AGH University of Science and Technology

ELSTAB electronically stabilized fiber optic system for time and frequency distribution with picoseconds accuracy

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Presentation outline

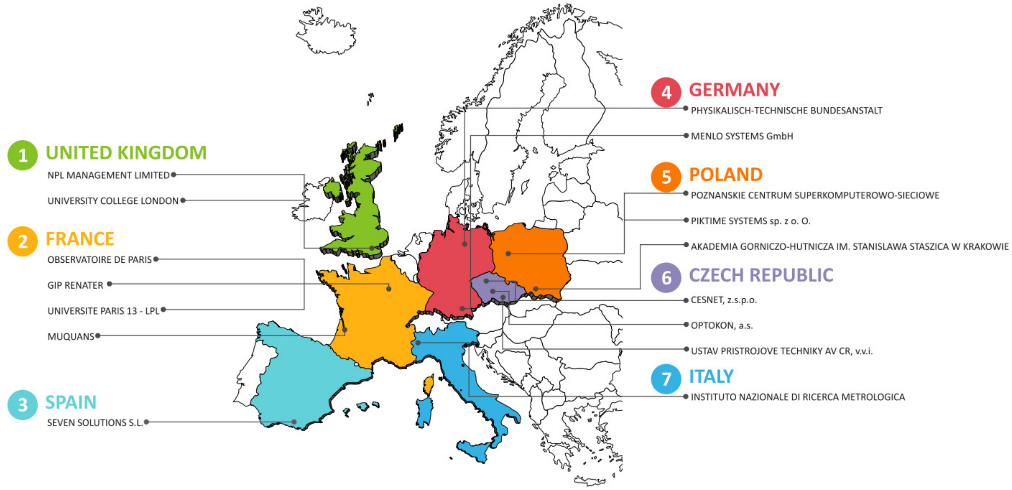
1. International projects related to fiber T/F distribution
2. General idea of T/F distribution
3. Fiber optic T/F distribution
4. Electronically stabilized fiber T/F transfer with ELSTAB
   - idea
   - time transfer calibration
5. Experimental results & implementations
   - PIONIER related links in Poland
   - OTT with Deutsche Telekom and PTB
5. Summary

International projects related to fiber TF transfer

CLONETS – Clock Network Services

The project aims at partnership building and innovation for high performance time and frequency services over optical fiber networks and to prepare the implementation of such European backbone network.

<u>Project structure</u>:
WP1: Definition of key technologies and trends, collecting information from research infrastructures, NRENs and TF community as information for roadmaps
WP2: Definition of technology development roadmaps and strategic agenda, developing of global vision for TF services over fiber in Europe, leading to pan-European roadmaps and deployment strategies
WP3: Identification of additional applications and markets utilizing TF transmission over fiber
WP4: Impact, training and dissemination of project results.



CLONETS involved 16 partners from 7 European countries, representing 4 main areas:

National Metrology Instututes:
OBS Paris(FR), NPL(UK), PTB(DE), INRIM(IT)

National Research and Education Networks:
RENATER(FR), CESNET(CZ), PSNC(PL)

Academic Laboratories:
AGH(PL), UP13(FR), UCL(UK), ISI(CZ)

Industrial:
MUQUANS(FR), MENLO(DE), PIKTIME(PL), SEVEN SOL(SP), OPTOKON(CZ)

European Commission | Horizon 2020 European Union funding for Research & Innovation

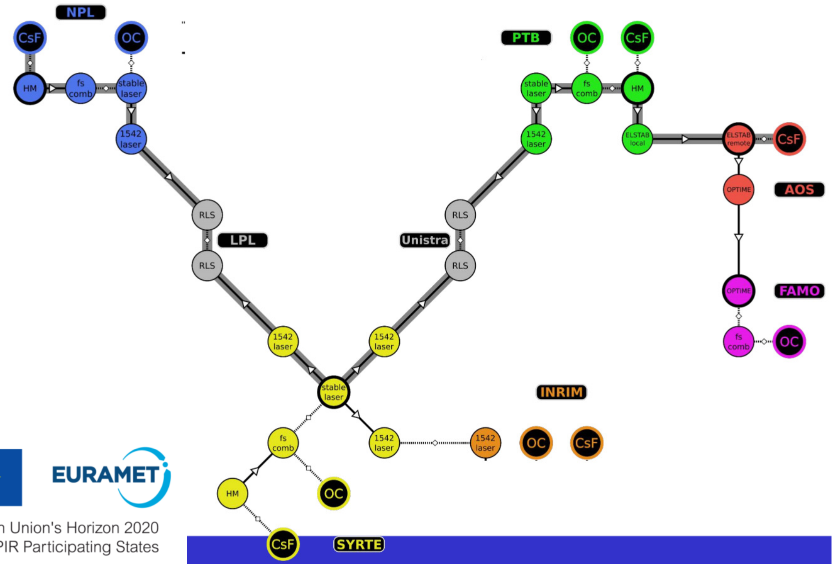
Project CLONETS received fundings from EU's HORIZON 2020 research and innovation programme under grant agreement 731107 and is being realized in years 2017-2019

