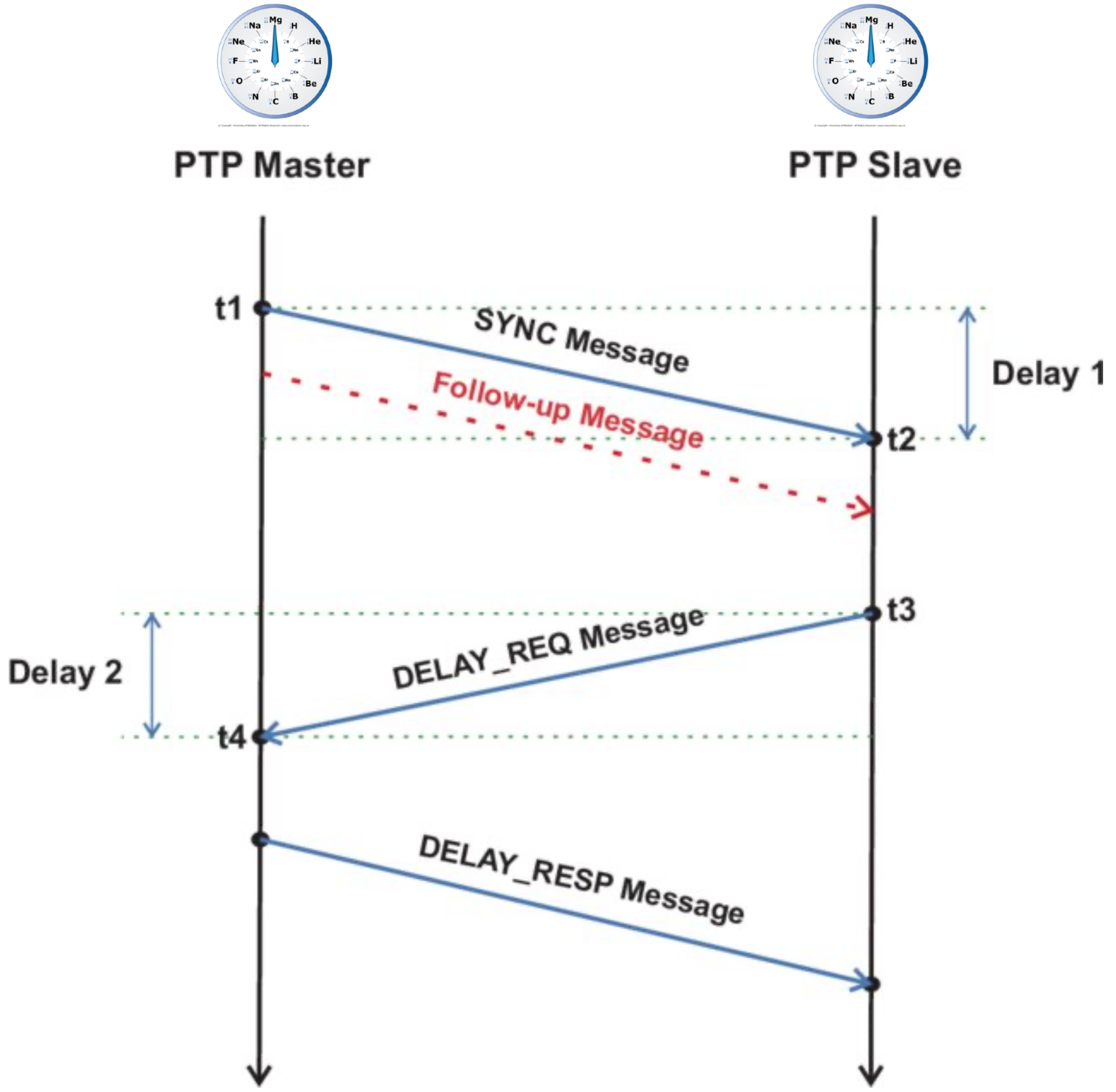
Time and frequency transfer using White Rabbit

P.-E. Pottie

Outline

- Introduction to White Rabbit Technology
- Building a wide area WR Network: an Exemple with REFIMEVE
- Comparisons with GNSS: Experimental Results
  - 3-km baseline
  - 300-km baseline
- Perspectives and Outlook

Precise Time Protocol: PTP



Based on exchange of timestamps through data telecommunications.

Emission (TX) and Reception (RX) timestamps are recorded at each site.

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 $\tau_{MS} \neq \tau_{SM}$:

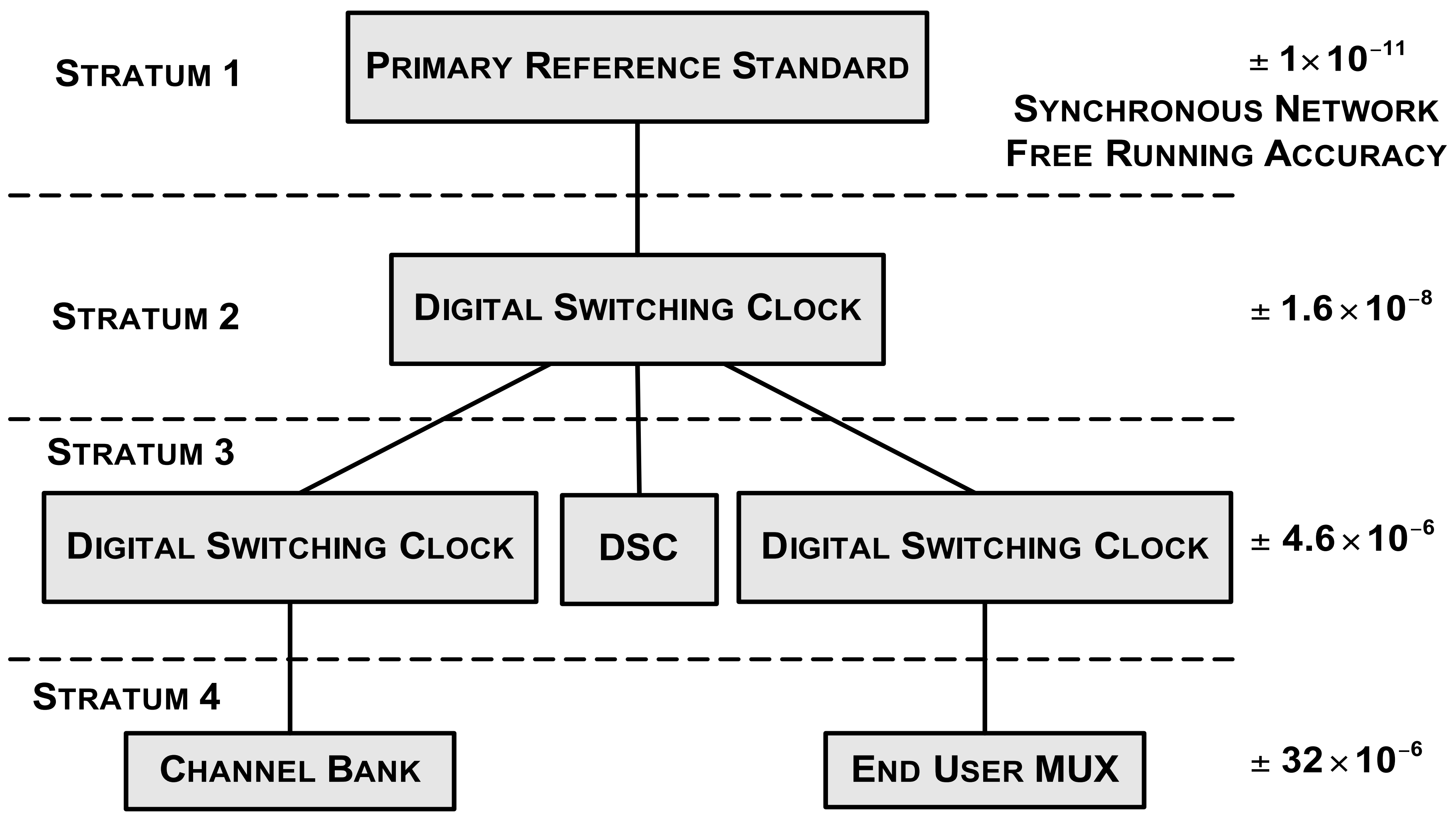
$$\text{time error} = \frac{\tau_{MS} - \tau_{SM}}{2}$$

These data are used to discipline a local oscillator

Outputs: a 1 pulse-per-second (PPS) signal, plus a 10 MHz RF signal in some cases.

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



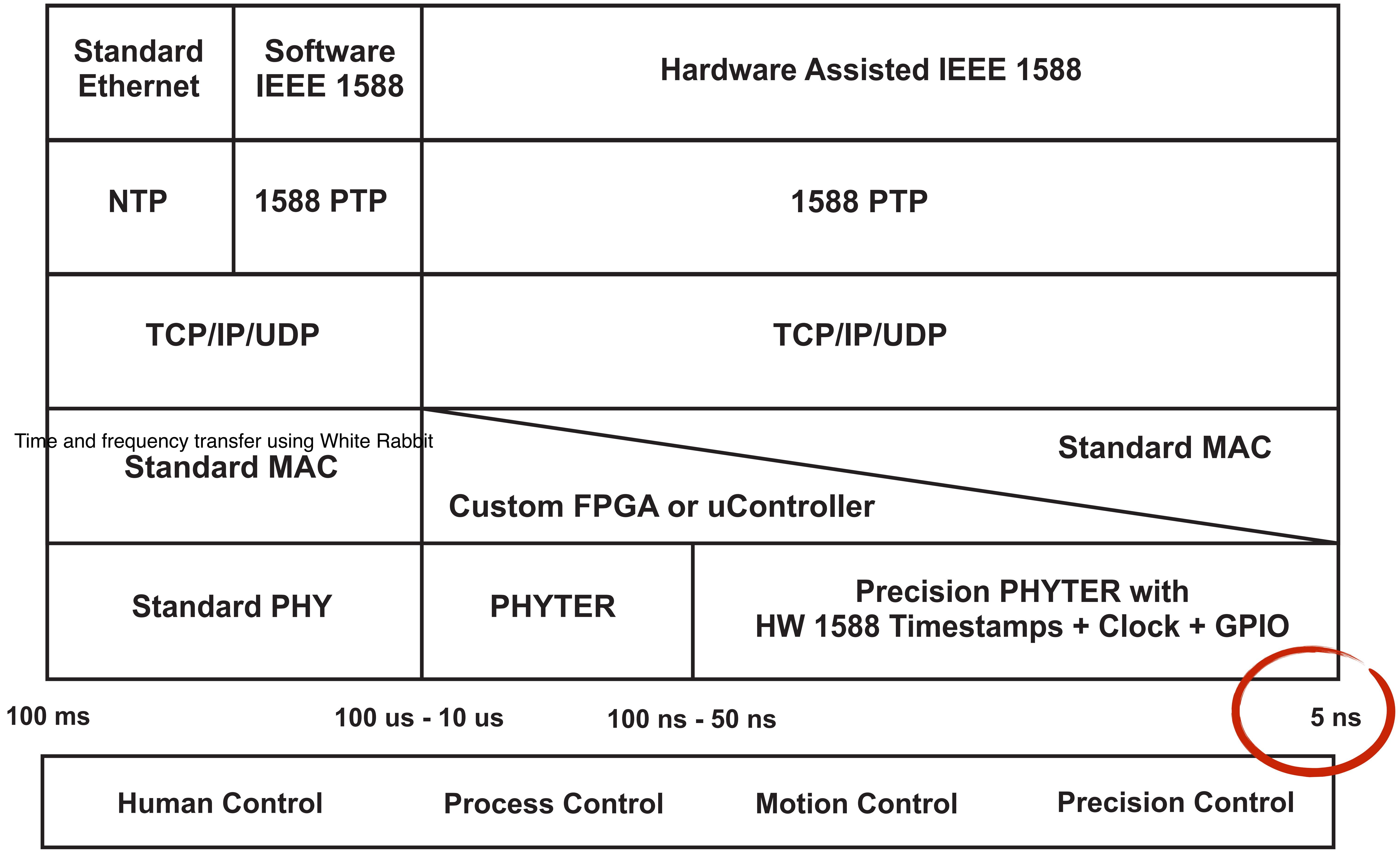


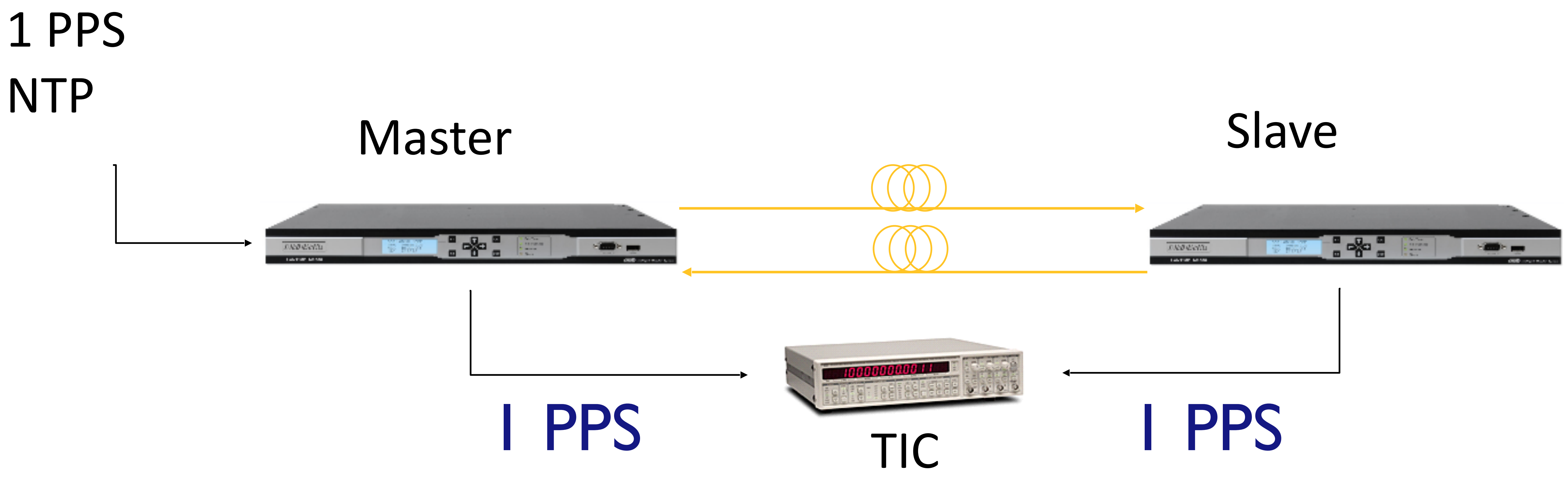
Figure 5. Implementation choices to achieve better time synchronization [32].

