Systèmes sol de distribution du temps

P.-E. Pottie

Outline

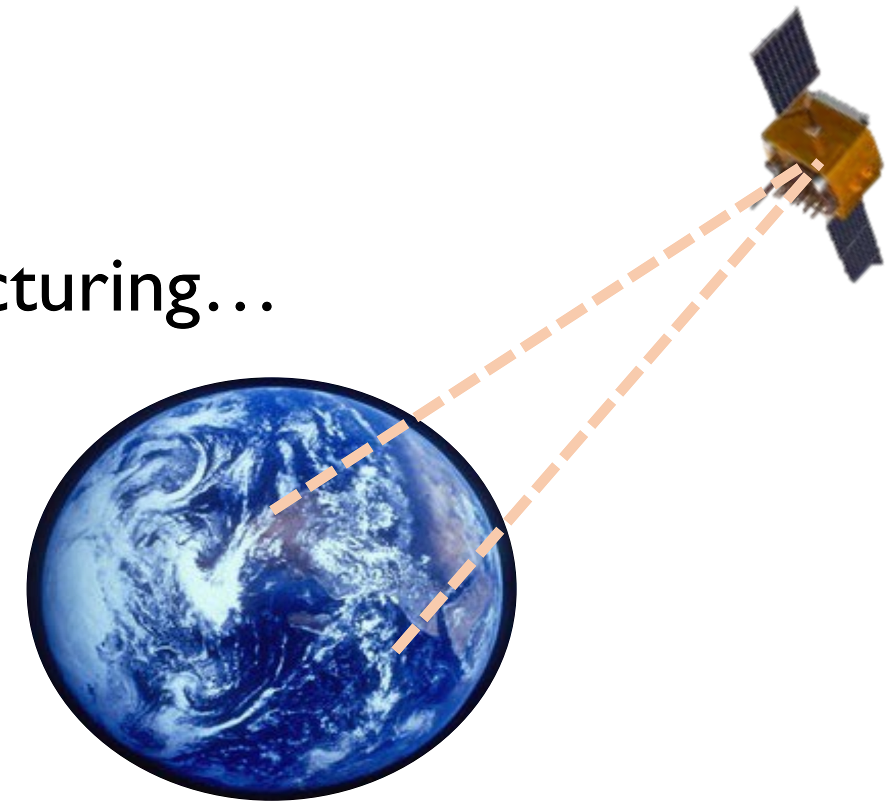
- Motivations for extremely accurate time and frequency transfer
- Optical fibers
- Fiber links
  - Concepts
  - PTP / WR-PTP
  - Optical frequency transfer
- On-going projects, prospects and outlook

Motivations for time and frequency dissemination

Dissemination of Time and Frequency from standards (atomic clocks, timescales)

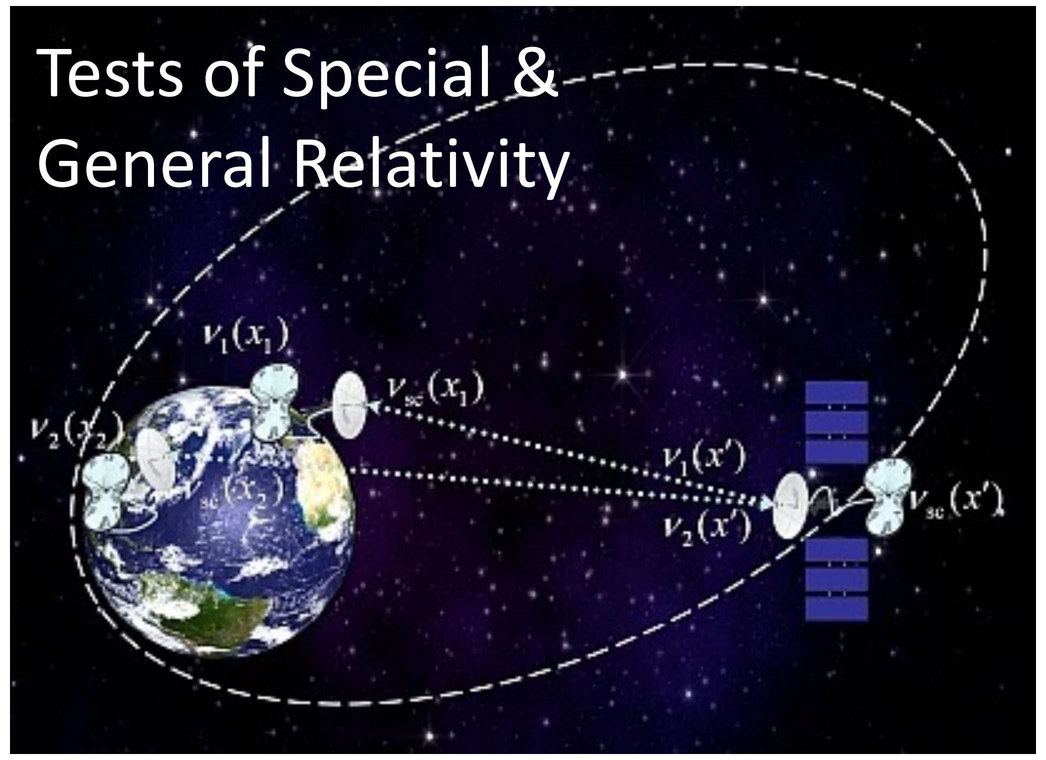
for industry / society : Telecom and network synchronisation, smart grids, finance, manufacturing…

Timing+syntonisation:
ms-ns, 1e-11-1e-15
Traceability



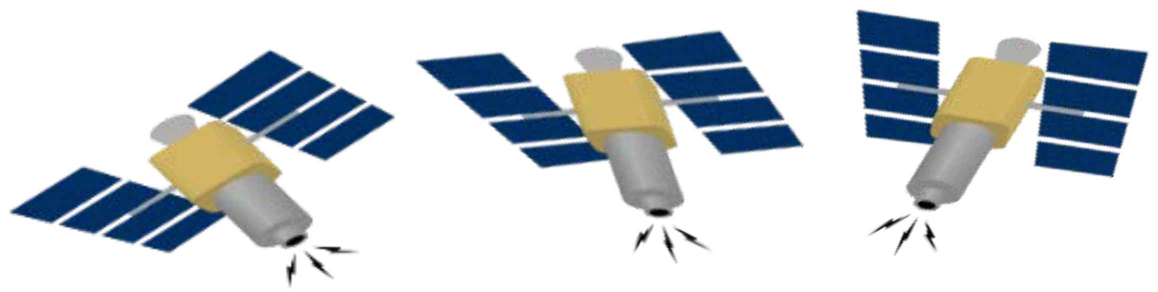
Fundamental Scientific Applications

Definition & Variations in fundamental constants

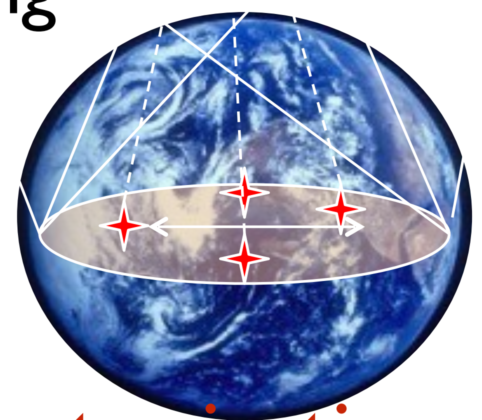


Sensing/Defense:

Positioning, Navigation and Timing



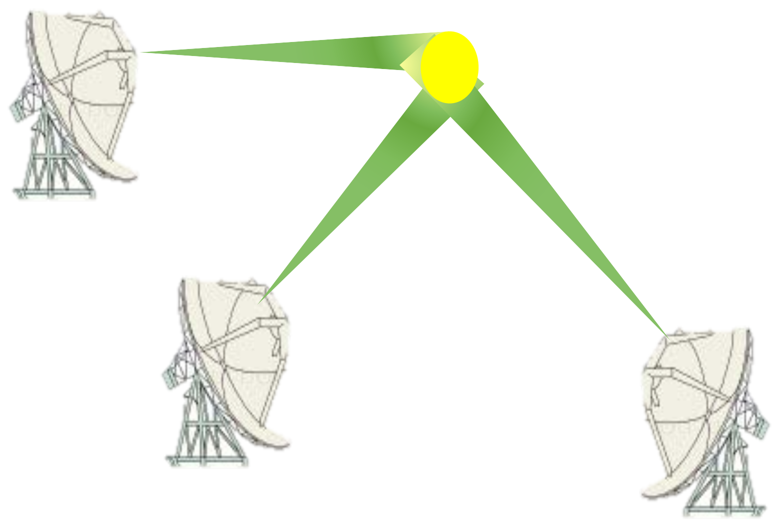
synthetic aperture
global imaging



Timing+syntonisation:
ns, 1e-13-1e-16
Resiliency

Large instruments, array of detectors

astronomy, astro particle, geoscience
multi-messenger astronomy, seismology

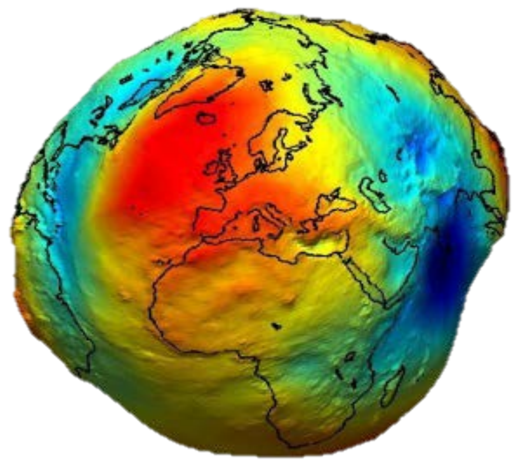


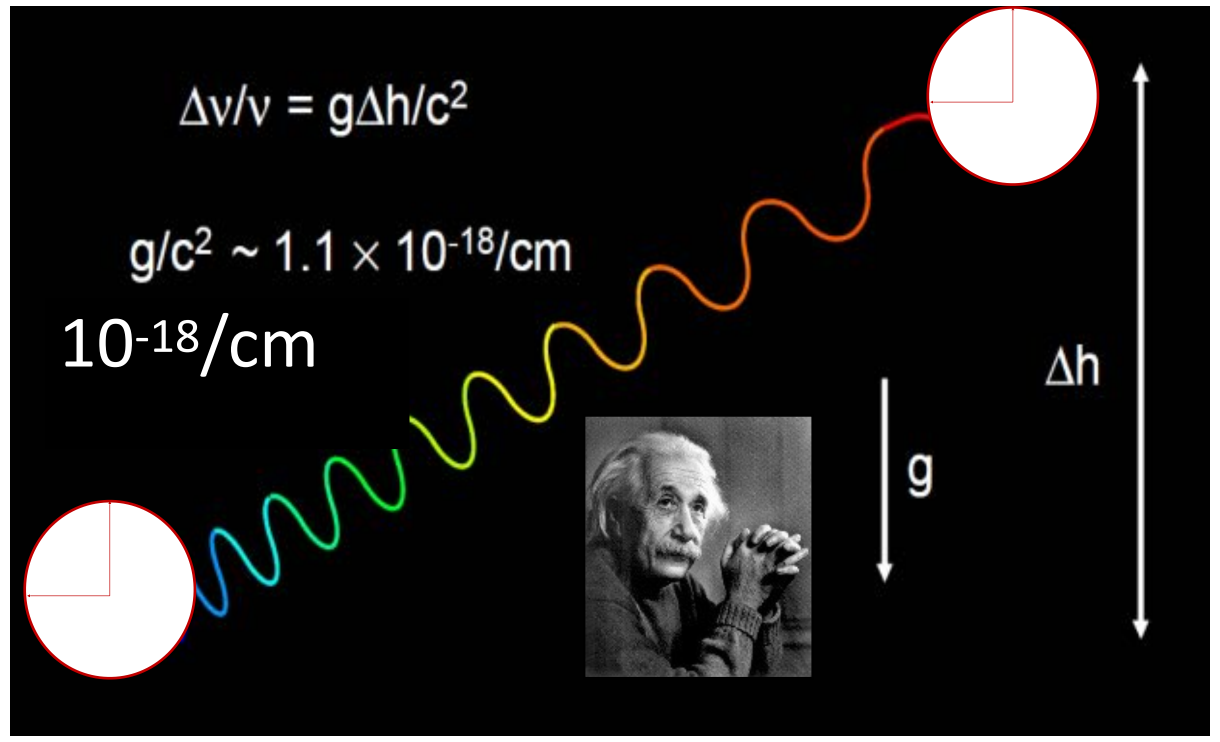
VLBI…

Timing+syntonisation:
ns-ps, 1e-16
Comparisons

Earth Science and climate change

geodesy, chronometric leveling



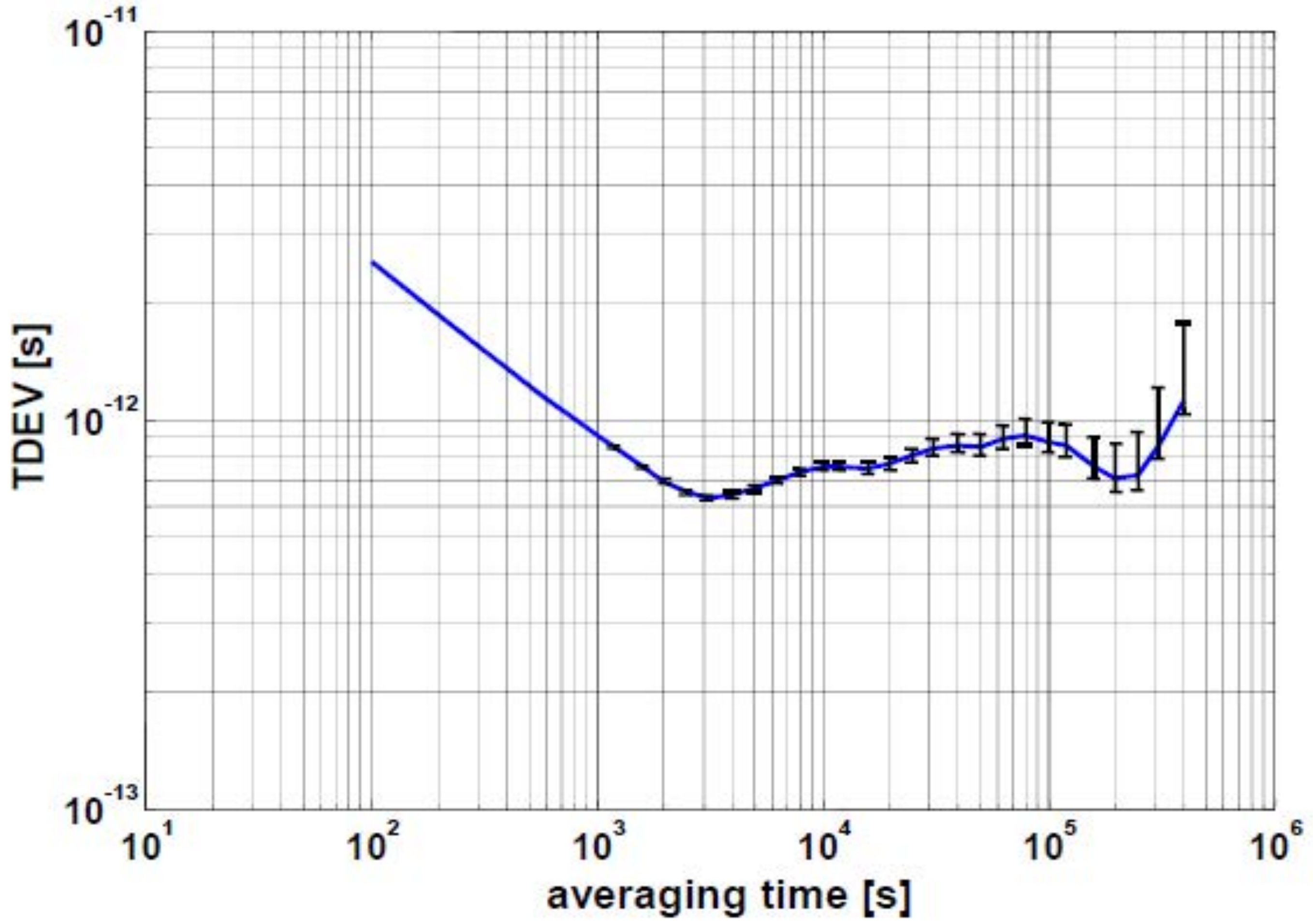


Timing+syntonistion:
ps, 1e-18 and better!
Comparisons

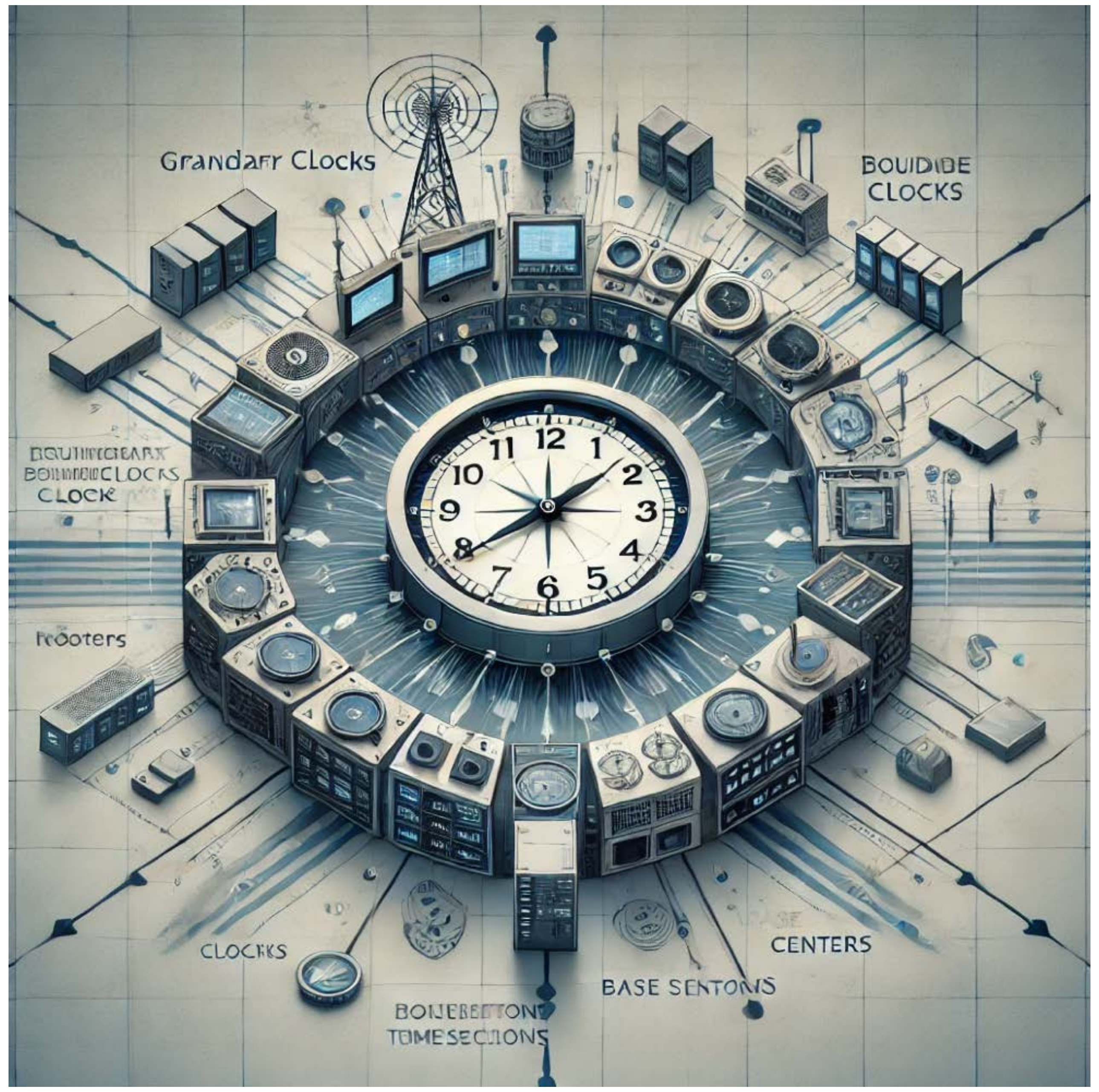
Illustrations: courtesy N. Newbury, NIST

Means for time and frequency dissemination on ground

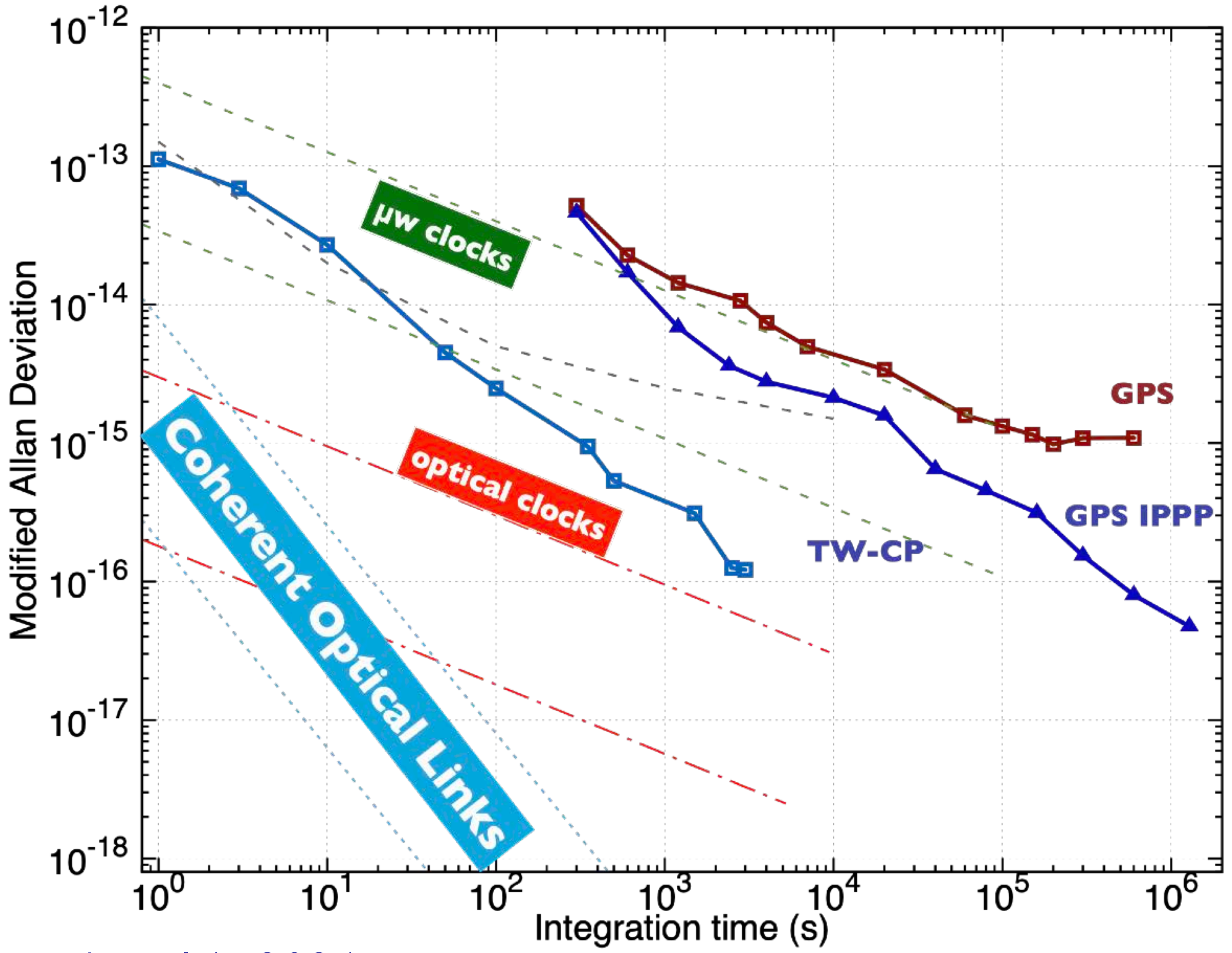
Analog RF+ time transfer (ELSTAB) Precision: < 10 ps



PTP / PTP-High Aaccuracy : Precision: < 1 µs

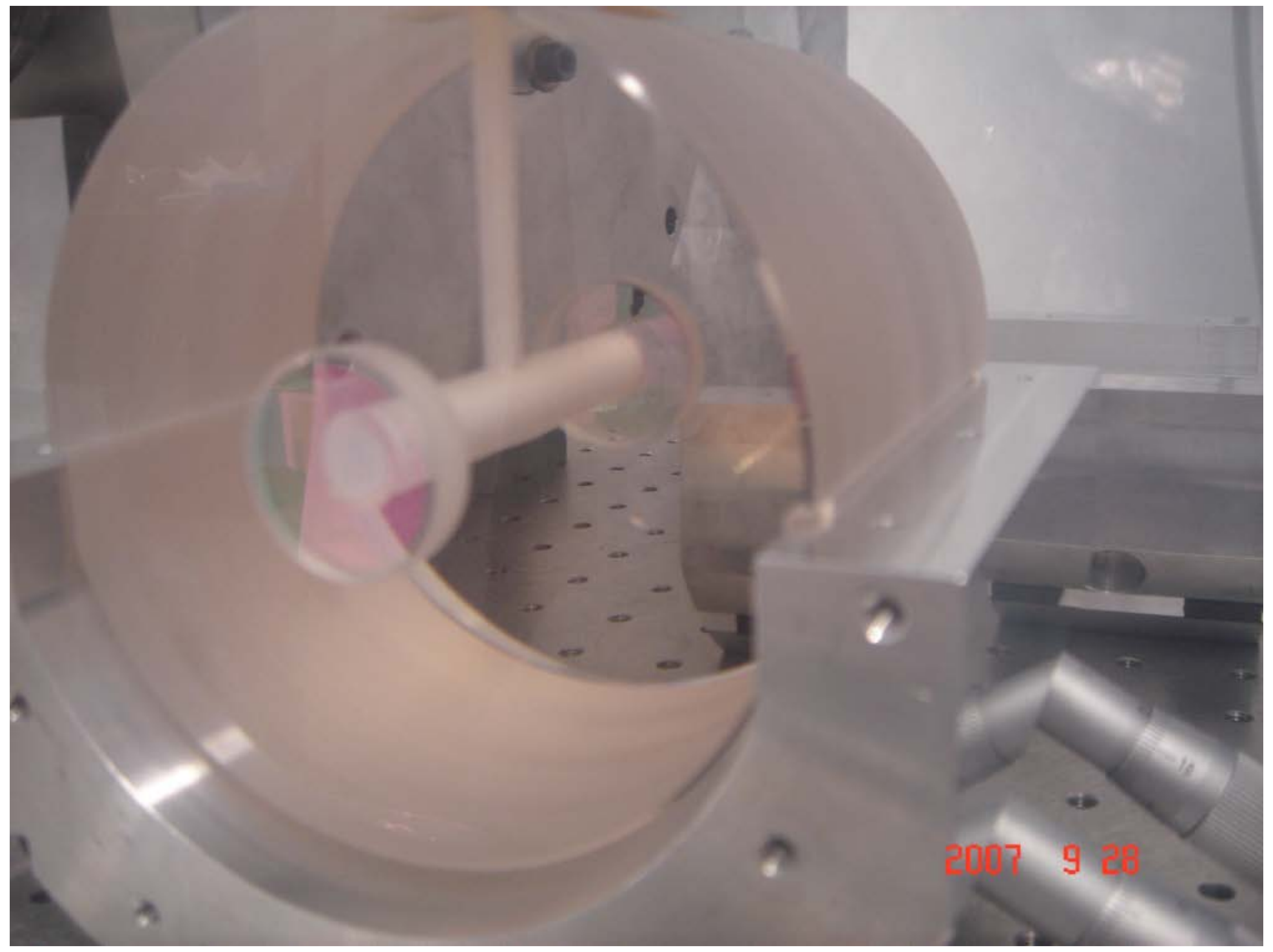


Analog optical frequency transfer Precision: < 10 fs



Lasers in time and frequency metrology nowadays

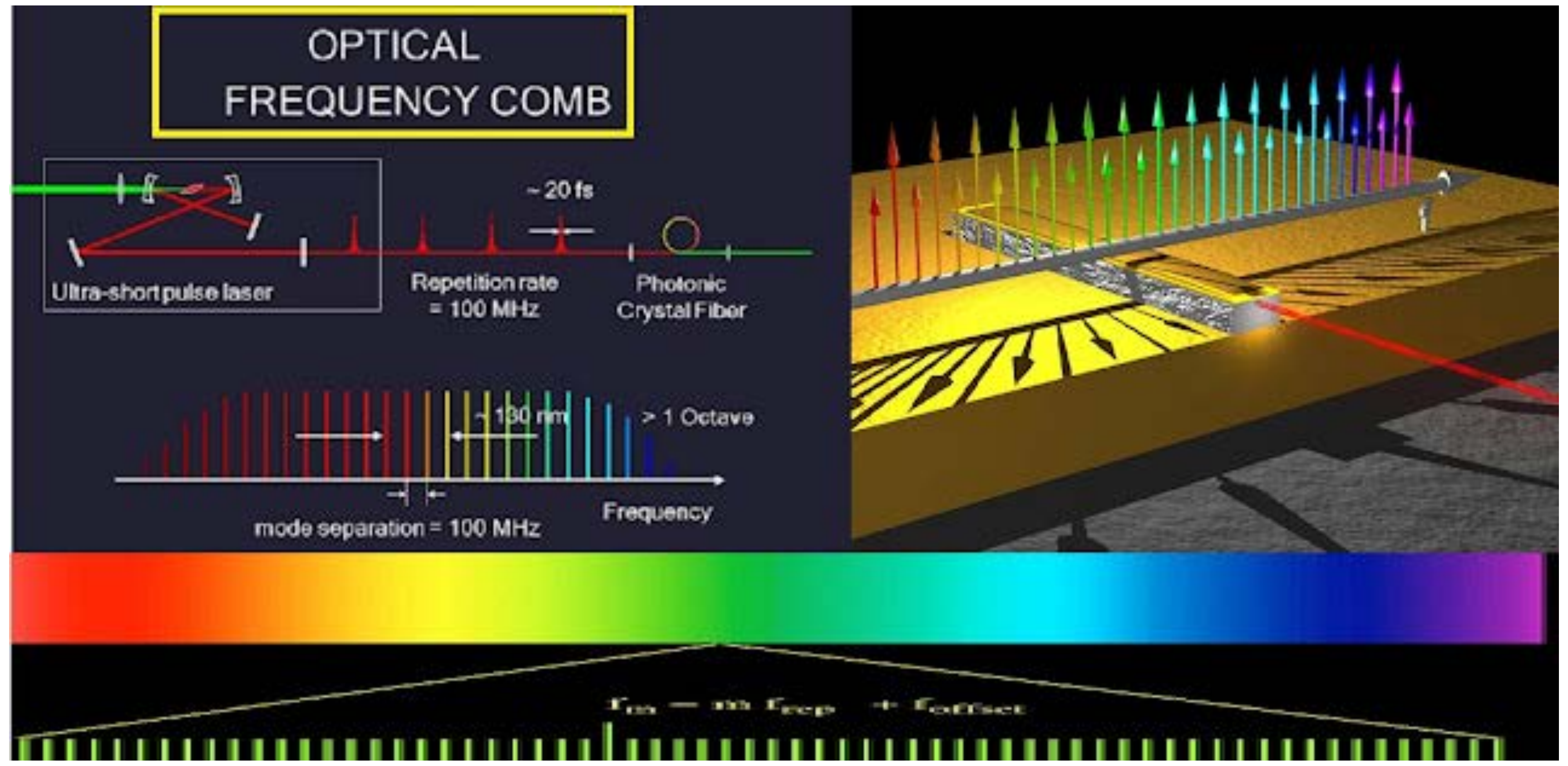
Ultra-stable laser probe atomic transition



Laser is stabilized on a high-finesse Fabry-Pérot cavity.

Credit: H. Jiang, G. Santarelli, OP-PSL

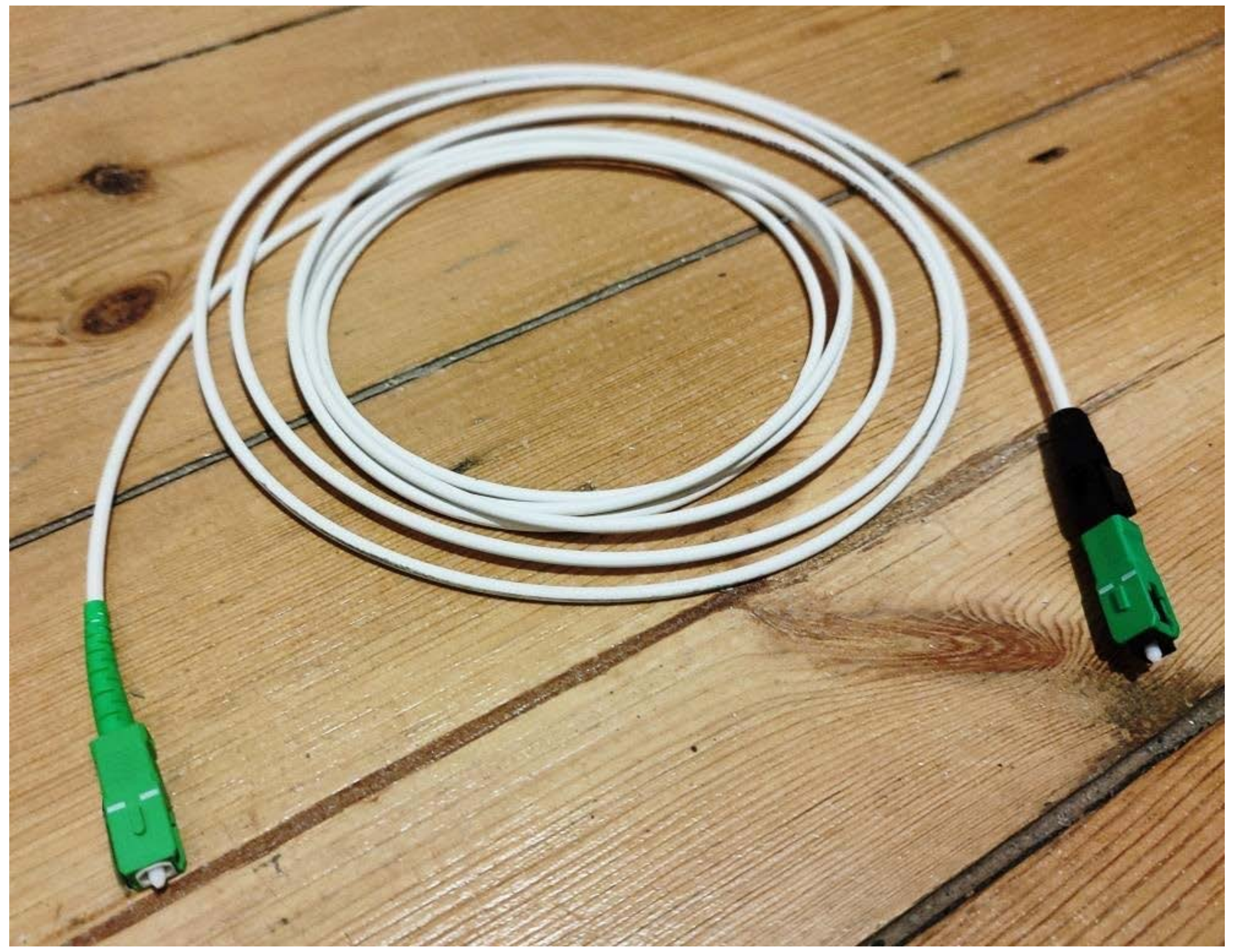
Optical frequency comb measures frequency ratio (optical down to microwave domain)



High-repetition rate laser stabilized on a cavity generate a frequency comb (Fourier transform).

