Coherent Optical Fibre Links in Physics and Metrology

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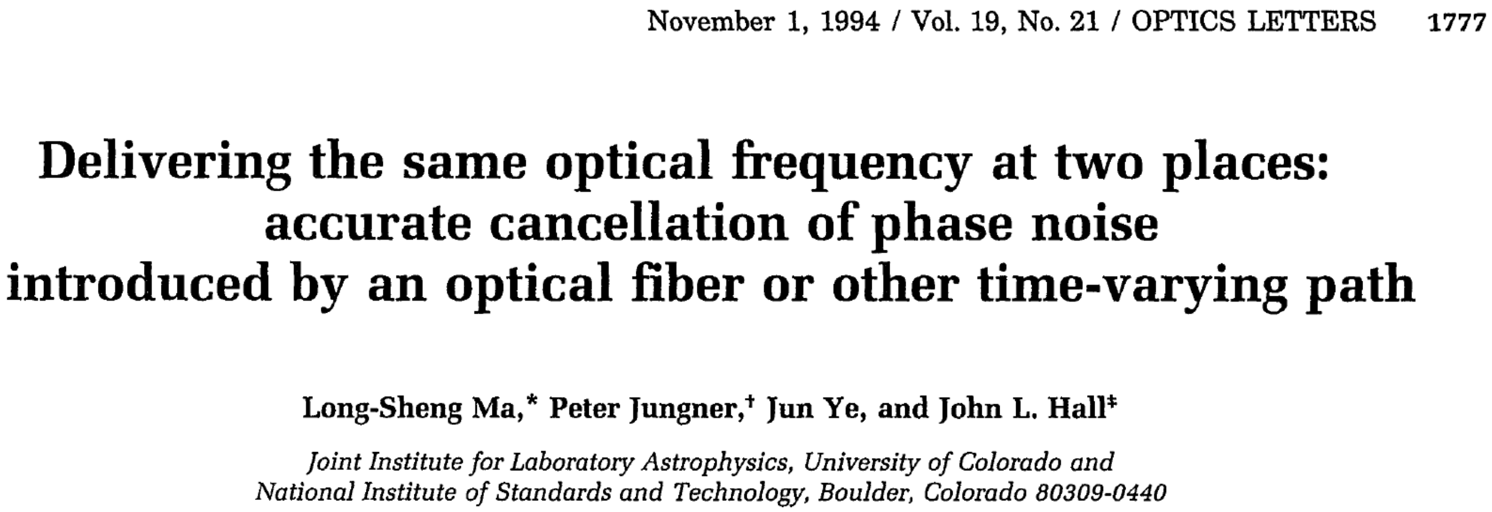
Optical Carrier Transfer: The basic idea

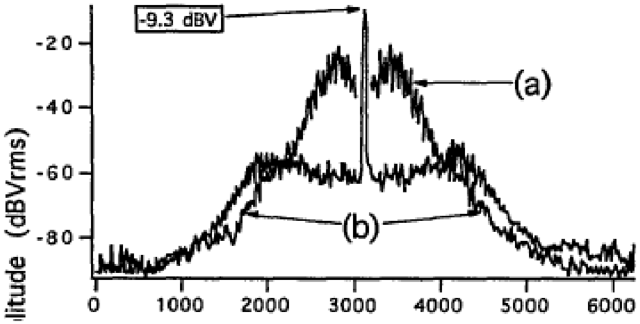


November 1, 1994 / Vol. 19, No. 21 / OPTICS LETTERS 1777

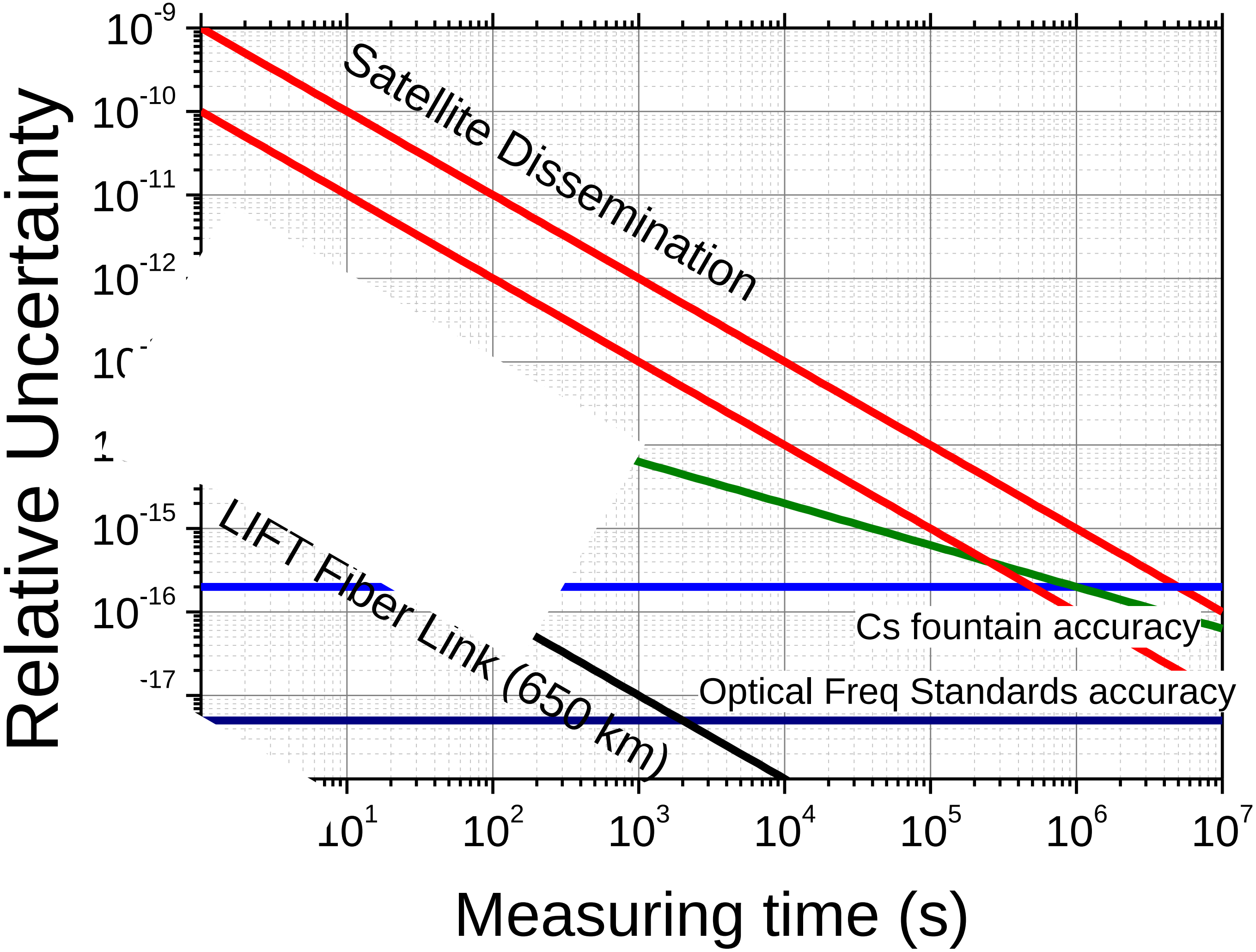
Delivering the same optical frequency at two places: accurate cancellation of phase noise introduced by an optical fiber or other time-varying path

Long-Sheng Ma,* Peter Jungner,† Jun Ye, and John L. Hall‡

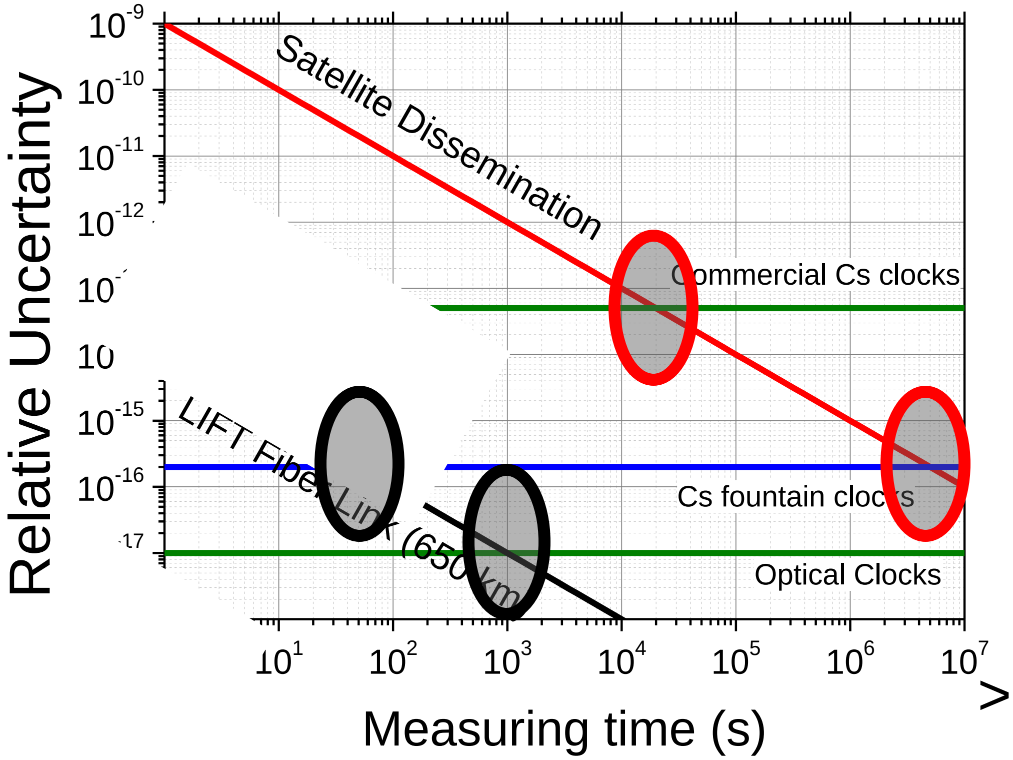
Joint Institute for Laboratory Astrophysics, University of Colorado and
National Institute of Standards and Technology, Boulder, Colorado 80309-0440



Time/Frequency Dissemination: performances



Atomic Frequency standards Comparison



<u>Satellites:</u>

>4 h for commercial Cs

>20 g for Cs fountains

>100 g optical frequency standards

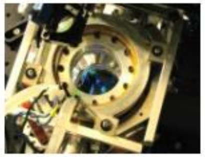
<u>Link in Fibra:</u>

Always better than a commercial Cs

100 s for Cs fountains

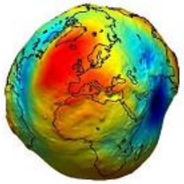
1000 s for optical frequency standards

Optical Fibre Links: a broad range of applications

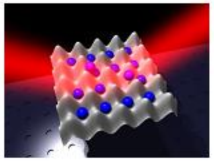


Remote clocks comparisons

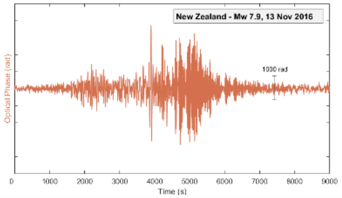
VLBI radioastronomy and geodesy



Relativistic Geodesy



High-precision spectroscopy



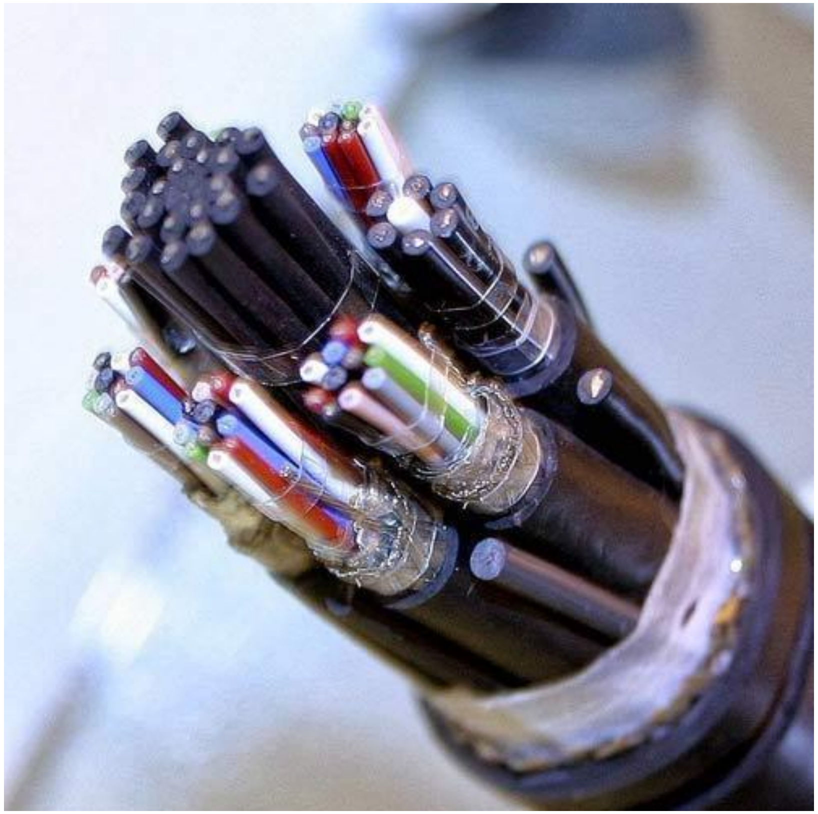
Seismology

Optical Fiber Links: a worldwide snapshot

① Fiber Link in use

★ Ongoing projects

Standard telecommunication optical fibre



- Made of glass (silica)
- 125 μm diameter (slightly thicker than human hair)
- Very low loss (0.2 dB/km)

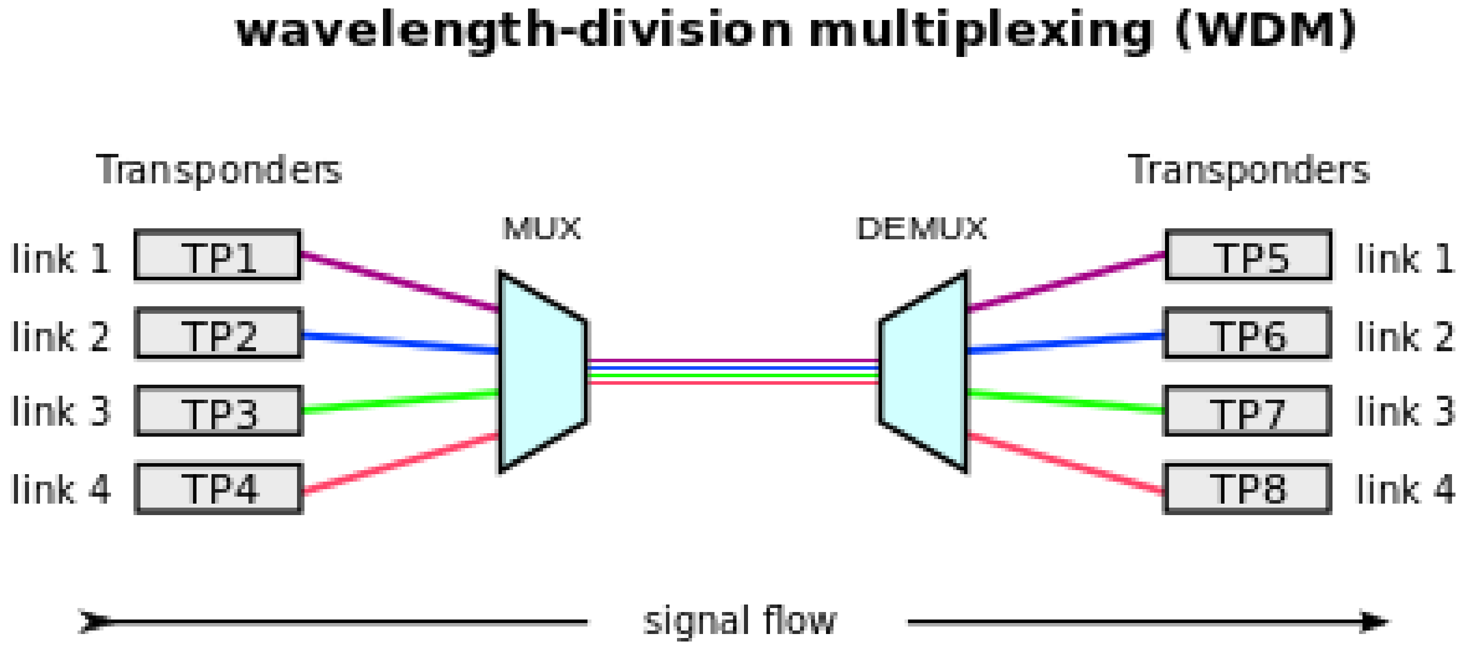
Architectures:

- Dark Fibre (dedicated)
- Coarse Division Wavelength Multiplexing (CWDM): spectrum divided into channels (16 nm each)
- Dense Division Wavelength Multiplexing (DWDM): spectrum divided into channels (100 GHz each, but also 12.5 - 50 GHz) ITU grid: “channel ITUxx”

In Europe, hystorically, we use ITU44 with a central wavelength at 1542.14 nm

- With DWDM and CWDM: we can have **metrological signals and data traffic at the same time.**

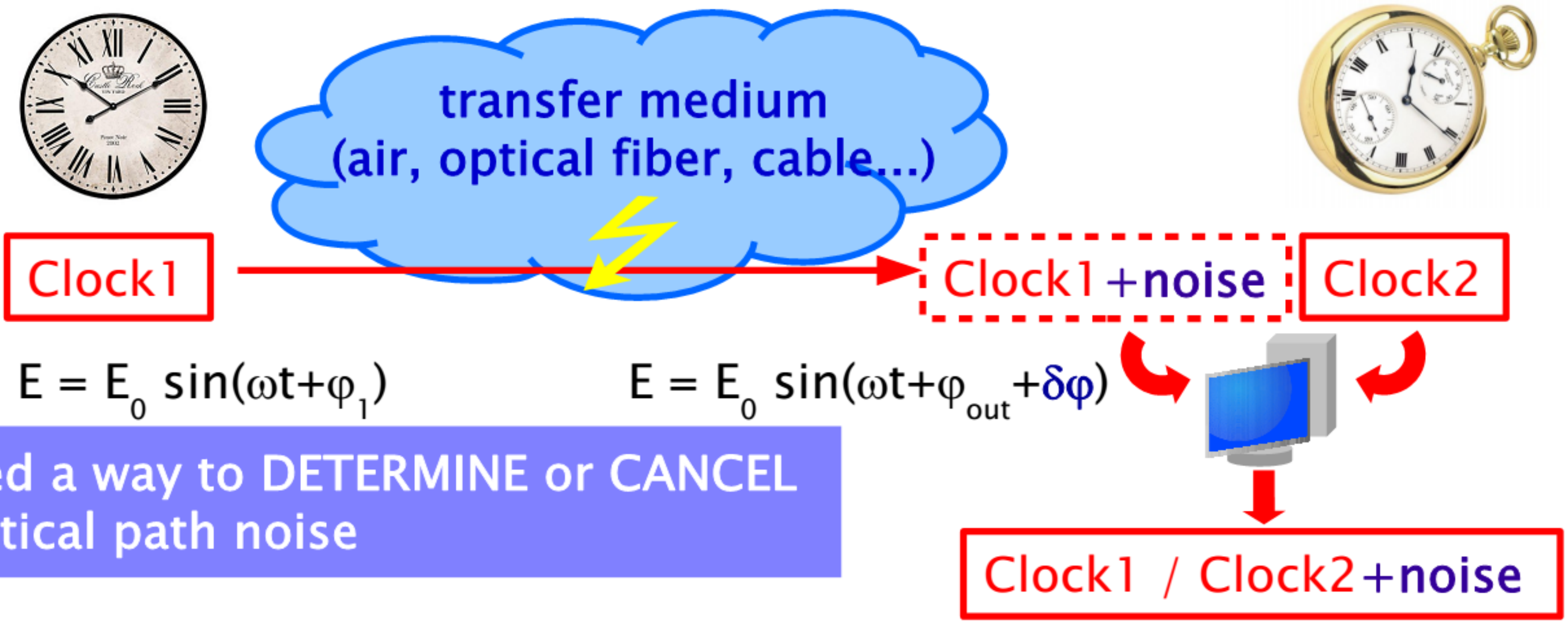
- Use od Optical Add and Drop Multiplexer or Wavelength Divison Multiplexer (OADM or DWM) to Add/Drop a specific wavelength (basically, they are bragg filters)



A network of distant clocks: how?

- Portable clocks
- Remote comparisons

Real:

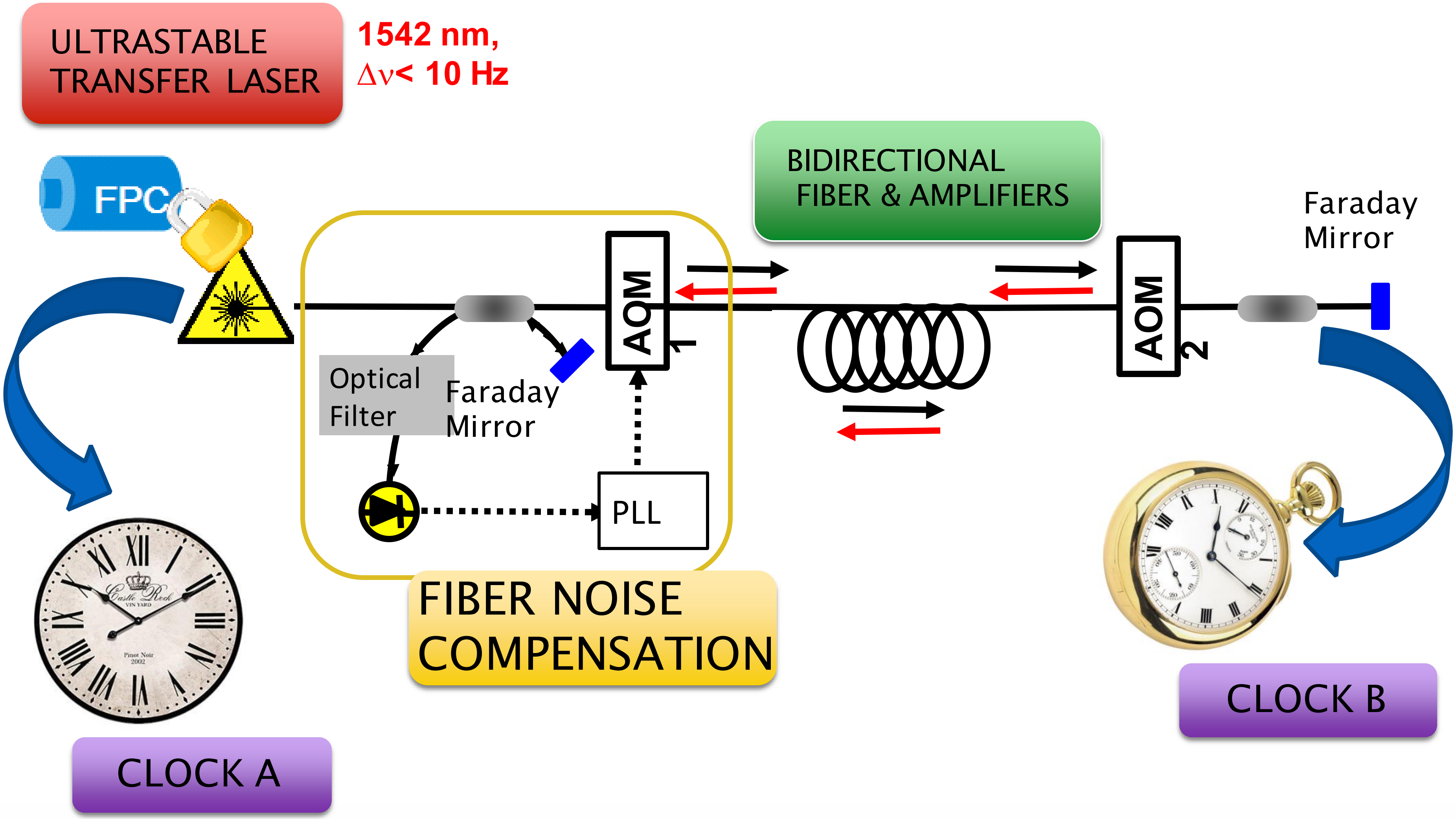


$E = E_0 \sin(\omega t+\varphi_1)$

$E = E_0 \sin(\omega t+\varphi_{out}+\delta\varphi)$

→ Need a way to DETERMINE or CANCEL optical path noise

Coherent Fiber Link: how it works



ULTRASTABLE TRANSFER LASER

1542 nm,
Δν< 10 Hz

FPC

BIDIRECTIONAL
FIBER & AMPLIFIERS

Faraday
Mirror

AOM 1

AOM 2

Optical
Filter

Faraday
Mirror

PLL

FIBER NOISE
COMPENSATION

CLOCK B

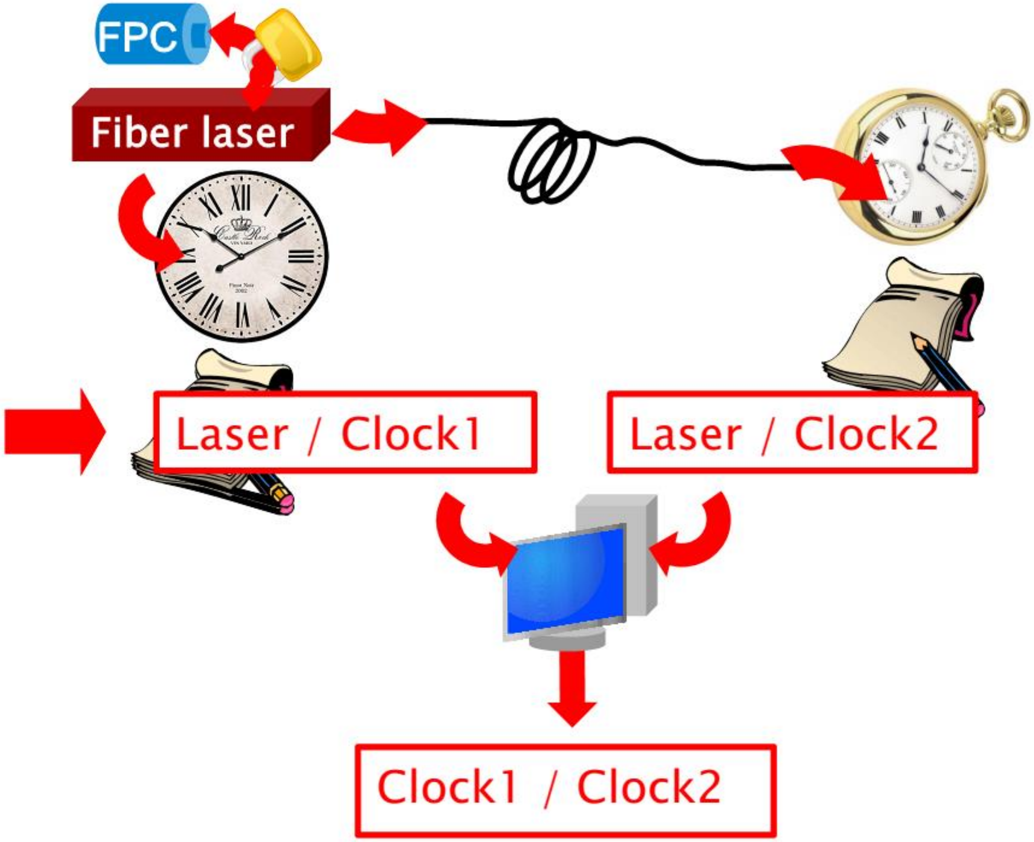
CLOCK A

Step-by-step remote comparison procedure

1. Take an ultrastable laser at the Metrology Institute and measure its frequency vs local (primary) atomic clock

2. Transfer the same laser to the remote lab through an optical fiber

3. Measure the received laser frequency vs local clock



FPC

Fiber laser

Laser / Clock1

Laser / Clock2

Clock1 / Clock2

Frequency transfer through optical fiber

- Exploits the same fibers which are used for the Internet

But….

- The metrological information is the absolute frequency of the optical electric field travelling the fiber, i.e.:

$$E = E_0 \sin(\omega t + \varphi)$$

- Need full-optical path from transmitter to receiver

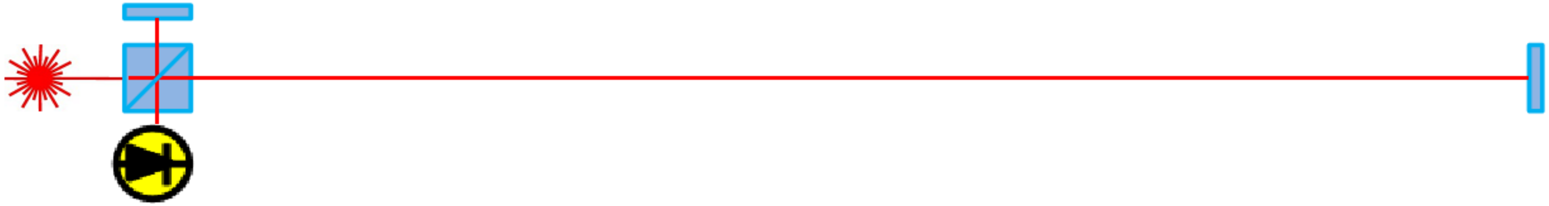
- Any environmental effect which affects the fiber length changes φ, as:

$$\varphi = 2\pi L/\lambda \quad \rightarrow \quad \Delta\varphi = 2\pi \Delta L/\lambda$$

..and this in turns affects ω, since $\omega = \frac{d}{dt}(\Delta\varphi)$

The Doppler-noise cancellation technique

Considers the fiber as a (very) long arm of a Michelson interferometer



Interference appears on the photodiode between:

$$E_{short} = E_0 \sin(\omega_1 t+\varphi_{short}) = E_0 \sin(\omega_1 t+2\pi\,\Delta L_{short} / \lambda)$$
$$E_{long} = E_0 \sin(\omega_2 t+\varphi_{long}) = E_0 \sin(\omega_1 t+2\pi\,\Delta L_{long} / \lambda)$$

We are interested in the difference:

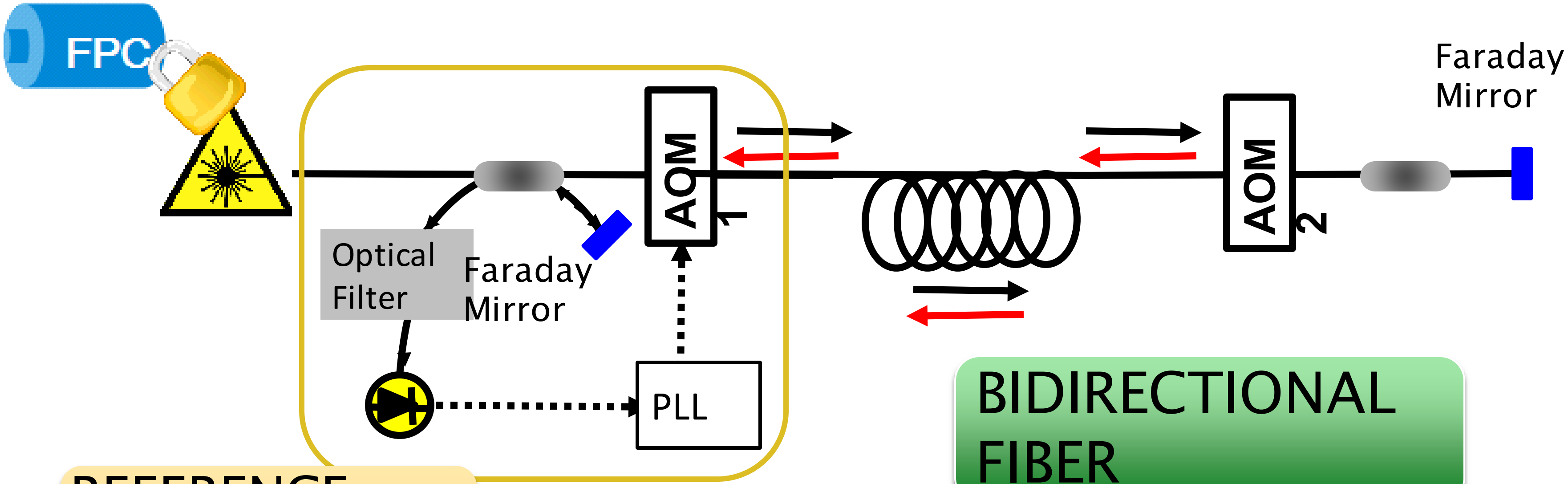
$$\ldots \rightarrow V_{photodiode} \propto \sin[2\pi/\lambda\,(\Delta L_{short} - \Delta L_{long})] \sim \sin[(2\pi/\lambda)\,\Delta L_{long}]$$

An actuator changes the optical phase by an equal amount, opposite in sign

Coherent Fiber Link: noise sources

LASER NOISE

Use Stabilised lasers, with coherence length > 2x link length



BIDIRECTIONAL FIBER

REFERENCE PATH NOISE

Should be short and Temperature Controlled

$$S_{remote}(f) = \frac{4\pi^2}{3}\left(f\,\frac{nL}{c}\right)^2 S_{fiber}(f)$$

Williams *et al.*, JOSA B25,1284 (2008)

1284 J. Opt. Soc. Am. B/Vol. 25, No. 8/August 2008 Williams *et al.*

High-stability transfer of an optical frequency over long fiber-optic links

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[*]Corresponding author: pwilliam@boulder.nist.gov

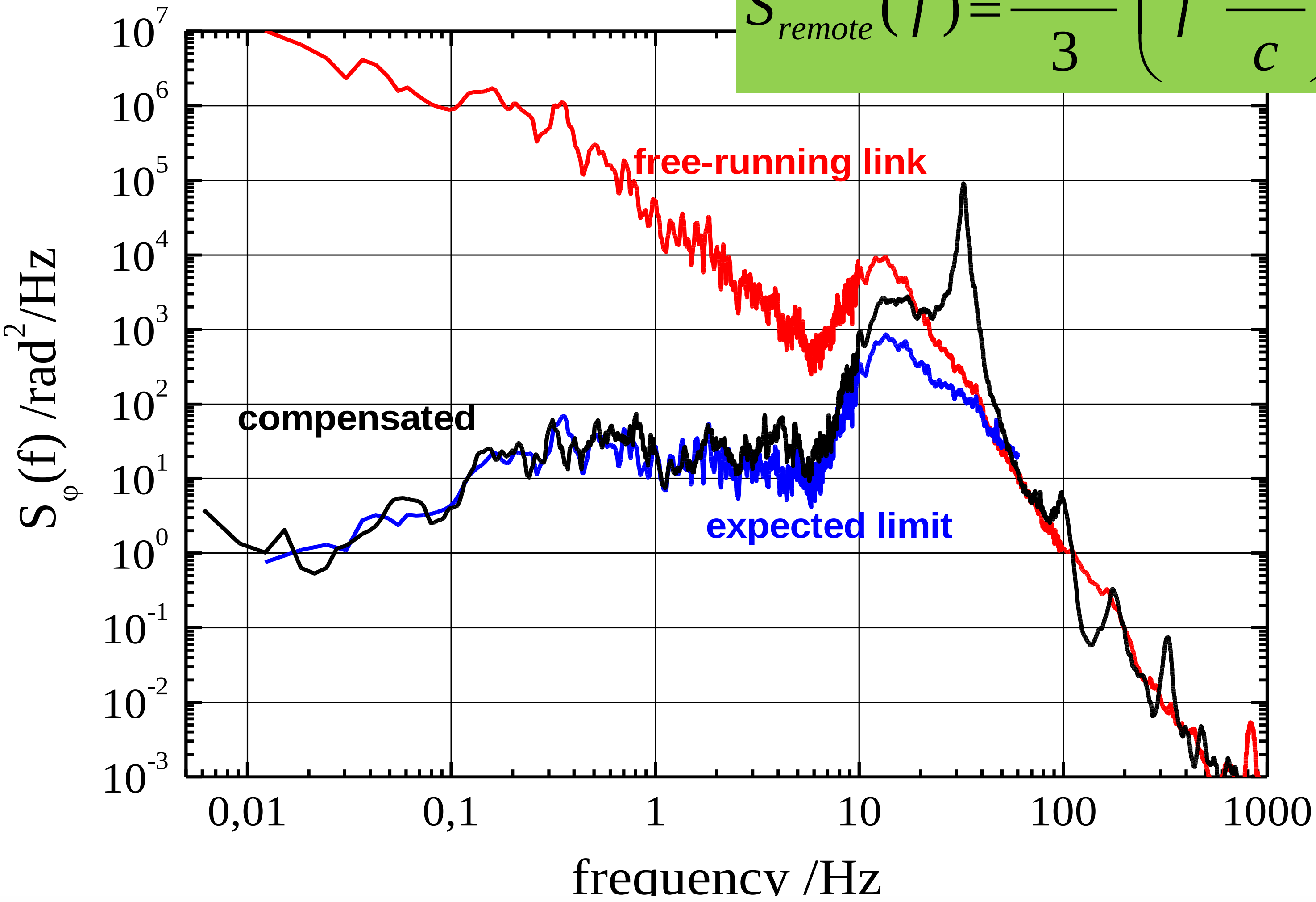
Received February 25, 2008; revised May 2, 2008; accepted May 31, 2008;
posted June 9, 2008 (Doc. ID 93074); published July 17, 2008

We present theoretical predictions and experimental measurements for the achievable phase noise, timing jitter, and frequency stability in the coherent transport of an optical frequency over a fiber-optic link. Both technical and fundamental limitations to the coherent transfer are discussed. Measurements of the coherent transfer of an optical carrier over links ranging from 38 to 251 km demonstrate good agreement with theory. With appropriate experimental design and bidirectional transfer on a single optical fiber, the frequency instability at short times can reach the fundamental limit imposed by delay-unsuppressed phase noise from the fiber link, yielding a frequency instability that scales as link length to the 3/2 power. For two-way transfer on separate outgoing and return fibers, the instability is severely limited by differential fiber noise.

OCIS codes: 060.2360, 120.3930.