International projects related to fiber TF transfer

OFTEN – Optical Frequency Transfer a European Network

OFTEN project aimed at:

- Fiber connections between European optical clocks
- Assessing and improving stability and accuracy of frequency transfer
- Improving reliability of fiber metrological links
- Operation of long-distance fiber optic links between European Cs fountains
- Facilitating the take up of technology and measurement infrastructure developed within the project by the measurement supply chain an end users (space, geodesy, telecom, etc.



EMPIR EURAMET
The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

Project structure:

WP1: Remote OC comparisons via joint fiber links
WP2: Techniques for optical frequency transfer over fiber network
WP3: Remote Cs fountain comparisons through optical fiber links
WP4: Applications based on fiber optical links for non-NMI end users

OFTEN involved 11 partners from 8 European countries, representing 3 main areas:

National Metrology Instutetes:
OBS Paris(FR), NPL(UK), PTB(DE), INRIM(IT), SP(SW), TUBITAK(TR)

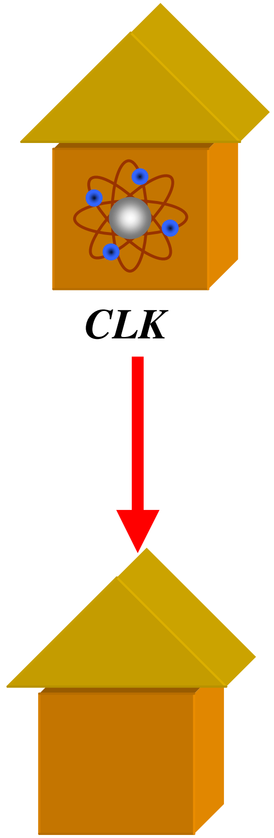
Academic Laboratories:
AGH(PL), UP13(FR), CHALMERS(SW), CMI(CZ)

National Research and Education Networks:
PSNC(PL)