Source: https://www.technopediasite.com/2019/07/what-is-optical-frequency-comb.html

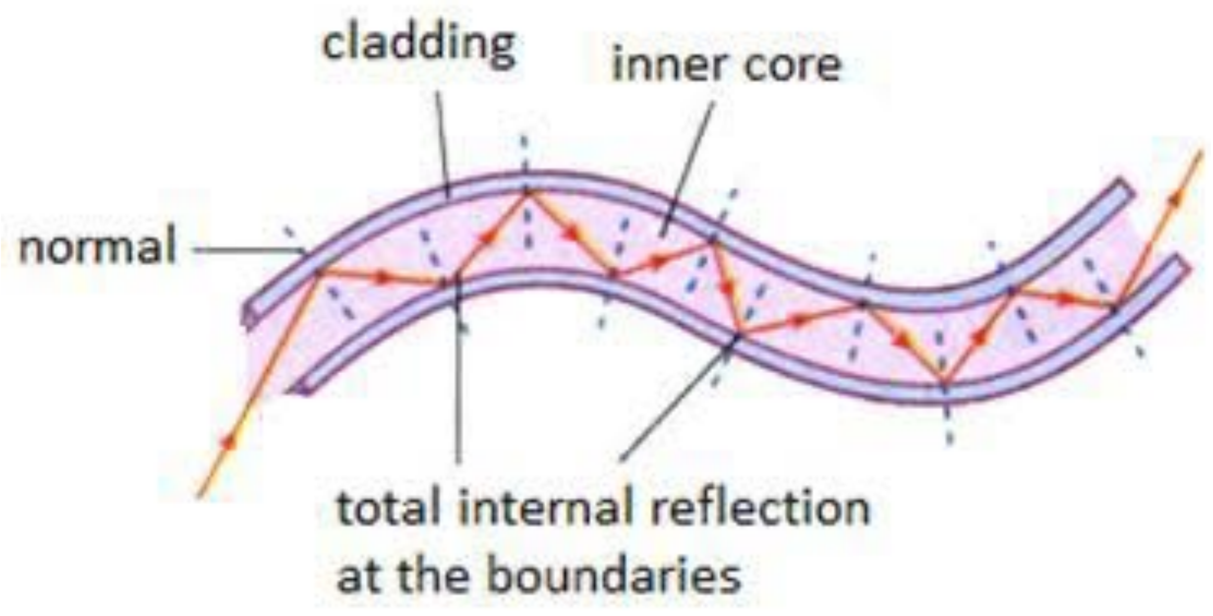
Optical link enable optical frequency dissemination



Single mode fiber enable low-loss and low-interference telecommunications.

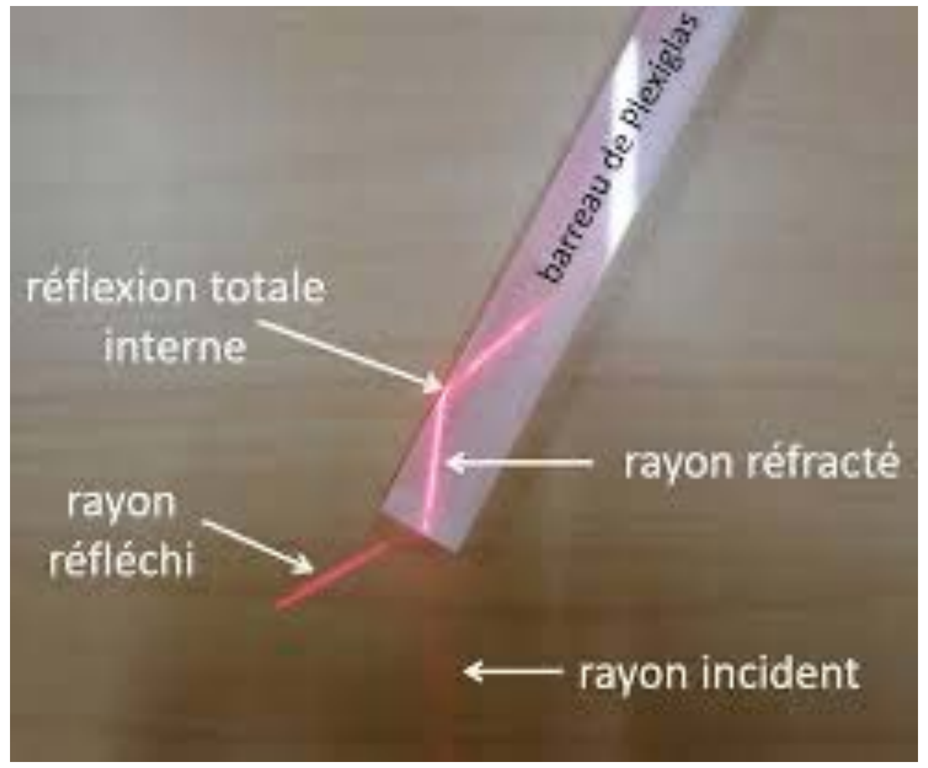
Credit: wikipedia

Guided propagation

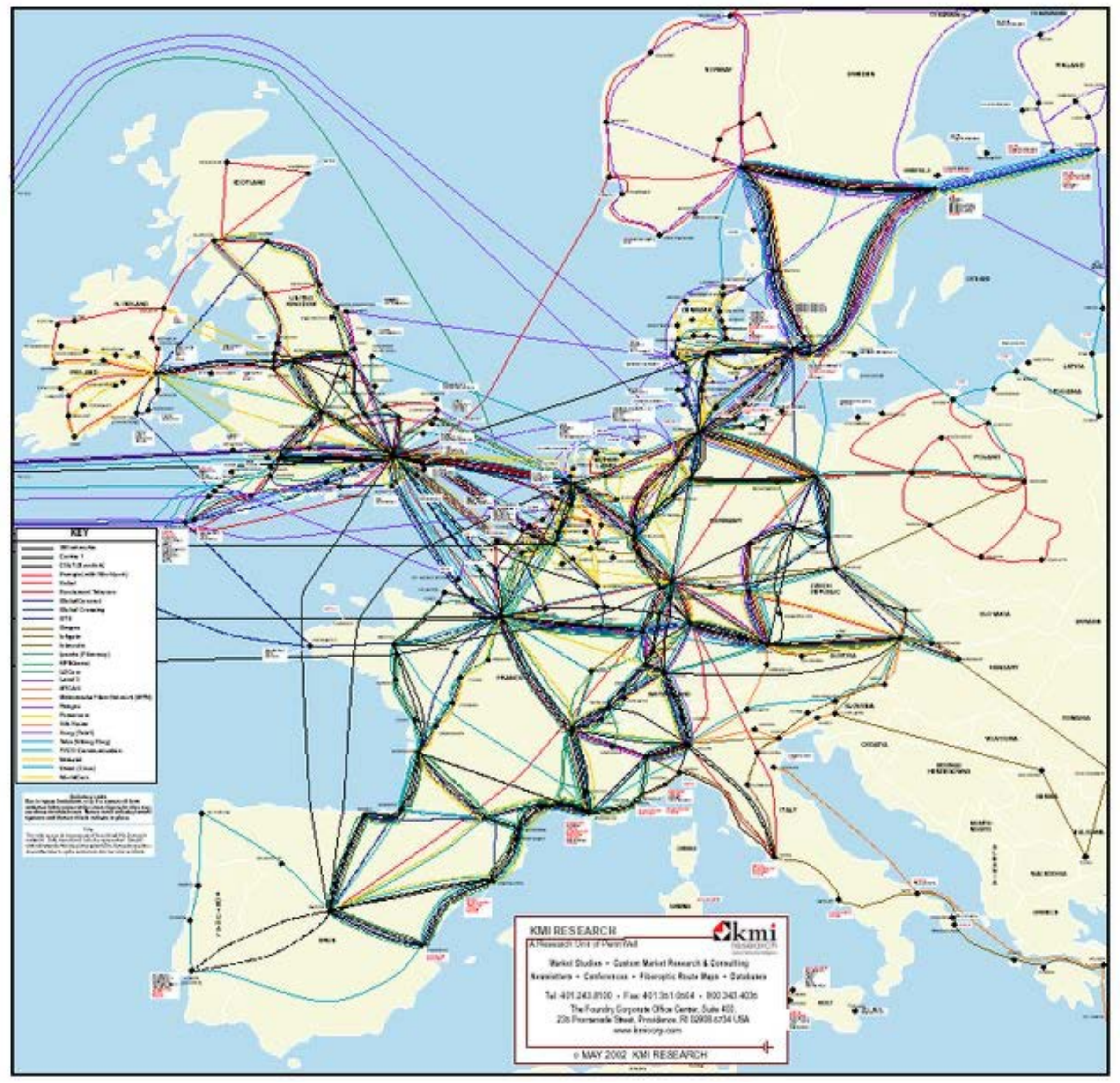


Credit : https://physics.stackexchange.com/

- Light guided by total internal reflection.
- Many engineering designs for various applications:
  - Single mode / multi-mode
  - Polarisation maintaining
  - Rare-Earth doped
  - Photonic crystal fibers, hollow cores…
- In this lecture, we deal only with single mode, non-polarisation maintaining fibre, as used in telecommunications for 40 years.
- It exists a telecommunication fiber infrastructure:
  - Fiber optic cables first used to carry phone calls in the 1970s.
  - Nowadays, these cables bring high-speed internet to much of the world.
  - Around the globe, cables are buried underground, hang from poles and snake across the seafloor. Together, they span some 4 billion kilometers of cable (by 2023).



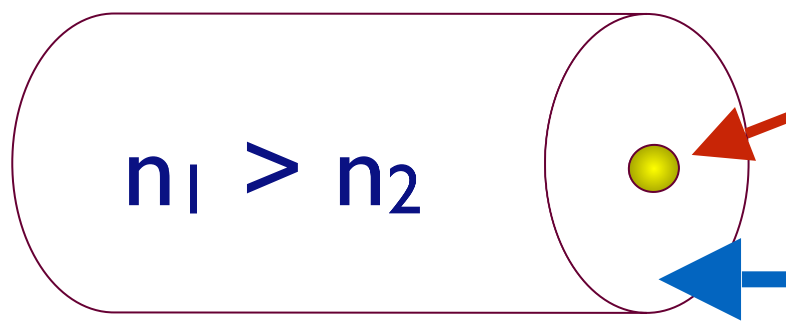
Credit : https://www.sfoptique.org/



Source: DOI: 10.1007/s11067-005-6208-z

Optical fiber

Optical waves are guided inside the core of the optical fibers



Core (glass) : central zone with higher optical index $\mathbf{n_1}$, where most of the light propagates.
diameter 2a ≤10µm for near-infrared (800 - 2000 nm)

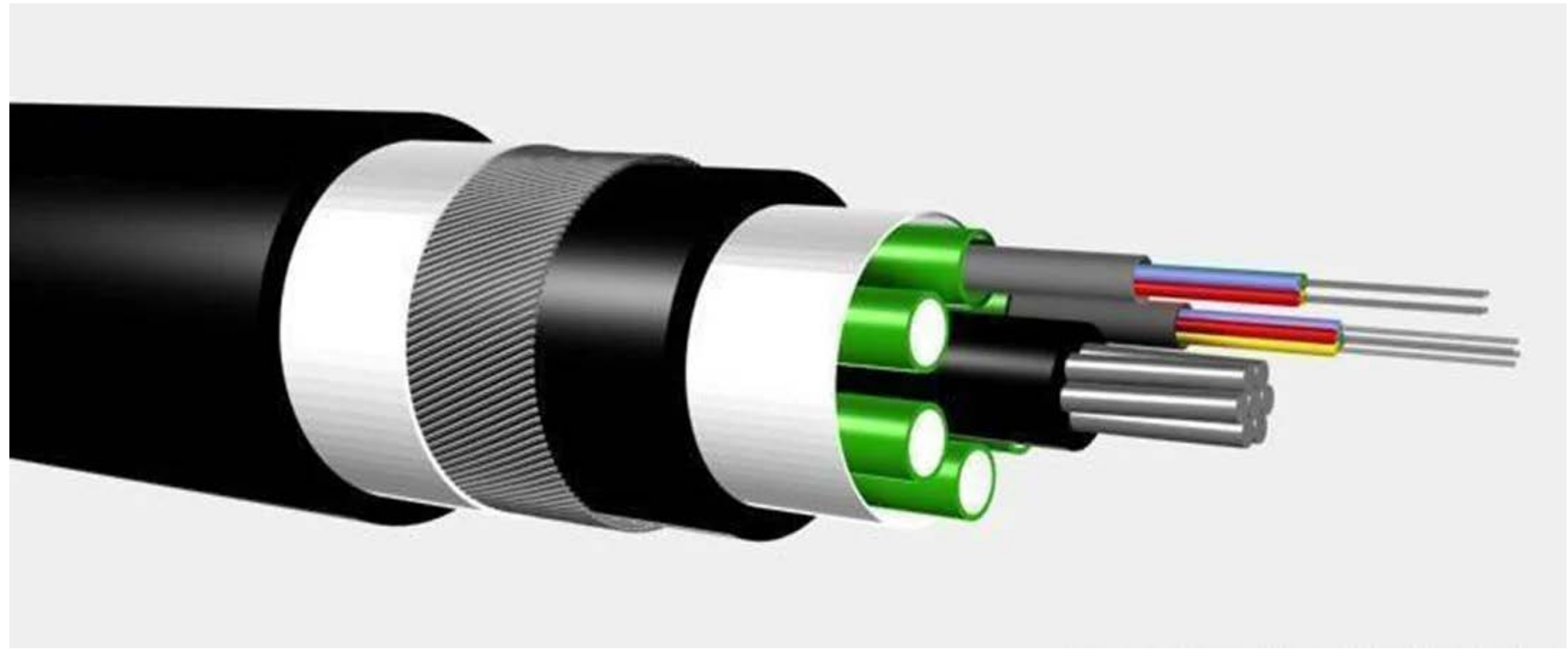
Cladding (glass): surrounding zone with (a little) lower index $\mathbf{n_2}$, guides light by internal reflection. Typical diameter 125 µm

Critical angle $$\theta_c = \arcsin\left(\frac{n_2}{n_1}\right)$$

Numerical aperture $$NA = \sqrt{n_1^2 - n_2^2}$$

typical NA 0.13

- n ≈ 1.47 at 1.55 µm; δn ≈ 5 10^{-3}
- Velocity ≈ c/n ≈ 2 x 10^8 m/s



- Propagation delay ≈ 5 ns /m

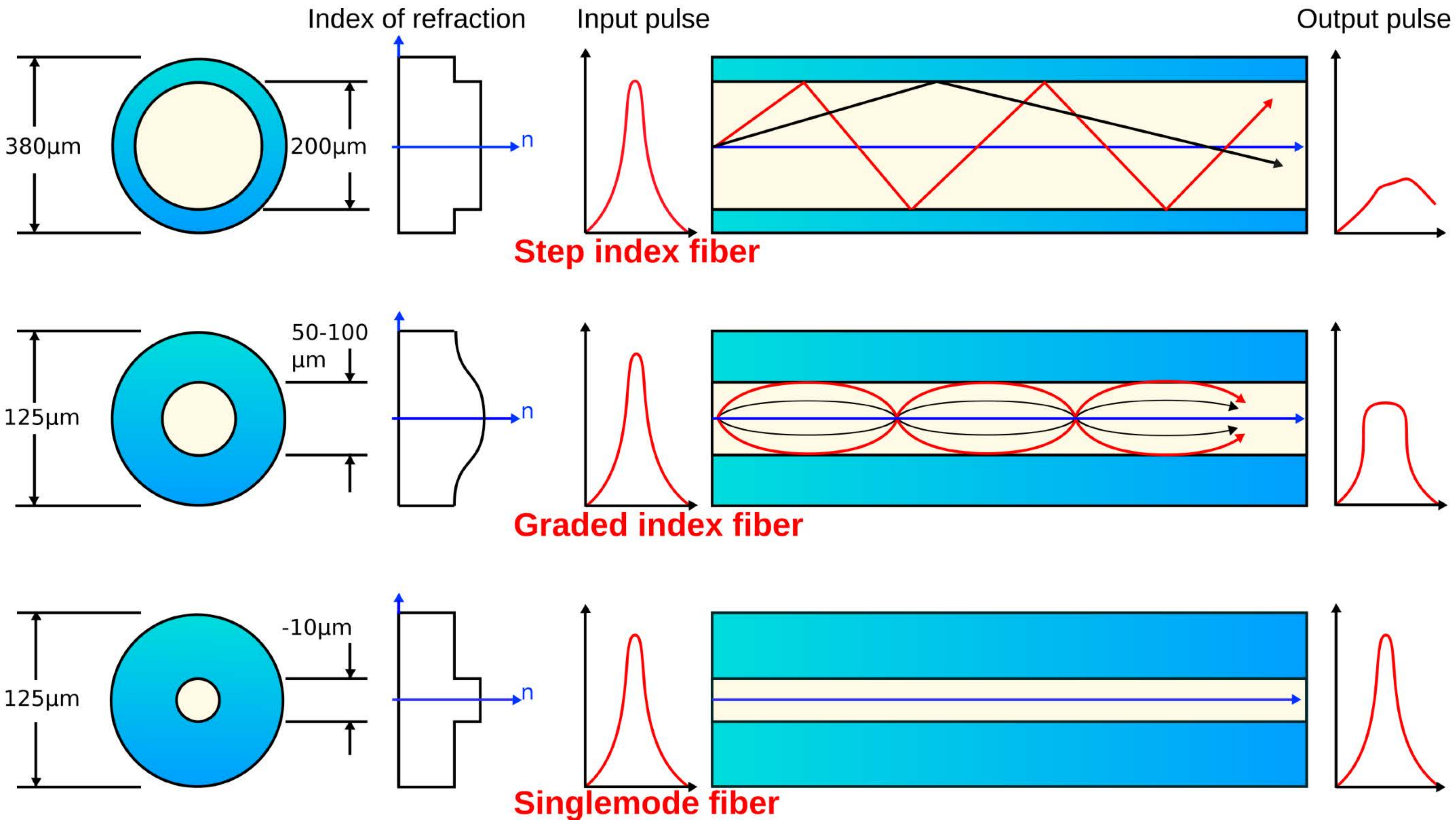
- Nota bene : additional jackets to protect the fiber :
- coating (polymer, 250 µm): mechanical protection, makes fibre resilient to bending
- Buffer (plastic, 900 µm to 3 mm): mechanical protection, simplifies handling
- More jackets: temperature and humidity, rats…
- Fiber cables may have hundred of fibers.
- Industrial are thinking about multi-core fiber to face exponential growth of data traffic.

Credit: https://www.rfvenue.com/blog/2016/03/16/multi-mode-vs-single-mode

Single-mode fiber

Single mode propagation if $$V = \frac{2\pi a}{\lambda}\sqrt{n_1^2 - n_2^2} < 2.4$$

a : core radius
λ: light wavelenght



Multi-mode:

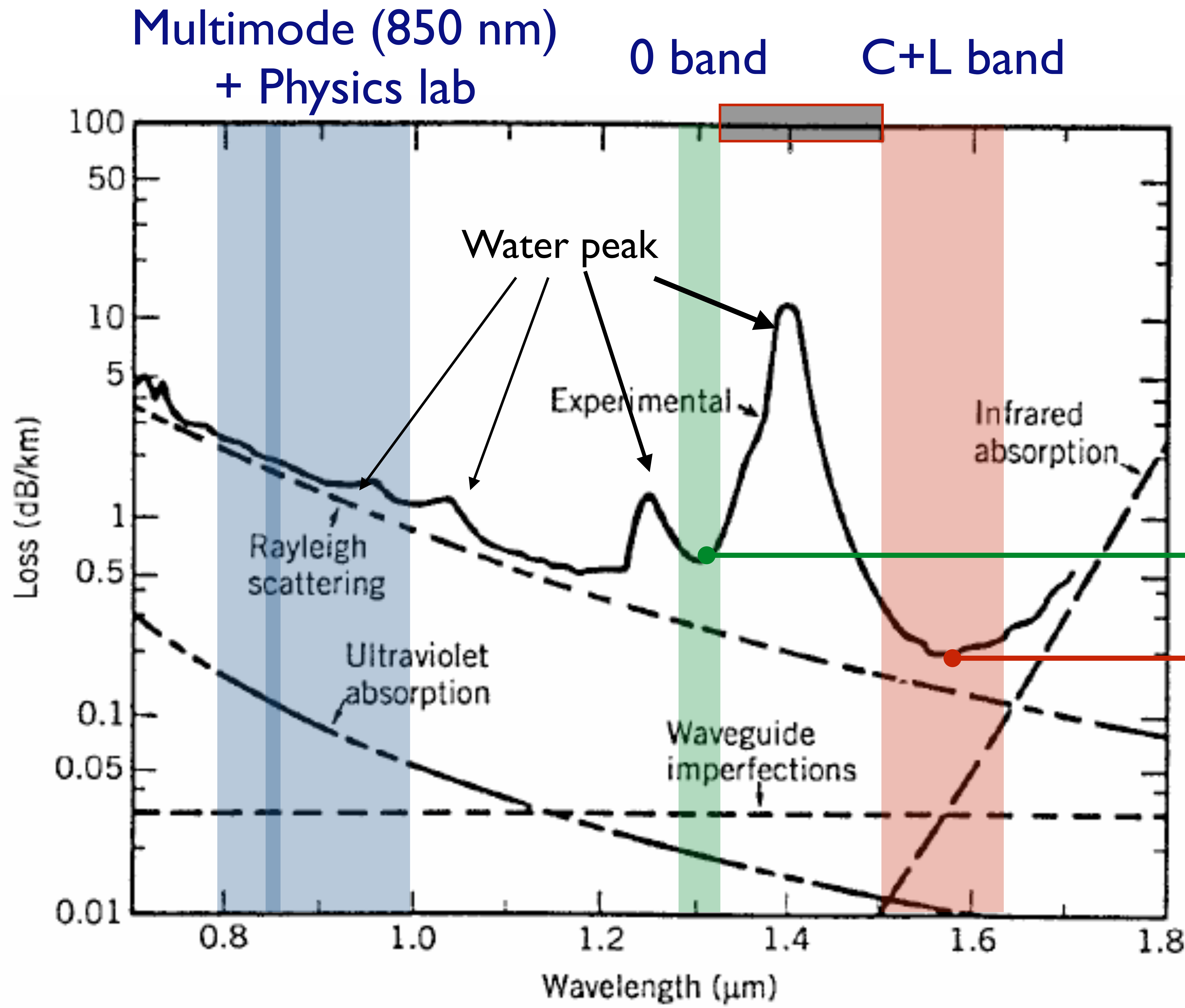
- Higher core diameter
- Modal dispersion: several paths are possible !
- Easier to manipulate, less expensive

Single-mode:

- Unicity of path !
- Longer range (> 1 km)
- Higher bandwidth (> 1 GHz)

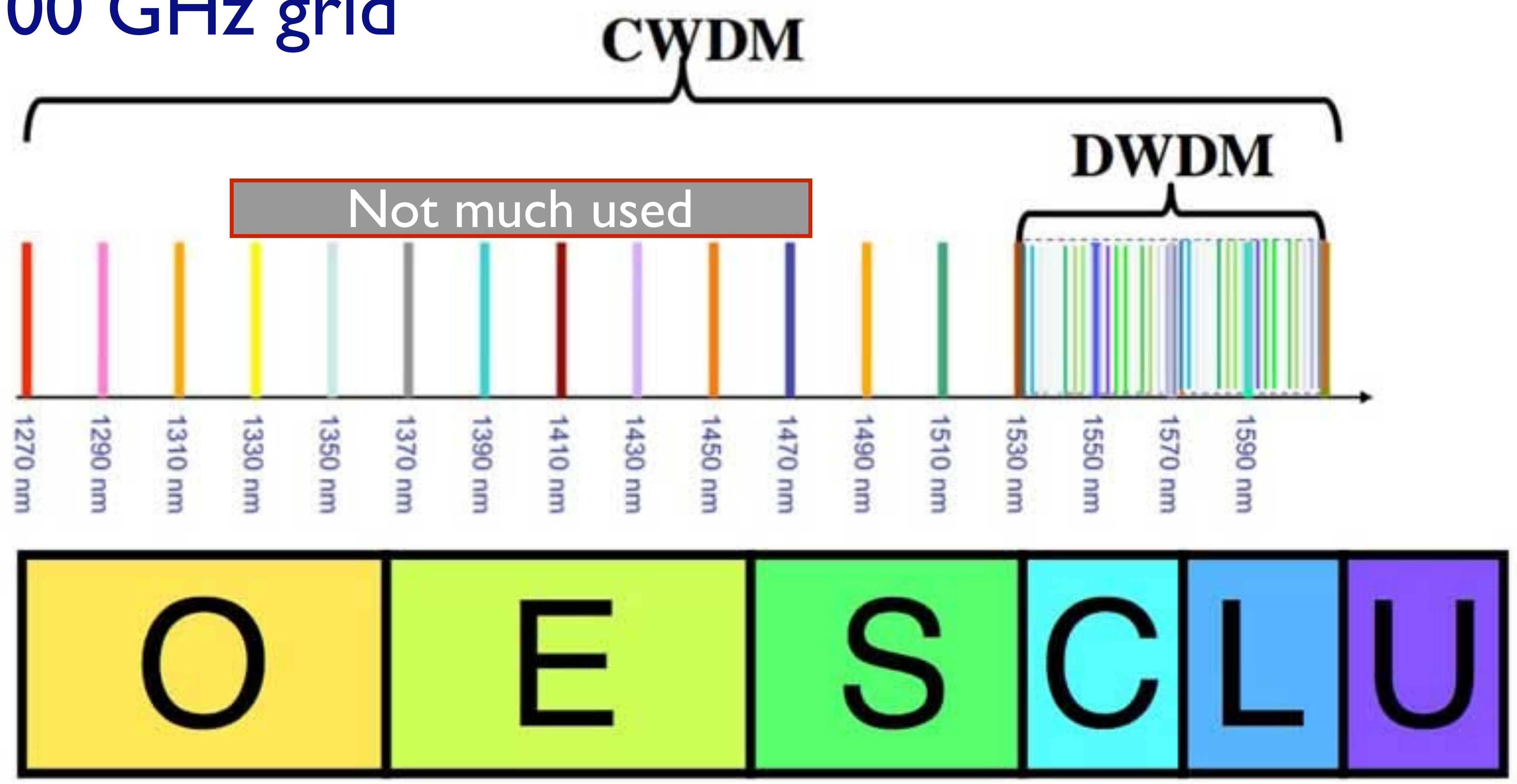
Source: https://en.wikipedia.org/wiki/Optical_fiber#/media/File:Optical_fiber_types.svg

Attenuation



https://www.fiberoptics4sale.com/blogs/archive-posts/95052294-optical-fiber-attenuation

Telecommunication bands: ITU-T G.694.1 DWDM 100 GHz grid



0.5 dB/km @ 1310 nm

0.2 dB/km @ 1550 nm

- In Europe, optical frequency transfer are mostly operated at
  - 1542.14 nm (in vaccum)
  - ITU Channel #44
  - Frequency = 194.4 THz

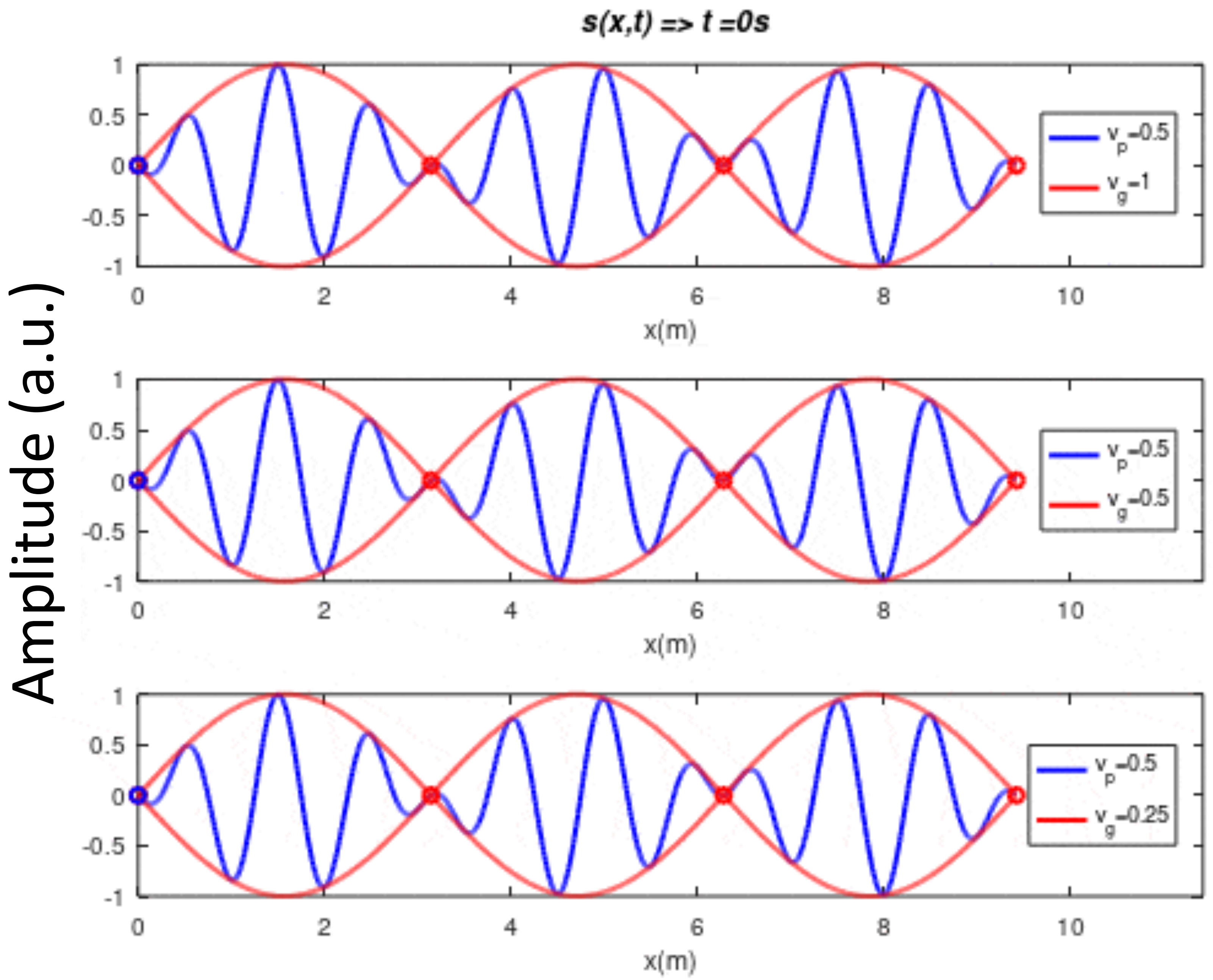
Dispersion

For a signal s $s(t,z) = f(\omega t - \beta z)$

ω : angular frequency
β: angular wavenumber

Phase velocity: $v_\phi = \dfrac{\omega}{\beta} = \dfrac{c}{n}$

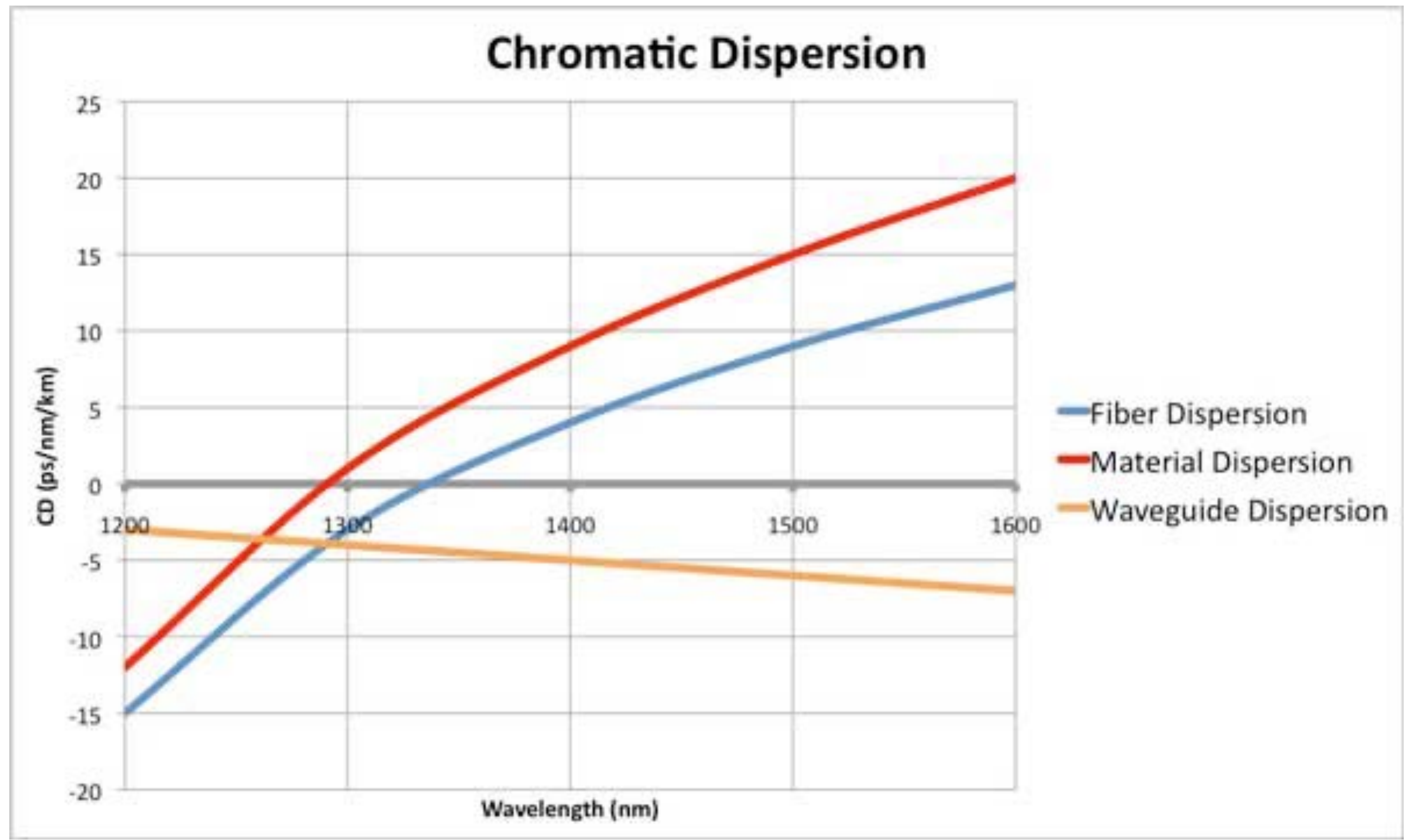
Group velocity: $v_g = \dfrac{d\omega}{d\beta} = \dfrac{c}{n + \omega \frac{dn}{d\omega}}$



https://electroagenda.com/

Index of refraction of a fiber is dispersive.

