Time transfer through optical fibers

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

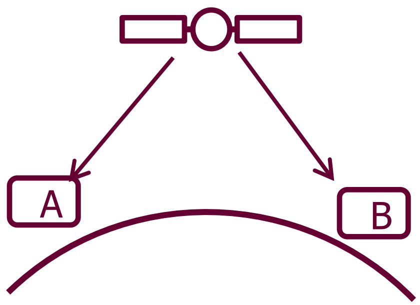
Outline

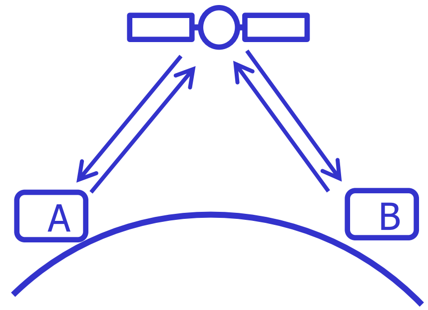
- Overview of time transfer current performance
- Time Transfer through Optical Fiber
  - Network protocol
  - Two-way time transfer
  - Delay-stabilized time transfer
- Two-way time transfer over Internet fiber Network

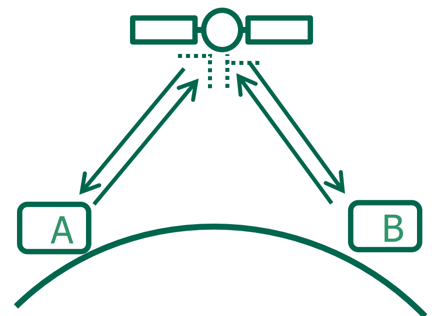
Many thanks to P.0. Hedekvist, M. Merimaa, V. Smotlacha, P. Krehlik, D. Piester for providing most recent results

State of the art of time transfer

- Satellite time transfer







Laser pulse reflection and datation

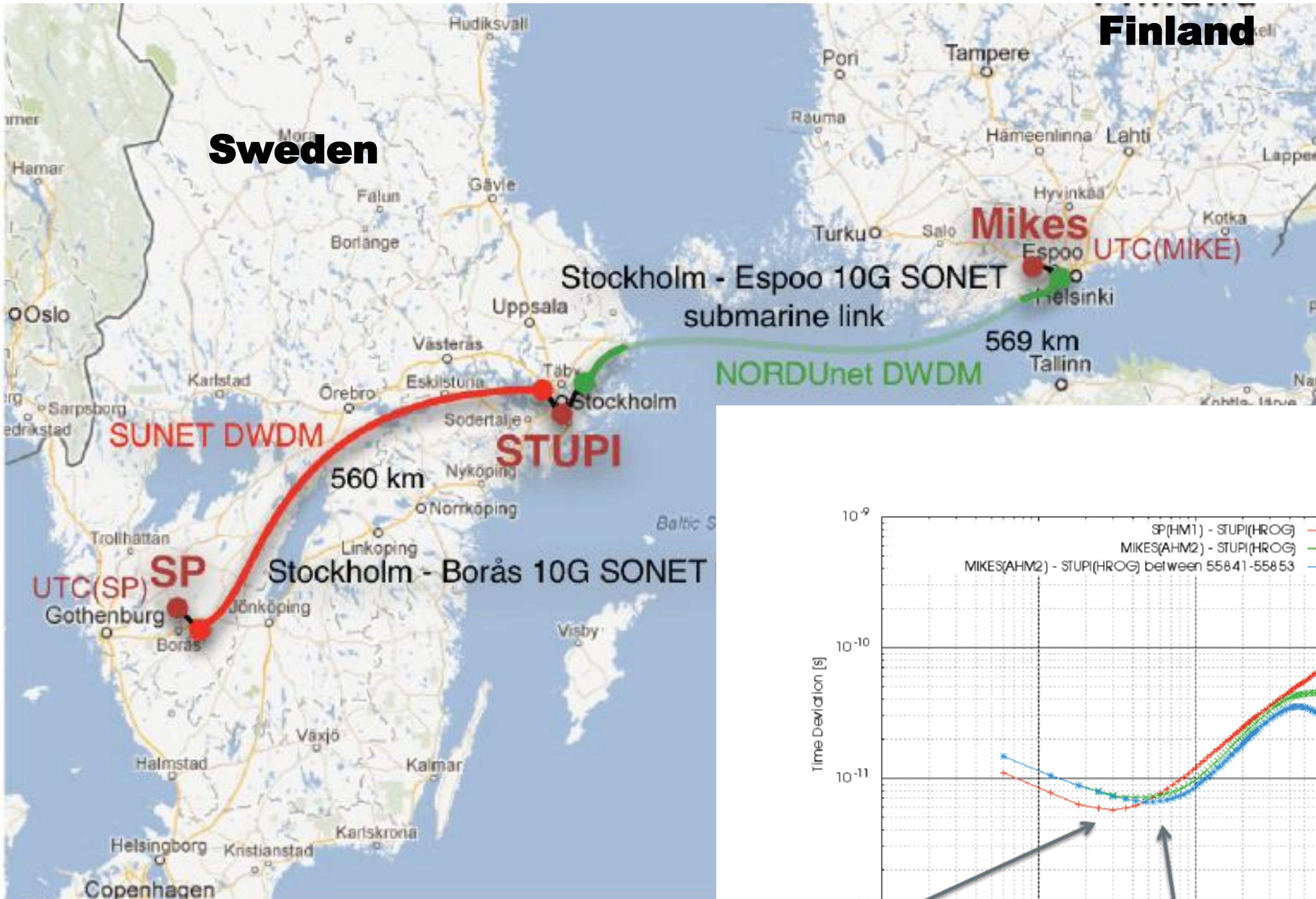
	GPS P3	GPS carrier-phase	GPS PPP	TWSTFT Two-way satellite t & f tr.	T2L2 Time Tr. by Laser Link
Accuracy	3 ns	3 ns	3 ns	1 ns	200 ps (expected)
Stability (1d)	0.2 ns	0.1 ns	80 ps	40 ps	<10 ps (100 s)

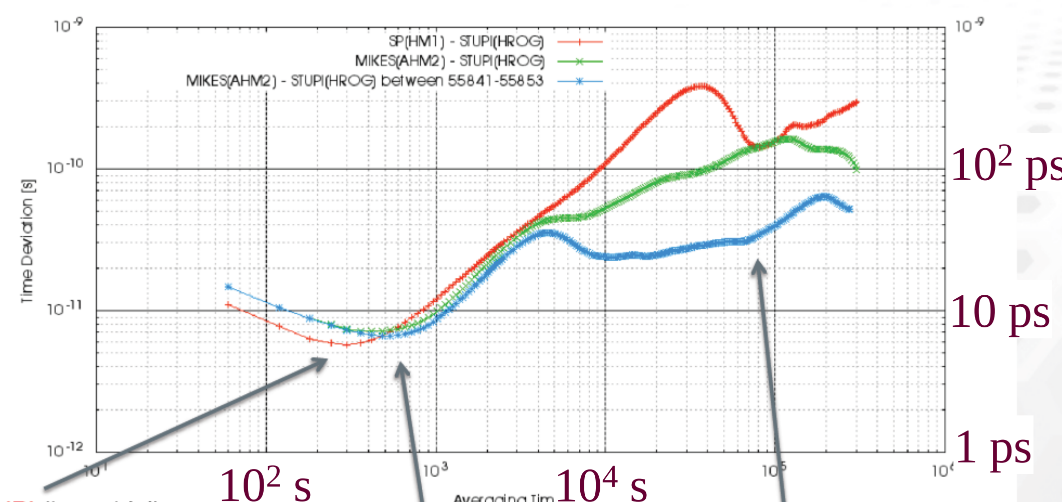
Time transfer through optical fiber

- Network protocol (fiber or cable)
  - Accuracy 1 ms (NTP) - 1 µs (Precise Time Protocol PTP)
- Two-fiber timing transfer
  - SP/Mikes/STUPI (Sweden/Finland) 570 km using SONET frame: dayly variation ~ a few ns, best stability (1 d) ~30 ps (submarine)
  - Cesnet/IPE/Austria (Smotlacha et al) 550 km: stability (1 d)~1 ns
- Delay-stabilized time transfer
  - AGH Poland 60 km (480 km), accuracy ~7 ps, stability(1 d) ~0.3 ps
- Single-fiber two-way time transfer
  - PTB/Hannover 73 km : accuracy ~75 ps, stability (1 d) ~50 ps
  - LPL-Syrte 540 km : accuracy ~200 ps, stability (1 d) ~20 ps

Time Transfer between SP and MIKES

Passive SONET frame listening and detection done just before/after the router client ports