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

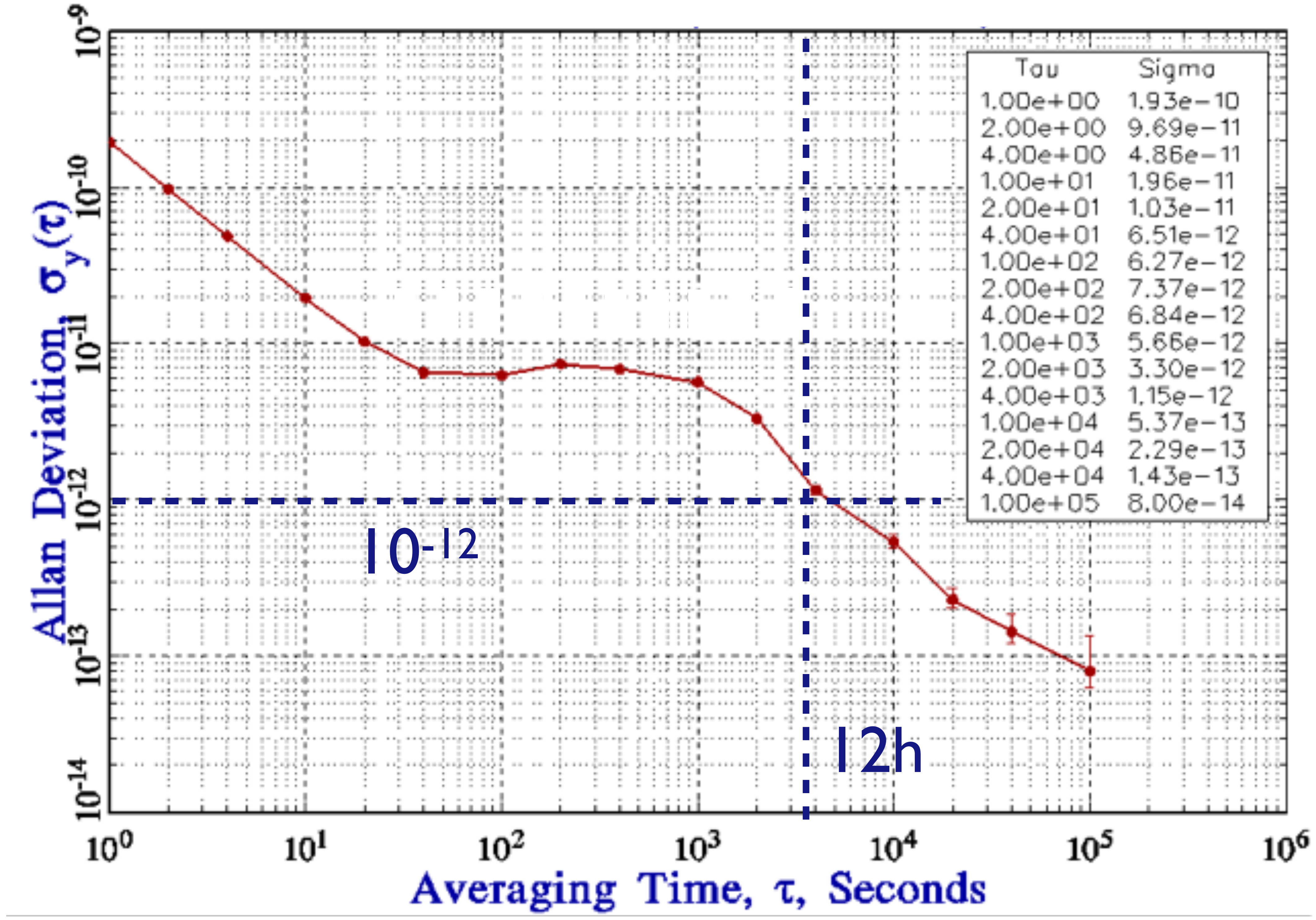
Precise Time Protocol: experimental results

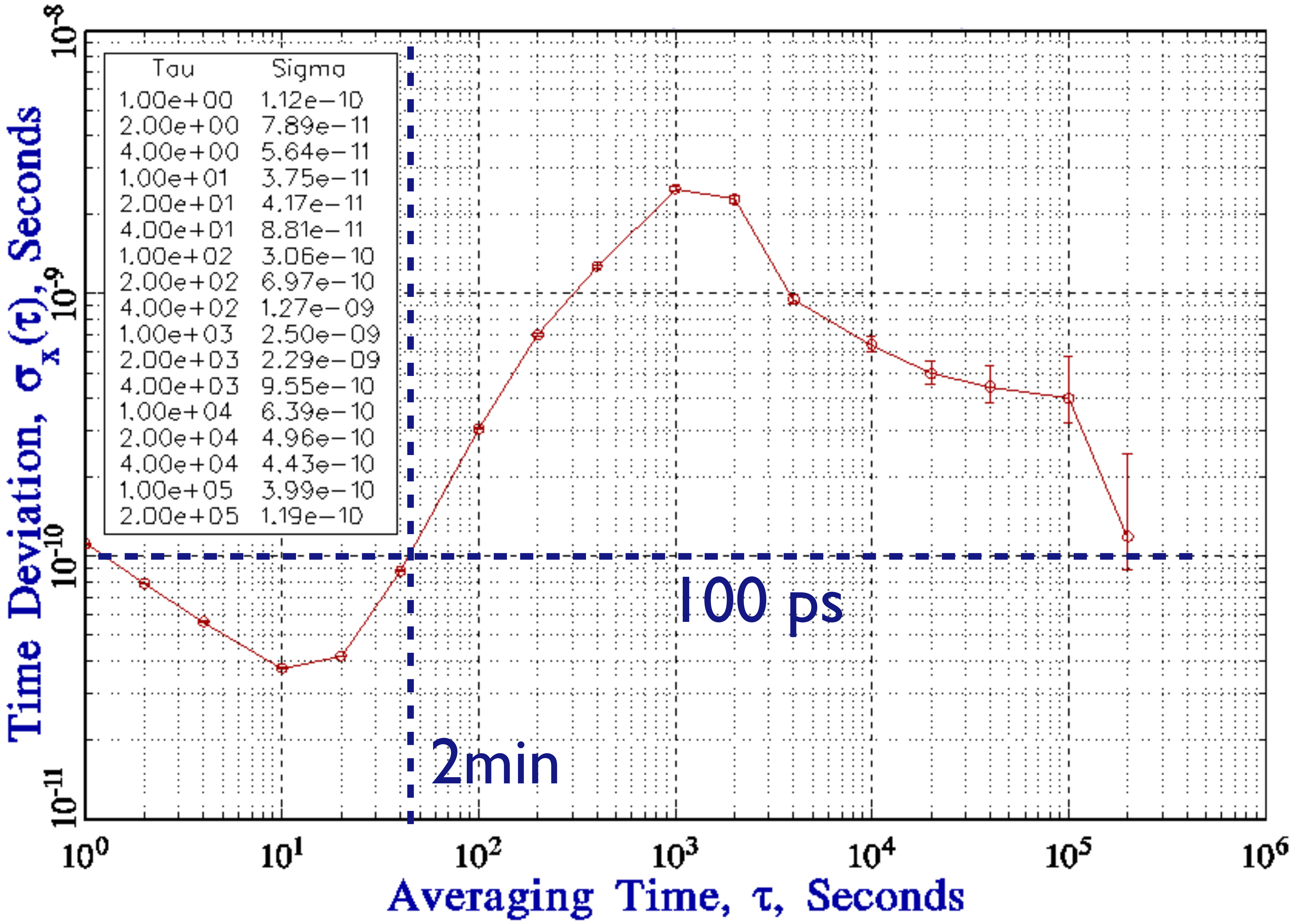
National Physical Laboratory

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.



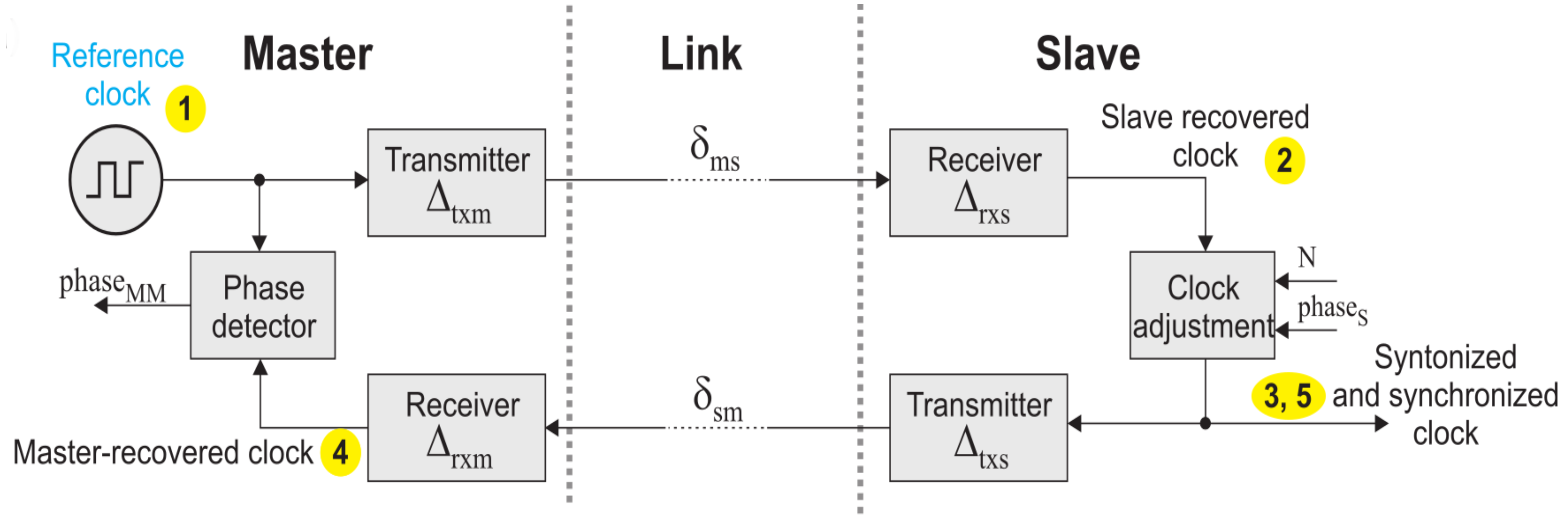


Courtesy E. Laier-English (NPL)

WR-PTP

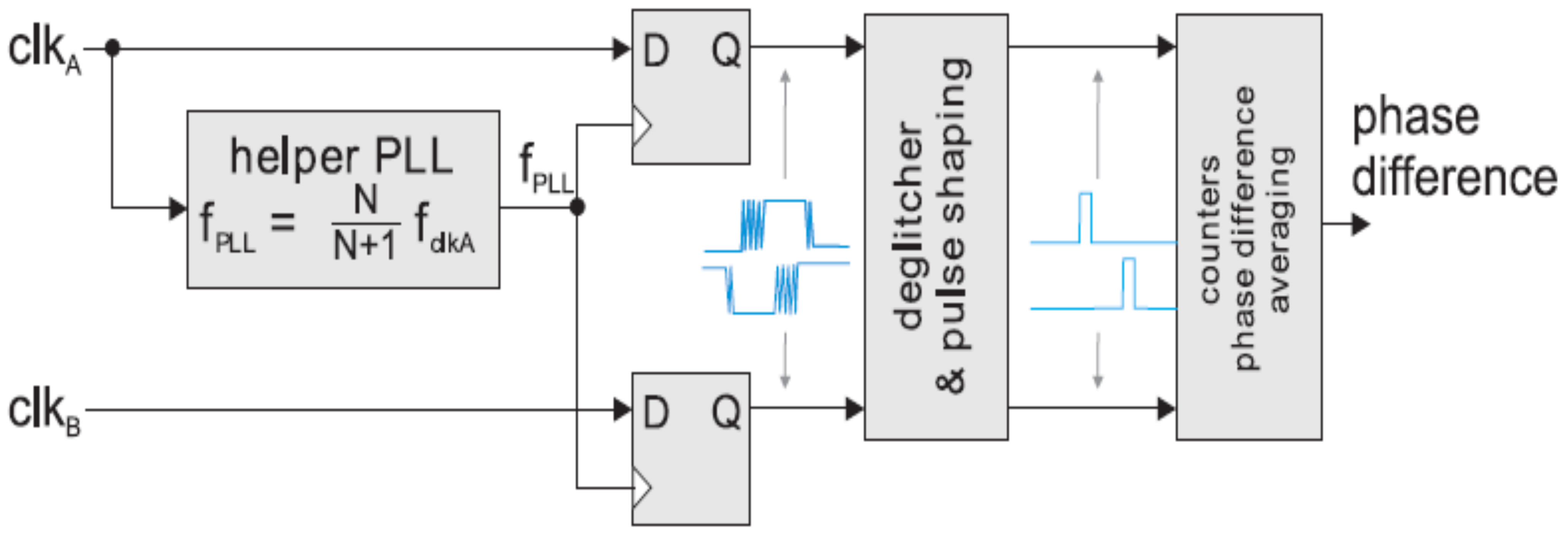
Synchronous Ethernet (SyncE)