- Chromatic dispersion (CD): typically 18 ps/(nm.km) @ 1550 nm
  - Caused by frequency fluctuations of the laser source
  - Bandwidth of the modulation (if any)
- Polarisation mode dispersion (PMD): typically 0.2 ps/√km
  - Polarisation rotation by the fiber, caused by core non-circularity and external variables as mechanical stress (bending, pressure waves,…)



https://www.thefoa.org/tech/ref/testing/test/CD_PMD.html/

Delay and delay variations

One way delay: $\tau = \frac{nL}{c}$ L : length of the fiber

- The optical length **n L** varies with time
  - Refractive index varies with time: $n(T, \epsilon)$. Dominant term.
  - Physical length varies with time: $L(T, \epsilon)$. Second order term.
- Mainly acoustical (short term) and thermal (mid term) fluctuations

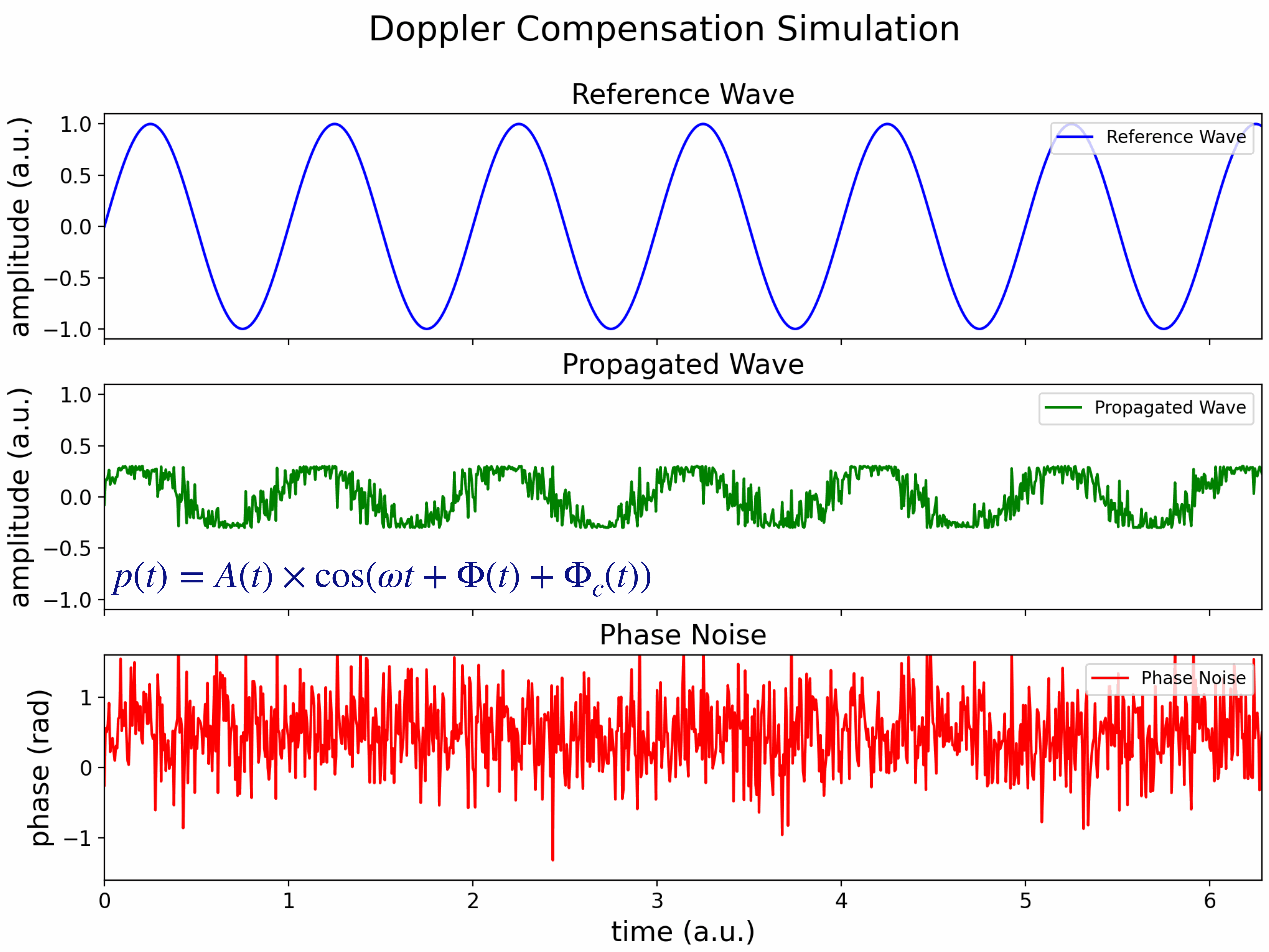
- Thermo-optic coefficient: $\frac{dn}{dT} \simeq 10^{-5} K^{-1}$
- Strain-optic coefficient $\frac{dn}{d\epsilon} \simeq 0.2$
- Thermal expansion: $\frac{1}{L}\frac{dL}{dT} \simeq 5 \times 10^{-7} K^{-1}$
- Strain: $\epsilon = \frac{dL}{L}$

See for instance :
L. G. Cohen et J.W. Fleming, « Effect of temperature on transmission in lightguides », (1979),; doi: 10.1002/j.1538-7305.1979.tb03328.x.
D. Stowe, D. Moore, et R. Priest, « Polarization fading in fiber interferometric sensors », (1982); doi: 10.1109/JQE.1982.1071402.
Imaoka et M. Kihara, « Long-term propagation delay characteristics of telecommunication lines », (1992); doi: 10.1109/19.177337.
M. Froggatt et J. Moore, « High-spatial-resolution distributed strain measurement in optical fiber with Rayleigh scatter » (1998); doi: 10.1364/AO.37.001735.

Optical fibers are excellent sensors ! …

Doppler shift and Doppler canceller

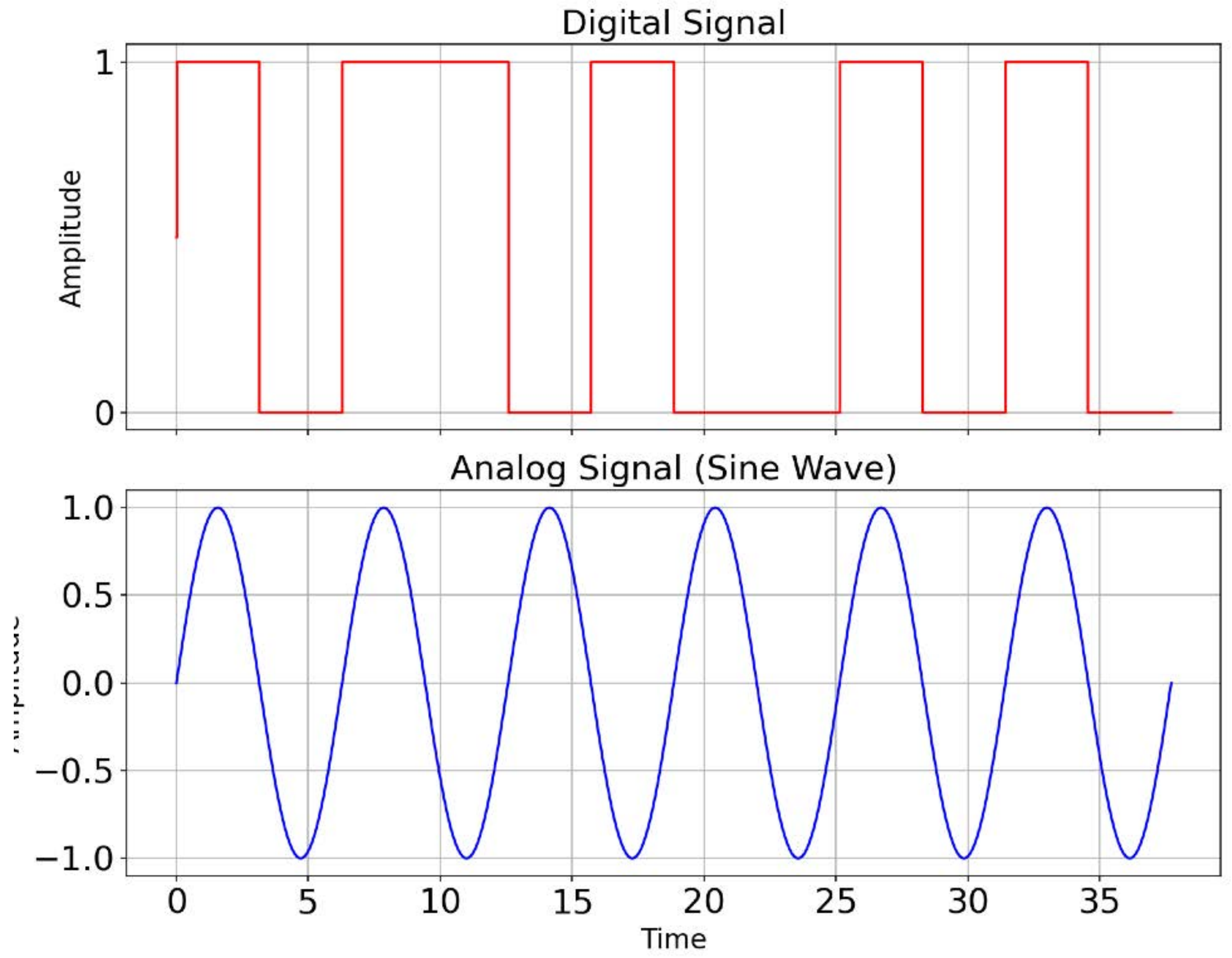
- Phase fluctuations induce frequency fluctuations: $f(t) = \frac{1}{2\pi}\frac{d\phi}{dt}$ Doppler shift: $\nu_{RX} = \nu_{TX}\left(1 - \frac{v}{c}\right)$

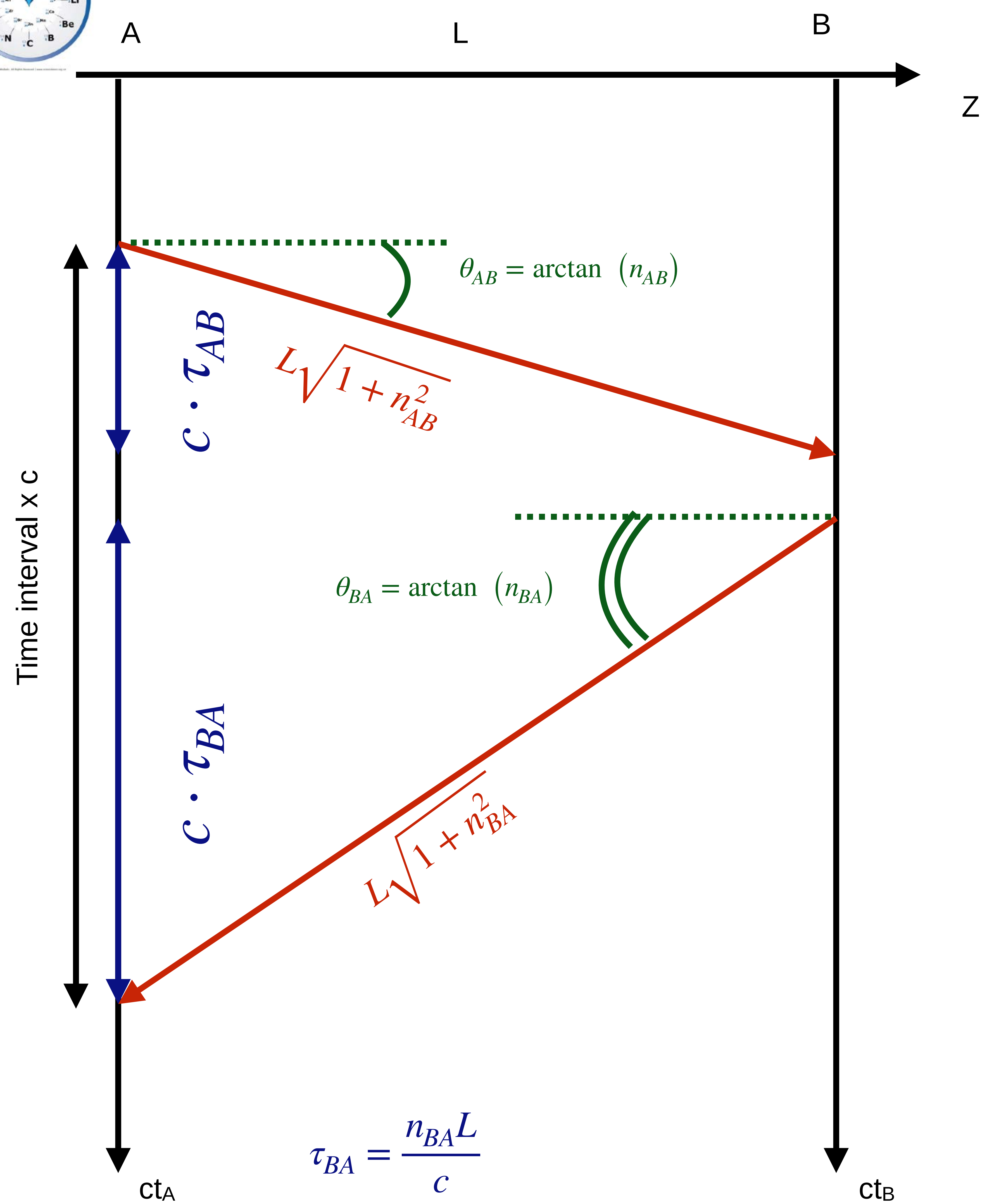


- Variable delays induce a Doppler shift.
  - $\frac{d\tau_D}{dt} = \frac{v}{c}$
- Mainly white phase noise + white frequency noise (< 10 Hz).
- Modulation index is defined as the peak-to-peak amplitude of phase variation. It can be >> 1 for long haul links.
- Compensation system acts to make $\phi_c(t) = -\Phi(t)$
- In loop, the two waves are in phase, with an unknown phase offset.

Classes of fiber links

- Propagation noise compensation: affects stability and accuracy
  - One way:
    - None ! Unstabilized fiber links
    - Compensation from propagation model
  - Two-way
    - Post-processed: mainly used for comparisons
    - Active, real-time compensation: mainly used for transfer
- Topology: affects reciprocity properties and correlations
  - uni-directional
  - Bi-directional
- Signals: affects the scalability
  - Digital
  - Analog





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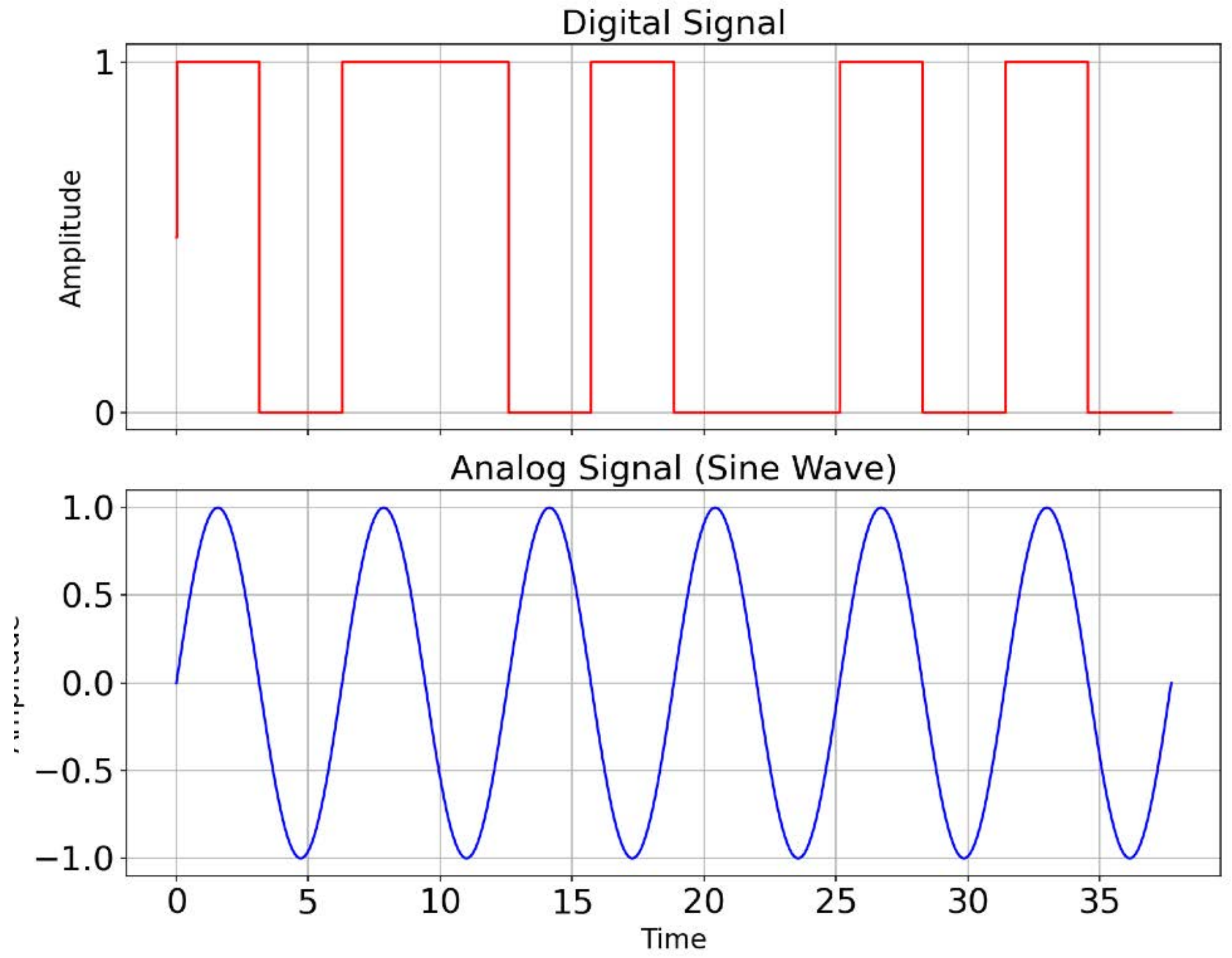

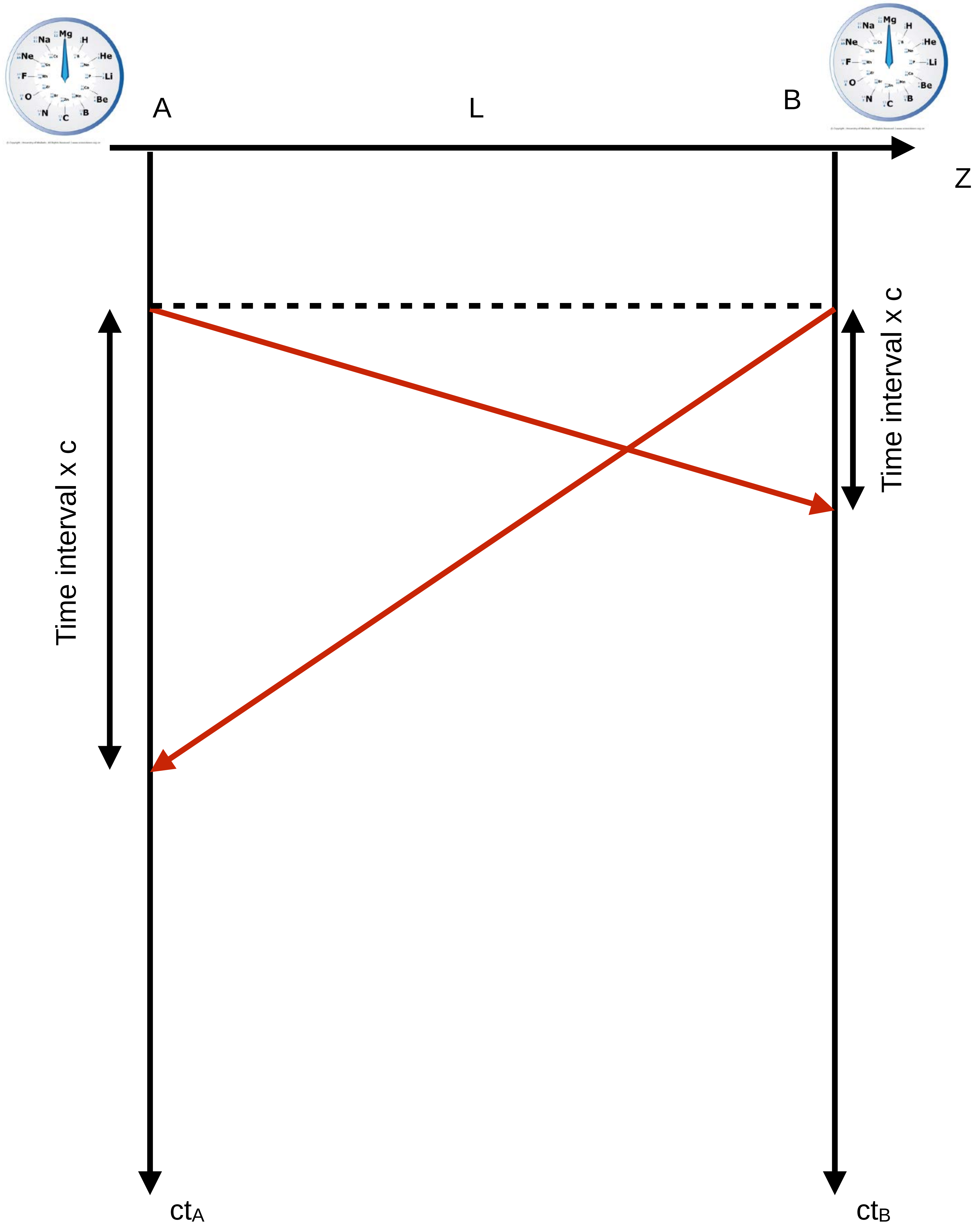

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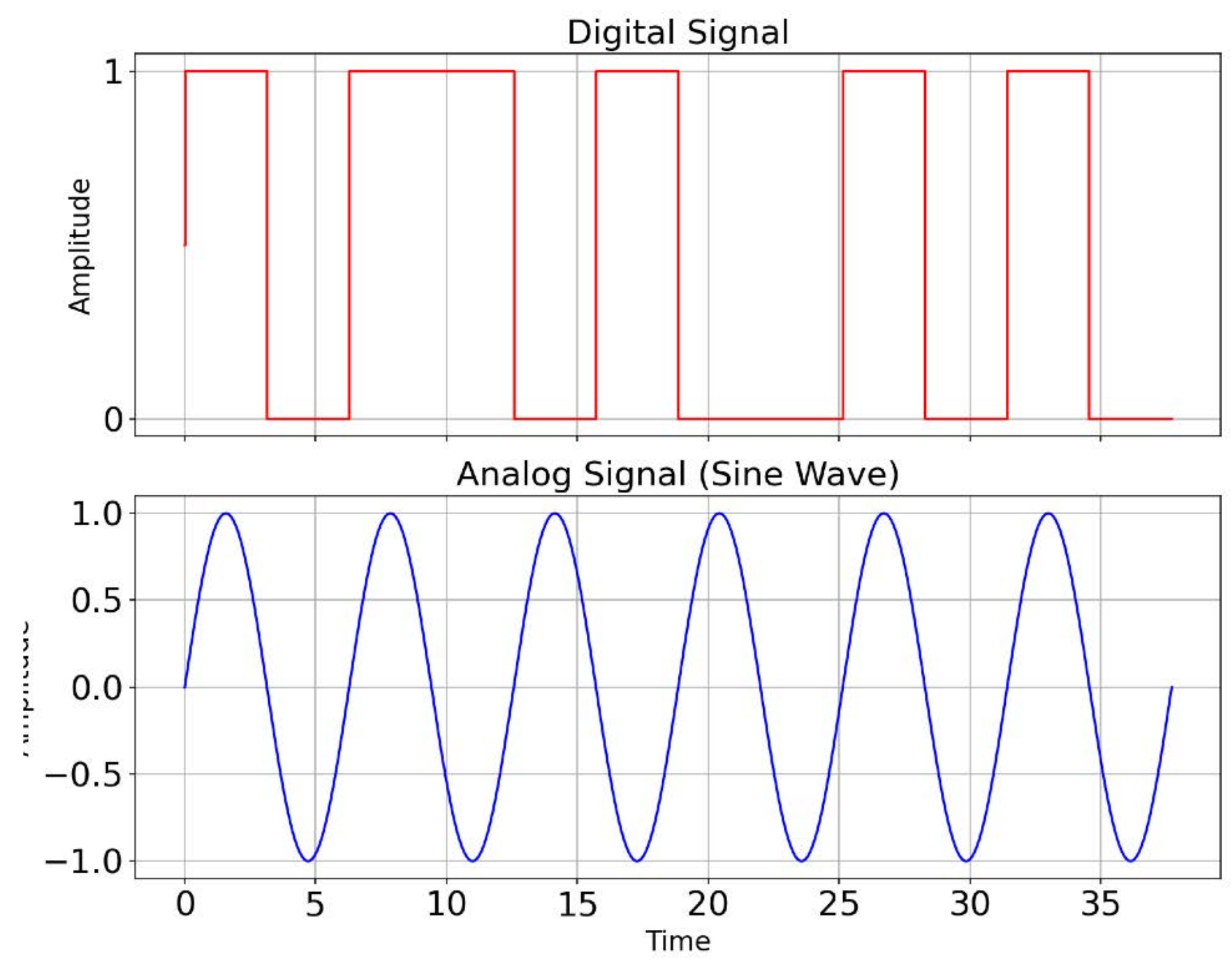
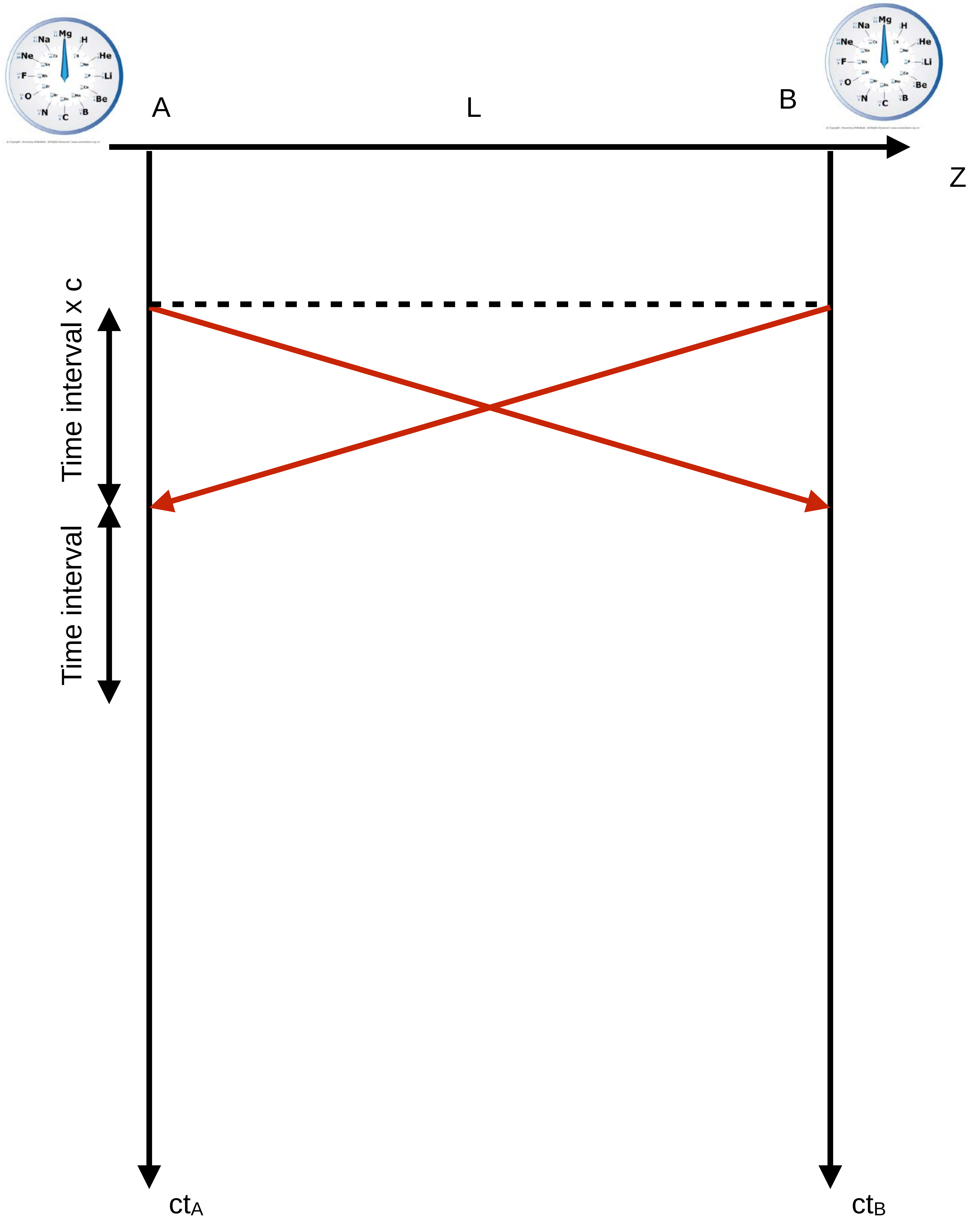
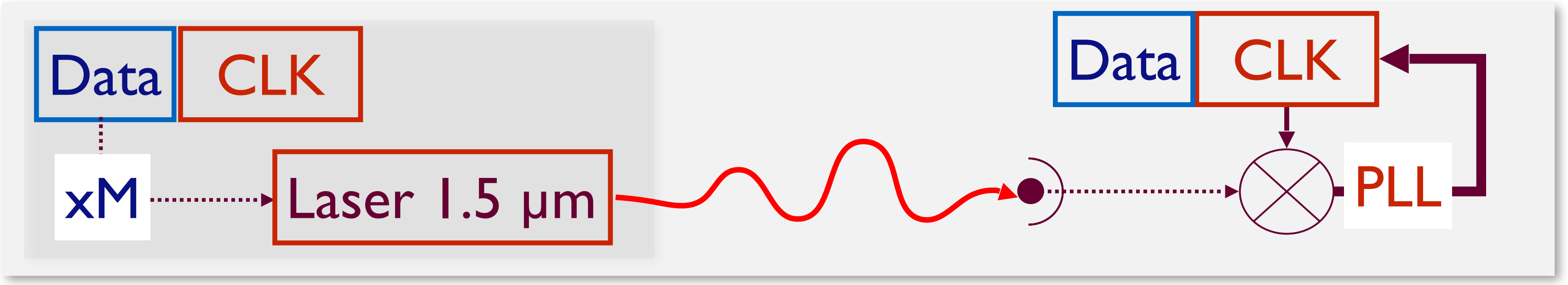




2 classes of methods

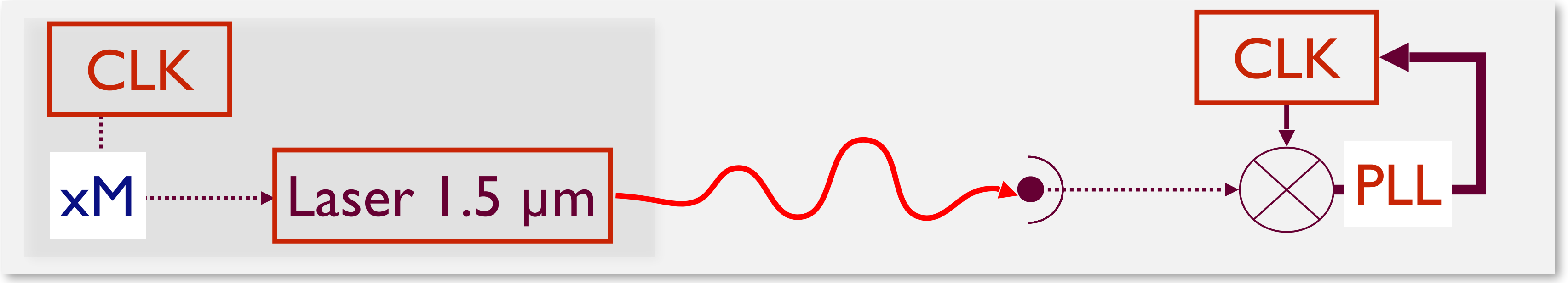
- Indirect transfer : Optical waves carry information by modulation
  - AM, FM, PM,…
  - Well-suited to microwave clocks comparison and time transfer

Digital



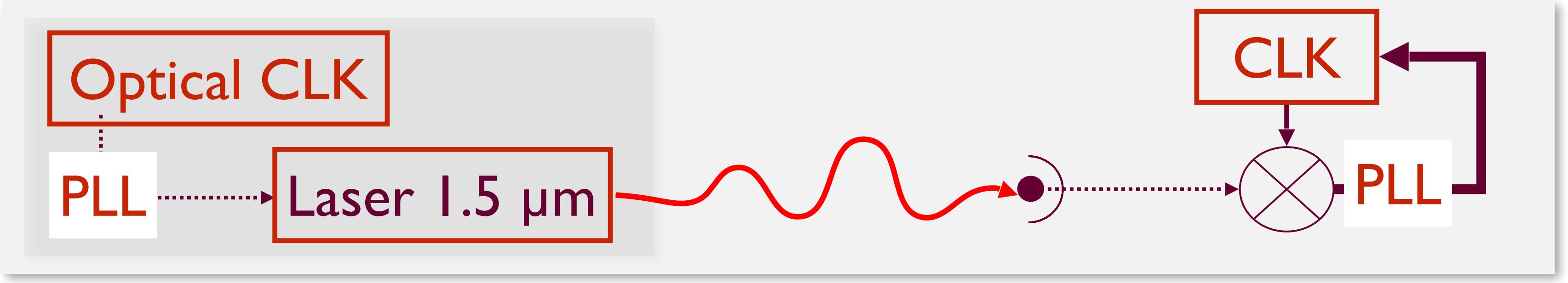
CLK : 'clock' signal
PLL : Phase-Lock Loop