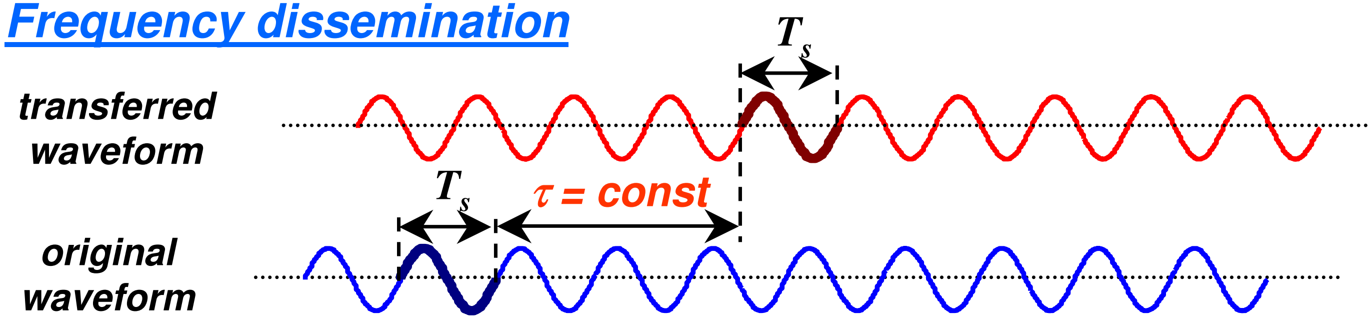
Introduction

general idea of T/F dissemination; frequency vs. time

T/F dissemination

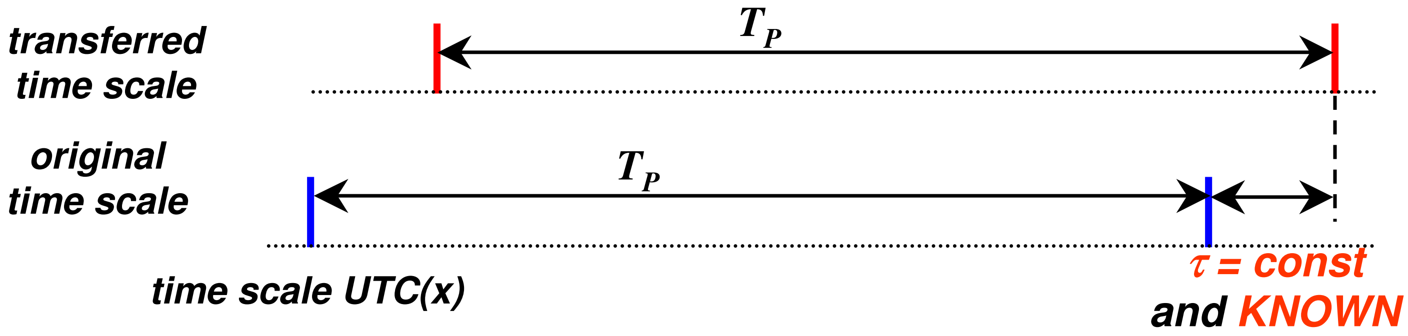


Frequency dissemination



f = 5 MHz, 10 MHz, 100 MHz, optical frequencies (~200 THz)

Time scale dissemination

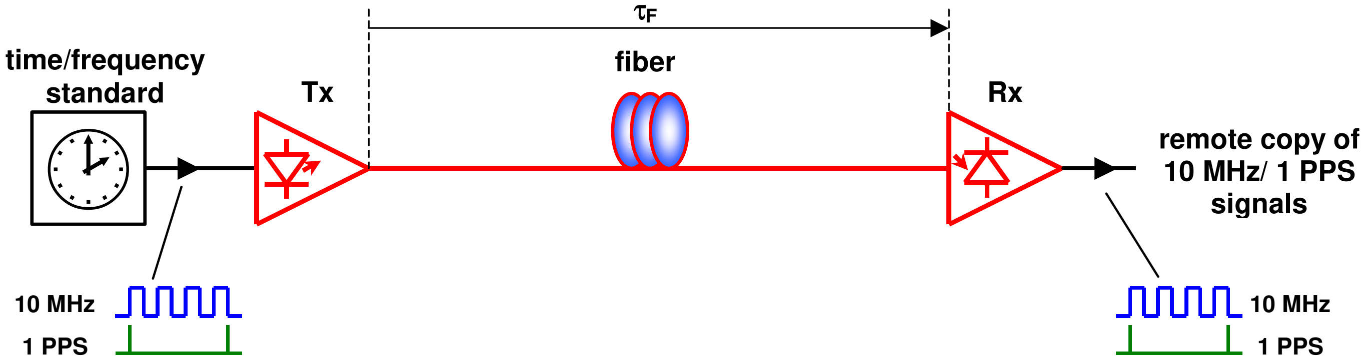


time scale UTC(x)

1PPS (Pulse Per Second)

Introduction

direct approach - one-way, uni-directional fiber T/F transfer



$$\Delta\tau_F = \frac{L}{c}\frac{\partial n_g}{\partial T}\Delta T_{FIB} + \frac{Ln_g}{c}\frac{\partial L}{L\partial T}\Delta T_{FIB} + \frac{L}{c}\frac{\partial n_g}{\partial \lambda}\Delta\lambda_{LAS}$$

Fundamental limit:

