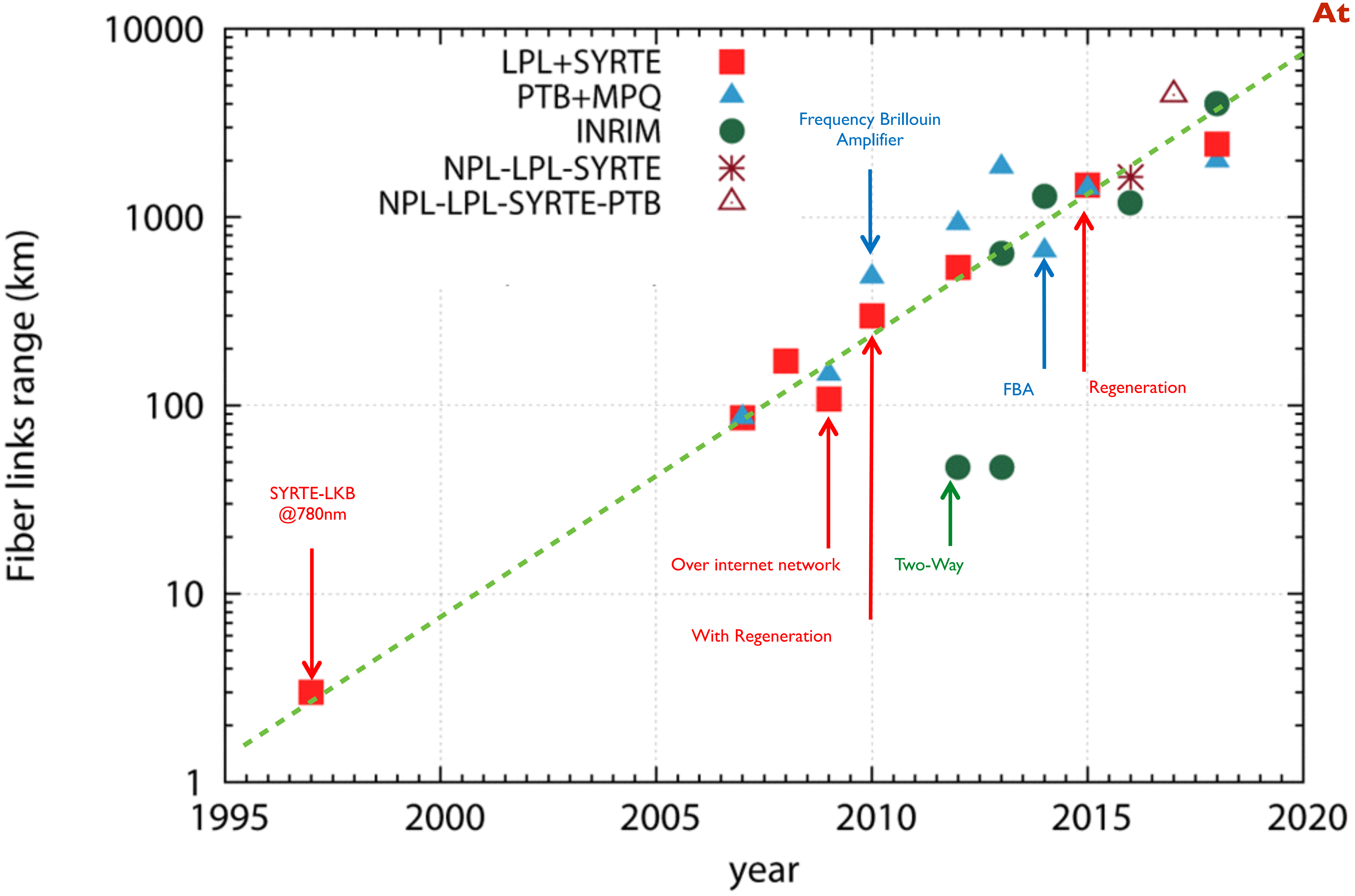
- First measurement of submarine cables in the optical domain,
- ~100 km submarine cable in Italy
- HV cable bundled to the fiber cause excess of noise at high Fourier frequency

Passive ethernet frame listening between SP (Sweden) and MIKES (Finland)

S.-C. Ebenhag, et al. in Proc. 43rd PTTI 431–442 (2011)

C.Clivati et al., Optica 5, 893 (2018)

CLONETS : towards Research Infrastructures



At horizon 2020 : 8000 km

Towards a large research infrastructure ?