Analog



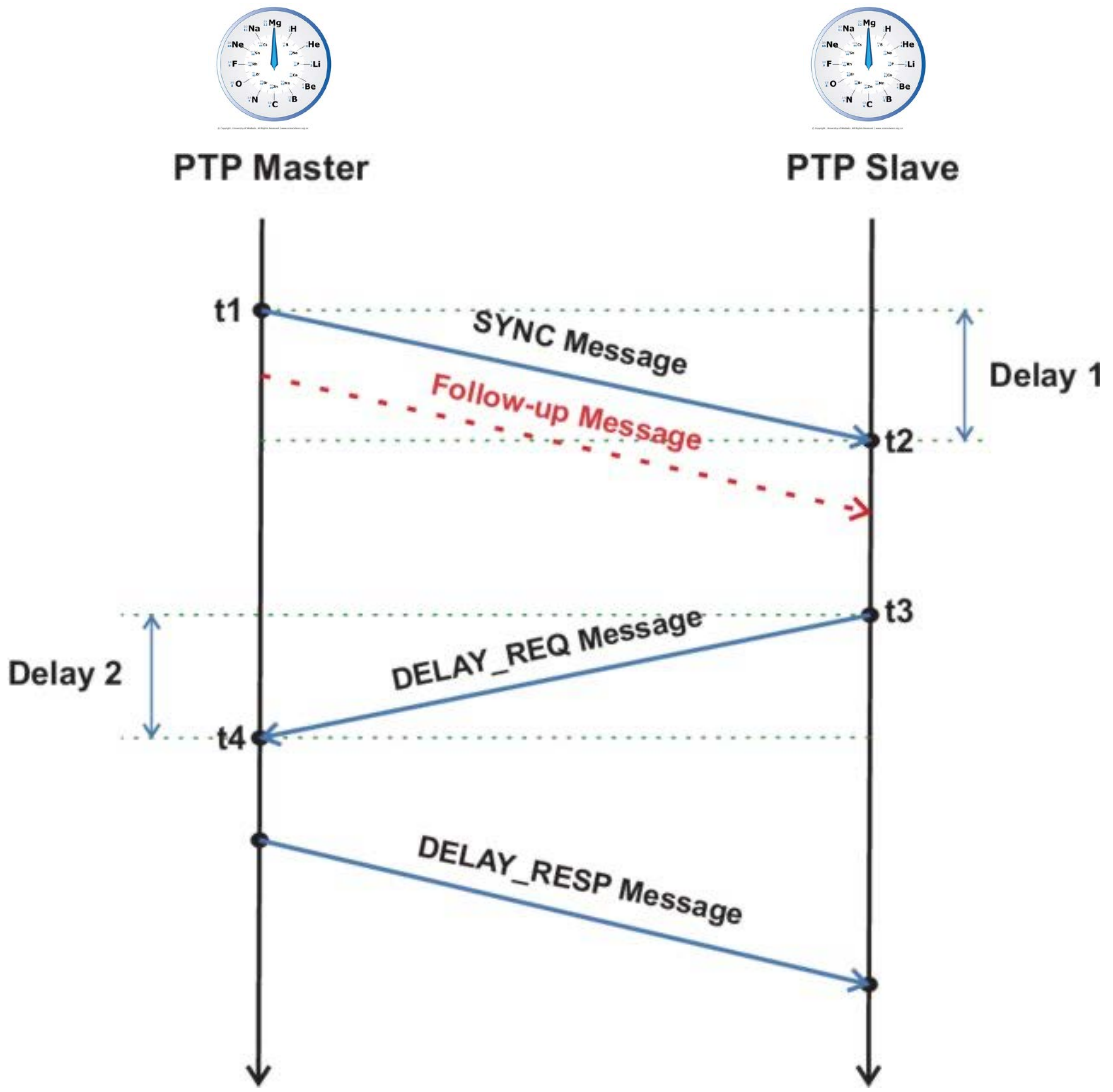
- RF or MW transfer (10 MHz to 10 GHz)
- Time transfer

- Direct transfer of an optical frequency
  - Well-suited to optical clocks comparison



- CLK is a local oscillator signal
  - Low-phase noise
  - Frequency might be inaccurate
  - As continuous as possible
  - RF/hF : quartz, H-maser
  - Optical domain : laser

Precise Time Protocol: PTP



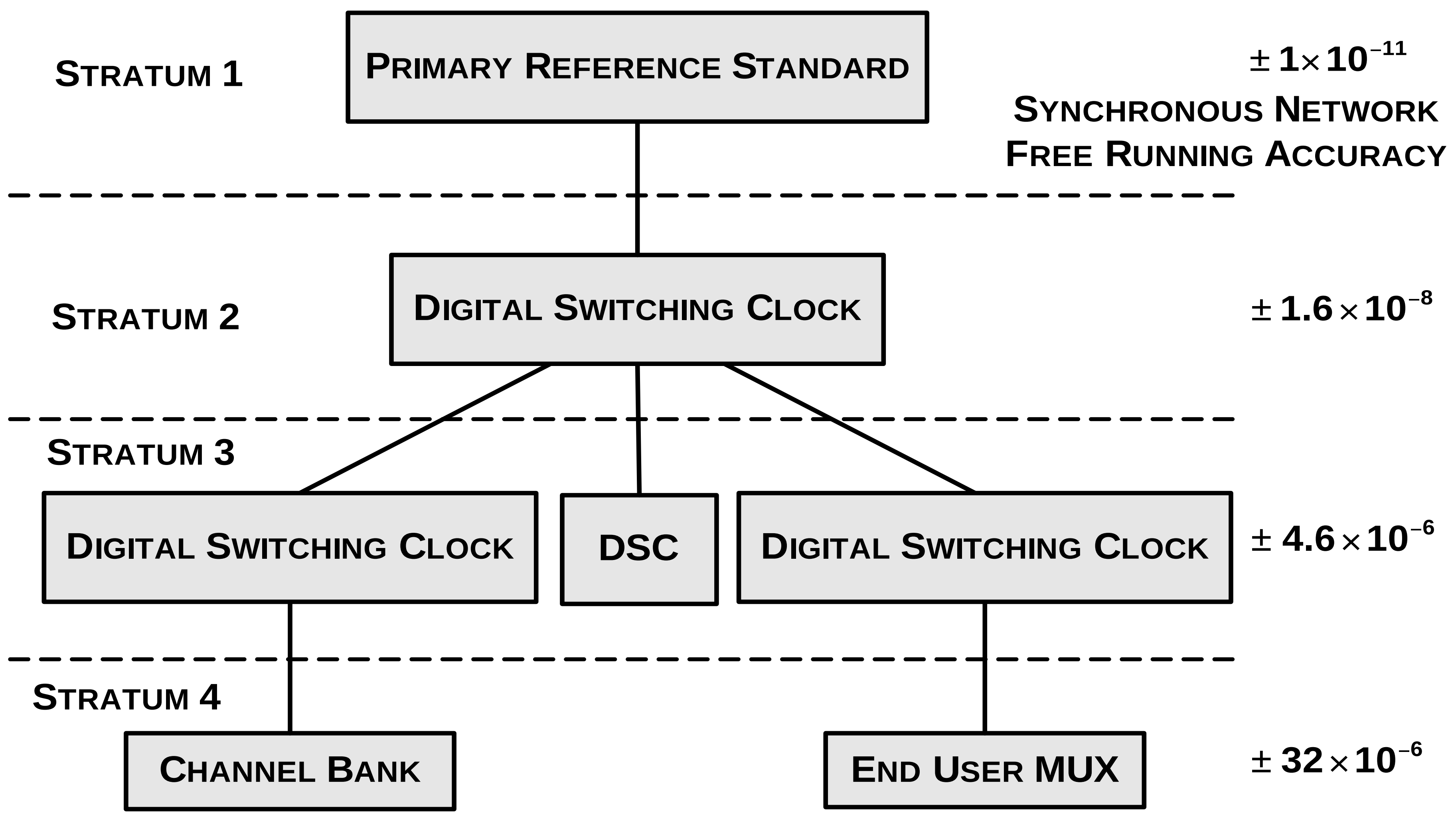
PTP accounts for instrumental asymmetries.

- Round trip time: $\tau_{rtt} = (t_2 - t_1) - (t_4 - t_3)$
- Clock offset : $t_B - t_A = (t_2 - t_1) + \tau_{MS}$
- In case of asymmetry $\tau_{MS} \neq \tau_{SM}$:

$$\text{time error} = \frac{\tau_{MS} - \tau_{SM}}{2}$$

NB: NTP works almost the same way, but in this description the transmit timestamps T1 and T3 are softstamps measured by the inline code. Softstamps are subject to various queuing and processing delays.

Precise Time Protocol: PTP



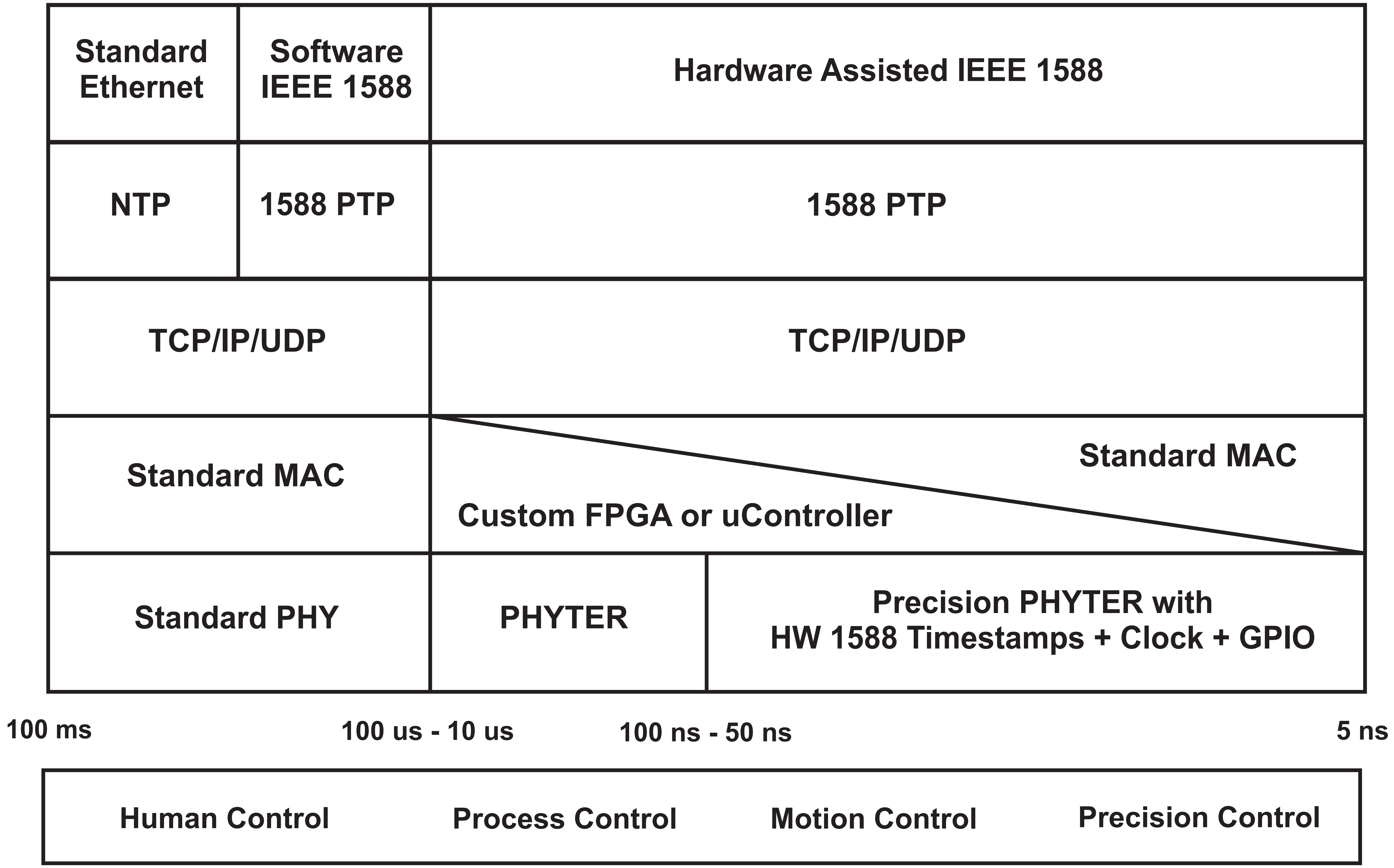
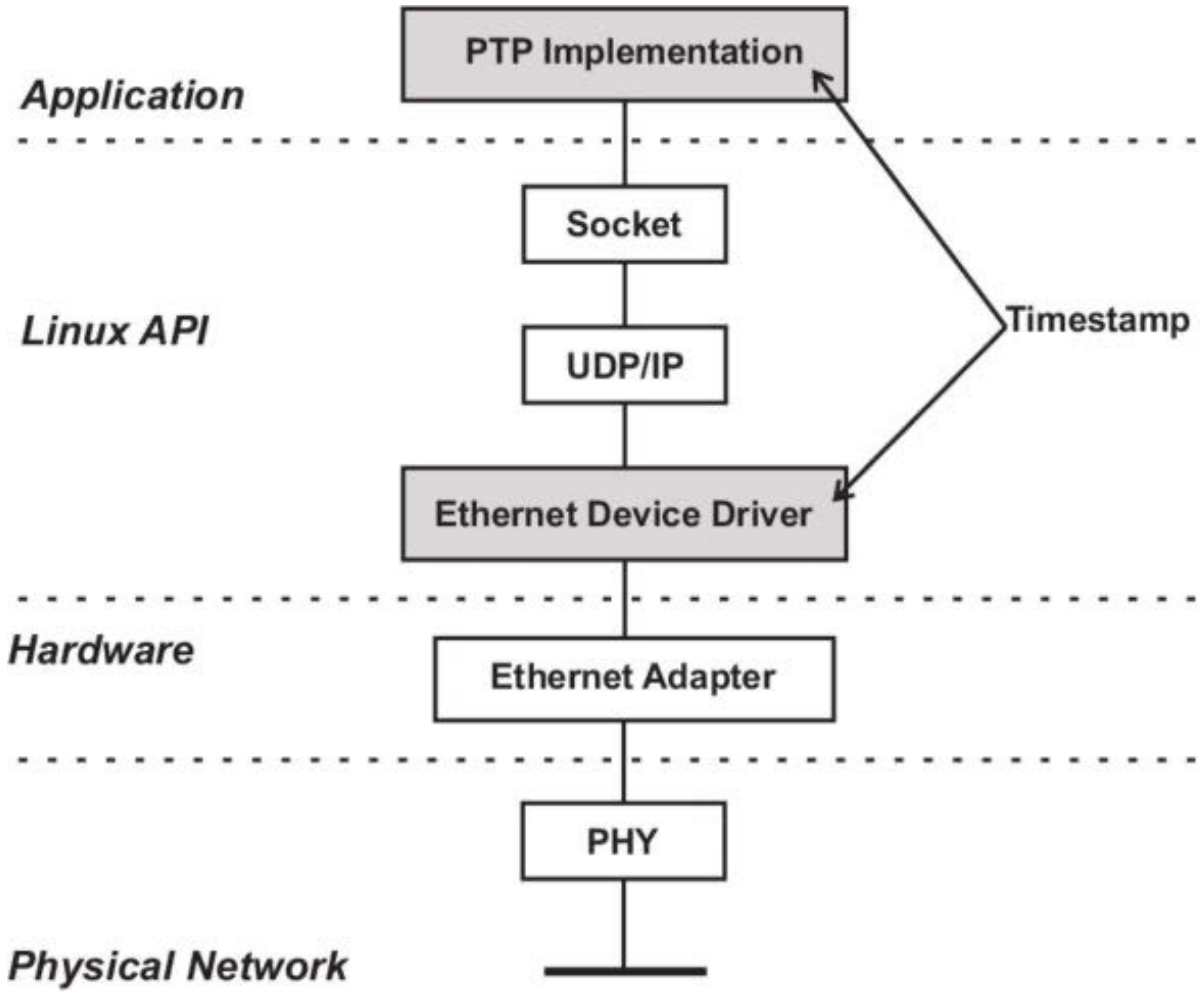


Figure 5. Implementation choices to achieve better time synchronization [32].

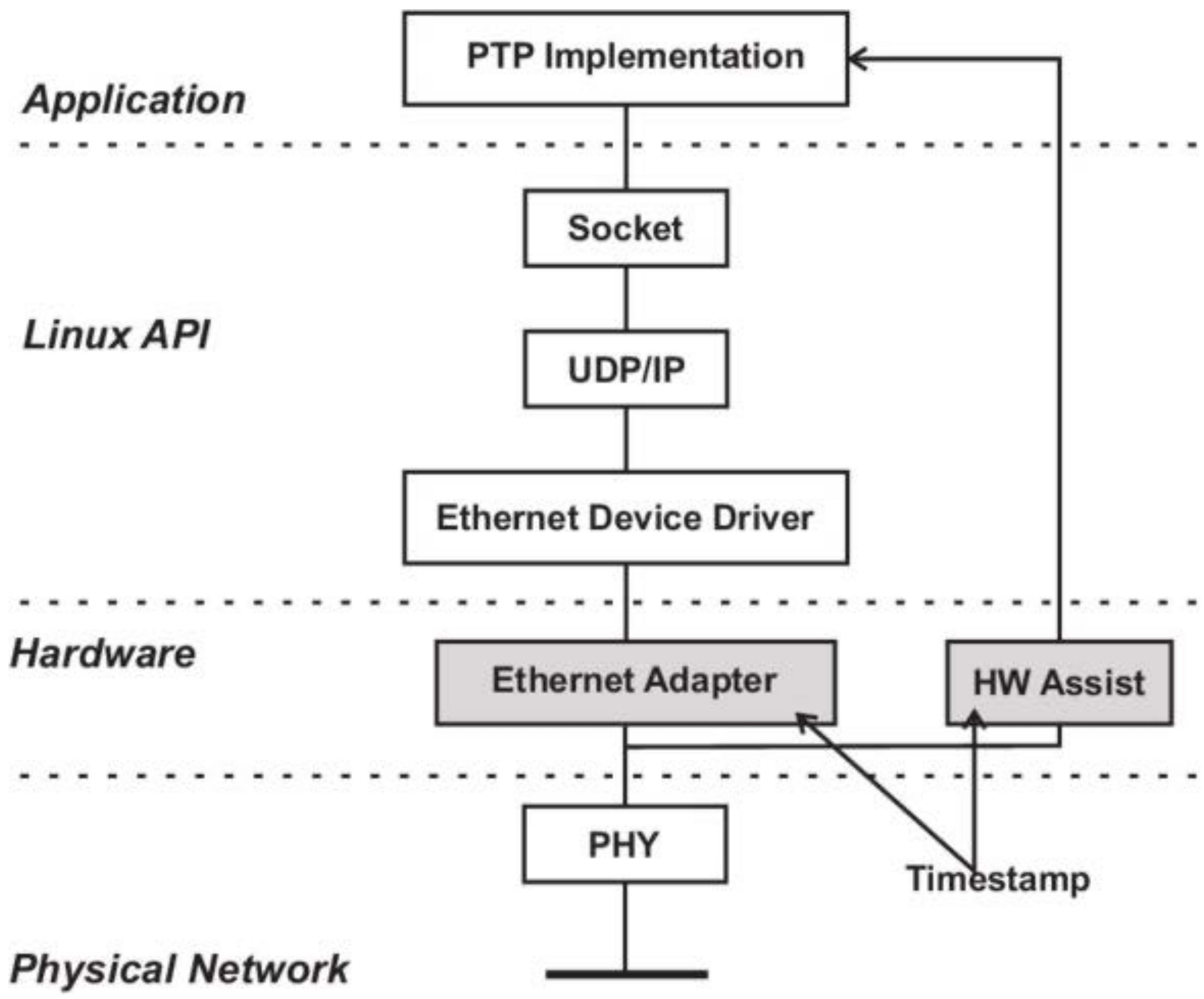
A. Arteaga et al., Electronics (2024), doi: 10.3390/electronics13020458.

Precise Time Protocol: PTP

Software based



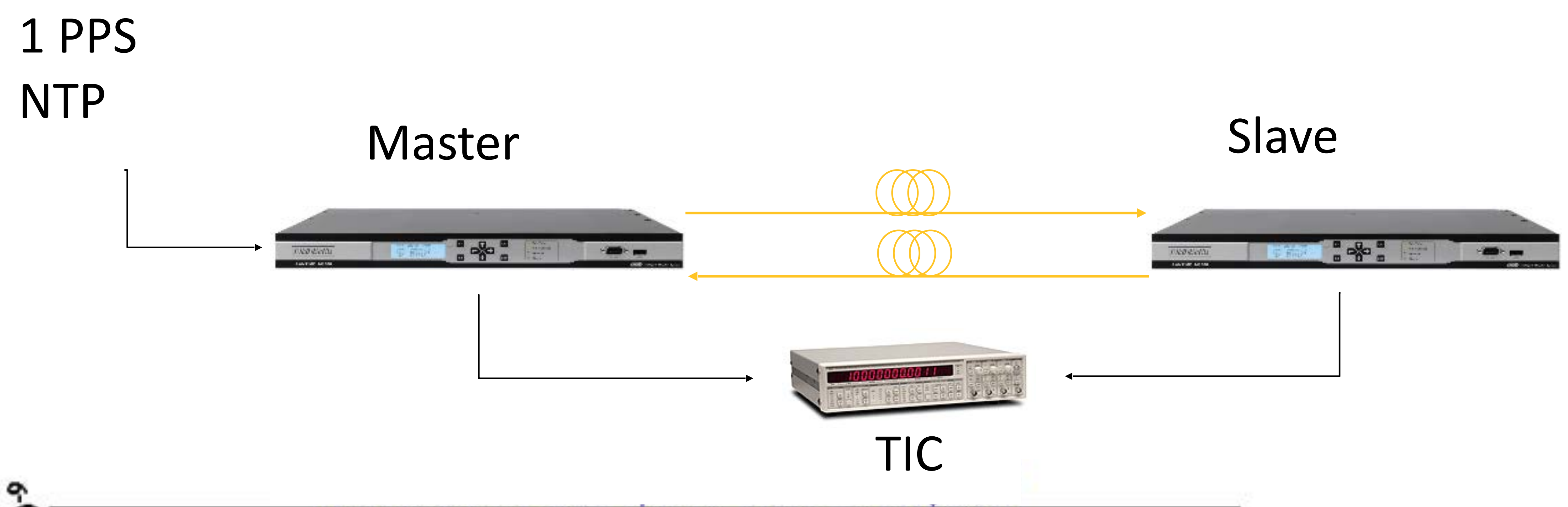
Hardware based



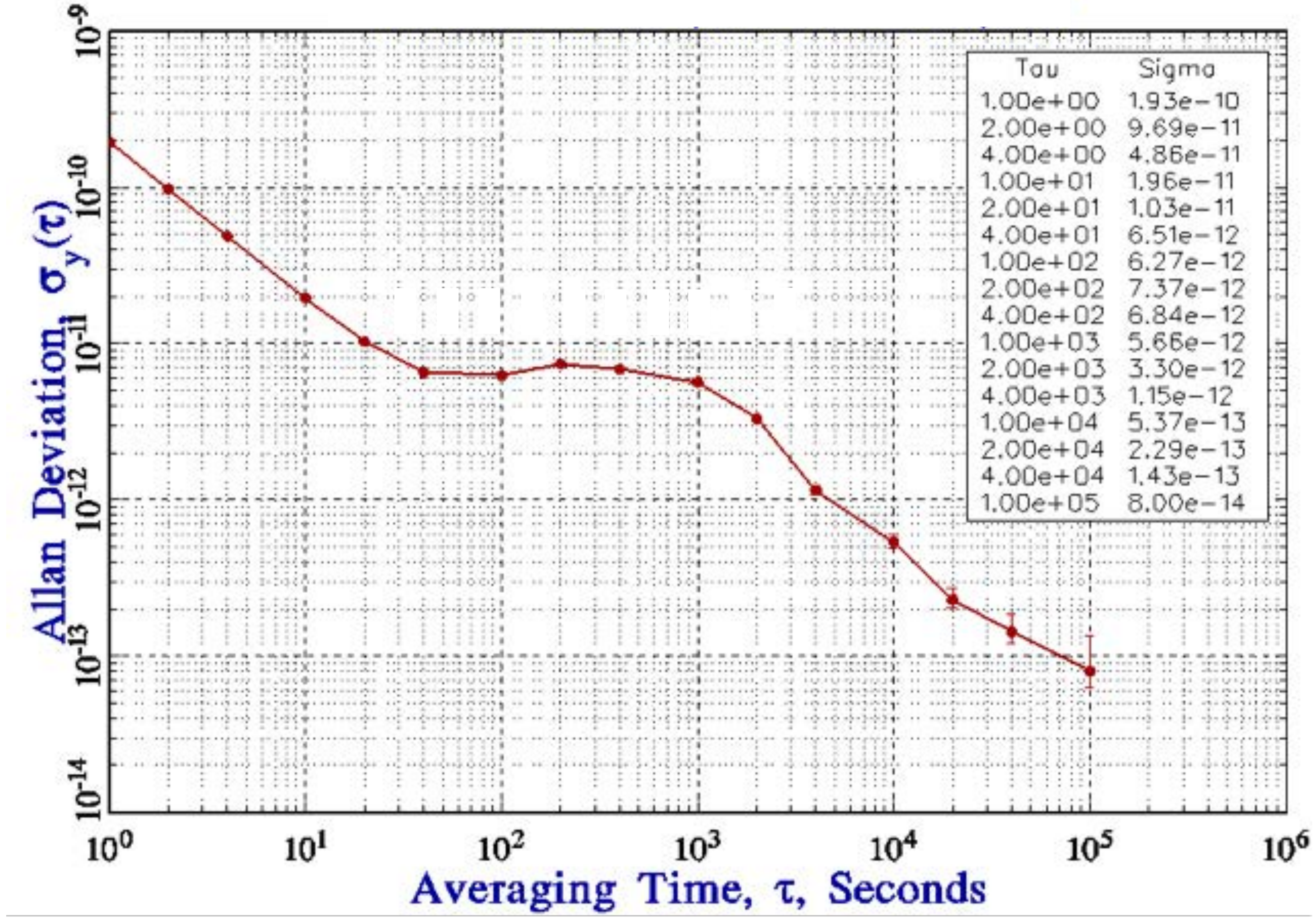
A. Arteaga et al., Electronics (2024), doi: 10.3390/electronics13020458.

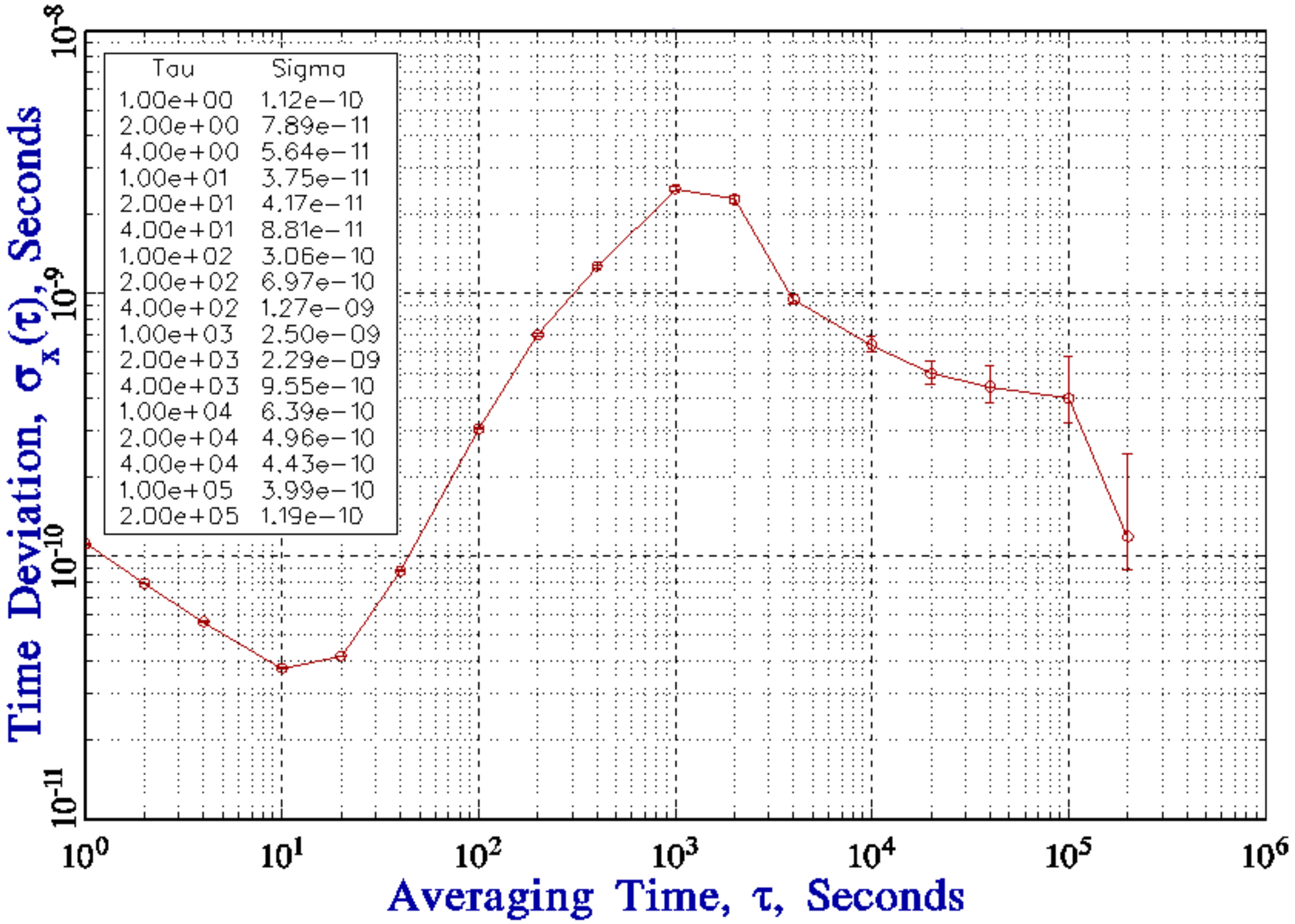
Precise Time Protocol: experimental results

Results from test set-up using M1000 units



- Test set-up:
- Master M1000 unit transmitting PTP to a slave M1000
- 1PPS and NTP reference from UTC(NPL) unit
- Two 50km fibre spools with long range SFPs.