time dependence of the propagation delay of the optical fiber

$$\boxed{\tau_F = f(T) = f(t)}$$

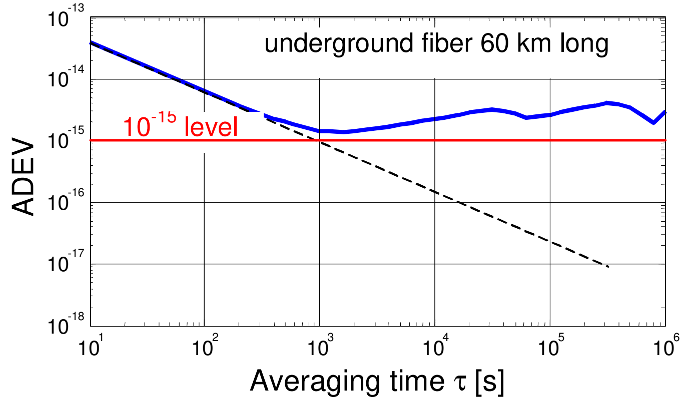
thermo optic coefficient

$$\frac{\partial n_g}{\partial T} \approx 1.1\cdot 10^{-5}\ \mathrm{K}^{-1}$$

thermal expansion coefficient

$$\frac{\partial L}{L\partial T} \approx 5.5\cdot 10^{-7}\ \mathrm{K}^{-1}$$

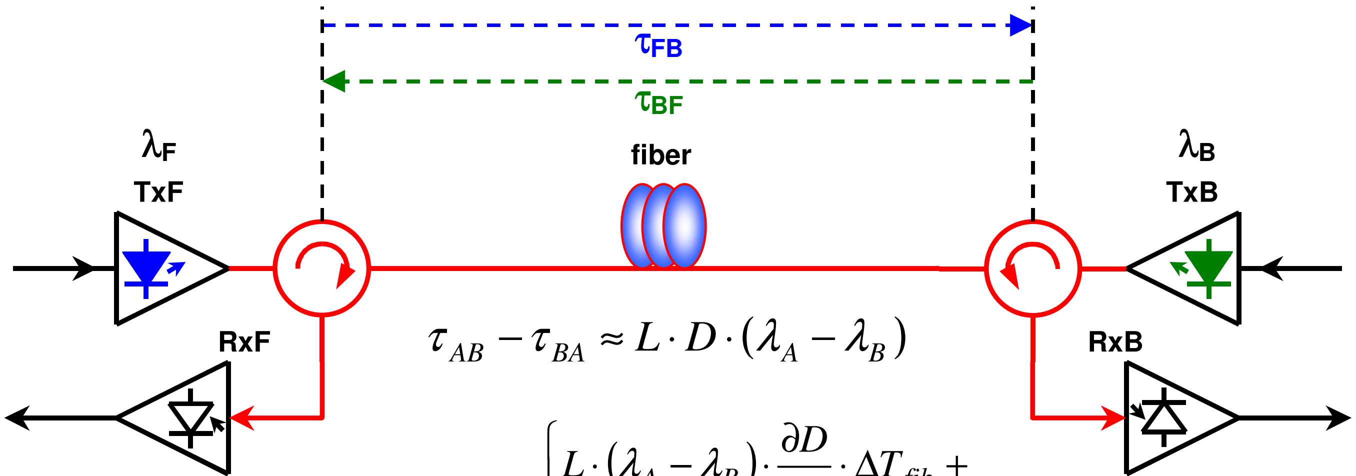
$$\frac{1}{L}\frac{\partial \tau_F}{\partial T} \approx 37\ldots 40\ \mathrm{ps}\cdot\mathrm{km}^{-1}\cdot\mathrm{K}^{-1}$$



Introduction

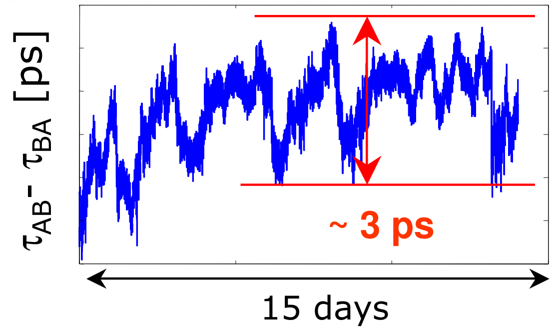
so why fiber is so perfect for T/F transfer?

it's relatively easy to arrange a very symmetric link where delay fluctuations (i.e. phase noise) affects very similarly the forward and backward directions



$$\tau_{AB} - \tau_{BA} \approx L \cdot D \cdot (\lambda_A - \lambda_B)$$

$$\Delta(\tau_{AB} - \tau_{BA}) \approx \begin{cases} L \cdot (\lambda_A - \lambda_B) \cdot \dfrac{\partial D}{\partial T} \cdot \Delta T_{fib} + \\ D \cdot (\lambda_A - \lambda_B) \cdot \dfrac{\partial L}{\partial T} \cdot \Delta T_{fib} + \\ L \cdot D \cdot \dfrac{\partial (\lambda_A - \lambda_B)}{\partial T} \cdot \Delta T_{las} \end{cases}$$



80 km spooled fiber
$\Delta T = 20^{\circ}$
$\Delta\lambda = 0.4$ nm

$$\frac{1}{L}\frac{\partial(\Delta\tau)}{\partial T \partial \lambda} \approx 4.7\ \mathrm{fs \cdot km^{-1} \cdot K^{-1} \cdot nm^{-1}}$$

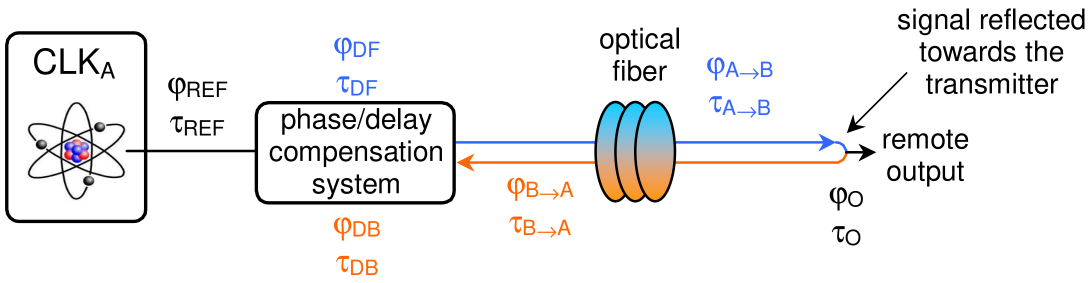
agrees well with the chromatic dispersion thermal coefficient

$$\frac{\partial D}{\partial T} \approx 4 \ldots 8\ \mathrm{fs \cdot km^{-1} \cdot K^{-1} \cdot nm^{-1}}$$