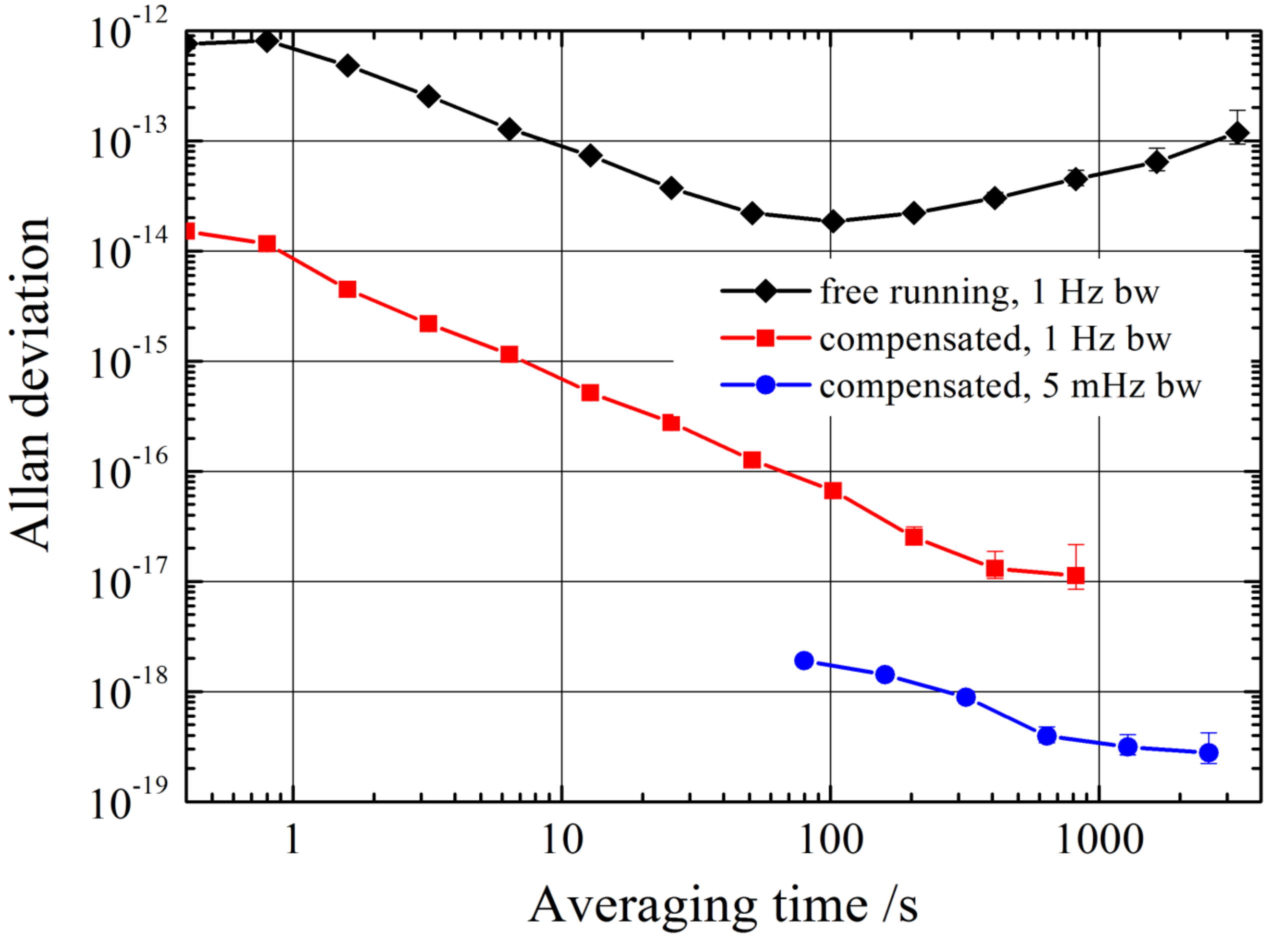
Link PSD, Example: LIFT Link 1284 km (642 kmx2)

$$S_{remote}(f) = \frac{4\pi^2}{3}\left(f\,\frac{nL}{c}\right)^2 S_{fiber}(f)$$



Ultimate Limit due
to finite speed of ligh

Italy, LIFT Link 1284 km (642 kmx2)
ADEV

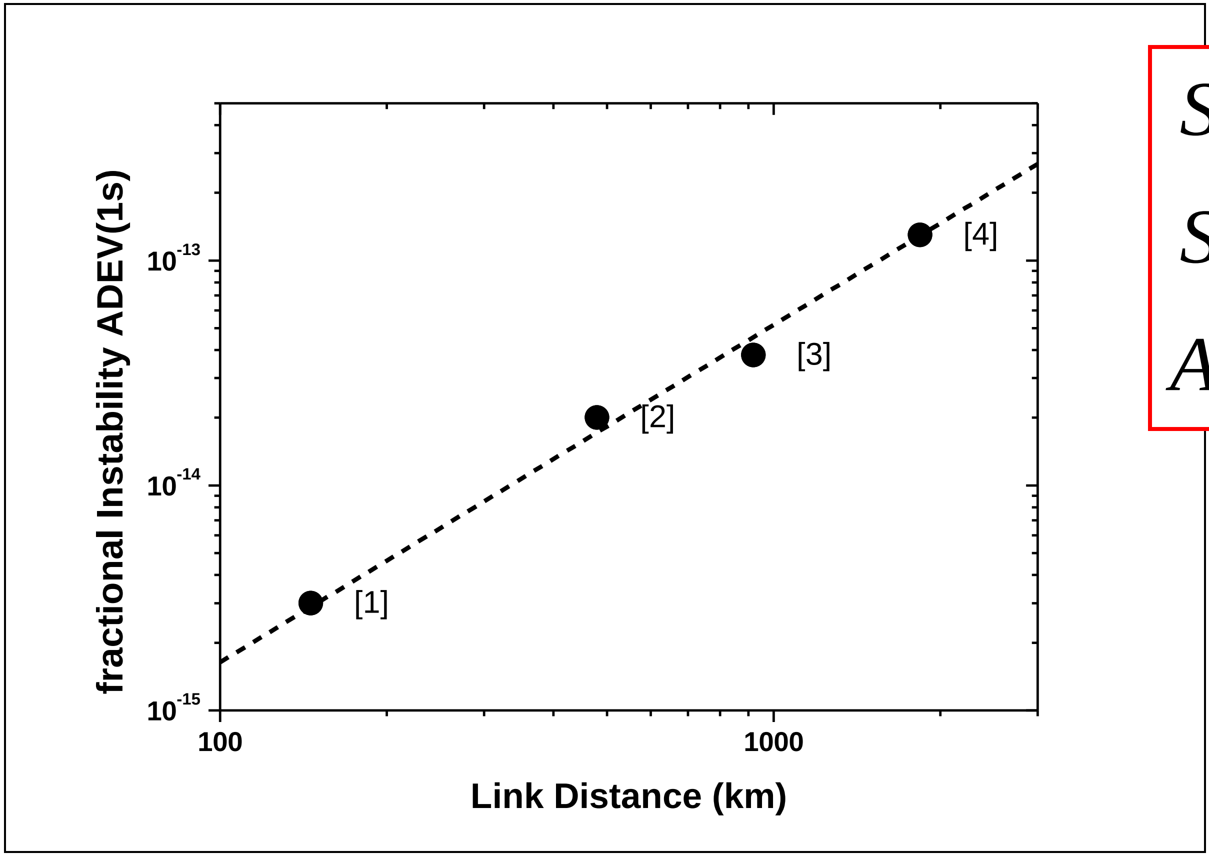


Offset between delivered and original signal $<5\times10^{-19}$

D. Calonico et al., Applied Physics B, **117,** 979 (2014).

Instability: Link Length Scaling Law

Assuming uniform noise distribution with fiber link length.



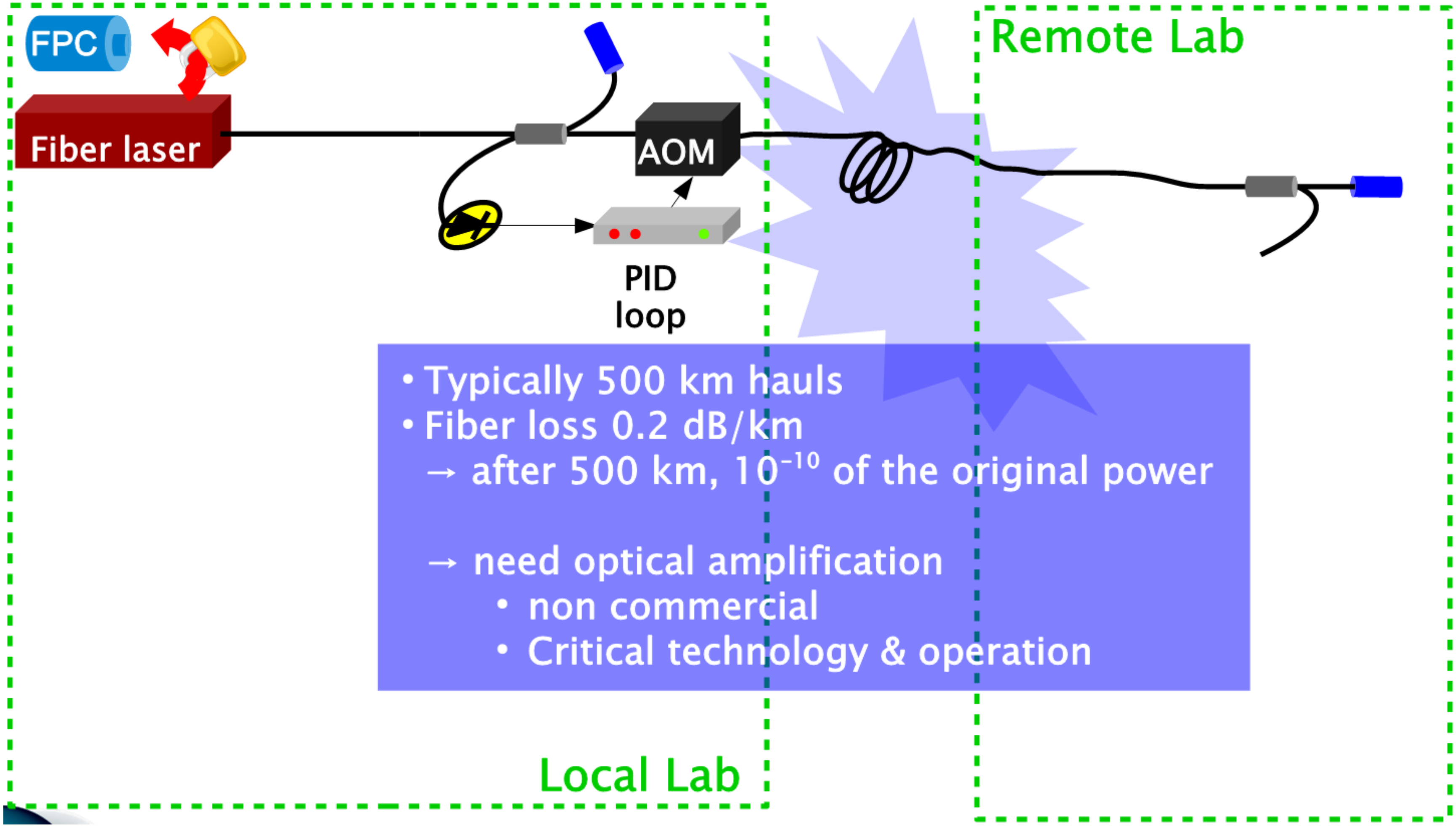
$$S_{\Phi}^{fiber}(f,L) \propto L \quad \Rightarrow$$

$$S_{\Phi}^{remote}(f,L) \propto L^{3} \Rightarrow$$

$$ADEV(L,1s) \propto L^{3/2}$$

N. R. Newbury et al., Opt. Lett. **32**, 3056 (2007)

The Doppler–noise cancellation technique



- Typically 500 km hauls
- Fiber loss 0.2 dB/km

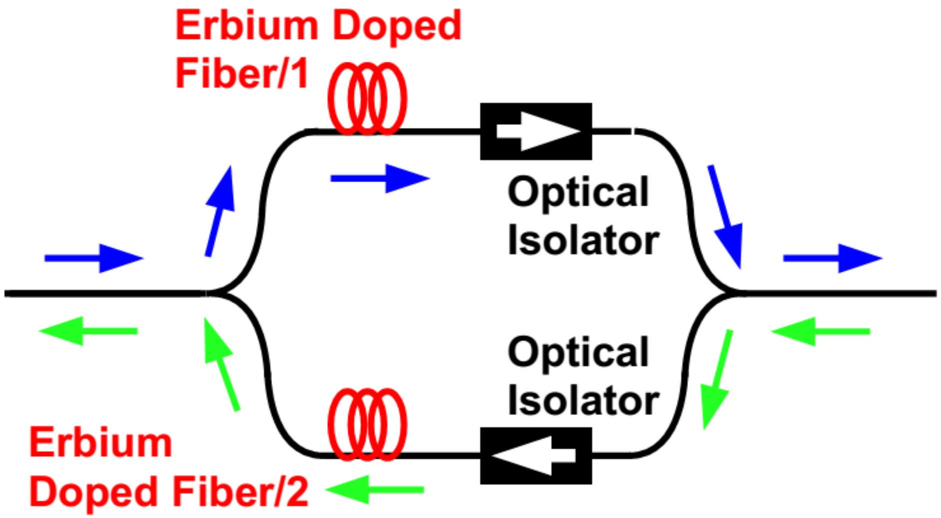
  → after 500 km, 10^{-10} of the original power

  → need optical amplification
  - non commercial
  - Critical technology & operation

Erbium Doped Fiber Amplifiers

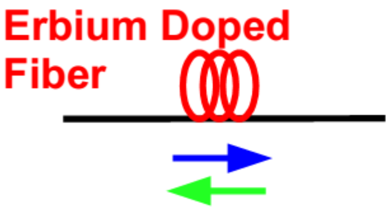
Why not commercial ones?

✗ fiber is not the same in the two ways
→ noise is different



Custom developed EDFAs

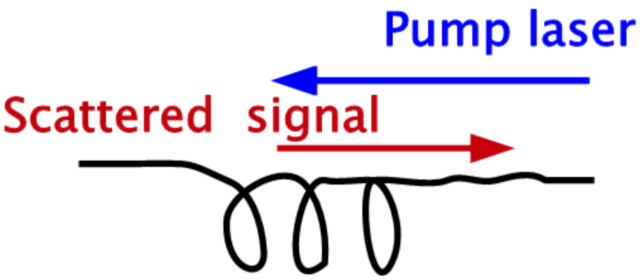
✓Only one fiber
→ fully symmetrical

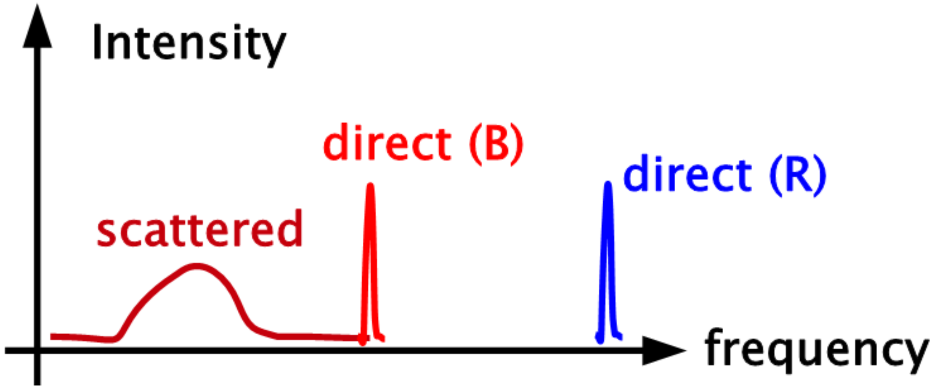


✗ easily saturated by direct and bakscattered ASE
→ span length < 100 km

All coherent optical links so far rely on bidirectional EDFAs

Distributed Amplification





Non linear effects in optical fibers:

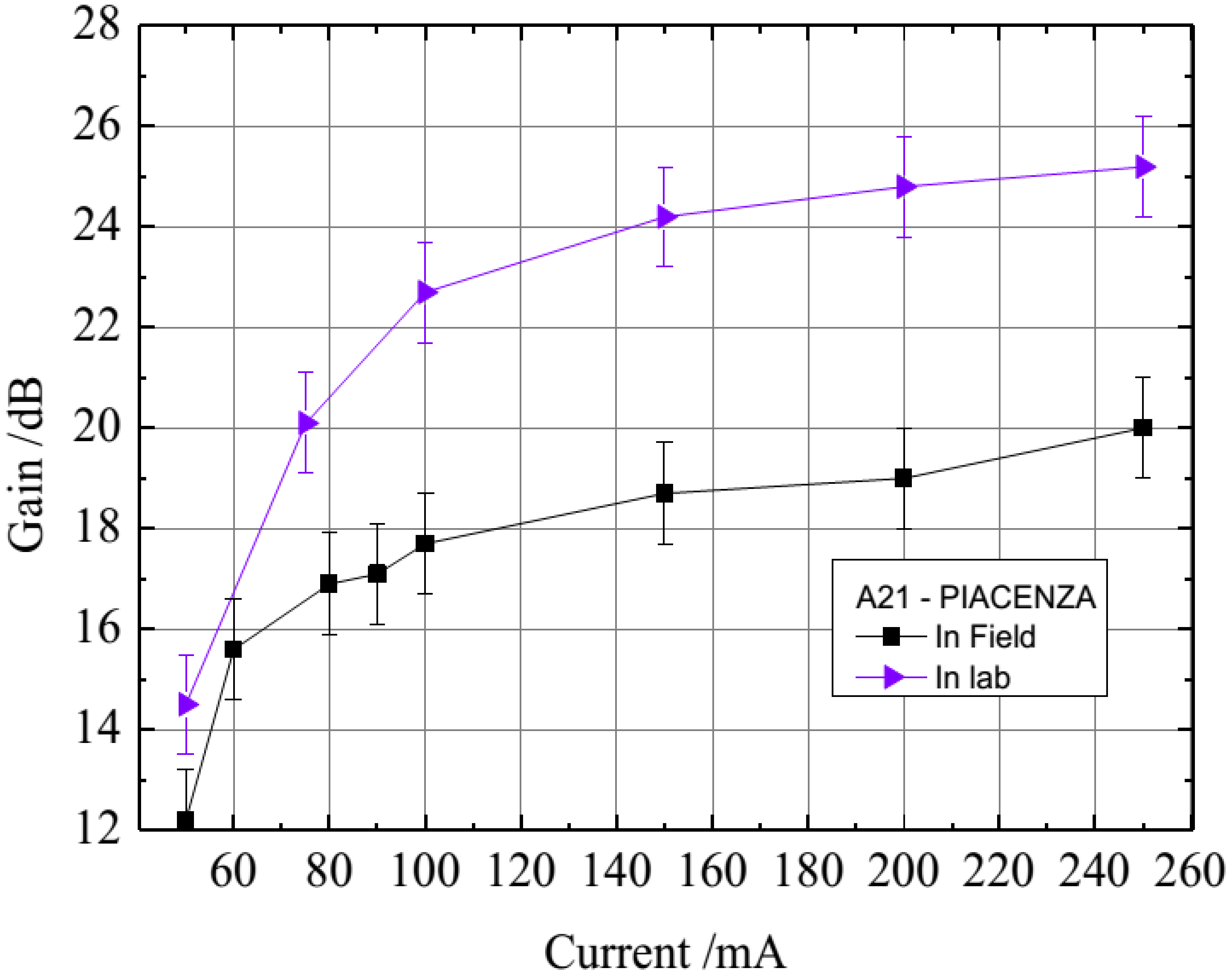
- Stimulated Raman Scattering (10 THz shift)
- Stimulated Brillouin Scattering (10 GHz shift)

✓ No special fiber is needed
(the gain medium is standard fiber)
✓ Fully symmetrical
✓ High gain (gain is distributed on 20 km!)

C. Clivati et al., IEEE Photon. Techn. Lett. 25, 1711 (2013)

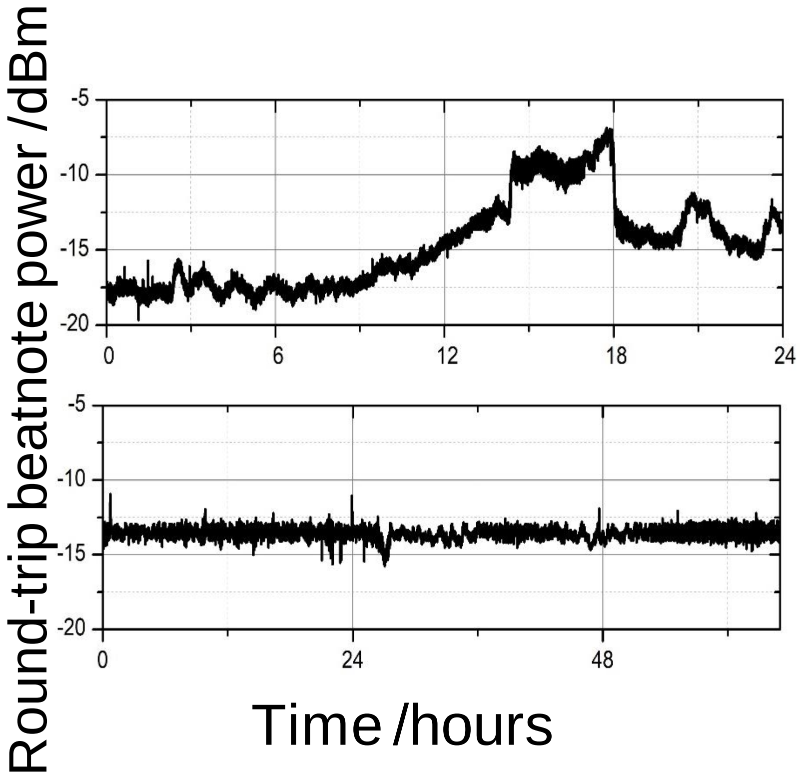
O. Terra et al., Opt. Expr.18, p. 16102 (2010)

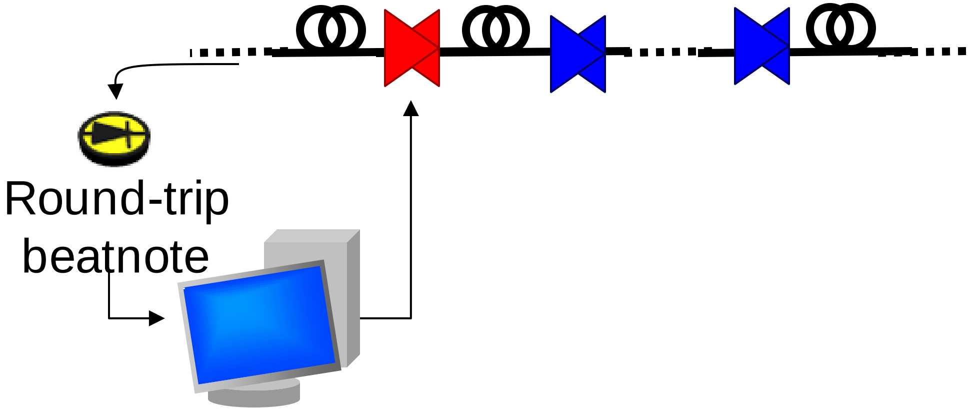
Bidirectional EDFA saturation in-field



Challenges: reliability

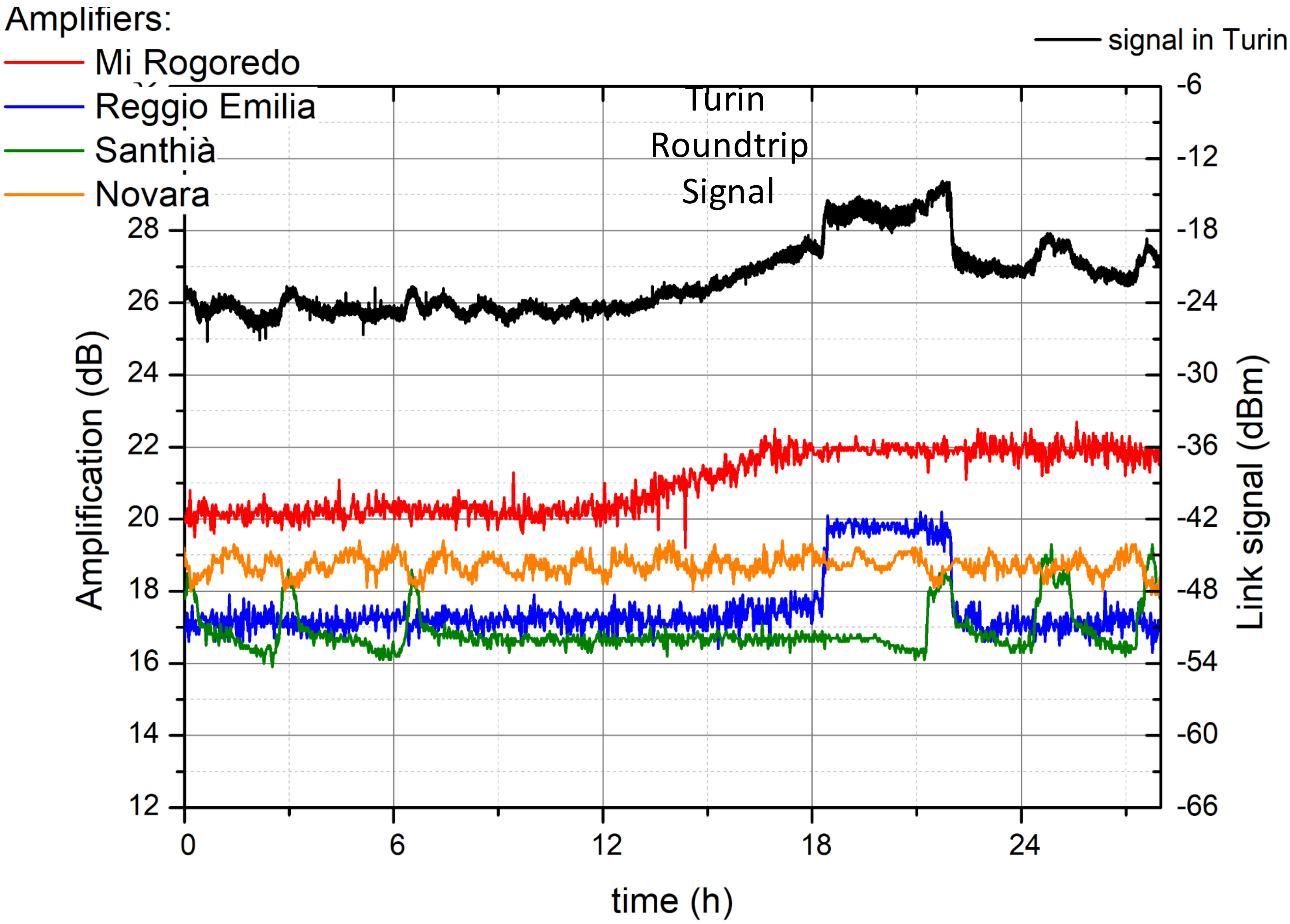
- Small gain (15-20 dB) & filtering
- Automated amplifiers gain adjustment





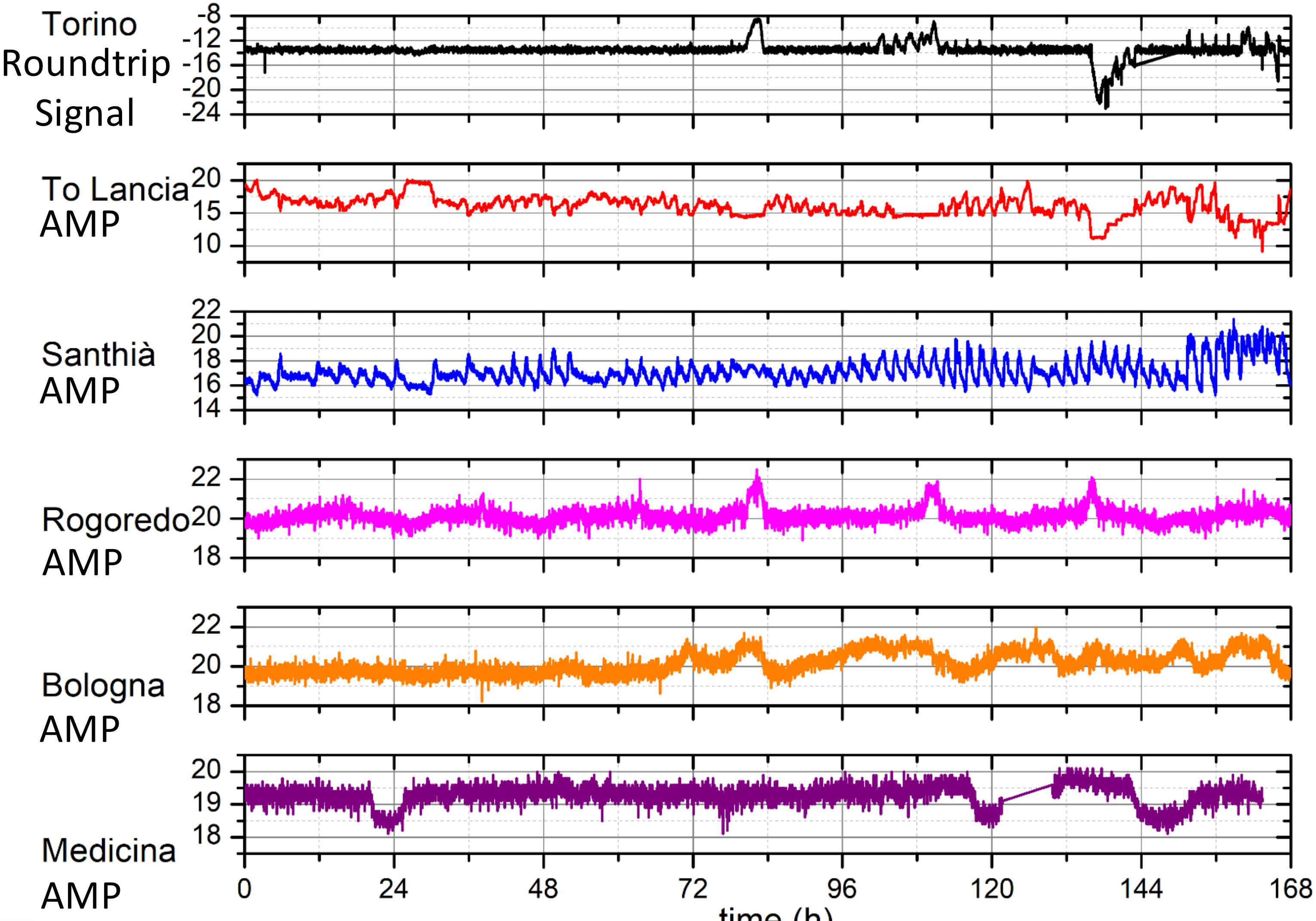
Monitoring and Control

Fluctuations of the Amplifiers Gain used to take the system to delock



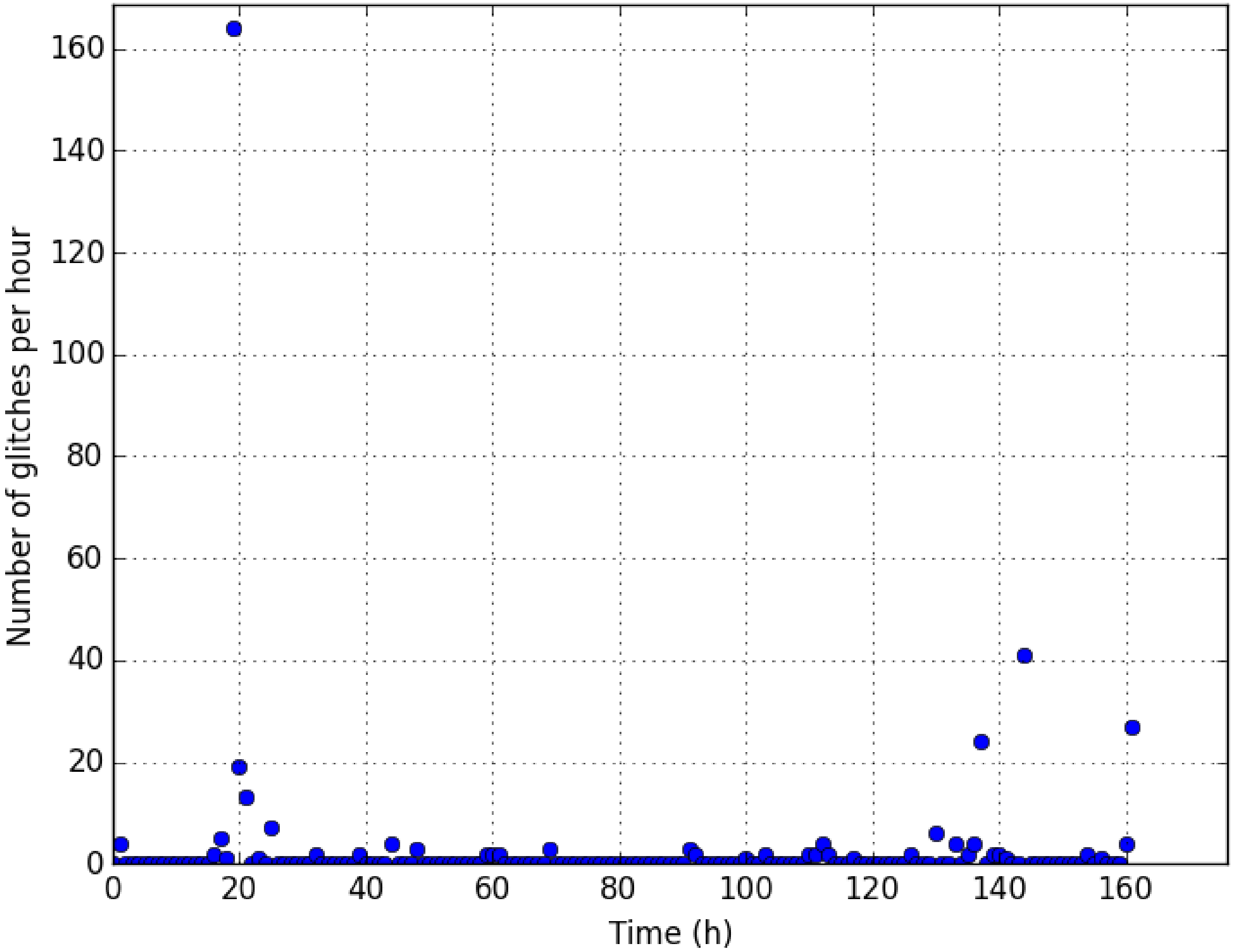
Monitoring and Control /2

New Monitor and telecontrol allows for continuous operations over weeks

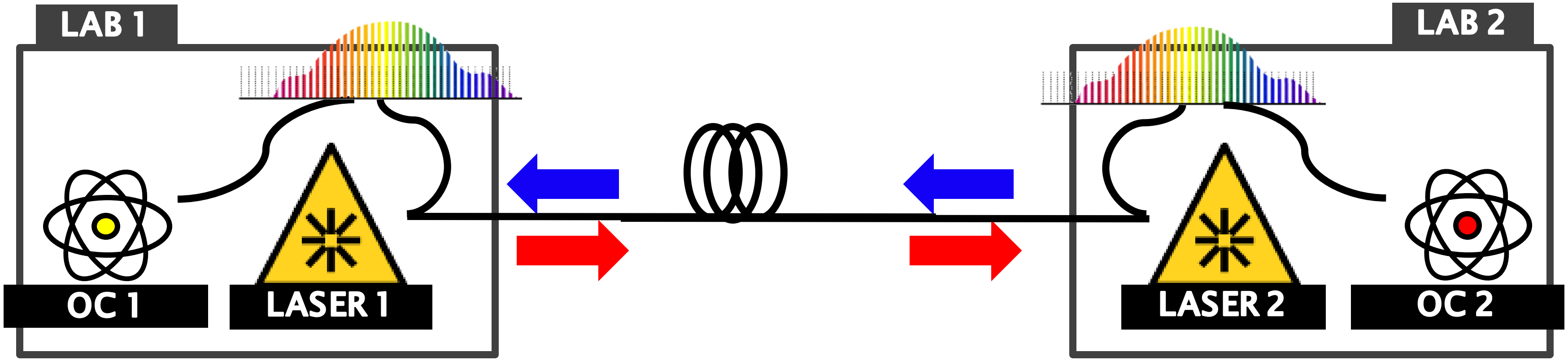


Cycle Slips

Total 377 cycle slips in 160 hours



TWO-WAY Optical Transfer



Advantages:

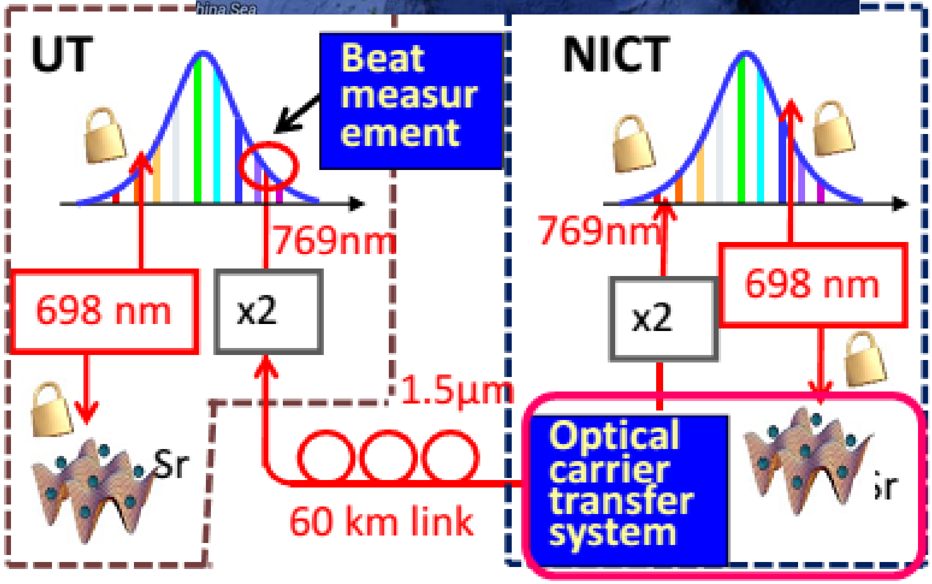
- Lower attenuation (no need of a round-trip)
- Higher SNR at detection

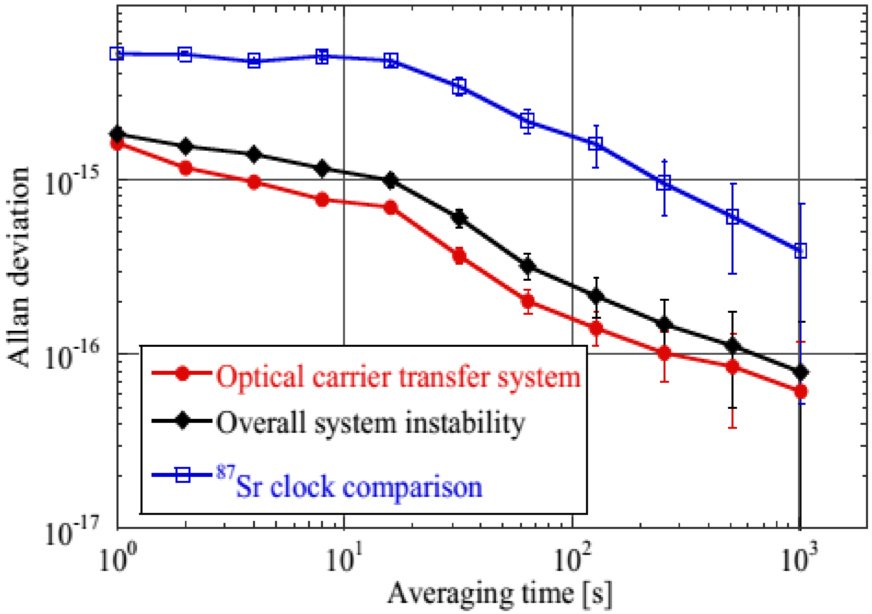
To be investigated:

- ''Real'' testbed: indepenedent detection and aquisition systems
- Data exchange between remote laboratories

C. E. Calosso, et al. Opt. Lett. 40, 131-134 (2015)
C. E. Calosso, et al., Opt. Lett. 39, 1177-1180 (2014)

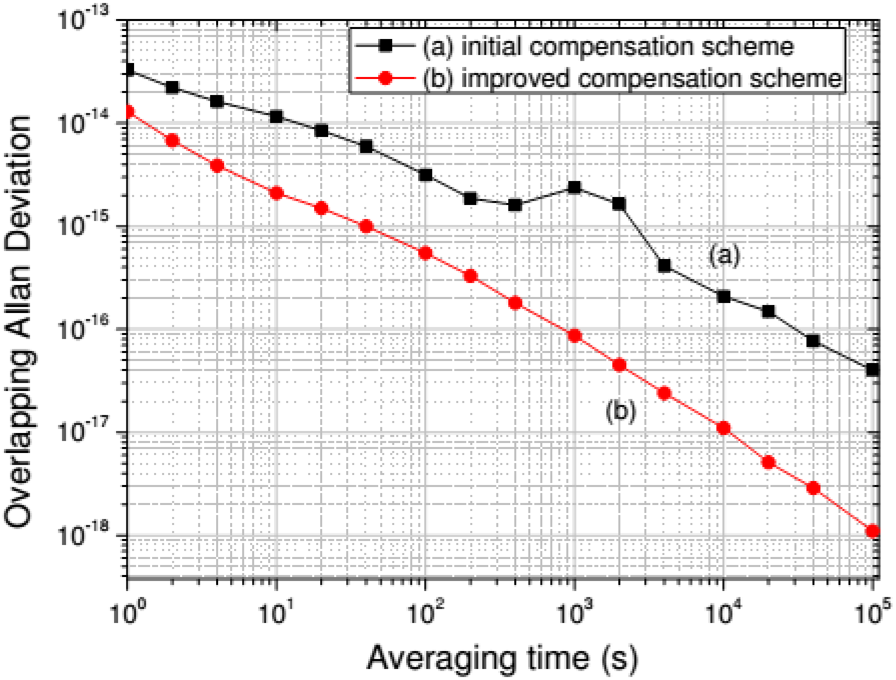
120 km Link in Japan





Hong, F.-L. et al. Opt. Lett. 34, 692–694 (2009).