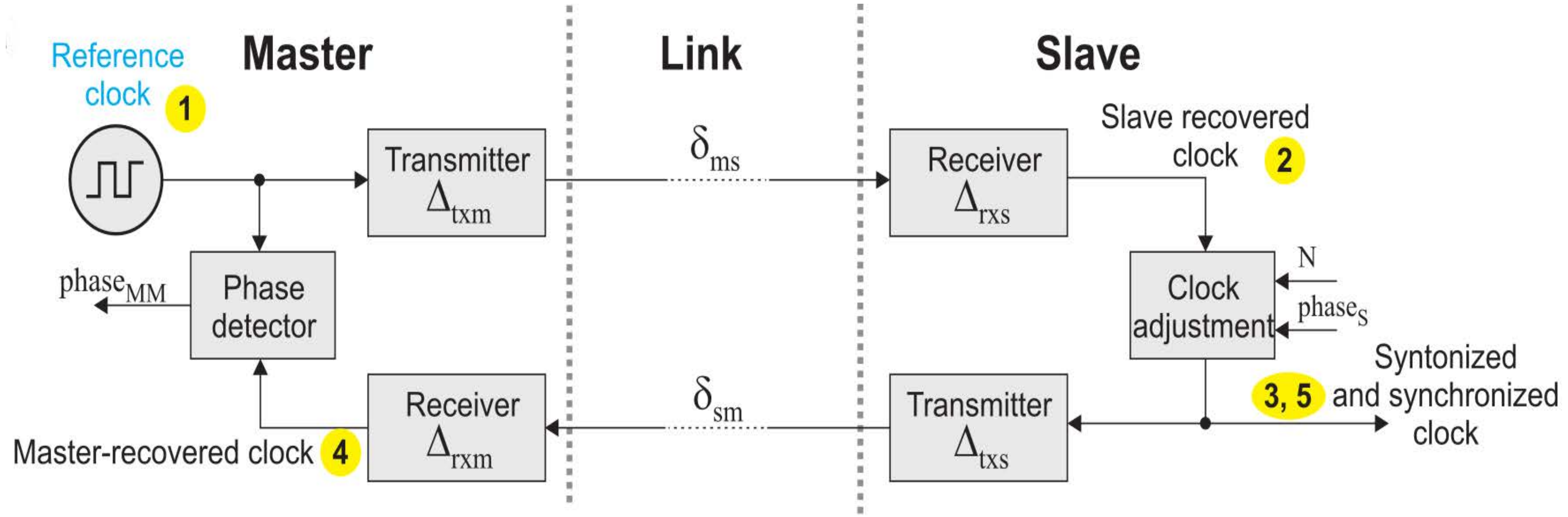


Courtesy E. Laier-English (NPL)

WR-PTP

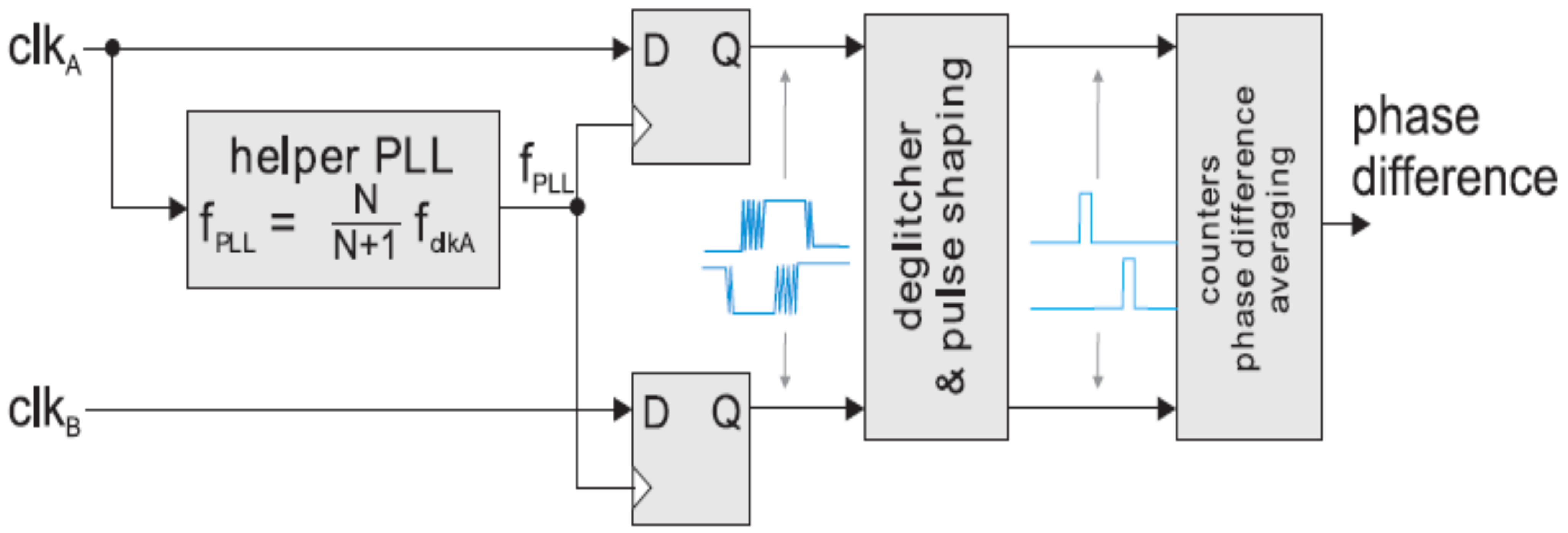
Synchronous Ethernet (SyncE)

- Layer-1 syntonization
- A common frequency reference for the entire network
- All nodes of the network are locked to the frequency of the System timing master



Digital Dual Mixer Time Difference (DDMTD)

- Precise phase measurement
- A phase compensated clock signal for the slave



Asymmetry compensation

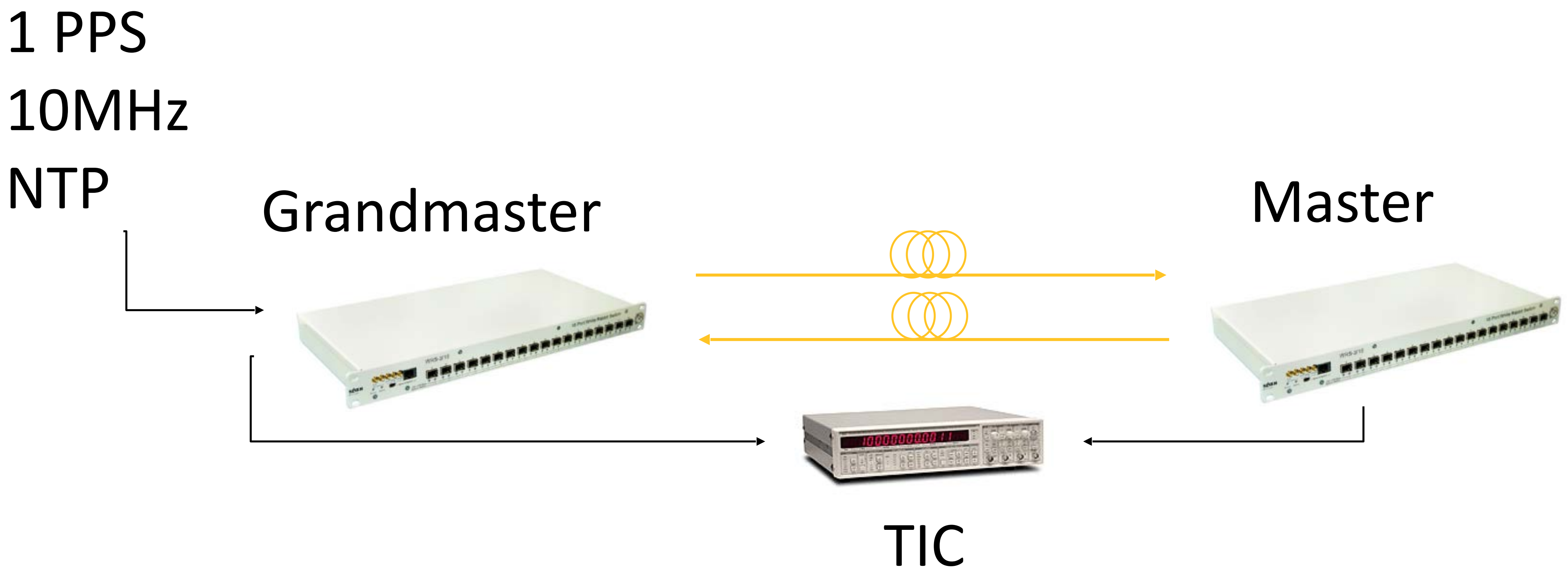
- Sources of propagation asymmetry in a White Rabbit link:
  - Chromatic dispersion
  - Unequal fiber lengths
- 'Static' correction of propagation asymmetry possible with WR.

$$\text{time error} = \frac{\tau_{MS} - \alpha \cdot \tau_{SM}}{2}$$

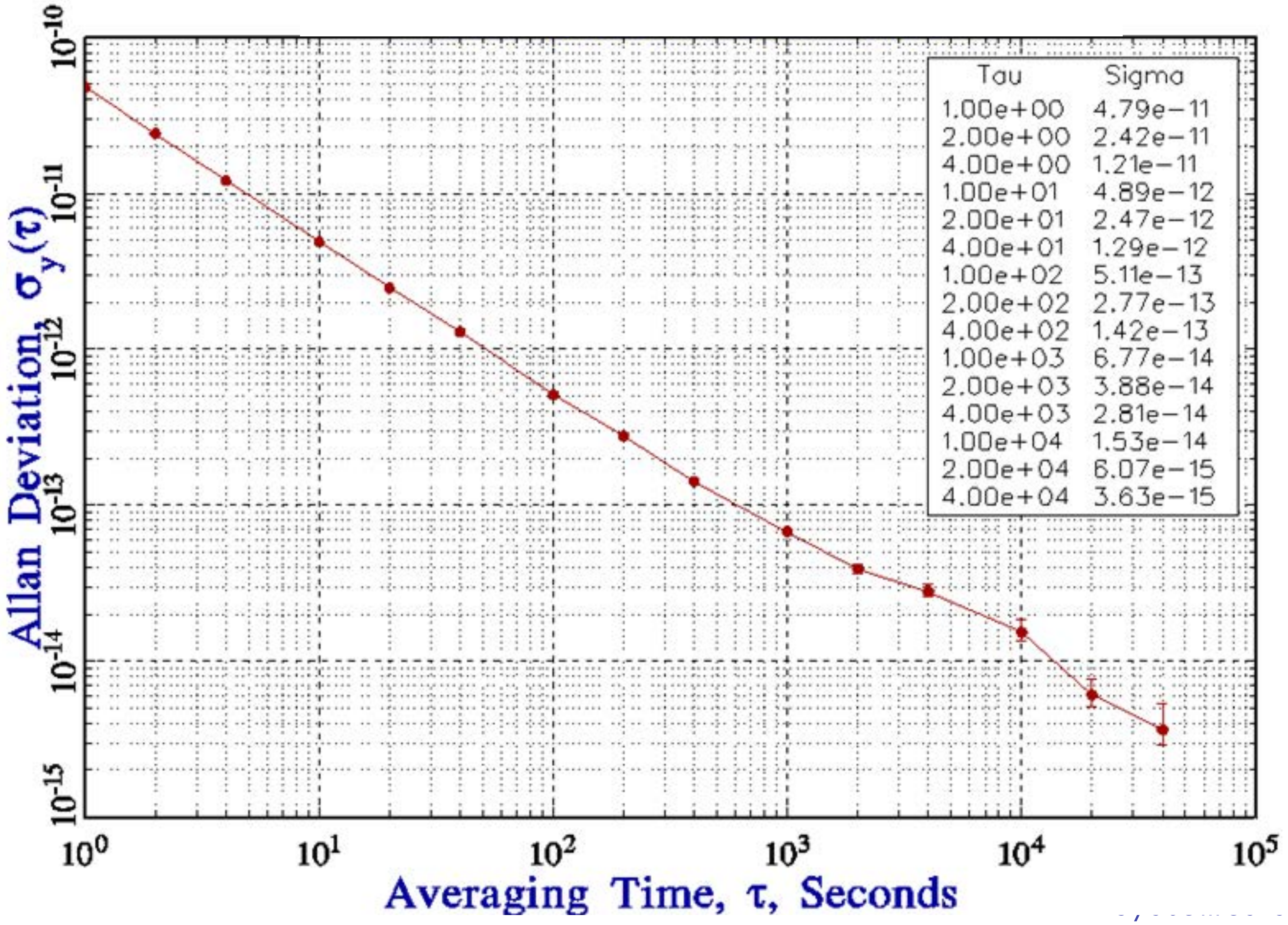
G. Daniluk,(CERN). Nuclear Instruments and Methods in Physics Research **725**, 187–190 (2013).

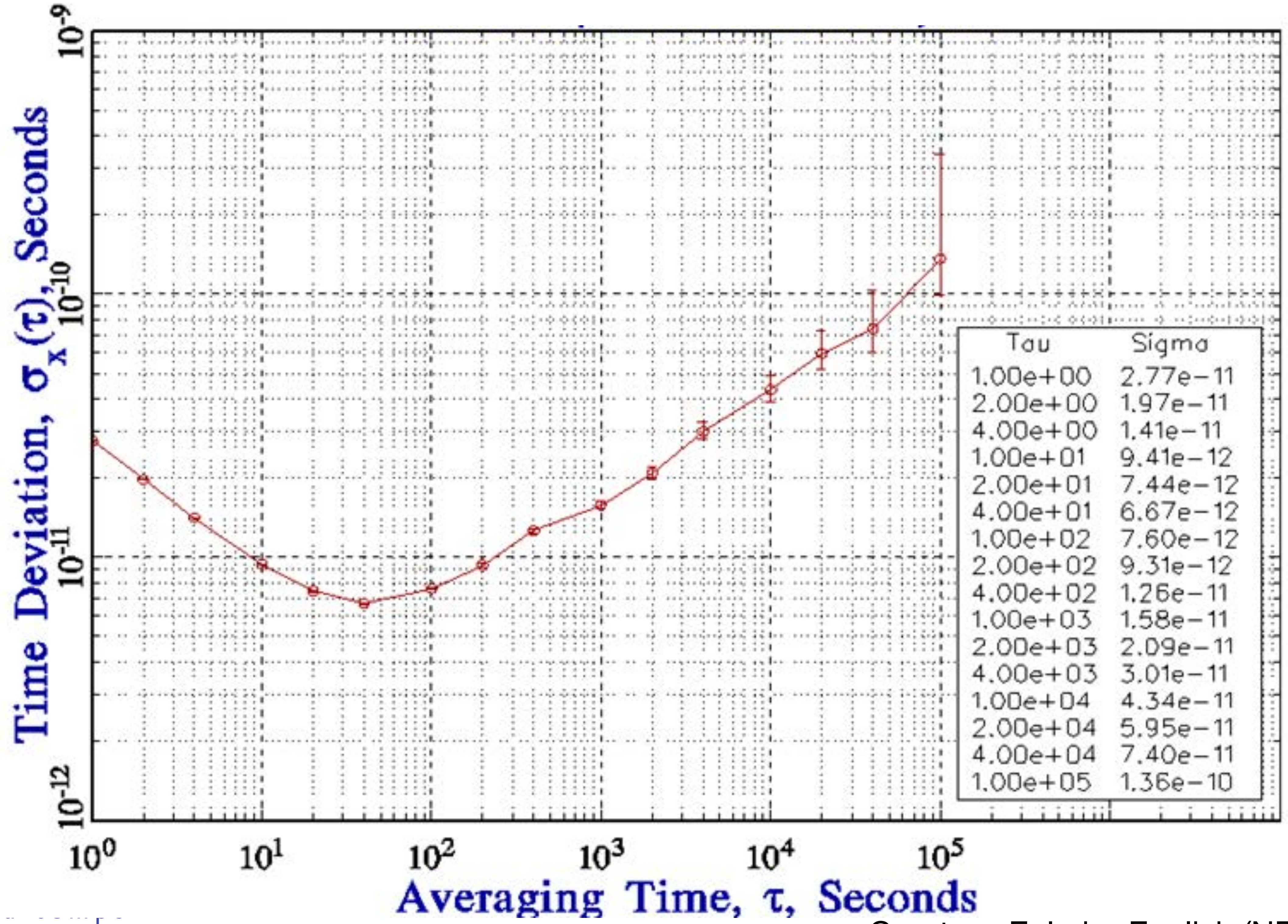
WR- PTP: experimental results

NPL National Physical Laboratory



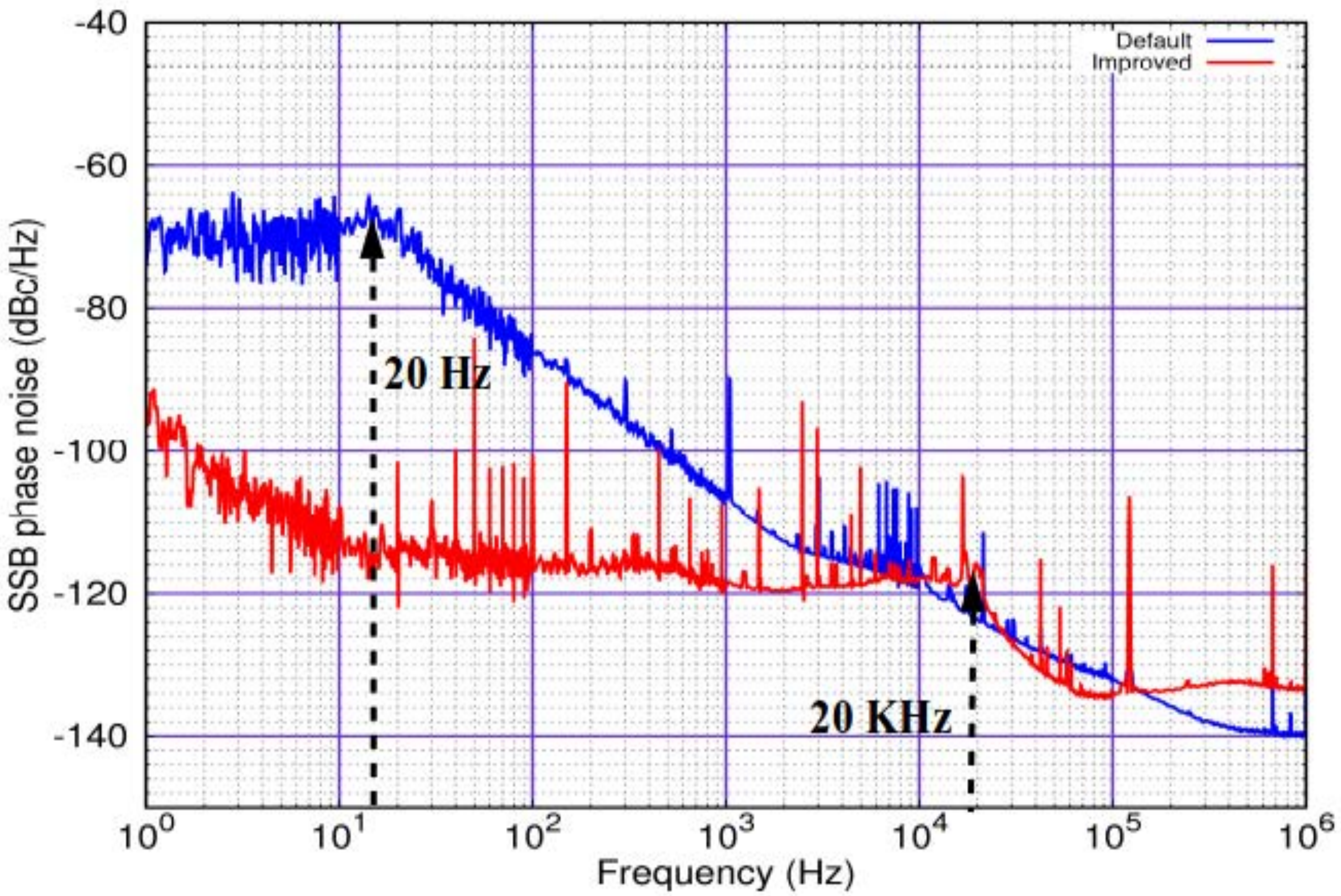
- Test set-up:
- Grand master switch unit transmitting WR-PTP to a WR switch slave
- 1PPS and NTP reference from UTC(NPL) unit
- Two 50km fibre spools with long range SFPs.

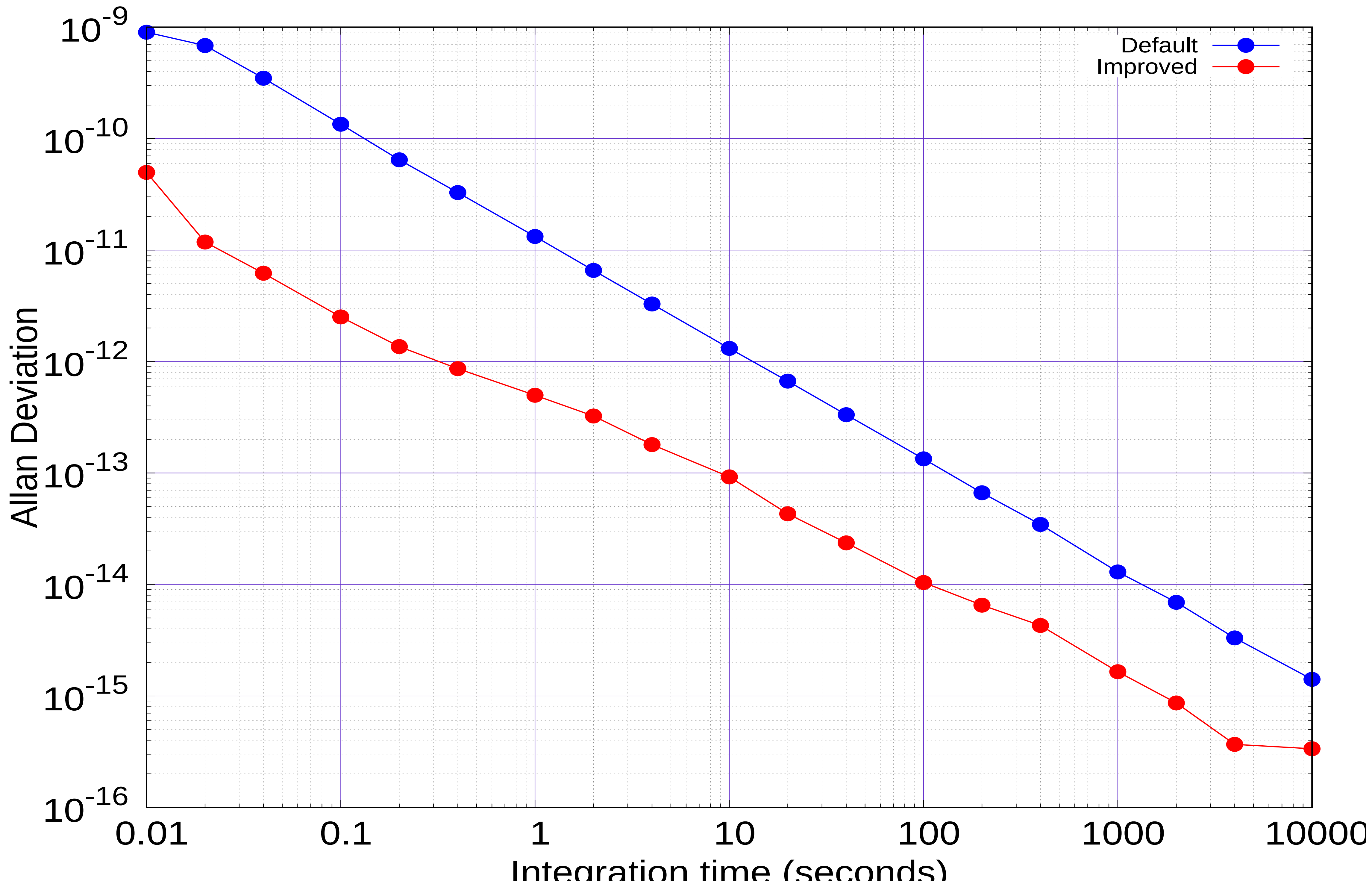




Courtesy E. Laier-English (NPL)

Ways to improved WR

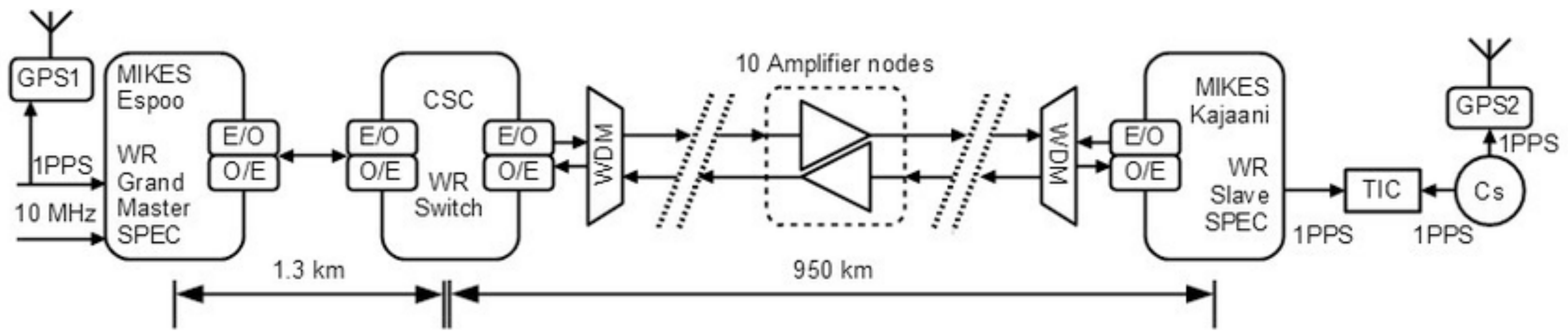




- **Trick** : increased PLL bandwidth of the GM L.O. to a good quality reference signal (H-Maser) (M. Rizzy)
- Many other work to improve performances of WR (better clocking scheme, better choice of components (clock fan out), etc
- WR community is very active !

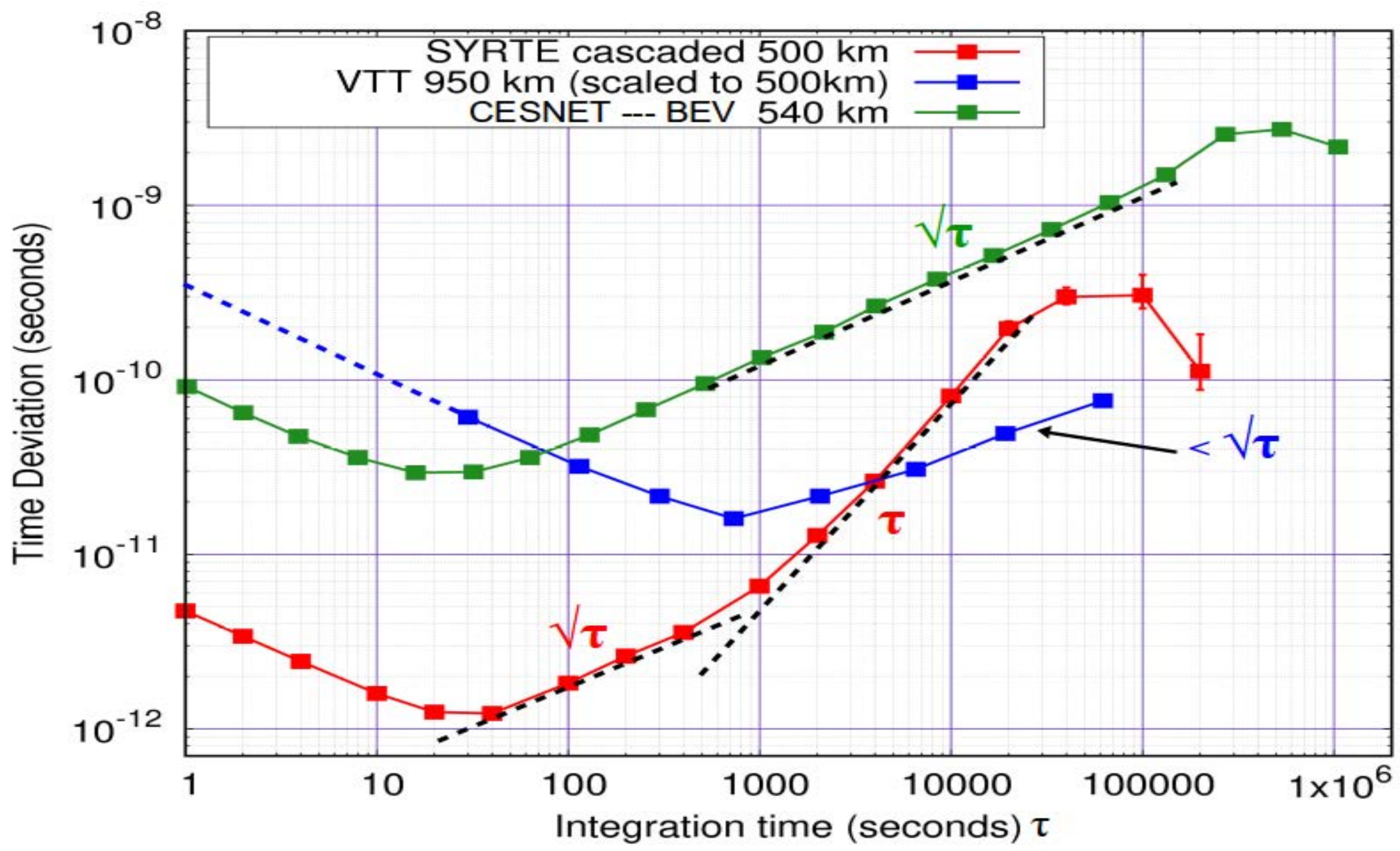
Namneet Kaur Thesis
https://hal.archives-ouvertes.fr/tel-01909292

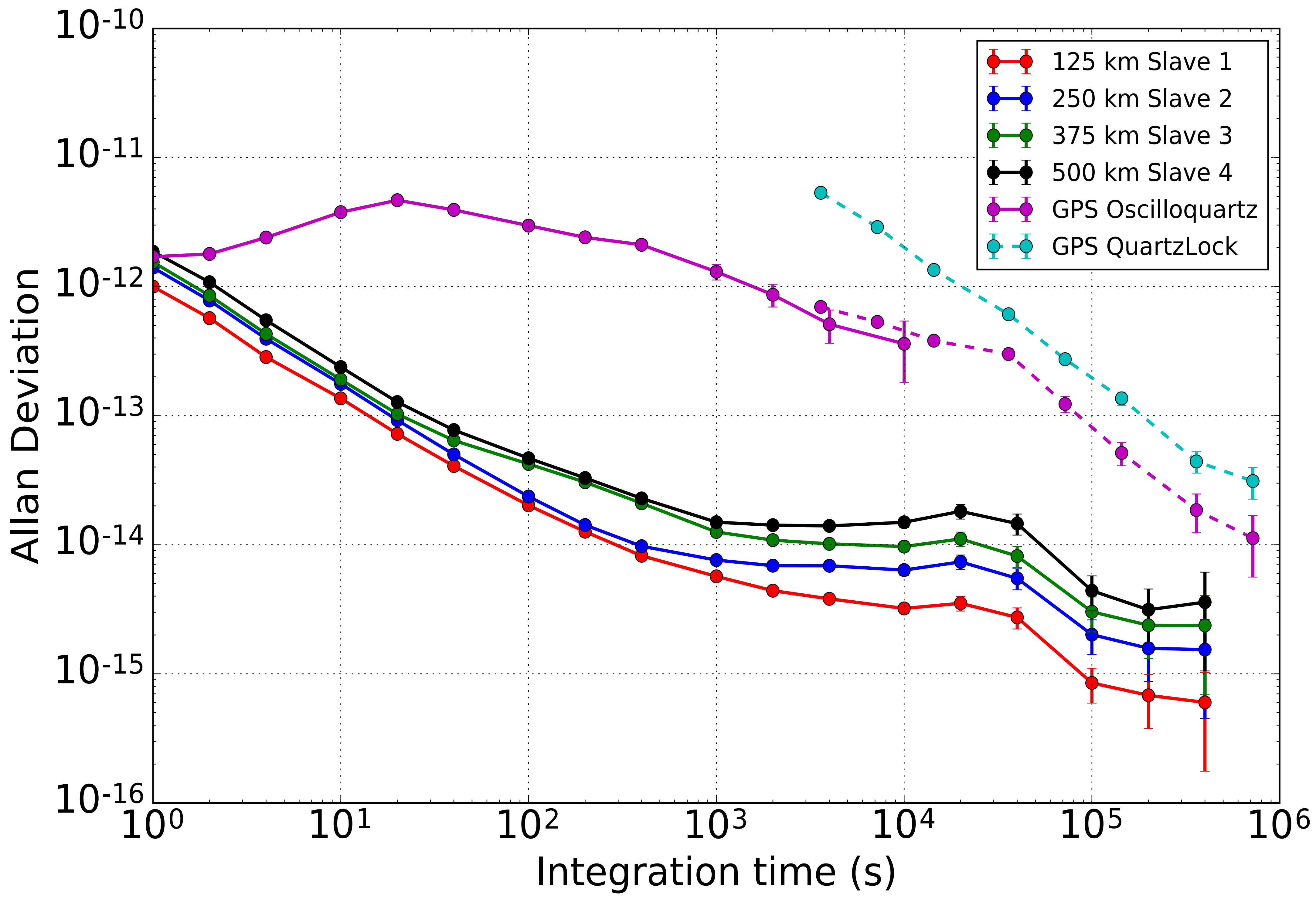
WR-PTP on long haul xWDM networks



E.F. Dierikx, et al. IEEE T-UFFC 63, 945–952 (2016).

- 2 architectures possible
  - 1 wavelength, 2 fibers
  - 2 wavelengths, 1 fiber
- Challenge : asymmetry determination and time accuracy



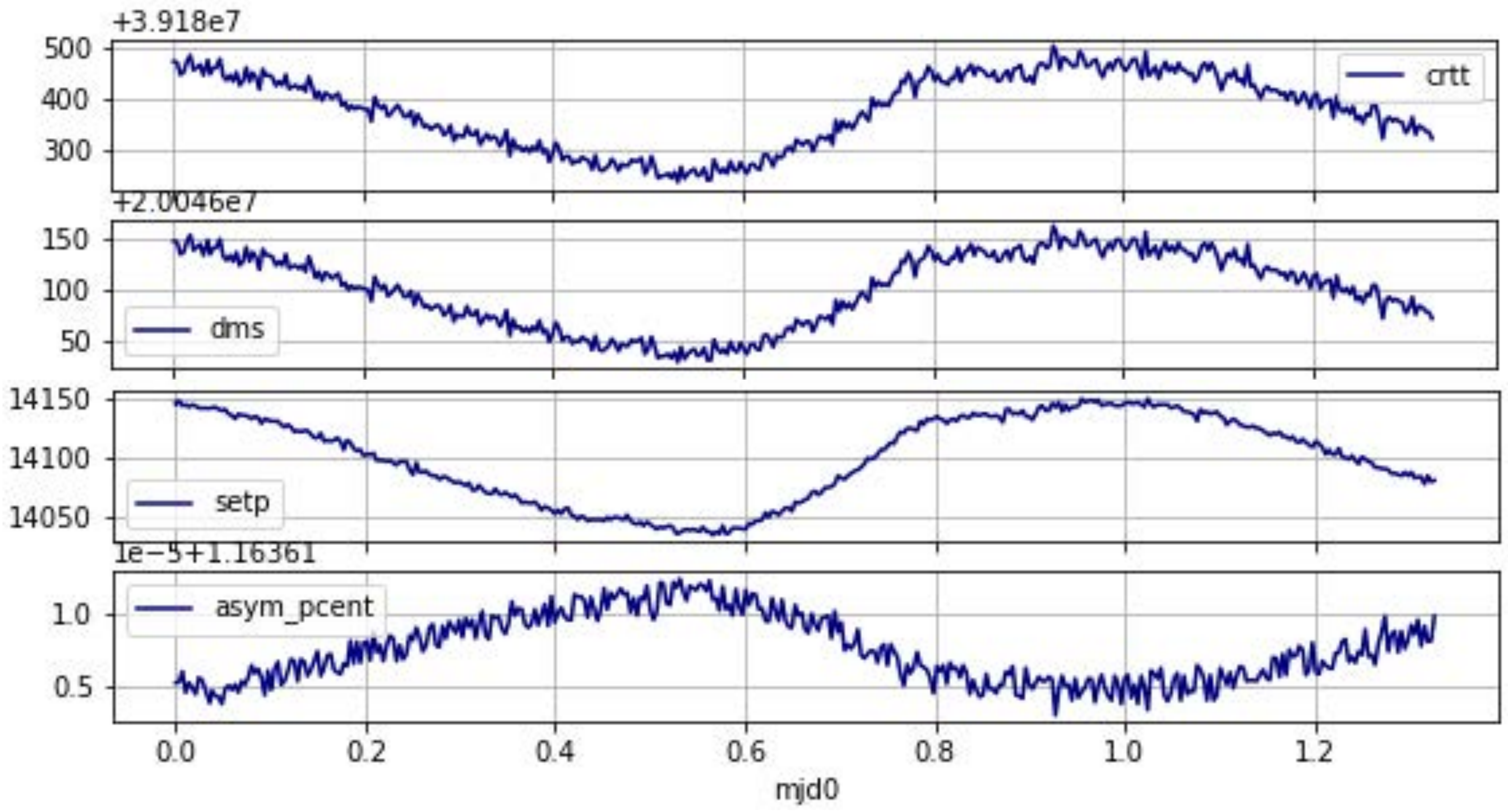


https://hal.archives-ouvertes.fr/tel-01909292

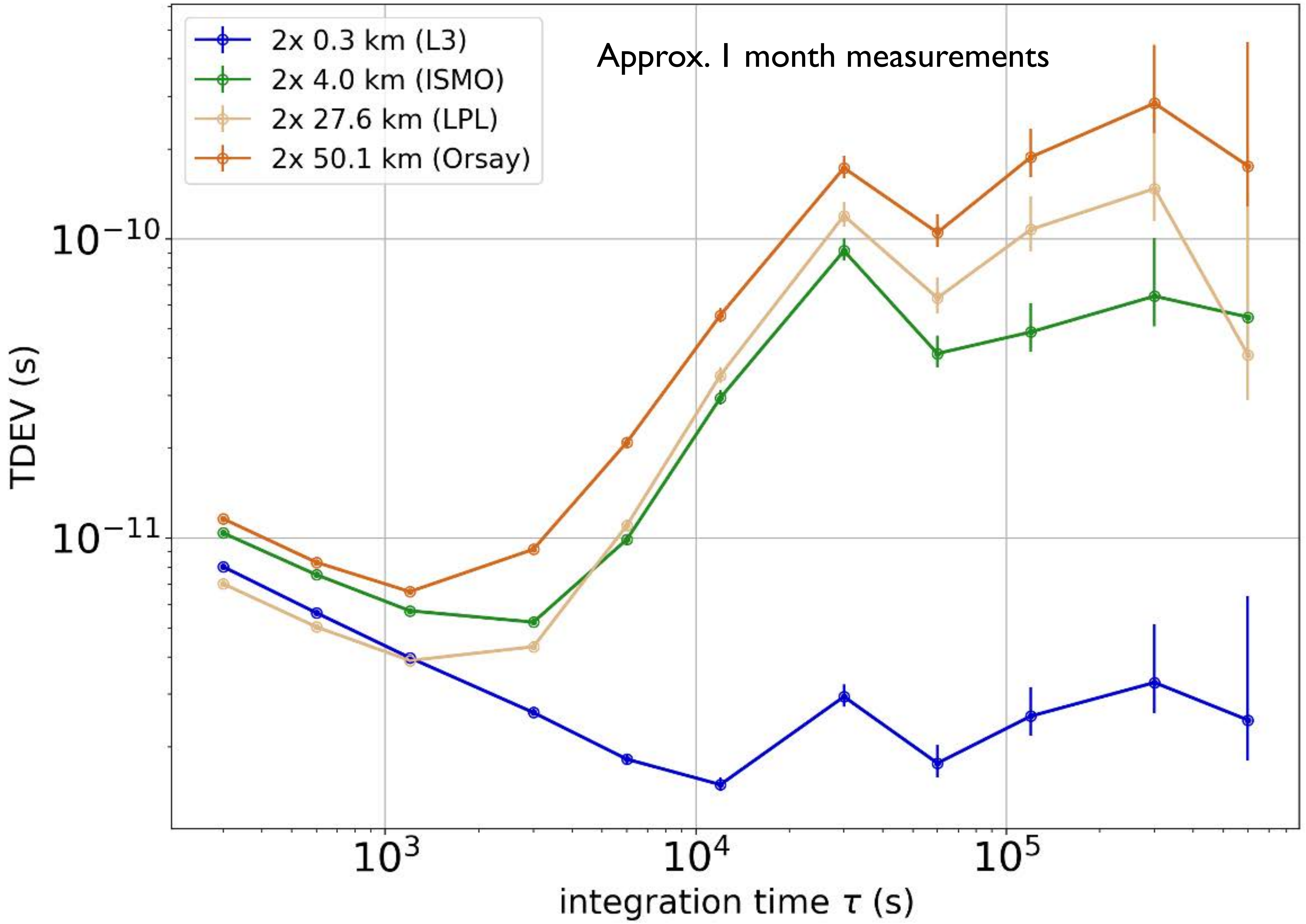
WR network: monitoring and supervision

- Supervision of ~10 wrs in Paris area
- Implement monitoring of *wrs* and *zen-tp periodic poling of the devices*

Exemple of monitoring for wr switch at ISMO (Paris Saaly), for 1 day



TDEV for round-trip time over the regional network

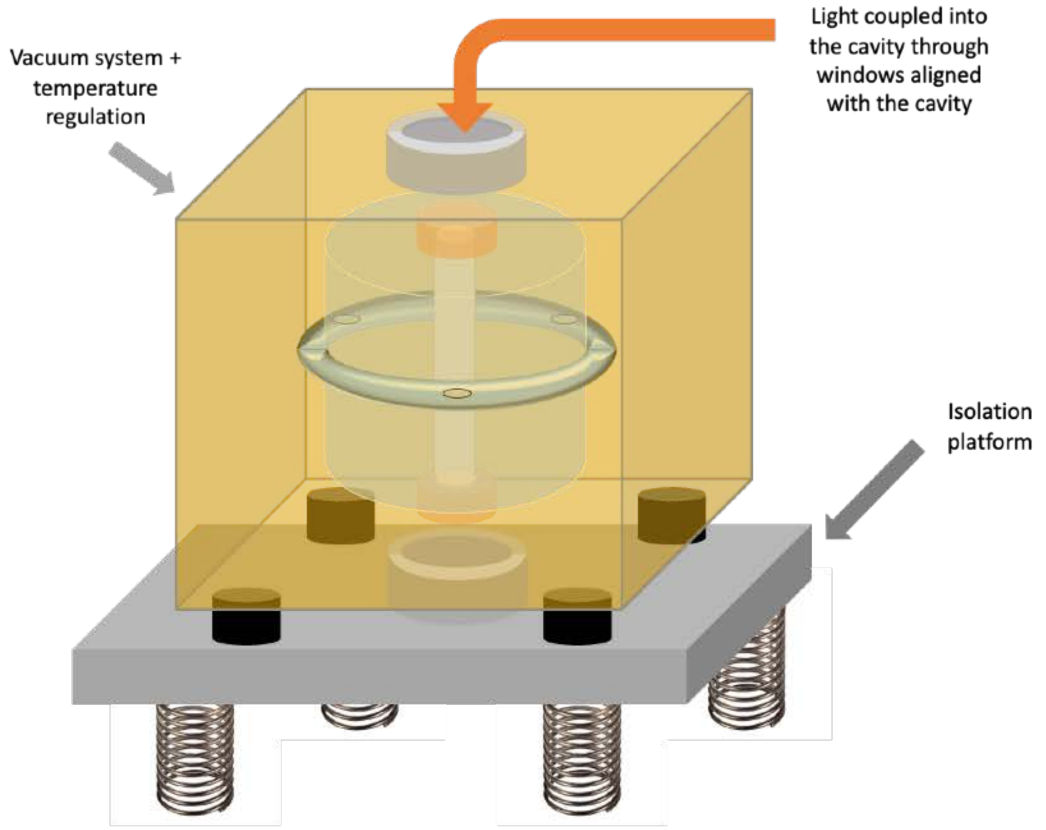


Embedded monitoring resolution ~ 10 ps
Round-trip time < 1 ns / 40 days

We observe diurnal perturbations on mid-range links.

