Transfert de temps par fibre optique

O. Lopez, C. Chardonnet, A. Amy-Klein
Laboratoire de Physique des Lasers (LPL), Université Paris 13, Villetaneuse
A. Kanj, P.E. Pottie, D. Rovera, J. Achkar, G. Santarelli
LNE-SYRTE, Observatoire de Paris, Paris

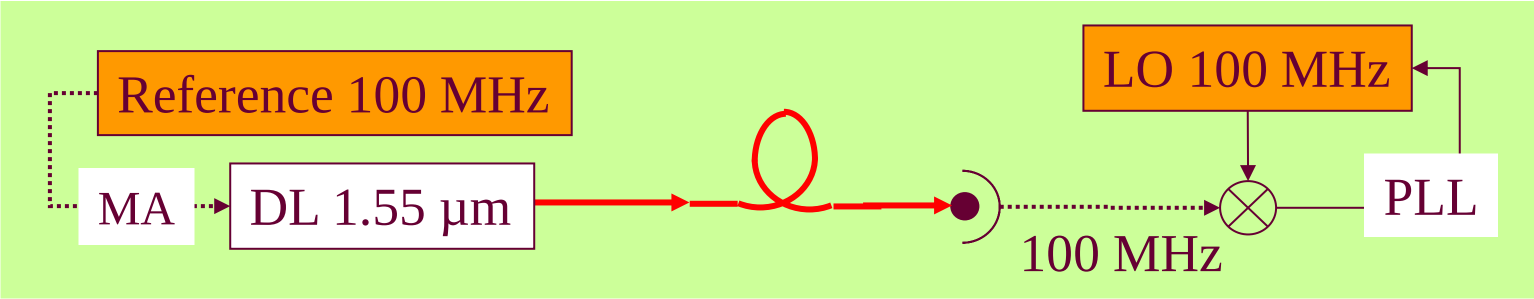
Plan de l'exposé

- Introduction sur les liens optiques
- Transfert de temps par fibre optique : les différentes techniques utilisées
- Transfert de temps Two-way sur fibre

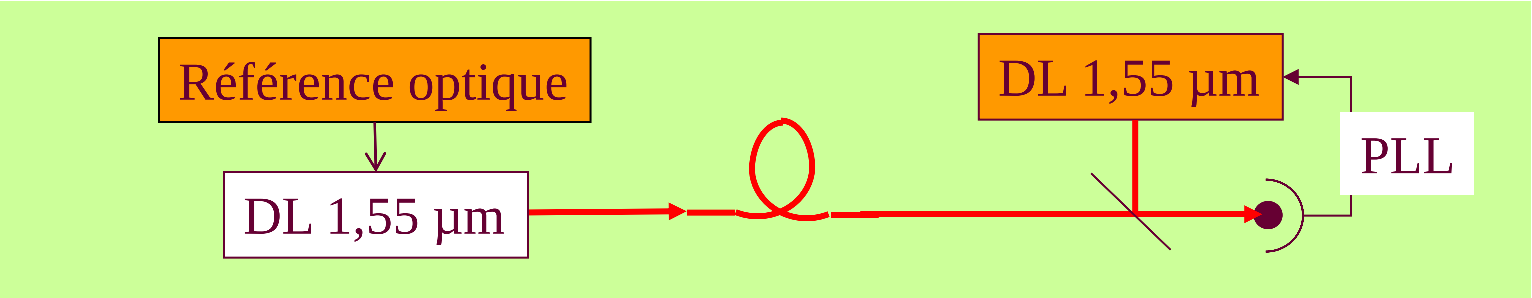
Transfert de fréquence sur fibre optique

- Liens optiques fibrés
  - Fort développement ces 10 dernières années
  - Transfert fiable sur des distances de 100-200 km, record = 920 km

- Transfert d'une référence de fréquence RF ou optique



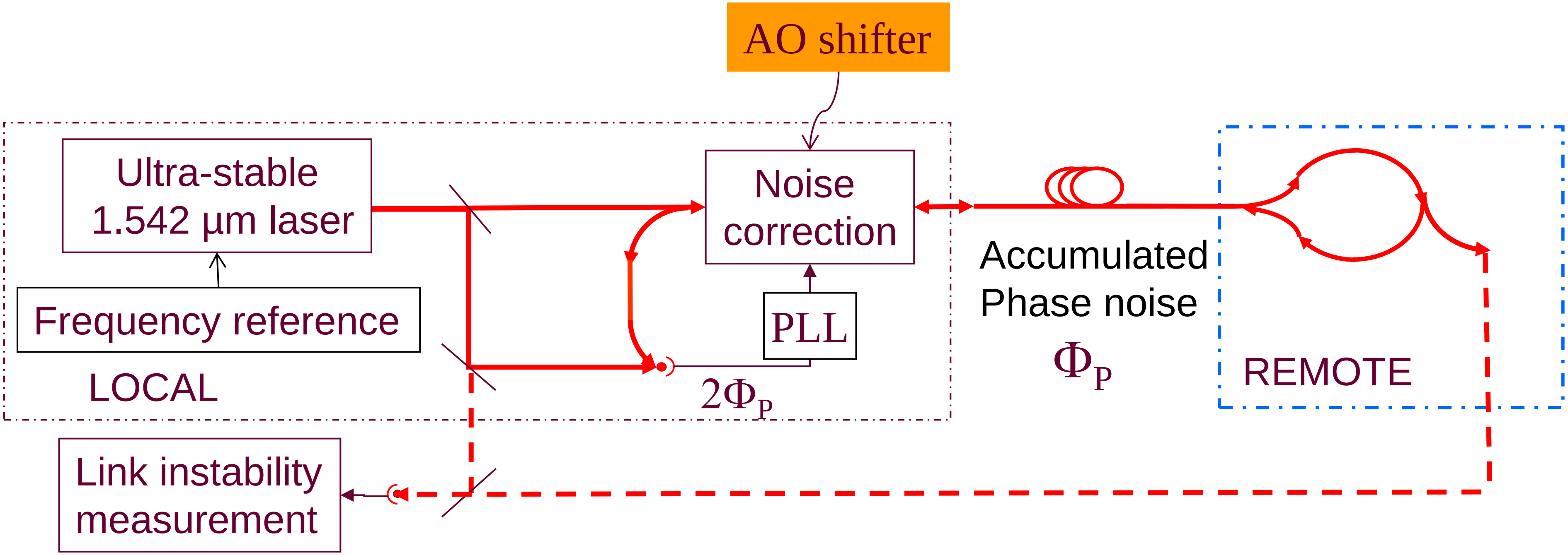
Aussi 1GHz et 10 GHz



Le standard actuel

Compensation du bruit de phase accumulé pendant la propagation

- Fluctuation du temps de propagation du signal
- Compensation de ce bruit avec la méthode « round-trip »



- Démonstration avec deux extrémités de la fibre au même endroit

Lien optique longue distance

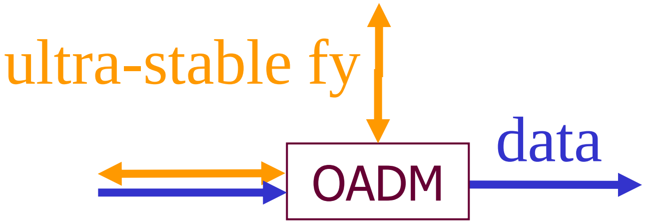
- Plusieurs liens en cascade reliés par des stations de régénération
- Problème majeur : accessibilité de la fibre
  - Fibre dédiée très coûteuse et difficile à obtenir
  - Notre choix : utilisation du réseau fibré existant et multiplexage en longueur d'onde

    → Transmission simultanée du flux de données numériques et du signal métrologique sur des « canaux » différents

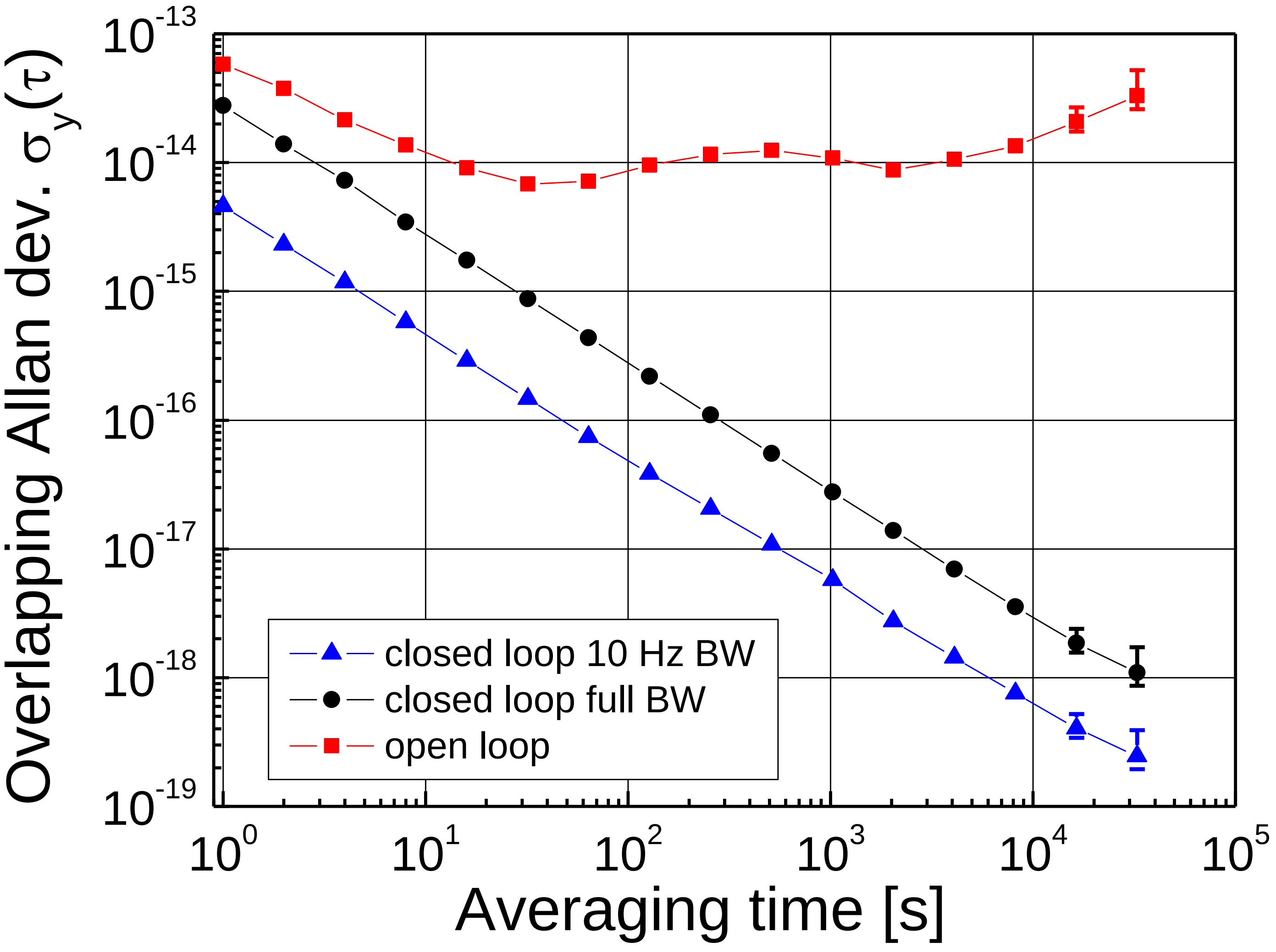
    → « Canal dédié »