SP-STUPI (terrestrial)
5-6 ps at 300 s

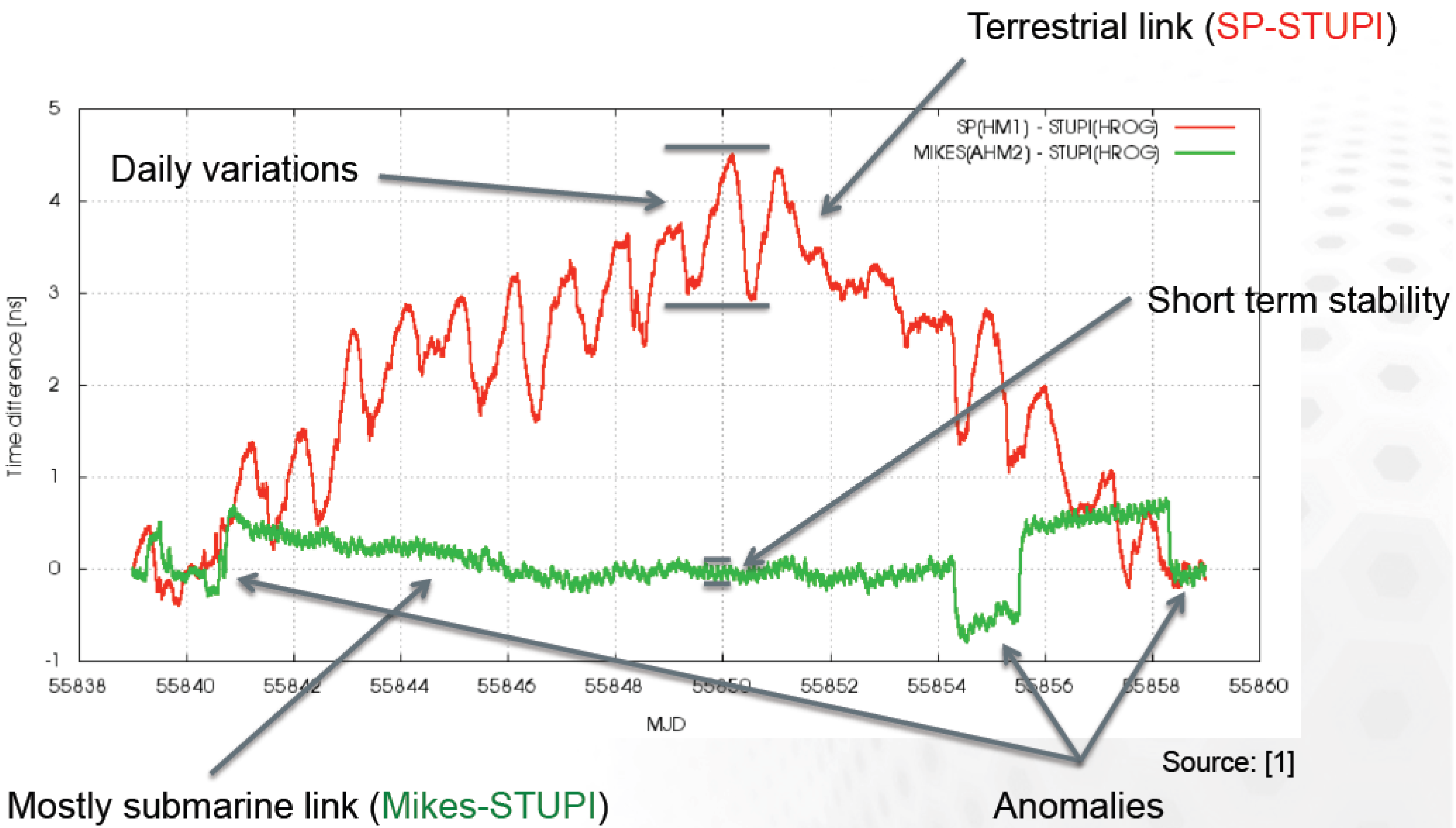
Mikes-STUPI (submarine)
6-7 ps at 600 s

Mikes-STUPI "best results" (submarine)
30 ps at one day (80400 s)

Source: [1]

Sven-Christian Ebenhag, P. O. Hedekvist et al (SP, Technical Research Institute of Sweden), Peter Löthberg (STUPI, Sweden), M. Merimaa et al (Mikes, Centre for metrology and accreditation, Finland)

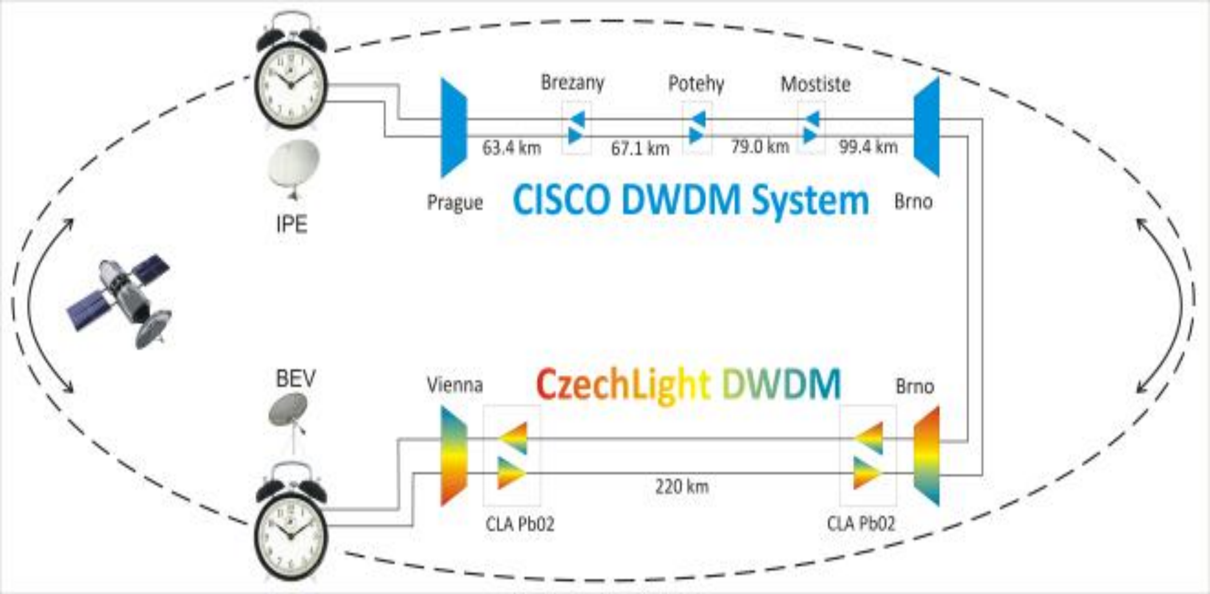
Clock difference SP-STUPI and Mikes-STUPI



"Time Transfer between UTC(SP) and UTC(MIKE) Using Frame Detection in Fiber-Optical ommunication Networks", S-C Ebenhag et al, Proceedings of PTTI 2011

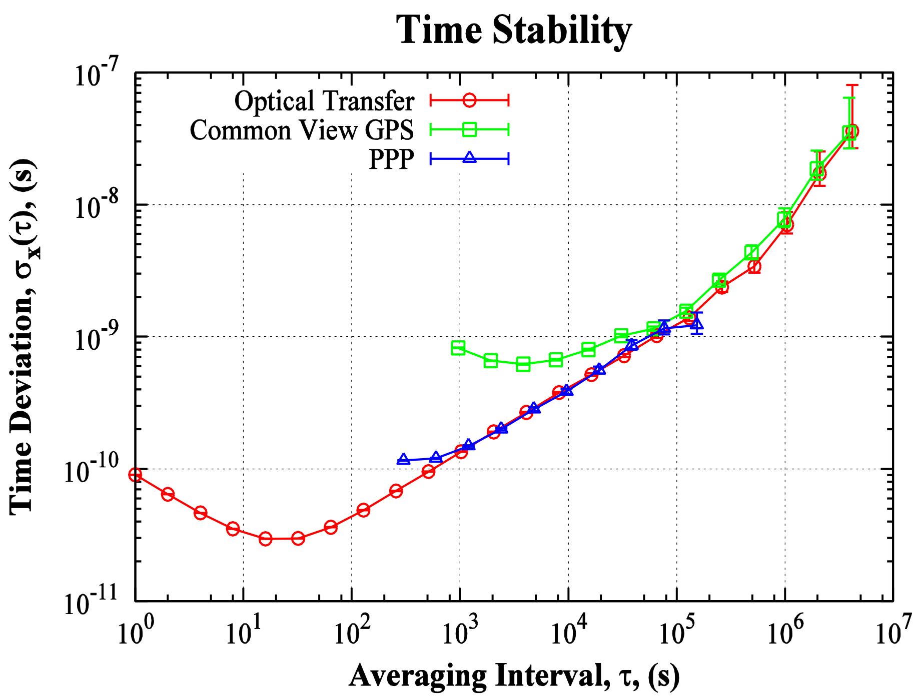
Time Transfer between Prague and Vienna

- comparison of time scales UTC(TP) and UTC(BEV)
- bidirectional time transfer using two fiber threads
- optical link length 550 km
  - 529 km of all-optical lambda in production DWDM systems
  - 21 km of dark fiber
- utilizes SFP/SFP+ transceivers
- continuous operation since August 2011