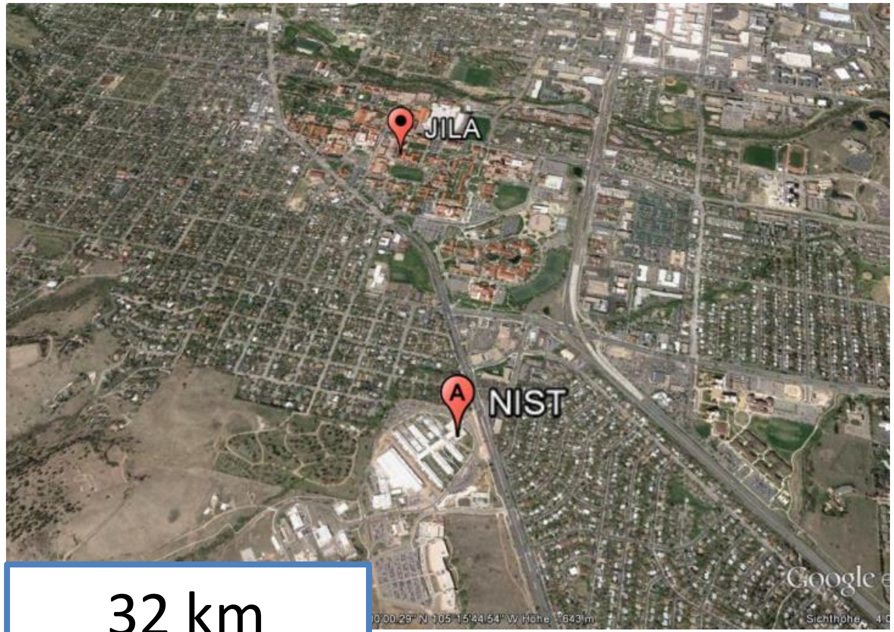
50 km Link in China NIM-THU, Beijiin



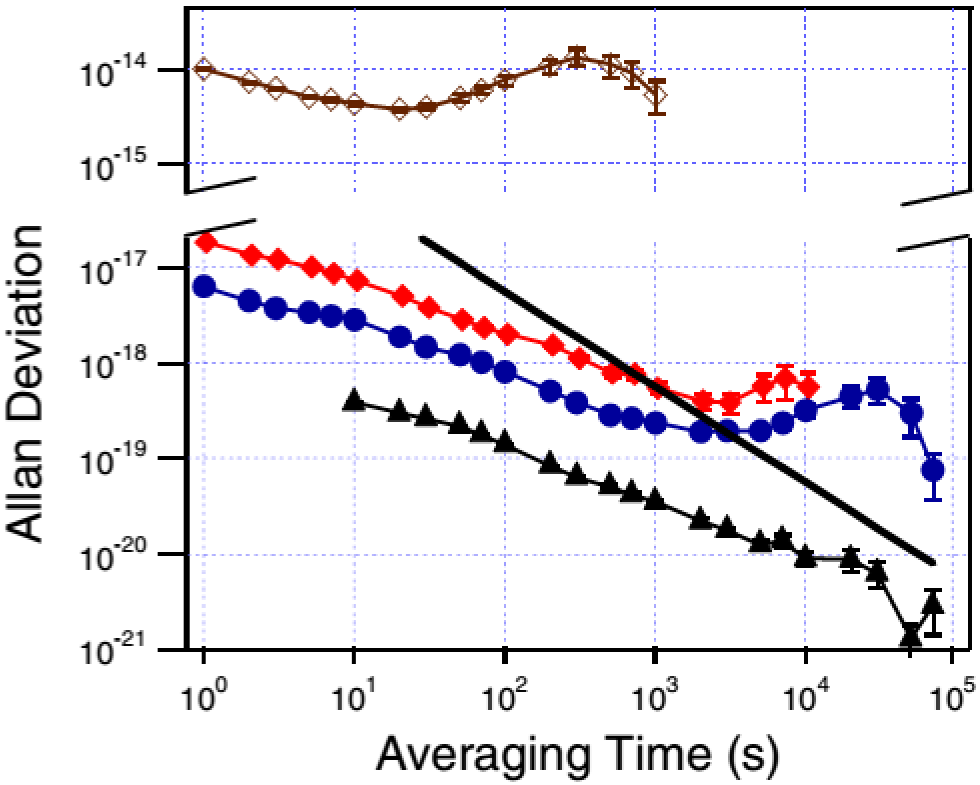
Carrier Amplitude modulation up to 9.2 GHZ

Kun Liang, et al. Proc. 2015 Joint Conf. of the IEEE FCS & EFTF Forum, 12-16 Apr., 2015, Denver,USA, pp. 742-746, 2015

U.S.A.: the NIST-JILA link

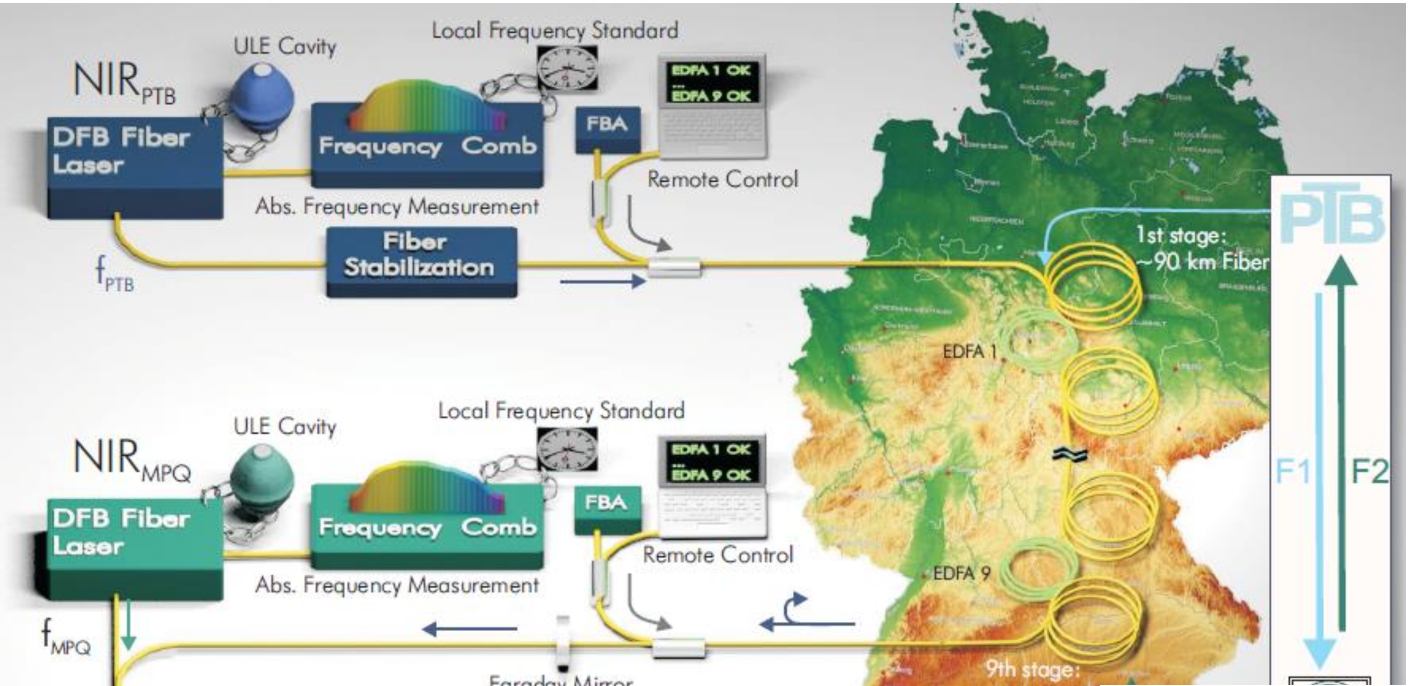


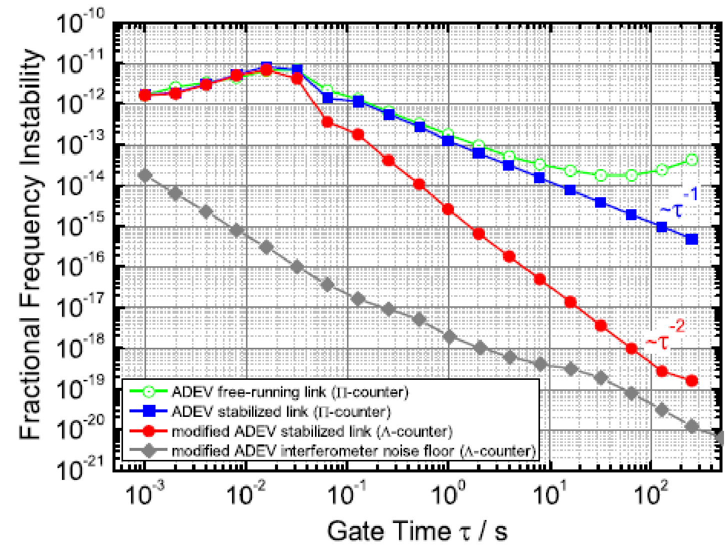
32 km



Jefferts S.R., et al., IEEE Trans. Instrum. Meas., 46, 209-211 (1997)
Foreman S.M., et al., Phys. Rev. Lett.,99, 153601 (2007)
P. A. Williams et al., *J Opt. Soc. Am. B* ***25*** , 1284 (2008)

920 km Link in Germany PTB-MPQ





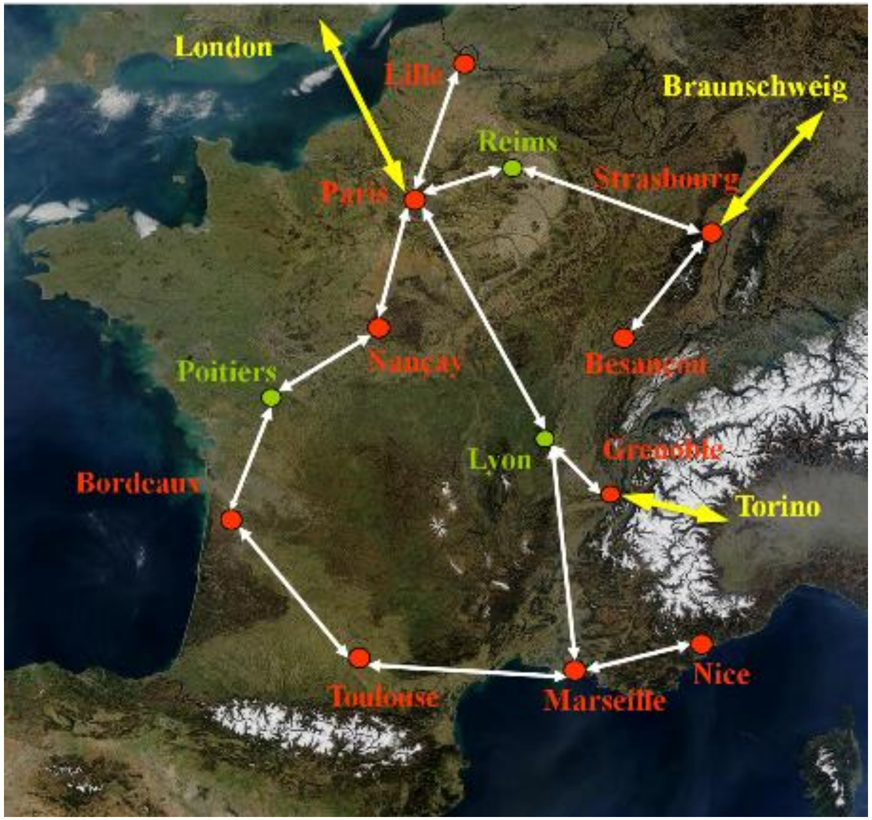
1840 km loop link, MPQ-PTB-MPQ

$\sigma_y < 4 \times 10^{-19}$ @ 100 s

Rel. uncertainty $<3 \times 10^{-19}$

K. Predehl et al; Science 336 (2012) 441-444

S. Droste et al.; PRL 111,110801 (2013)

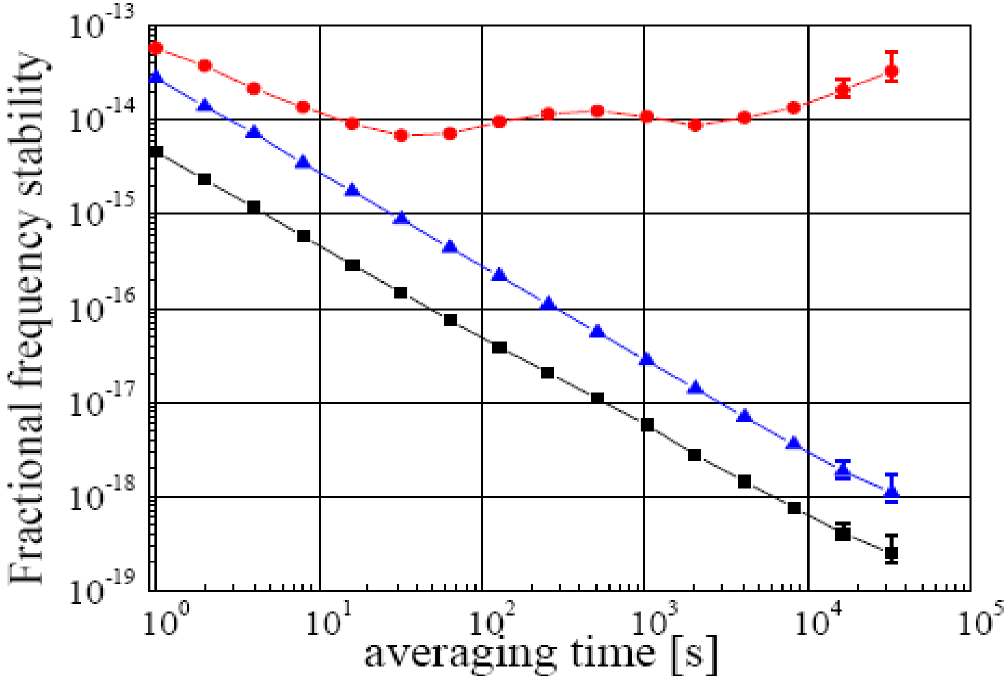


France, Project REFIMEVE+

Fibré Métrologique à Vocation Européenne

Results on 740 km

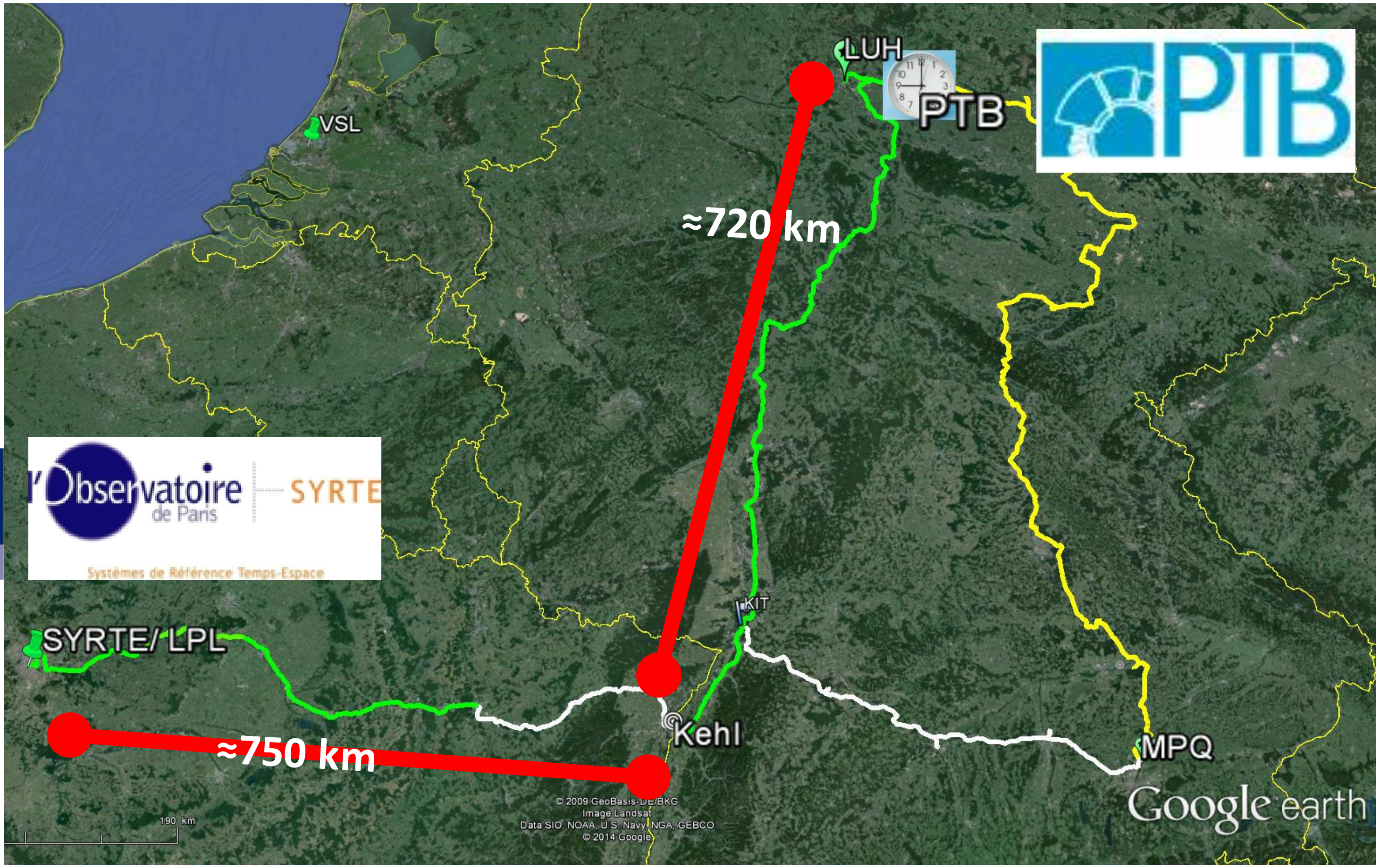
using the Internet fiber network
(DWDM dark channel architecture)



ADEV $3\times10^{-14}/(\tau/s)$ (full bw)

Olivier Lopez *et al.;* Opt. Exp (2012) 20, p. 23518

1500 km Link PTB, Braunschweig - LNE-SYRTE, Paris



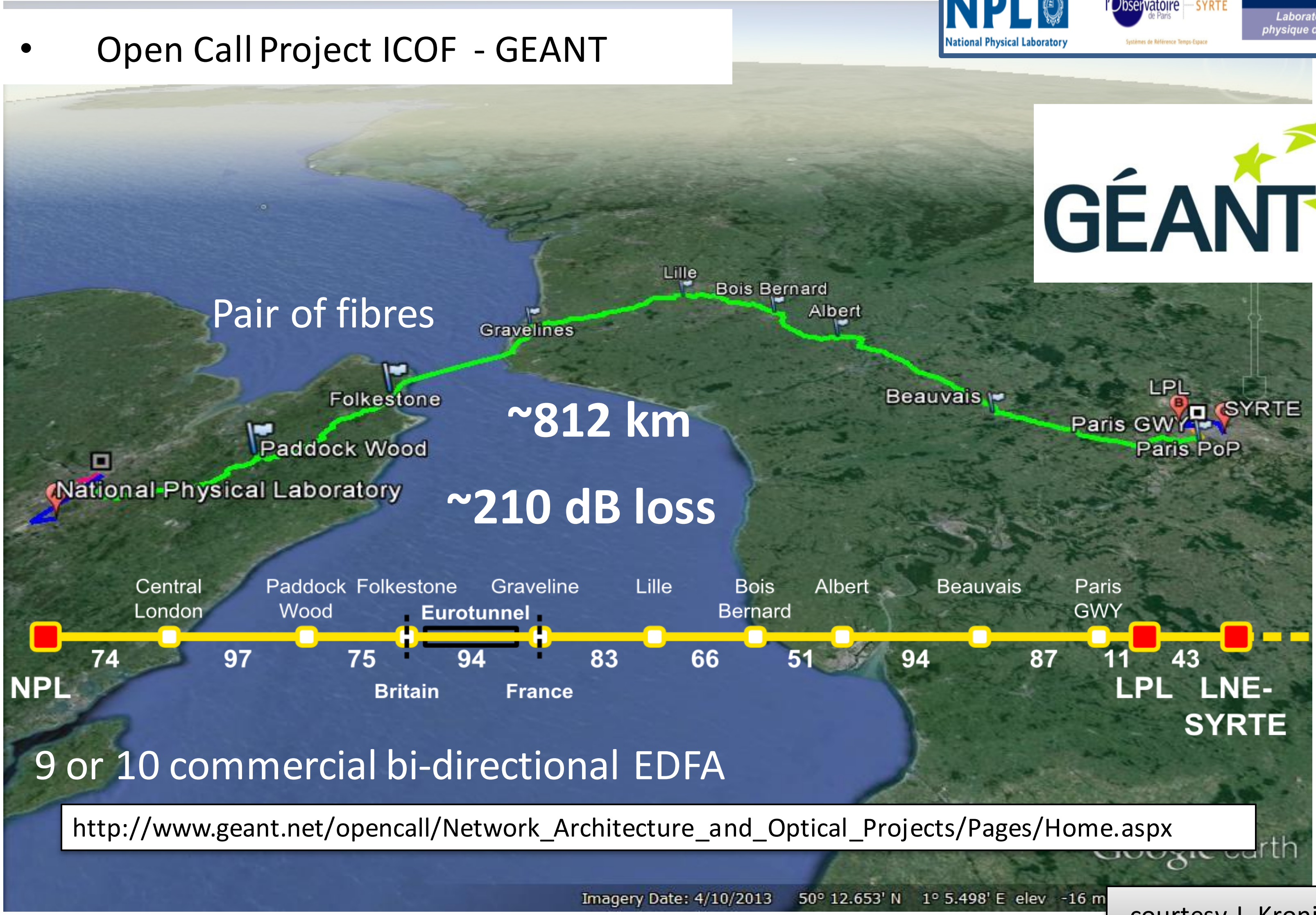
LPL
Laboratoire de physique des lasers

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

Presenlty under operation

812 km London-Paris link

- Open Call Project ICOF - GEANT



Pair of fibres

~812 km

~210 dB loss

9 or 10 commercial bi-directional EDFA

http://www.geant.net/opencall/Network_Architecture_and_Optical_Projects/Pages/Home.aspx

courtesy J. Kronjaeger, NPL

Italy: LIFT, 1800 km

- Quantum Technologies
- Radioastronomy
- Ultracold atoms Physics
- Space - Galileo
- Finance

7 Research Institutes linked:

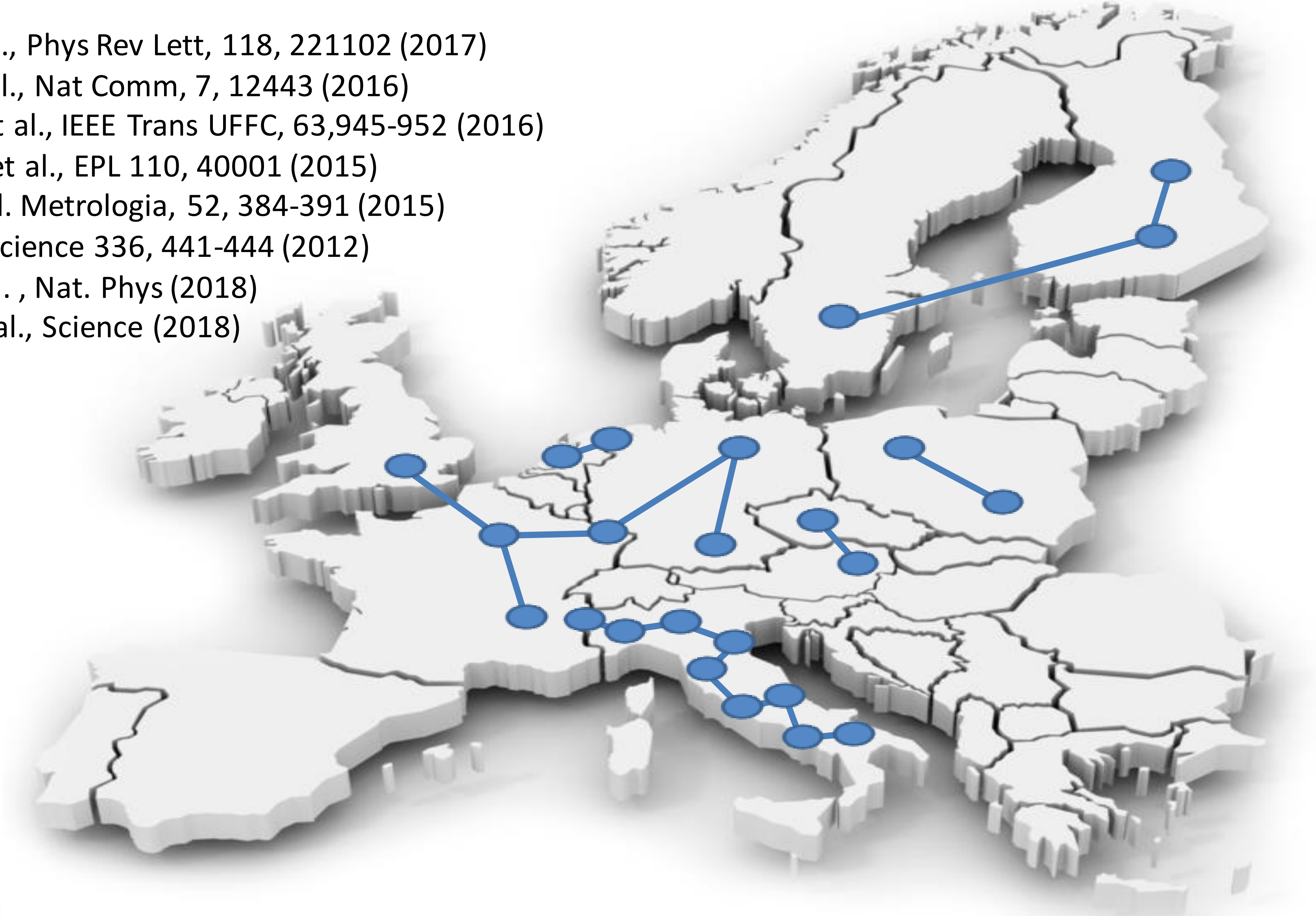
CNR – National Research Council
ASI – Italian Space Agency
INAF – Italian Astrophysics Institute

3 Industrial Users

Thales Alenia Space Italy
Telespazio;
Consortium Top-IX

European fibre links

P. Delva et al., Phys Rev Lett, 118, 221102 (2017)
C. Lisdat et al., Nat Comm, 7, 12443 (2016)
E. Dierickx et al., IEEE Trans UFFC, 63,945-952 (2016)
D. Calonico et al., EPL 110, 40001 (2015)
Z. Jiang, et al. Metrologia, 52, 384-391 (2015)
K. Predehl, Science 336, 441-444 (2012)
J. Grotti et al. , Nat. Phys (2018)
G. Marra et al., Science (2018)



European fibre links

BIPM

and WG ATFT of CCTF

European Commission

And DG Connect

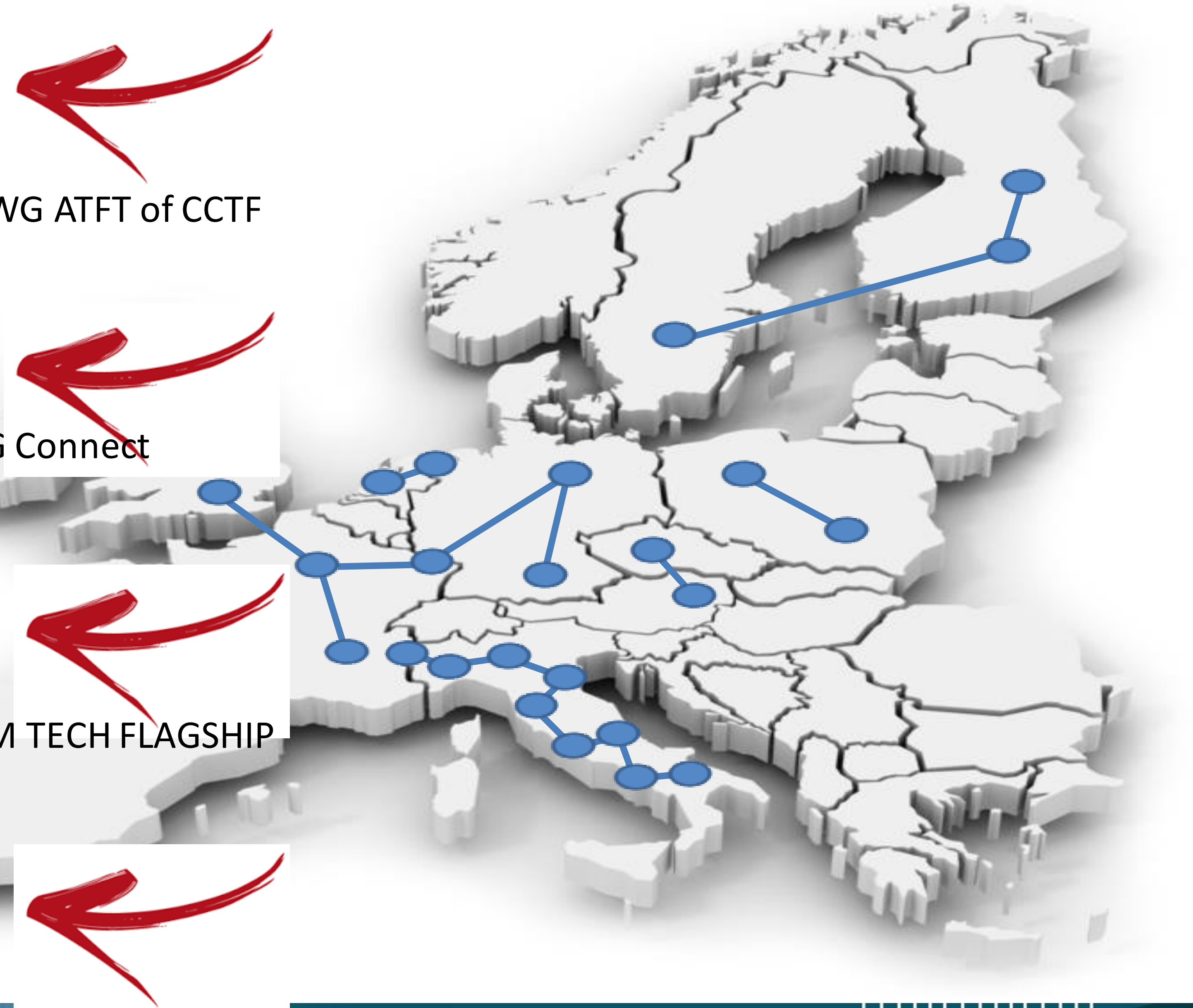
QuantumManifesto

A New Era of Technology

May 2016

And QUANTUM TECH FLAGSHIP

EURAMET



European fibre links

- In Europe there is an intense research activity on fibre links
- There is a variety of techniques: Coherent FL, Electronic Stabilized Links, PTP Hich Accuracy (White Rabbit) Time Transfer, Optical Combs over fibre
- So far, Large projects involving links

(NMI coordination):

EMRP-NEAT-FT / EMPIR-OFTEN

H2020-CLONETS/ H2020-DEMETRA

European Projects on fibre links

H2020-INFRAINNOV

THE FRAMEWORK PROGRAMME FOR RESEARCH AND INNOVATION
HORIZON 2020

CLONETS
CLOCK NETWORK SERVICES

Strategy and innovation for clock services over optical-fibre networks
16 partners, Coordination: OP

l'Observatoire de Paris — SYRTE — Systèmes de Référence Temps-Espace
INRiM — ISTITUTO NAZIONALE DI RICERCA METROLOGICA
NPL — National Physical Laboratory
PTB — Physikalisch-Technische Bundesanstalt Braunschweig und Berlin
LPL — Laboratoire de physique des lasers
PSNC
RENATER — CONNECTEUR DE SAVOIRS
MenloSystems GmbH
AGH — AGH University of Science and Technology
top IX
Consortium GARR
µQUANS

APPLICATIONS

- Optical Clock Comparisons
- Frequency dissemination for VLBI radioastronomy and geodesy
- Relativistic geodesy with clocks
- Earthquake detection with coherent optical fibers
- Atomic and Molecular Spectroscopy

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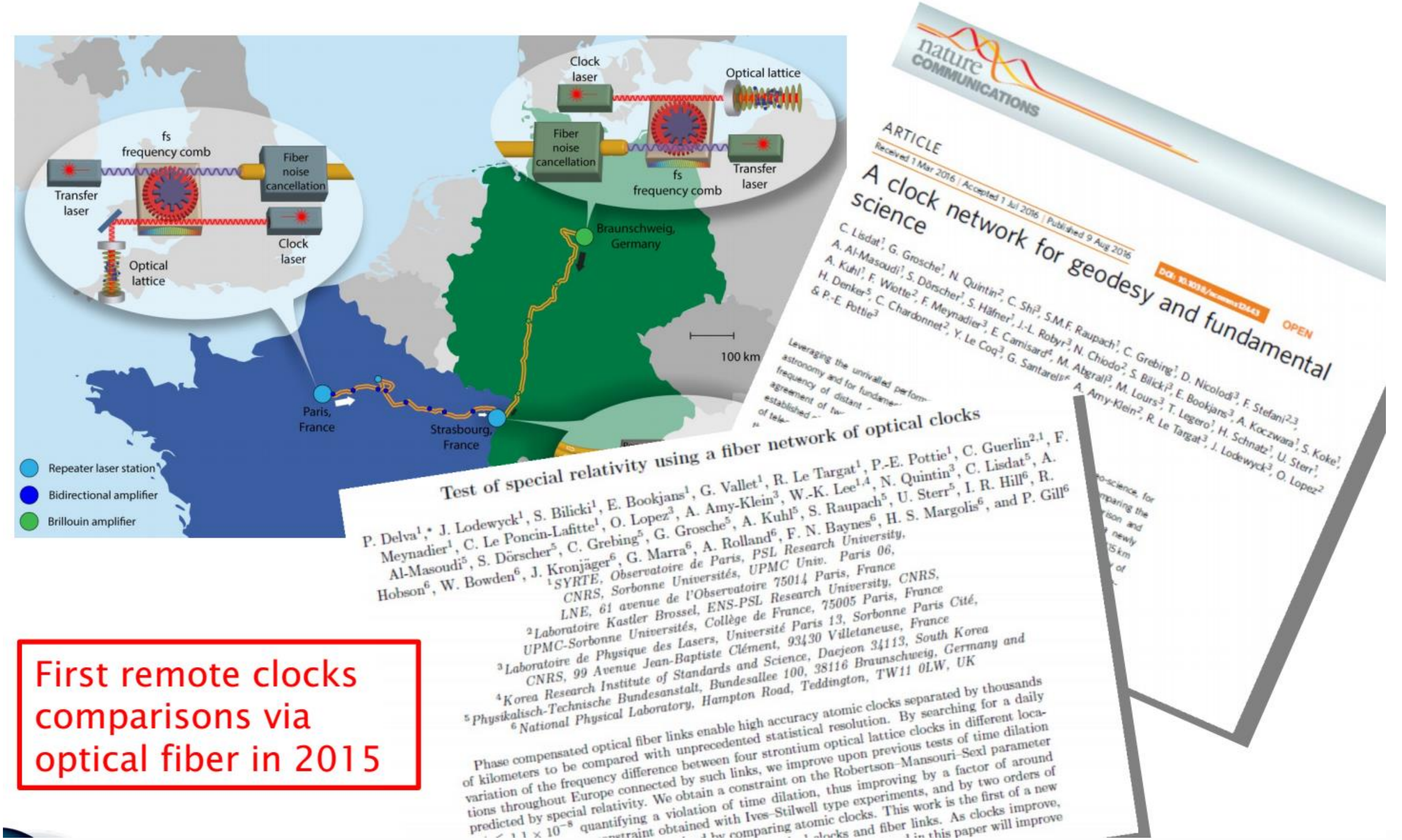
Towards a European network of atomic clocks



nature COMMUNICATIONS

ARTICLE

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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]