- Collaboration avec RENATER, Réseau National de télécommunications pour la Technologie, l'Enseignement et la Recherche

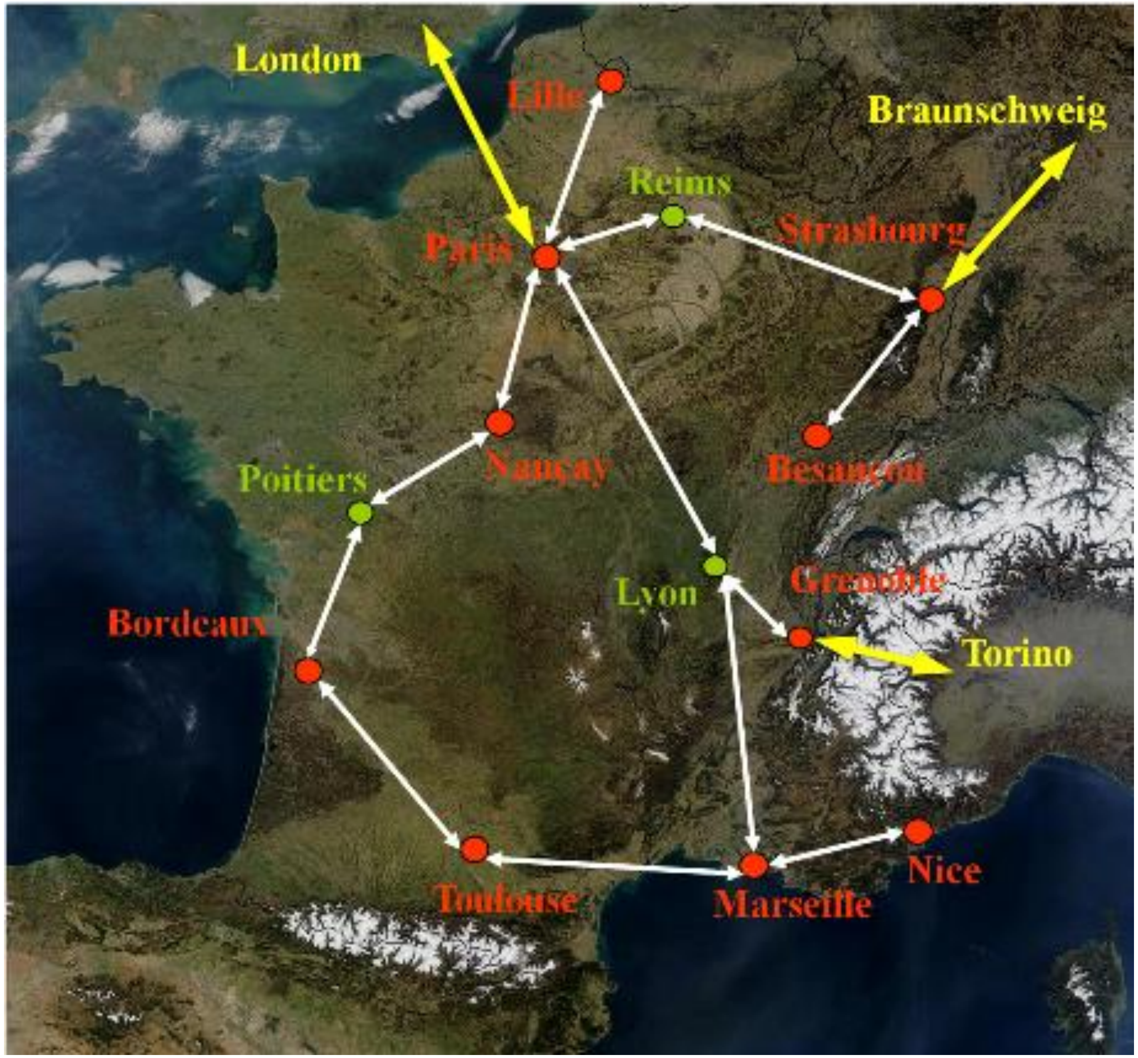
- OADM (optical add drop multiplexer) pour insérer et extraire le signal
  - Pertes < 1dB, Isolation > 25 dB
  - Bidirectionnel



End-to-end stability of a LPL-Reims-LPL 540-km link



« Réseau Fibré Métrologique à Vocation Européenne » – REFIMEVE+



Funded January 2012

Tranfert de temps par fibre optique : les différentes techniques utilisées

- Protocole “réseau”
- Transfert de temps par stabilisation du délai
- Transfert de temps “Two-way”
  - Sur 2 fibres
  - Sur une fibre

Transfert par réseau Internet (fibre ou cable)

- Network Time Protocol (NTP) : accuracy 1 ms
- Precise Time Protocol (PTP) : accuracy 1 µs

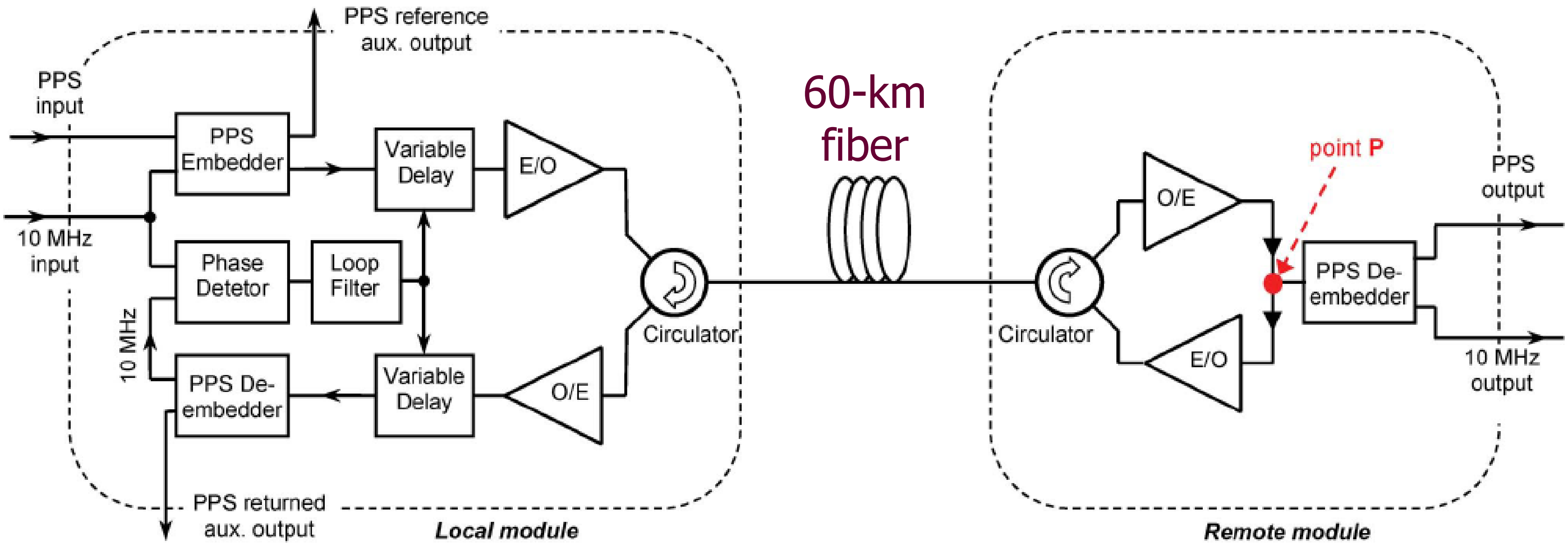
- White Rabbit (CERN, Erik van der Bij & Maciej Lipinski)
  - Transfert sur fibre unique < 10 km
  - Extension of Precision Time Protocol
    - Link delay evaluated by measuring and exchanging packets timestamps
    - Synchronous Ethernet **syntonization**
    - Digital Dual-Mixer Time Difference **phase detection** and clock frequency correction
  - Accuracy < ns, stability < ps

Transfert de temps par stabilisation du délai

- AGH University of Science and Technology, Krakow, Poland
  - 60 km : accuracy ~7 ps, stability (1 d) ~ 0.3 ps
  - Current development on 420 km between Borowiec and Varsaw

- See P. Krehlik, Ł. Śliwczyński, Ł. Buczek, M. Lipiński, IEEE Trans. on Instr. and Meas. (2012).