- 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



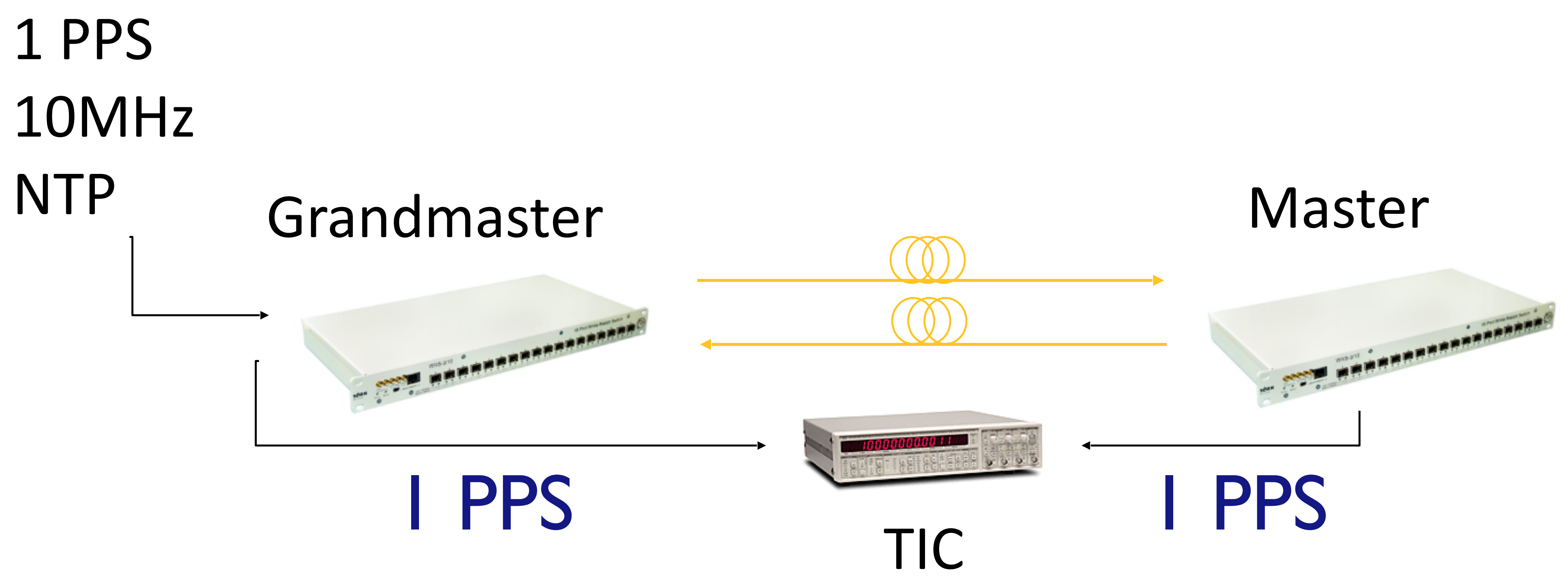
Asymmetry compensation

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

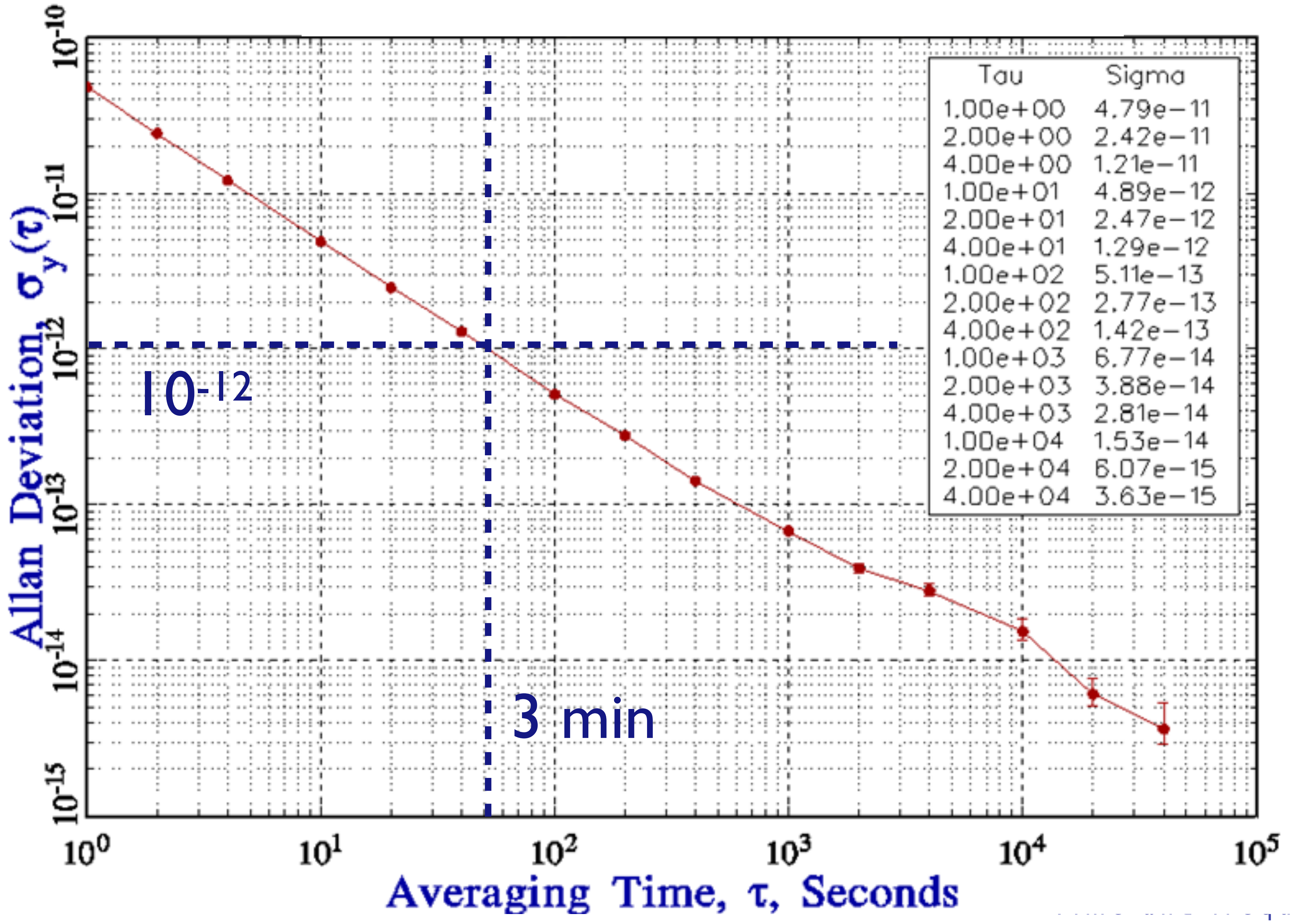
$$\text{time error} = \frac{\tau_{MS} - \beta \cdot \tau_{SM}}{2}$$

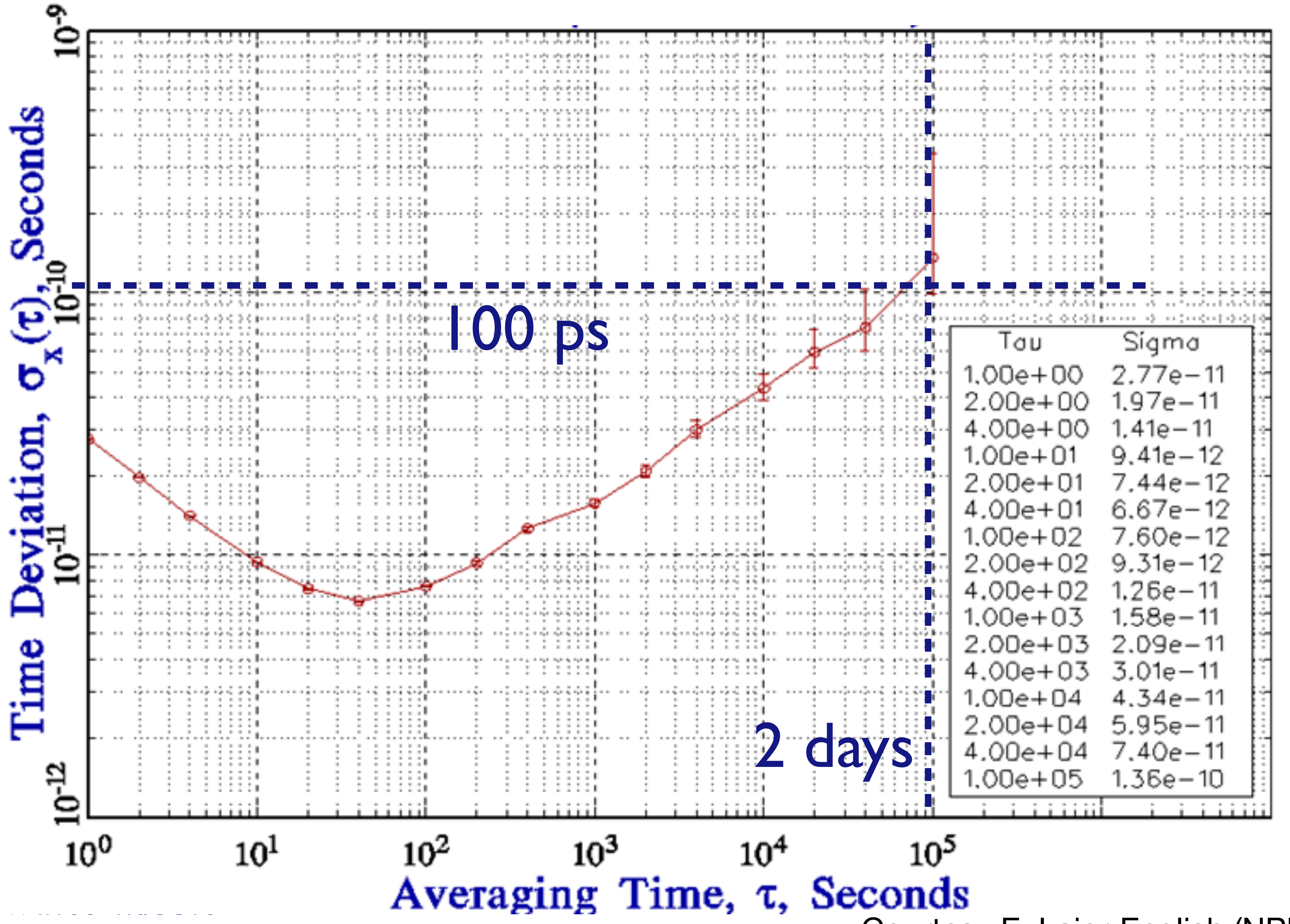
G. Daniluk,(CERN). Nuclear Instruments and Methods in Physics Research **725**, 187–190 (2013).

WR- PTP: experimental results



- 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.