Introduction

an idea of a stabilized T/F fiber transfer

we need a distributed feedback system where the signal is delivered to the remote end
but
actuation is made in a real time at the local end only



phase stabilization:

$\varphi_O = \varphi_{REF} + \varphi_{DF} + \varphi_{A\to B}$

$\varphi_{RT} = \varphi_{DF} + \varphi_{A\to B} + \varphi_{B\to A} + \varphi_{DB}$

if $\varphi_{RT} = 0$ (kept by feedback)
then

$$\varphi_O = \varphi_{REF} + \left.\begin{matrix} + (\varphi_{DF} - \varphi_{DB})/2 + \\ + (\varphi_{A\to B} - \varphi_{B\to A})/2 \end{matrix}\right\} \cong 0$$

delay stabilization:

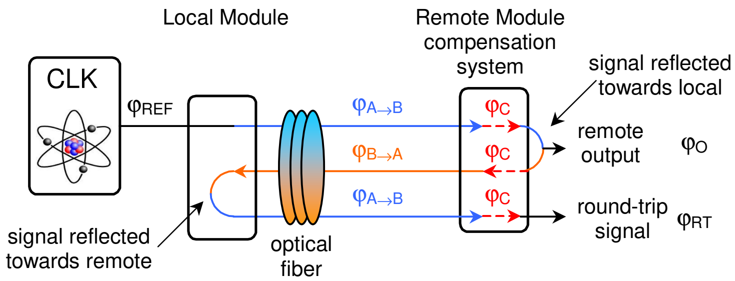
$\tau_O = \tau_{REF} + \tau_{DF} + \tau_{A\to B}$

$\tau_{RT} = \tau_{DF} + \tau_{A\to B} + \tau_{B\to A} + \tau_{DB}$

if $\tau_{RT} = const.$ (kept by feedback)
then

$$\tau_O = \tau_{REF} + \tau_{RT}/2 + \left.\begin{matrix} + (\tau_{DF} - \tau_{DB})/2 + \\ + (\tau_{A\to B} - \tau_{B\to A})/2 \end{matrix}\right\} \cong 0$$

it is also possible to revert this scheme and shift the actuation to the remote end
(this is a bit more complex, however…)



idea of phase stabilization:

$\varphi_O = \varphi_{REF} + \varphi_{A\to B} + \varphi_C$

$\varphi_{RT} = \varphi_O + \varphi_C + \varphi_{B\to A} + \varphi_{A\to B} + \varphi_C$

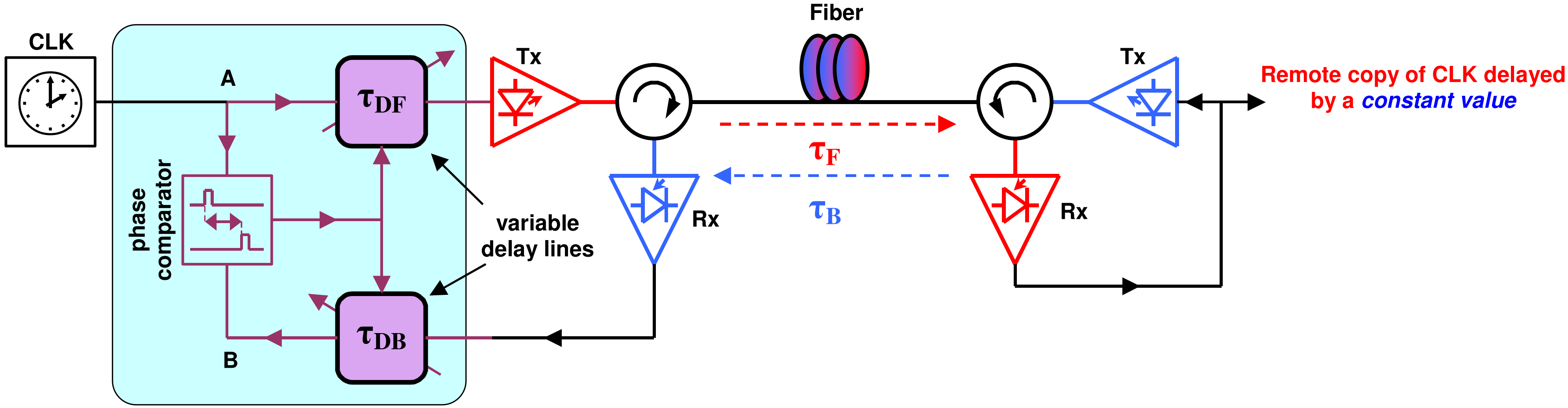
if $\varphi_{RT} = 0$ (kept by feedback)
then