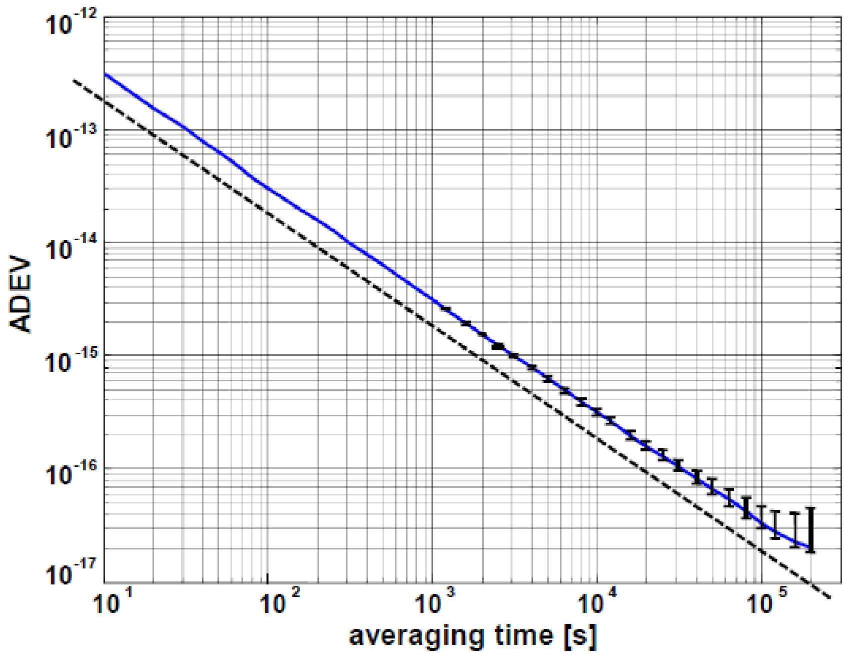
Fiber-Optic Joint Time and Frequency Transfer with Active Stabilization of the Propagation delay



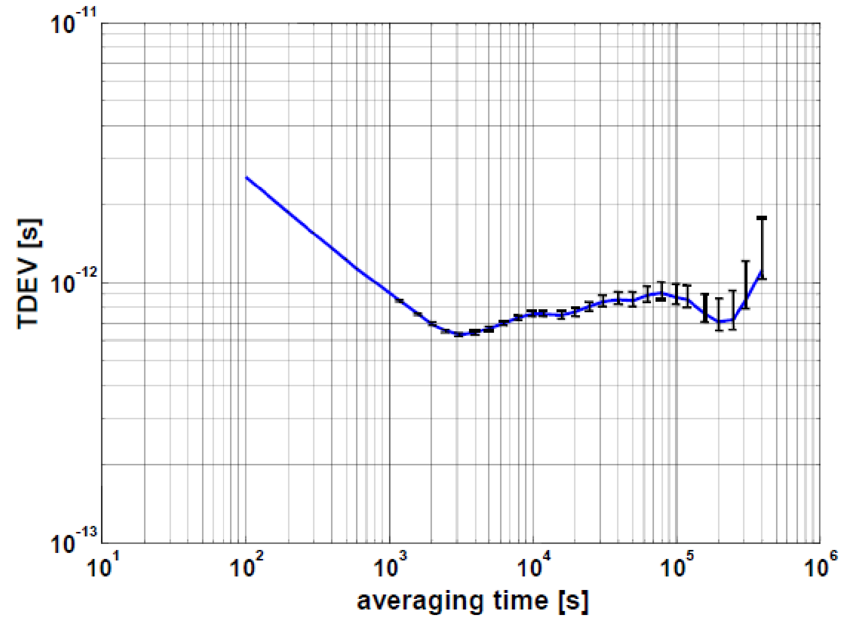
- 10-MHz + 1pps joint transfer through intensity modulation of the optical carrier
- Roundtrip propagation in the same fiber for noise correction
- Active stabilization of the propagation delay through a variable delay module (DLL)

Delay-stabilized time transfer

- 60-km loop fiber (Polish Telecom -Krakow-Skawina and back)
  - Accuracy 7 ps, Stability (1d) : 0.3 ps
- Results on 480-km spooled fiber



•Allan Deviation (10MHz)
480 km spooled fiber + 8 SPBAs
6 days measurement in varying temperature



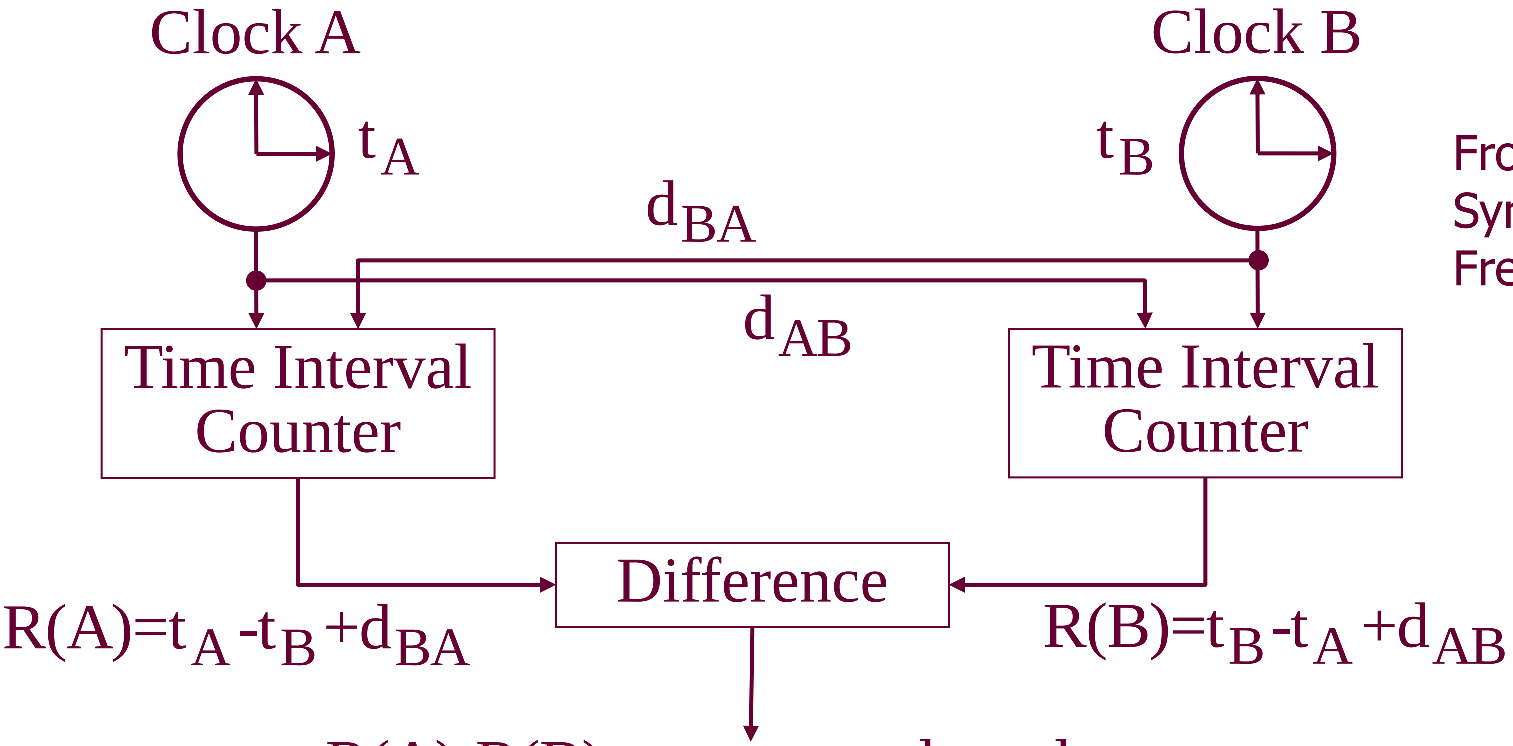
Time Deviation (1PPS)
480 km spooled fiber + 8 SPBAs
20 days measurement in varying temperature

Tranfert de temps “Two-way”

- Transfert sur 2 fibres (aller et retour)
  - Utilise le réseau fibré Internet
  - Pas de calibration du délai (donc pas de transfert de temps exact)
  - SP/Mikes/STUPI (Sweden/Finland) 570 km
    - Avec des trames SONET
    - Stabilité sur 1 jour ~ qq ns (fibre terrestre) à 30 ps (fibre sous-marine)
  - Cesnet/IPE/Austria (Smotlacha et al) 550 km
    - Stabilité sur 1 jour ~1 ns

- Transfert « Two-way » sur 1 fibre
  - PTB/Hannover 73 km : accuracy ~75 ps, stability (1 d) ~50 ps
  - LPL-Syrte 540 km : accuracy ~200 ps, stability (1 d) ~20 ps

Two-way time transfer



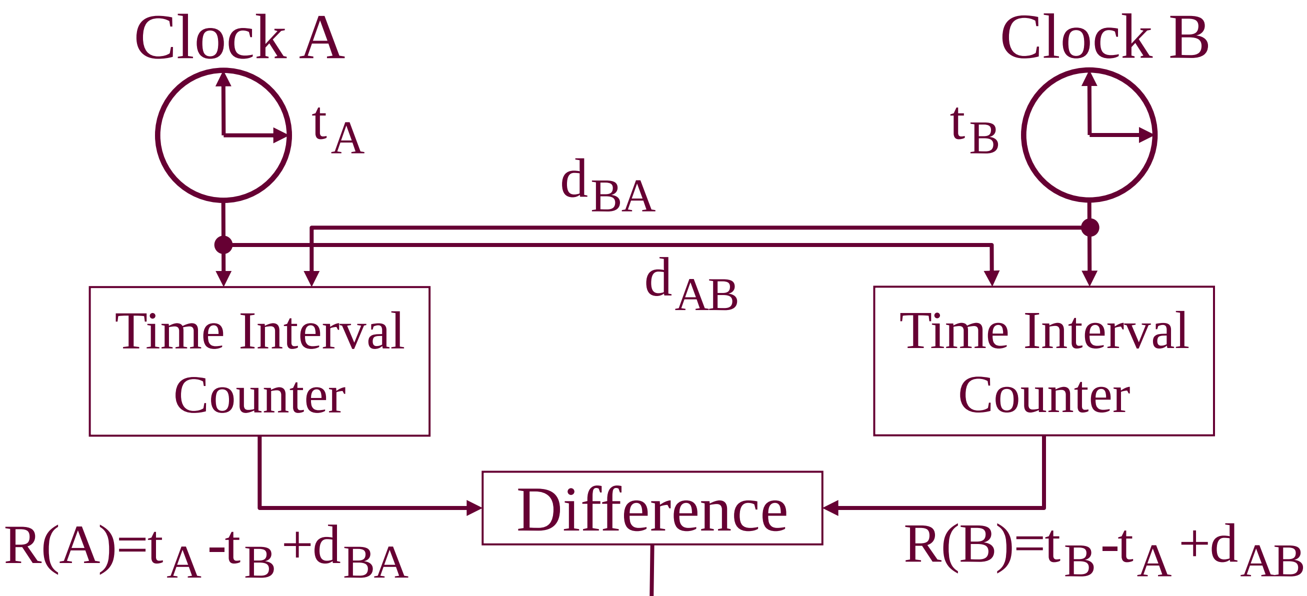
From Hanson, 1989 Symposium on Frequency Control