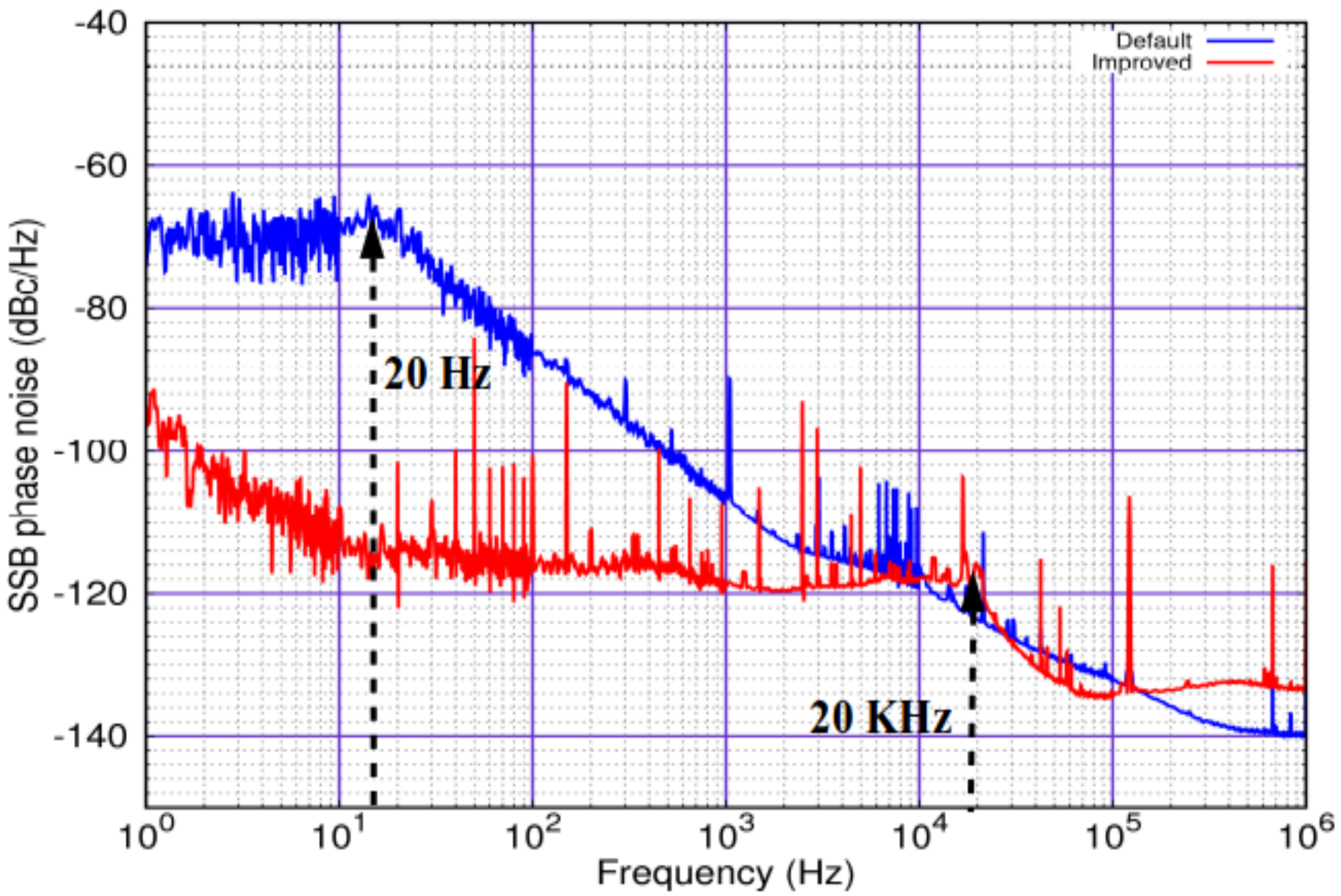




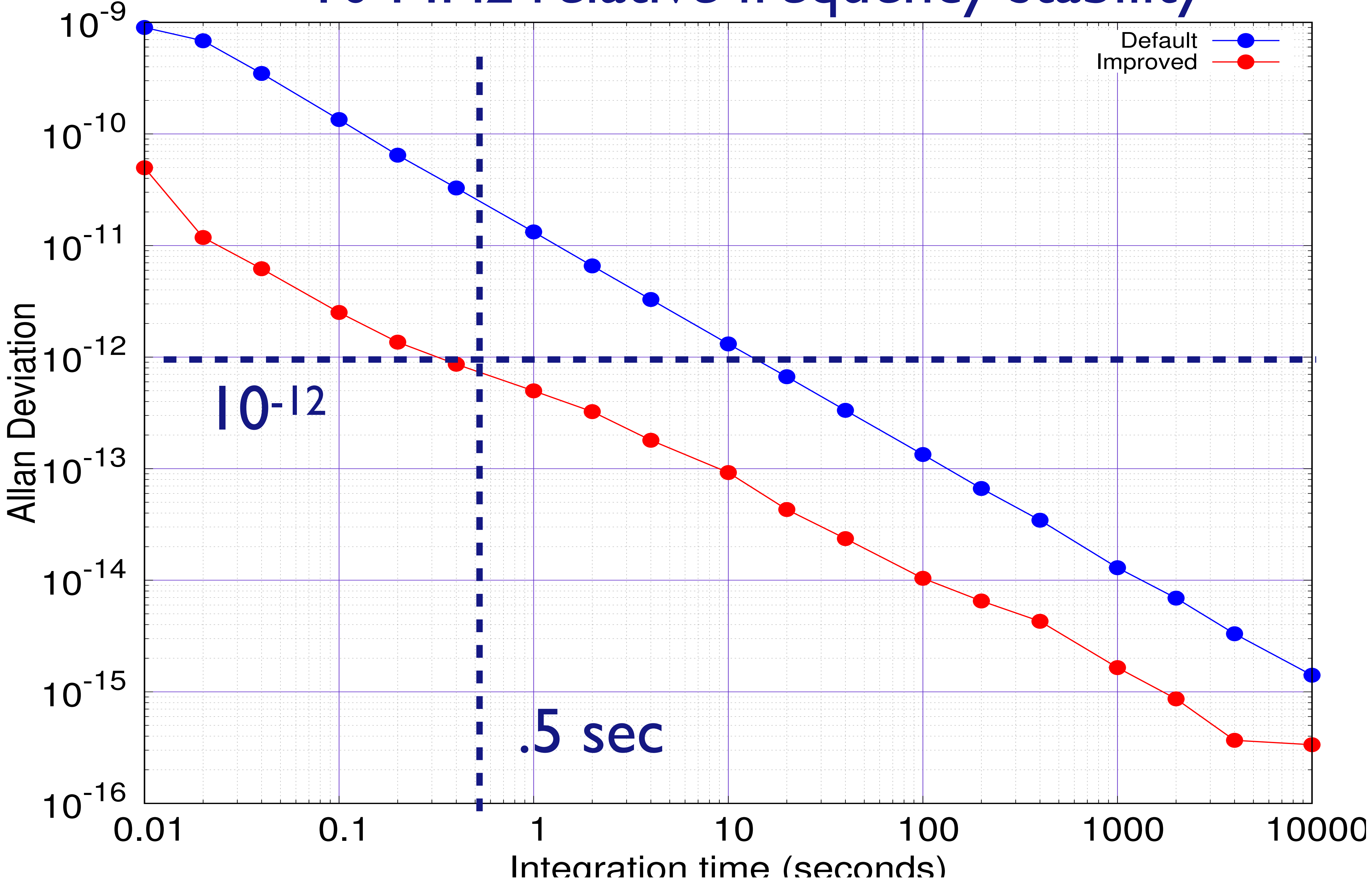
Courtesy E. Laier-English (NPL)

Ways to improved WR: noise floor performance (no link)

10 MHz signal phase noise



10 MHz relative frequency stability



- **<u>Trick</u>** : 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 !

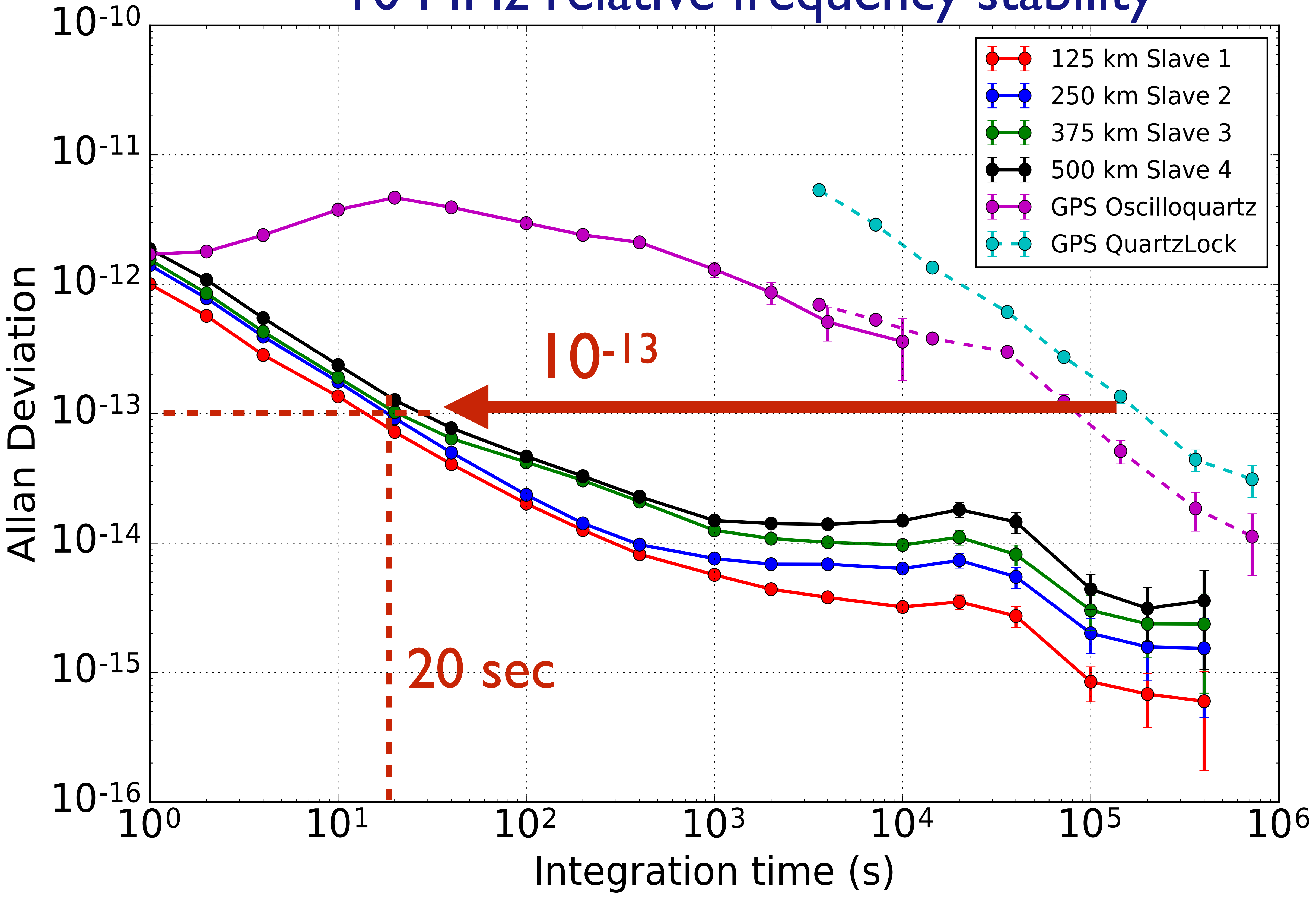
Namneet Kaur Thesis: https://hal.archives-ouvertes.fr/tel-01909292
Application in particle physics:: K. Popov: https://doi.org/10.48550/arXiv.2512.21212
See https://white-rabbit.web.cern.ch/

White Rabbit on uni-directional architecture

- Complement the optical carrier service with RF and time services:
  - for measurements at nodes
  - For measurements at user's end
- Allows cross-comparisons and self-assessment (optical frequency transfer in REFIMEVE)
- For industrial applications :
  - 1E-13 accuracy in 20 s instead of 1-2 days
- Potential back-up technology for critical infrastructure

White Rabbit on 500-km uni-dir on spools

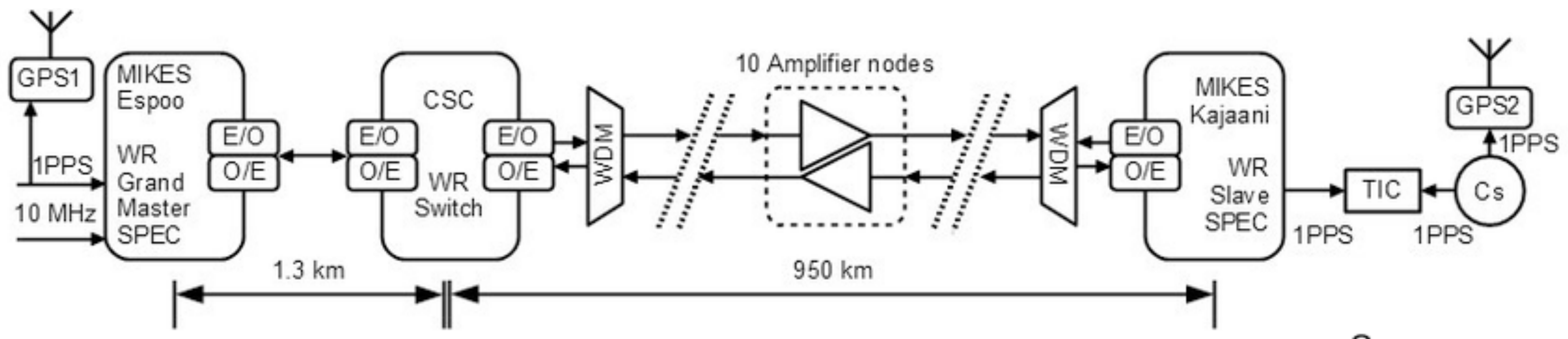
10 MHz relative frequency stability



N. Kaur doi: 10.1109/TUFFC.2021.3134163. (2022)

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

WR-PTP on long haul xWDM networks

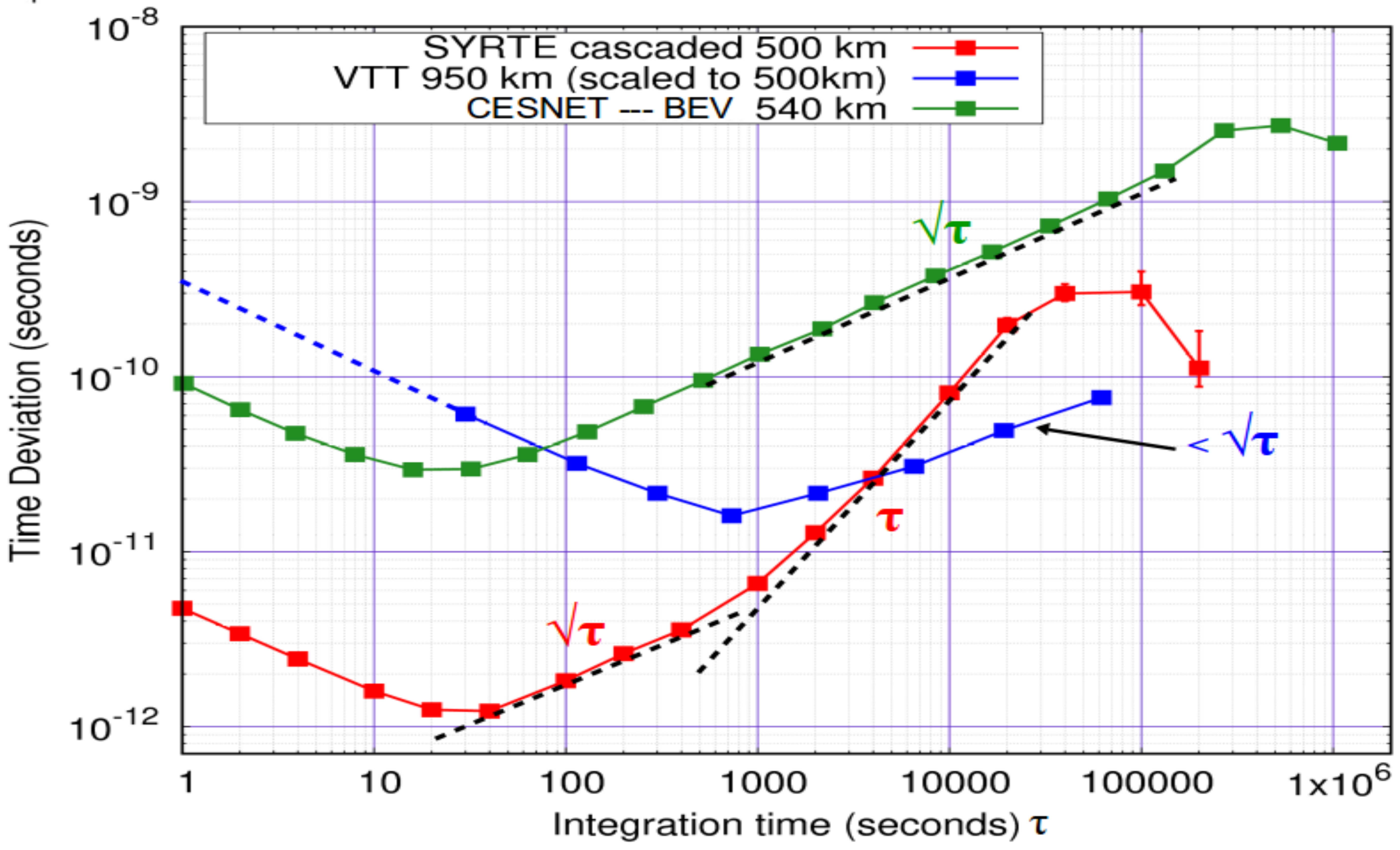


E.F. Dierikx, et al. IEEE T-UFFC 63, 945–952 (2016).