GÉANT
connect • communicate • collaborate

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

NRENs can play a major role !

CLONETS : a paper study (Coordination and support action)

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

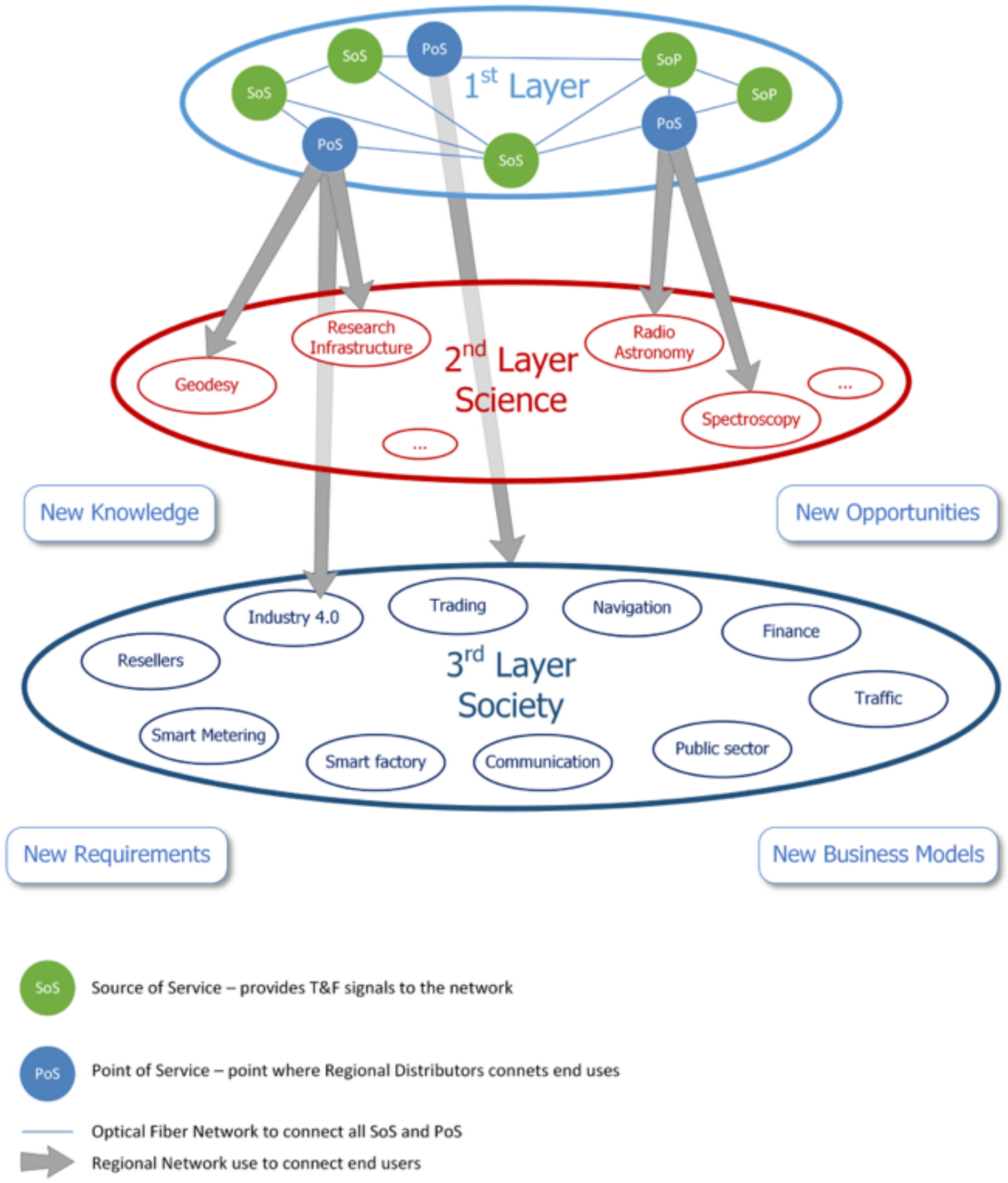
5 CZECH REPUBLIC
- CESNET, z.s.p.o.
- USTAV PRISTROJOVE TECHNIKY AV CR, v.v.i.
- OPTOKON