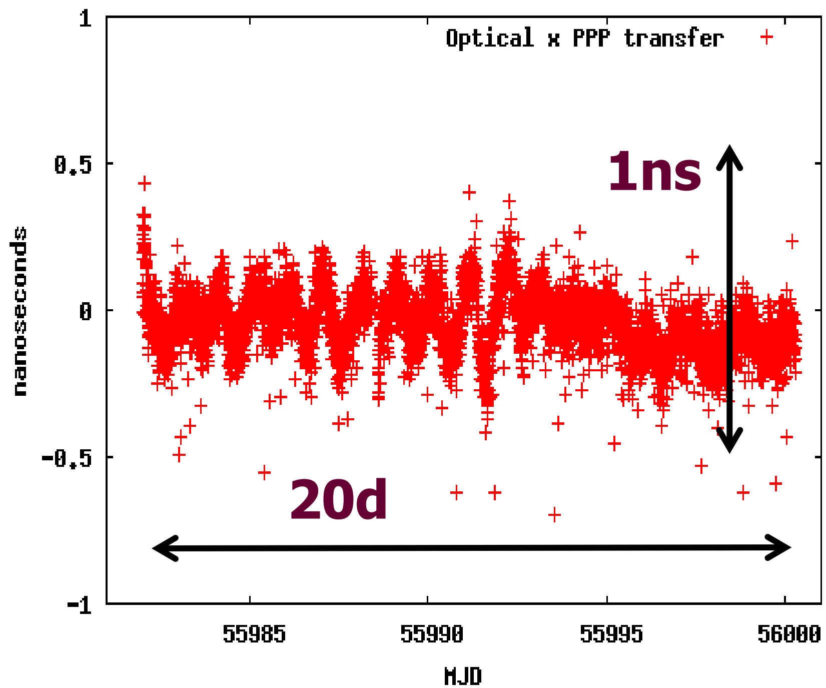


V. Smotlacha, A. Kuna, "Two-Way Optical Time and Frequency Transfer between IPE and BEV", proceedings of EFTF2012

Results of Time Transfer between Prague and Vienna



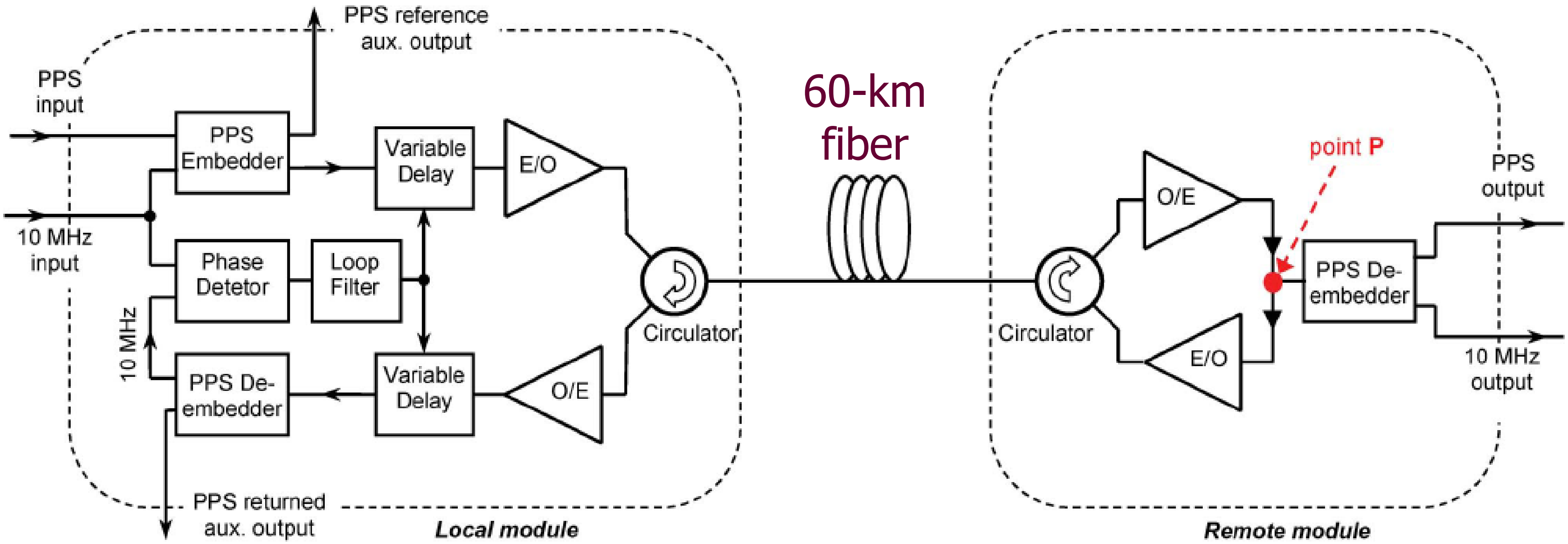
Time transfer stability
stability (1d)~1ns



Difference between optical time transfer and GPS carrier phase method

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

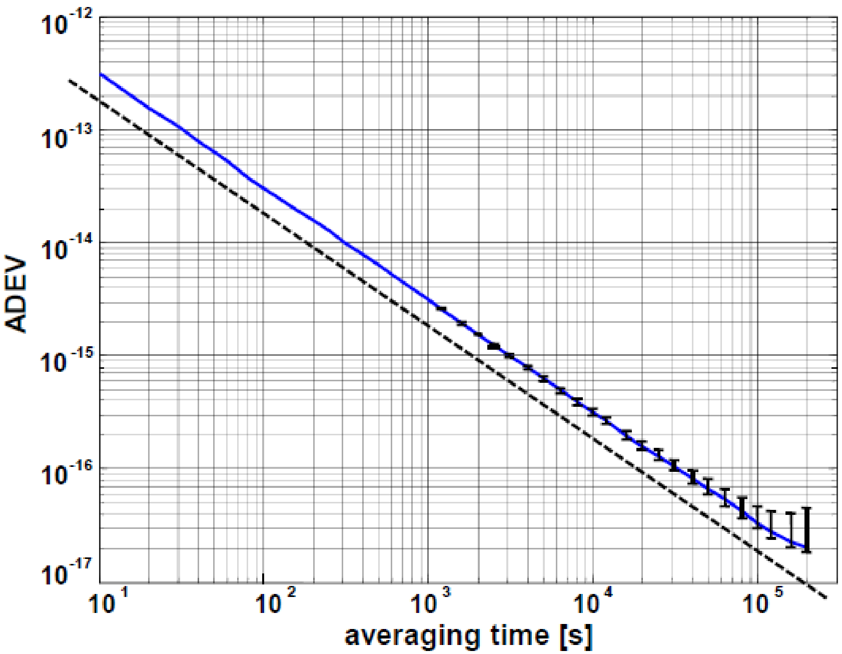
P. Krehlik, Ł. Śliwczyński, Ł. Buczek, M. Lipiński, AGH University of Science and Technology, Institute of Electronics, Kraków, Poland, IEEE Trans. on Instr. and Meas. (2012).

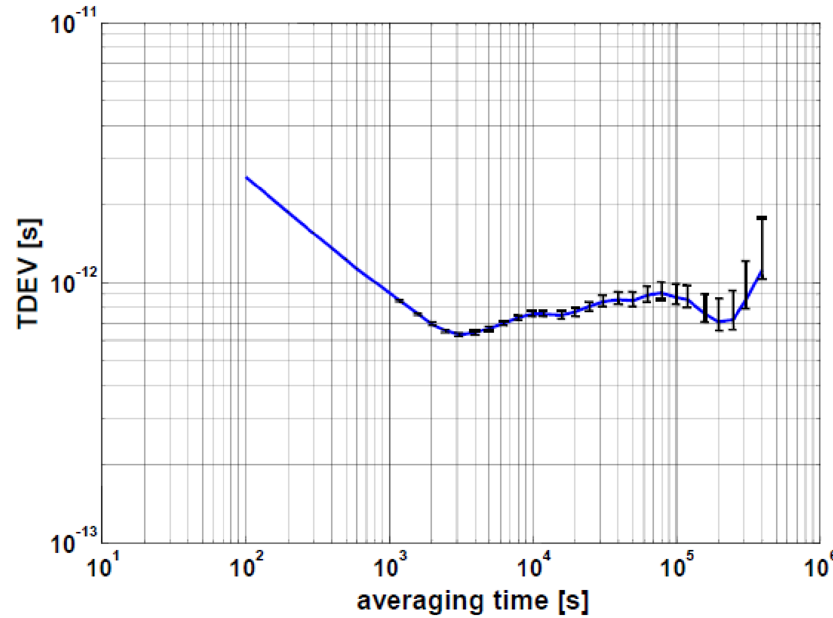


- 10-MHz + 1pps joint transfer through intensity modulation of the optical carrier
- Roundtrip propagation in the same fiber for noise correction
- Active stabilization of the propagation delay through a variable delay module (DLL)

Delay-stabilized time transfer (II)

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

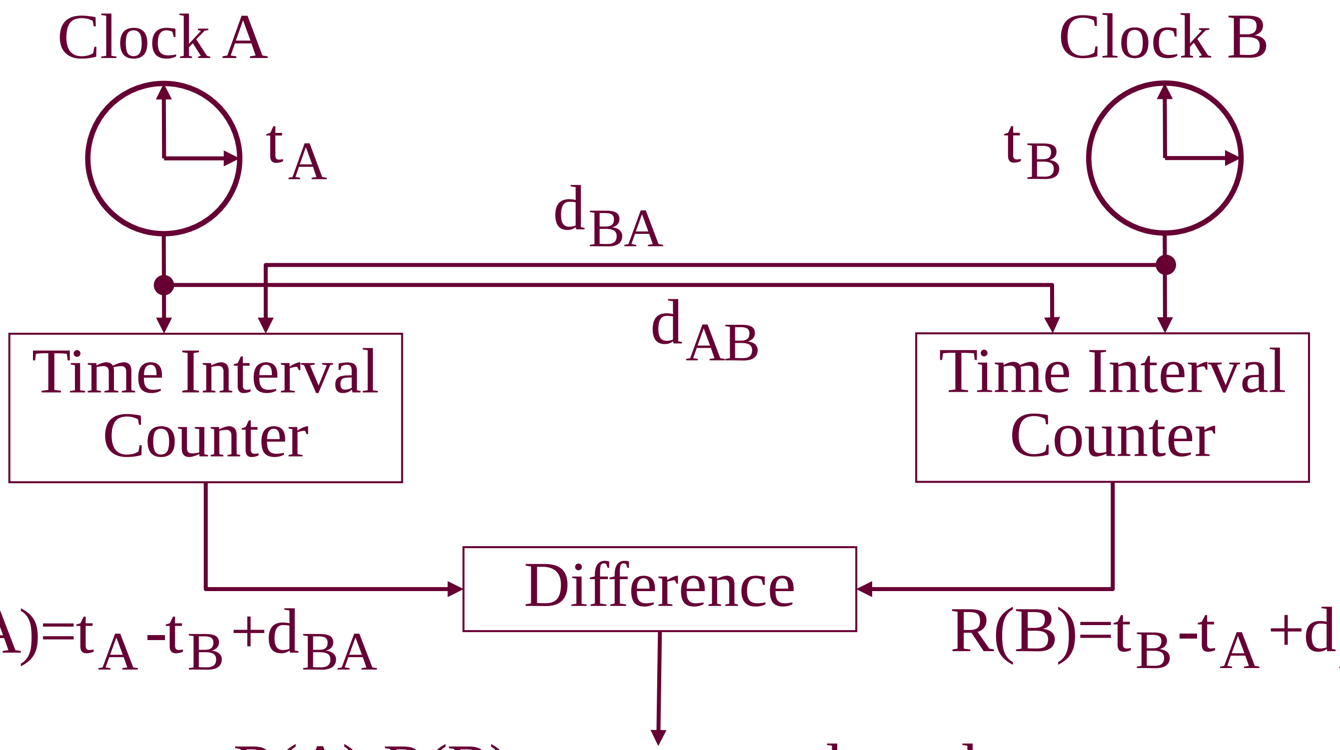




•Allan Deviation (10MHz)
480 km spooled fiber + 8 SPBAs
6 days measurement in varying temperature