- Up to ~1000 km (Finland, USA)
- 2 architectures possible
  - 1 wavelength, 2 fibers
  - 2 wavelengths, 1 fiber
- Both options are deployed in EU

https://ohwr.org/project/white-rabbit/-/wikis/uploads/1de8ac2cde4c71bfea22bb4f4a30fda3/2021-10-07_WR_WS_presentation_R.Sundblad.pdf
https://nog.fi/event/4/contributions/27/attachments/20/28/Wallin_nog-fi_2019-05-17.pdf
In USA :
https://ieeexplore.ieee.org/document/7579503

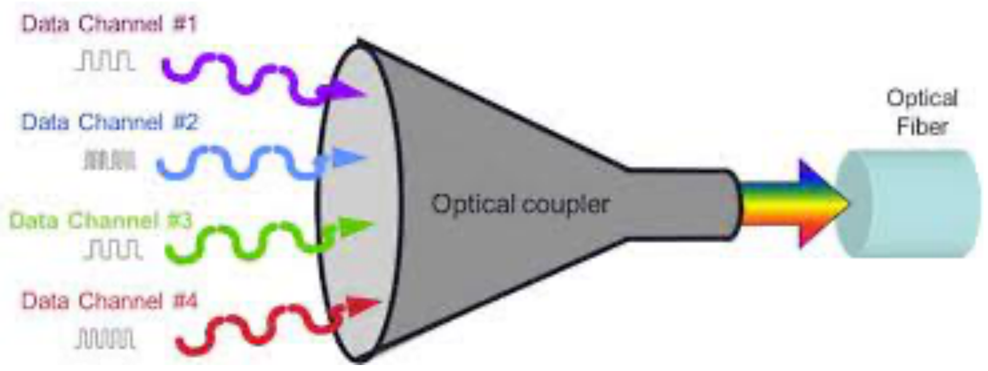
1 PPS time stability

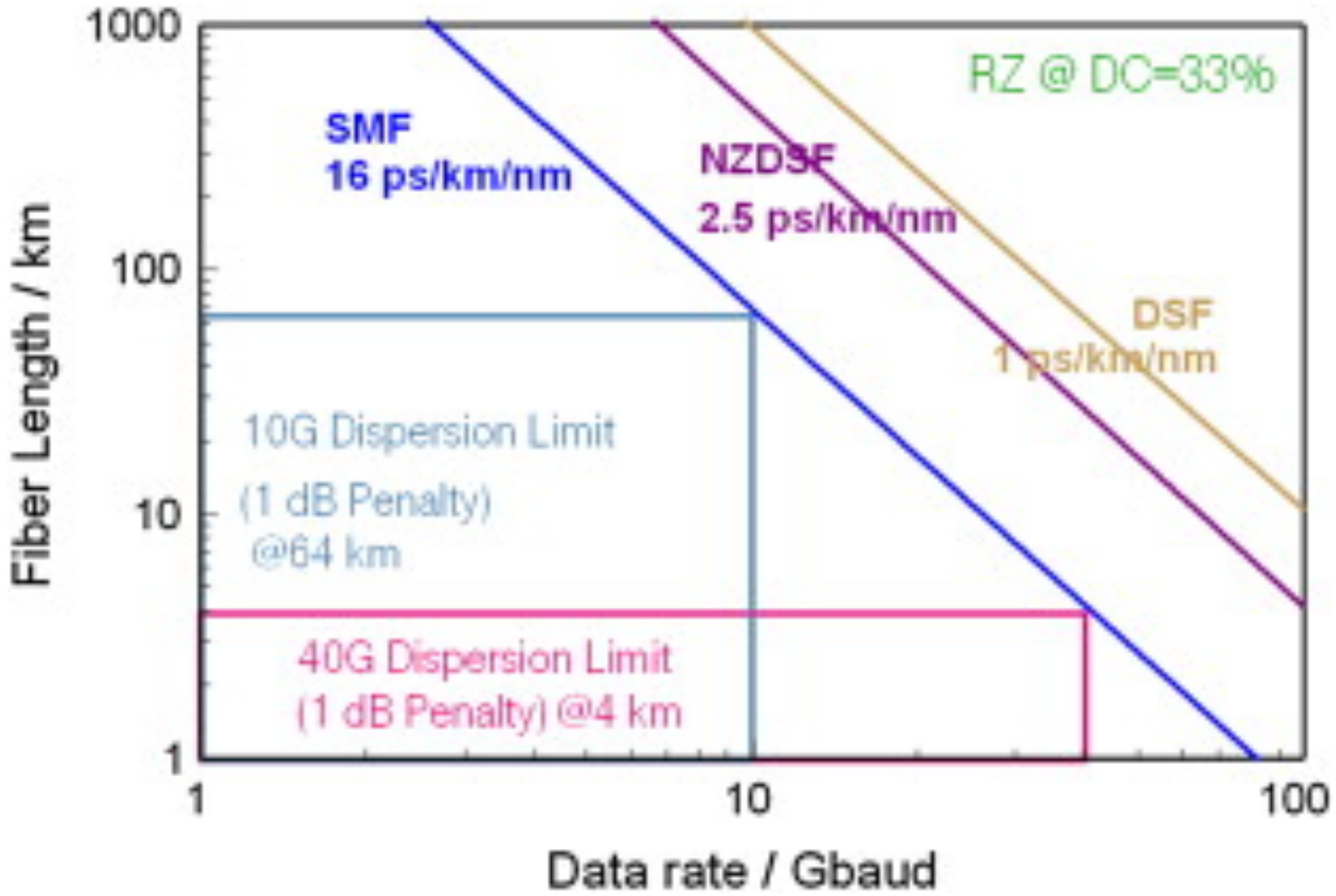


https://hal.archives-ouvertes.fr/tel-01909292

WR network: plans and challenges

- DWDM:
  - No dedicated optical amplifiers : no CAPEX, no OPEX
  - No allocation of a single-one wavelength
  - Integration as an alien wavelength for NRENs
    - 1 Gb/s. Transport at10/100 Gb/s ?
- Challenges :
  - Mitigate link asymmetry
  - Mitigate chromatic dispersion for link > 1000 km
  - Interface with critical infrastructures:
    - Decision processes
    - Live monitoring, network security,…
    - Traceability





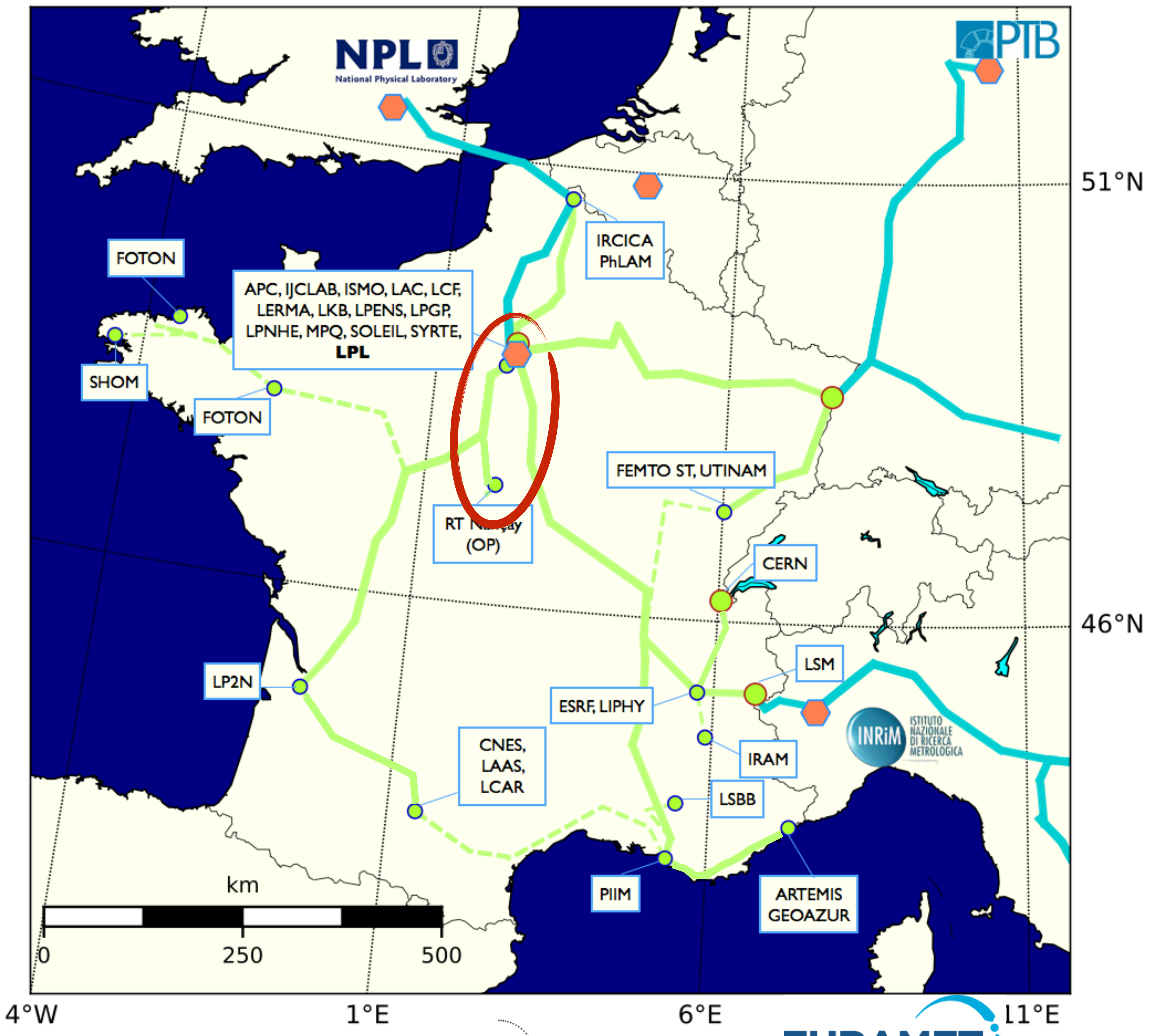
EURAMET TC-TF project **WIND**

From Werner Weiershausen, Malte Schneiders,
Optically Amplified WDM Networks, Chap. Transport Solutions for Optically Amplified Networks, p. 297-339 (2011)
https://doi.org/10.1016/B978-0-12-374965-9.10011-1

Refimeve: a high-way for time and frequency dissemination

Refimeve+
Réseau fibré métrologique
à vocation européenne

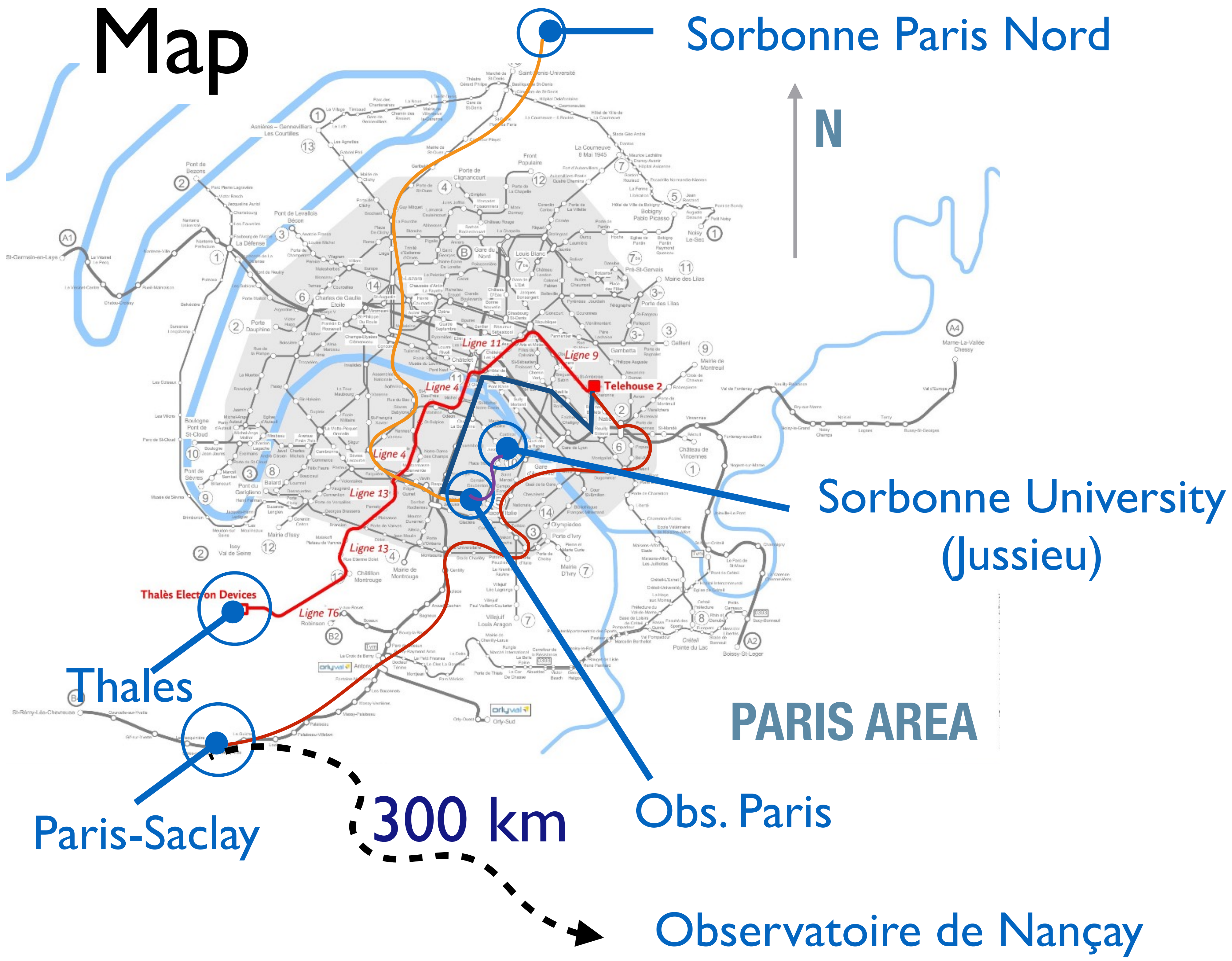
- 4 international connections (DE, UK, IT + CERN)
- Clocks in UK, France, Germany and Italy connected
- REFIMEVE connects +30 labs by 09/2025
- REFIMEVE connects 6 research infrastructures
    - LSM, CERN, SOLEIL (done)
    - ESRF, IRAM, LOFAR (planned)
  - *Link* with EPOS-FR (seismology), …
- REFIMEVE deploy WR on all its links (2x5000 km) as a an alien lambda for RENATER (DWDM)