Leveraging the unrivalled perform
astronomy and for fundame
frequency of distant
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Test of special relativity using a fiber network of optical clocks

P. Delva[1],* J. Lodewyck[1], S. Bilicki[1], E. Bookjans[1], G. Vallet[1], R. Le Targat[1], P.-E. Pottie[1], C. Guerlin[2,1], F. Meynadier[1], C. Le Poncin-Lafitte[1], O. Lopez[3], A. Amy-Klein[3], W.-K. Lee[1,4], N. Quintin[3], C. Lisdat[5], A. Al-Masoudi[5], S. Dörscher[5], C. Grebing[5], G. Grosche[5], A. Kuhl[5], S. Raupach[5], U. Sterr[5], I. R. Hill[6], R. Hobson[6], W. Bowden[6], J. Kronjäger[6], G. Marra[6], A. Rolland[6], F. N. Baynes[6], H. S. Margolis[6], and P. Gill[6]

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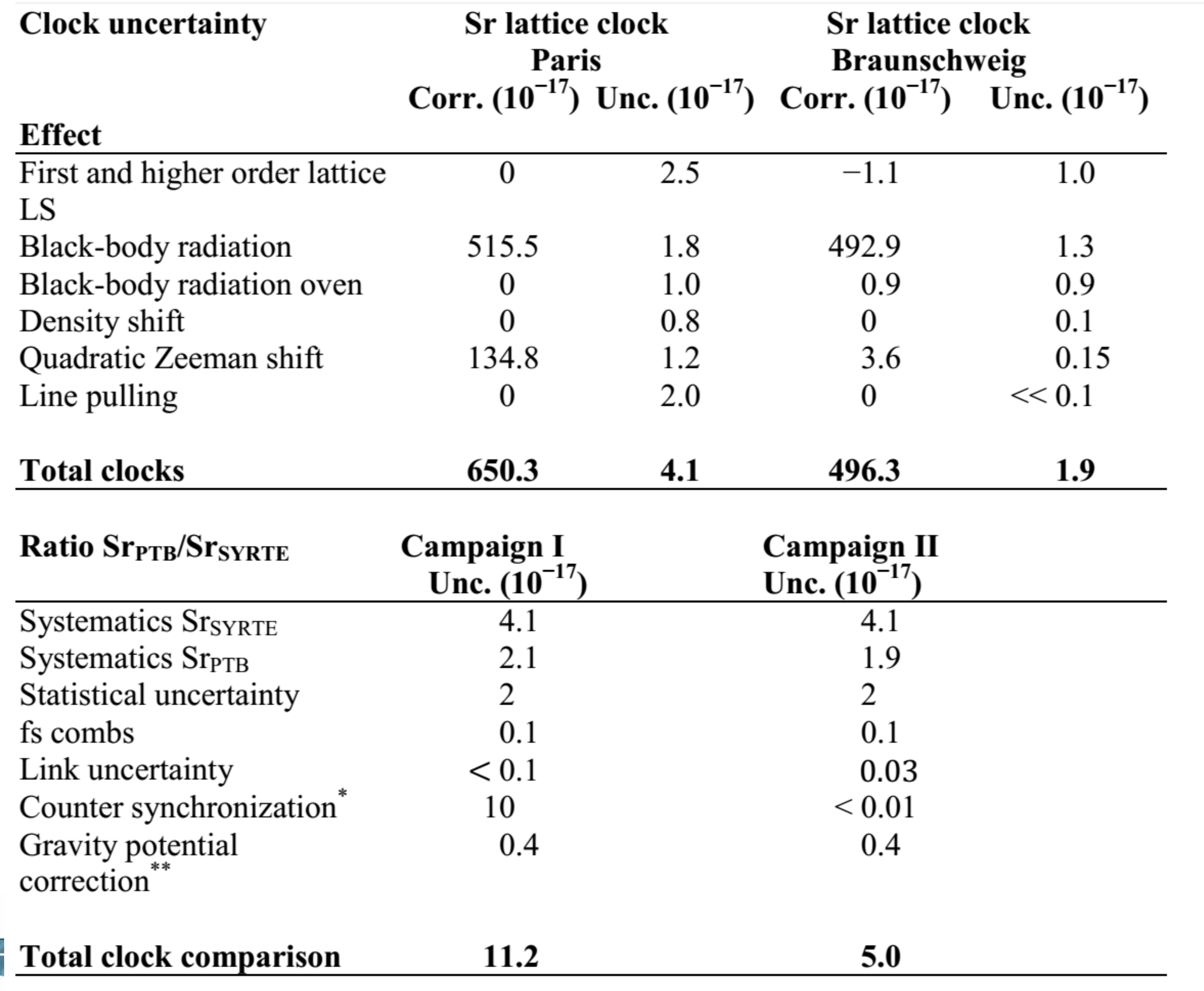
Phase compensated optical fiber links enable high accuracy atomic clocks separated by thousands of kilometers to be compared with unprecedented statistical resolution. By searching for a daily variation of the frequency difference between four strontium optical lattice clocks in different locations throughout Europe connected by such links, we improve upon previous tests of time dilation predicted by special relativity. We obtain a constraint on the Robertson–Mansouri–Sexl parameter
$< 1.1 \times 10^{-8}$ quantifying a violation of time dilation, thus improving by a factor of around
onstraint obtained with Ives–Stilwell type experiments, and by two orders of
by comparing atomic clocks. This work is the first of a new
clocks and fiber links. As clocks improve,
in this paper will improve

First remote clocks comparisons via optical fiber in 2015

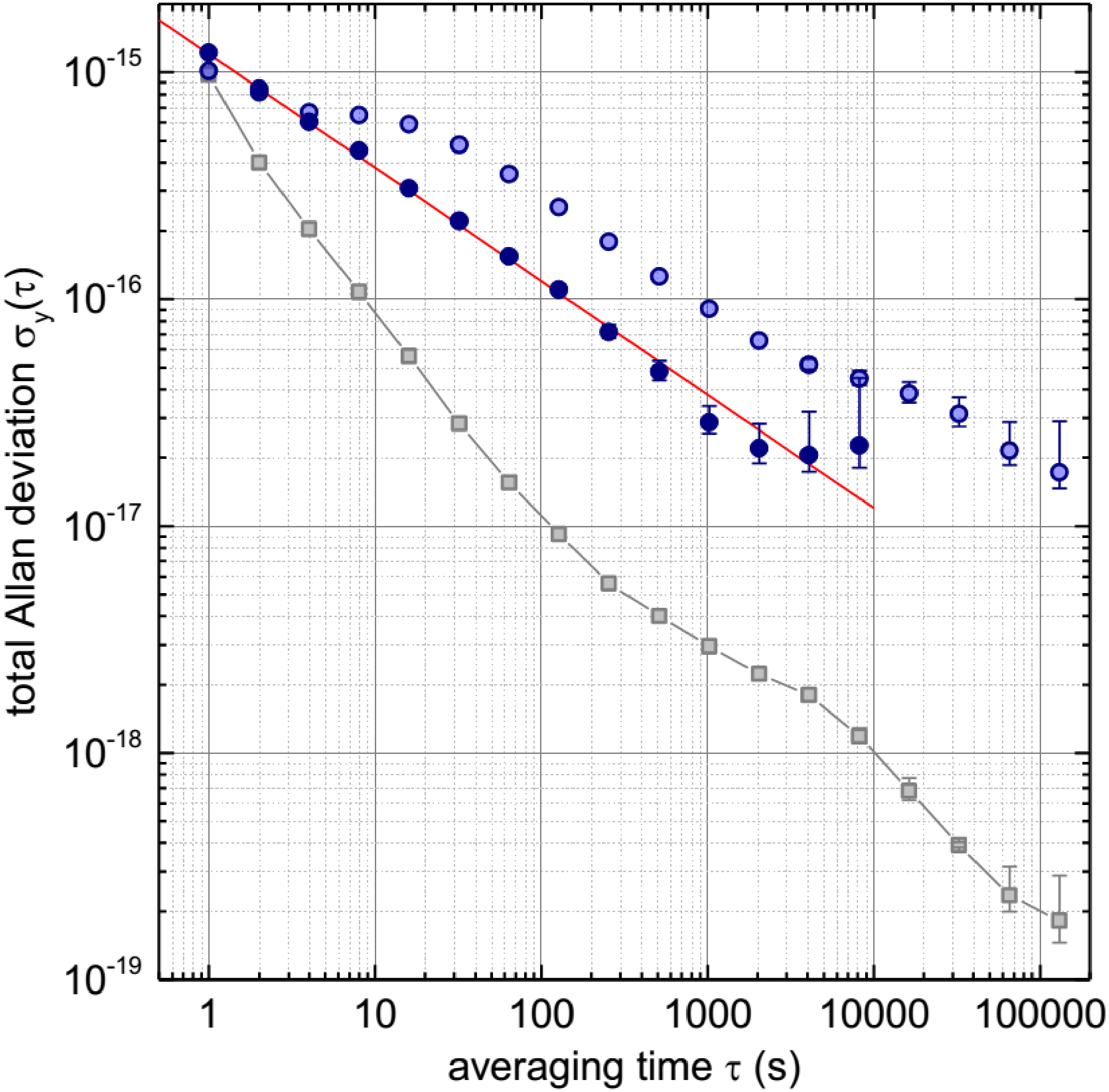
Coherent Fibre link comparing optical clocks at parts in 1e17



Clock uncertainty	**Sr lattice clock Paris**		**Sr lattice clock Braunschweig**	
	Corr. (10^{-17})	**Unc. (10^{-17})**	**Corr. (10^{-17})**	**Unc. (10^{-17})**
Effect				
First and higher order lattice LS	0	2.5	−1.1	1.0
Black-body radiation	515.5	1.8	492.9	1.3
Black-body radiation oven	0	1.0	0.9	0.9
Density shift	0	0.8	0	0.1
Quadratic Zeeman shift	134.8	1.2	3.6	0.15
Line pulling	0	2.0	0	<< 0.1
Total clocks	**650.3**	**4.1**	**496.3**	**1.9**

Ratio Sr_{PTB}/Sr_{SYRTE}	**Campaign I Unc. (10^{-17})**	**Campaign II Unc. (10^{-17})**
Systematics Sr_{SYRTE}	4.1	4.1
Systematics Sr_{PTB}	2.1	1.9
Statistical uncertainty	2	2
fs combs	0.1	0.1
Link uncertainty	< 0.1	0.03
Counter synchronization*	10	< 0.01
Gravity potential correction**	0.4	0.4
Total clock comparison	**11.2**	**5.0**

Coherent Fibre link comparing optical clocks at parts in 1e17



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Dissemination for radioastronomy

T/F fibre links for Radioastronomy :

- Faster operations
- Better mm-VLBI: above 80 GHz, H-Masers are the main limit to resolution

  M. Rioja, et al. Astron. J., vol. 144, no. 4, art. no. 121, 2012.
  B. Nikolic, et al. Astron. Astrophys., vl. 552, art. no. A104, Apr. 2013.
  M. Rioja and R. Dodson, Astron. J., vol. 141, no. 4, art. no. 114, 2011
- Existing mm-VLBI Telescope in Europe: MPIfR (Germany), IRAM (Spain), Onsala (Sweden), Metsahovi (Finland),

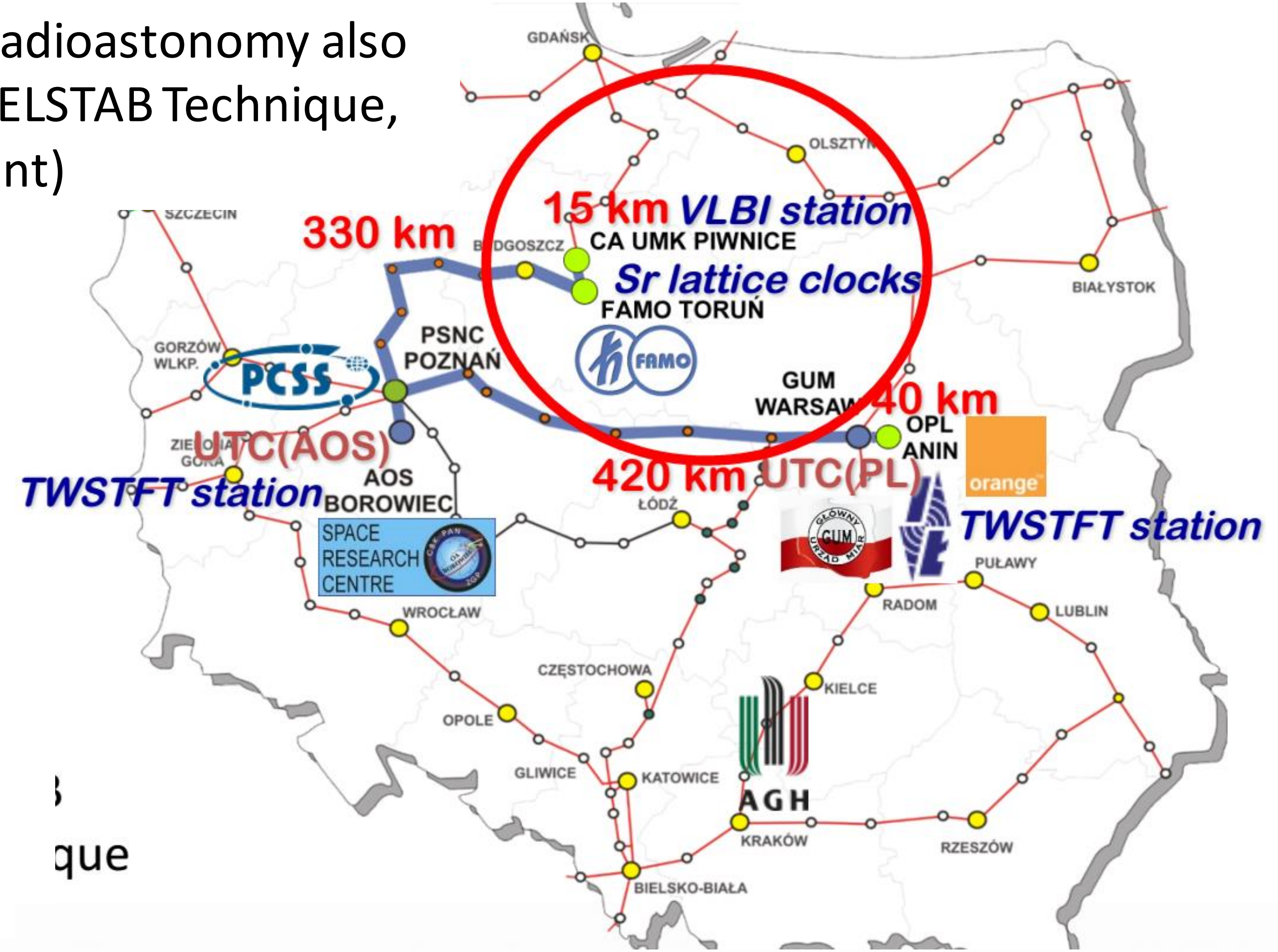
- Study of compact radio sources (better angular resolution) and interstellar molecular clouds
- In Geodesy VLBI, accuracy is relevant and 1-mm positioning accuracy requires clocks uncertainties at 1e-16.

  A. Neill, et al. Report of Working Group 3 to the IVS Directing Board, Sep. 2005.
- Studying Pulsar through absolute accurate time

  Andrew Lyne, EFTF2016

Dissemination for radioastronomy

A link for Radioastonomy also in Poland (ELSTAB Technique, not coherent)



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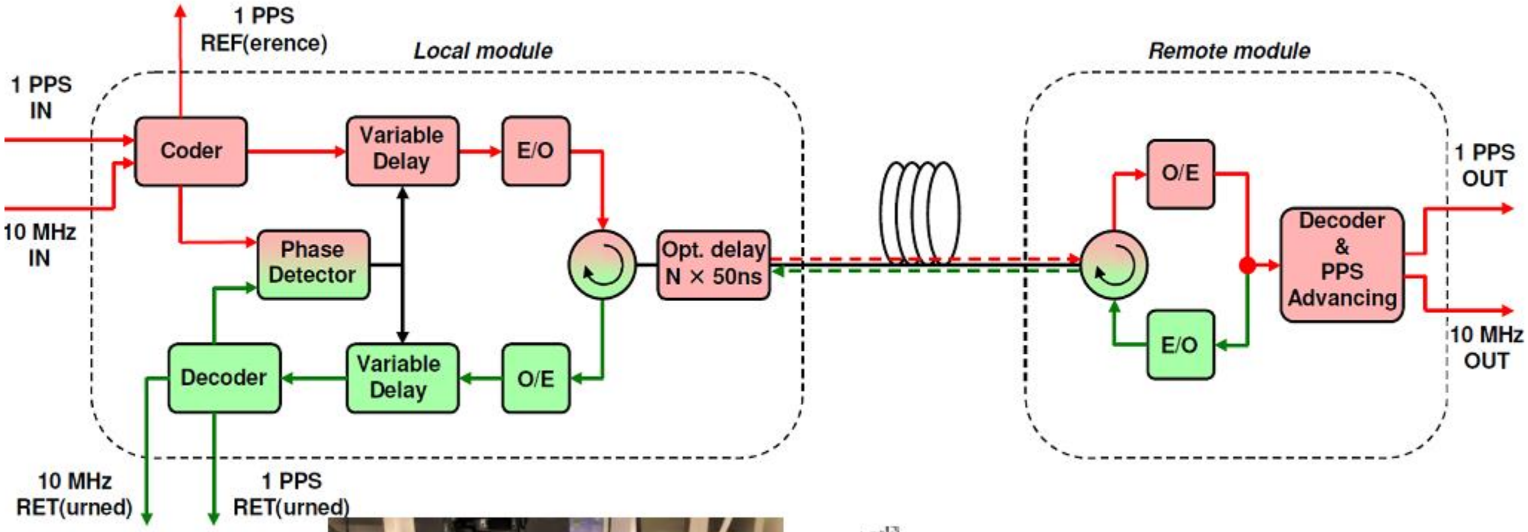
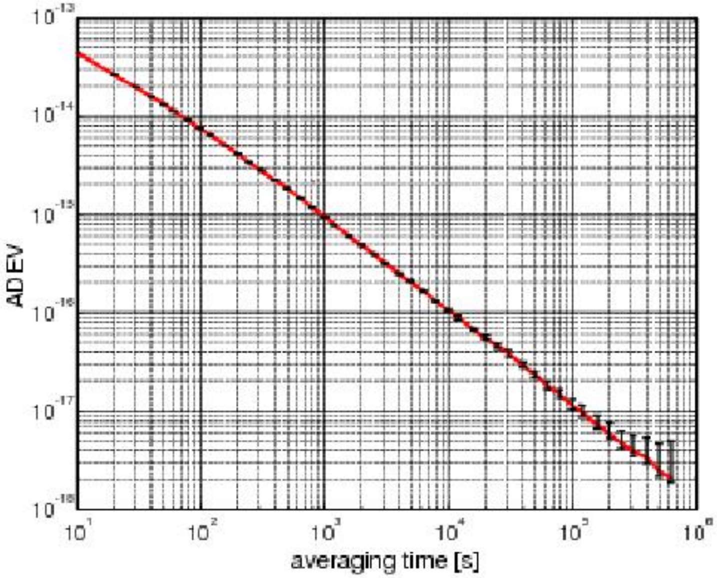
Dissemination for radioastronomy

A link for Radioastonomy also in Sweden
(ELSTAB Technique, not coherent)

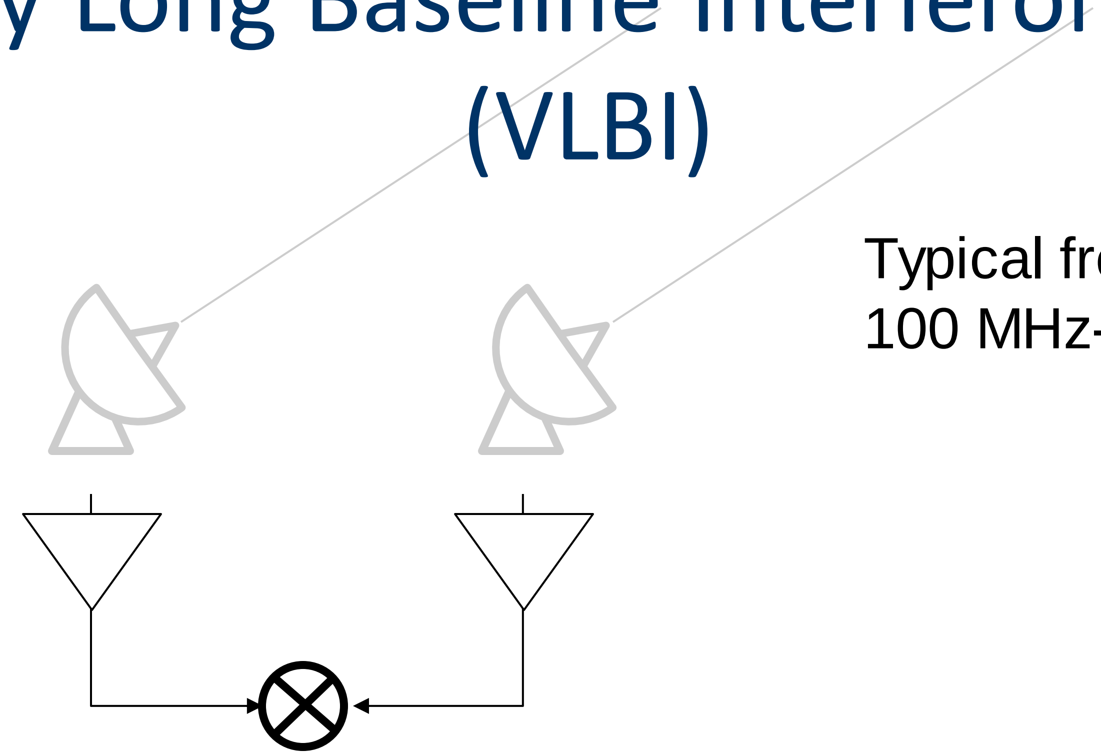
Goteborg-Onsala, 50 km

ELSTAB – the minimum introduction



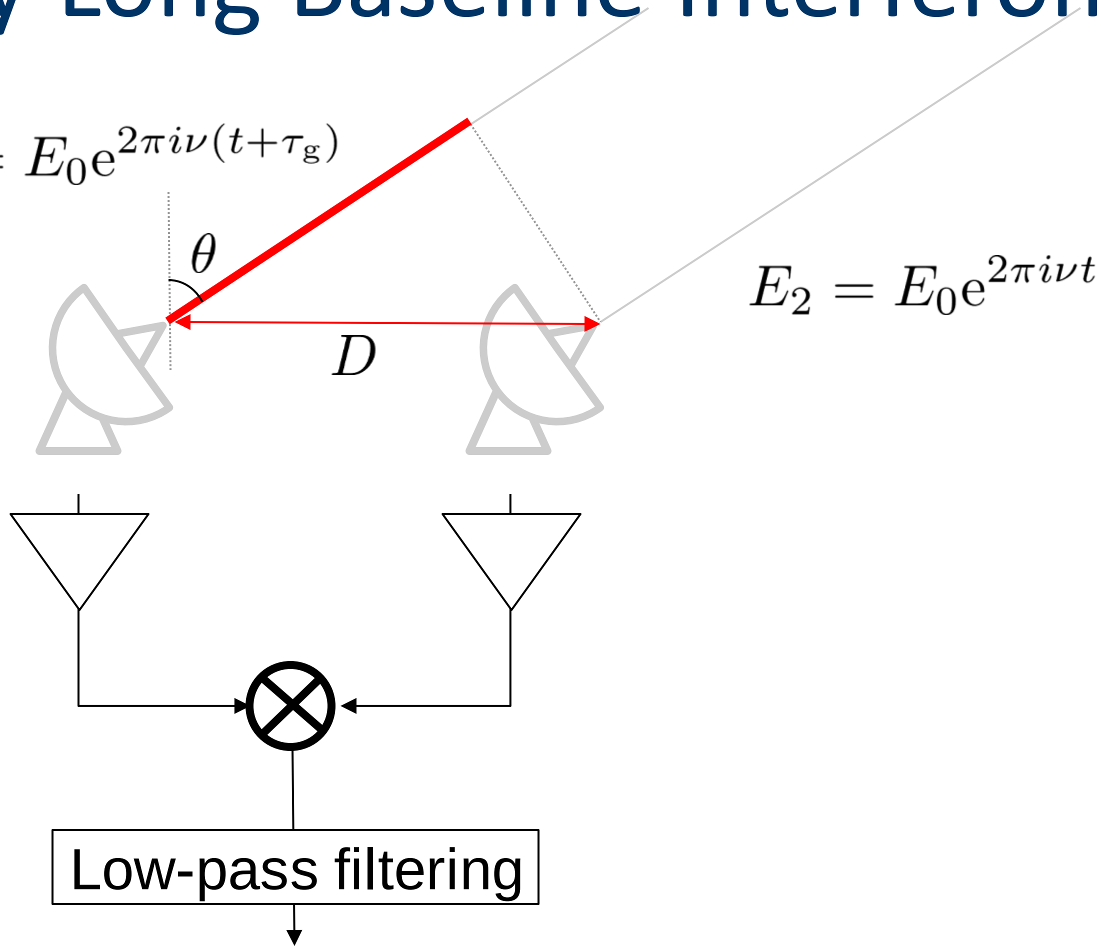


Very Long Baseline Interferometry (VLBI)



Typical frequency range:
100 MHz-30 GHz

Very Long Baseline Interferometry



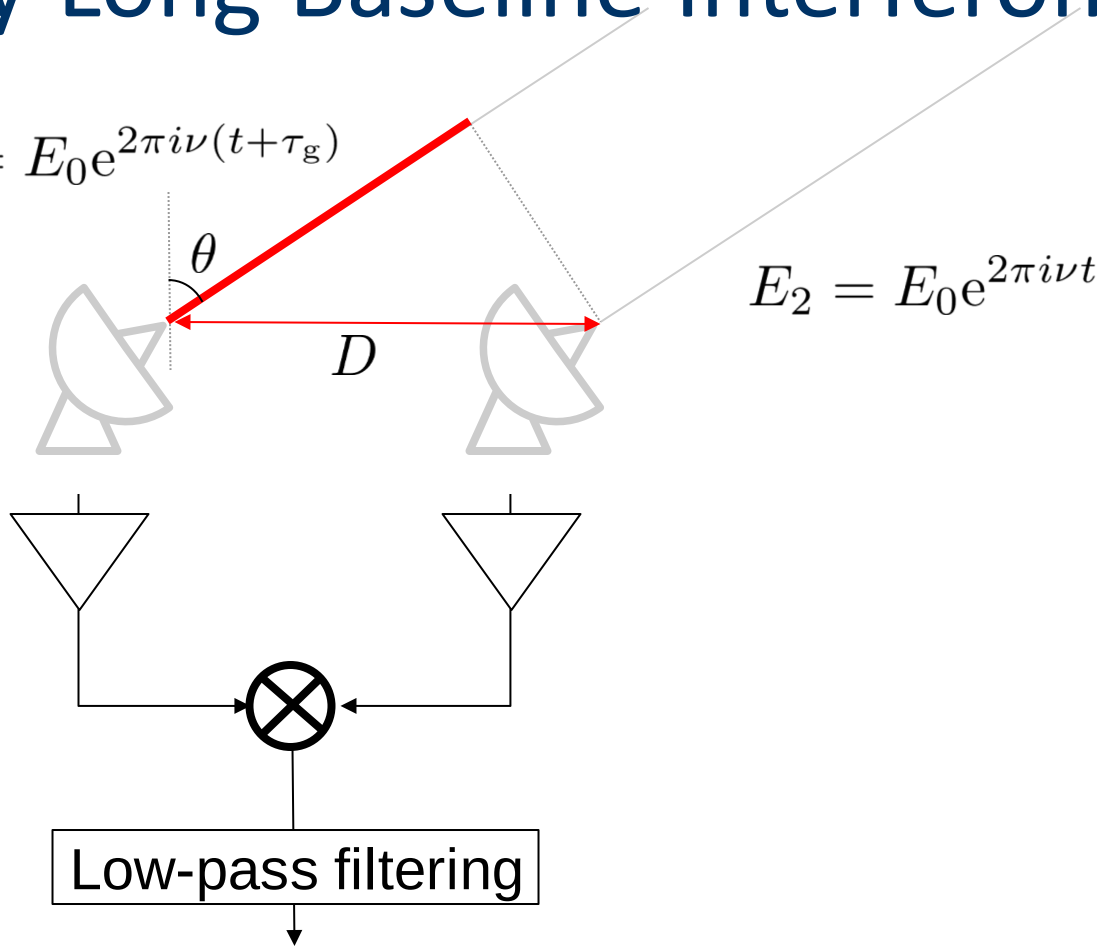
$$E_1 = E_0 \mathrm{e}^{2\pi i \nu (t+\tau_{\mathrm{g}})}$$

$$\tau_{\mathrm{g}} = \frac{D \sin\theta}{c}$$

$$E_2 = E_0 \mathrm{e}^{2\pi i \nu t}$$

$$r = \cos\left(2\pi\nu\frac{D\sin\theta}{c}\right)$$

Very Long Baseline Interferometry



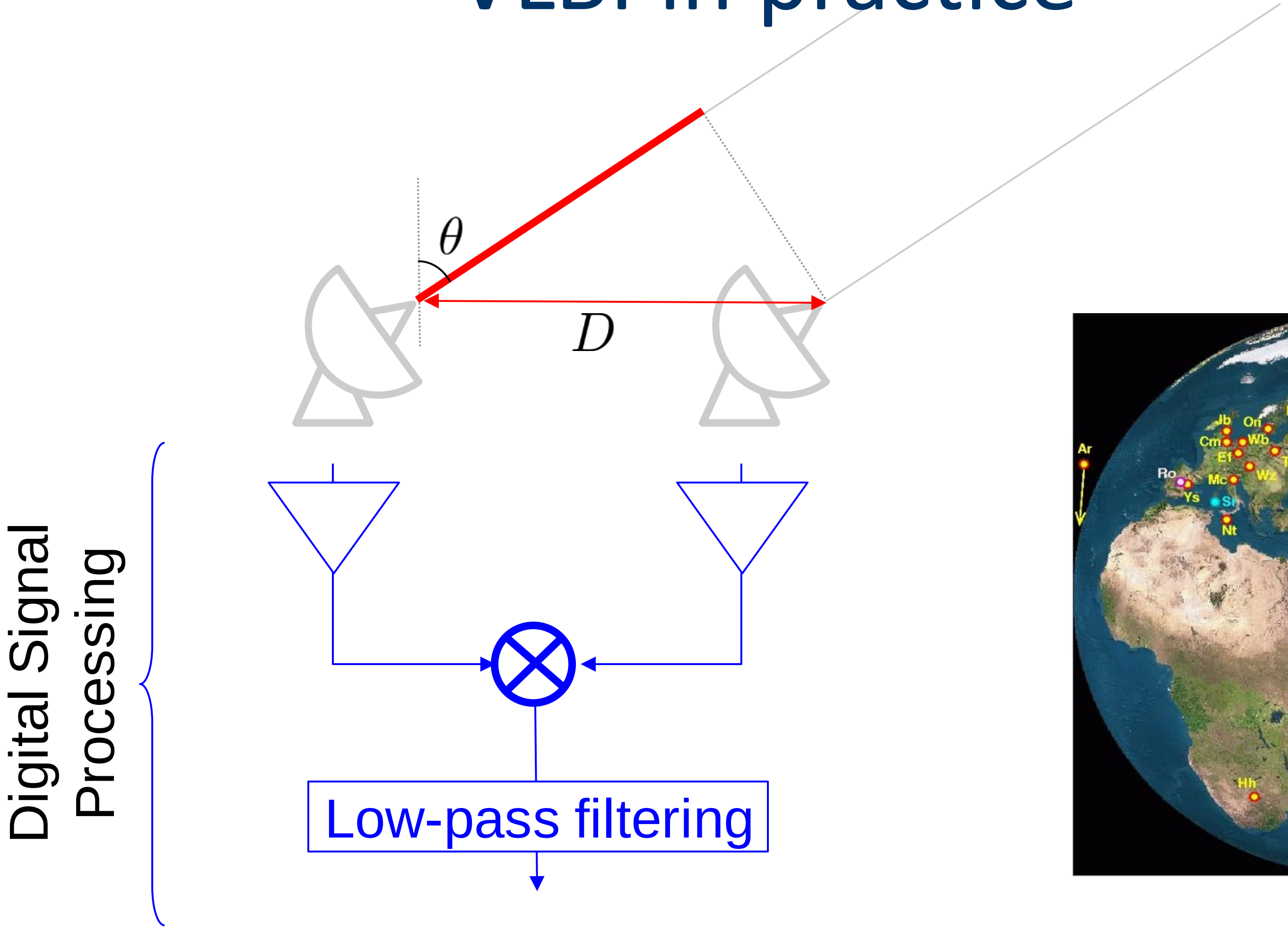
$$E_1 = E_0 \mathrm{e}^{2\pi i \nu (t+\tau_\mathrm{g})}$$