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

Two-way time transfer



From Hanson, 1989 Symposium on Frequency Control

$$R(A)=t_A-t_B+d_{BA}$$

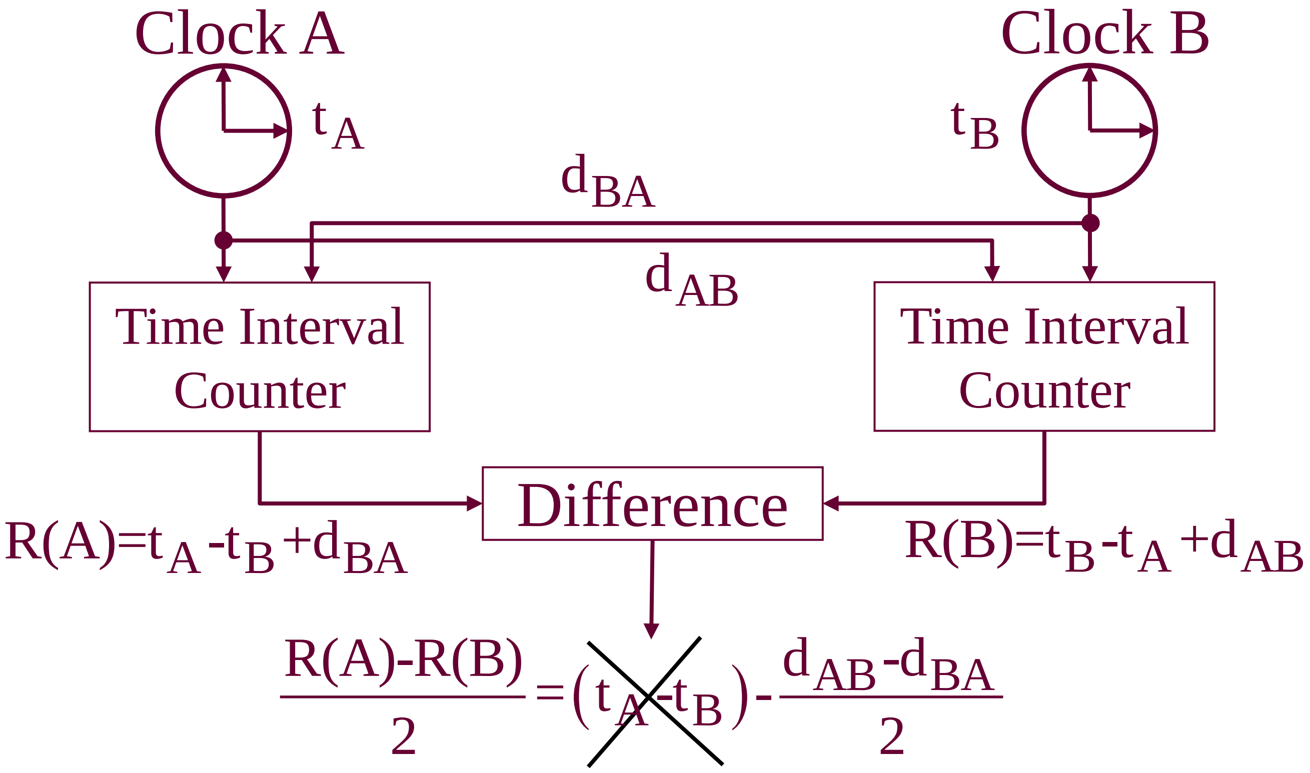
$$R(B)=t_B-t_A+d_{AB}$$

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

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

Calibrated/Calc | Calibrated | Calculated

Fiber two-way time transfer



- Clock A = clock B

+ link length =1m

→ Calibration of differential instrumental delay

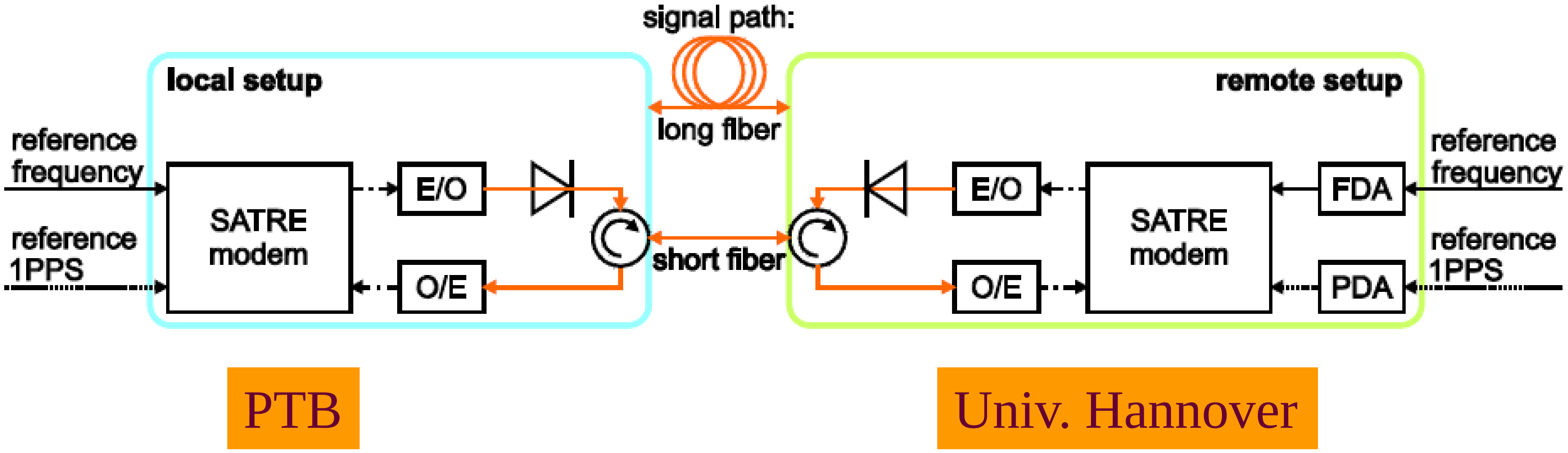
- Clock A = clock B

+ various fiber lengths

→ Calibration of differential propagation delay

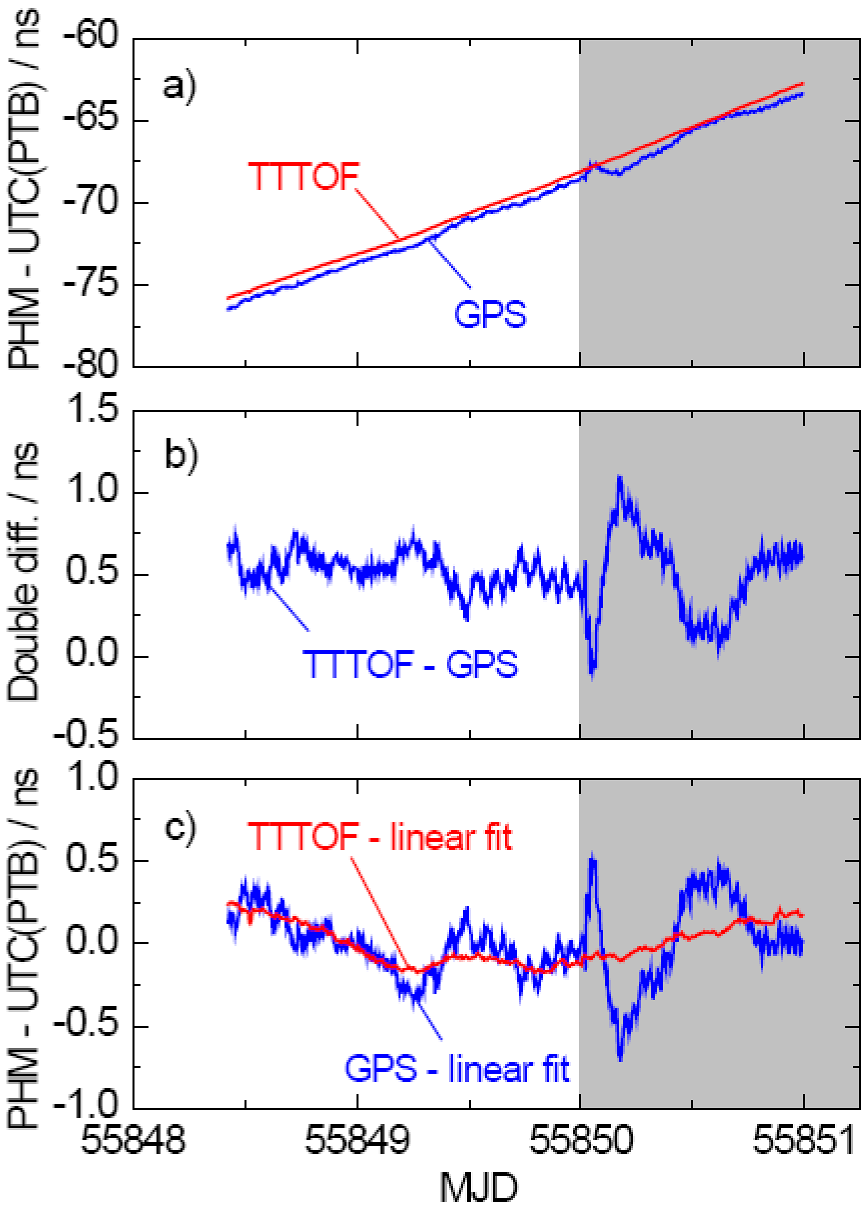
Time transfer through 73-km fiber between PTB and Hannover (I)

- 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



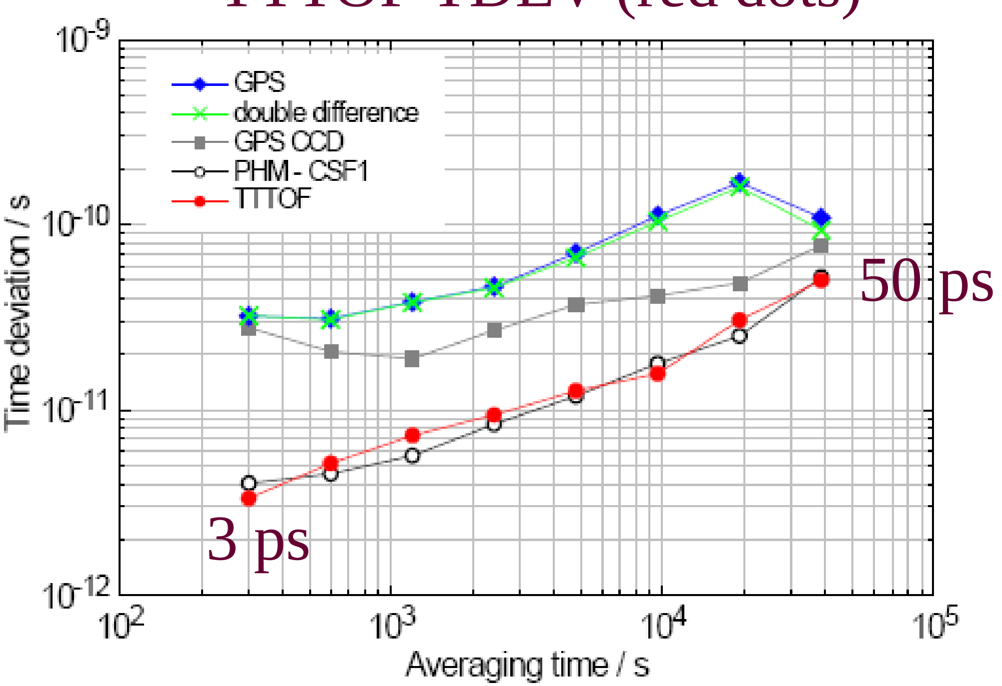
- GPS calibration system used in parallel
- Calibration with 1 m fiber at PTB and common clock
- Total uncertainty 74 ps