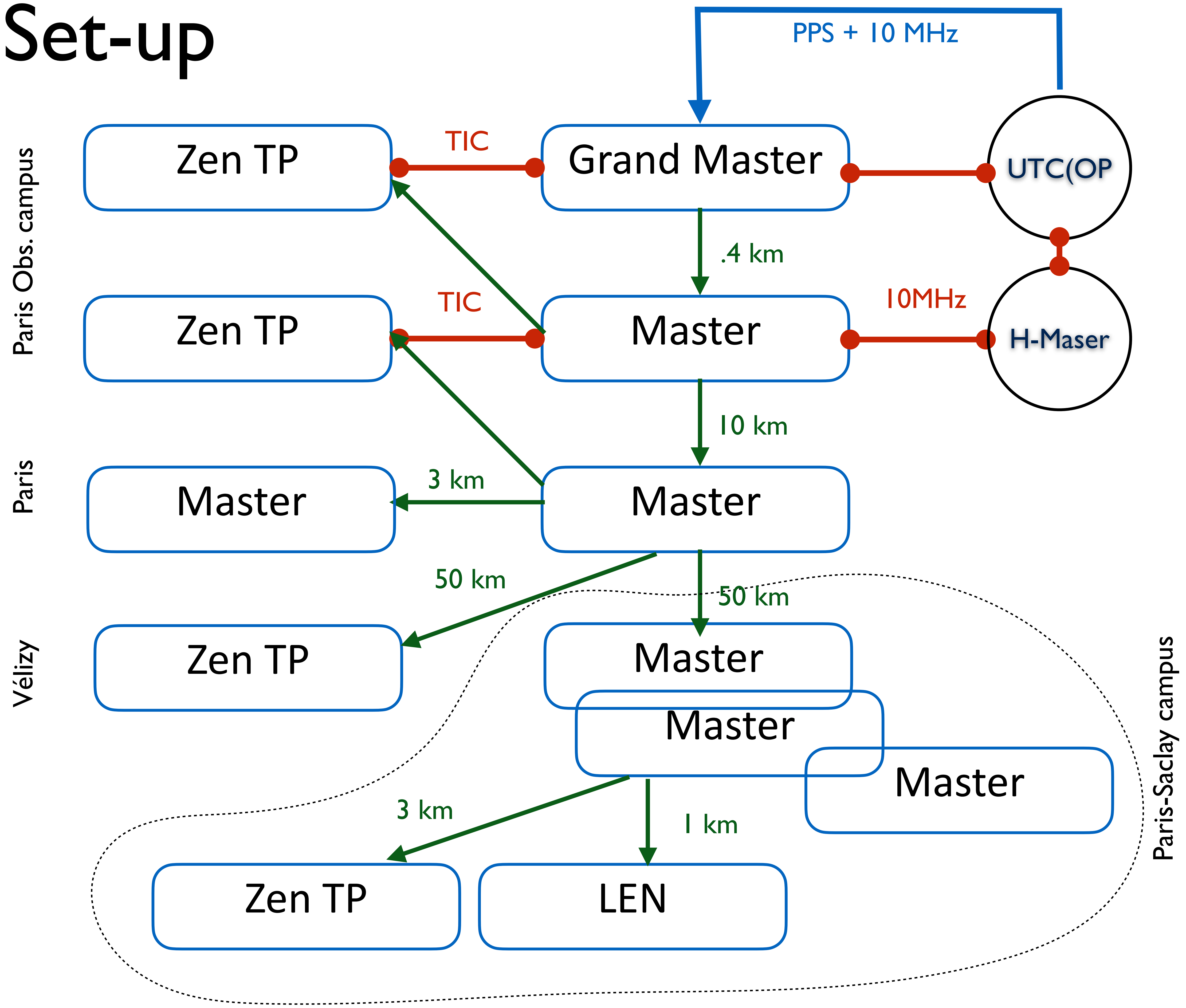
AGENCE NATIONALE DE LA RECHERCHE ANR · INVESTISSEMENTS D'AVENIR · INVESTIR L'AVENIR · FIRST TF · EURAMET

WR network : regional area by Paris and one long-haul link to Obs. Nancay

Map



Set-up



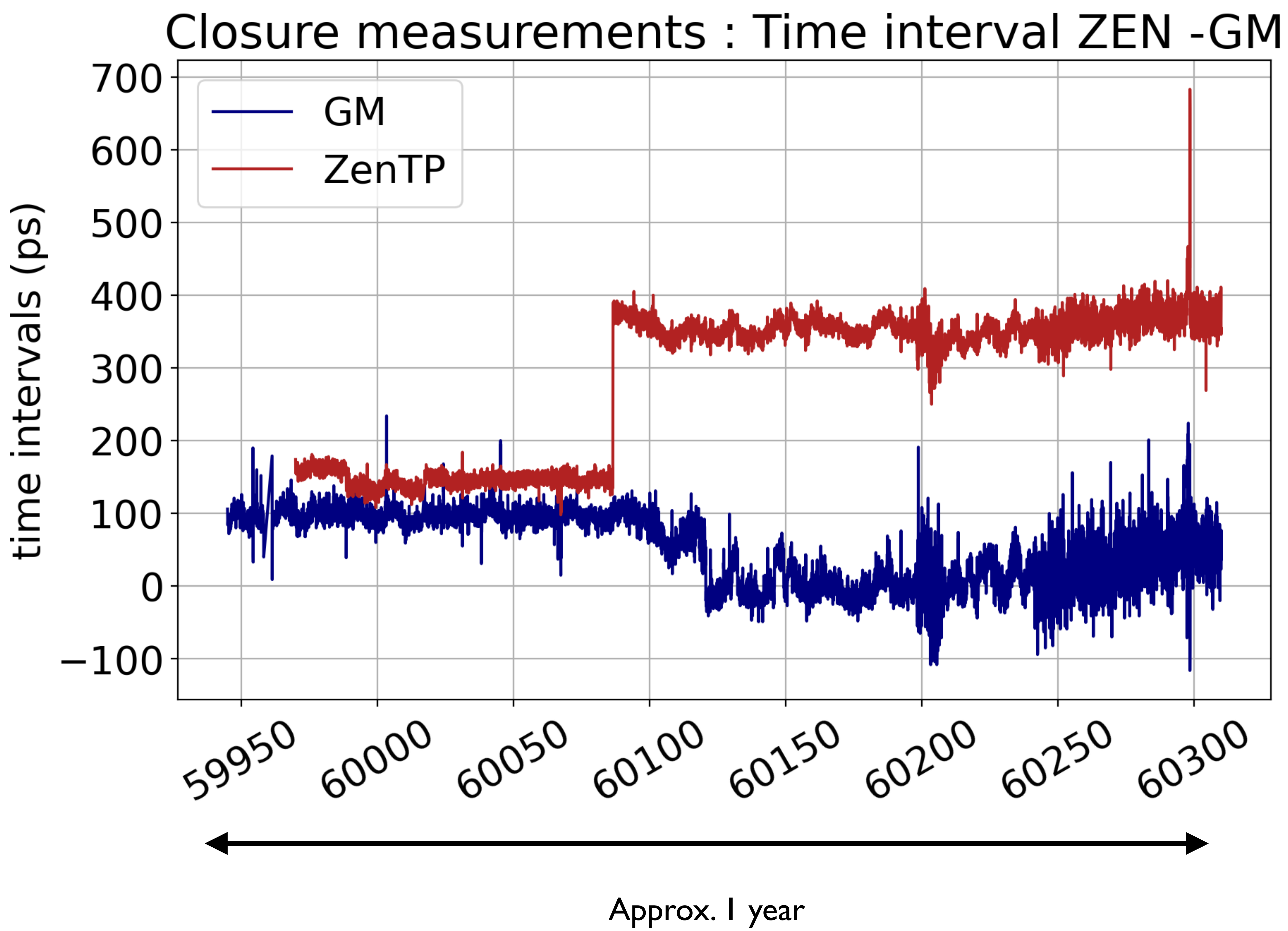
- Grand Master seeded with UTC(OP)
- In campus: closure measurements on PPS and 10 MHz
- @LPNHE: measurement versus passive H-Maser and GNSS
- One long haul link to Observatoire de Nançay, 300 km far from Paris: measurement versus Rb clock and GNSS

- 1310/1490 when link < 5 km
- 1510, 1550, 1560 nm, … (DWDM) when link > 10 km

TIC: Time Interval Counter

WR network: traceability to the source

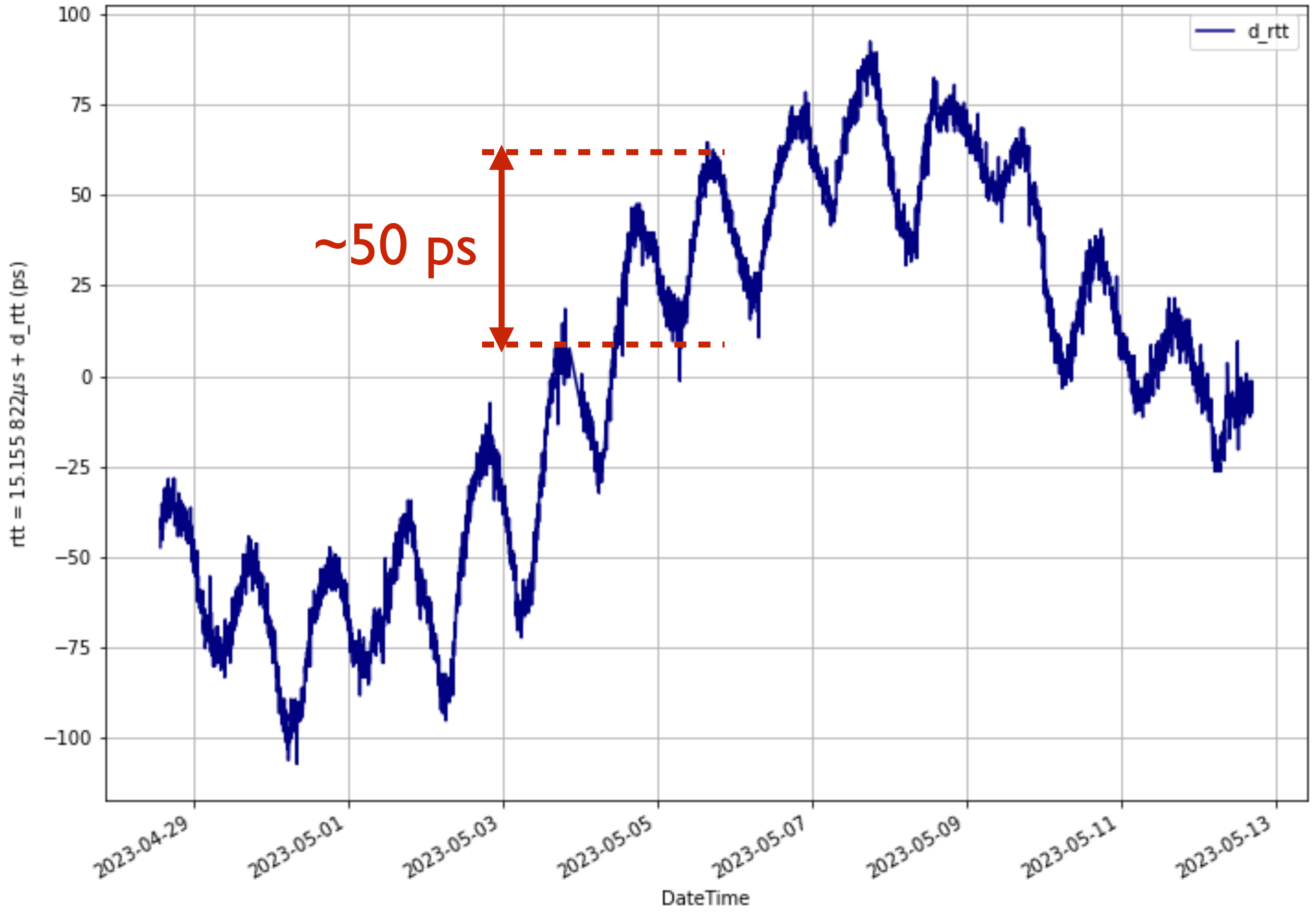
- We measure time intervals between PPS outputs at RNT.
  - Link length ~2x300m, rtt ~2x 3 μs.
  - Time offset ~200 ps
- We measure time intervals between PPS outputs **and** frequency of clock outputs at the lab.
  - Link length ~ 2x10 km, rtt~2x 100 μs.
- We observe over year scale:
  - Very low noise signals < 10 ps.
  - Jumps ~250 ps happens sometimes.