$$E_2 = E_0 \mathrm{e}^{2\pi i \nu t}$$

$$\tau_\mathrm{g} = \frac{D \sin\theta}{c}$$

$$r = \cos\left(2\pi\nu \frac{D \sin\theta}{c}\right) * \{I(\theta)\}$$

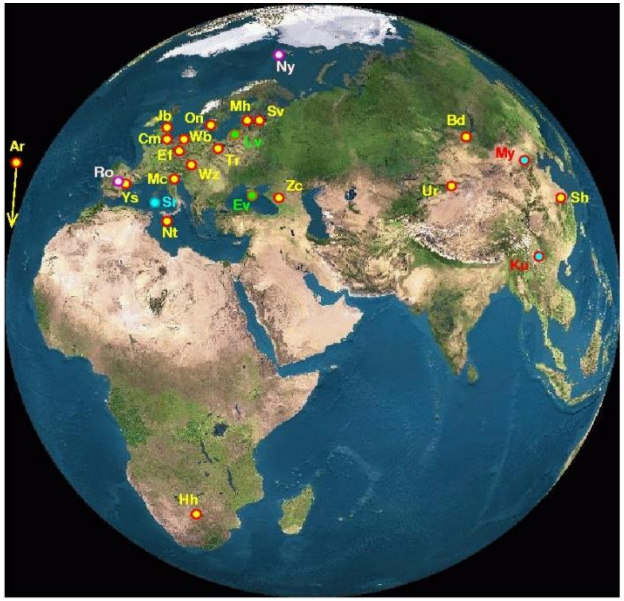
VLBI in practice



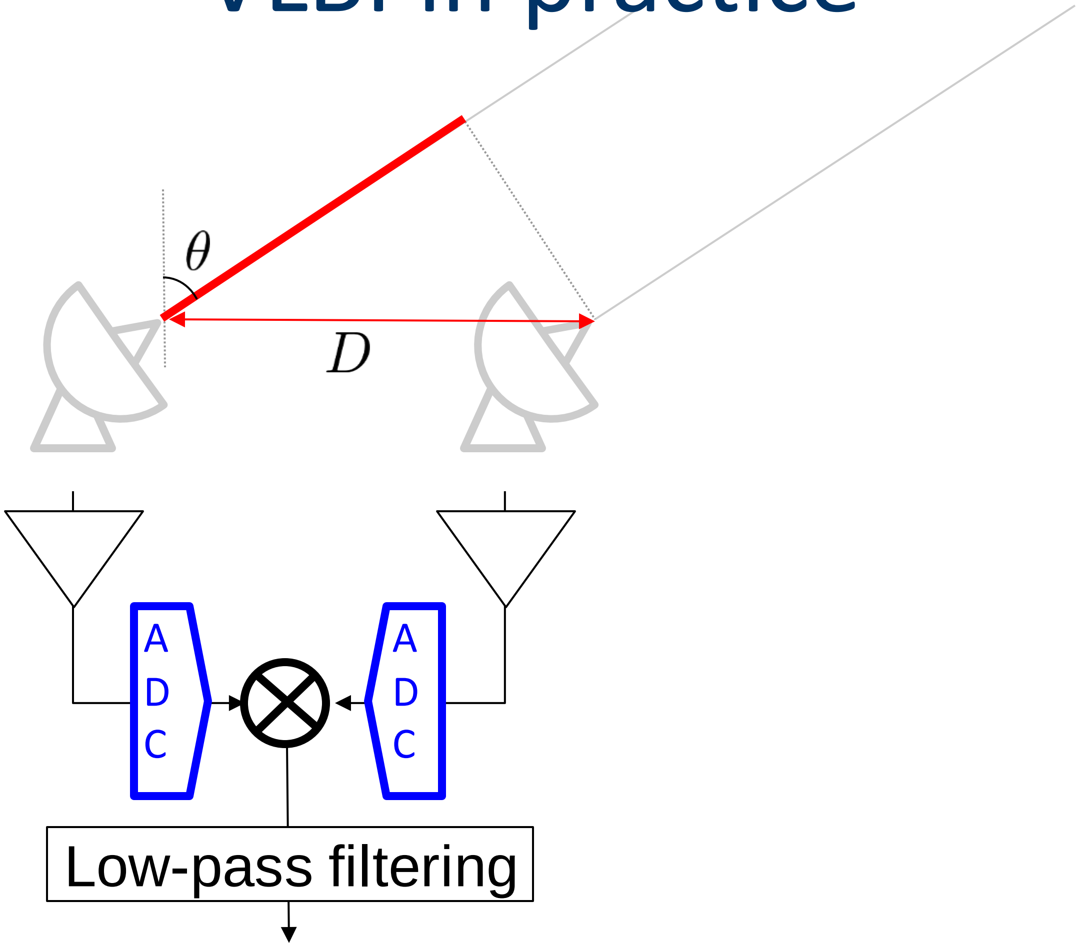
Digital Signal Processing

Low-pass filtering

$$r = \cos\left(2\pi\nu\frac{D\sin\theta}{c}\right) * \{I(\theta)\}$$



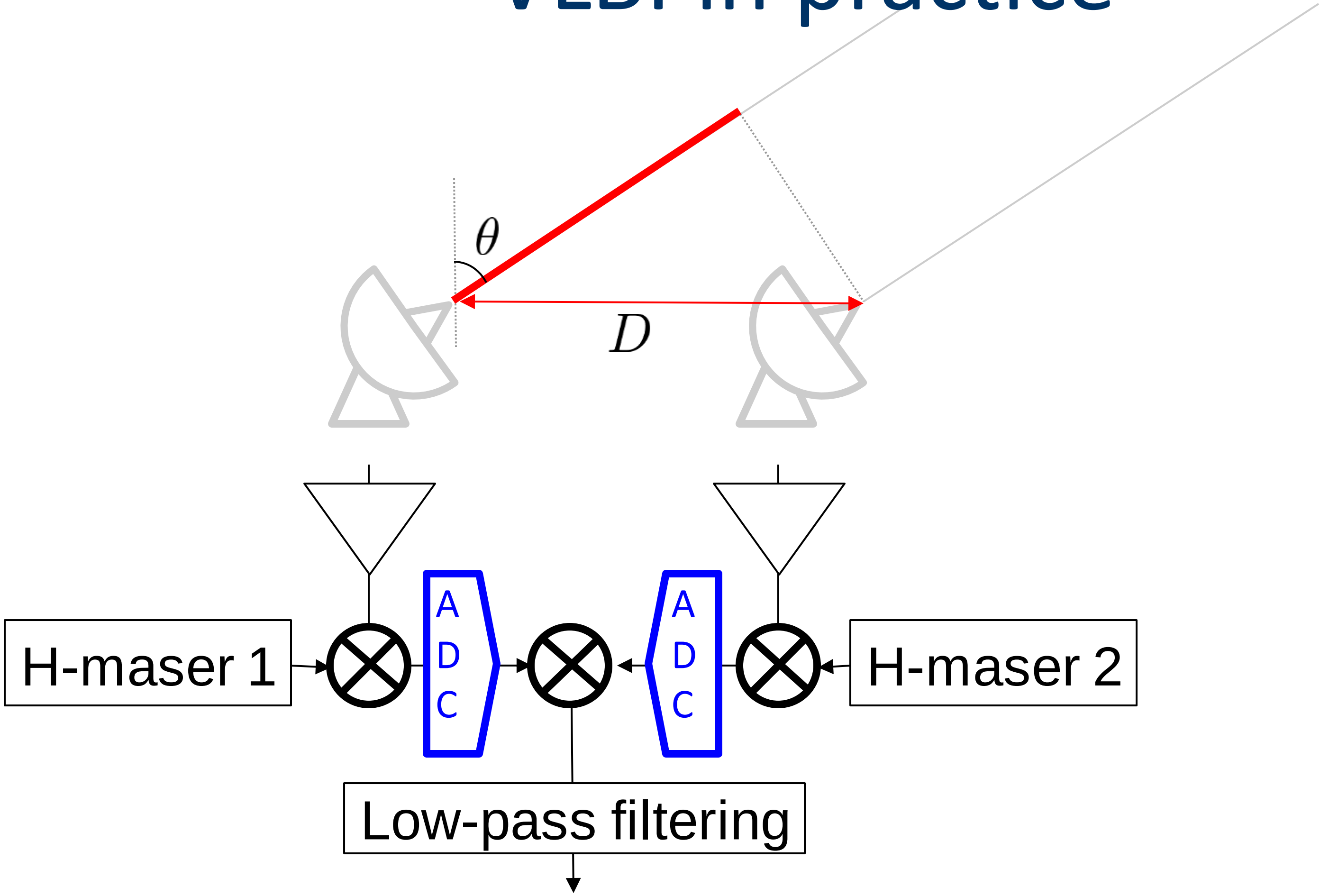
VLBI in practice



Low-pass filtering

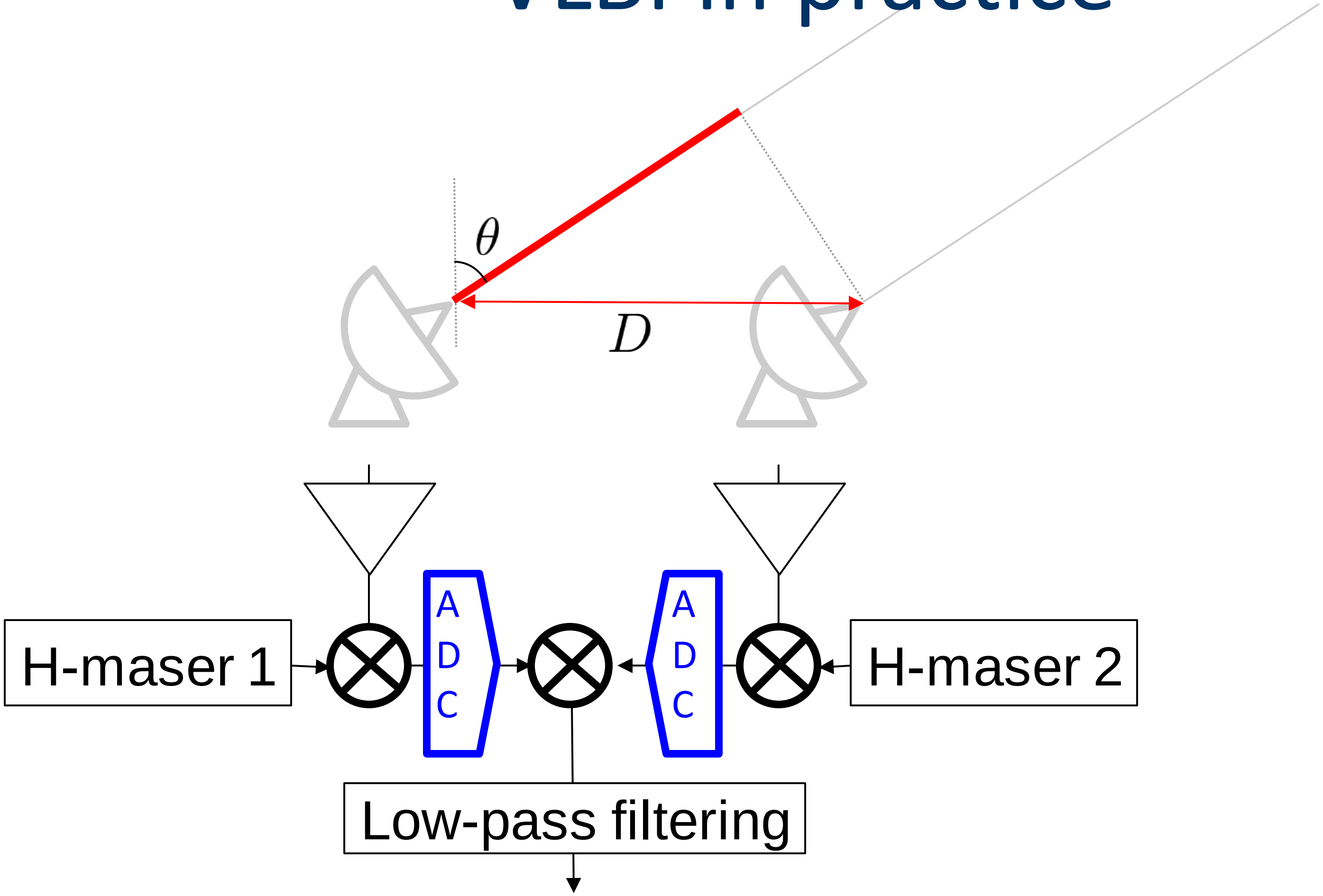
$$r = \cos\left(2\pi\nu\frac{D\sin\theta}{c}\right) * \{I(\theta)\}$$

VLBI in practice



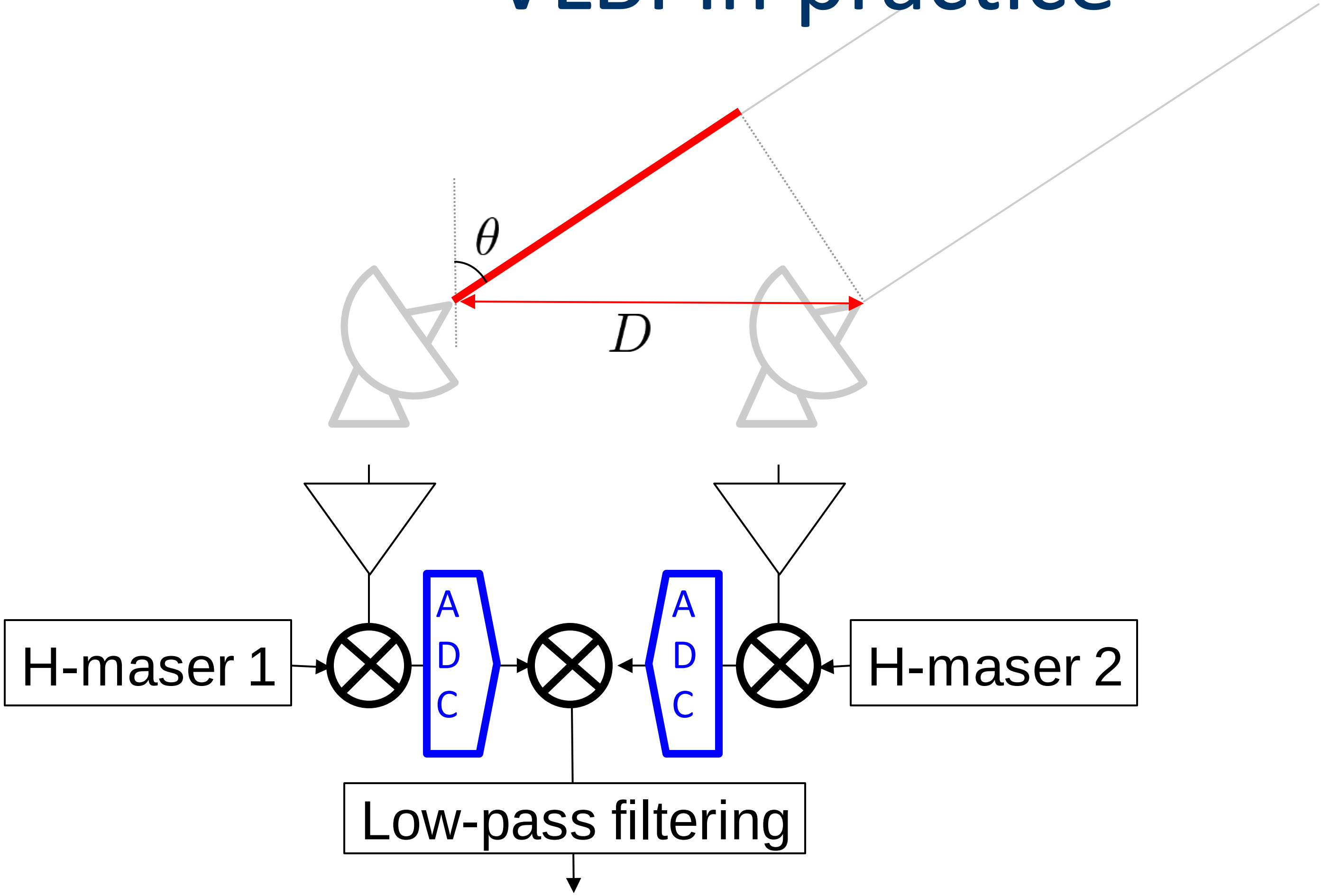
$$r = \cos\left(2\pi\nu\frac{D\sin\theta}{c} + \phi_{\text{clocks}} + \ldots\right) * \{I(\theta)\}$$

VLBI in practice



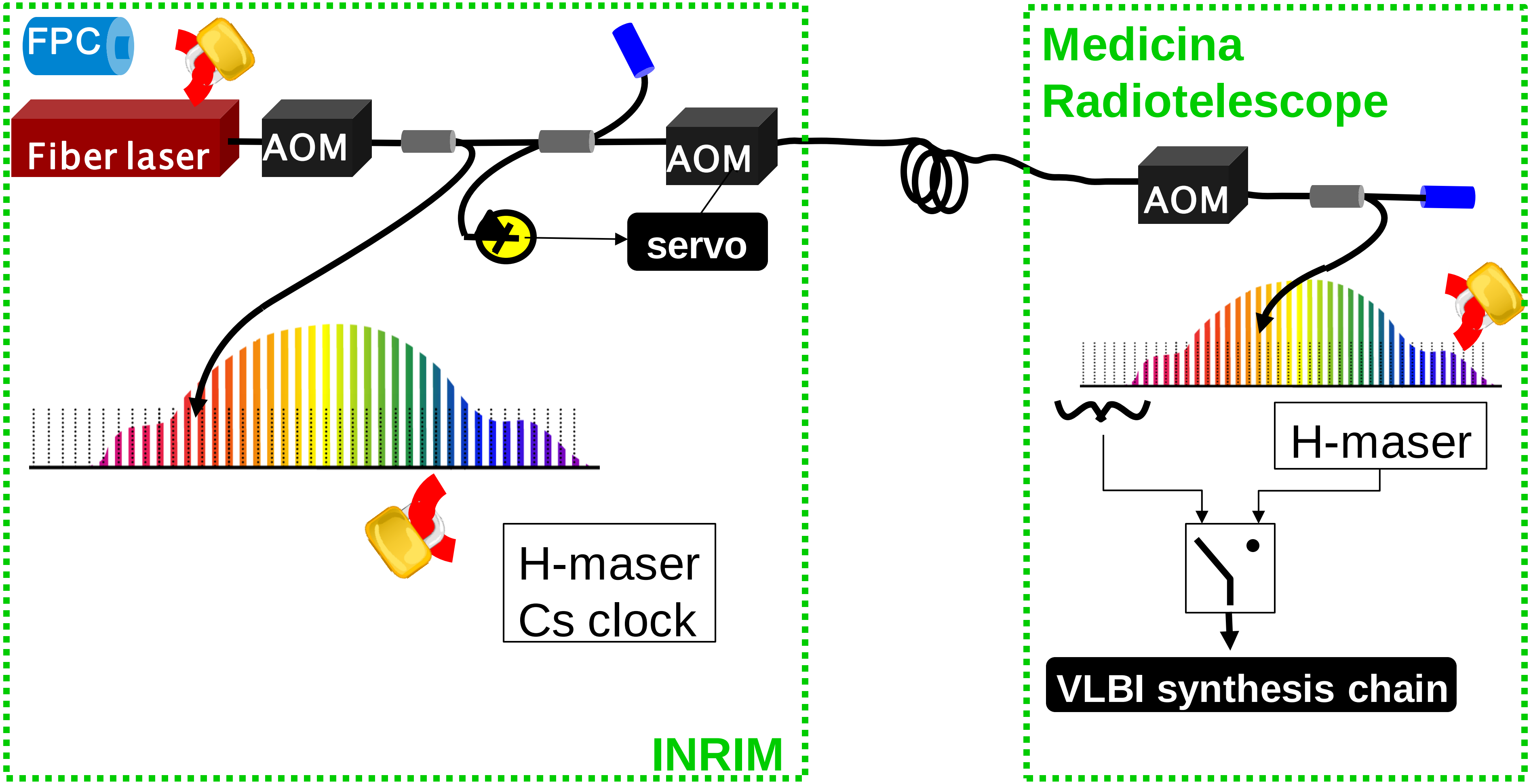
$$r = \cos\left(2\pi\nu\frac{D\sin\theta}{c} + \phi_{\text{clocks}} + \phi_{\text{atm}} + \ldots\right) * \{I(\theta)\}$$

VLBI in practice



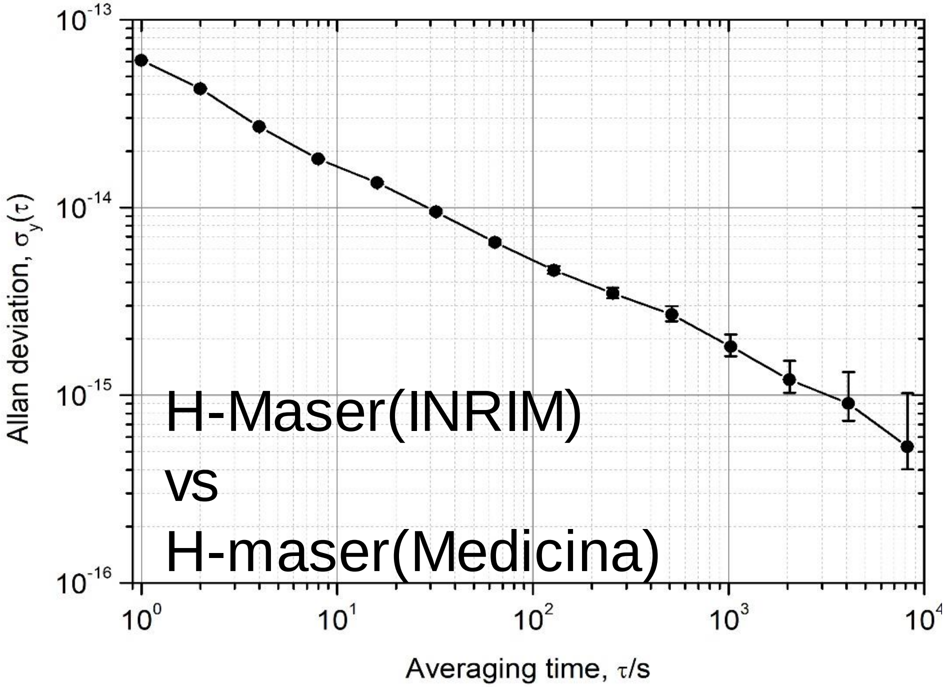
$$r = \cos\left(2\pi\nu\frac{D\sin\theta}{c} + \phi_{\text{clocks}} + \phi_{\text{atm}} + \phi_{\text{instr}}\right) * \{I(\theta)\}$$

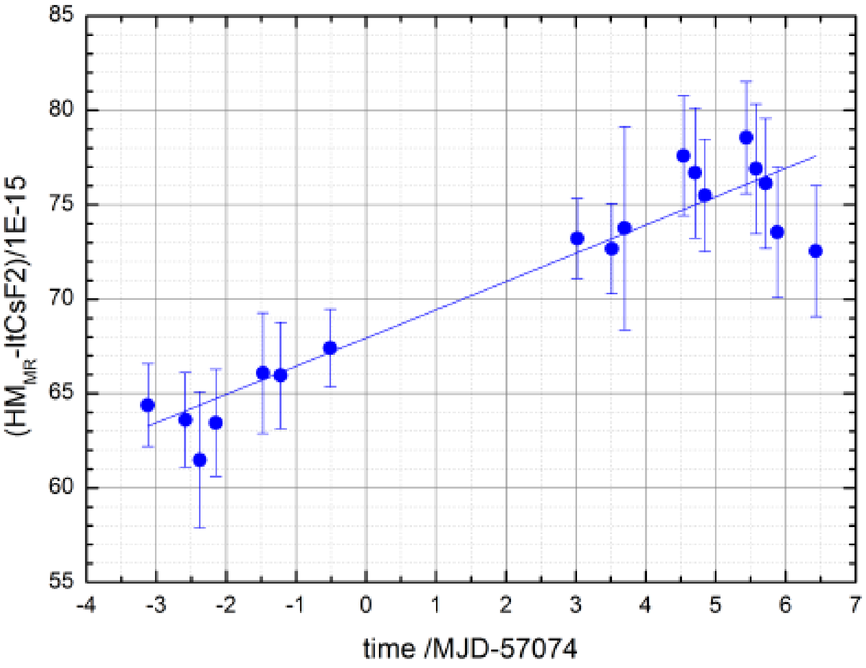
Delivering the same clock to multiple telescopes



Delivering the same clock to multiple telescopes

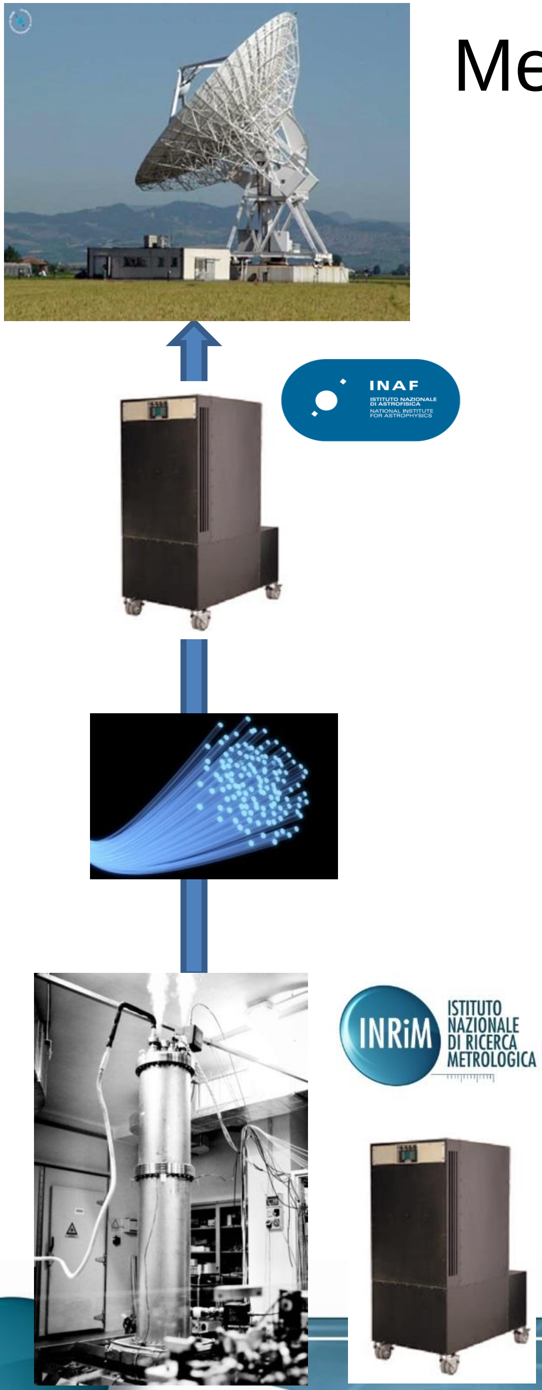
- Remote calibration of Medicina H-maser





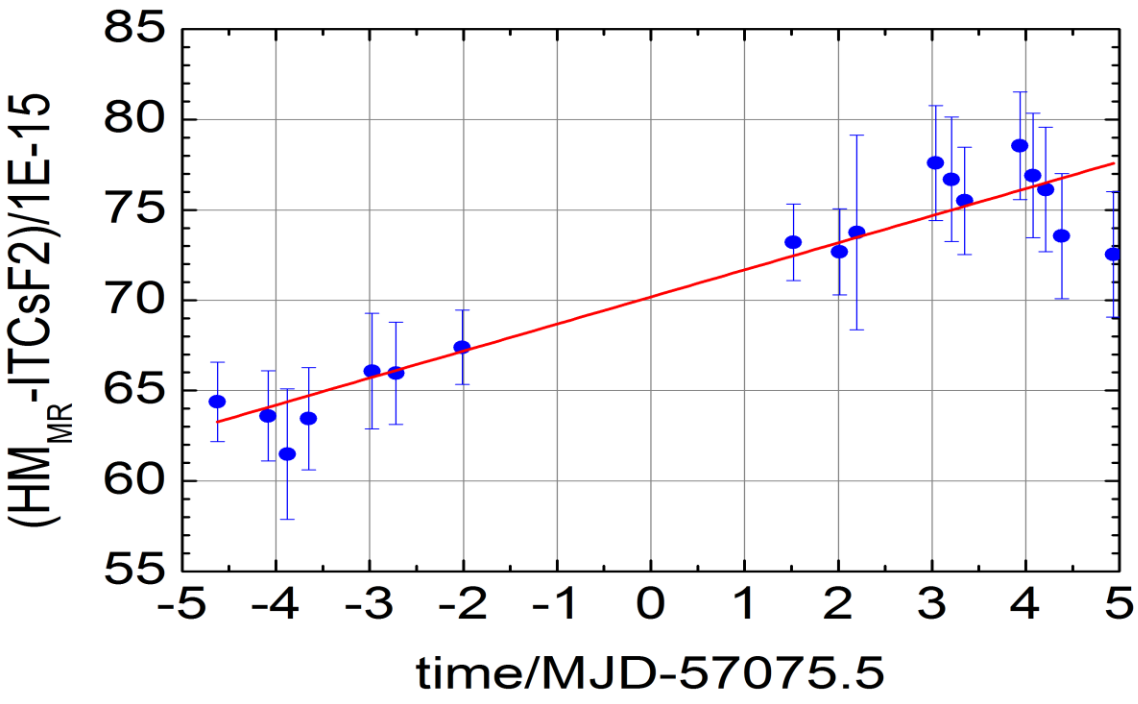
C. Clivati et al., UFFC **63**, 2015

Medicina H-Maser Absolute calibration



- HM frequency = $(70.2 \pm 0.4)10^{-15}$
- HM drift = $(1.5 \pm 0.1)10^{-15}$/day

- 4×10^{-16} Uncertainty, dominated by HMs
- Accuracy and resolution otherwise impossible



C. Clivati er al., IEEE TRANS. UFFC, 62, 1907 (2015)

Experiment EUR137

Radioantennas involved:

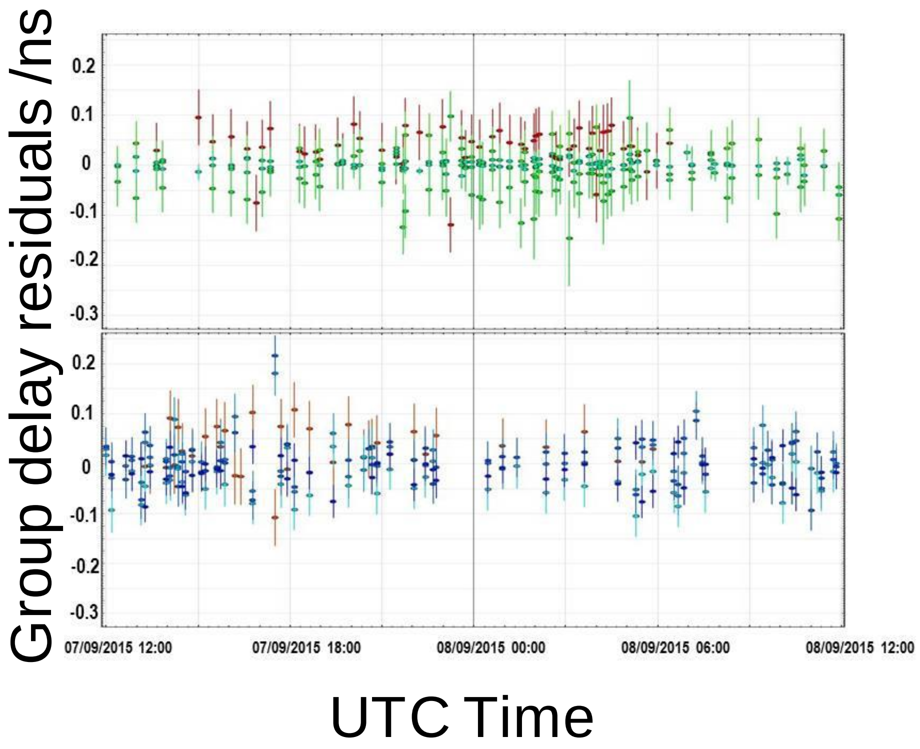
DSS65A (SPAIN)
MEDICINA (ITALY)
METSAHOV (FINLAND)
NYALES20 (SVALBARD)
ONSALA60 (SWEDEN)
WETTZELL (GERMANY)

Delivering the same clock to multiple telescopes

- Fringe recovery using a remote H-maser:

→ Residuals of ϕ after modeling at the same level using local or remote clock

→ Improvement expected by connecting two clocks



C. Clivati et al., Sci. Rep **7**, 2017

INRIM- INAF- ASI: geodesy and radioastronomy

INRiM
ISTITUTO NAZIONALE
DI RICERCA METROLOGICA

- Enhanced Geodetic VLBI with 4 radioantennas (more in the international campaigns)
- LIFT to connect Bologna (INAF) and Matera (ASI)
- Not fibre connected VLBI stations in Noto, Sicily (INAF) and in Cagliari, Sardinia (INAF)

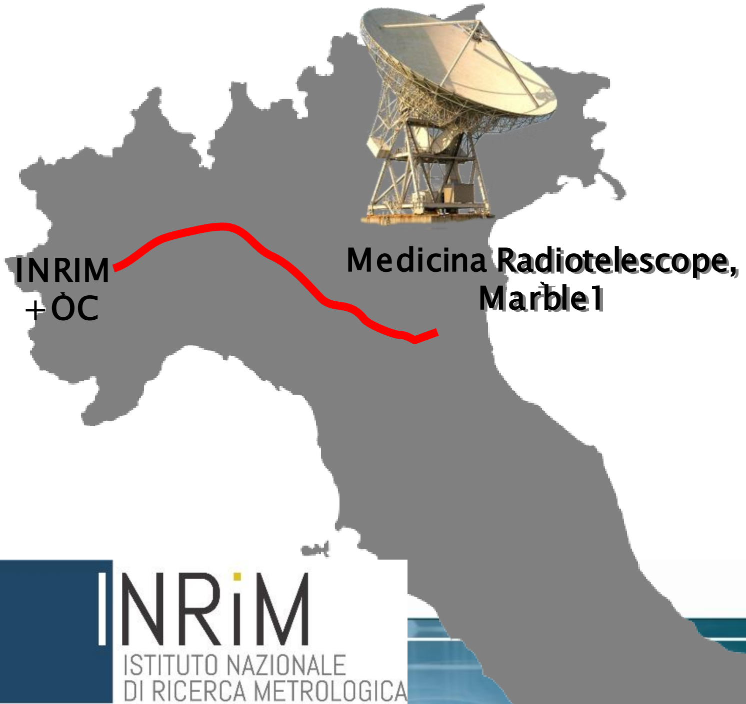
VLBI clocks comparison

- Can atomic clocks be compared with VLBI techniques?

$$\phi = \phi_{\text{geom}} + \phi_{\text{source}} + \phi_{\text{atm}} + \phi_{\text{instr}} + \phi_{\text{clocks}}$$

→ VLBI clock comparison between Italy and Japan (Sept./Oct. 2018)

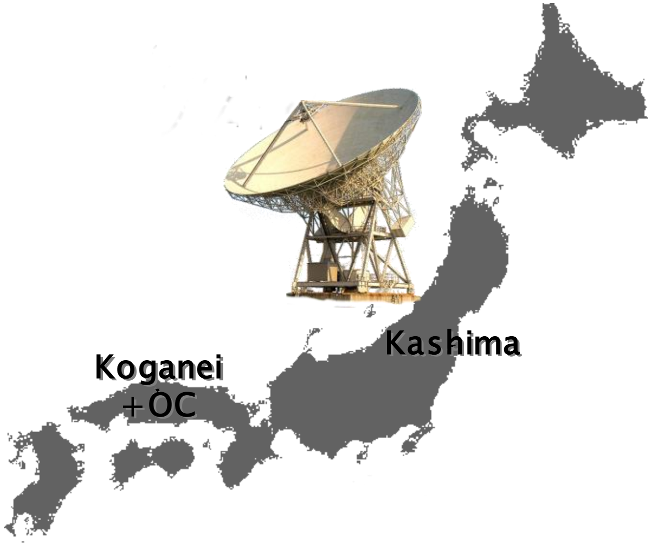
  - Koganei (JAP) and *Marble1* (IT) *transportable* antennas
  (+ Kashima & Medicina telescopes for support)
  - All stations equipped with a local H-maser
  - Optical clocks available from NICT / INRIM via optical fiber



National Institute of Information and Communications Technology

INAF ISTITUTO NAZIONALE DI ASTROFISICA NATIONAL INSTITUTE FOR ASTROPHYSICS

INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA



APPLICATIONS

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Chronometric levelling

- Determining *ΔU* as

$$\Delta U(L) = \int_{L_0}^{L_0+L} g(l)\, dl$$

- **Standard geodetic methods:**
  - Geometric levelling + local *g(l)* measurements

    (u ~ 1 mm over short distances)
  - GNSS positioning+gravity models from terrestrial/satellite *g* data

    (u depends on quality of models over small/regional areas & GNSS accuracy)

Chronometric levelling

- Determining *ΔU* as

$$\Delta U(L) = \int_{L_0}^{L_0+L} g(l)\, dl$$

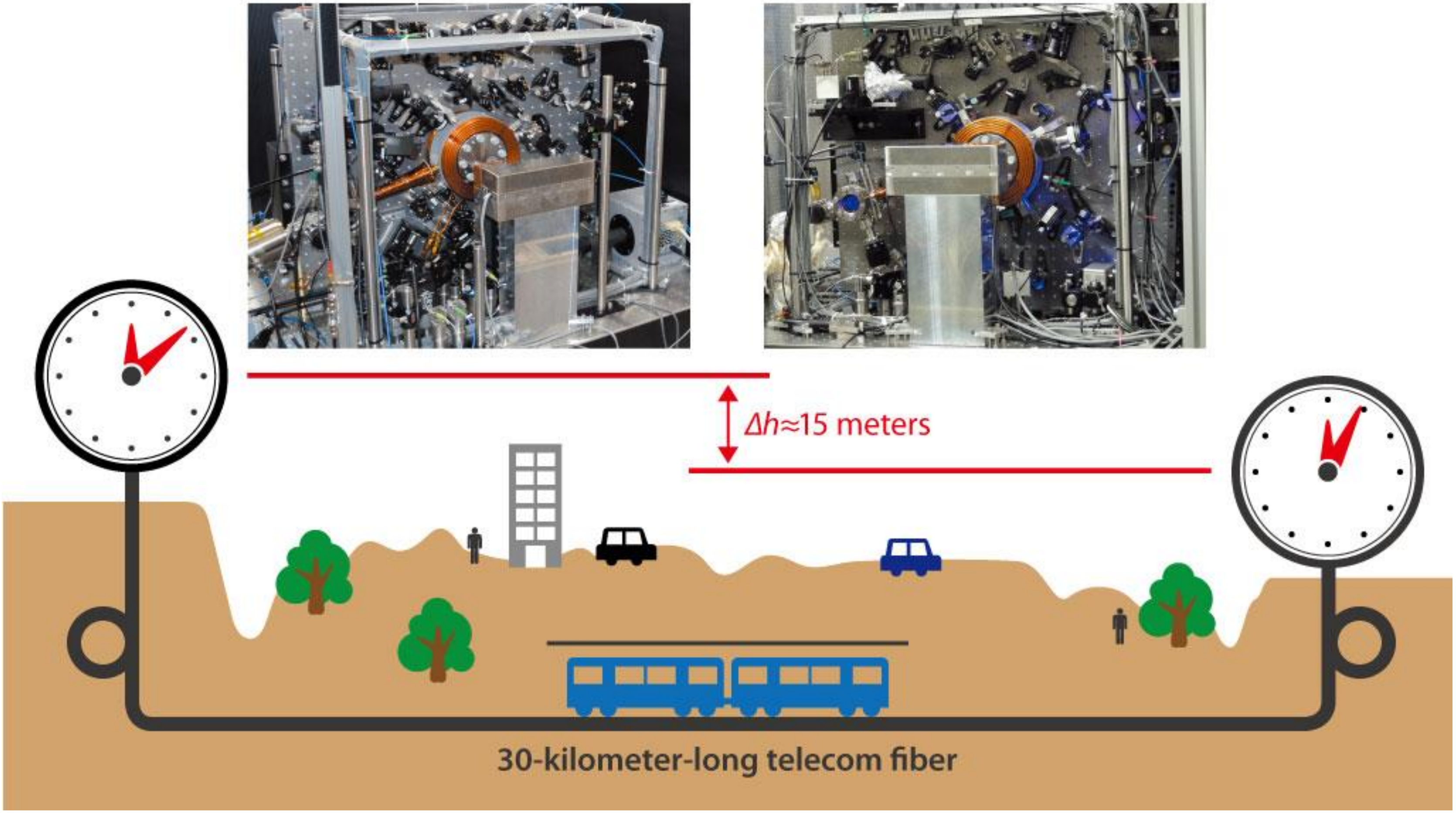
- **Gravitational potential difference between two sites measured by gravitational redshift**
  - Sensitivity is ~1E-16/m on Earth's surface
  - Clocks at 1E-17 → differences in height measured with 10 cm accuracy:

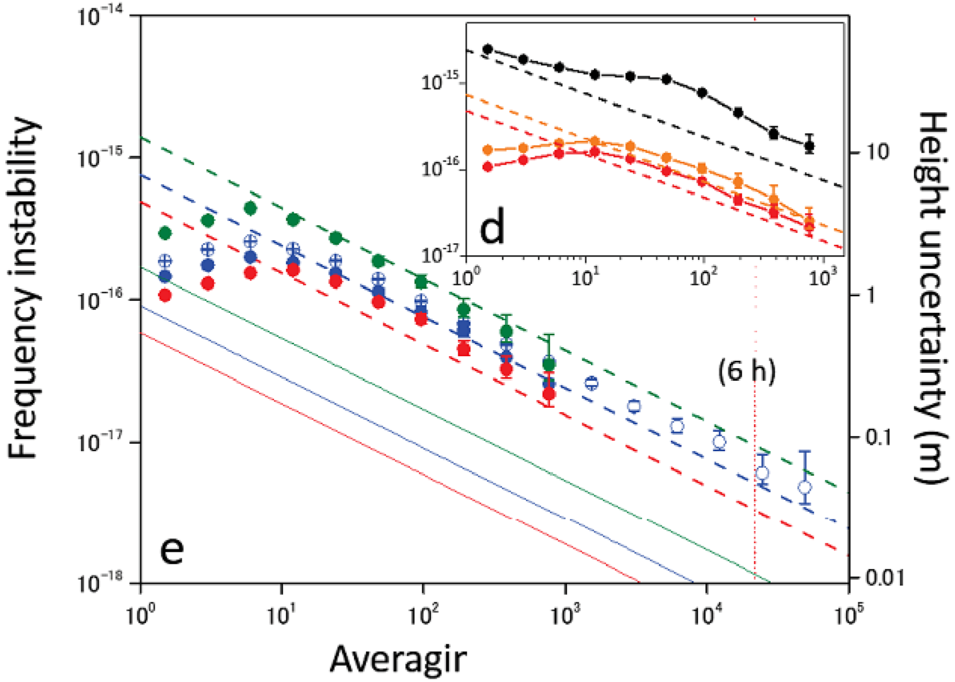
$$\frac{\Delta\nu}{\nu} = \frac{\Delta U}{c^2} \approx 10^{-16}/\mathrm{m}$$

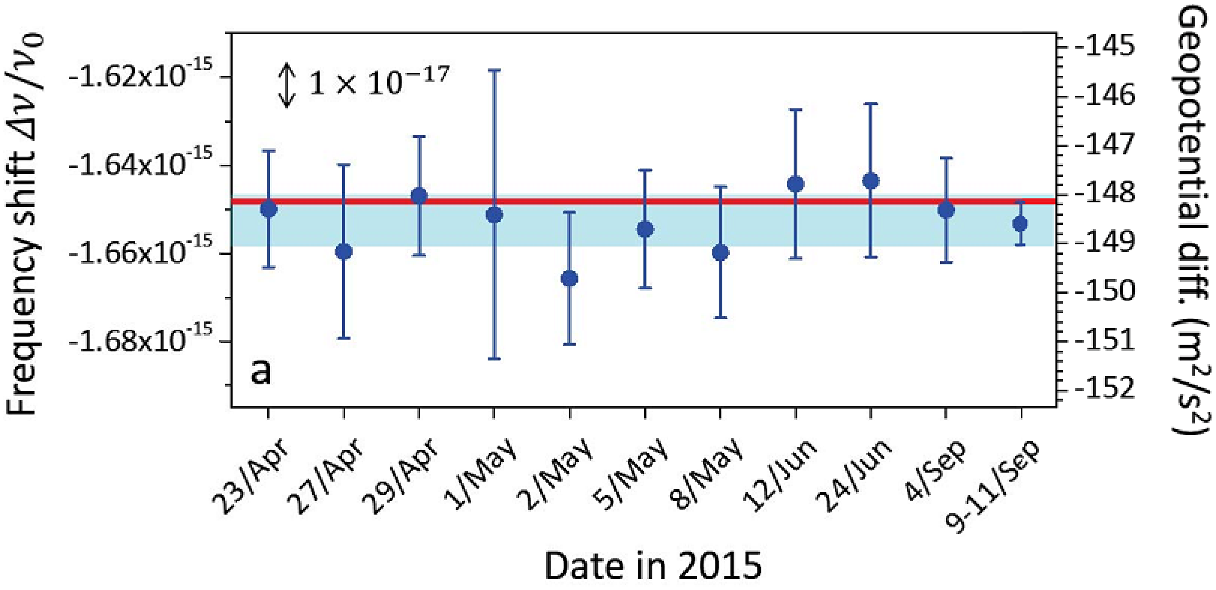
  - Combines high resolution over large distances (optical links)
  - Can detect time variations of *ΔU*

Chronometric levelling

Takano, T., et al. Geopotential measurements with synchronously linked optical lattice clocks. *Nature Photonics* **10,** 662–666 (2016).