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

TTTOF TDEV (red dots)



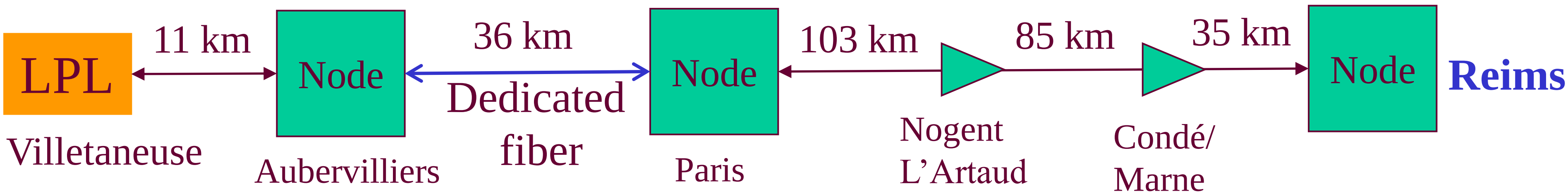
Joint time and frequency transfer over a public fiber network

- Two-way time transfer using Satre modems
- Two ends at same place for calibration purpose

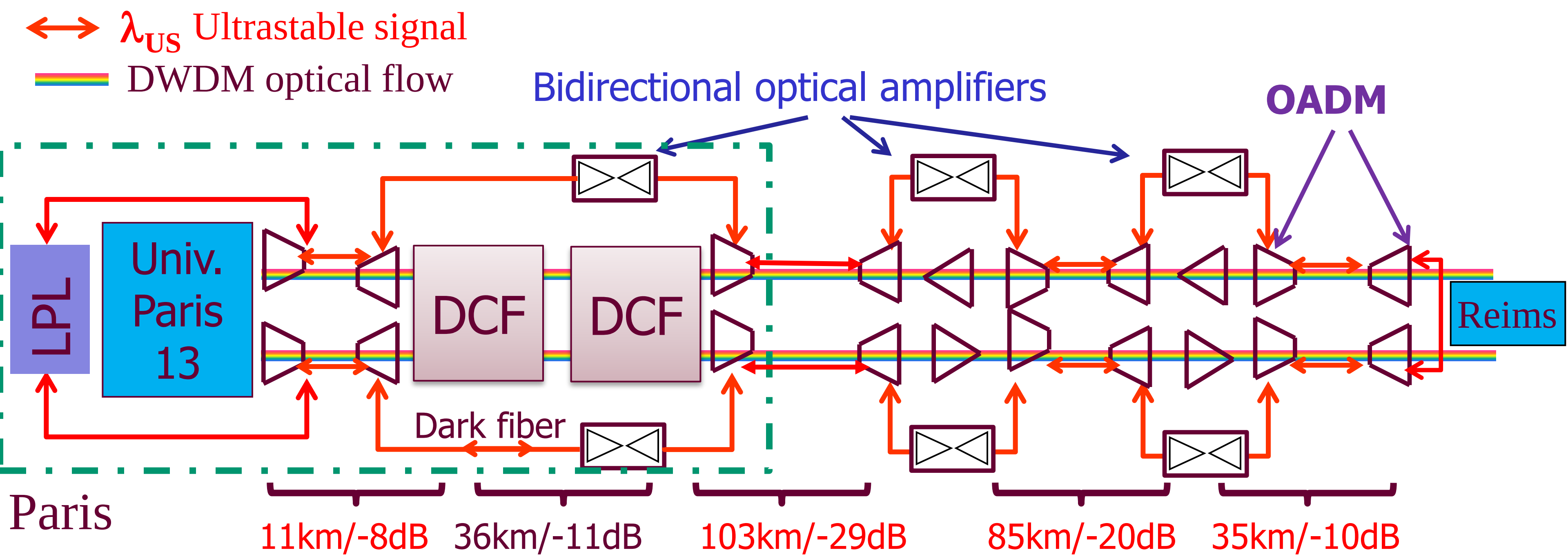
- Fiber link = public telecommunication fiber with data traffic
- Collaboration with National Research and Education Network (NREN), in France : RENATER
  - Dense Wavelength-Division Multiplexing (DWDM) :

    fiber is shared between multiple signals, each of them is attributed a 100 GHz optical frequency range (=channel)
  - 1 channel of the fiber is attributed to time and frequency transfer, channel #44 centered at 1542.14 nm
  - Other channels are used for data traffic
  - Multiplexers to separate channels

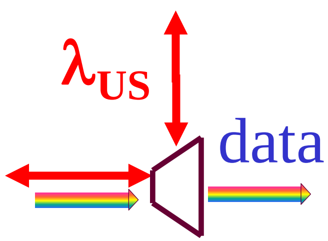
540-km optical link Paris-Reims-Paris



540 km LPL-Reims-LPL optical link

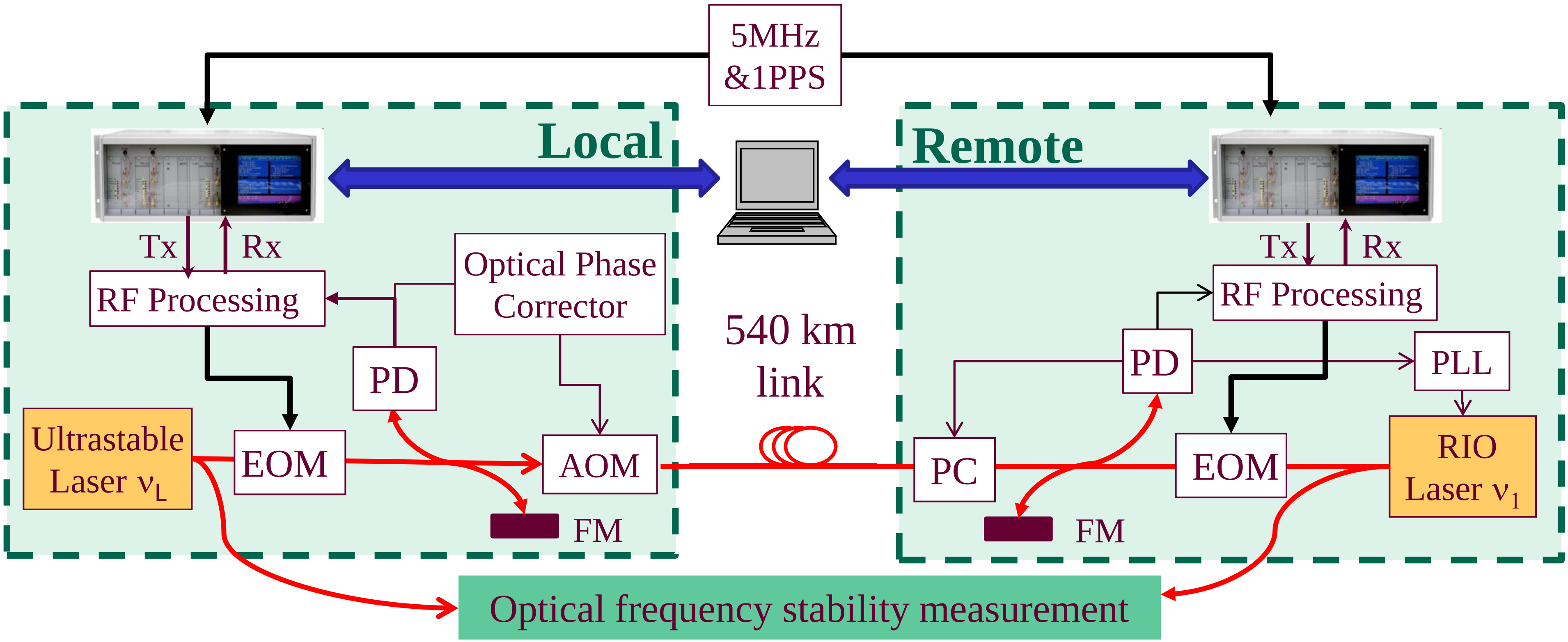


- 16 OADMs (optical add drop multiplexer) to add and extract signal (100 GHz filter)
- Bidirectional continuous propagation
- Total link attenuation>160 dB , 6 bidirectional EDFA (gain~100 dB)