Optical frequency transfer

Ultra-stable laser at telecom wavelength



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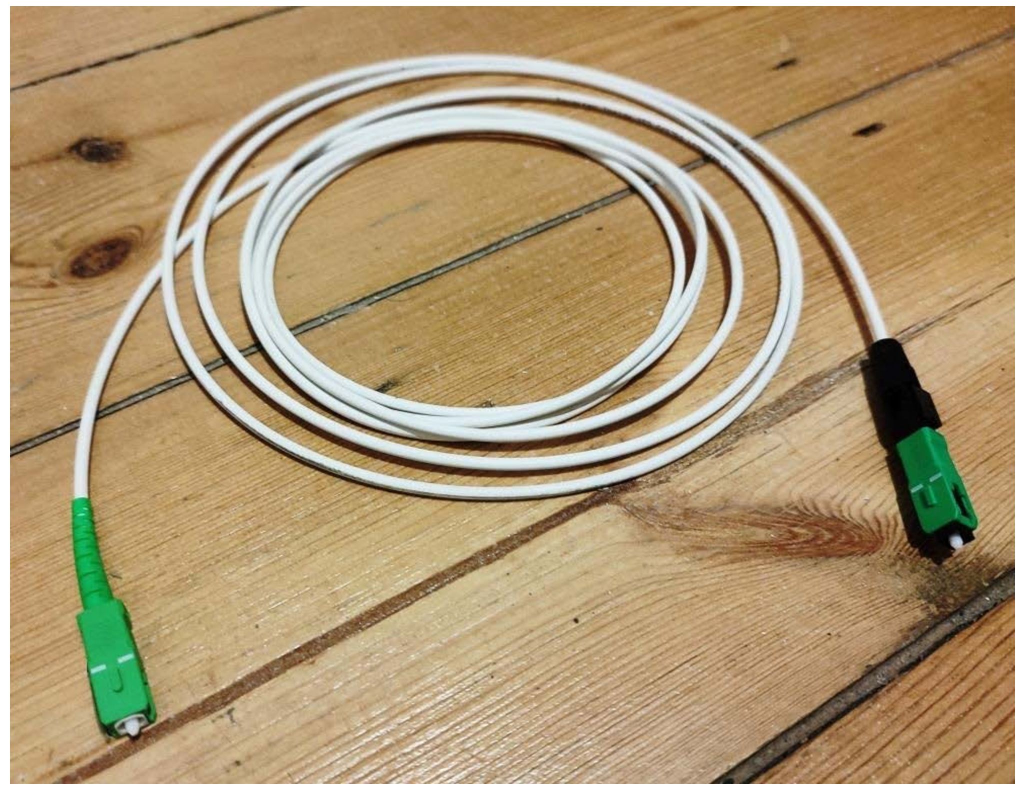
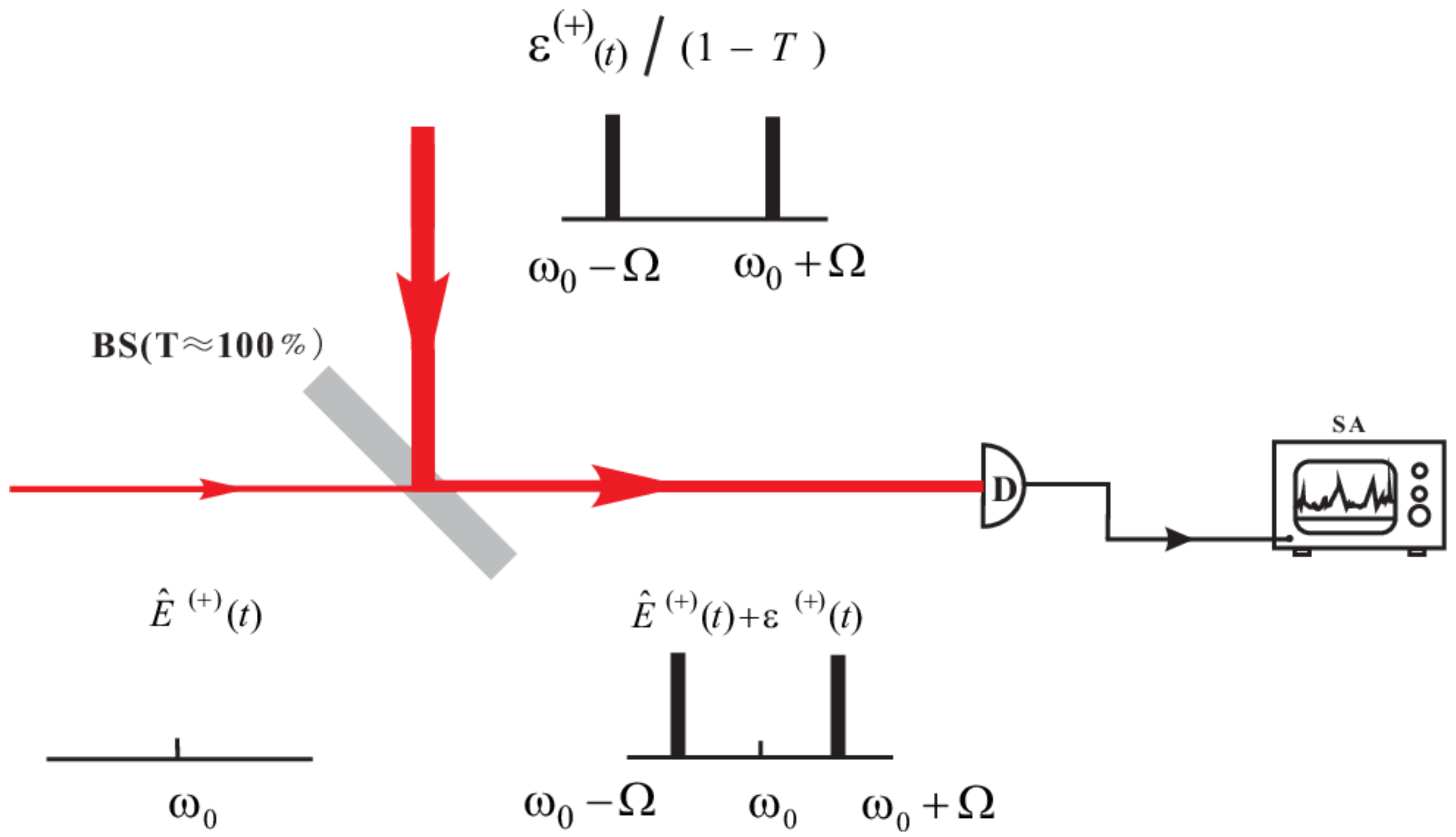


<u>No modulation</u>
No CD
No PMD

<u>Bidirectional propagation</u>
No non-reciprocity

Heterodyne detection : emission and detection are not at the same frequency.

\+



heterodyne detection to resolve path ambiguity

Fig. From S. Feng et al., arXiv: Quantum Physics, déc. 2011
https://www.semanticscholar.org/paper/Balanced-heterodyne-detection-of-sub-shot-noise-Feng-Lu/84f3cf0c839dd1cbd06c6a89d30a907c4fdd9718

Conference on Lasers and Electro-Optics/Quantum Electronics and Laser Science Conference and Photonic Applications Systems Technologies
OSA Technical Digest Series (CD) (Optica Publishing Group, 2007), paper CMKK1

CLEO

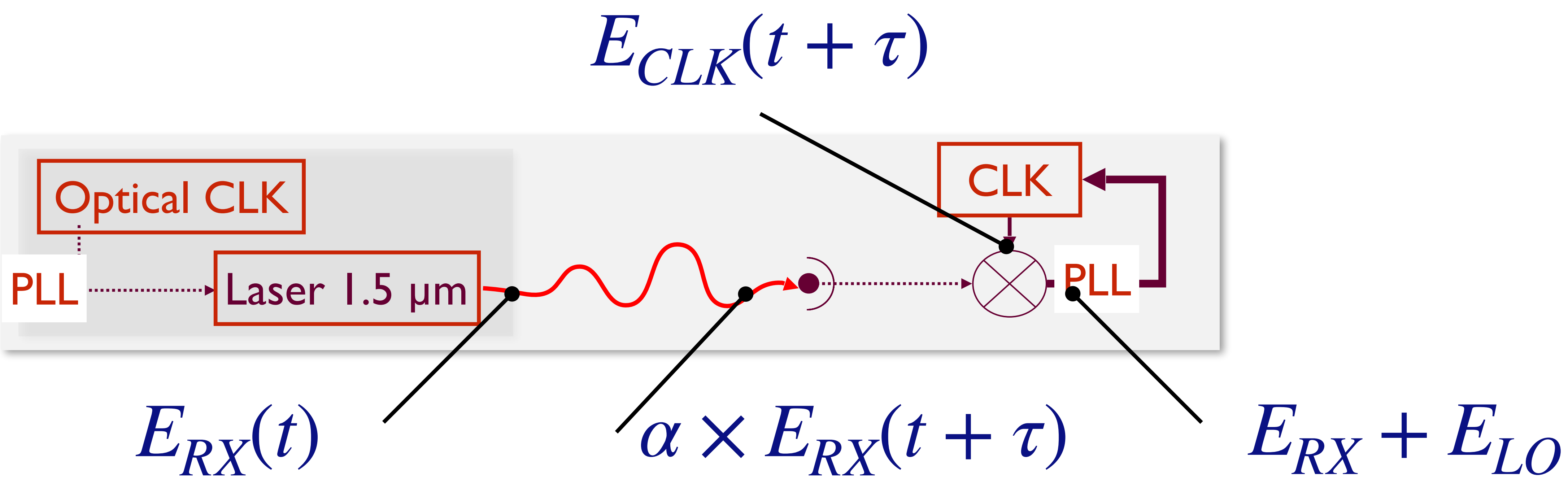
Transmission of an Optical Carrier Frequency over a Telecommunication Fiber Link

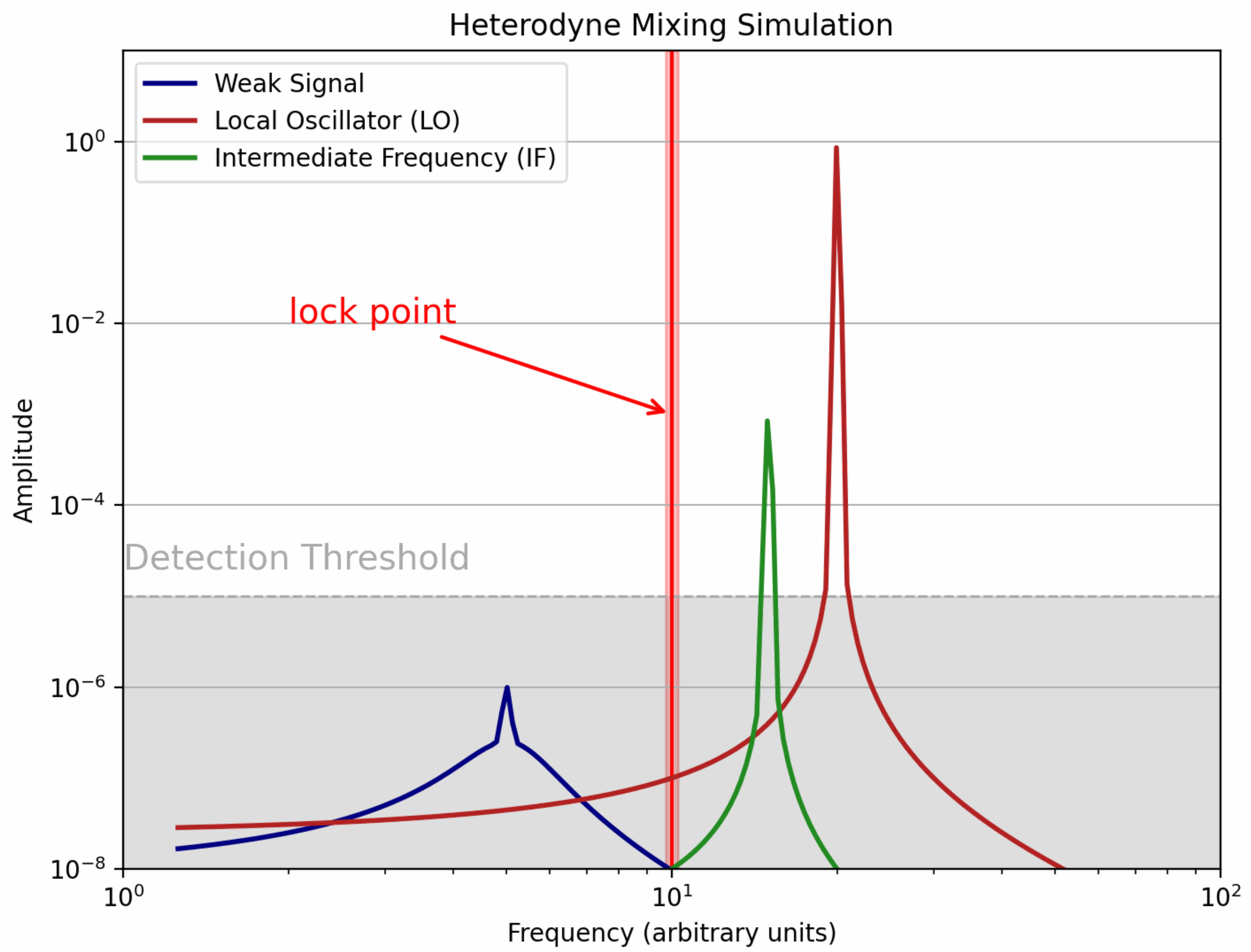
G. Grosche, B. Lipphardt, H. Schnatz, G. Santarelli, P. Lemonde, S. Bize, M. Lours, F. Narbonneau, A. Clairon, O. Lopez, A. Amy-Klein, and Ch. Chardonnet

Author Information ▾ Find other works by these authors ▾

- Introduce frequency shifters (e.g. acousto-optic modulator) at both ends of the fiber link so that the frequency of the detected beat-notes unveil unambiguously the light travel path.
- Mandatory for live fiber network !

Advantages of the full optical method

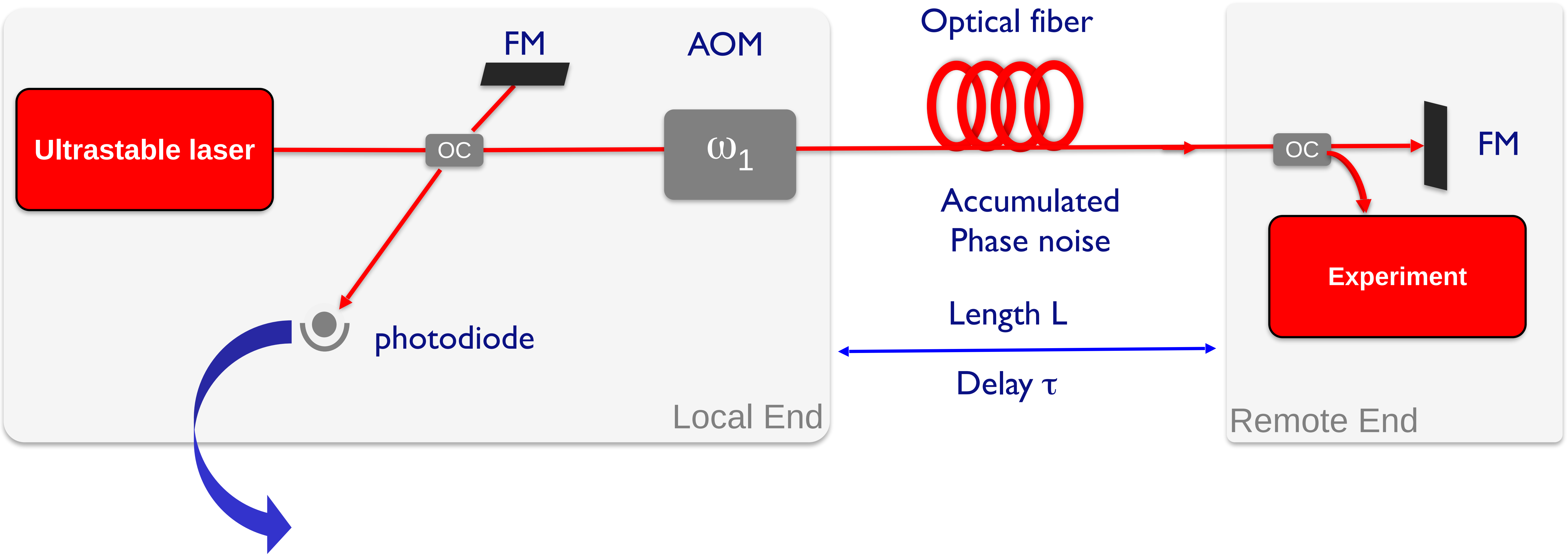


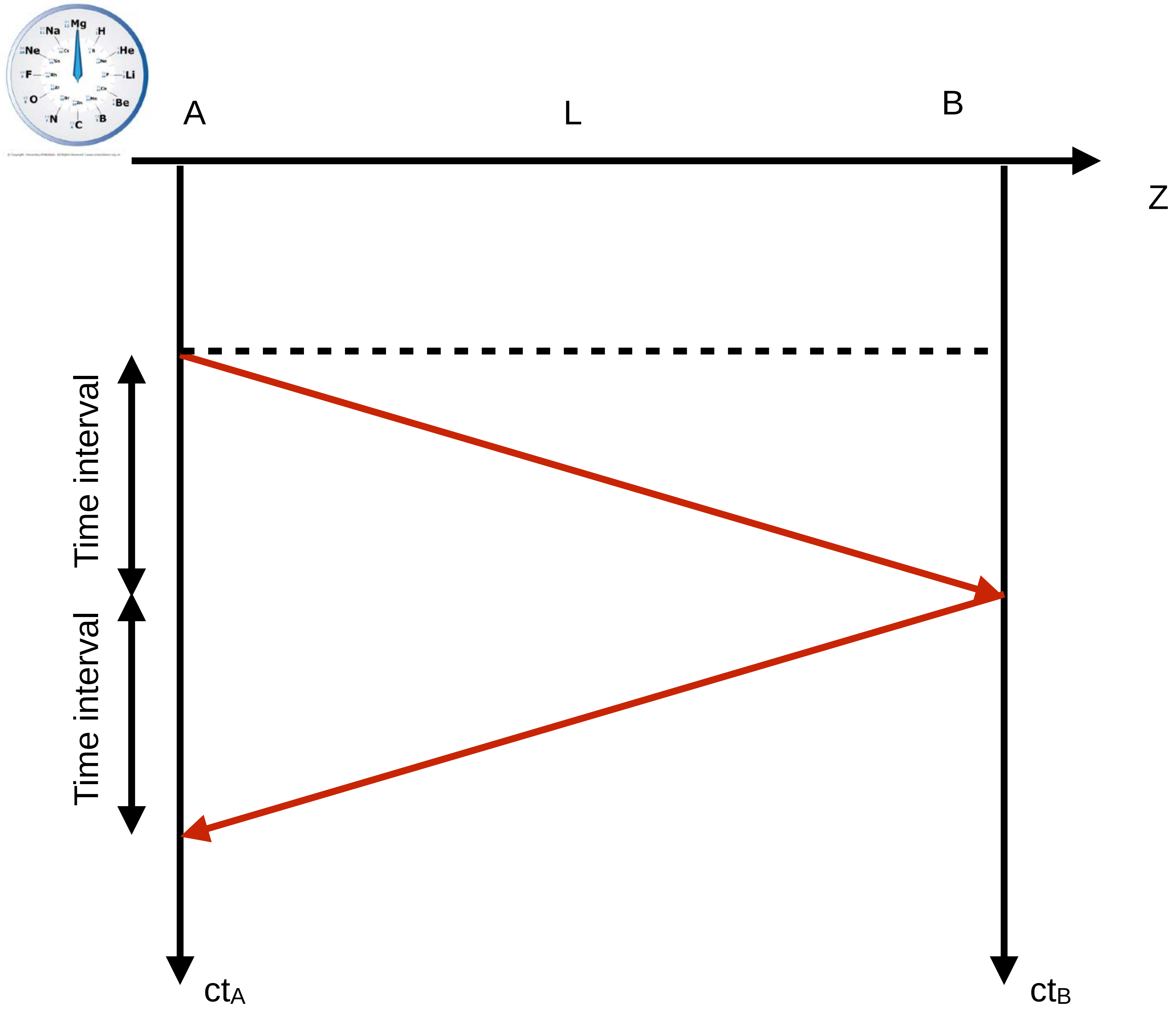


- Heterodyne detection at remote end:
  - Signal $s(t) = |\alpha \times E_{RX}(t+\tau) + E_{CLK}(t+\tau)|^2$
- After AC filter:
  - Signal $S_{PLL}(t+\tau) \propto \alpha(A_{RX} \cdot A_{CLK}) \cdot \cos(\Theta)$
  - $\Theta = (\omega_{RX} - \omega_{CLK})\, t + \Phi_{RX} + \Phi_{CLK} + \Phi_p$
- Detection of the transmitted field and not its intensity
- Detected signal is reduced by half the fiber losses in dB.
- The trick works at any frequency. But then its a matter of filtering to isolate the IF frequency. It is very convenient for RF-shifts of optical carriers.
- As a consequence, long hauls are easier to achieve with direct optical frequency transfer method than with indirect x-modulation frequency transfer methods.

Detection of round-trip noise

- Strongly unbalanced Michelson interferometer
- Frequency shifter ω_l → heterodyne detection at $2\omega_l$
- Using Faraday mirrors automatically aligns polarisations at detection

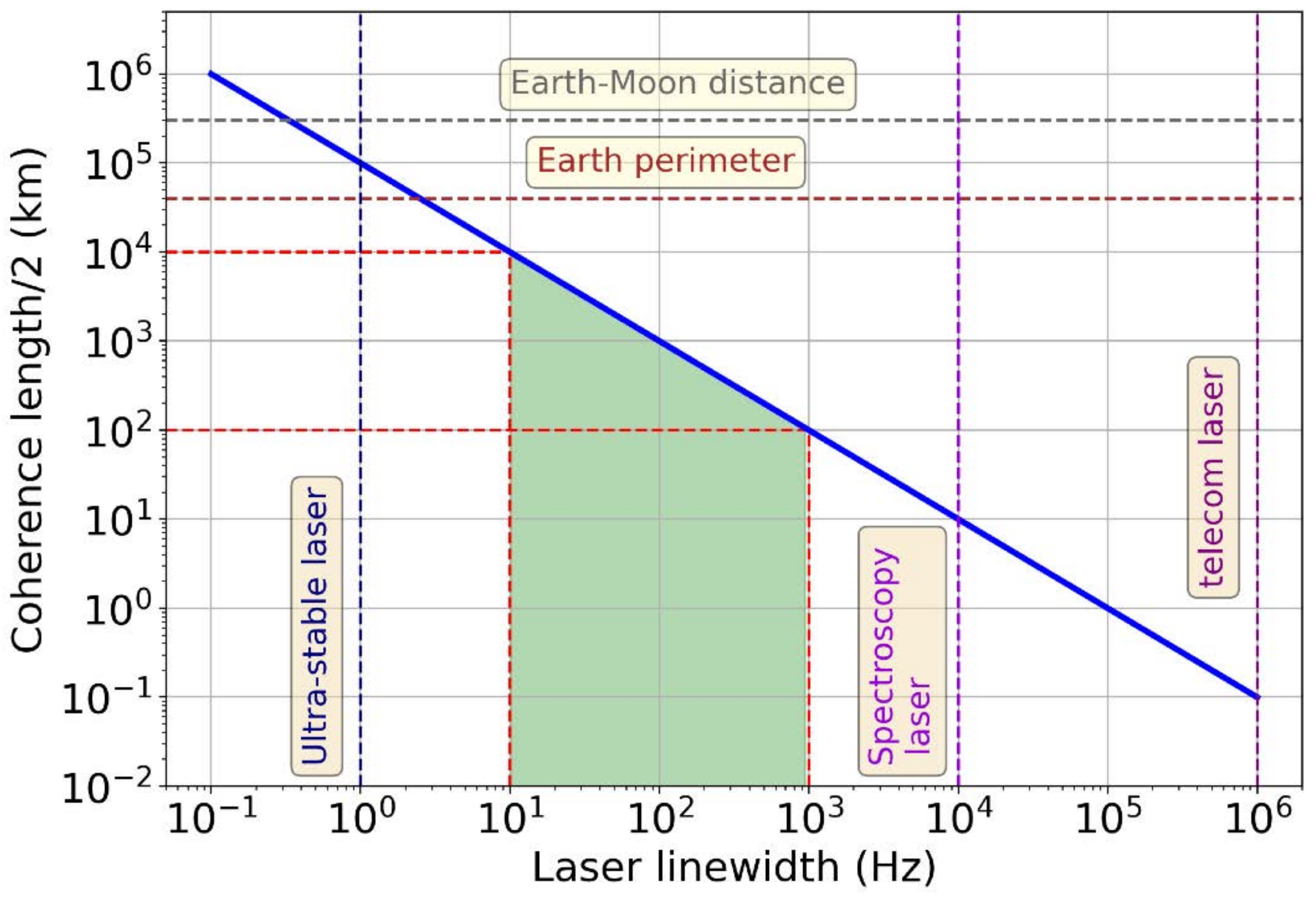




→ Round-trip fiber propagation noise + laser auto-correlation noise

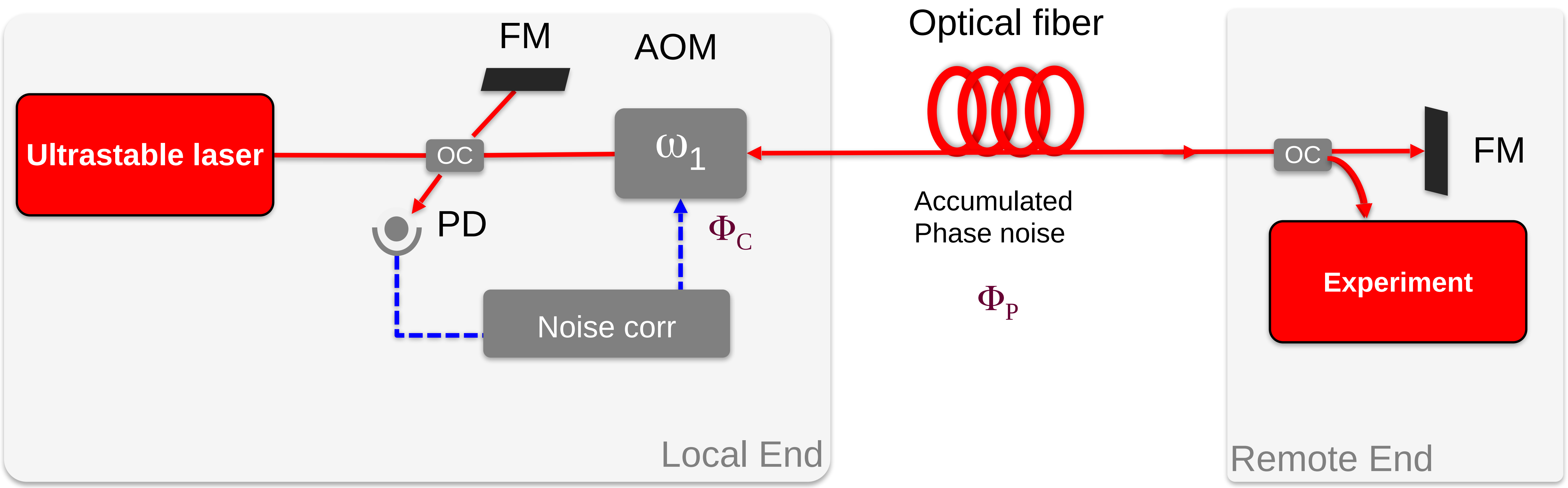
$$\Phi_{Laser}(t) - \Phi_{Laser}(t - 2\tau)$$

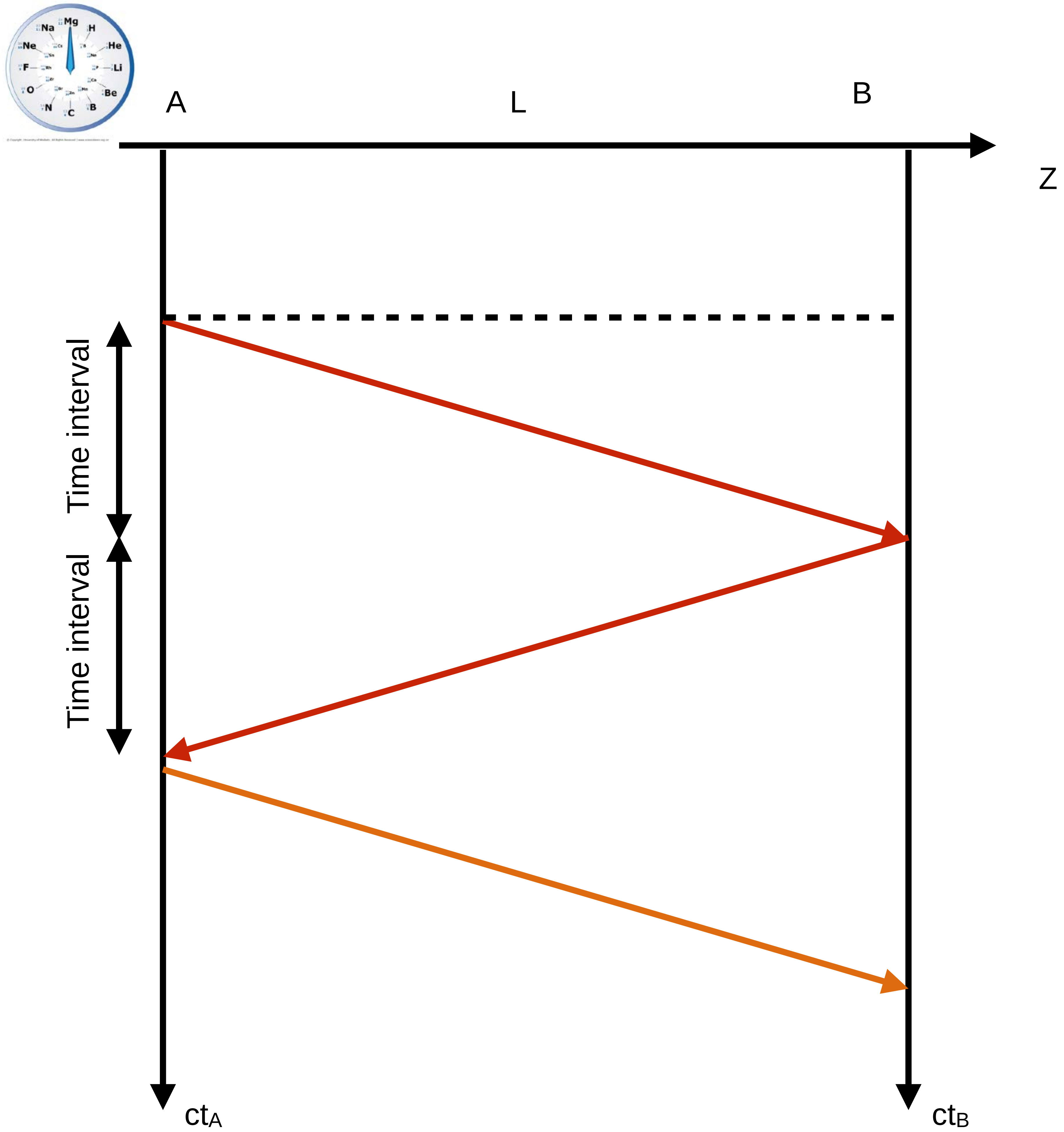
- Ultra-stable laser are needed with coherence length > 2L to keep the coherent regime