Frequency instability
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
Averagir
Height uncertainty (m)
10
1
0.1
0.01
(6 h)
e
d
10^{-15}
10^{-16}
10^{-17}
10^{0}
10^{1}
10^{2}
10^{3}


Frequency shift $\Delta\nu/\nu_0$
-1.62x10^{-15}
-1.64x10^{-15}
-1.66x10^{-15}
-1.68x10^{-15}
$\updownarrow 1\times10^{-17}$
a
Geopotential diff. (m^2/s^2)
-145
-146
-147
-148
-149
-150
-151
-152
23/Apr
27/Apr
29/Apr
1/May
2/May
5/May
8/May
12/Jun
24/Jun
4/Sep
9-11/Sep
Date in 2015

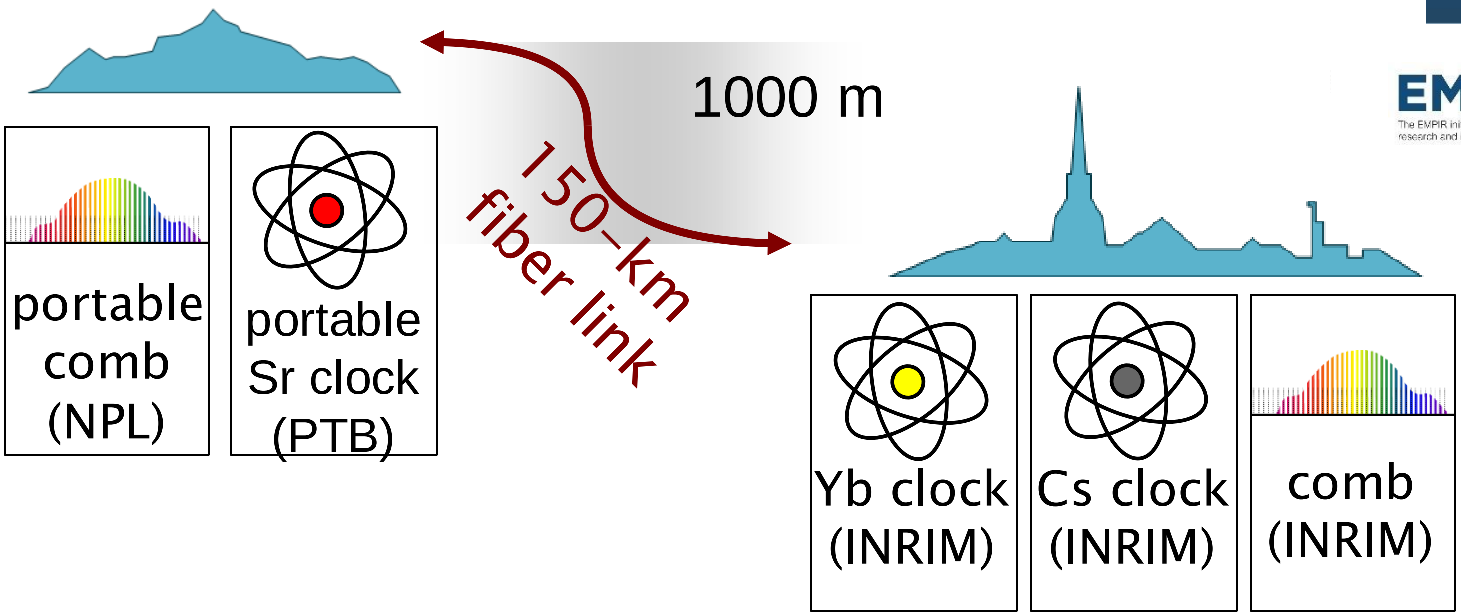
Contributor	^{87}Sr (UT)		^{87}Sr (UT)-^{87}Sr (RIKEN1)	
	Correction (10^{-18})	Uncertainty (10^{-18})	Correction (10^{-18})	Uncertainty (10^{-18})
Quadratic Zeeman shift	109.0	0.9	-8.2	0.5
Blackbody radiation shift*	79.1	0.9	24.9	1.2
Lattice light shift†	3.5	5.0	0.0	4.4
Clock light shift	0.047	0.023	0.0	0.014
First-order Doppler shift	0.0	0.5	0.0	0.7
AOM chirp & switching	0.0	0.2	0.0	0.3
Servo error†	1.3	3.9	0.6	0.5
Density shift†	1.1	5.2	0.7	3.3
Systematic total	194.8	8.3	18.7	5.7

Chronometric levelling

- How to translate this into a “real instrument”?

→ Transportable optical clocks + fibre link

A proof-of-principle geodesy experiment on the Alps



1000 m

150-km fiber link

portable comb (NPL)

portable Sr clock (PTB)

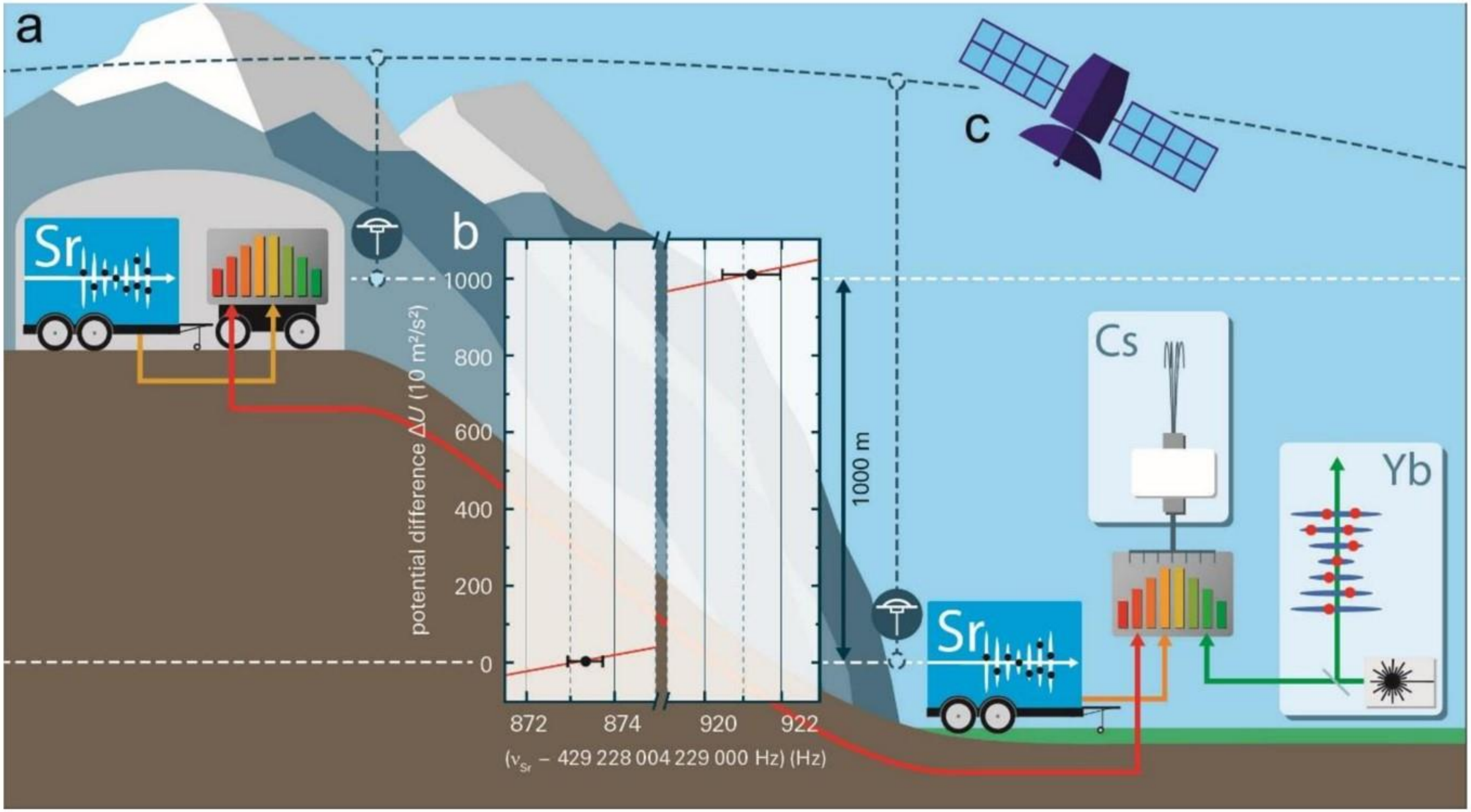
Yb clock (INRIM)

Cs clock (INRIM)

comb (INRIM)

J. Grotti et al., Nature Phys. **14**, 2018

Chronometric Levelling (Relativistic Geodesy)



J. Grotti et al., Nature Phys. **14**, 2018

Chronometric levelling

$$\Delta U_{\text{clocks}} = 10{,}034(174)\ \text{m}^2\text{s}^{-2}\ \Delta U_{\text{GNSS}} = 10{,}032.1(16)\text{m}^2\text{s}^{-2}$$

- First demonstration of chronometric levelling in real field with transportable clocks

Optical clocks + frequency links: a quantum tool for probing ΔU

- Short overlapped uptime between optical clocks in Modane/Turin; only Cs fountain used ↔ Resolution limited by averaging time

- Higher resolution expected through optical / optical clock comparison

J. Grotti et al., Nature Phys. **14**, 2018

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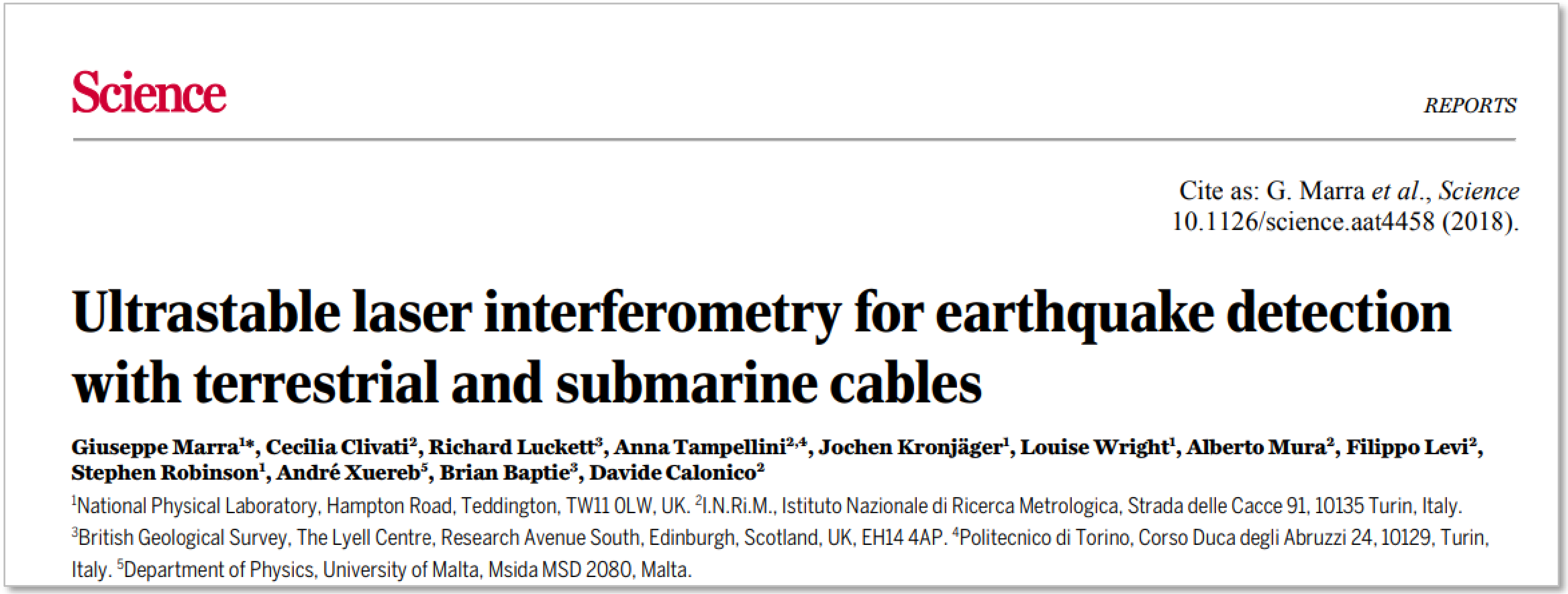
Earthquake detection with coherent optical fibers

A coherent optical fiber link is a giant Michelson interferometer
→ Able to detect fiber length changes as small as ~ 1 μm
→ Detection of seismic noise is feasible (...Earthquakes!)



Science REPORTS

Cite as: G. Marra *et al.*, *Science*
10.1126/science.aat4458 (2018).

Ultrastable laser interferometry for earthquake detection with terrestrial and submarine cables

Giuseppe Marra[1]*, Cecilia Clivati[2], Richard Luckett[3], Anna Tampellini[2,4], Jochen Kronjäger[1], Louise Wright[1], Alberto Mura[2], Filippo Levi[2], Stephen Robinson[1], André Xuereb[5], Brian Baptie[3], Davide Calonico[2]

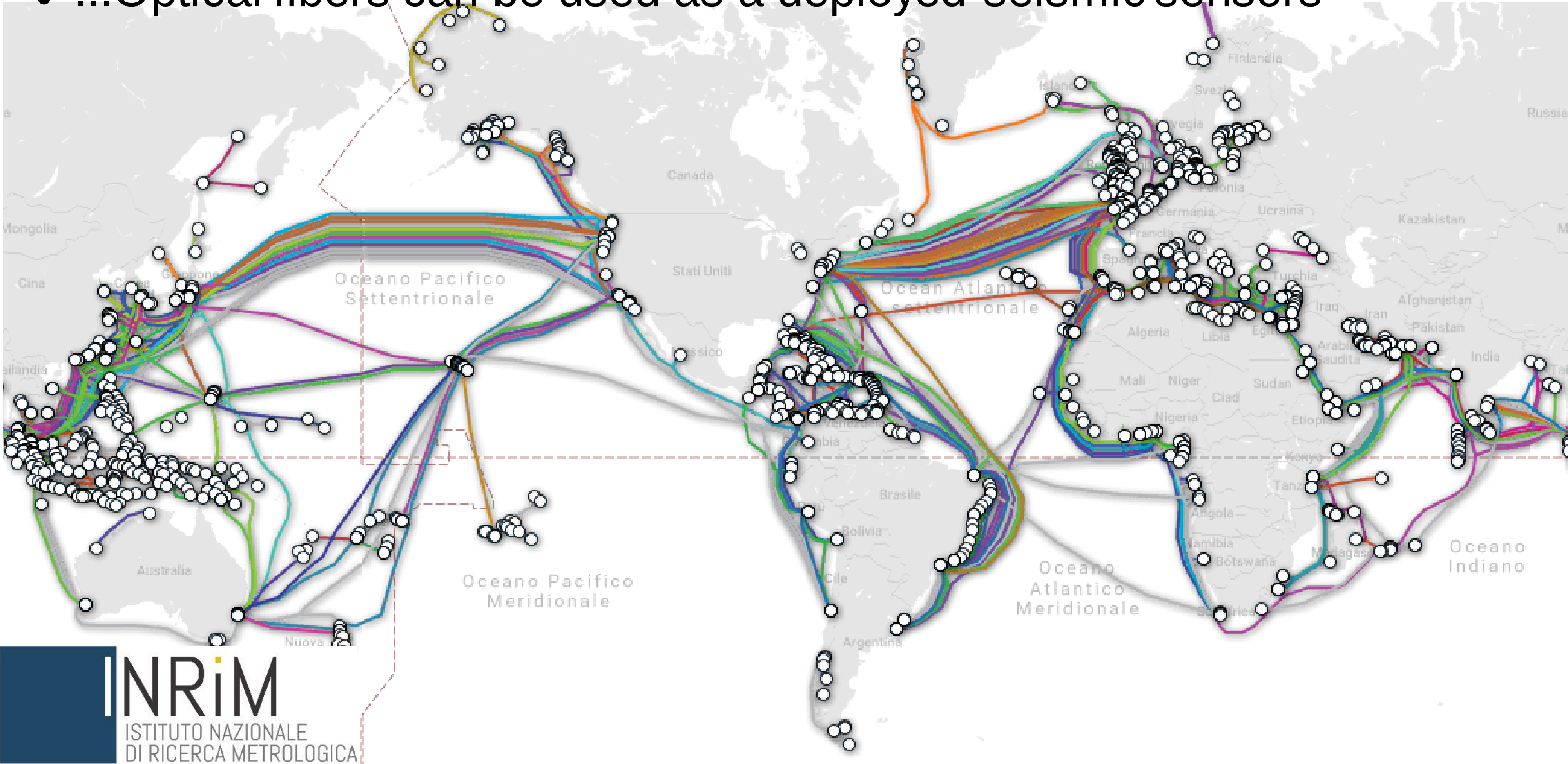
[1]National Physical Laboratory, Hampton Road, Teddington, TW11 0LW, UK. [2]I.N.Ri.M., Istituto Nazionale di Ricerca Metrologica, Strada delle Cacce 91, 10135 Turin, Italy. [3]British Geological Survey, The Lyell Centre, Research Avenue South, Edinburgh, Scotland, UK, EH14 4AP. [4]Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129, Turin, Italy. [5]Department of Physics, University of Malta, Msida MSD 2080, Malta.

Submarine Earthquakes detection

- Almost 70% of Earth covered by waters
- Ocean Bottom Seismometers: few, costly, difficult to operate

→ most of submarine Earthquakes undetected

- ...Optical fibers can be used as a deployed seismic sensors



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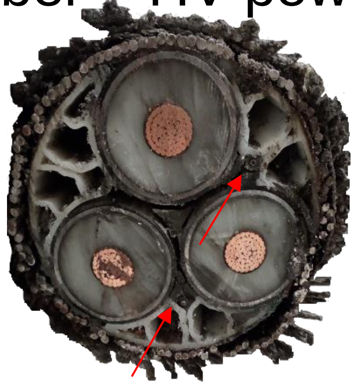
DI RICERCA METROLOGICA

Submarine Earthquakes detection

Two testbeds available in the Mediterranean Sea, Sicily to Malta:

- A 96.4 km telecom cable
(fiber only, buried 1 m below sand)
- A 117 km cable along electrical interconnection
(fiber + HV power, 1 m below sand)



INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA

NPL National Physical Laboratory | QMI Quantum Metrology Institute

British Geological Survey NATURAL ENVIRONMENT RESEARCH COUNCIL

L-Università ta' Malta

C. Clivati et al., Optica **14** (2018)
G. Marra et al., Science **361** (2018)

Submarine Earthquakes detection

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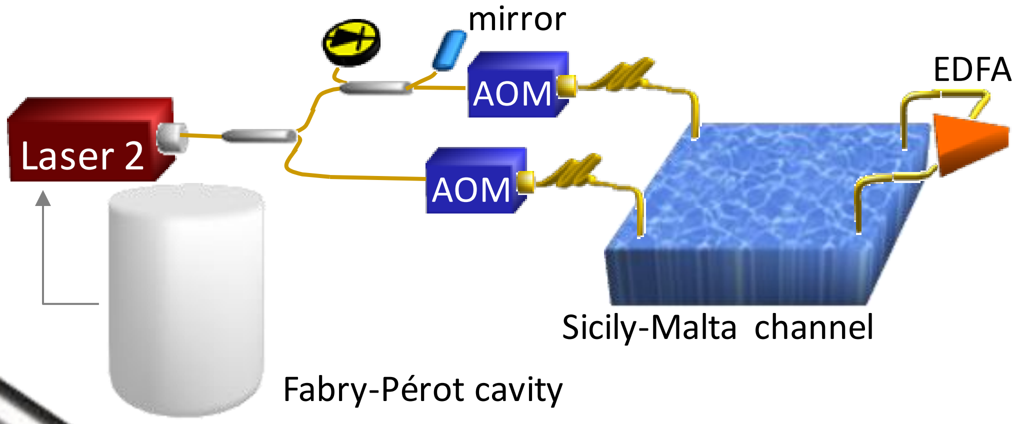
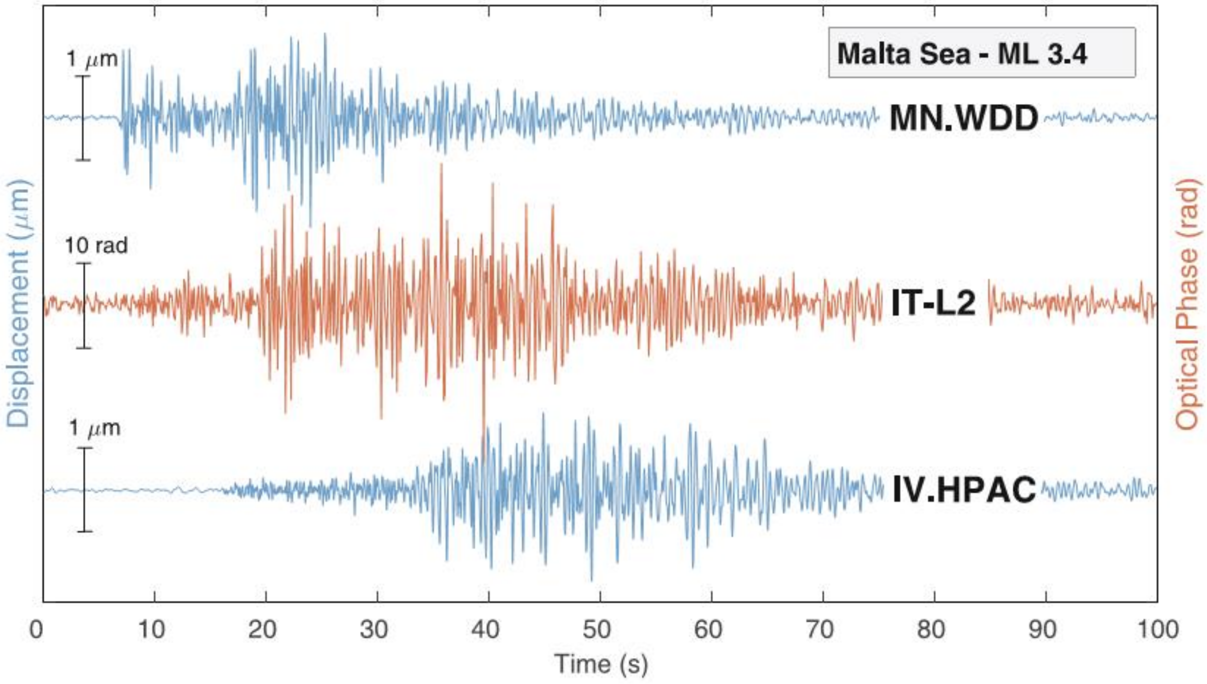
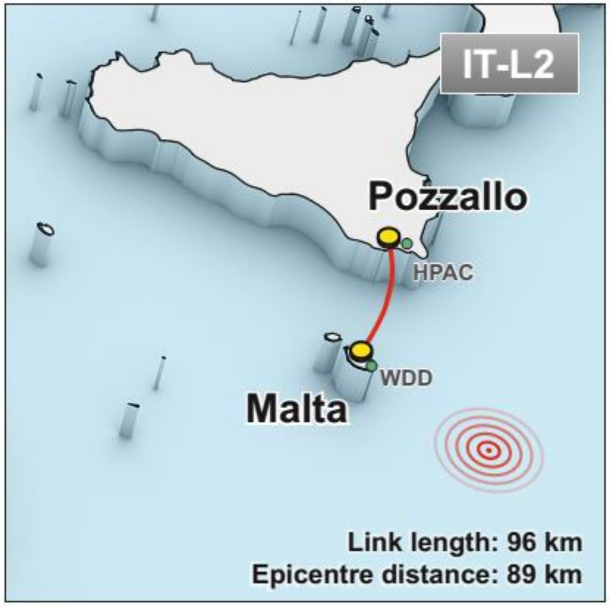


Submarine Earthquakes detection

- Two seismic events (ML = 3.4 and Mw = 5.1) detected on submarine fiber

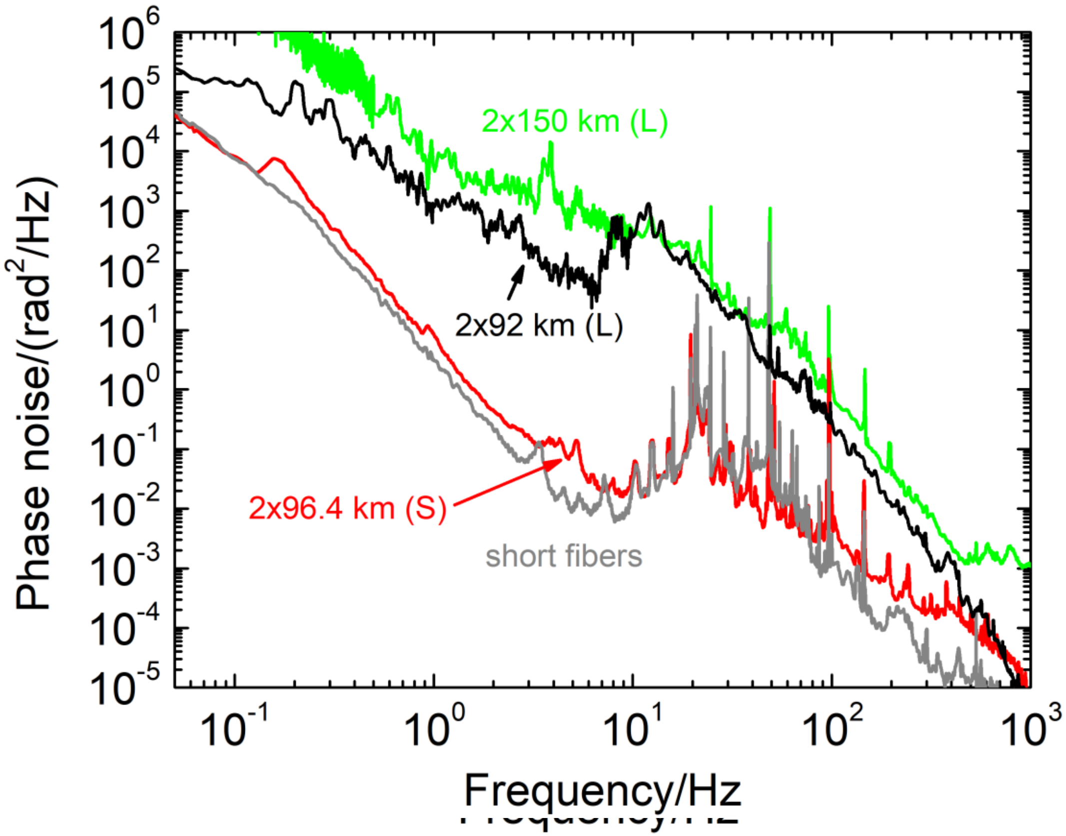


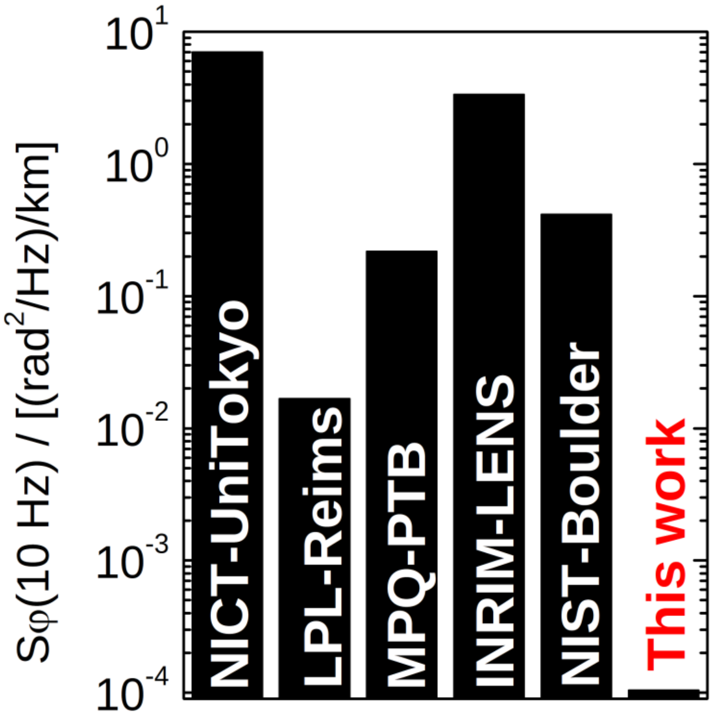


G. Marra et al., Science **361** (2018)

Submarine Earthquakes detection

Issue 1: Could we detect Earthquakes on transoceanic fibers
(L ~ 6000 km)?



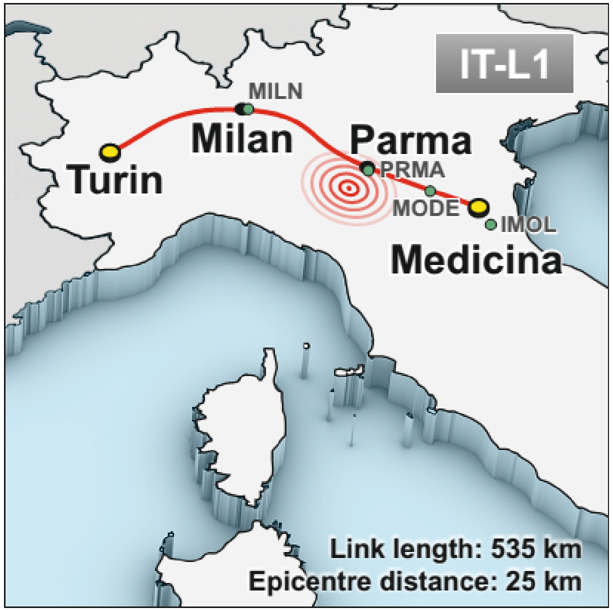


C. Clivati et al., Optica **14** (2018)

- Submarine fibers have up to 20 dB lower noise than terrestrial fibers
- High SNR achievable even on transoceanic links

Submarine Earthquakes detection

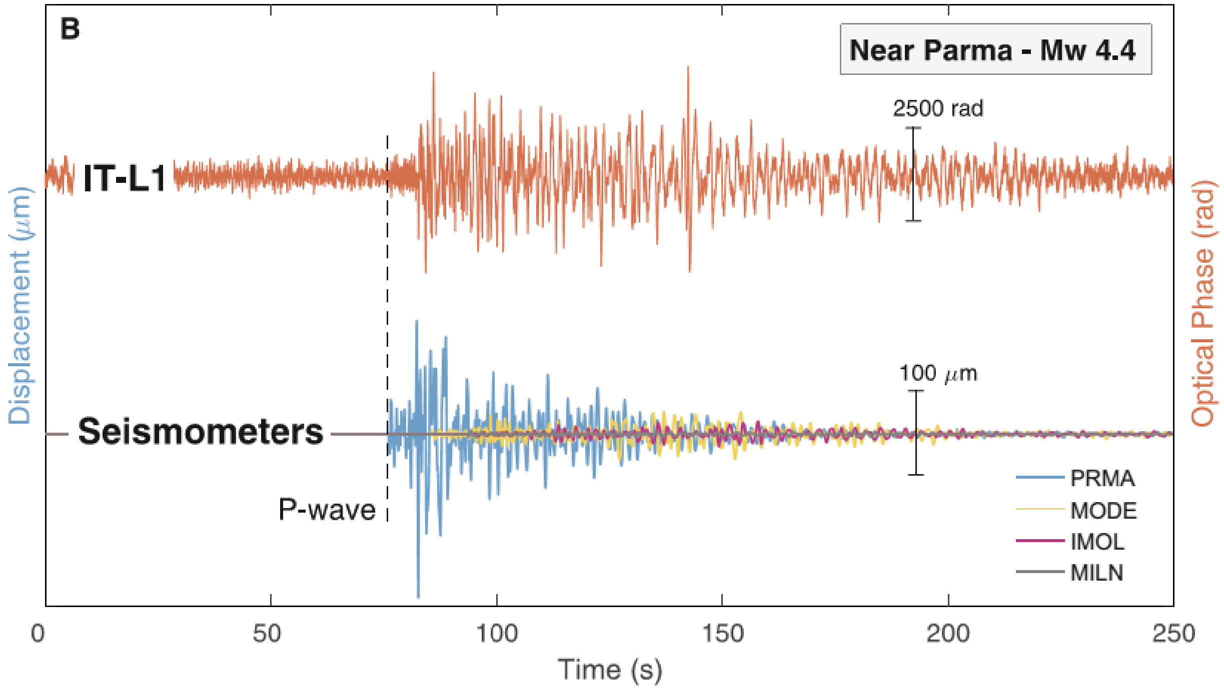
Issue 1: Could we detect Earthquakes on transoceanic fibers
(L ~ 6000 km)?

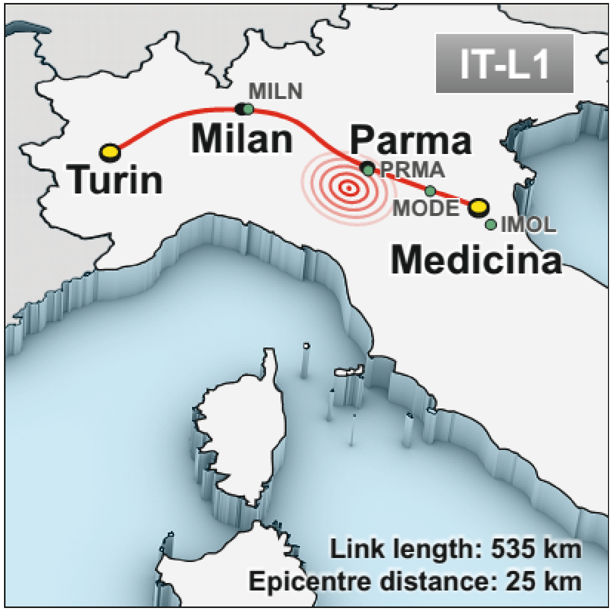


- Rms noise on this link is 8x that of submarine fiber
- If $S_{\varphi(f),\mathrm{F}} \propto L$, noise of a 6000 km link is still lower

Submarine Earthquakes detection

Issue 2: How to locate epicentre?