$$\frac{R(A)-R(B)}{2} = (t_A - t_B) - \frac{d_{AB} - d_{BA}}{2}$$

Delay d_{BA}-d_{AB} = propagation delay + instrumental delay + Sagnac

Calibrated/Calc — Calibrated — Calculated

Fiber two-way time transfer



$$\frac{R(A)-R(B)}{2} = (t_A - t_B) - \frac{d_{AB}-d_{BA}}{2}$$

- Clock A = clock B

\+ link length =1m

→ Calibration of differential instrumental delay

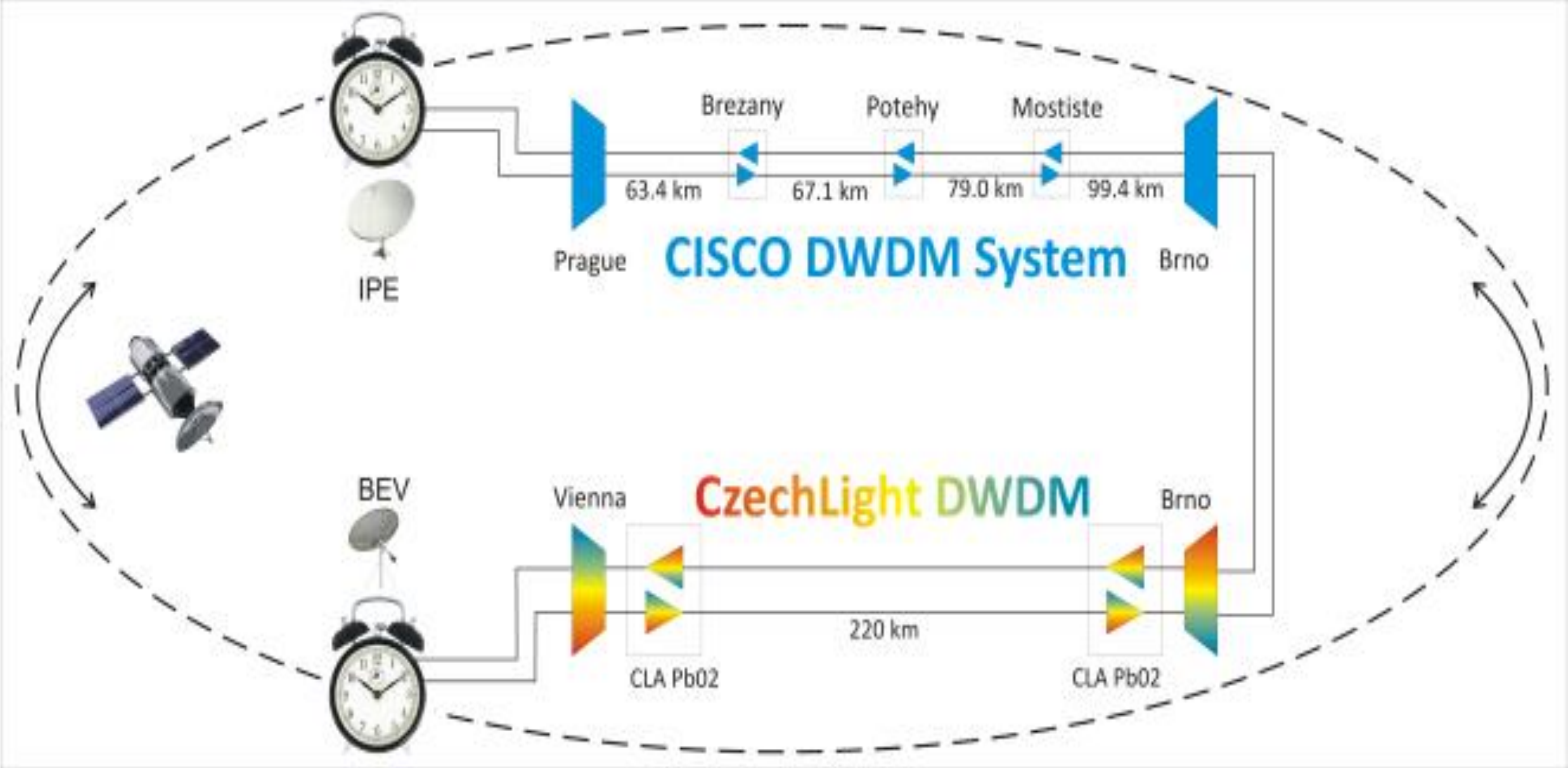
- Clock A = clock B

\+ various fiber lengths

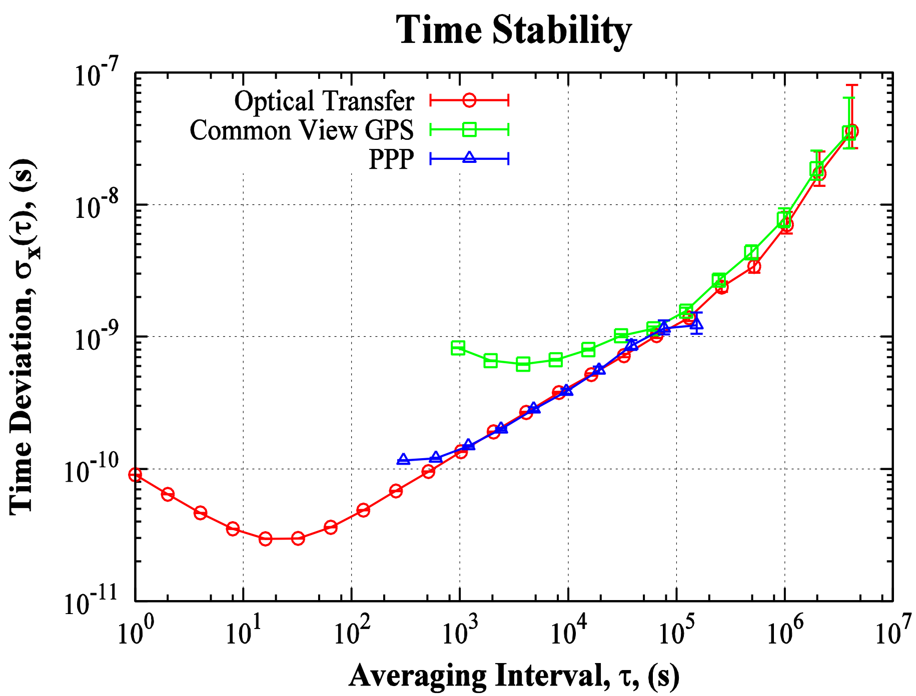
→ Calibration of differential propagation delay

Time Transfer between Prague and Vienna (550 km)

- comparison of time scales UTC(TP) and UTC(BEV)
- bidirectional time transfer using two fiber threads
- utilizes home-made transceivers

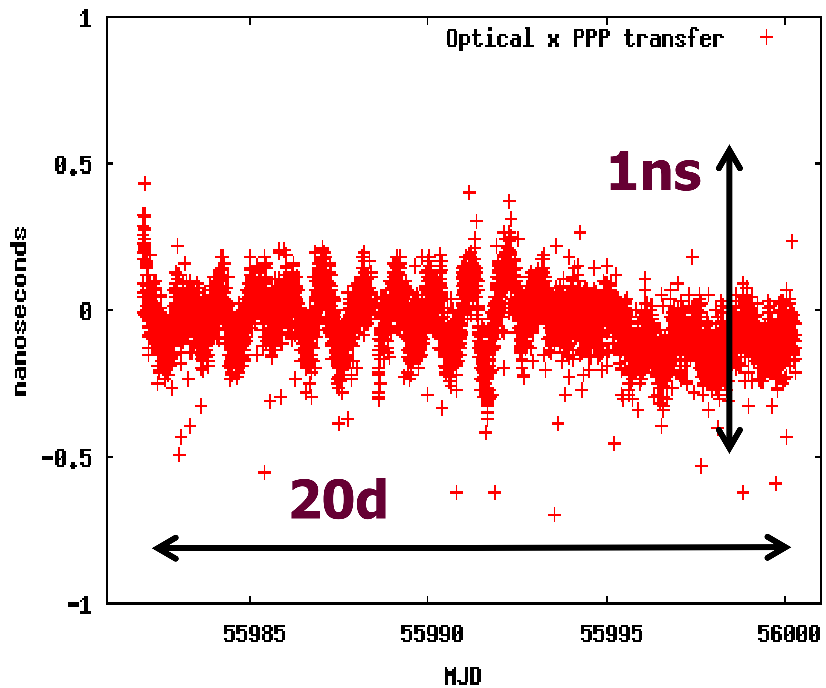


Results of Time Transfer between Prague and Vienna



Time transfer stability

stability (1d)~1ns

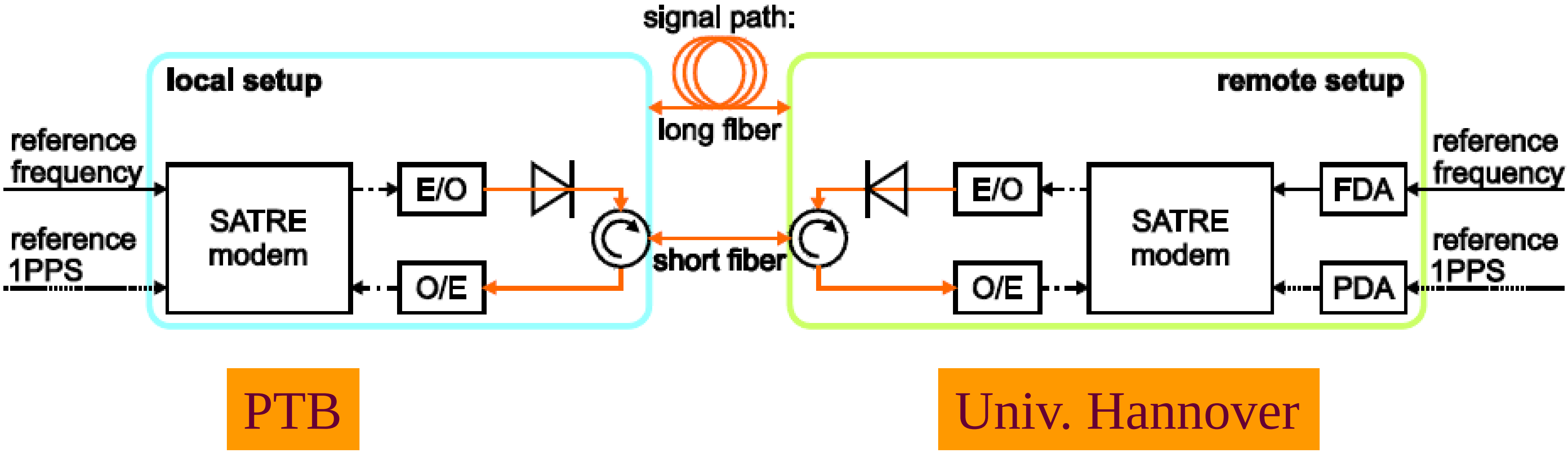


Difference between optical time transfer and GPS carrier phase method

V. Smotlacha, A. Kuna, "Two-Way Optical Time and Frequency Transfer between IPE and BEV", Proc. of EFTF2012

Time transfer through 73-km fiber between PTB and Hannover (I)