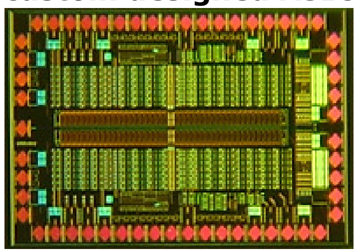
$\varphi_C = -(\varphi_{A\to B} + \varphi_{B\to A})/2$

so: $\varphi_O = \varphi_{REF} + {} + (\varphi_{A\to B} - \varphi_{B\to A})/2 \} \cong 0$

ELSTAB

electronically stabilized fiber T/F distribution system; principle of operation





custom designed ASIC

DLL equilibrium condition:

$$\tau_{DF} + \tau_F + \tau_B + \tau_{DB} = \text{const} \quad (1)$$

$$\Delta\tau_{DF} + \Delta\tau_F + \Delta\tau_B + \Delta\tau_{DB} = 0 \quad (2)$$

Constant delay requirement:

$$\tau_{DF} + \tau_F = \text{const} \quad (3)$$

$$\Delta\tau_{DF} + \Delta\tau_F = 0 \quad (4)$$

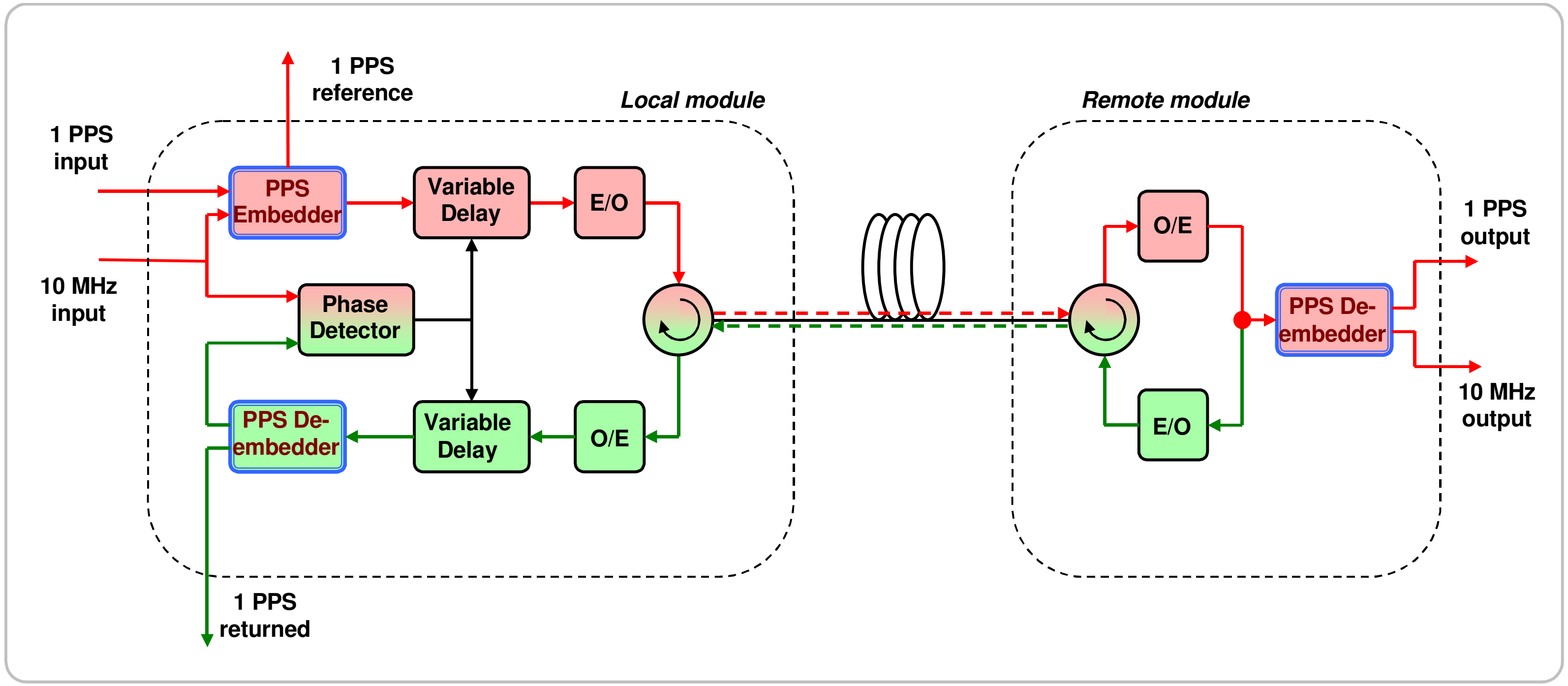
$$\Rightarrow \quad \Delta\tau_B + \Delta\tau_{DB} = 0, \quad \Delta\tau_F = \Delta\tau_B \text{ (~ ps)} \quad \Rightarrow \quad \Delta\tau_{DF} = \Delta\tau_{DB}$$