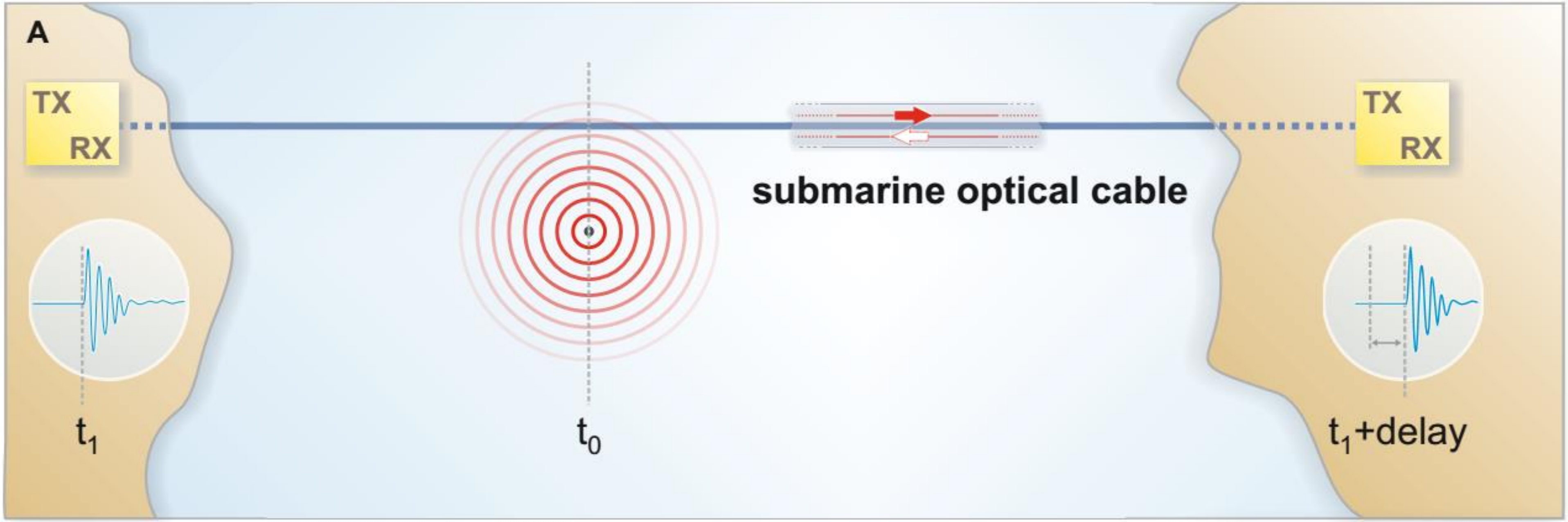




- Only fiber segment closest to epicentre contributes significantly
- P-wave arrival to closest point not affected by other locations

Submarine Earthquakes detection

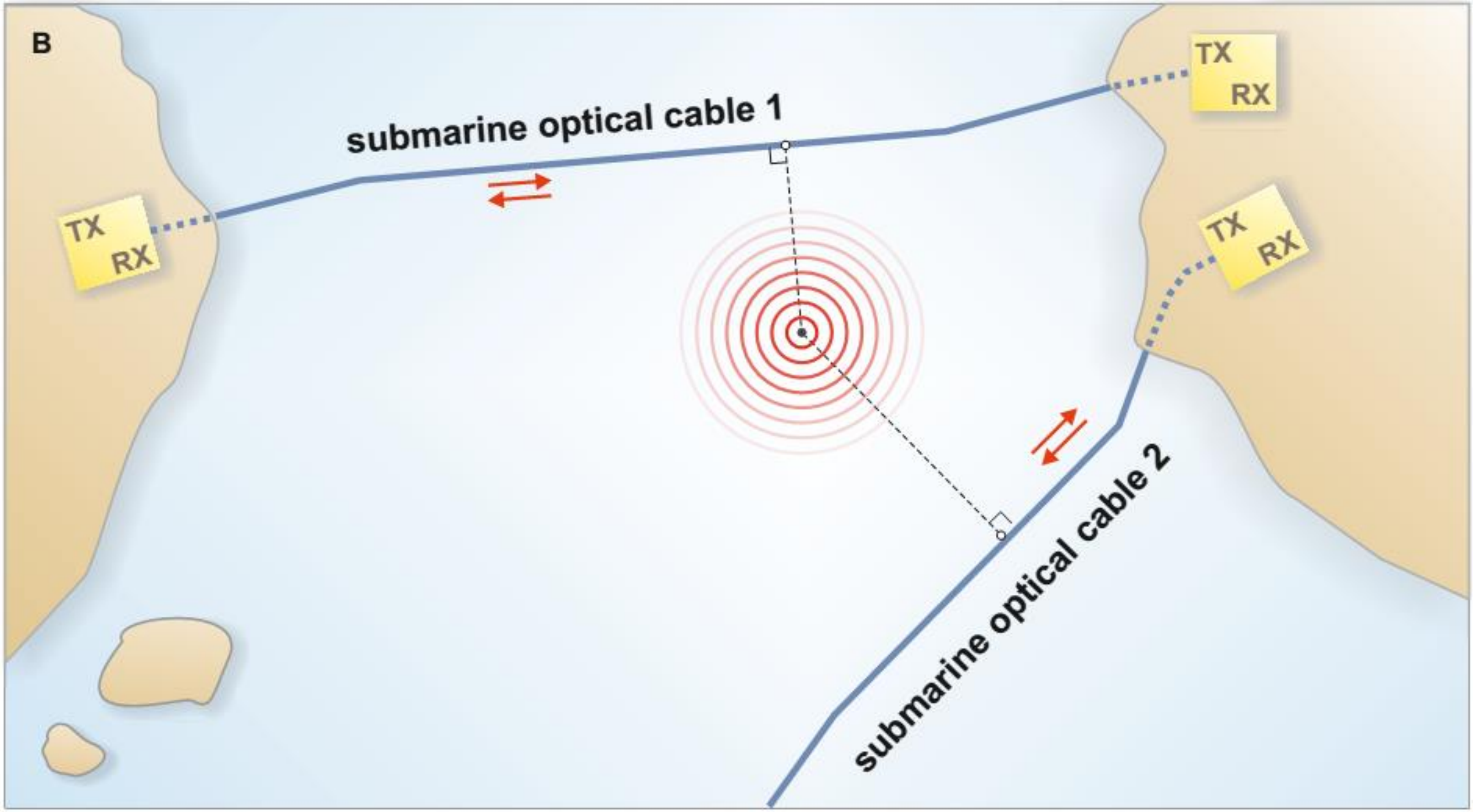
Issue 2: How to locate epicentre?



- Only fiber segment closest to epicentre contributes significantly
- P-wave arrival to closest point not affected by other locations
- Cross-correlation of measurements at opposite ends → direction

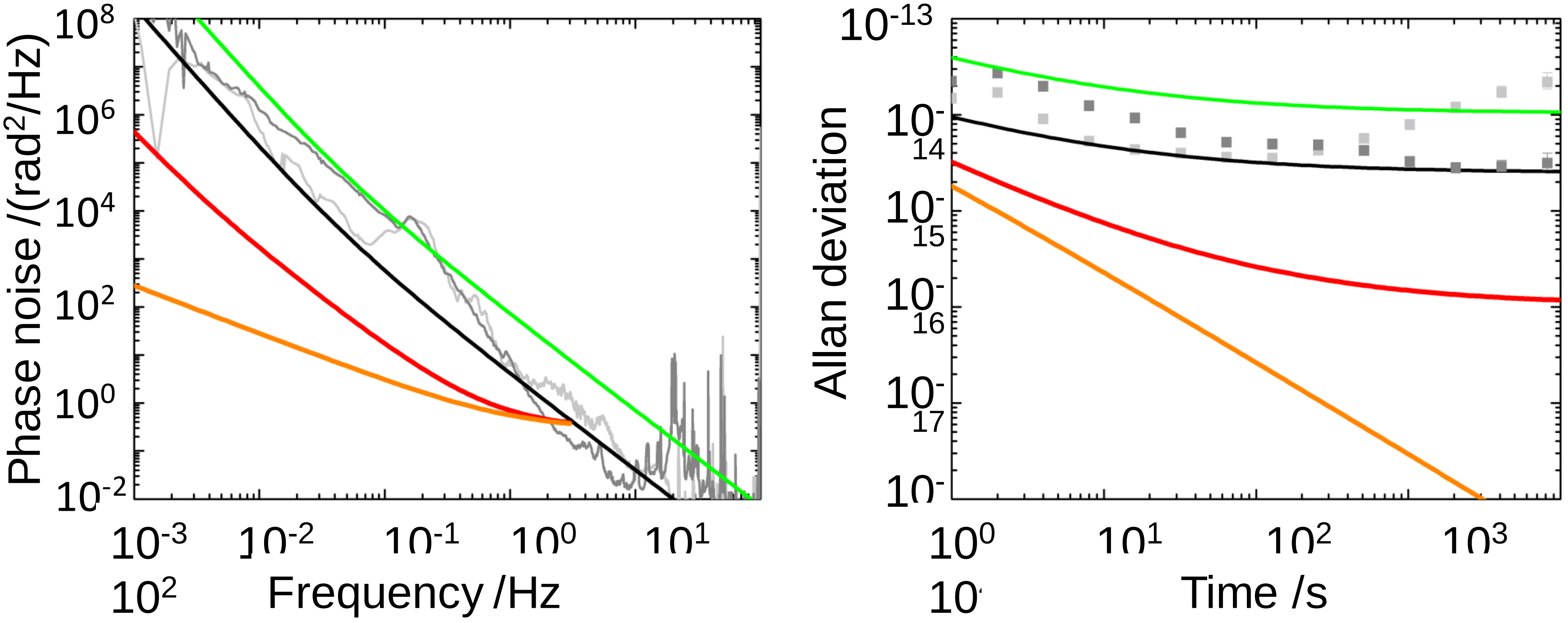
Submarine Earthquakes detection

Issue 2: How to locate epicentre?



- C
- P wave arrival to closest point not affected by other locations
- Cross-correlation of measurements at opposite ends → direction
- From 2 links, exact point can be extracted

Transoceanic comparisons of atomic clocks over fiber



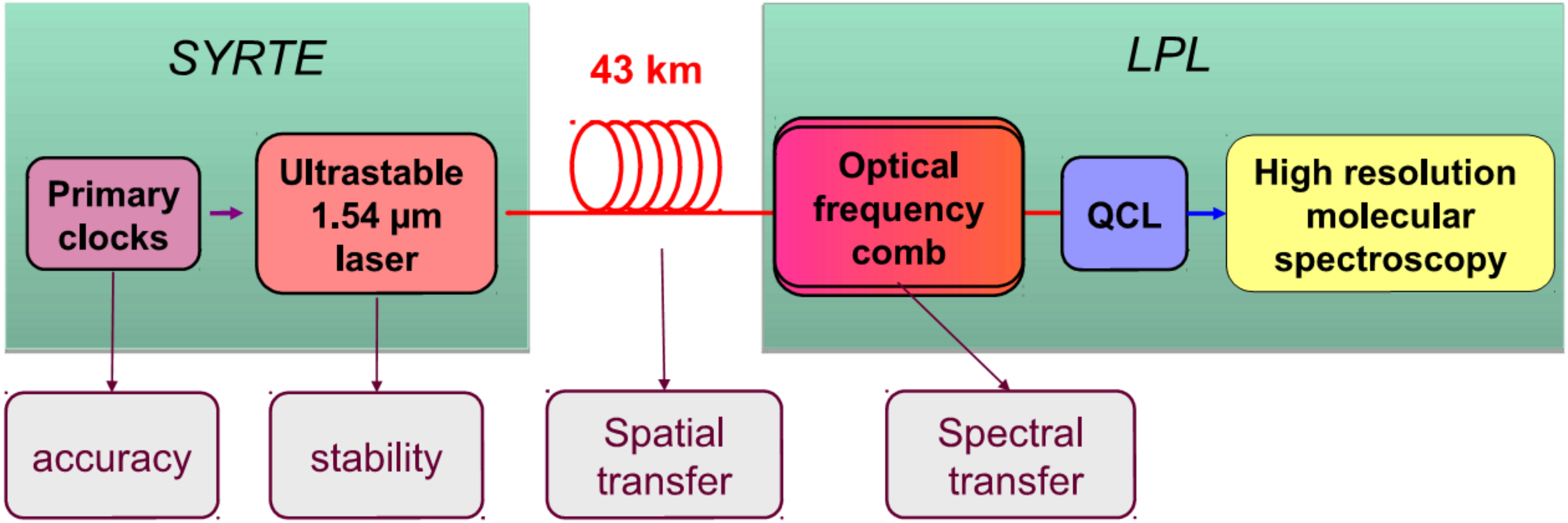
- Measurement→polynomial model
- Expected noise on free-running transcontinental fiber (7000 km)
- Frequency comparison (bidirectional fiber)
- Frequency comparison (fiber pair)

C. Clivati et al., Optica **14** (2018)

APPLICATIONS

- Optical Clock Comparisons
- Frequency dissemination for VLBI radioastronomy and geodesy
- Relativistic geodesy with clocks
- Earthquake detection with coherent optical fibers
- Atomic and Molecular Spectroscopy

Transfer of the stability/accuracy of a remote frequency reference to a QCL



Near-IR frequency reference

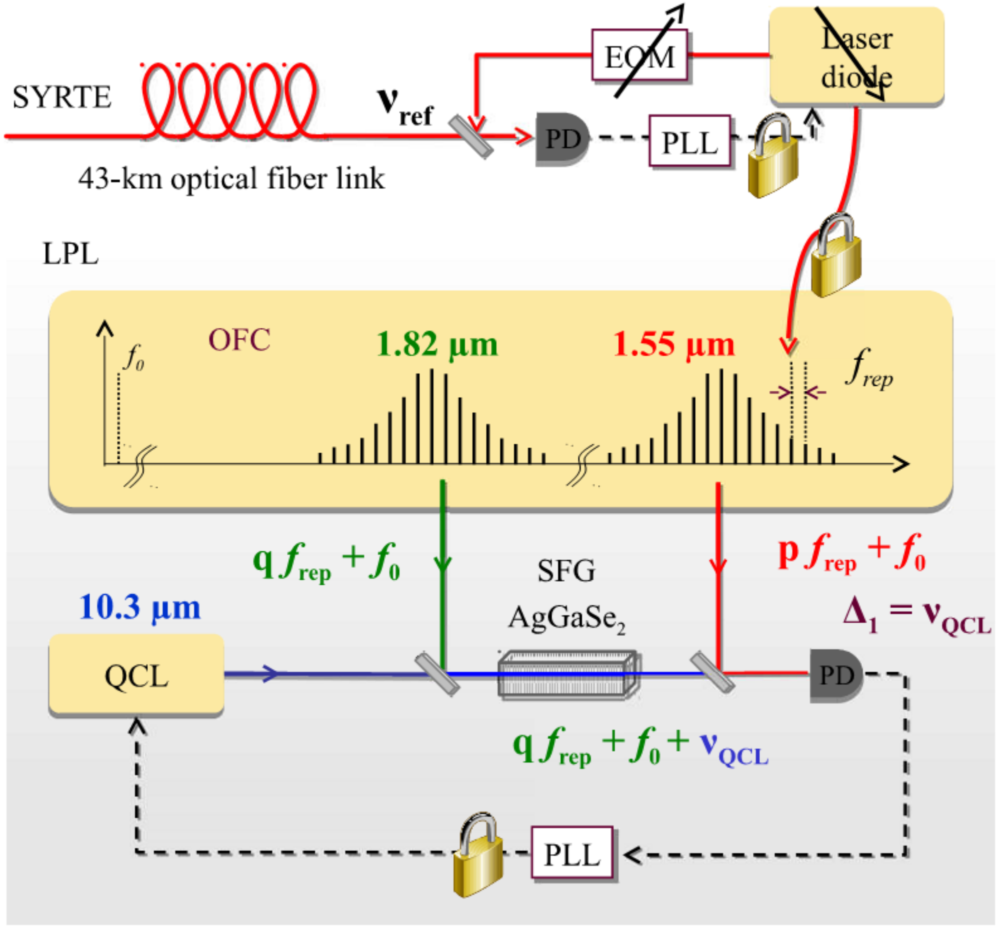
- 1s-stability ~10^{-15}
- Accuracy ~ 10^{-14} (0,3 Hz) at 100 s from H-maser
- Potentially: Cs fountain accuracy ~ 3.10^{-16}

Optical fiber link

- Free running stability ~≤ 10^{-14}
- Stabilized: $10^{-15}\ \tau^{-1}$ from 1 to 10^4 s

Courtesy Ann Amy Klein,

QCL stabilization and frequency tuning



$$\Delta_1 = \nu_{QCL} - (p-q)\, f_{rep}$$

a) Regeneration laser locked to the link reference, while being tunable throught the EOM driving frequency
b) Comb locked to regeneration laser
c) QCL locked to comb

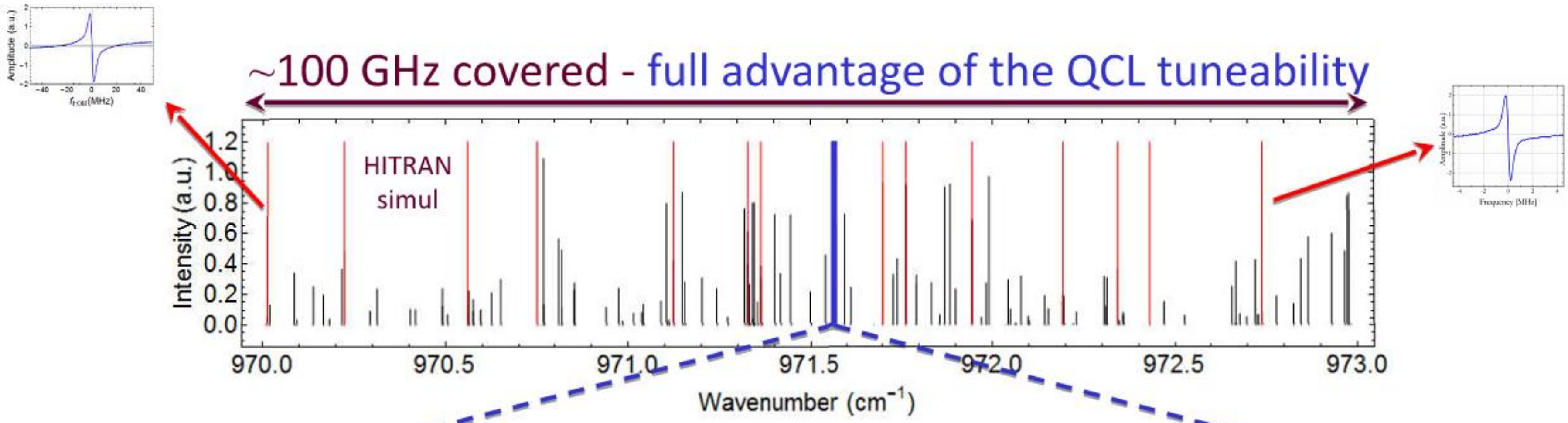
Scanning the EOM frequency,
→ Laser diode scanned
→ Comb scanned
→ QCL scanned

B. Argence, et al., *Quantum cascade laser frequency stabilization at the sub-Hz level,* Nature Photonics (2015)

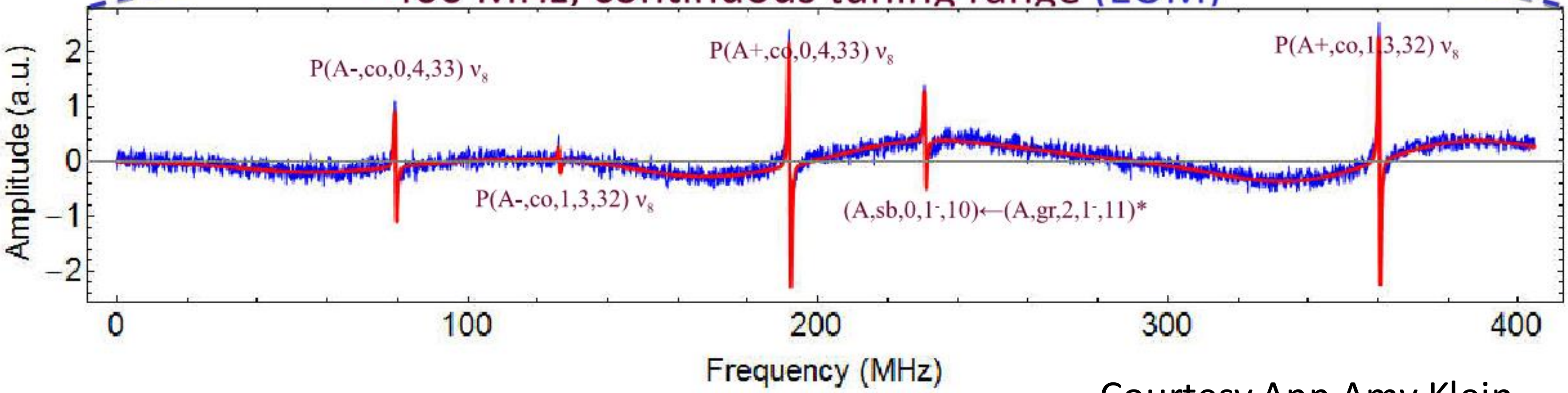
Courtesy Ann Amy Klein,

High-resolution spectroscopy of methanol: wide tuneability

~100 GHz covered - full advantage of the QCL tuneability



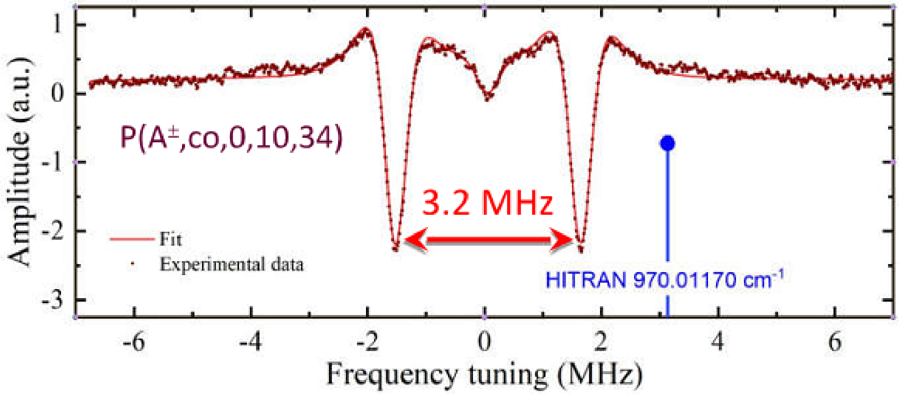
~400 MHz, continuous tuning range (EOM)



Courtesy Ann Amy Klein,

High-resolution spectroscopy of methanol: resolution

P(34, 10) $A^{\pm}$ line

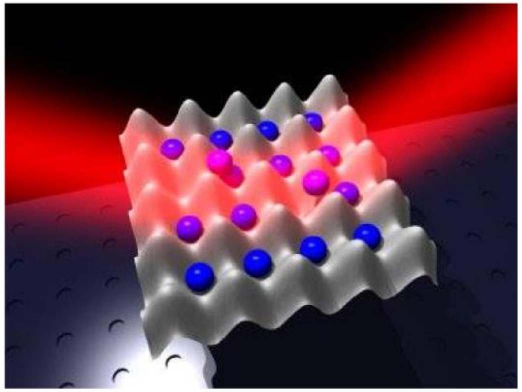


resolved K-doublet for lines of A symmetry, C-O stretch

Lines resolved for the first time, to the best of our knowledge

Courtesy Ann Amy Klein,

Coherent Fibre Link for ultracold gases

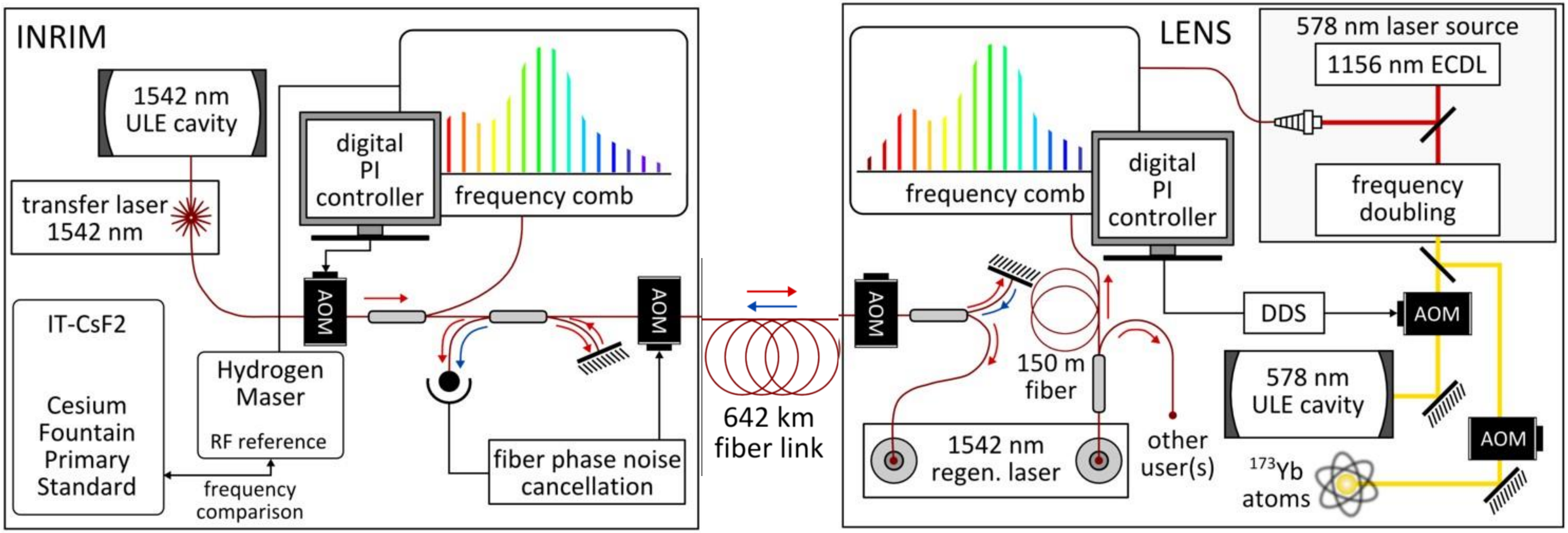


Alkaline atoms are the most promising platforms to develop new quantum technologies, thanks to the possibility to handle their orbital degree of freedom through the forbidden transition 1S0-3P0. They can be seen as **quantum simulators of fundamental effects** unattainable in their original physical context (e.g. solid physics)

Most experimental schemes rely on cyclical addressing of the clock transition (few Hz FWHM) for several hours: **need for manipulation lasers with narrow linewidth and long-term stability:**

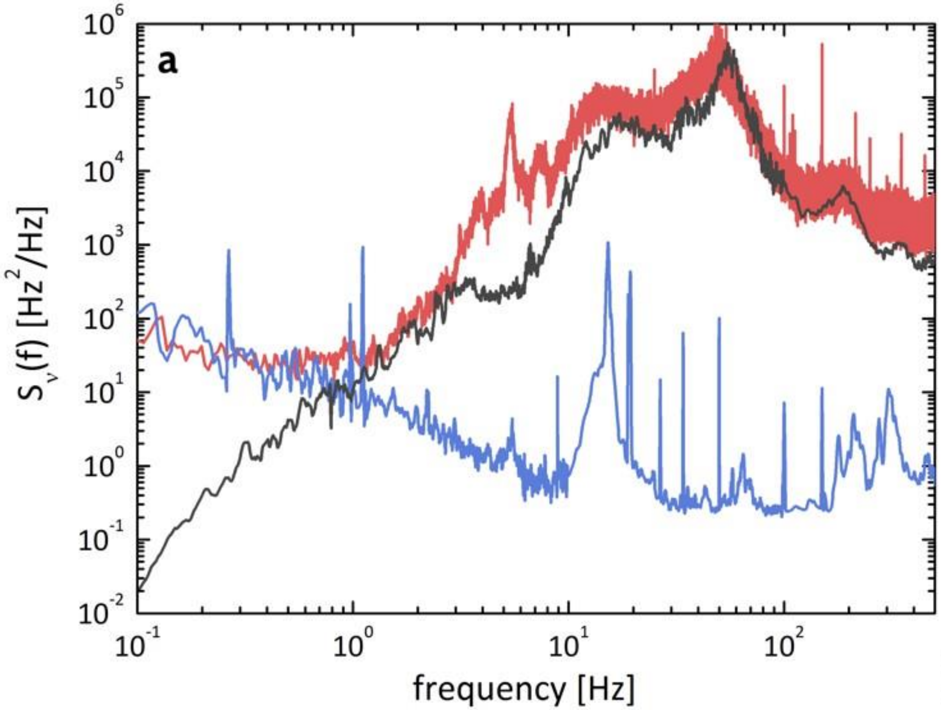
- Short Term stability: Local High-finesse cavity
- Long-term stability: referencing to INRIM atomic clocks via the fibre link

INRIM- LENS: dissemination for ultracold gases



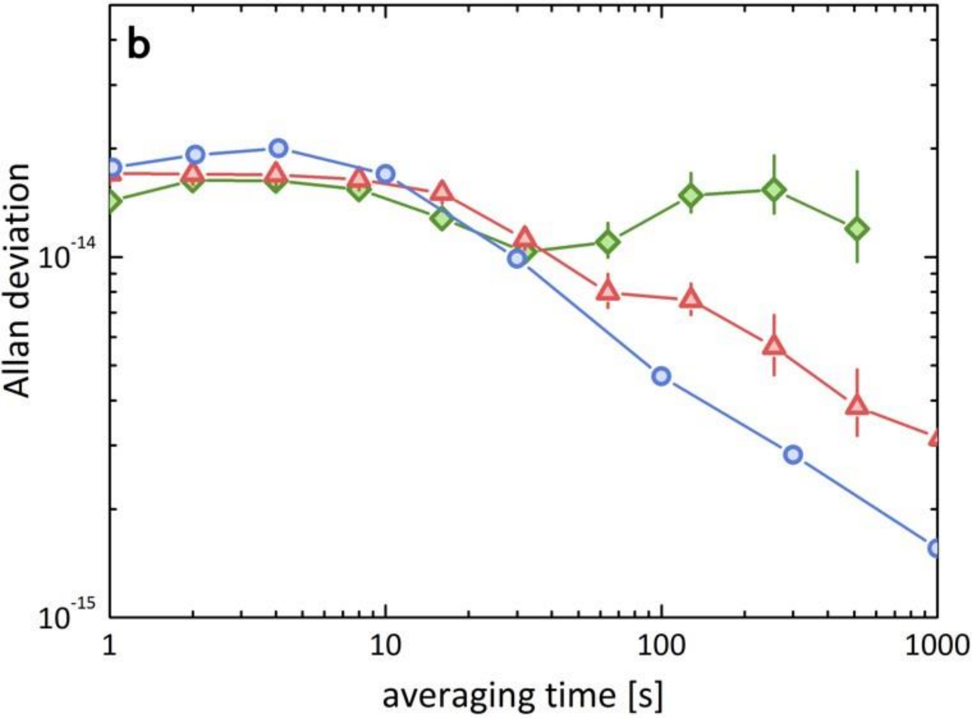
- ☐ At LENS: Ultracold 173Yb gas for manibody physics and quantum simulation.
- ☐ INRIM provided the ultrastable cavity to use the Yb clock transition to coherently address manibody effects
- ☐ The cavity ensures the short-term stability, then it is locked on the fibre link signal for long-term stability (and accuracy when needed)

INRIM- LENS: dissemination for ultracold gases



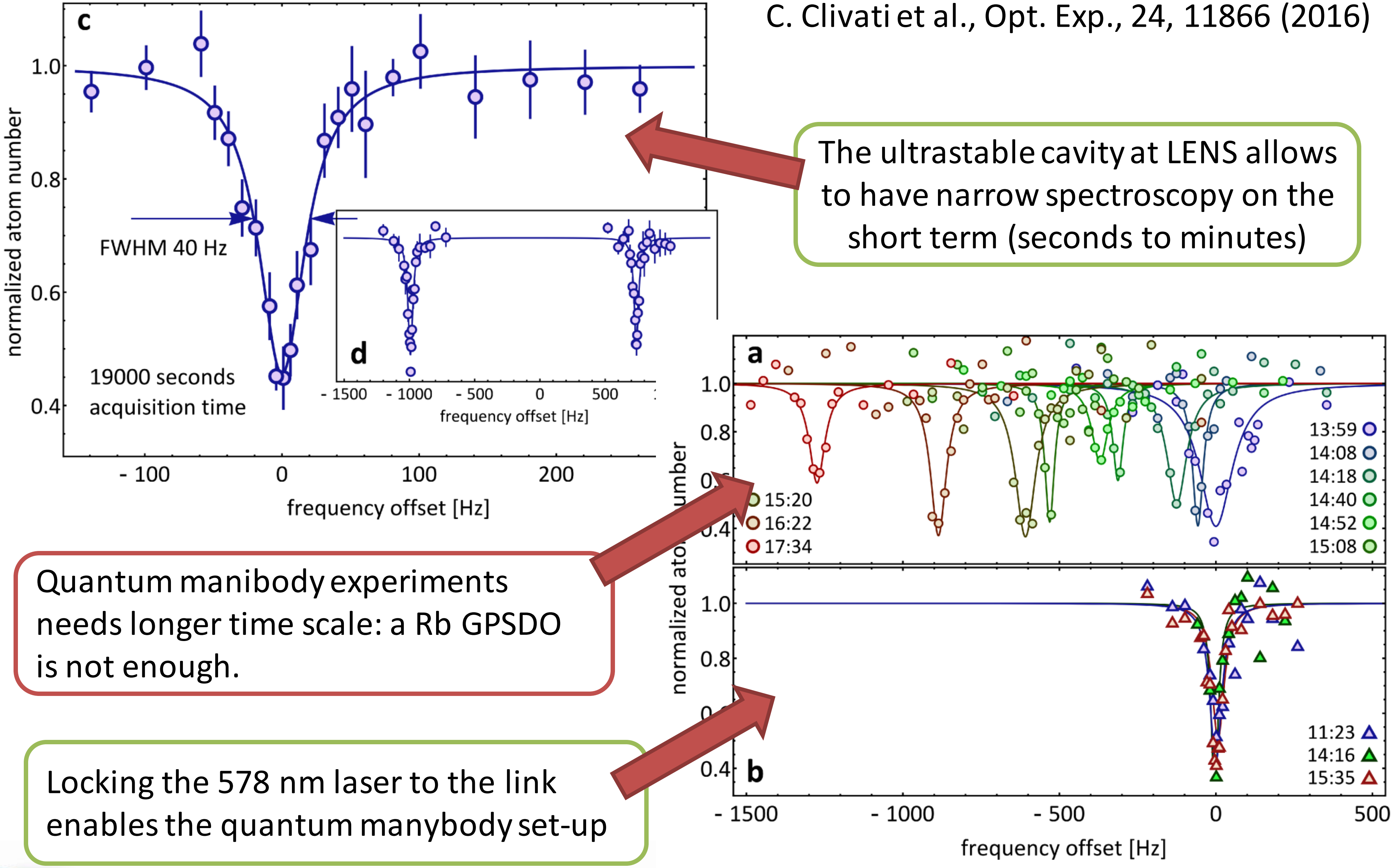
Red: local laser at 1156 nm vs link at 1542 nm;
Blue: noise of the H-maser-disciplined 1542-nm laser as measured at INRIM;
Black: expected contribution of the optical link.

Red triangles: Adev link at 1542 nm vs the local 1156-nm laser, locked to it;
green diamonds: Adev link 1542-nm laser and the local 1156-nm Laser (0.1 Hz/s drift removed).
Blue circles: Adev HM-disciplined 1542-nm laser as measured at INRIM;



INRIM- LENS: 173 Yb clock transition apectroscopy

C. Clivati et al., Opt. Exp., 24, 11866 (2016)



The ultrastable cavity at LENS allows to have narrow spectroscopy on the short term (seconds to minutes)

Quantum manibody experiments needs longer time scale: a Rb GPSDO is not enough.

Locking the 578 nm laser to the link enables the quantum manybody set-up

INRIM- LENS: 173 Yb clock transition spectroscopy

- 6 independent measurements, over three months, total time 40000 s (11 hours).
- Absolute frequency of the 173Yb 1S0-3P0 transition:

υ(173Yb) = 518 294 576 845 268 (10) Hz

- A factor 400 improved accuracy over the previous value
- Improved knowledge of the isotope shifts of the 1S0-3P0transition:

υ(171Yb) - υ(173Yb) = 1 259 745 597(10) Hz
υ(173Yb) - υ(174Yb) = 551 536 050(10) Hz.

- Such accuracy would not be reachable through a GPS-based reference

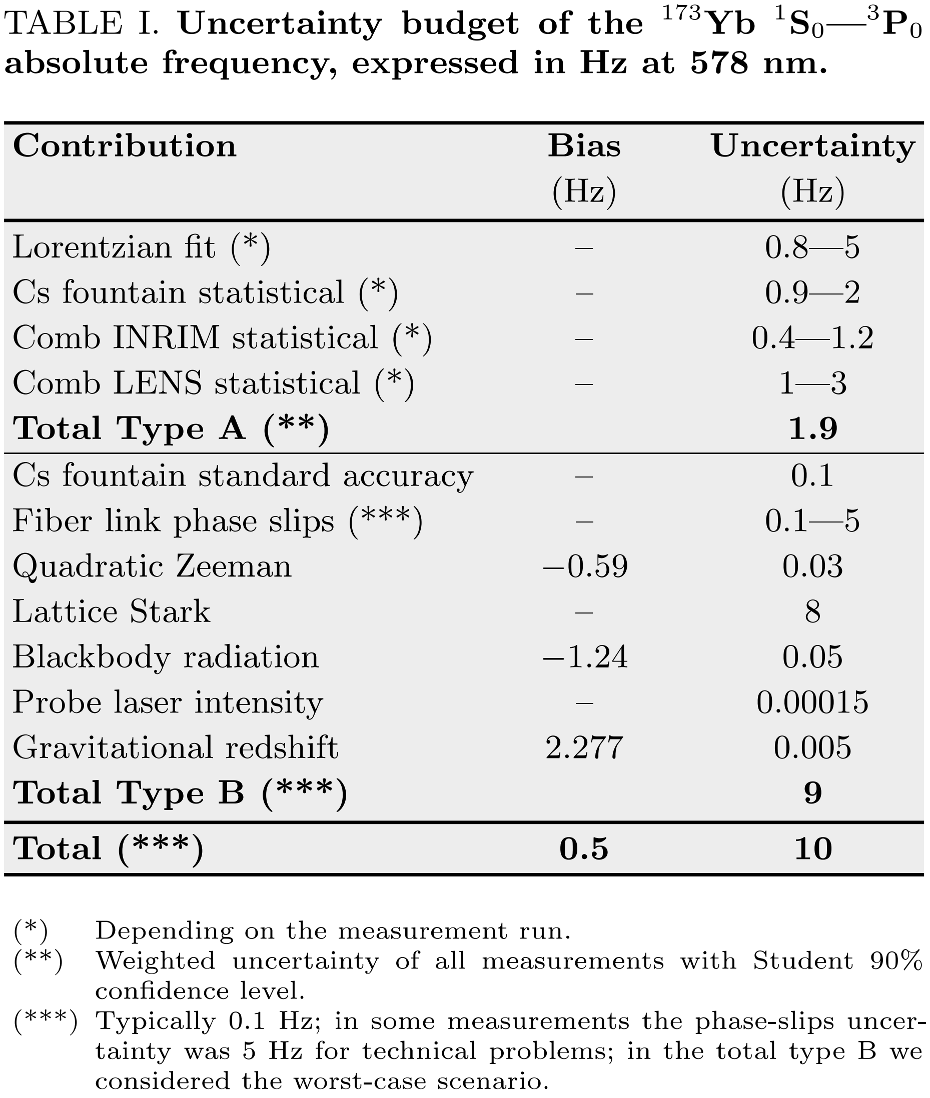


TABLE I. **Uncertainty budget of the ^{173}Yb $^{1}S_0$—$^{3}P_0$ absolute frequency, expressed in Hz at 578 nm.**

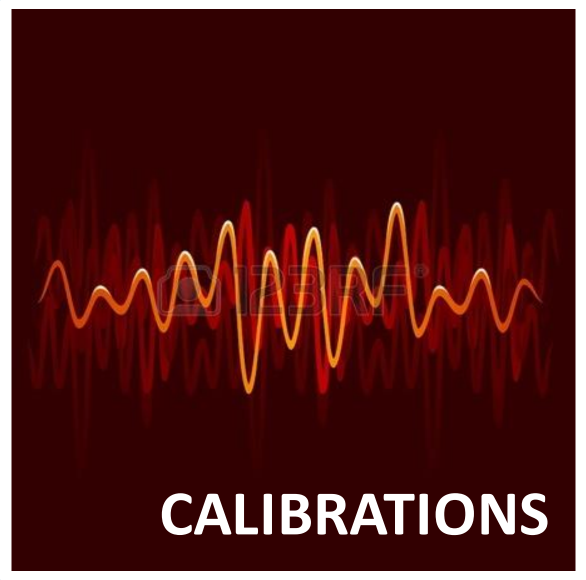
Contribution	**Bias** (Hz)	**Uncertainty** (Hz)
Lorentzian fit (*)	–	0.8—5
Cs fountain statistical (*)	–	0.9—2
Comb INRIM statistical (*)	–	0.4—1.2
Comb LENS statistical (*)	–	1—3
Total Type A (**)		**1.9**
Cs fountain standard accuracy	–	0.1
Fiber link phase slips (***)	–	0.1—5
Quadratic Zeeman	−0.59	0.03
Lattice Stark	–	8
Blackbody radiation	−1.24	0.05
Probe laser intensity	–	0.00015
Gravitational redshift	2.277	0.005
Total Type B (***)		**9**
Total (***)	**0.5**	**10**

(*) Depending on the measurement run.
(**) Weighted uncertainty of all measurements with Student 90% confidence level.
(***) Typically 0.1 Hz; in some measurements the phase-slips uncertainty was 5 Hz for technical problems; in the total type B we considered the worst-case scenario.