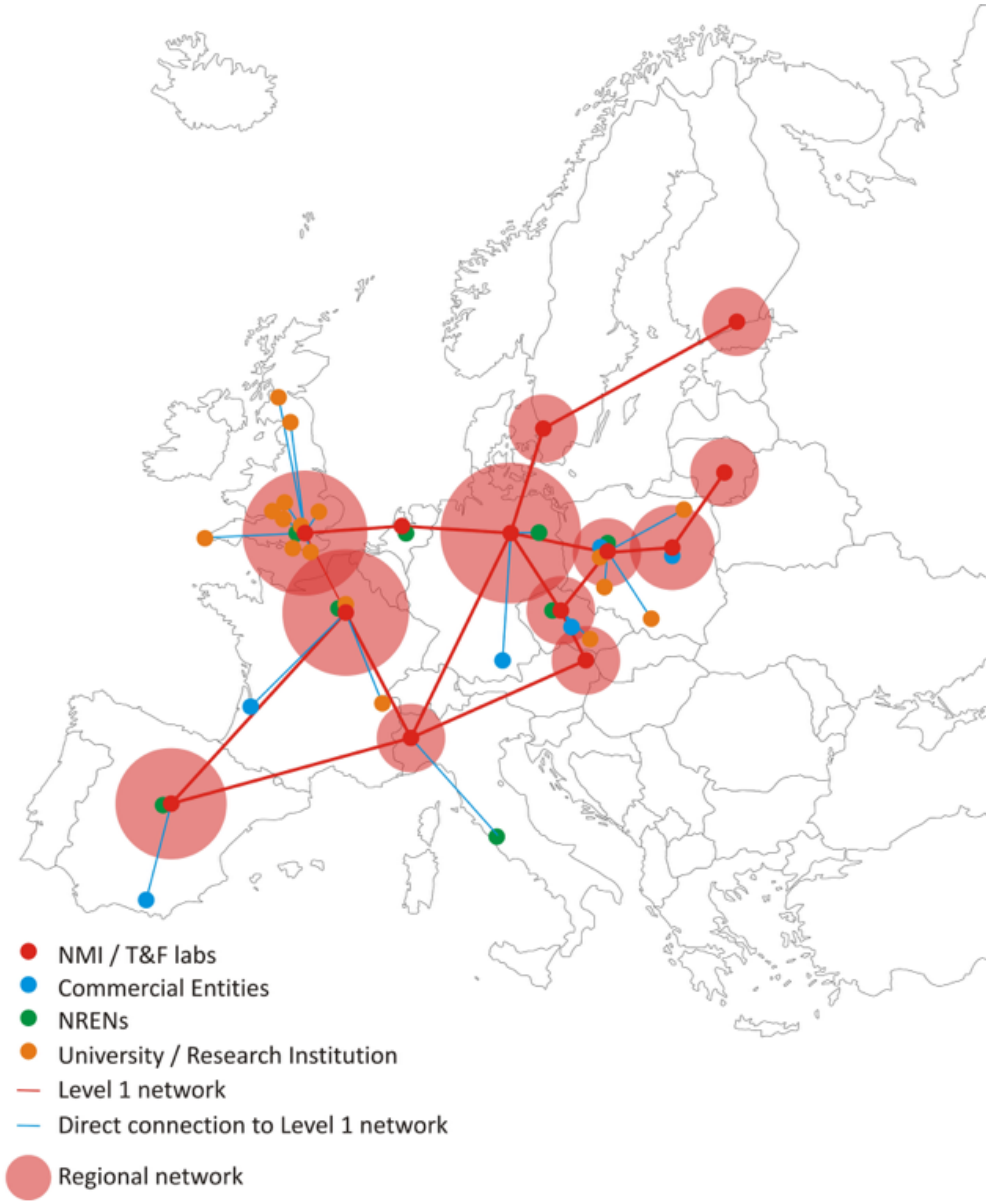
6 POLAND
- POZNANSKIE CENTRUM SUPERKOMPUTEROWO-SIECIOWE
- PIKTIME SYSTEMS sp. z o. o.
- AKADEMIA GORNICZO-HUTNICZA IM. STANISLAWA STASZICA W KRAKOWIE