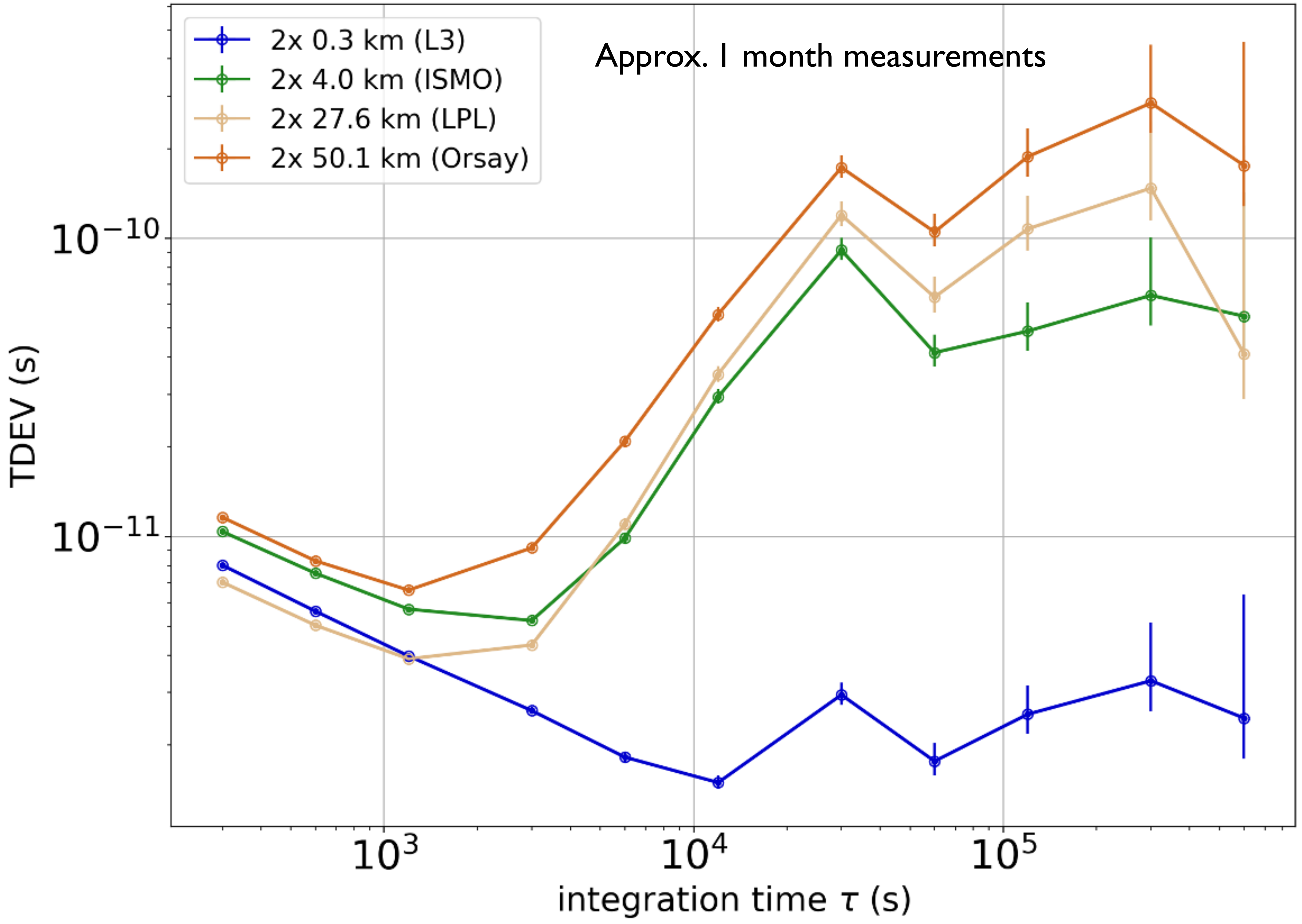
We observe excellent behaviors over long term.

WR network: monitoring and supervision

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



TDEV for round-trip time over the regional network

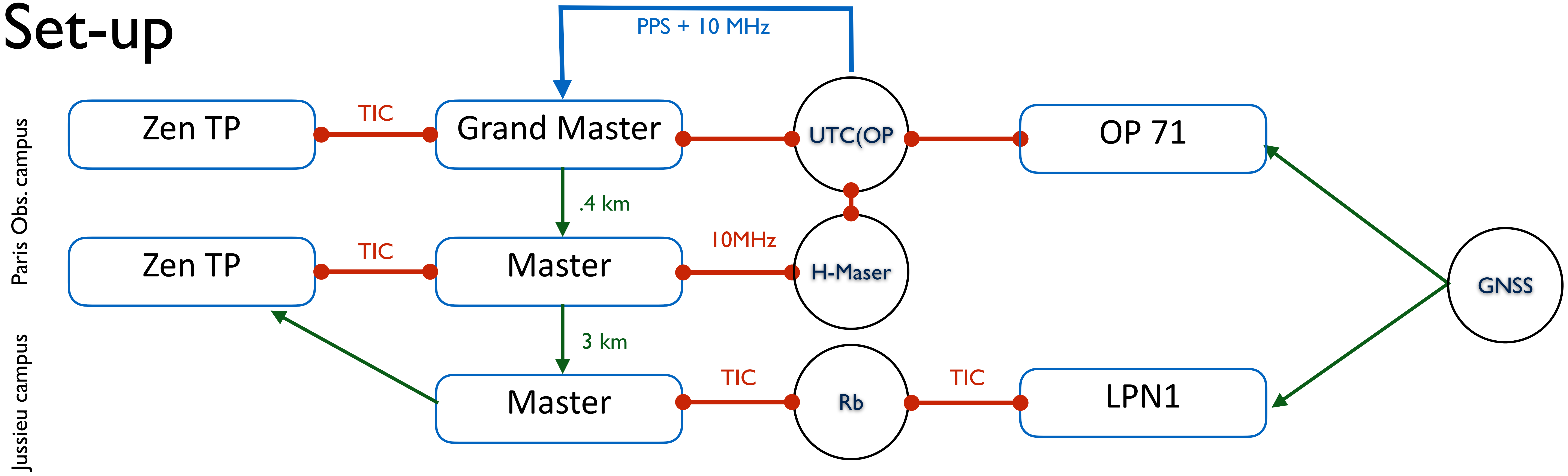


Embedded monitoring resolution ~ 10 ps

We observe diurnal perturbations on mid-range links.

GNSS vs WR - comparisons in Paris (3 km baseline)

Set-up

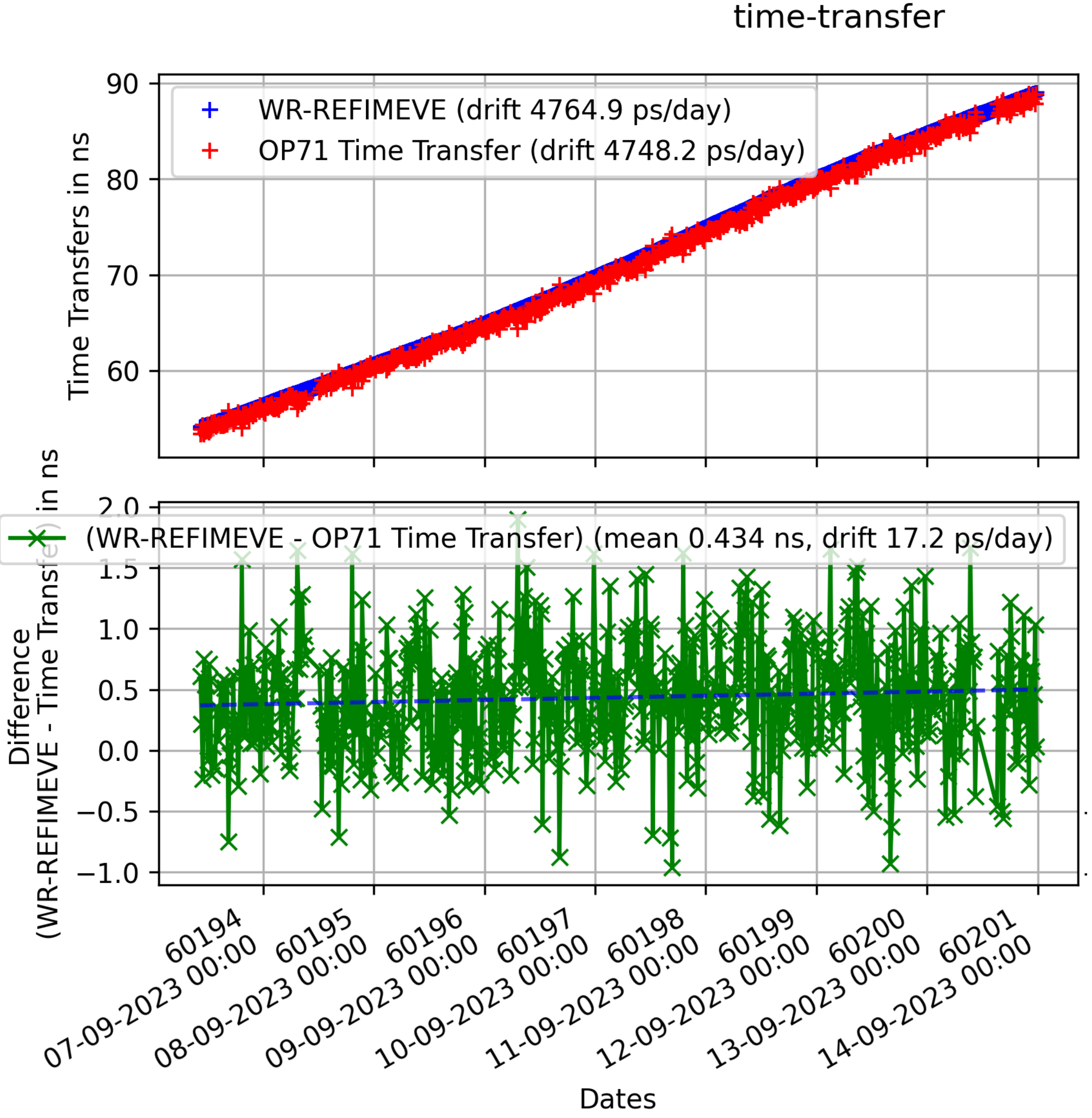


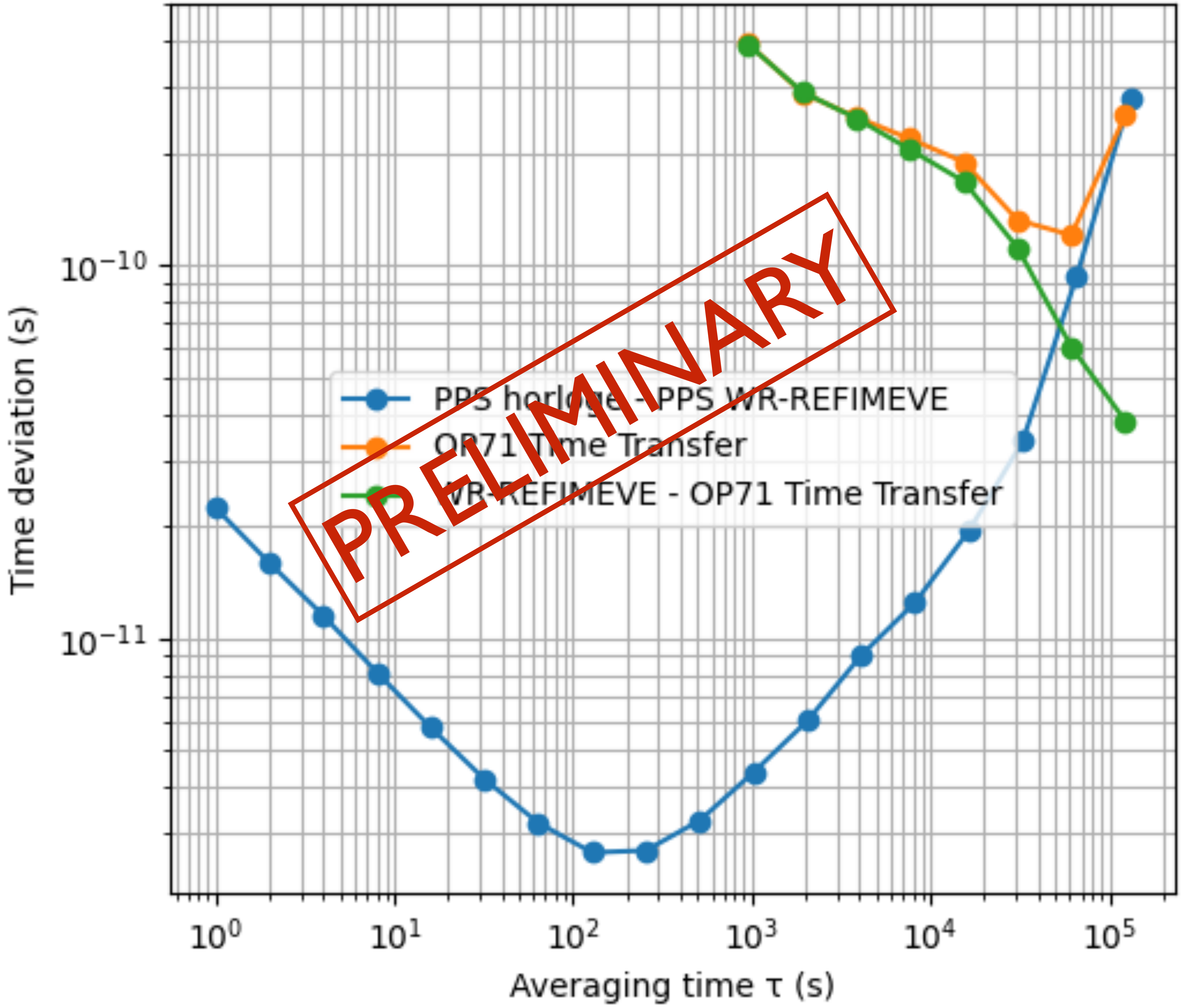
White Rabbit links

GNSS links

C. Dalmazzone *et al.*, « Precise synchronization of a free-running Rubidium atomic clock with GPS Time for applications in experimental particle physics », (2025,) doi: 10.1016/j.nima.2025.170358.