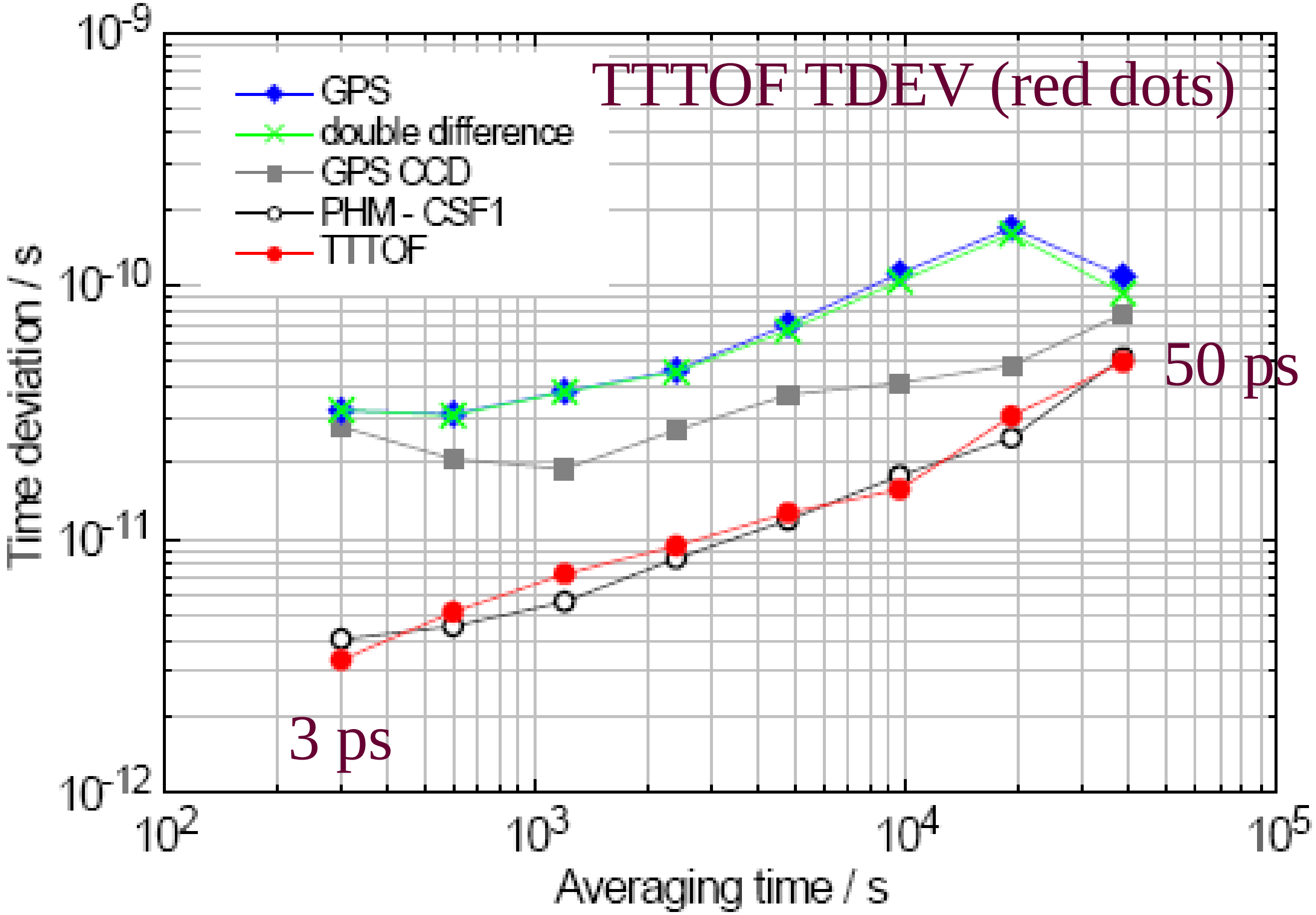
- Two-way time transfer with Satre modem, chip rate of 20 Mcps
- Modem output signals are intensity-modulating optical signal
- See M. Rost, D. Piester et al, Metrologia 2012



- GPS calibration system used in parallel
- Calibration with 1 m fiber at PTB and common clock
- Total uncertainty 74 ps

Time transfer PTB-Hannover (II)

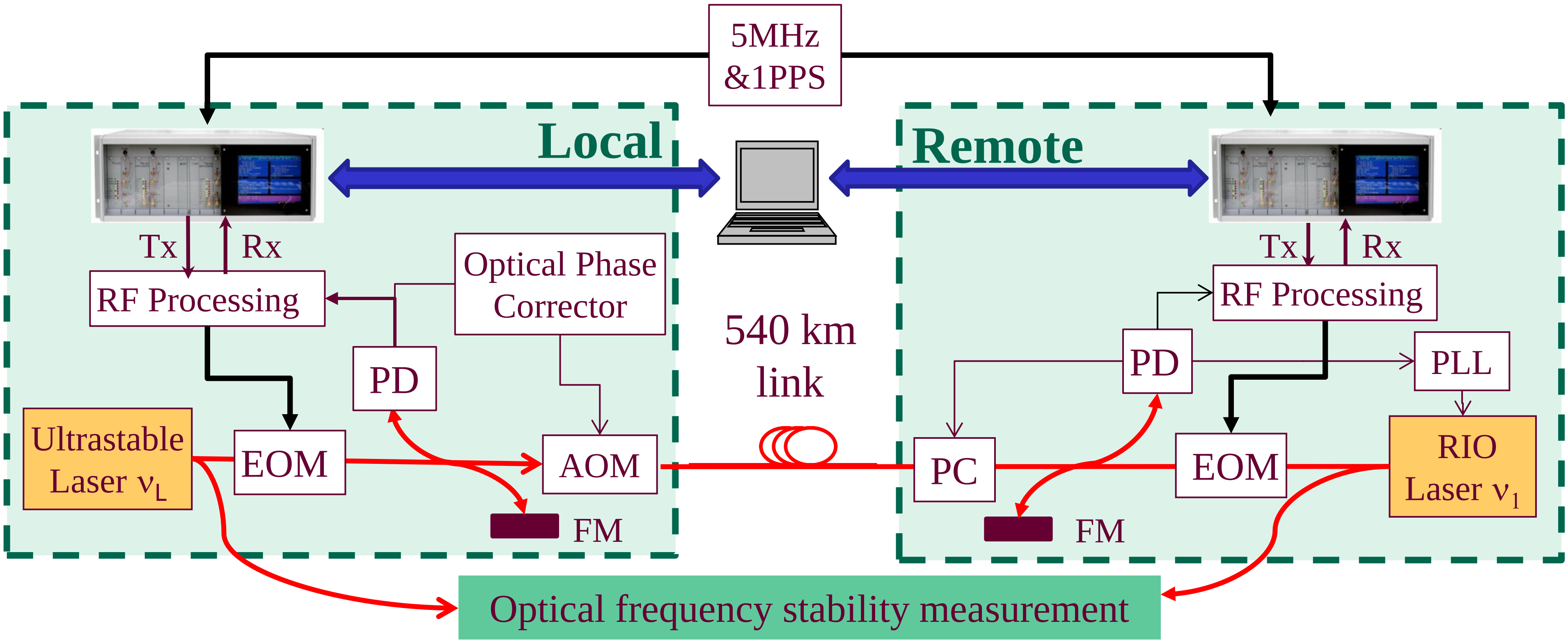
- TTTOF 10 times better than GPS
- Time instability limited by passive H-maser at Hannover
  → 3 ps @ 300 s, 50 ps @ 4×10^4s