7 SPAIN
- SEVEN SOLUTIONS S.L.

An EU-backbone to be designed

https://www.clonets.eu/





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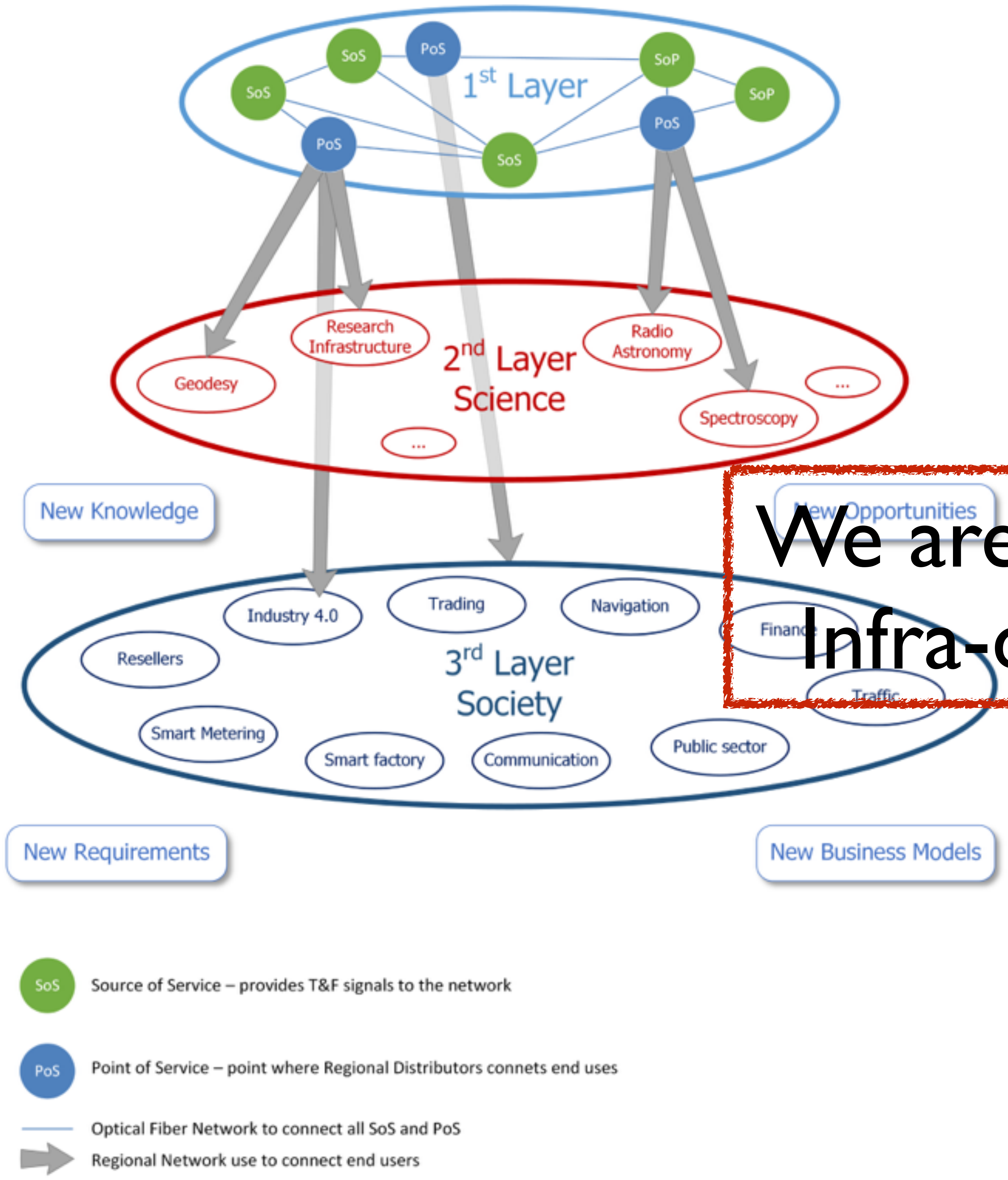