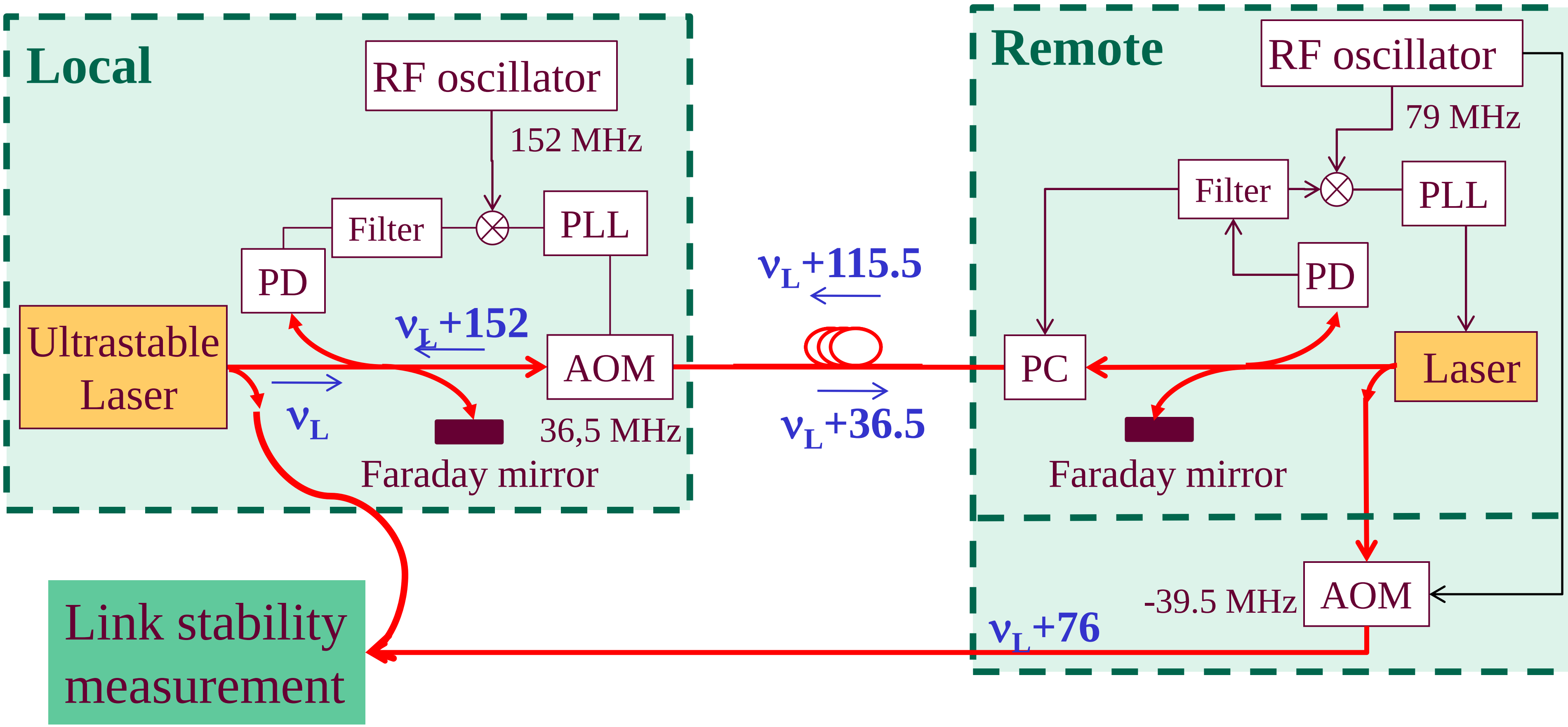
OADM and EDFA modules in Condé

Experimental set-up



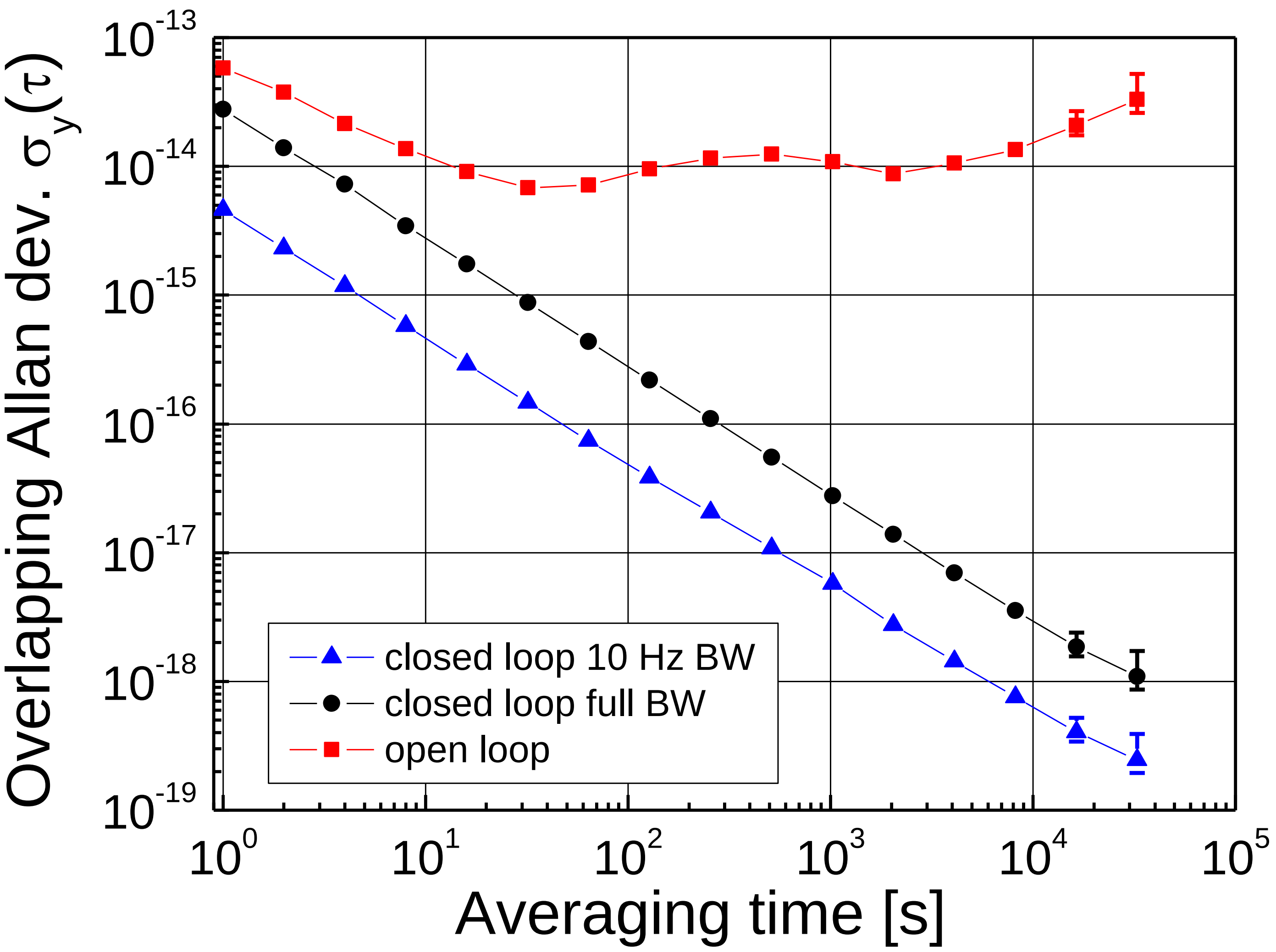
- Frequency transfer with « round-trip » method for fiber noise compensation
- Two-way time transfer using Satre modems

Frequency transfer

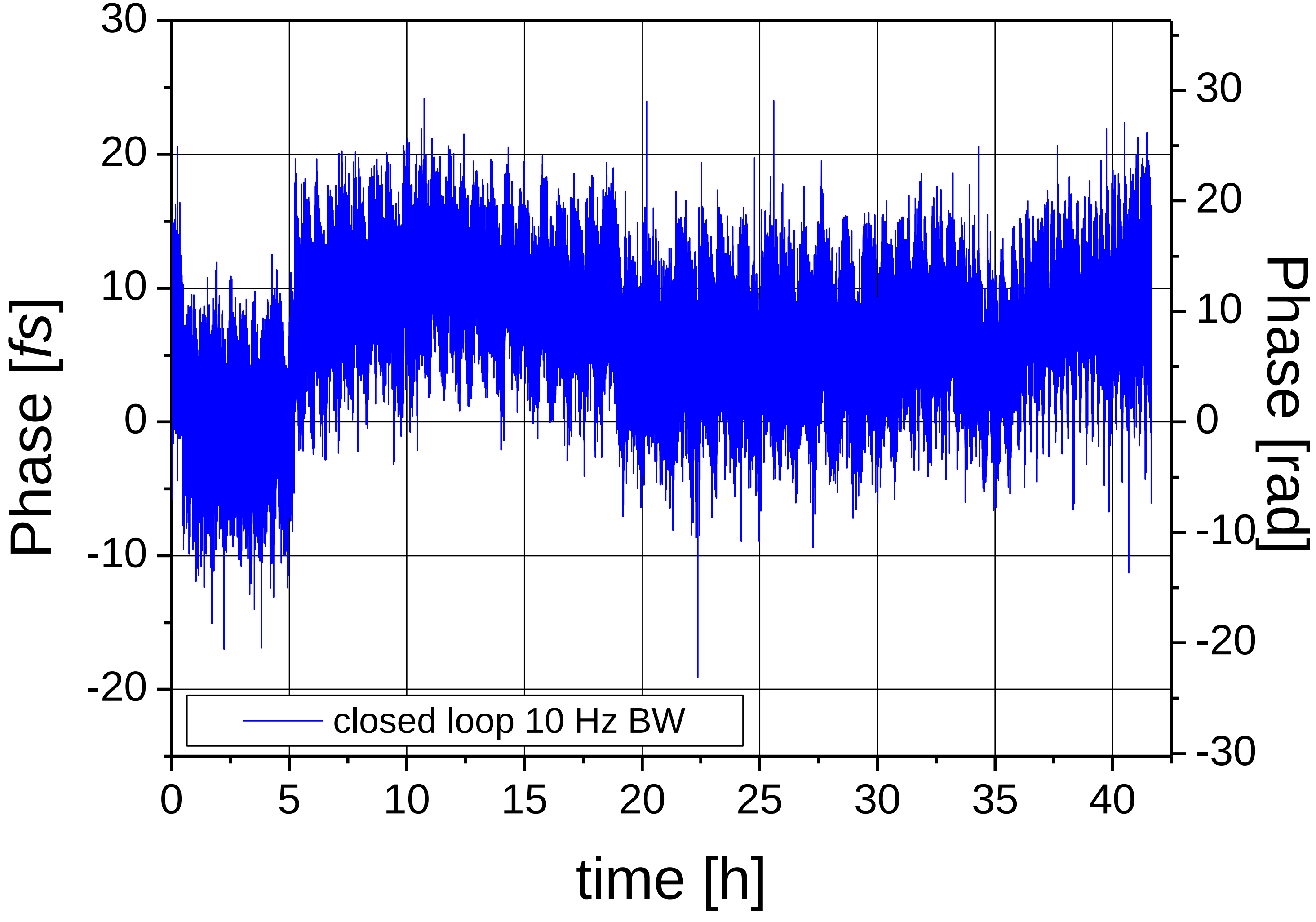


Autonomous lock (microcontroller), no stable RF clock at remote end, optical regeneration (PLL), automatic polarisation controller,