GNSS vs WR - comparisons in Paris (3 km baseline): results



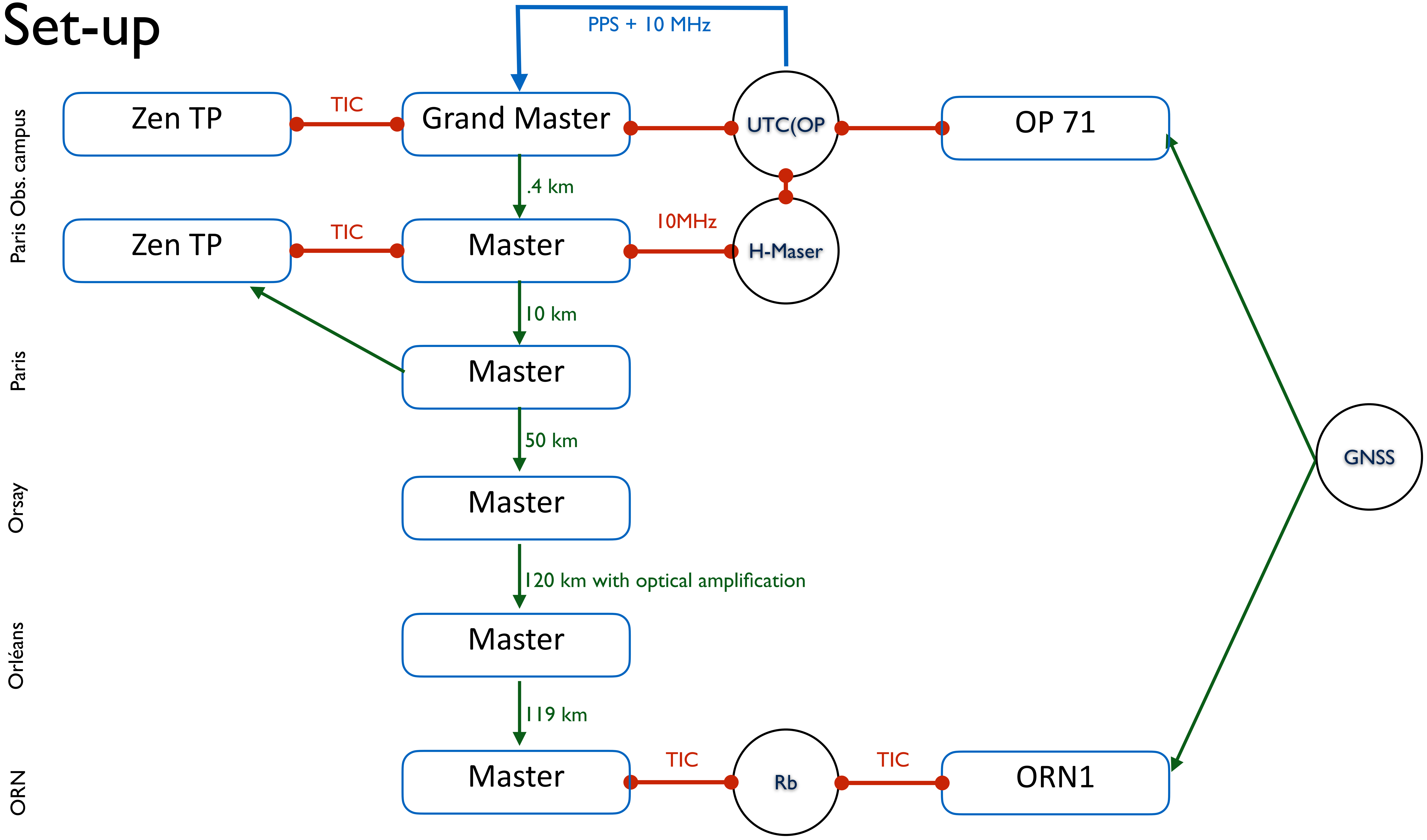


mean offset [GNSS-CV and WR-REFIMEVE] = 0.43 ns +/- 0.5 ns.

Credit: Vincent VOISIN (LPNHE)

GNSS vs WR - comparisons in Nancay (300 km baseline)

Set-up

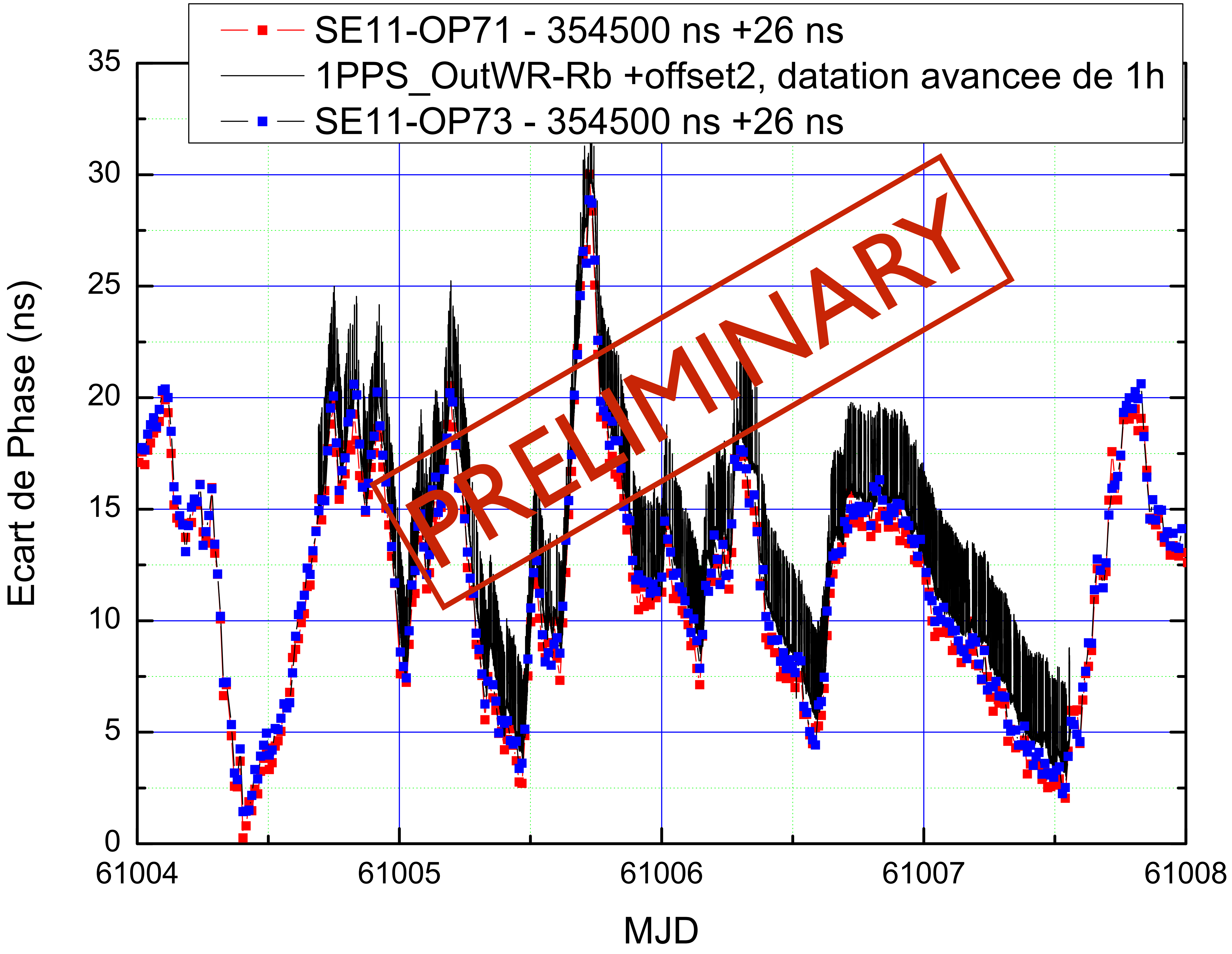


White Rabbit links

GNSS links

GNSS vs WR - comparisons in Nancay (300 km baseline): results

- We measure time intervals between PPS outputs at ORN.
  - Link length ~300km, rtt ~ 60 μs.
  - Time offset without alignment/ calibration: 1.2μs
- We observe excellent agreement between GPS and WR signals monitoring the same Rb clock.
- We observe 4 ns jumps of the Rb clock in Nançay with the WR signal that are difficult to observe with GNSS.

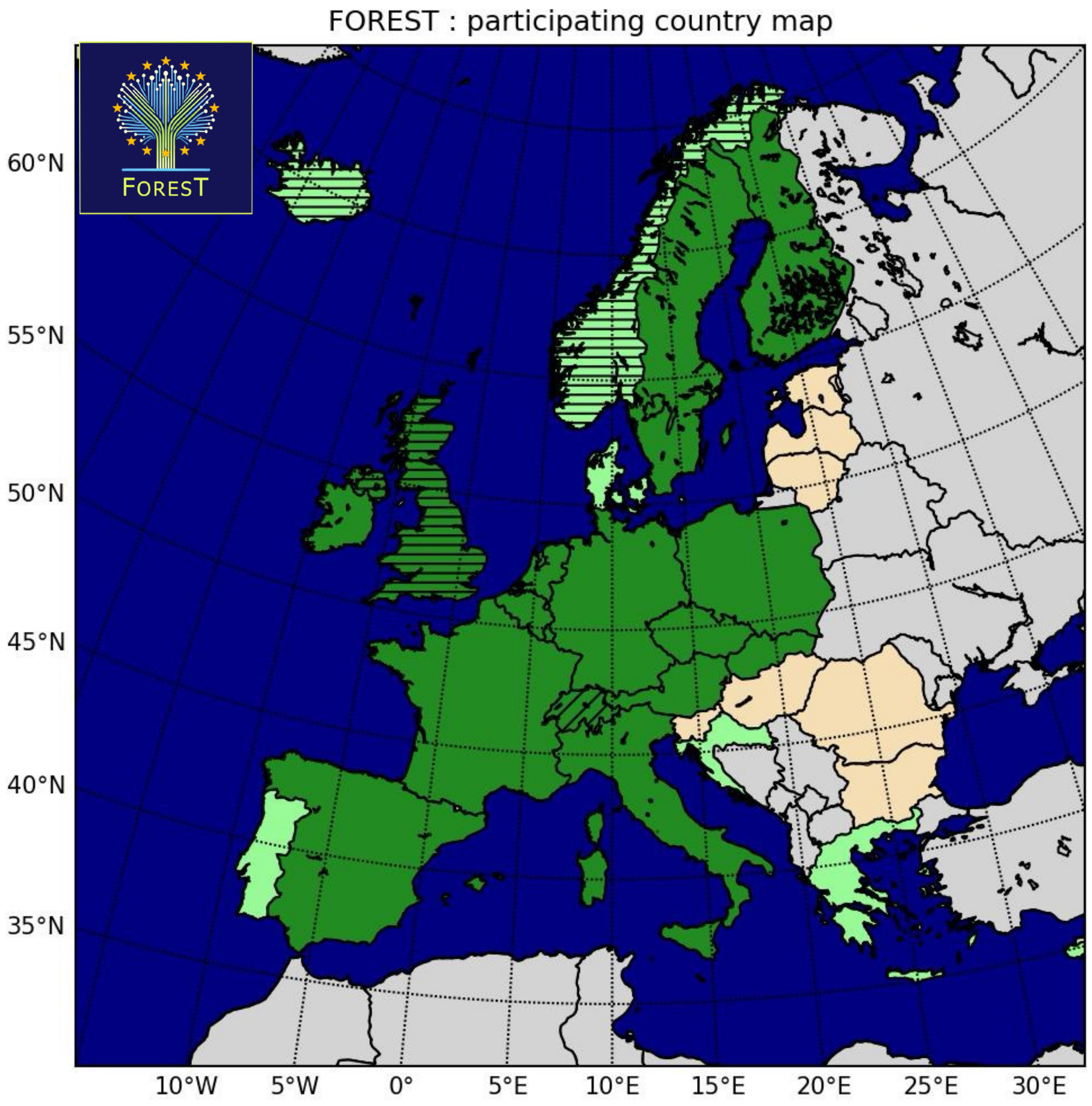


Credit: Michel ABGRALL (LTE)

Summary - key messages

- PTP / WR-PTP can be deployed at low cost on xWDM network
- 1 GB/s data rate enable long range
- Time stability < 1 ns
- Preliminary cross-comparisons with GNSS in Paris and in Nançay
- Main challenges :
  - propagation delay asymmetry variation over time
  - Time accuracy budget < 10 ns

Last words: towards a fiber network in Europe



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JRP: WRiTE
Tech project WIND

CLONETS
CLONETS-DS

Thank you for your attention !