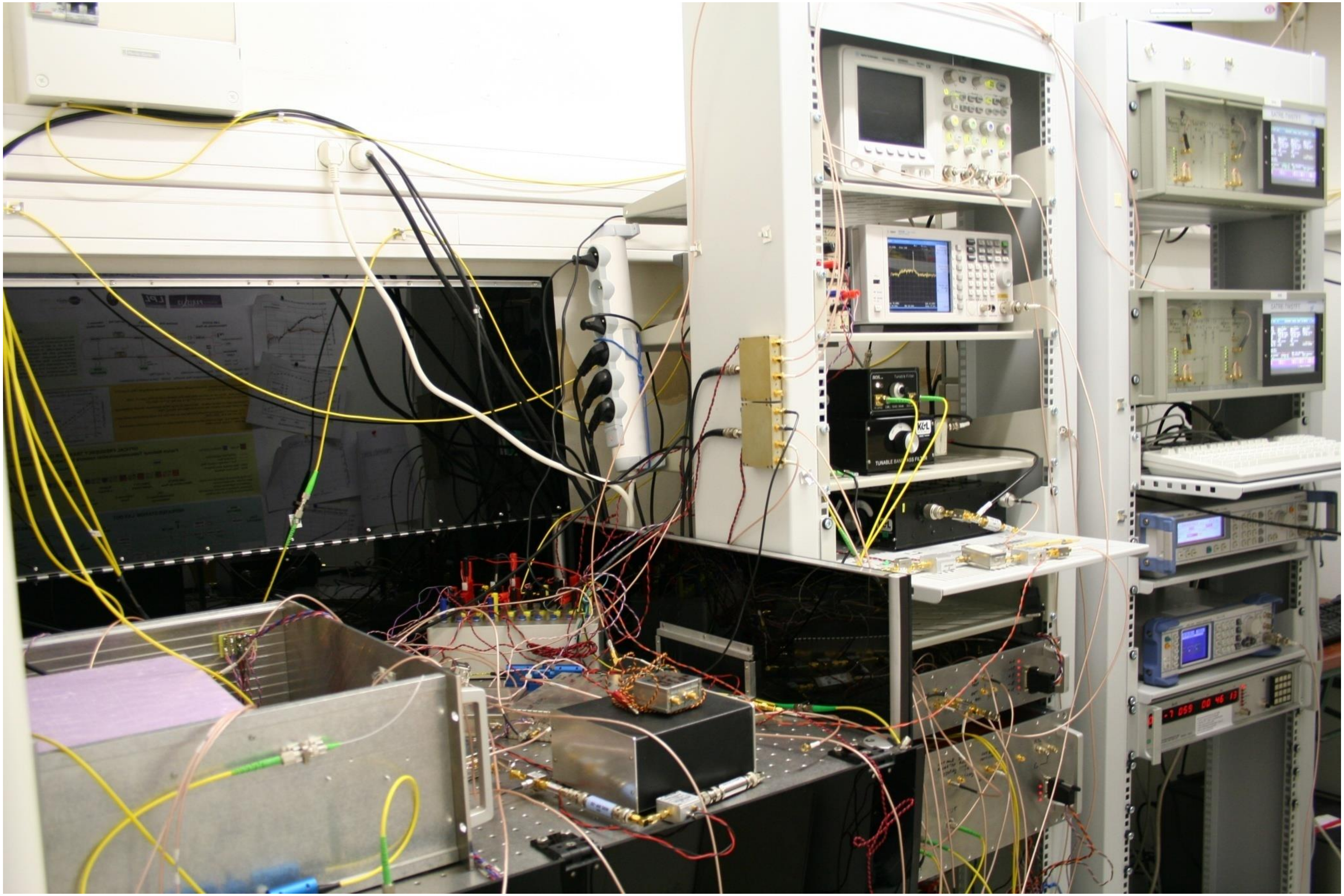
Joint time and frequency transfer over a public fiber network

- Collaboration between LPL (CNRS-UP13) and LNE-SYRTE (CNRS-Obs Paris-UPMC)
- Fiber link = public telecommunication fiber with data traffic

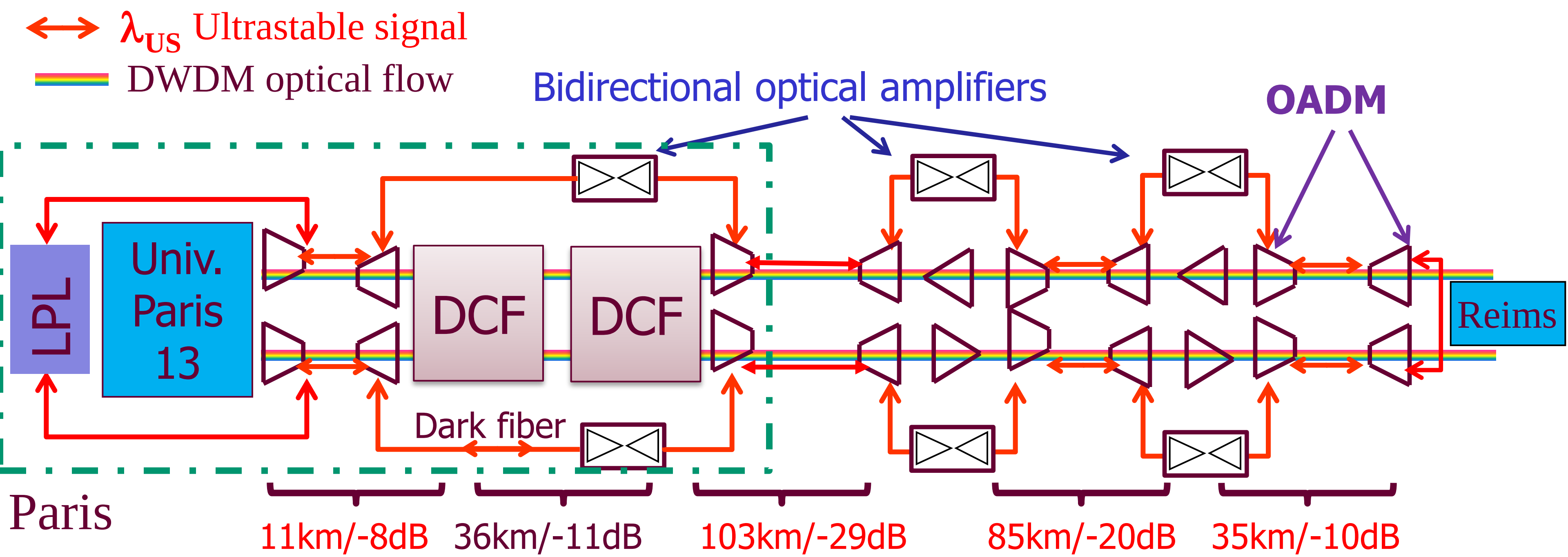
Experimental set-up



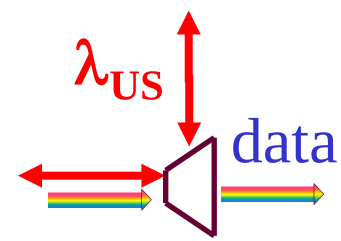
- Frequency transfer with « round-trip » method for fiber noise compensation
- Two-way time transfer using Satre modems



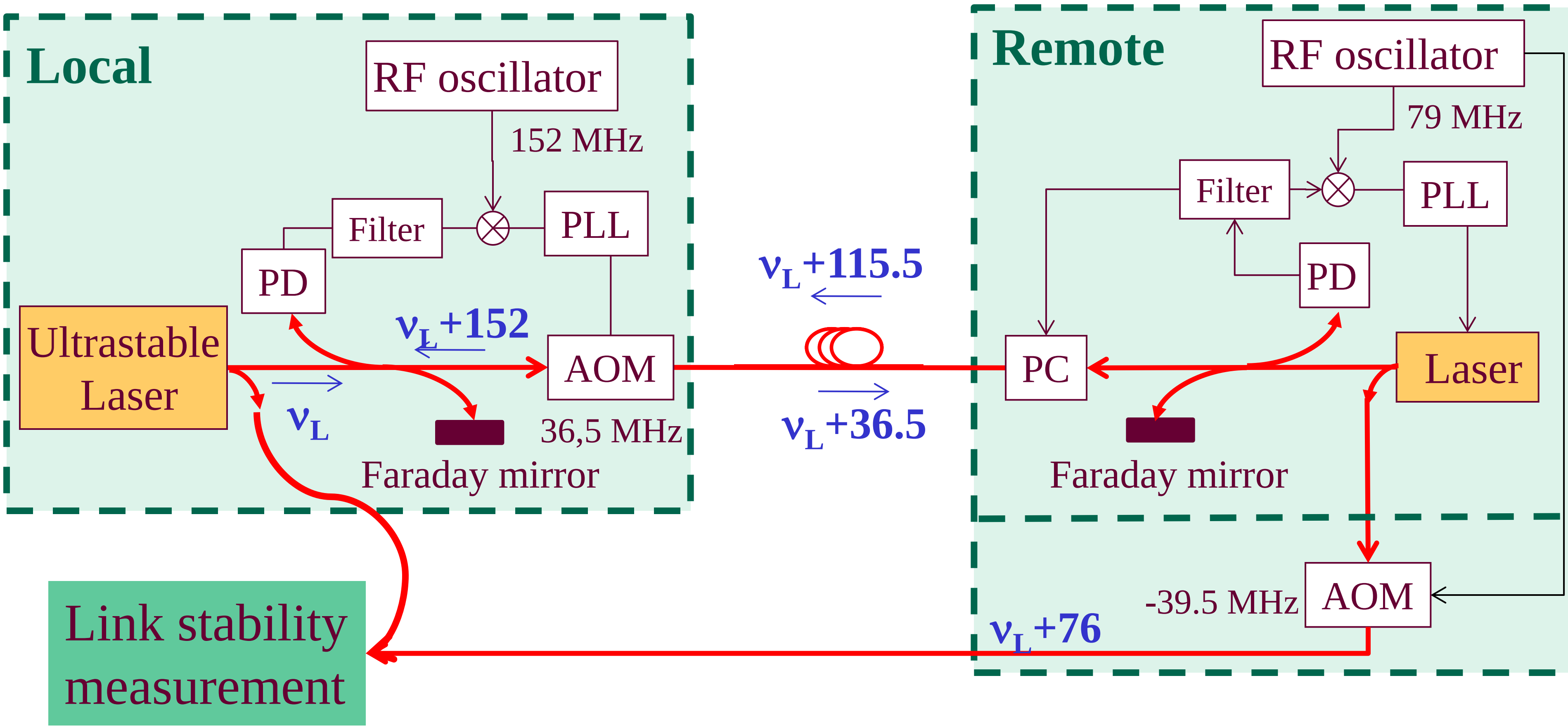
Lien optique LPL-Reims-LPL (540 km)



- 16 OADMs (optical add drop multiplexer) to add and extract signal (100 GHz filter)
- Bidirectional continuous propagation
- Total link attenuation>160 dB , 6 bidirectional EDFA (gain~100 dB)