matched delay lines

ELSTAB

joint time & frequency transfer

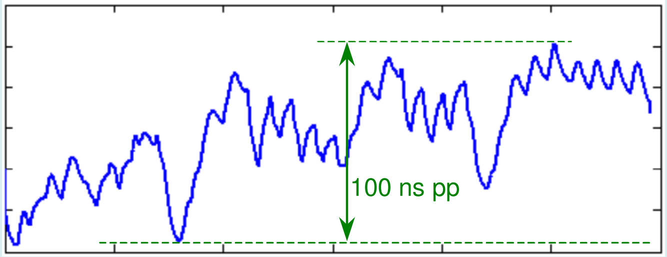
Time is transmitted in ELSTAB by local violations of the phase of frequency signals.
These violations are inserted by PPS Embedder and are further decoded by PPS De-embedder.
Additional De-embedder in Local Module is used for calibration (see next slides).



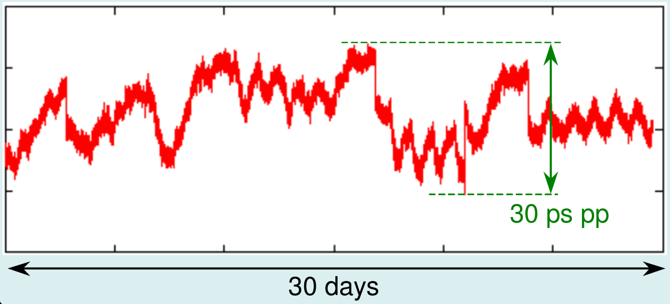
Example:

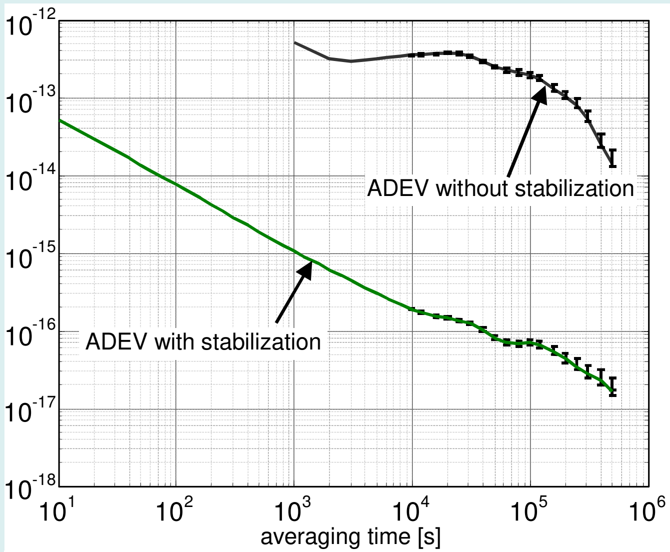
stability of 615 km long-distance transfer using ELSTAB