Active noise compensation in an optical fiber link

- Doppler noise compensation or active noise compensation



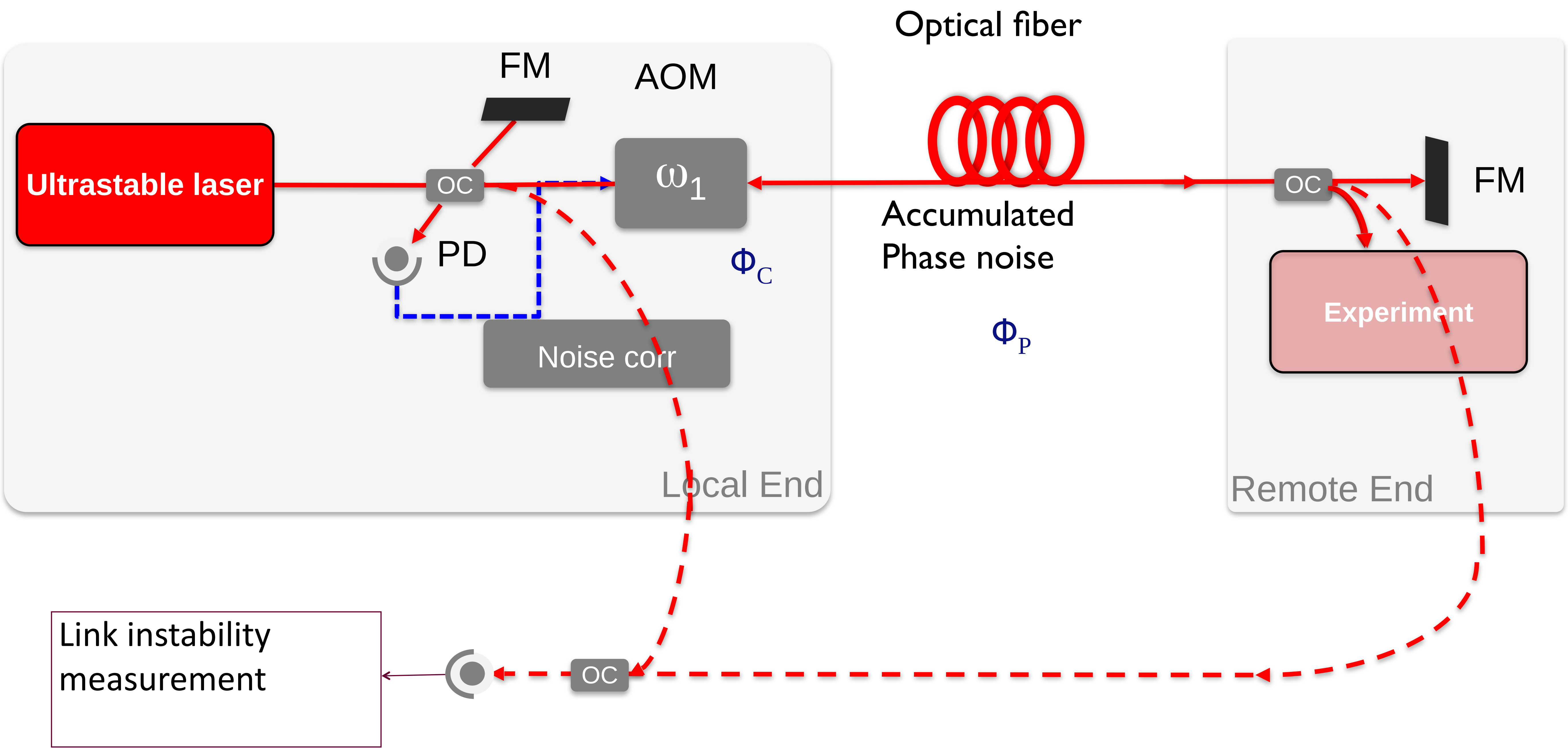


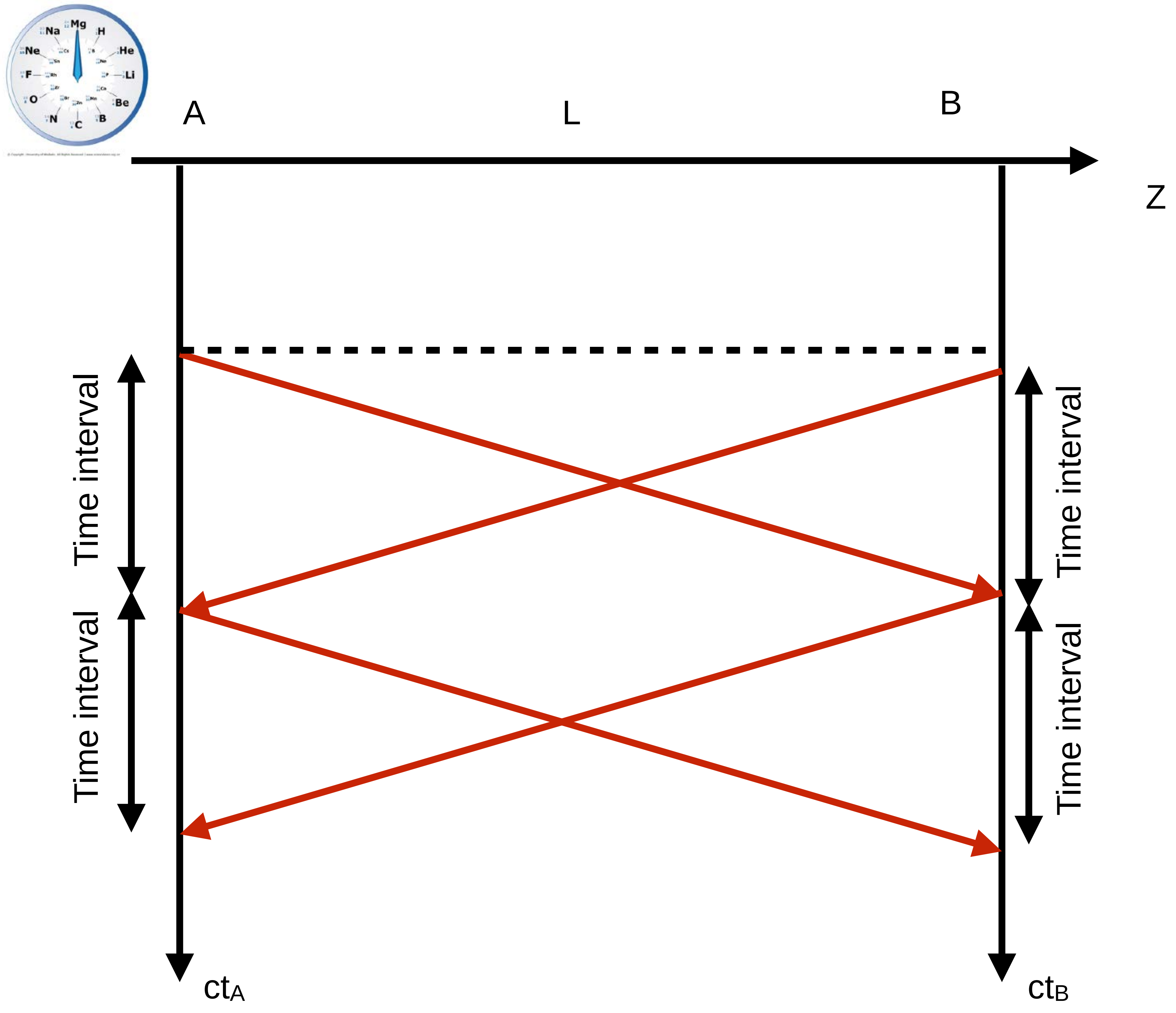
- Noise correction Φ_c applied at the link input: $2(\Phi_c + \Phi_p) = 0$
- Correction is applied by frequency shifting the light !
- Assumption : Forward noise = ½ Round-trip noise

→ corrects only reciprocal noise

Nota bene : the compensation process is continuous. The retro-action is delayed by at least twice the one-way propagation time.

Evaluation of noise compensation





- So-called "End-to-end" instability measurement
- Demonstration with 2 parallel fibers or one loop fiber: two ends at the same place.
- The average value is expected to be zero.

Example: phase noise of a 86 km optical link

- Propagation delay: $\tau = \frac{c}{nL} = \frac{v}{L}$
- Limited noise rejection:

Residual noise(t) at remote end

≈ forward noise – ½(round-trip noise)

≈ ½ (forward noise – backward noise)

≈ ½ (noise derivative) x (2τ)

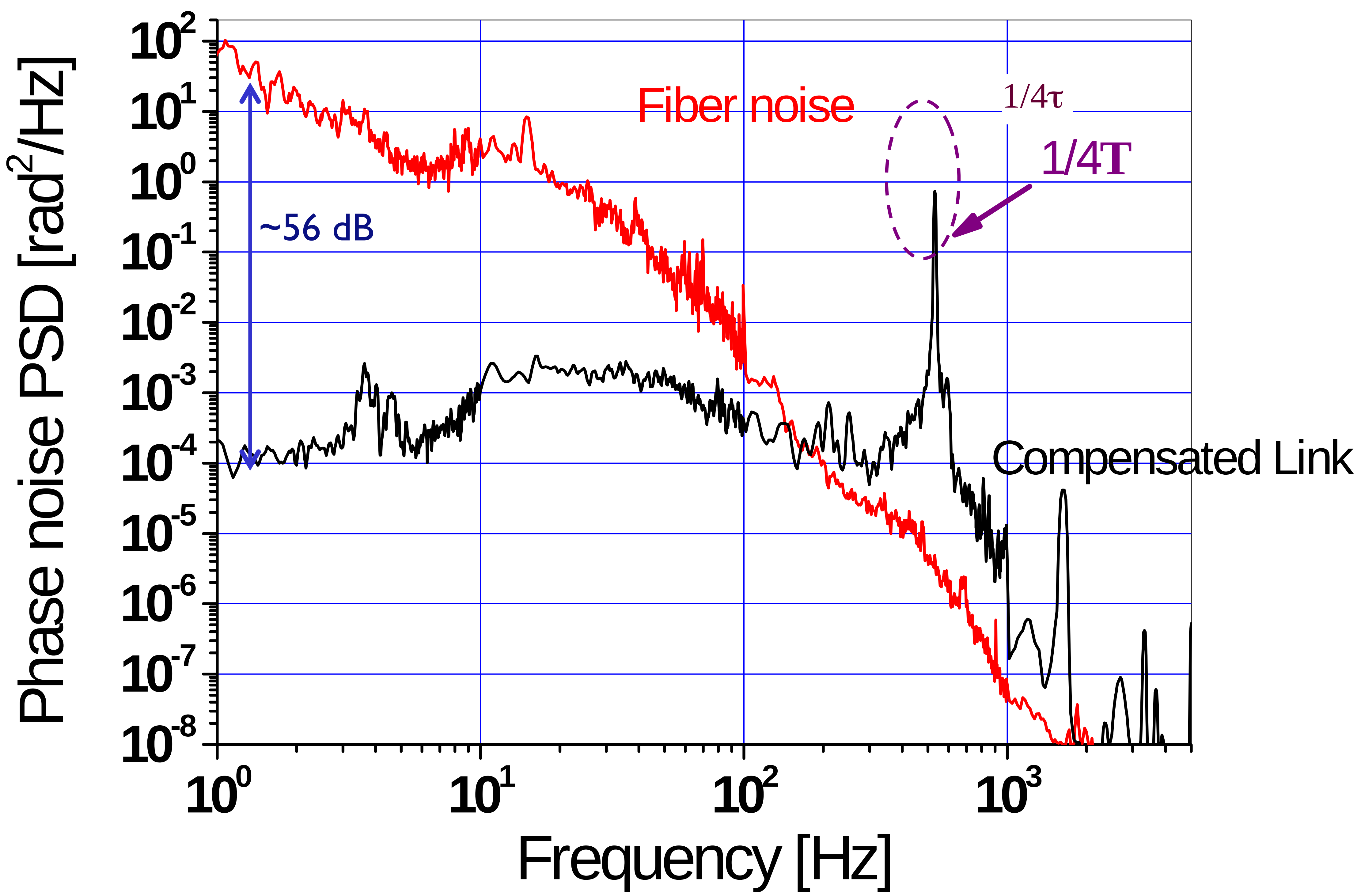
≈ (noise derivative) x τ

Fourier domain: residual noise (f) $\simeq$ noise$(f) \times (j2\pi f) \times \tau$

And the residual noise PSD ≈ $\simeq$ fiber noise PSD $\times (2\pi f\tau)^2$

- Servo loop theory : correction bandwidth limited to $\simeq \frac{1}{4\tau}$

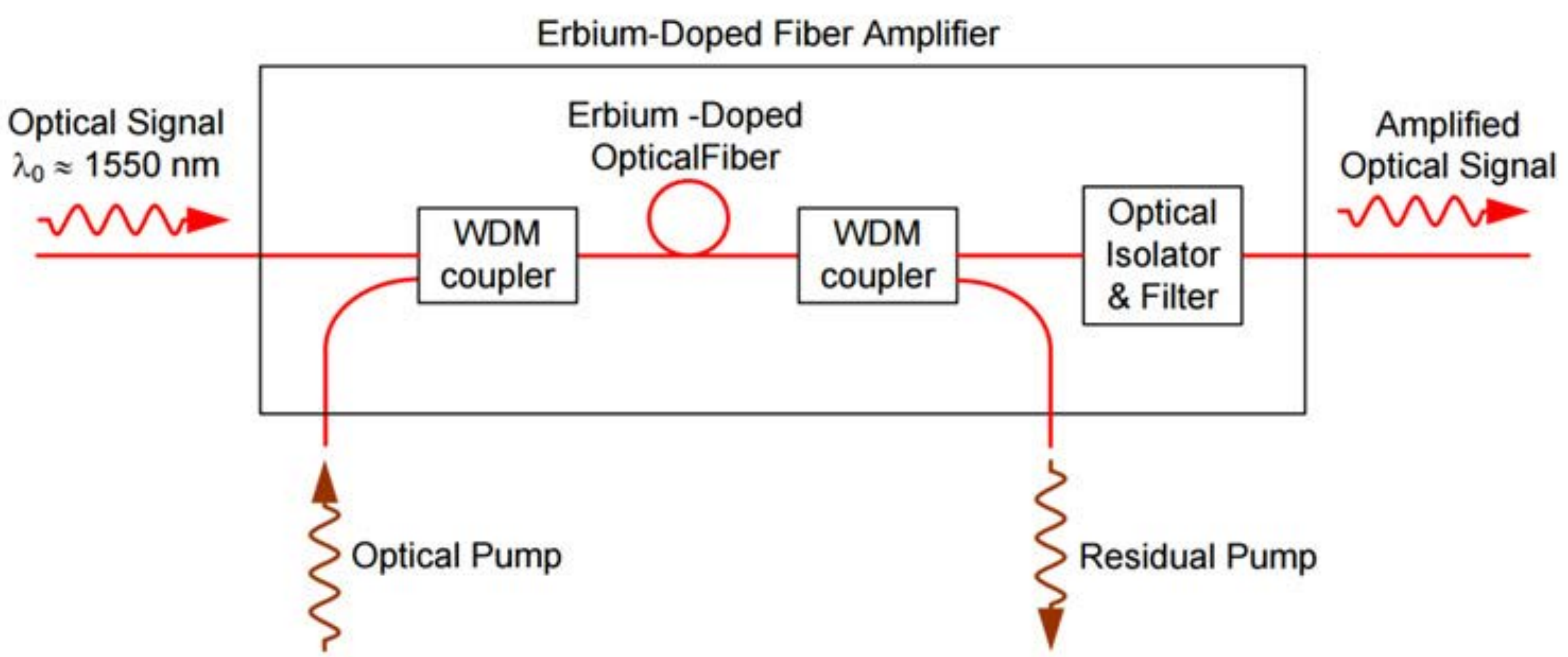
Carrier = 200 THz



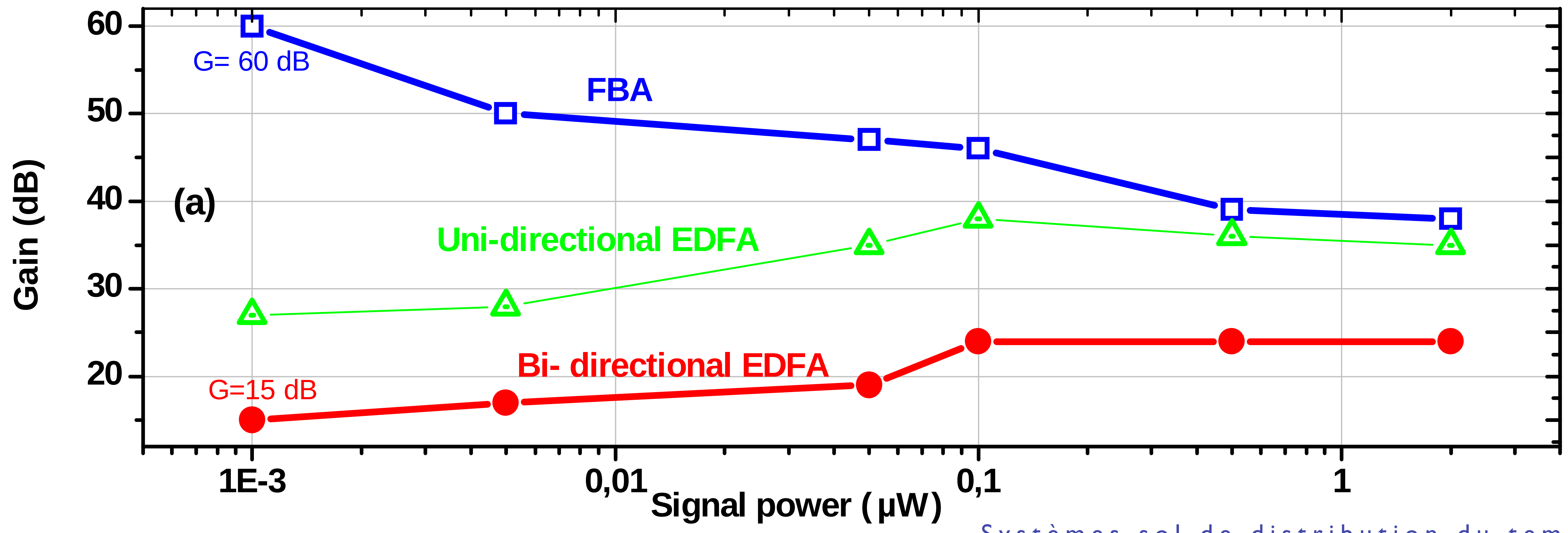
N. R. Newbury *et al.* (2007) doi: 10.1364/OL.32.003056. P. A. Williams *et al.* (2008) doi: 10.1364/JOSAB.25.001284.
Experimental curves: Jiang *et al*. (2008) doi: 10.1364/JOSAB.25.002029

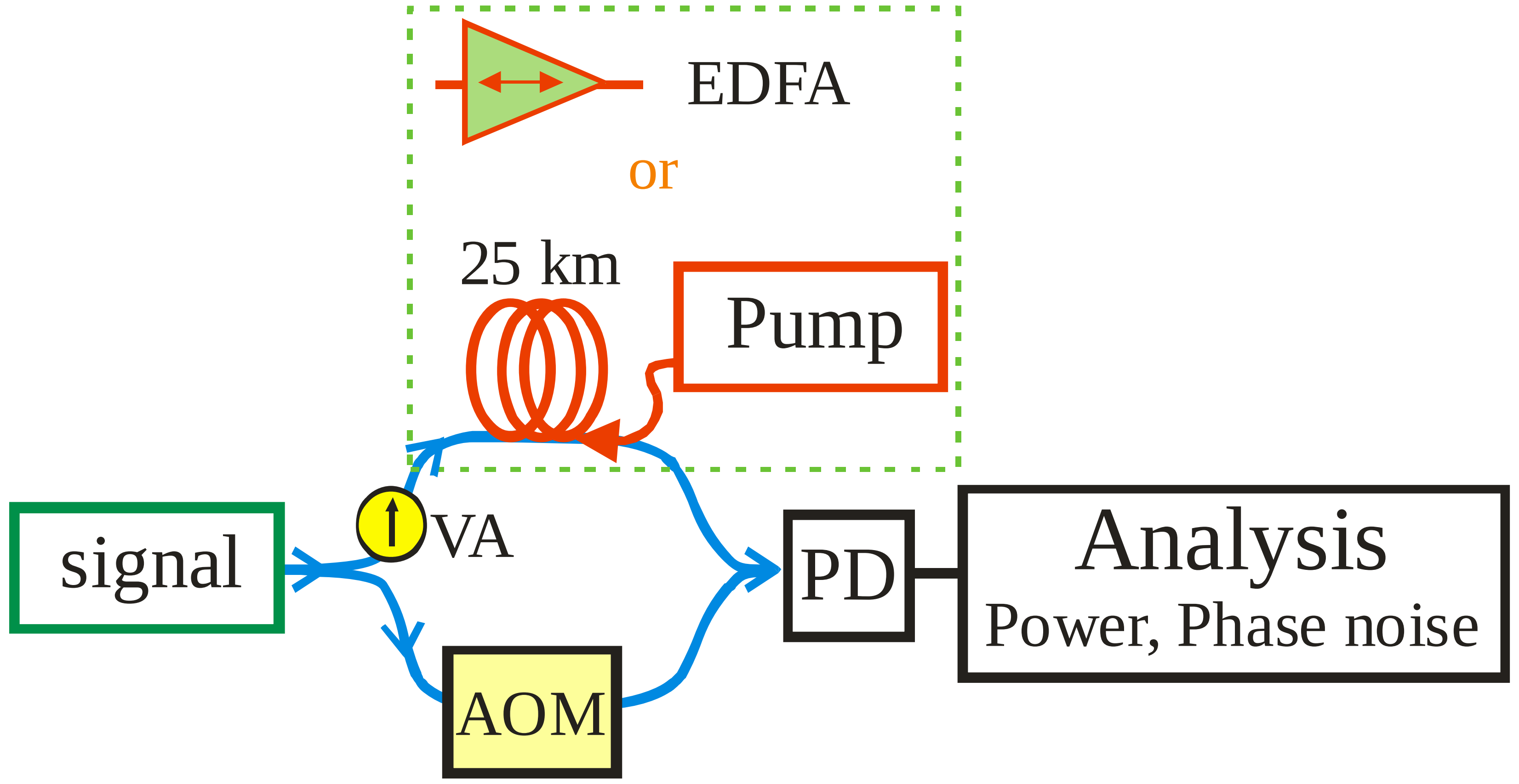
Bidirectional amplification

- Erbium-doped fiber amplifier (10<G<20 dB)
  - Large bandwidth (40 nm)
  - Gain should be limited to avoid self-oscillation !
- Fiber Brillouin amplifier (<60 dB)
  - Narrow bandwidth (10 MHz)
  - Very selective, enabling high gain
- Raman amplifier (20-25 dB)
  - Intermediate bandwidth (1THz)
  - High pump power, intermediate gain



https://www.softeloptic.com/news/working-principle-and-classification-of-optic-fiber-amplifieredfa/



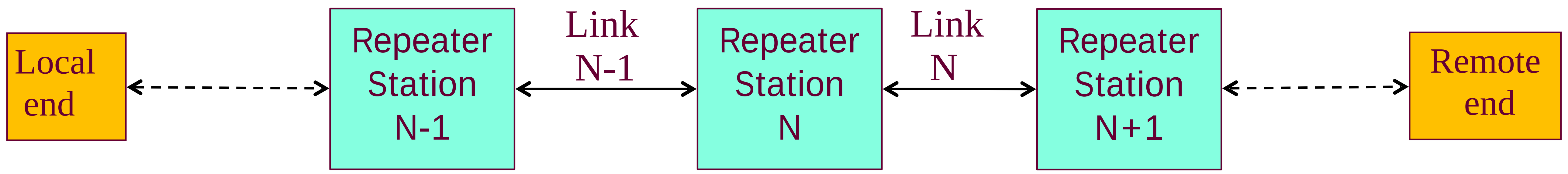


O.Terra *et al.* (2010) doi: 10.1364/OE.18.016102.

Cascaded links

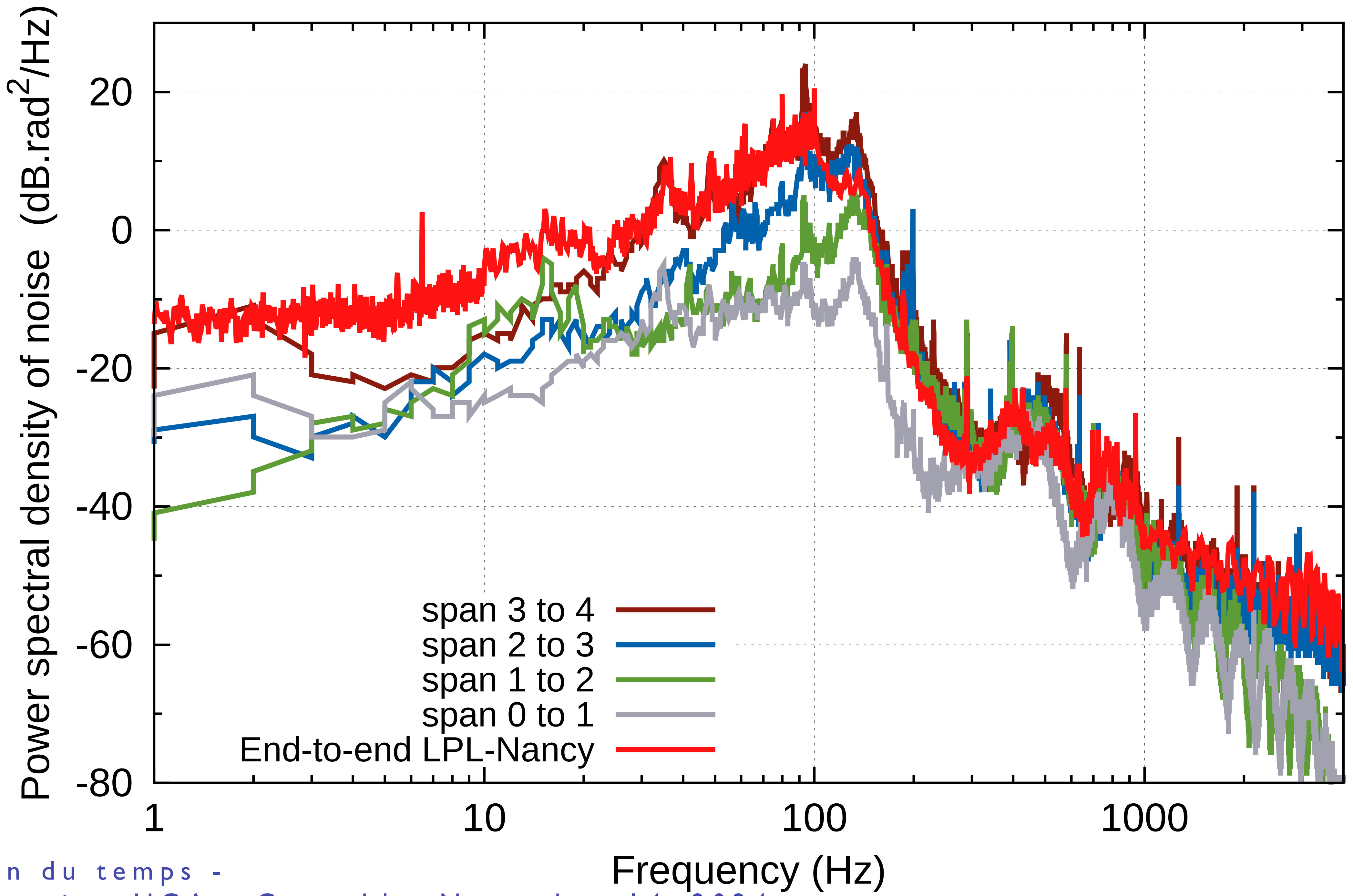
- Divide the link length into smaller spans
  - Reduces the accumulated phase noise
  - Reduced the propagation time
  - Increase the noise compression
- Demonstrations in hF and optical domain
- Demonstration in C and L band
- Compatible with EDFA, Raman, and FBAs
- Exists with interferometer on-chip

Multi-segment approach for long haul links



Repeater laser station (RLS) functionalities :

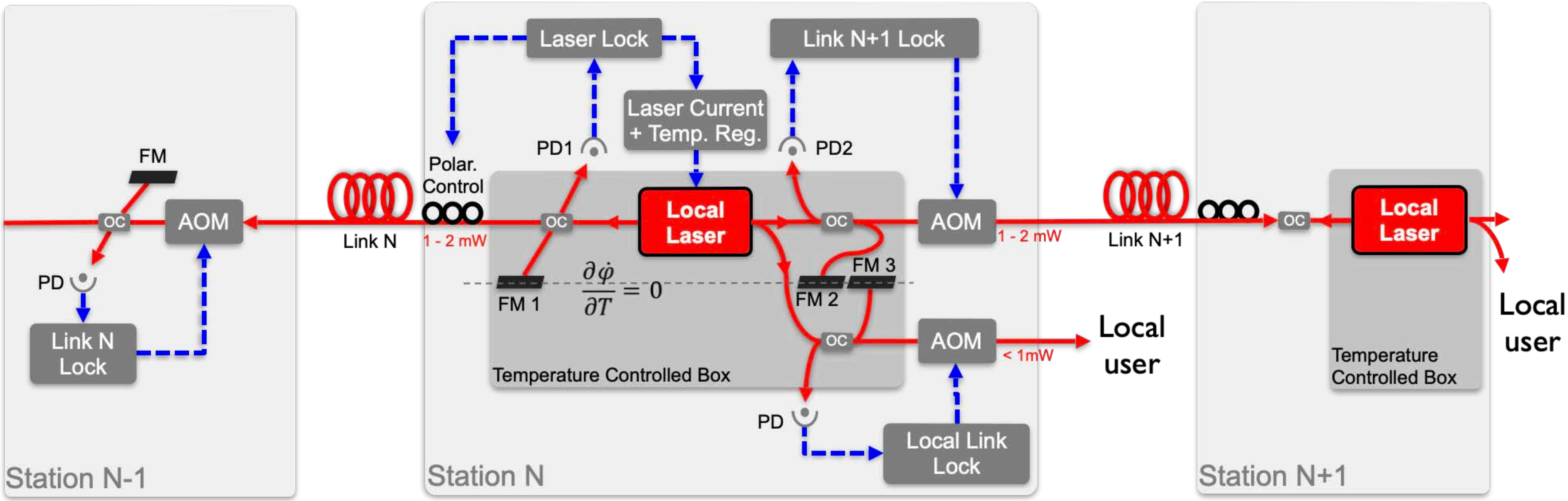
- sends back signal to station N-1,
- corrects the noise of next link N,
- provides a user output



S. M. Foreman, *et al.* (2007) doi: 10.1103/PhysRevLett.99.153601.
M. Fujieda, et al. (2010) doi: 10.1109/TUFFC.2010.1394.
O. Lopez et al. (2010) doi: 10.1364/OE.18.016849.
S. Koke et al. (2019) doi: 10.1088/1367-2630/ab5d95.
T. Akatsuka et al. (2020), doi: 10.1364/OE.383526.
X. Deng et al. (2020) doi: 10.1088/1674-1056/ab7b4f.
D. Husmann et al.(2021) doi: 10.1364/OE.427921
X. Deng *et al.* (2024) doi: 10.1088/1674-1056/ad0629.