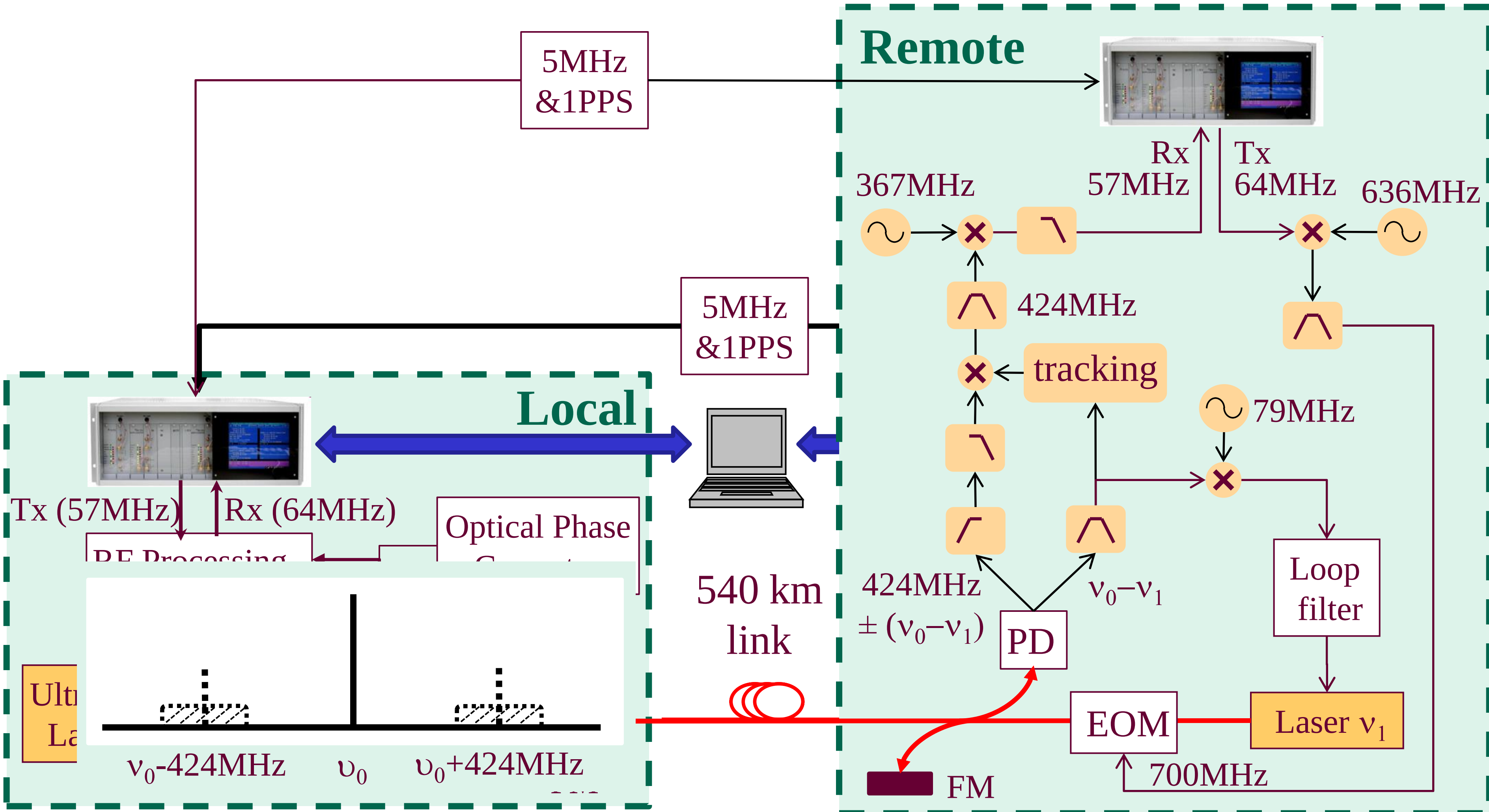
End-to-end stability of the 540-km link



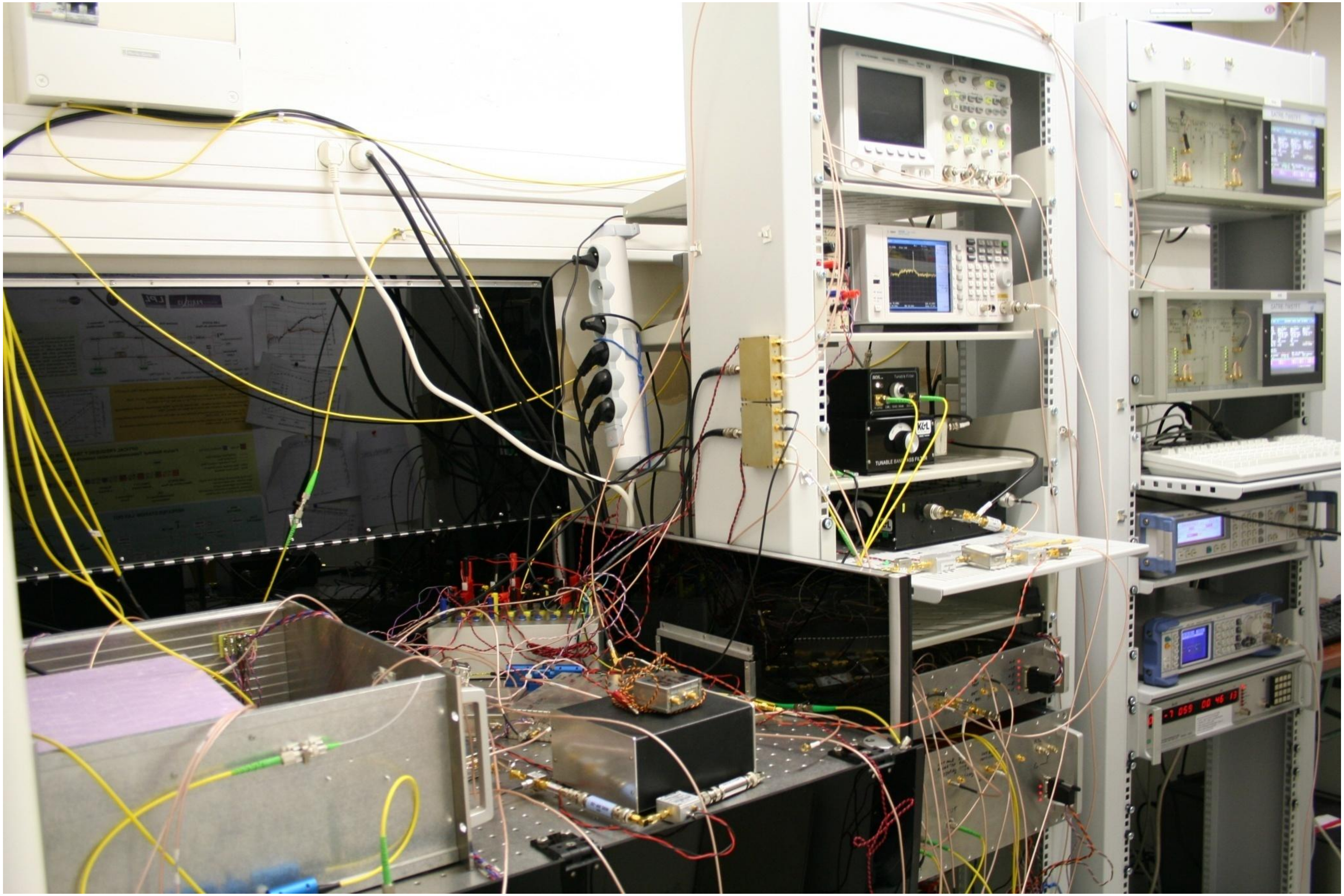
End-to-end phase variation of the compensated 540-km link