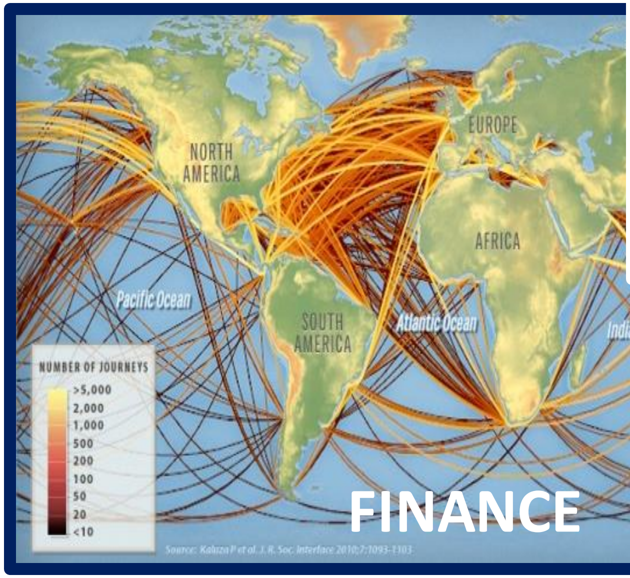
Time over Fiber: Industry

TELECOMMUNICATIONS

SPACE



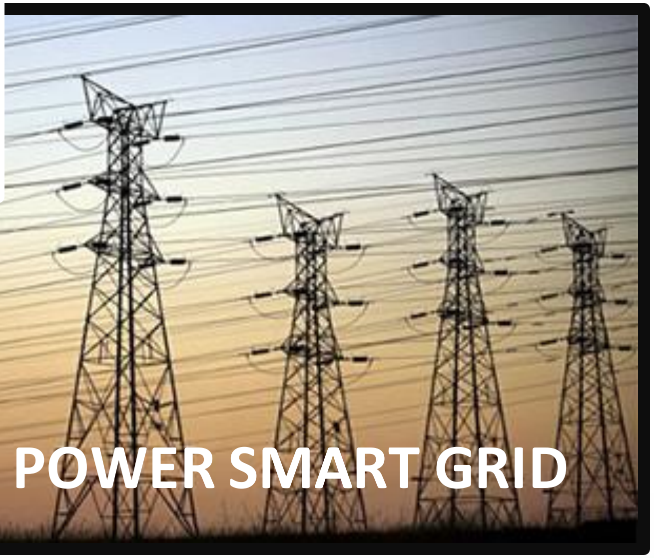
CALIBRATIONS



FINANCE

Source: Kaluza P et al. J. R. Soc. Interface 2010;7:1093-1103

Copyright Stratfor 2012 www.stratfor.com



POWER SMART GRID

SKIP TO CONCLUSIONS!

ESMA MiFID II Regulatory Technical Standard 25

Start January 2018

European Securities and Markets Authority

☐ Financial trades time stamping traced to UTC

☐ Most demanding requirement:

Accuracy 100 µs and «granularity» 1 µs

☐ Certified Traceability

☐ Robustness

ISTITUTO NAZIONALE DI RICERCA METROLOGICA

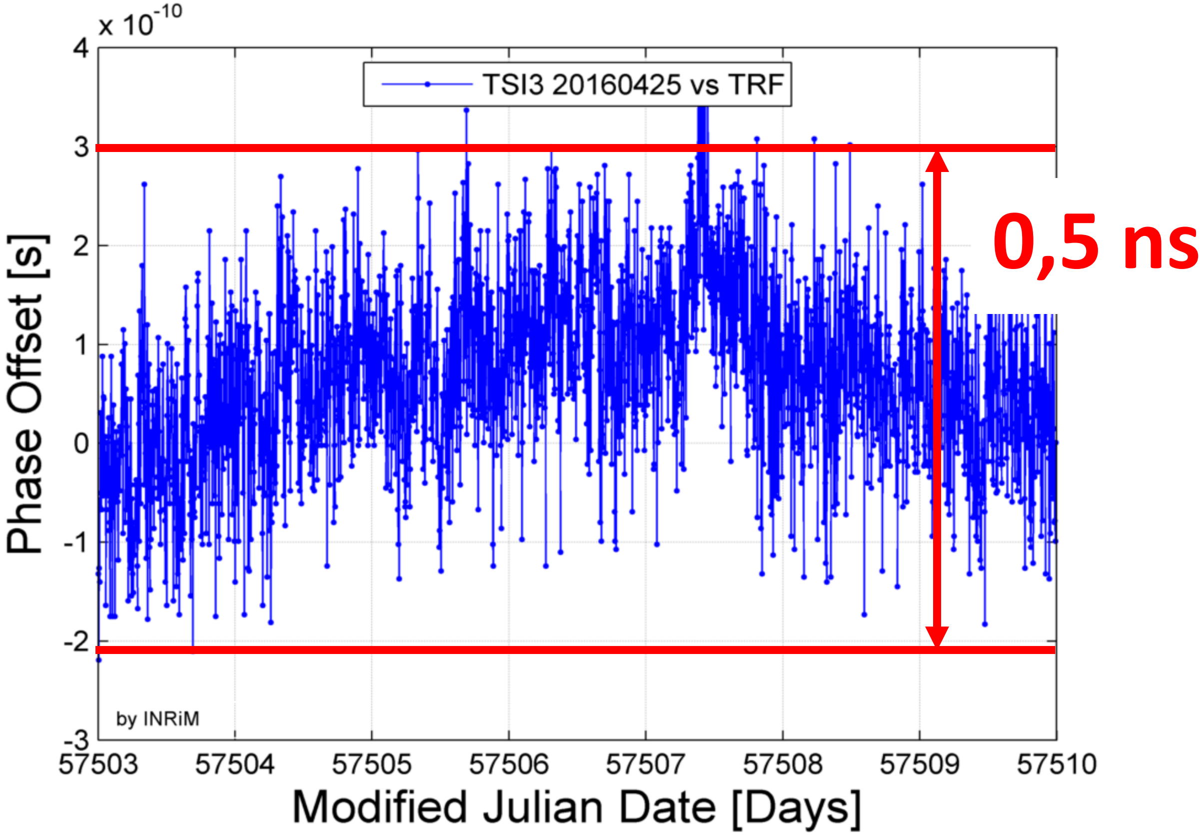
Time over Fibre for the Financial Market

- 160 km Fibre link dedicated to financial users
- Under operation since 2016
- Validation within H2020-Demetra now available as a service
- Cooperation with Consortium TOP-IX (telco consortium)
- White Rabbit / IEEE1588 Time dissemination
- Co-existence with data Traffic (DWDM architecture)

UTC(IT) @INRIM

Colocation Italian Stock Exchange in Milano

Time over Fibre for Finance: performances



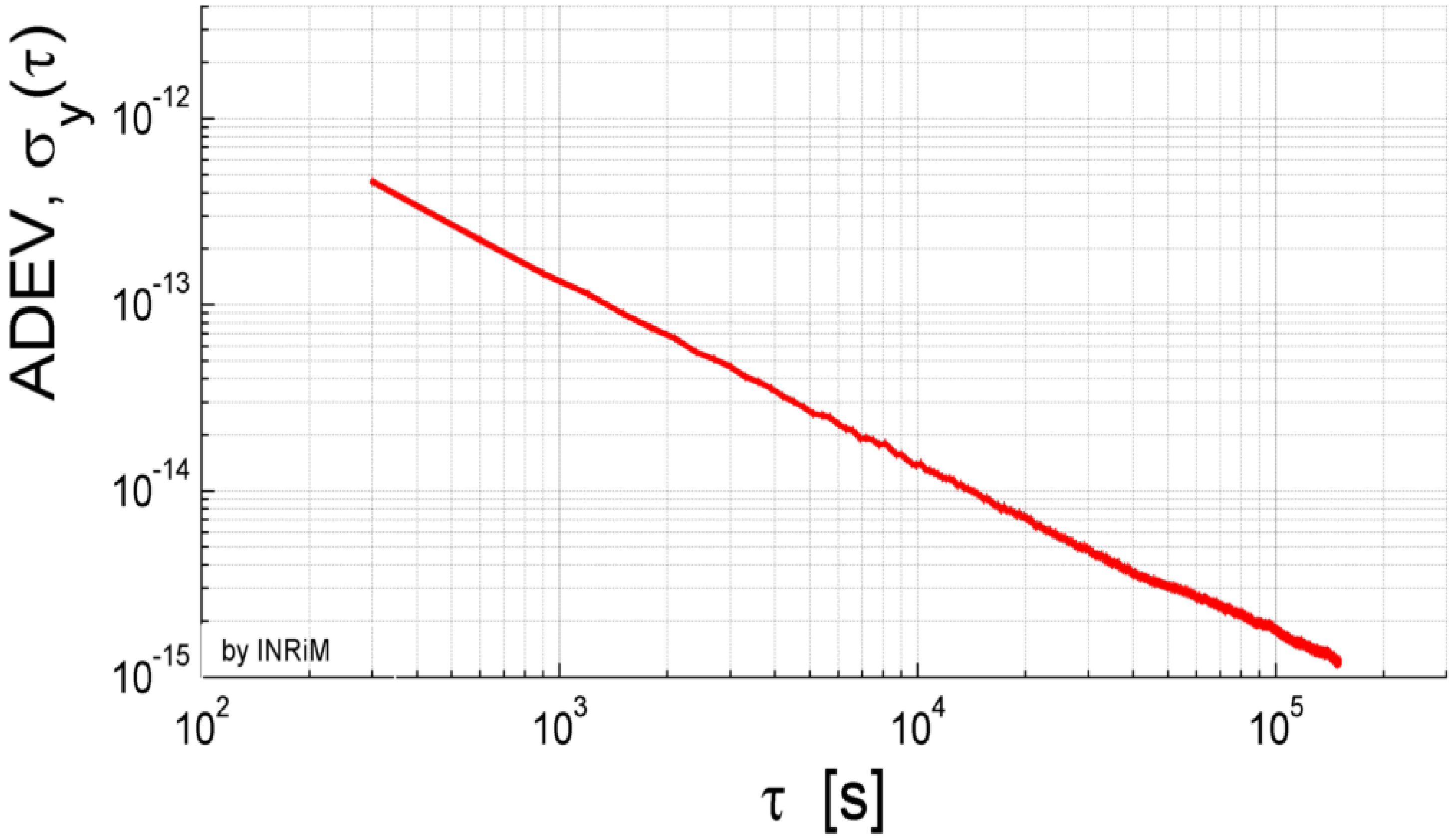
160 km real link with WR-PTP

In collaboration with Time Laboratory @INRIM

Validation:

- First in closed loop (equivalent haul, start/end at INRIM, no offset at <1 ns level .
- Validation: comparison vs GPS-PPP technique, accuracy<5ns within GPS accuracy
- Lesson learned: calibration issues on the devices; interoperability; remote control and monitor

Time over Fibre for Finance: performances



Adev: 1e-10@ 1s; 2e-15 @ 1e5 s

GPS-PPP
compatible

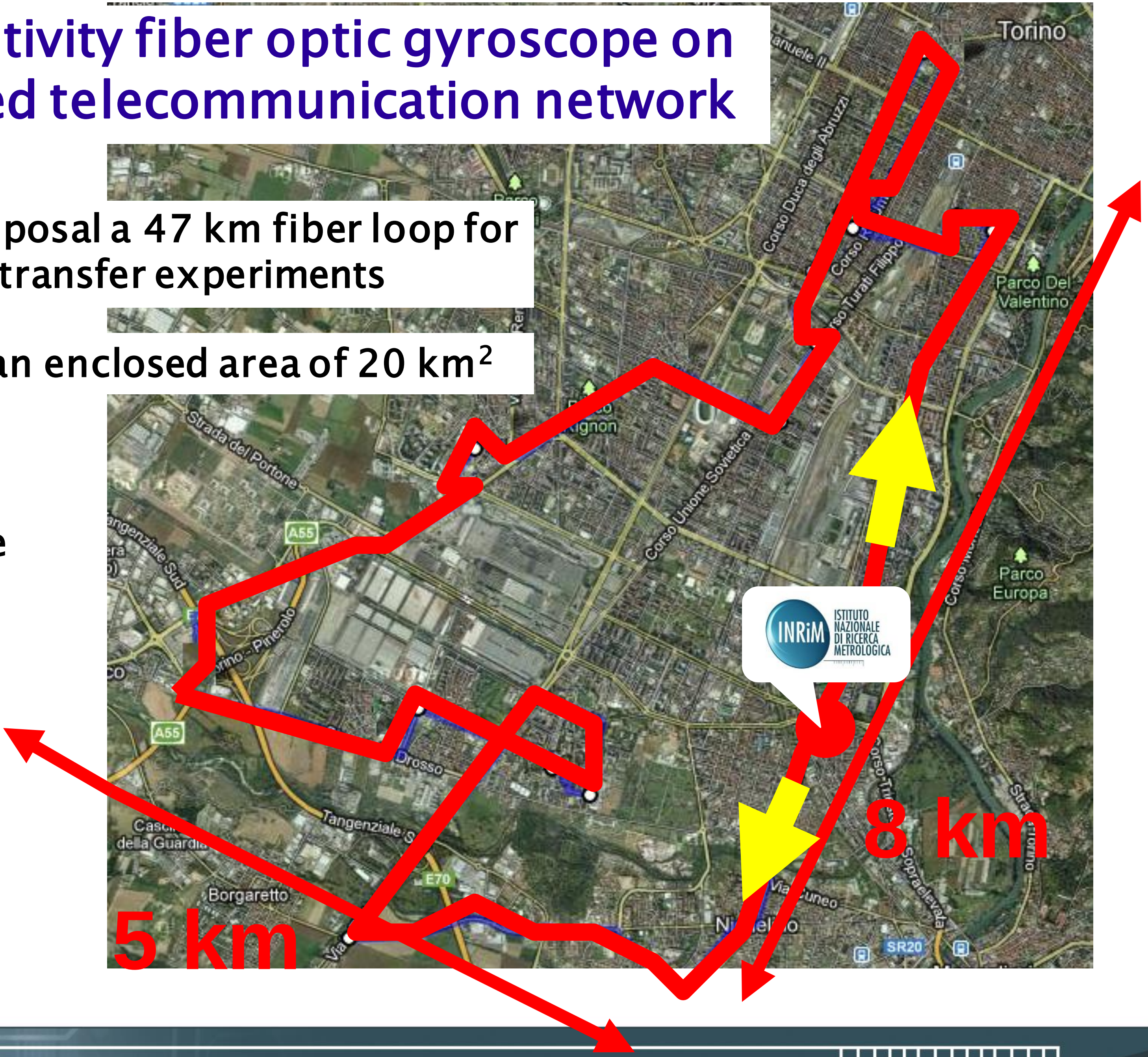
A Sagnac gyroscope and LIFT

A high sensitivity fiber optic gyroscope on a multiplexed telecommunication network

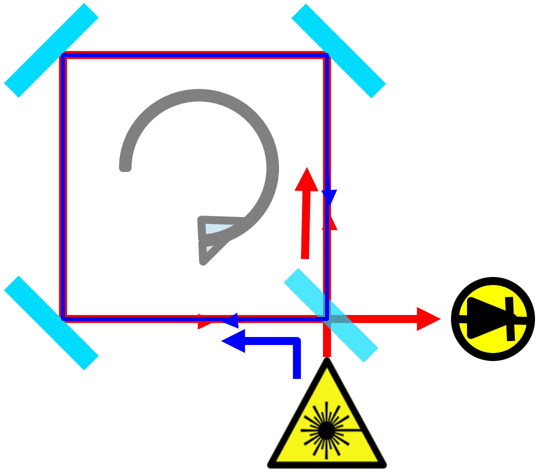
INRIM has at disposal a 47 km fiber loop for coherent phase transfer experiments

Fiber ring with an enclosed area of 20 km^2

Expected phase shift due to Earth rotation ~55 rad

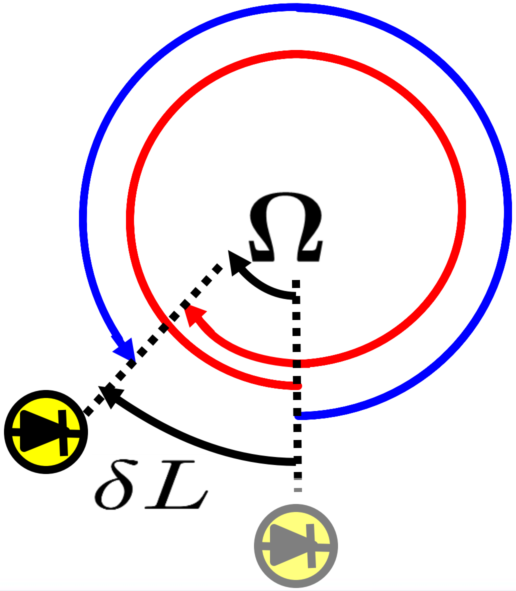


What is a laser gyroscope



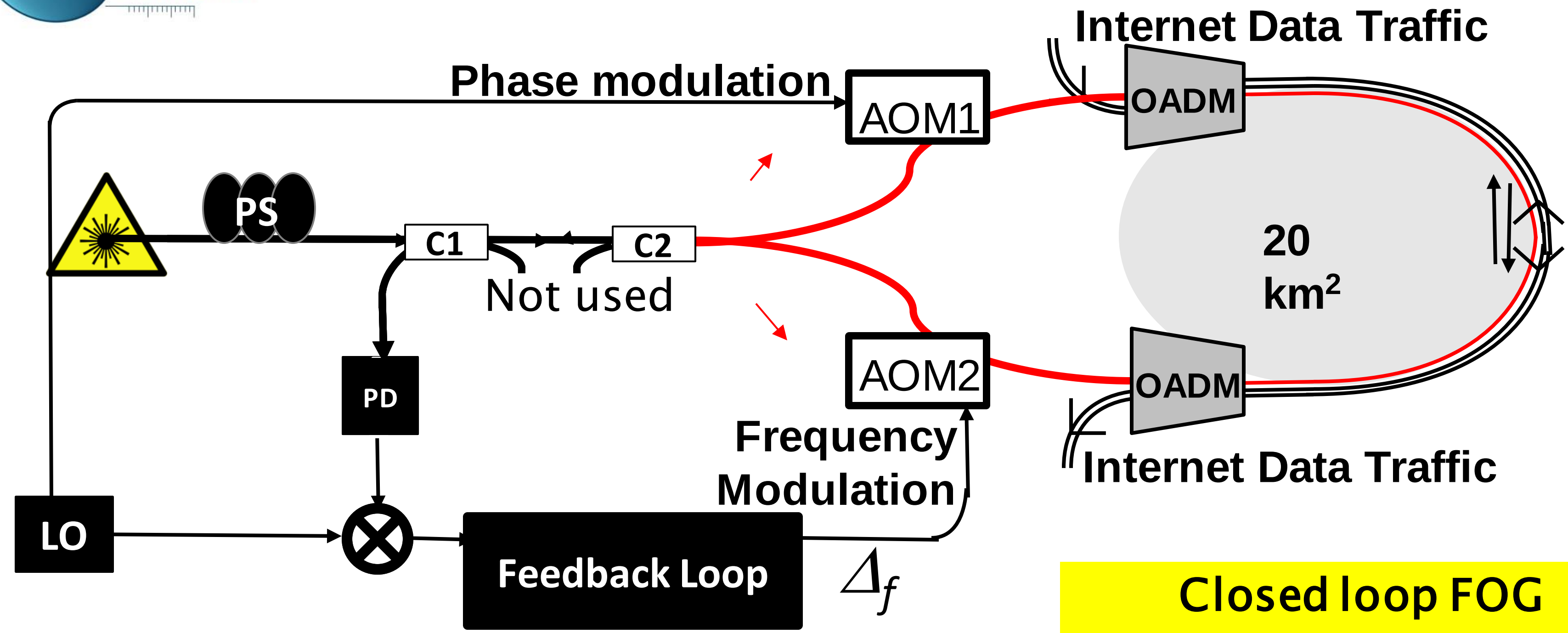
- Two beams follow the same path but in opposite directions
- The optical path must enclose an area
- The platform rotates
- The two beams accumulate a phase shift

$$\varphi_{\mathrm{S}} = \frac{8\pi\nu}{\mathbf{c}^2}\mathbf{A}\cdot\boldsymbol{\Omega}$$



- The sensitivity depends on: – enclosed area
  – orientation

Our experiment



Closed loop FOG

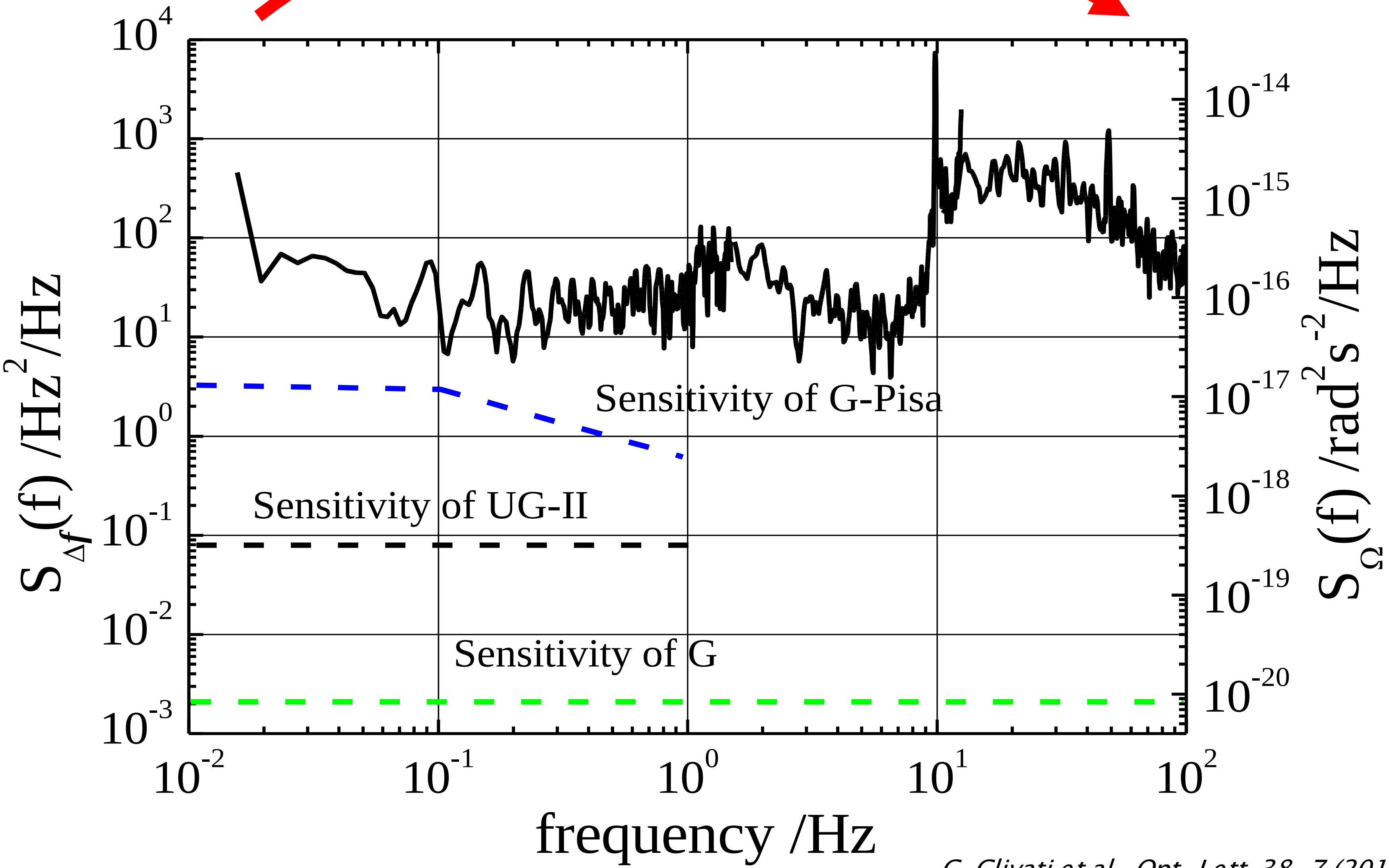
$$\varphi = 2\pi \frac{\mathbf{L}}{\mathbf{c}} \mathbf{\Delta_f} \pm 2\pi \mathbf{k}$$

$$\Delta_f = \frac{4\nu}{nLc} \mathbf{A} \cdot \mathbf{\Omega}$$

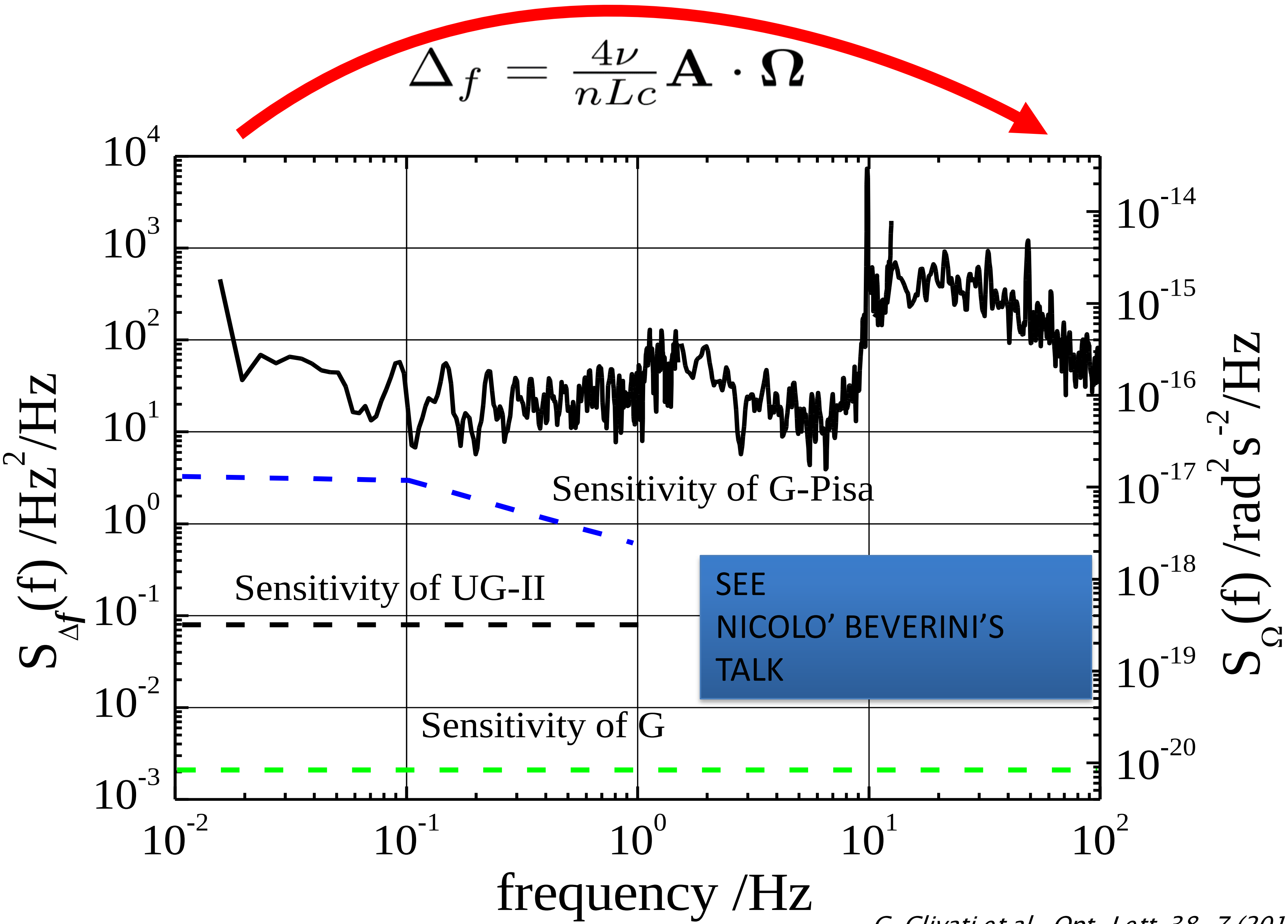
- ✓ Dedicated DWDM ITU 44 channel
- ✓ Non synchronous phase modulation
- ✓ Mixer output depends on senφ_S
- ✓ Feedback loop: frequency offset Δ_f to compensate the Sagnac phase

J. L. Davis et al., Opt. Lett. 6, 10, (1981)
C. Clivati et al., Opt. Lett 38, 7 (2013)

$$\Delta_f = \frac{4\nu}{nLc}\mathbf{A}\cdot\mathbf{\Omega}$$



C. Clivati et al., Opt. Lett. 38, 7 (2013)

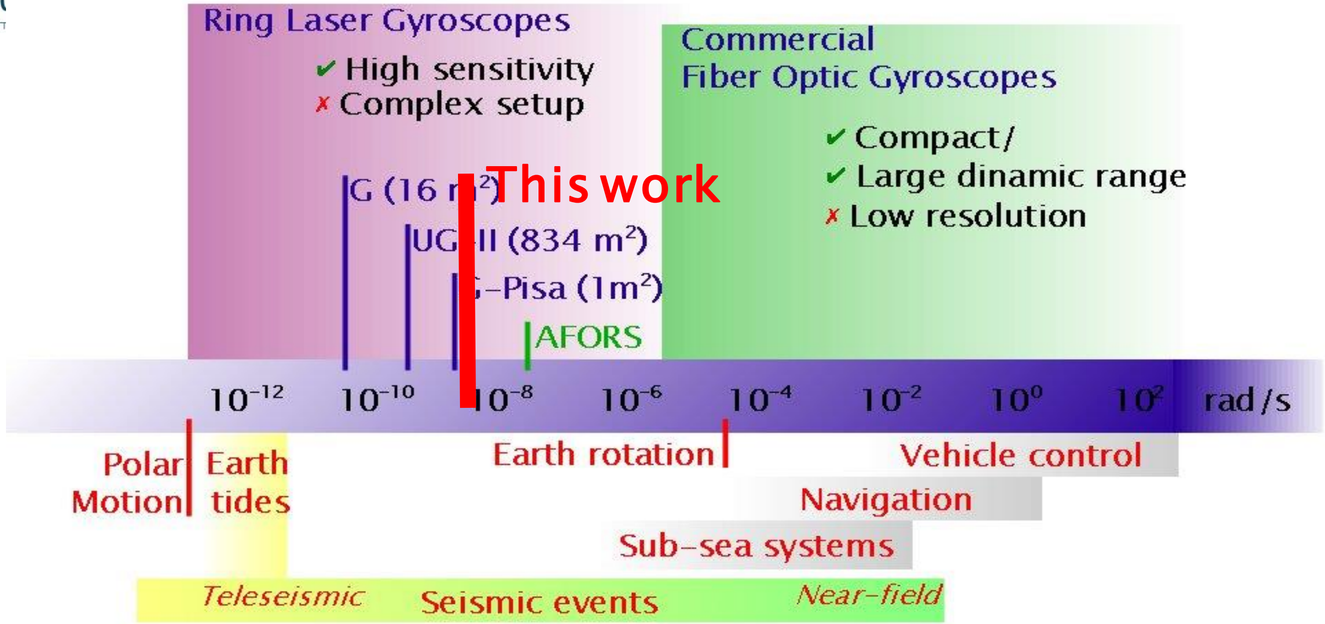


$$\Delta_f = \frac{4\nu}{nLc}\mathbf{A}\cdot\mathbf{\Omega}$$

SEE
NICOLO' BEVERINI'S
TALK

C. Clivati et al., Opt. Lett. 38, 7 (2013)

Applications and perspectives

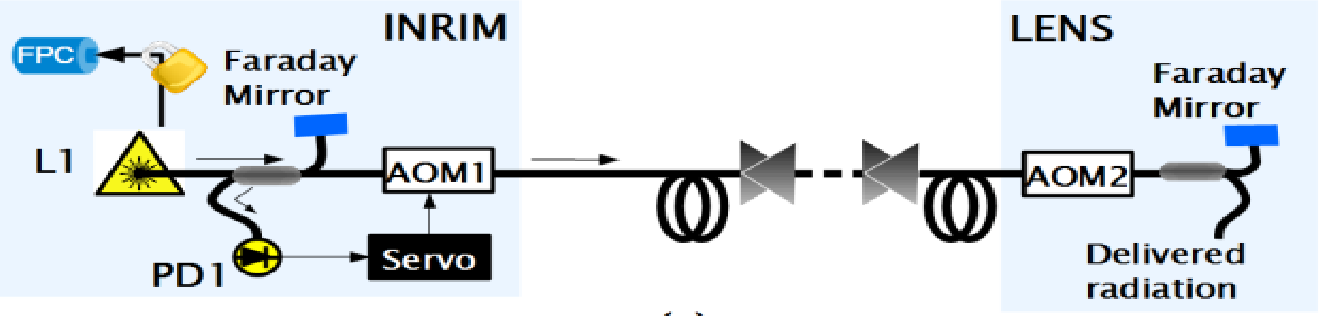


- Present sensitivity 3 x 10^{-9} rad/s   (10^{-8} (rad/s)/$\sqrt{\text{Hz}}$)

- Investigation on ground motions seen by a large sensor could open new opportunities for geophysical research

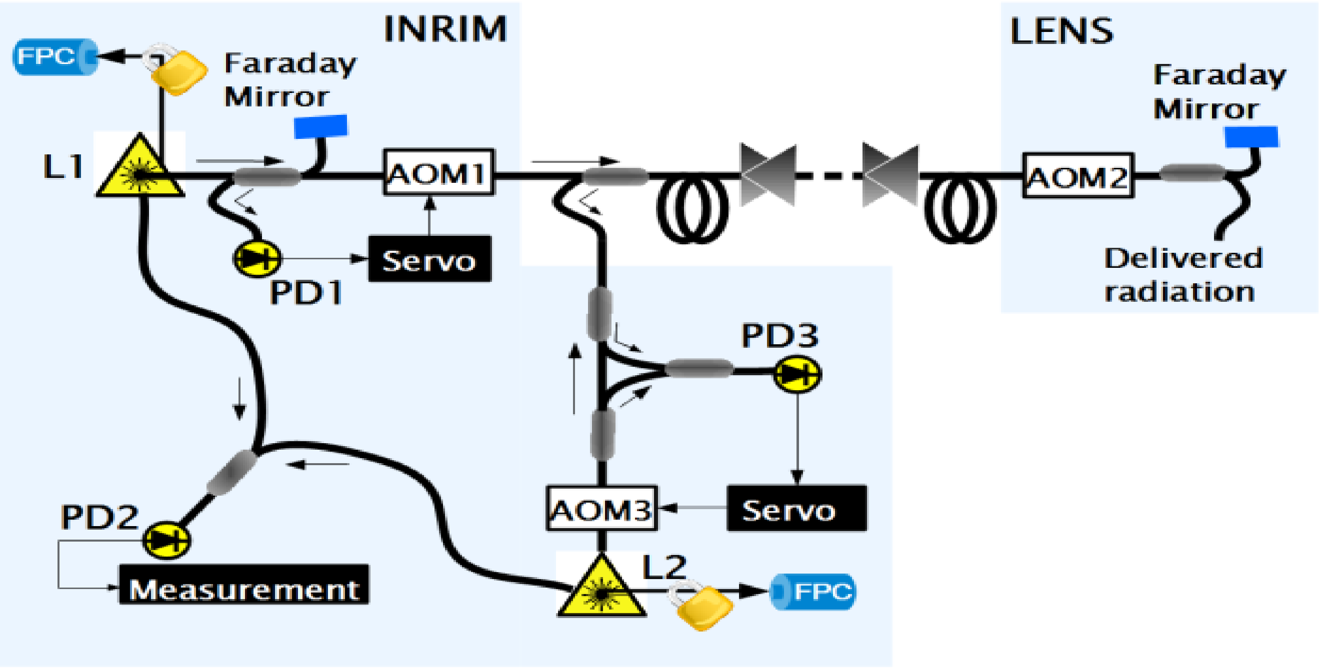
LIFT SET-UP : Link and Double Link

Single Link
642 km



(a)

Double Link
1284 km



(b)

Conclusions

- Coherent Fibre Links allow to compare optical clocks without limiting the uncertainty

- There are still not intercontinental link, but they are feasible with submarine cables (that are available)

- Coherent Fibre links offer a broad range of applications, in particular their scientific impact has been discussed

- Here we have not talk about Time over Fibre, in particular PTP High Accuracy (White Rabbit) and Electronic Stabilized Link (ELSTAB)

- There are increasing efforts to build a T/F fibre network in Europe link by 2019.