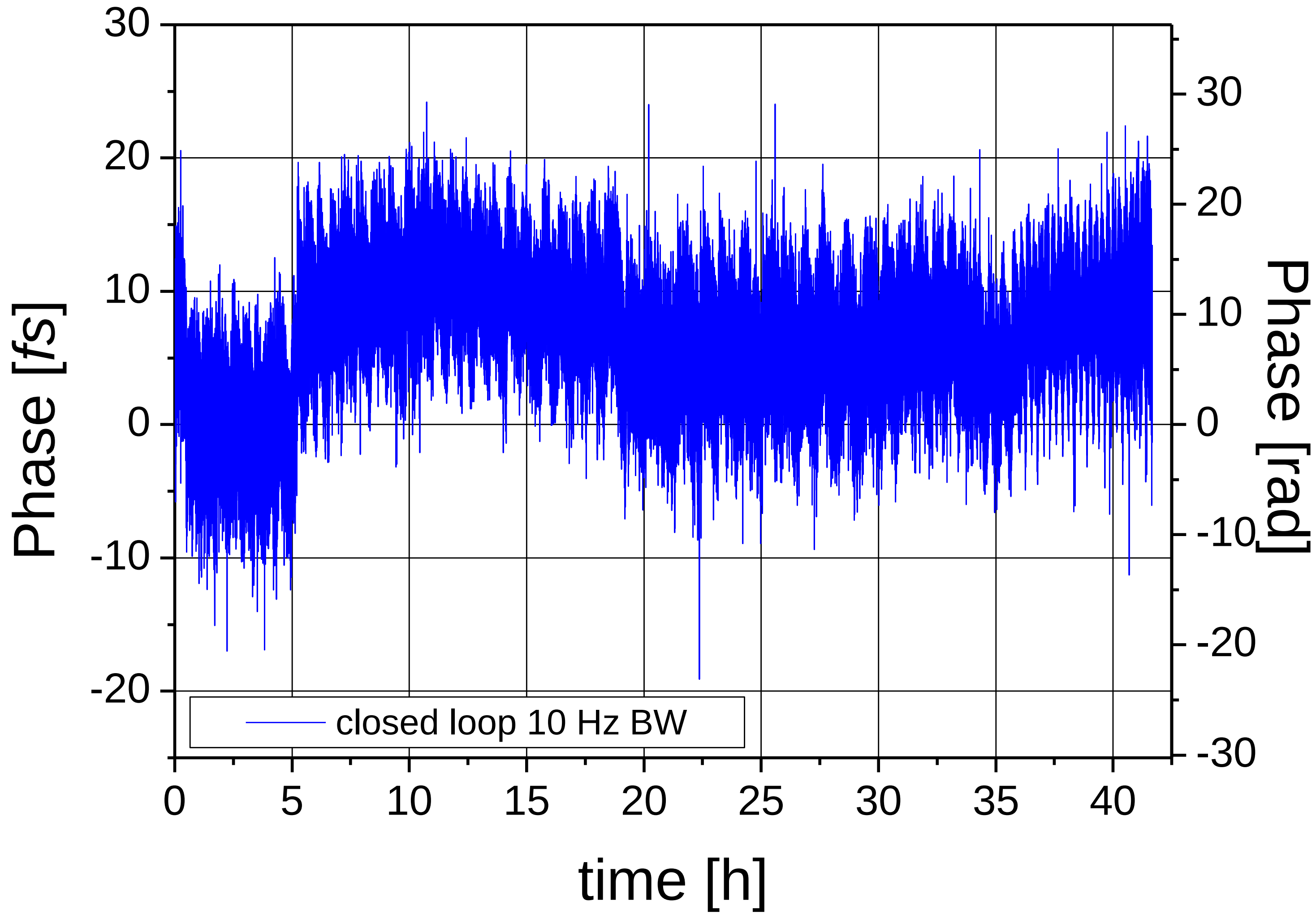


Frequency transfer

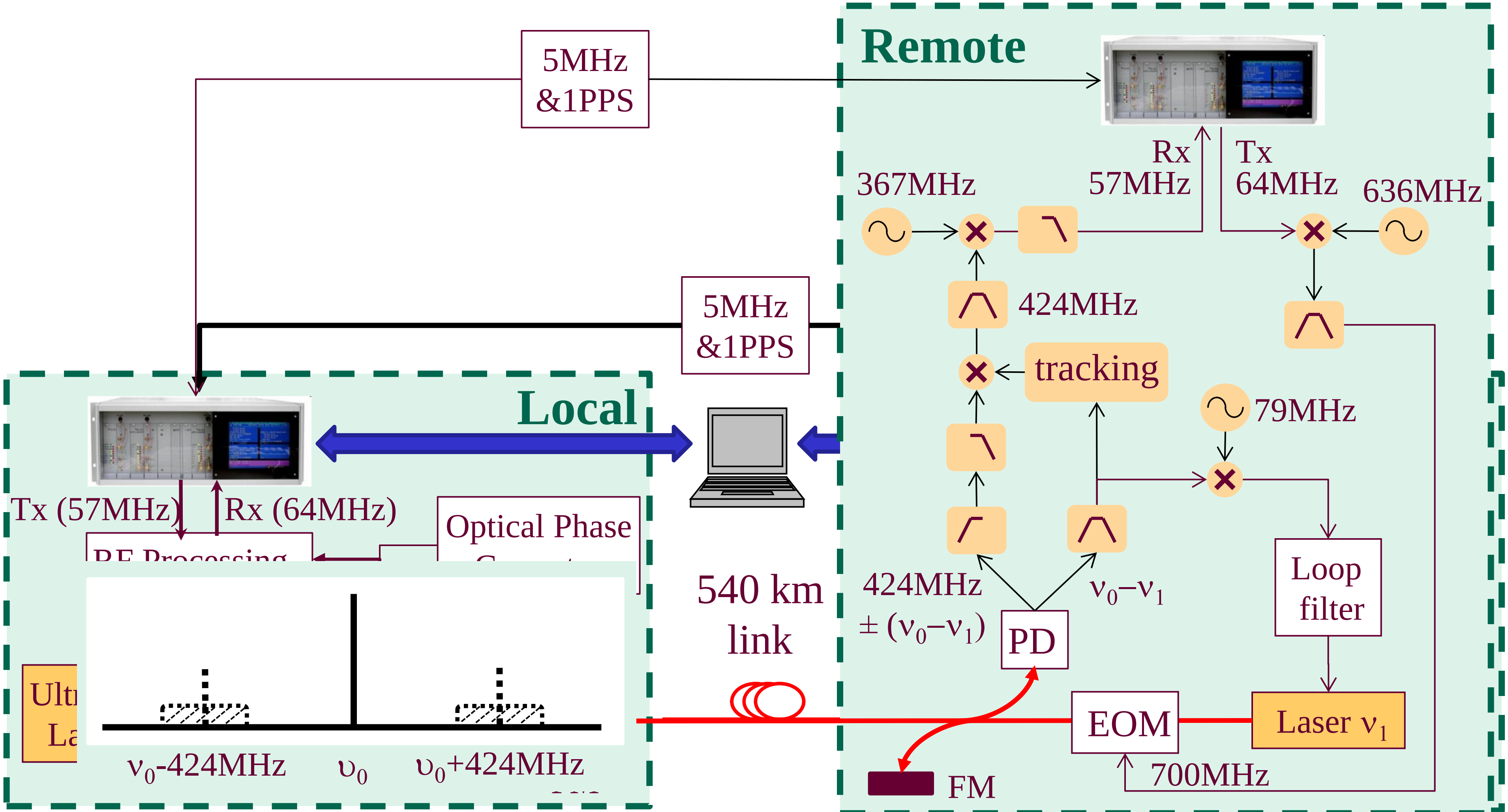


Autonomous lock (microcontroller), no stable RF clock at remote end, optical regeneration (PLL), automatic polarisation controller,

End-to-end phase variation of the compensated 540-km link

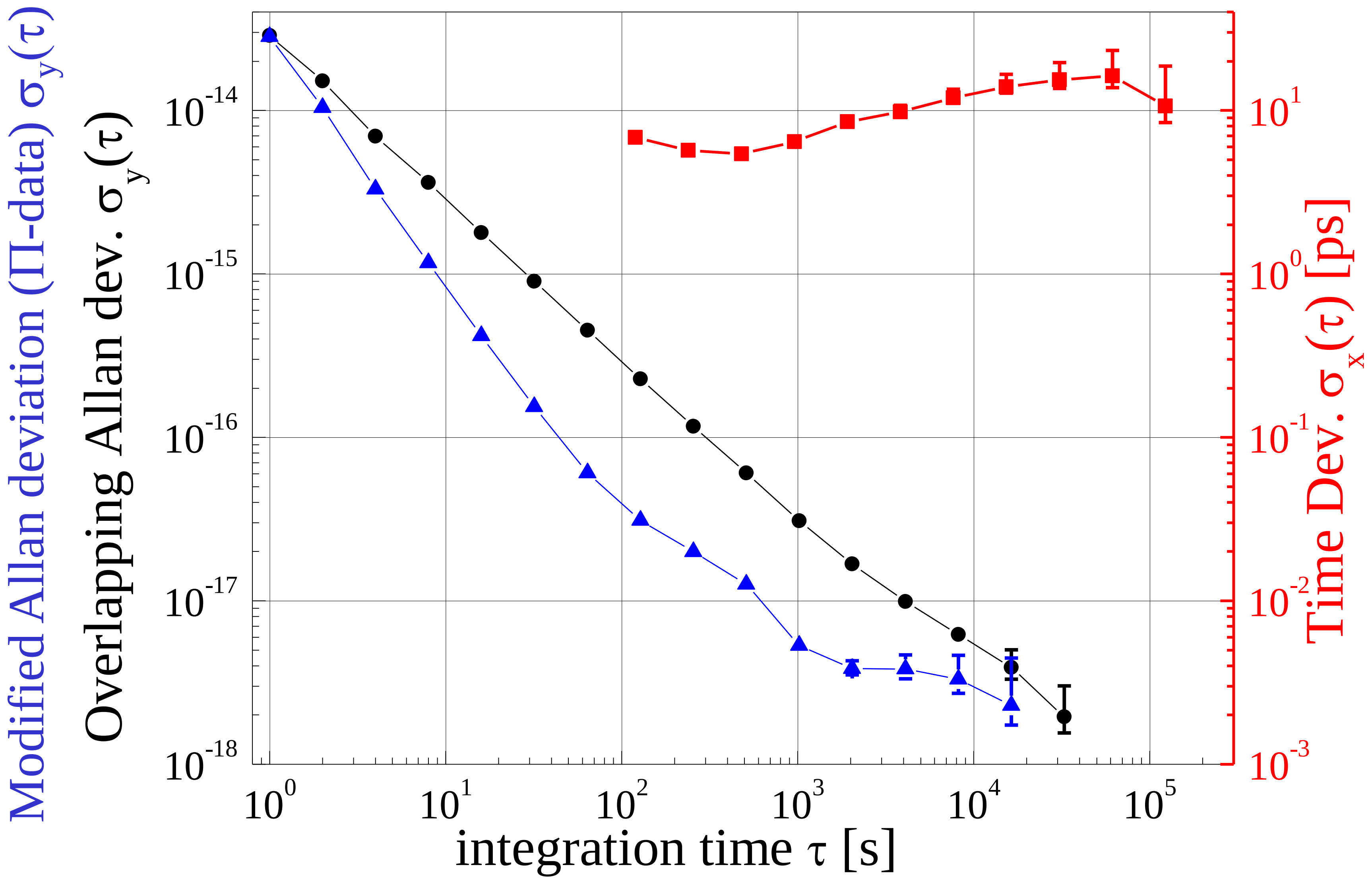


RF processing for time transfer



- Pseudo random noise modulation at 20 Mchip/s with Satre modems
- Phase modulation of the optical carrier with EOM (low modulation 1 %)