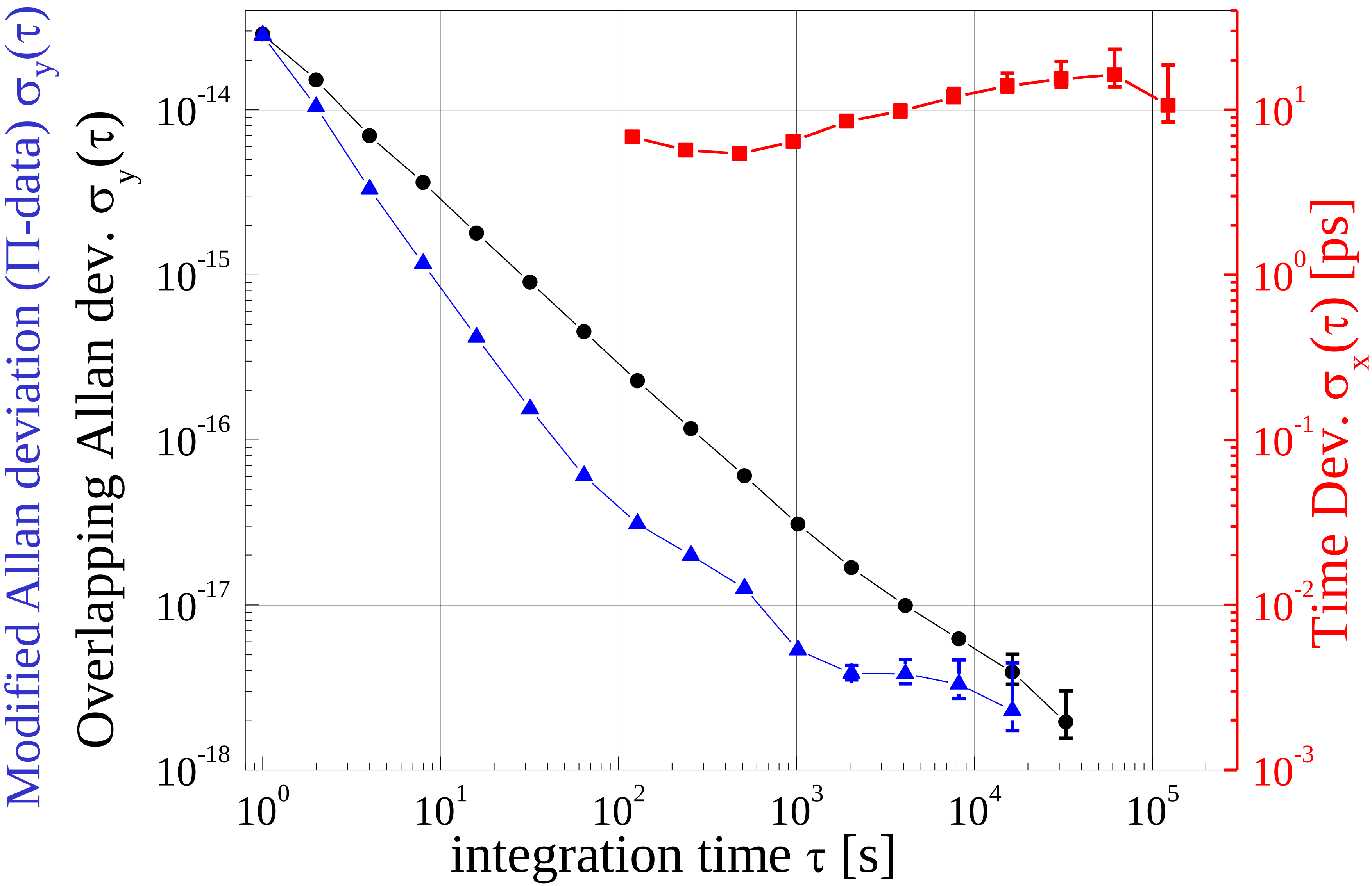
RF processing for time transfer



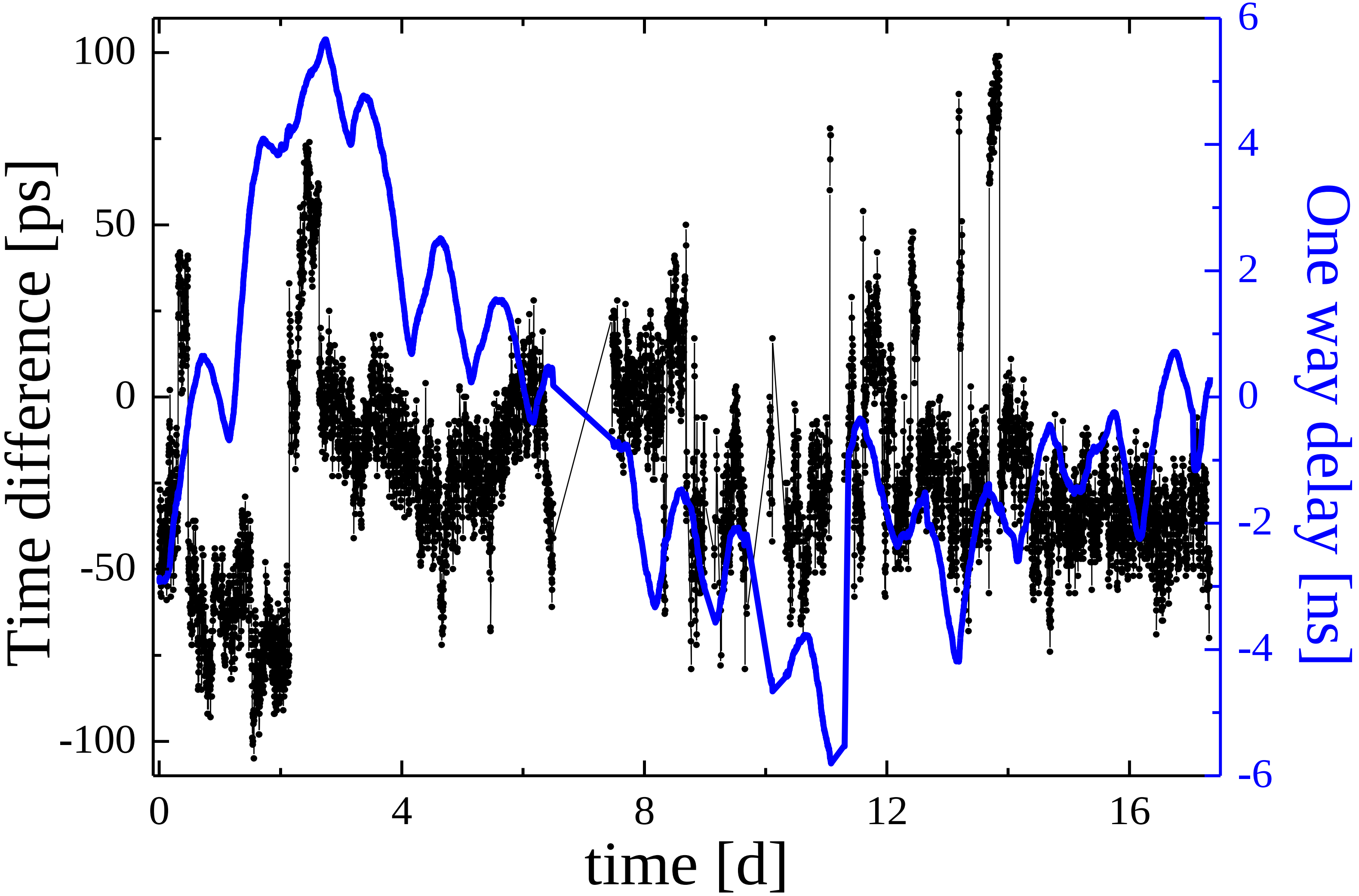
- Pseudo random noise modulation at 20 Mchip/s with Satre modems
- Phase modulation of the optical carrier with EOM (low modulation 1 %)



Time and frequency transfer stability



Time delay measurement



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 ?

Summary

- 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 better amplification along the link
  - Or with intermediate regeneration station (to be developed…)

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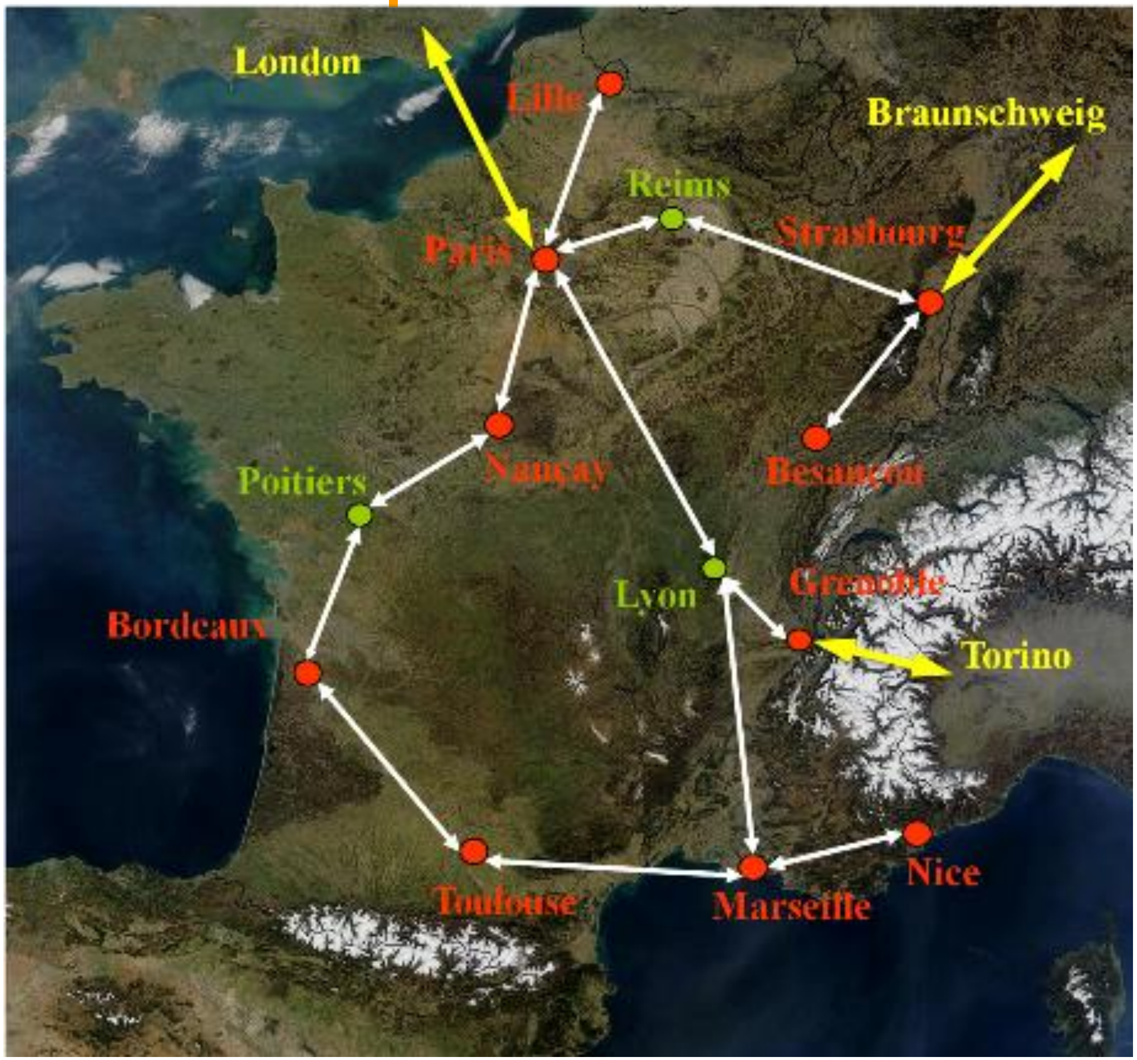

Funded
January 2012

Outlook

- Time Transfer Through Optical Fibers is developing very fast
  - Stability and accuracy outperforms satellite techniques
  - Active delay stabilisation enables the best stability and accuracy
  - Heterodyne detection at links ends enables long-distance time transfer
- Time Transfer Through Optical Fiber has been demonstrated on a 540-km public telecommunication network
  - Future development at the European scale is possible
- 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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