Repeater laser station (RLS)

SYRTE Observatoire de Paris | PSL LPL Laboratoire de physique des lasers



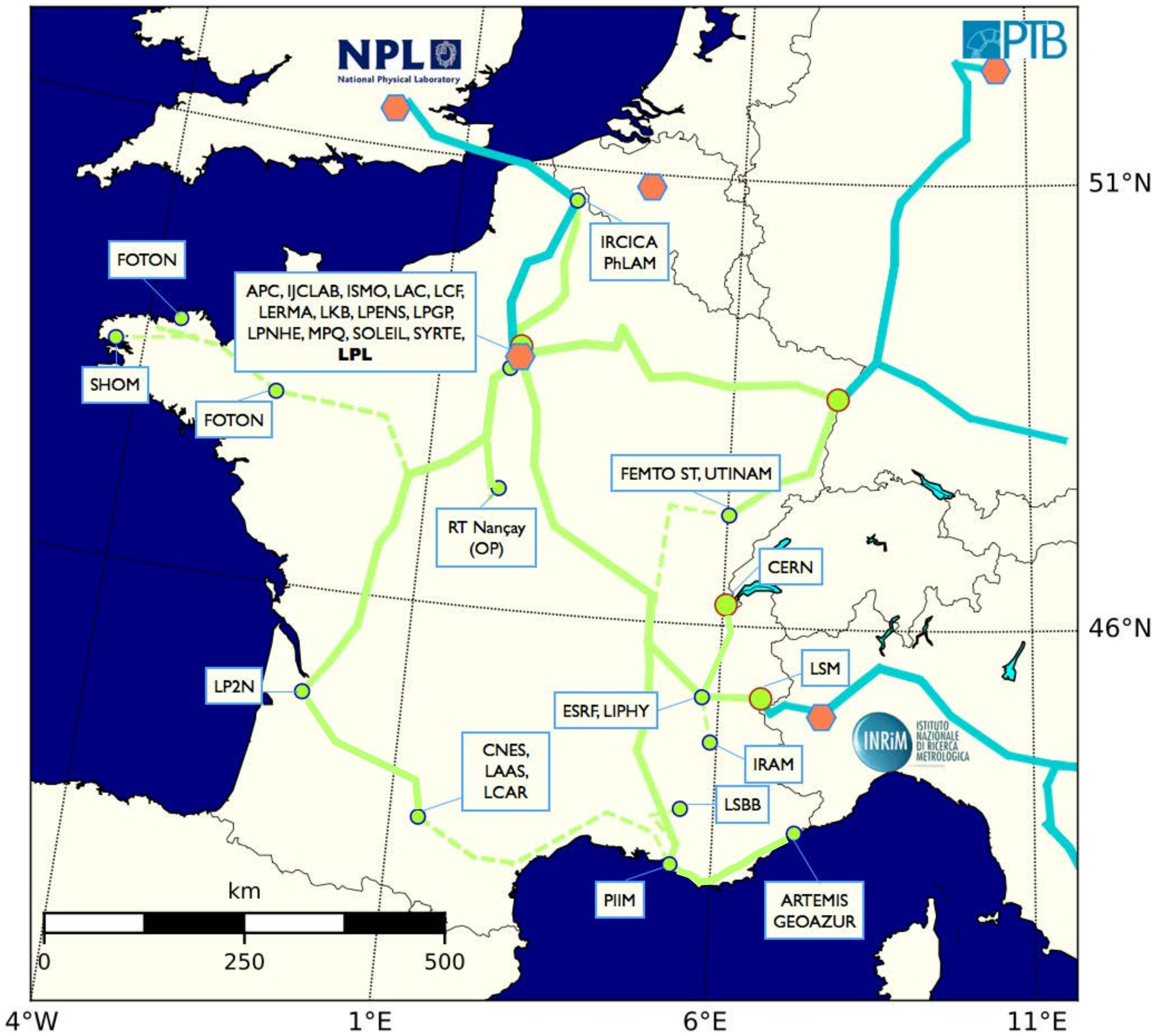
FM: Faraday Mirror; AOM : Acousto-Optic Modulator;
PD: PhotoDiode; OC: Optical Coupler; PC : Polarisation Controller

- Remote control & monitoring
- Automatic operation
- Polarisation control
- 2 Outputs
- Min input power ~-60 dBm

O. Lopez et al., Opt. Express, vol. 18, no. 16, pp. 16849–16857 (2010)
N. Chiodo et al., Opt. Express, vol. 23, no. 26, pp. 33927–33937 (2015)

Refimeve network map (2024)

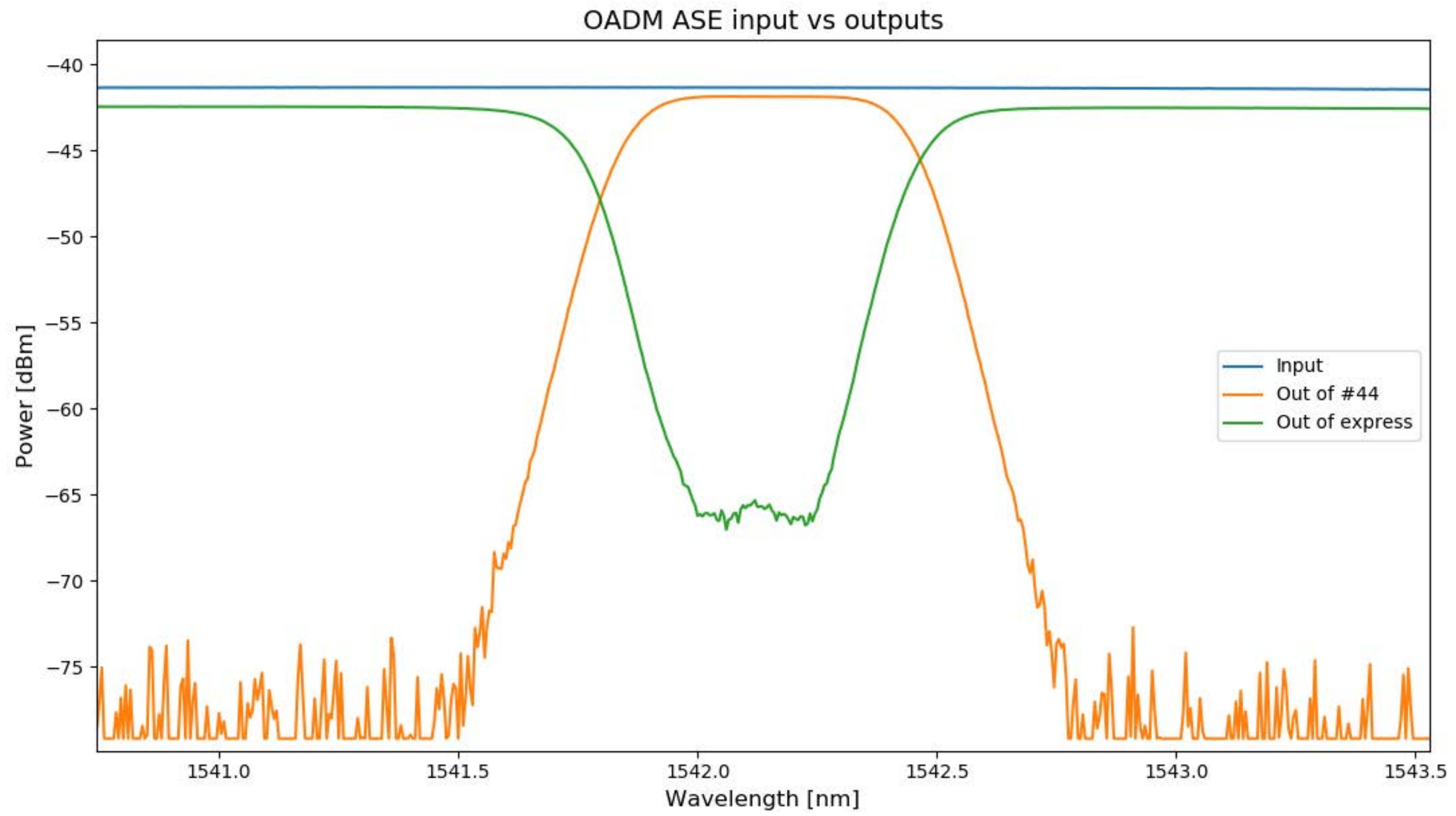
- 4 international connections (DE, UK, IT; CERN)
  - + Belgium-France cross-connection planned
- Clocks @INRIM, PTB, NPL, and SYRTE connected
- REFIMEVE connects 30 labs by 10/2024
- REFIMEVE connects 6 research infrastructures
  - LSM, CERN (done)
  - SOLEIL, ESRF, IRAM, LOFAR (planned)
  - *Link* with EPOS-FR, …
- FIRST-TF (Research federation) acts for the scientific animation of the French users connected by the fiber network
- EURAMET: 5 EU projects to develop technology, + run optical clock comparisons,…



FIRST TF EURAMET

From fiber links to a metrological network infrastructure

- **Availability of the fiber**
  - Dedicated frequency channel: parallel transmission of ultra-stable signal and data traffic in the same fiber on different frequency channels using dense wavelength division multiplexing (DWDM)
  - Low-noise bi-directional optical amplifiers are setup on the RENATER network backbone in their shelters
- **Technology maturation and knowledge transfers**
  - System vision, production, installation & operation
- **Network supervision**
- **Data** availability & usability (FAIR), documentation, archives, live monitoring, community management…



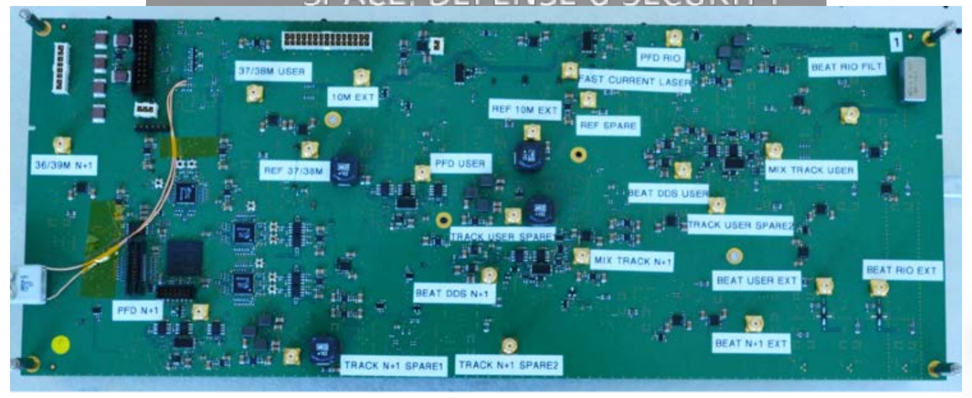
KEOPSYS THE LIGHT TOUCH

LUMIBIRD MORE THAN LASERS

μQUANS

exail

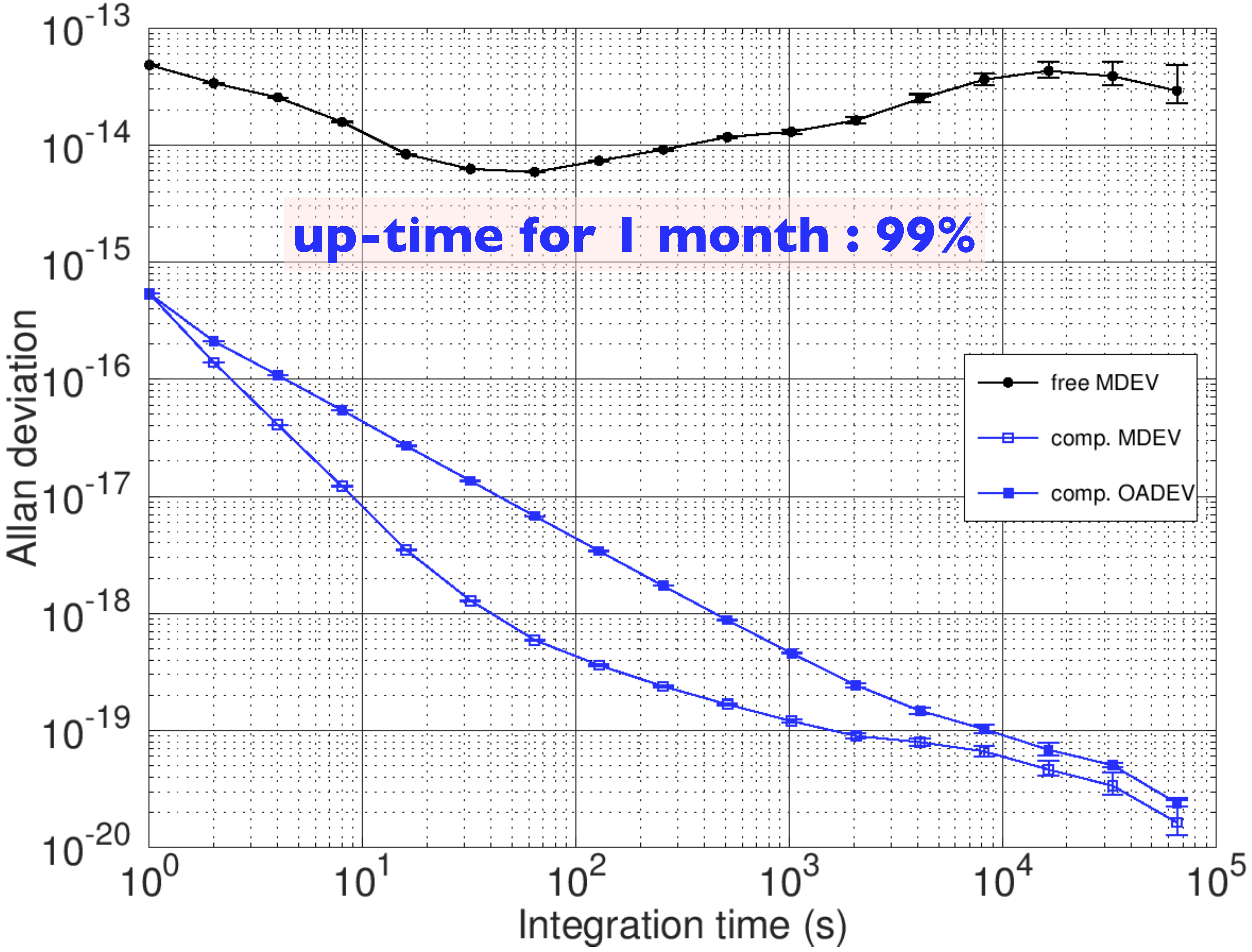
Syrlinks SPACE, DEFENSE & SECURITY



https://www.muquans.com/products/time-and-frequency-transfer/
https://www.keopsys.com/portfolio/bi-directional-fiber-amplifier/

Industrial grade fiber links

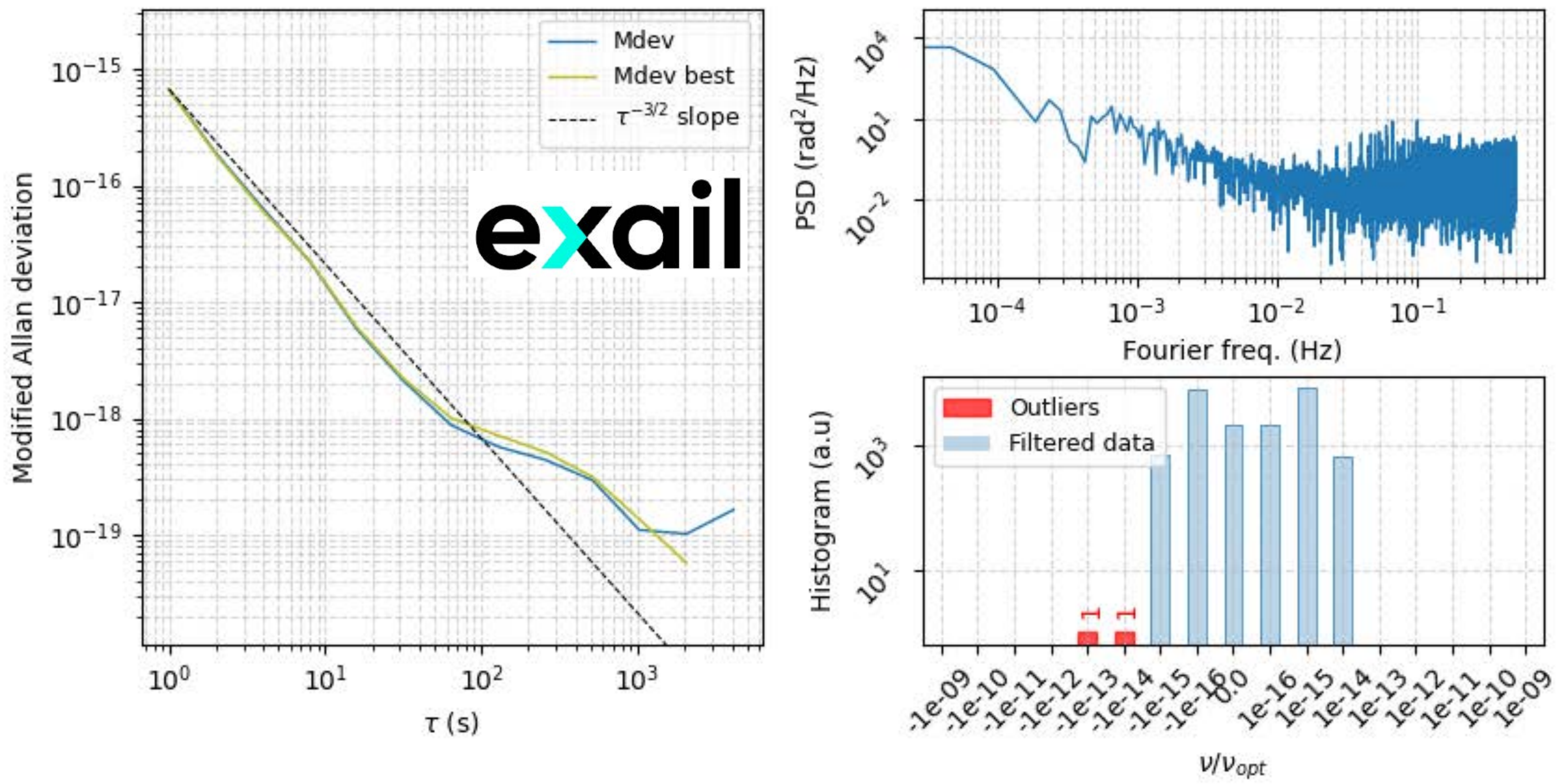
Tech. readiness level: from 5 in 2012 to 8-9 by 2018



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

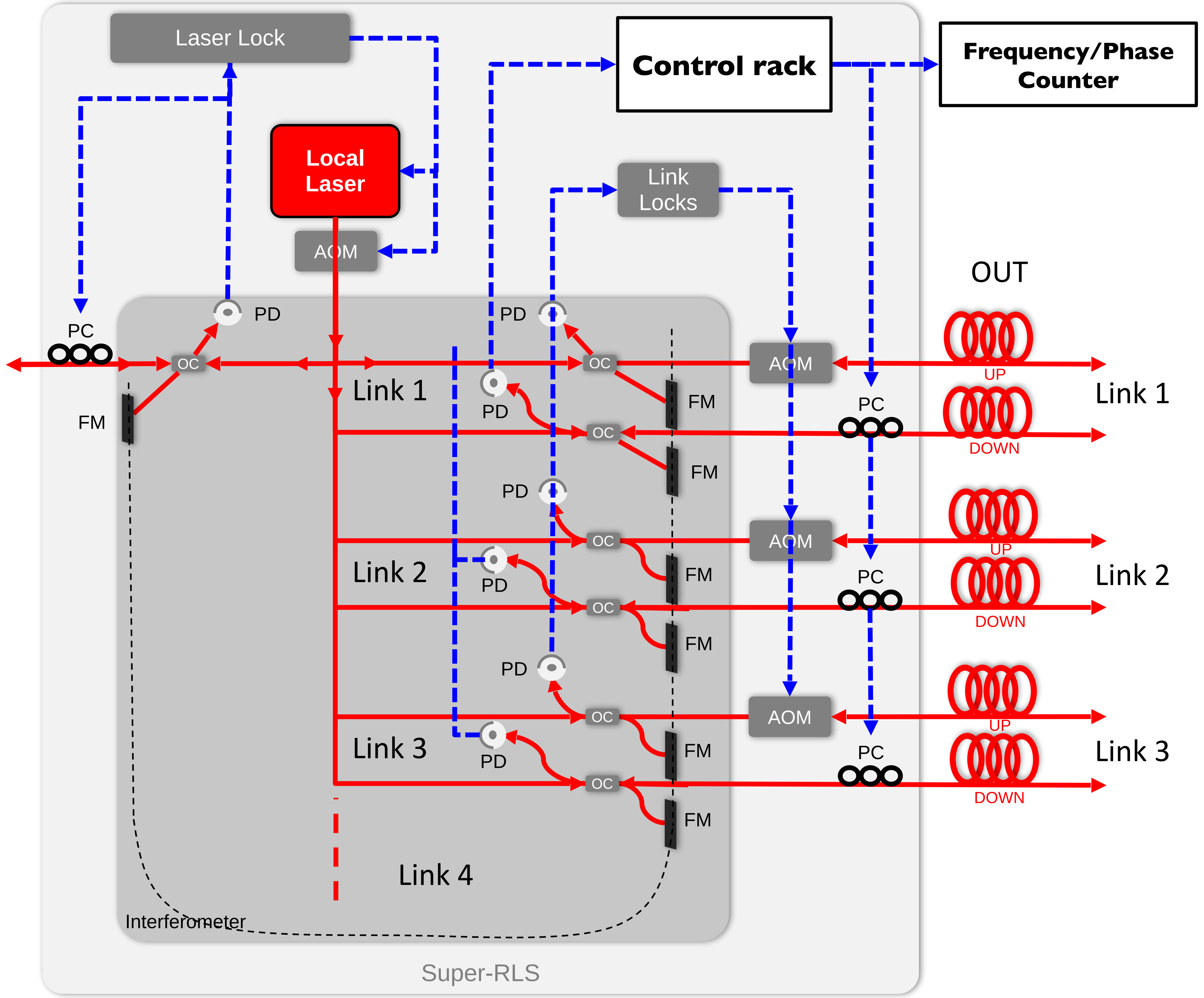
First industrial link: Paris - Lille - Paris (2x 330 km)

- Link performance monitoring example:



Exail (ex-iXblue, ex-MuQuans)'s supervision

Multi-branches laser station



- Free-space and fibered optics
- Low-temperature sensitivity by design
- Product design with Kylia > iXBlue > Exail
- Fast track for industrialization !

- Same electronic as in a repeater laser station: remote control, automatisation
- Balanced multi-arm interferometer

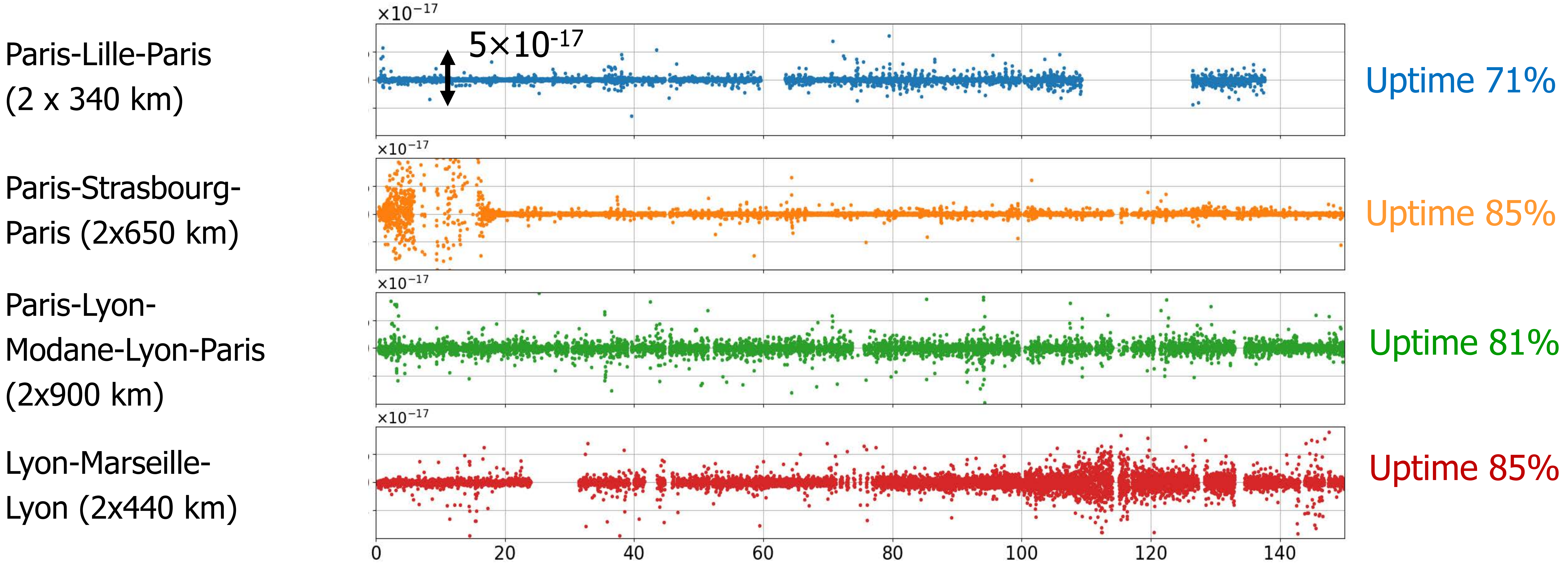
<u>temperature sensitivity:</u>
1st lab prototypes: 7fs / K
RLS industrial grade: < 1 fs / K
MLS industrial grade: < .04 fs / K

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

Towards a highly available signal

Relative frequency fluctuations vs time (days)

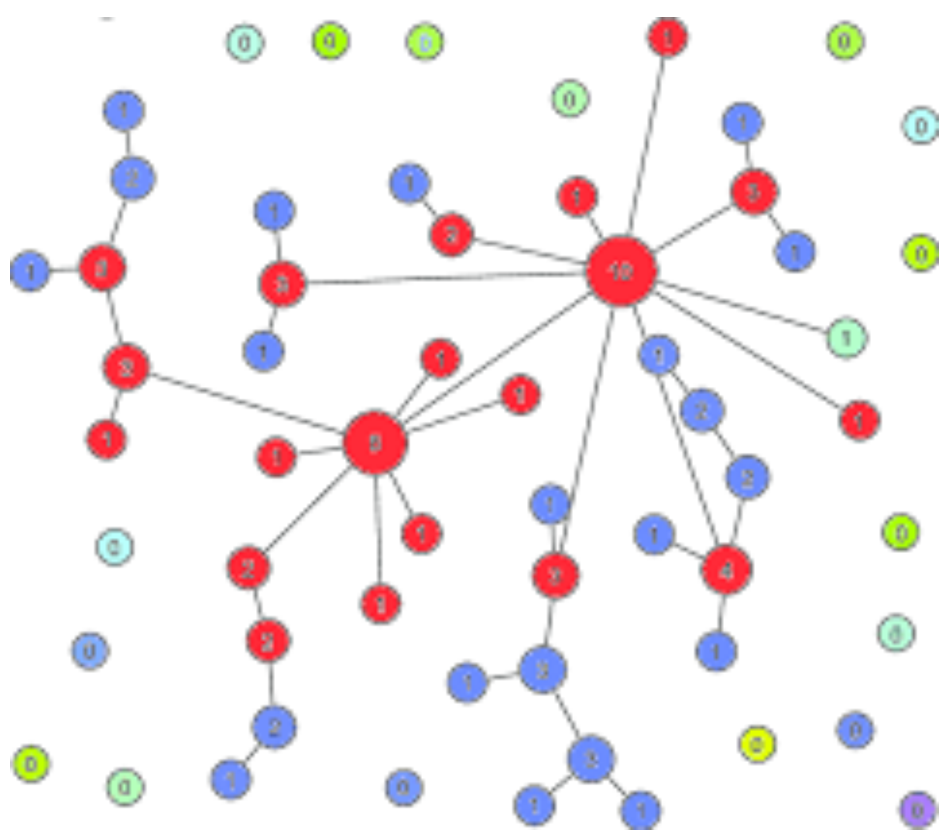
1000 s / point

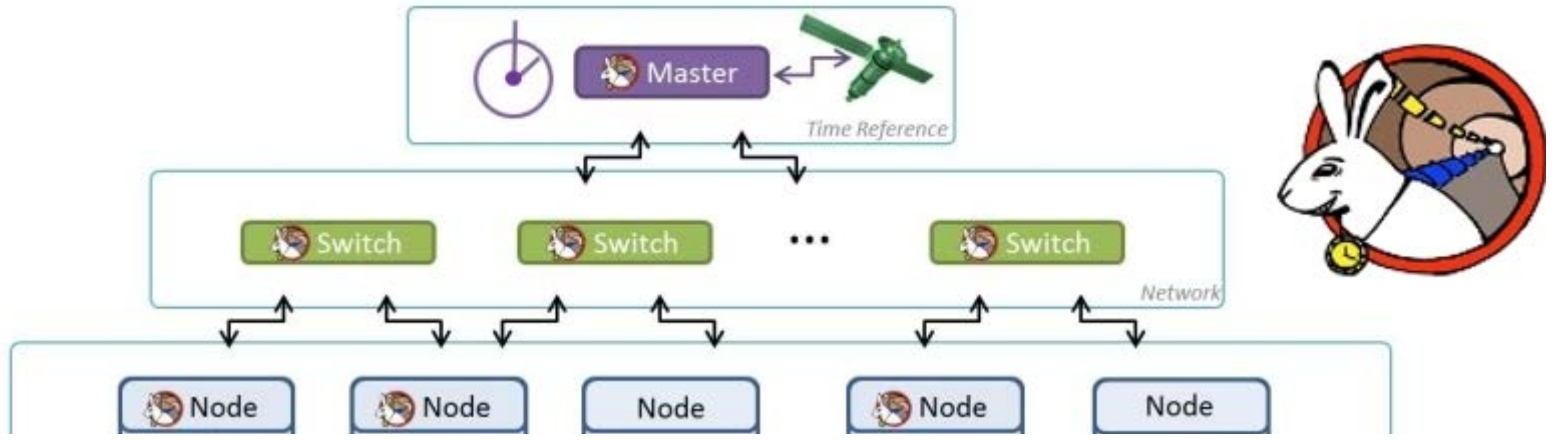


4 links: {340,650,900,440} km x2 = 2x2330 km
>70% / 1/2 year (2022)
>90% uptime for several months
<u>next objective: 90 % / year</u>

T-REFIMEVE (2021-2029)

- Extension to Brest, IRAM, CERN;
  - +14 new users;
  - + 8 new applicants to join the network.
- RF (1GHz) and time signal on the optical carrier (bi-directional, highest performance)
- WR: 10 MHz and time signal, mono-directional
  - Channel # 21 allocated by RENATER
  - Challenge : mitigation of link asymmetry on active telecom
- Mobile platform:
  - A test facility for the REFIMEVE users and exploration of chronometric geodesy
  - Extraction of the REFIMEVE signal in huts
  - Transportable shelter with ultra-stable cavity, comb, and room to host a transportable clock or a transportable quantum sensor



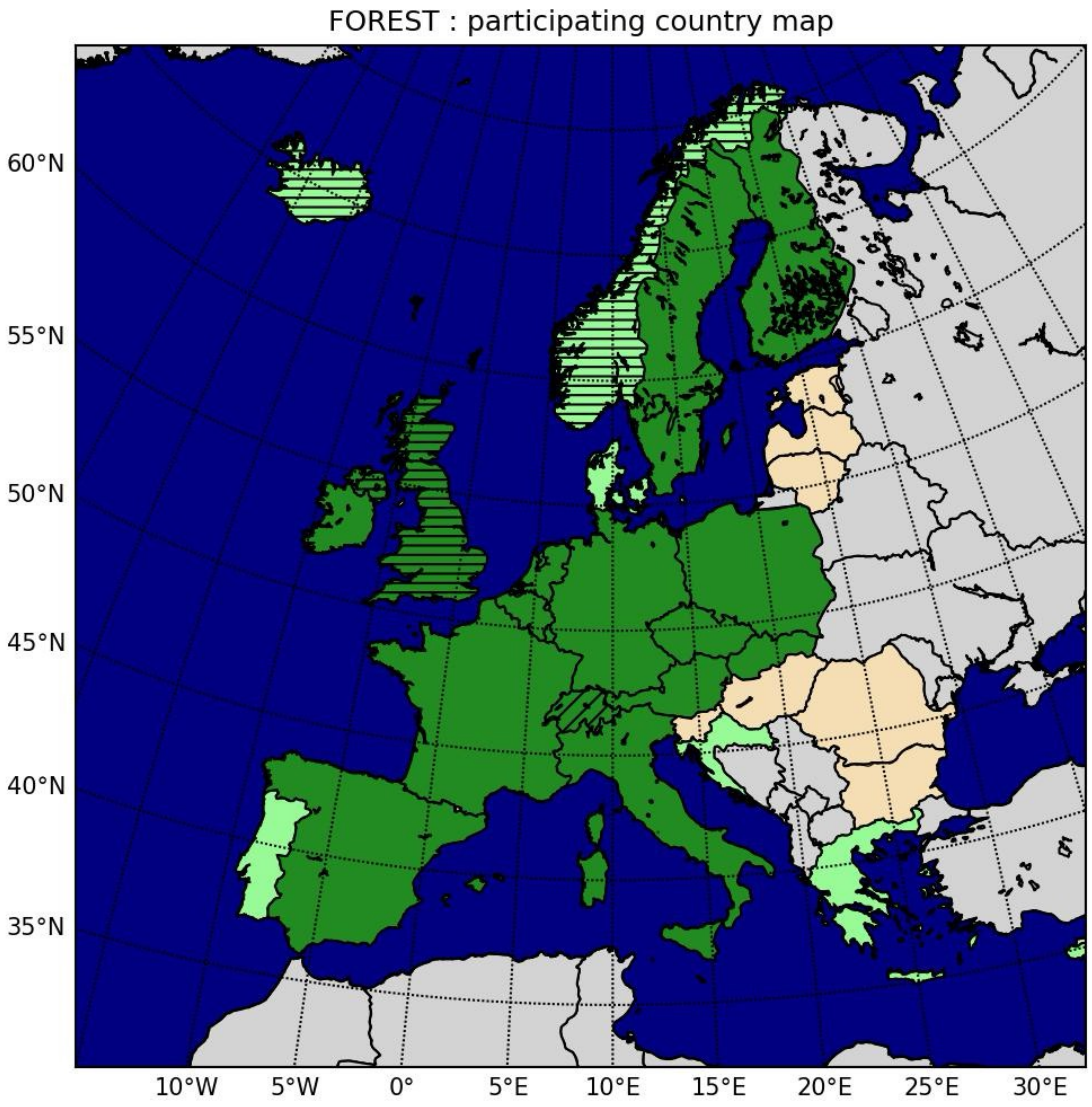


Not addressed in this lecture and that's a pity

- Many activities for radio- and hyper frequency dissemination, time transfer
- Only one technique is standardized at IEEE so far : White-Rabbit (RF and time transfer, digital)
- Only one technique reported time scale comparisons to BIPM: ELSTAB, on the link AOS-GUM (Poland)
- Optical combs can also be transferred. On fiber, the record distance (in one stretch) is about 160 km
- More and more work is done on free-space optical transfer
  - Using combs: goal is to reach satellite in low-Earth orbit

C. Liu *et al.*, « Ultrastable Long-Haul Fiber-Optic Radio Frequency Transfer Based on Dual-PLL », (2021) doi: 10.1109/JPHOT.2020.3043263.
D. R. Gozzard, *et al.*, « Simple Stabilized Radio-Frequency Transfer With Optical Phase Actuation » (2018) doi: 10.1109/LPT.2017.2785363.
W. McKenzie et al., « Clock synchronization characterization of the Washington DC metropolitan quantum network (DC-QNet) » (2024), doi: 10.1063/5.0225082.
P. Krehlik, *et al.*, « ELSTAB—Fiber-Optic Time and Frequency Distribution Technology: A General Characterization and Fundamental Limits », (2016) doi: 10.1109/TUFFC.2015.2502547.
E. D. Caldwell *et al.*, « Quantum-limited optical time transfer for future geosynchronous links », (2023), doi: 10.1038/s41586-023-06032-5.
Q. Shen *et al.*, « Free-space dissemination of time and frequency with 10−19 instability over 113 km », (2022) doi: 10.1038/s41586-022-05228-5.
B. P. Dix-Matthews *et al.*, « Towards optical frequency geopotential difference measurements via a flying drone », (2023) doi: 10.1364/OE.483767.

Last words: towards a fiber network in Europe



Fundings

LIOM, REMIF, REFIMEVE+, T-REFIMEVE, FIRST-FT

LOFIC

JRP: NEAT FT, OFTEN, WRiTE, TIFOON
ITOC, ROCIT (clock comparisons)
H2020: ICOF

INSU
GRAM

ROME, LICORNE, TORTUE, (…)

EU Research infrastructure

CLONETS
CLONETS-DS

TOCUP, ONSEPA, (…)

Thank you for your attention !