Time and frequency transfer stability

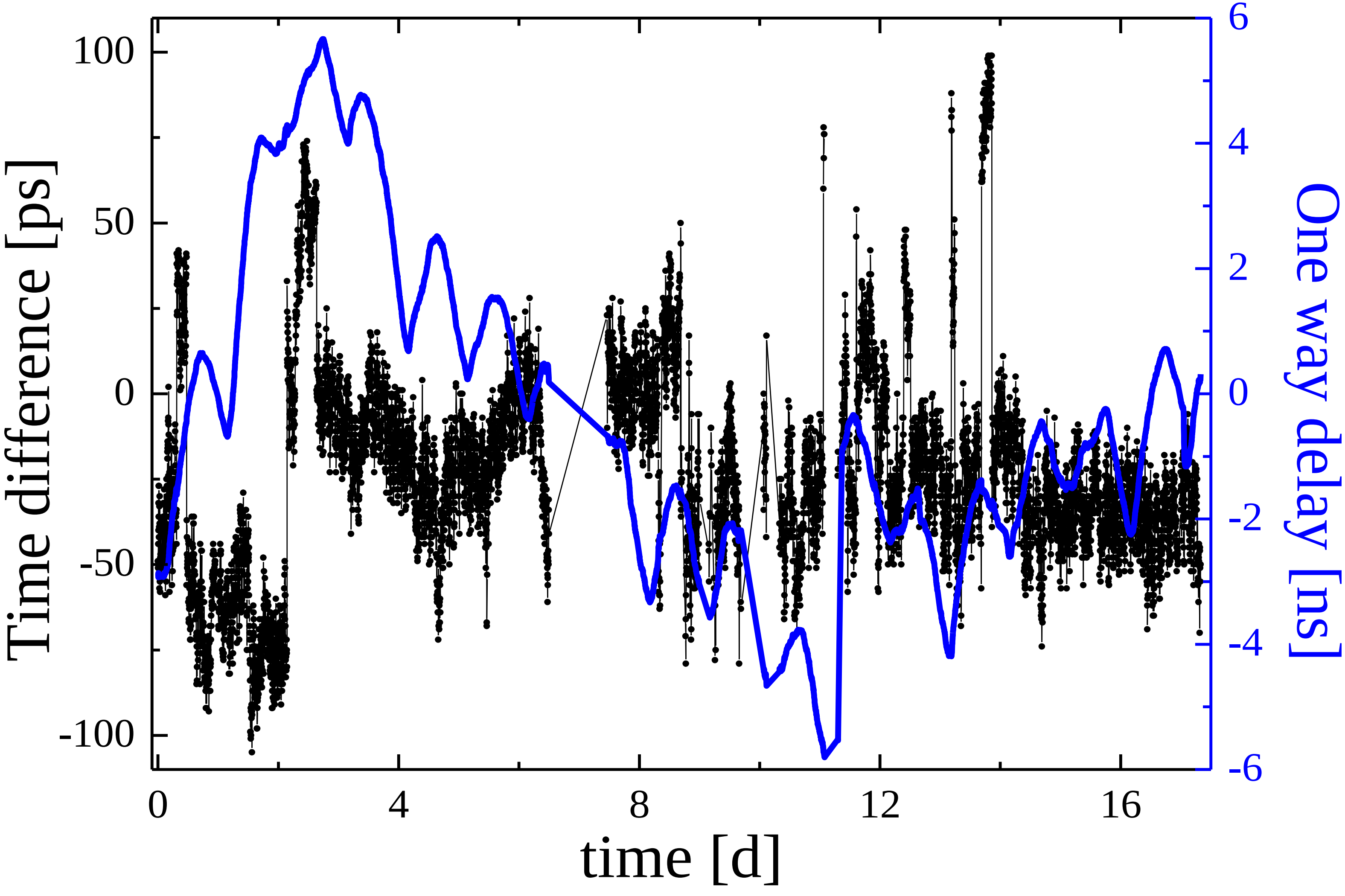


Time transfer reproducibility

- Delay calibration
  - Link length varied from 10 m to 94 km, 400 km and 540 km along the public telecommunication link with fixed overall attenuation (attenuators)
  - Same tests with 25 km, 50 km, 75 km, 175 km fiber spools
  - Differential delay variation< 50 ps
- Power sensitivity (modem at -60 dBm)< 15 ps/dB
- Fiber chromatic dispersion < 25 ps
- Polarisation mode dispersion (PMD) < 20 ps (network characteristics) < 50 ps (measurement)

- But scarce phase jumps of ~100 ps
  - Random and scarce thus difficult to analyse
  - Due to RF processing? Due to Satre dysfunction ?

Time delay measurement



Bilan

- Time and frequency transfer on a 540-km public fiber link with bidirectional amplifiers and 60 dB residual attenuation
  - Stability (1 d) ~20 ps
  - Accuracy ~250 ps
- Room for improvments
  - With wider pseudo-random codes (> 20 Mchip/s)
  - More simple if only two-way time transfer (without frequency transfer)
- Longer distances are possible
  - With a dedicated fiber
  - With a better amplification along the link
  - Or with intermediate regeneration station (to be developed…)

Conclusion et Perspectives

	GPS P3	GPS carrier-phase	TWSTFT TW satellite t & f tr.	T2L2 Time Tr. by Laser Link	TTTOF 60 km Delay-stabilisation	TTTOF 540 km Two-way public fiber
Accuracy	3 ns	3 ns	1 ns	200 ps (expected)	7 ps ~100 ps (420 km)	250 ps
Stability (1d)	0.2 ns	0.1 ns 80 ps (PPP)	40 ps	<10 ps (100 s)	0.3 ps	20 ps

- Perspectives
  - Remote clock comparison and calibration
  - Test of satellite links (ACES MWL, TWSTFT or GPS PPP)
  - Application to time synchronization in astrophysics or particle physics

Contributors

Collaboration between

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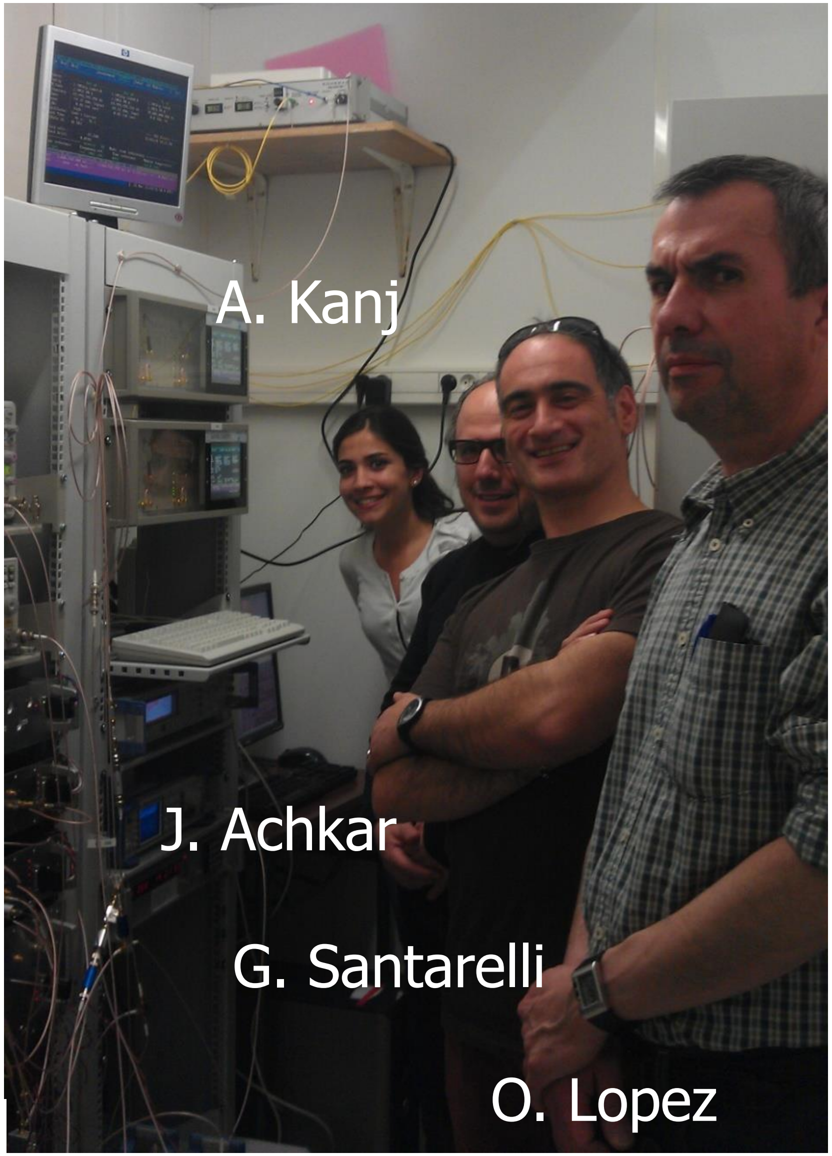

Lopez et al, APB 2013 (online 2012)