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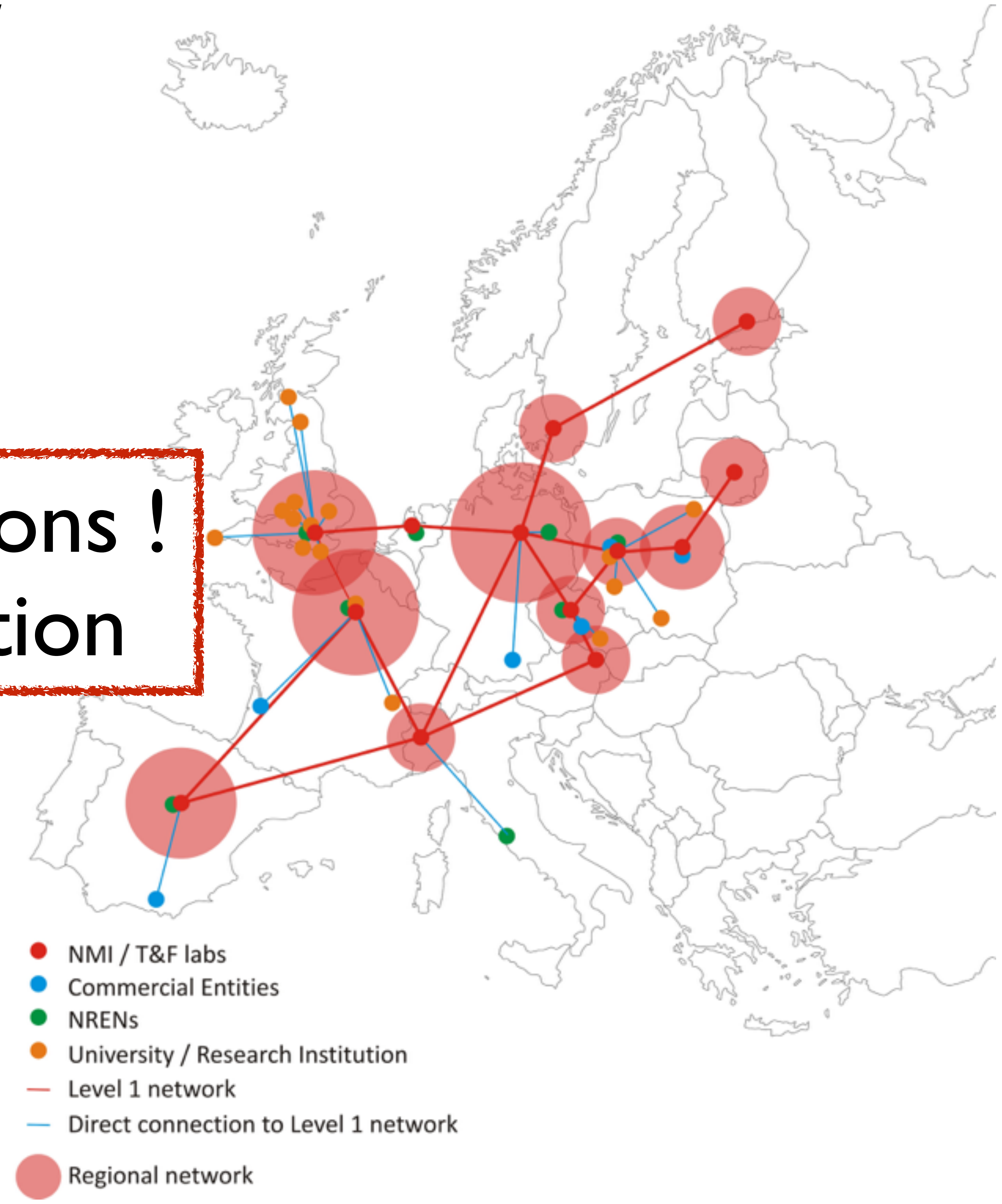
We are open for discussions !
Infra-dev call in preparation



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 https://www.refimeve.fr
- Next challenges and open questions:
  - Fiber network as a distributed sensor ?
  - Submarine links for transcontinental comparisons ?
  - Accurate time transfer
- Chronometric leveling : proof of concepts, consistent with other methods
- Towards EU research infrastructure, building a clock service

https://www.clonets.eu/

Thank for your attention !

Special thanks for :
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Emilie Camisard, Nicolas Quintin, Laurent Gydé (RENATER)