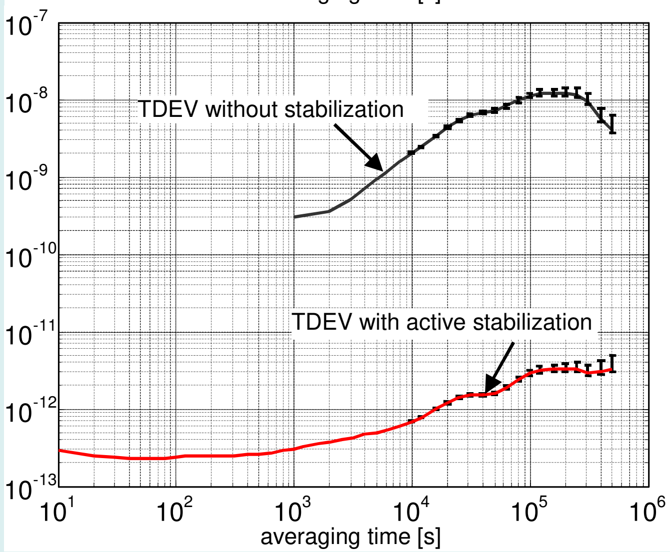
fiber delay fluctuations: 100 ns pp



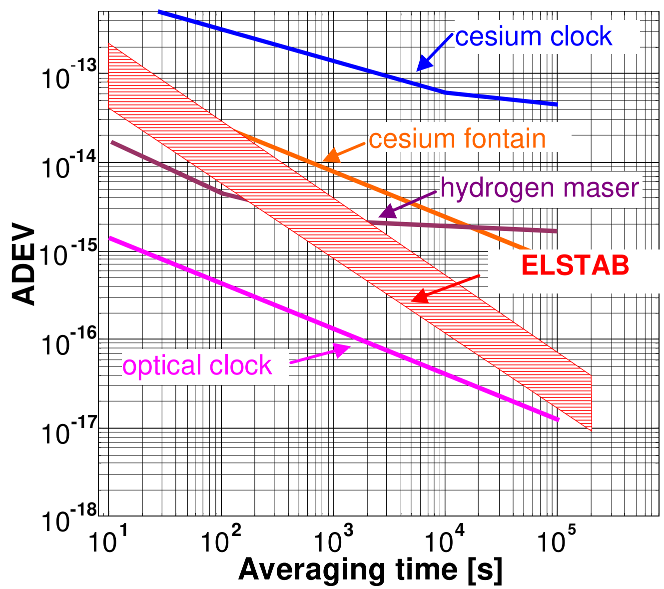
output signal fluctuations: 30 ps pp





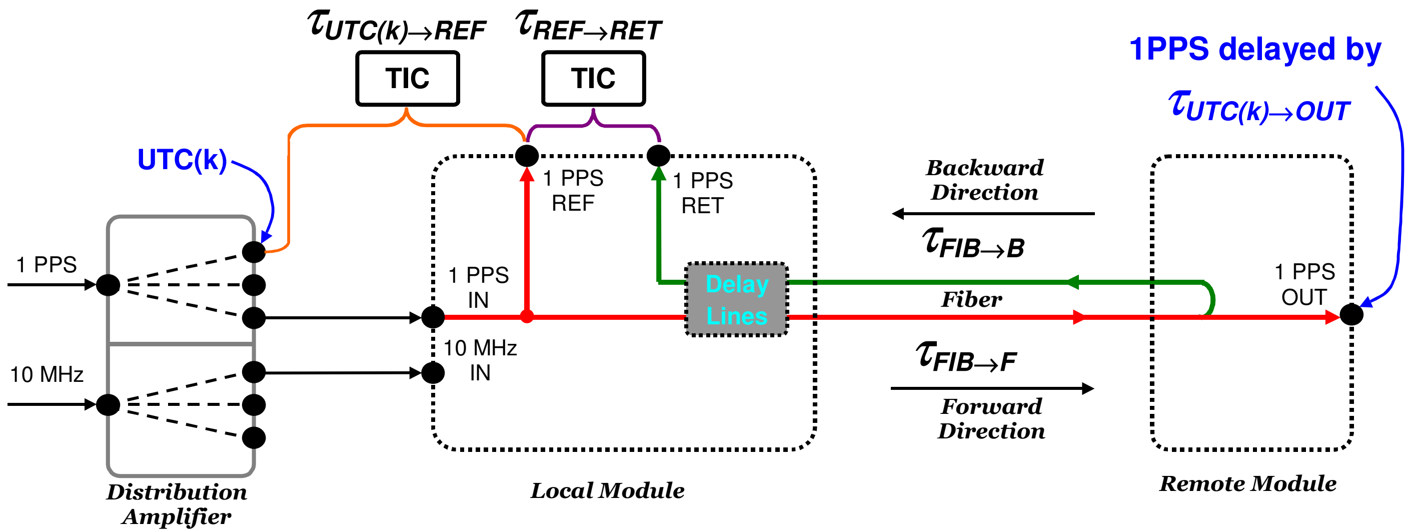


ELSTAB performance vs clocks instability



ELSTAB

time transfer timing model and calibration



Basic calibration formulas:

$$\tau_{REF\to OUT} = \frac{1}{2}\left[\tau_{REF\to RET} + \left(\tau_{FIB\_F} - \tau_{FIB\_B}\right) + \tau_C\right]$$

$$\tau_{UTC(k)\to OUT} = \tau_{UTC(k)\to REF} + \tau_{REF\to OUT}$$

Fiber forward-backward asymmetry:

$$\tau_{FIB\_F} - \tau_{FIB\_B} = D_T(\lambda_F - \lambda_B) \pm \frac{4\omega A_E}{c^2} + \tau_{BIR}$$

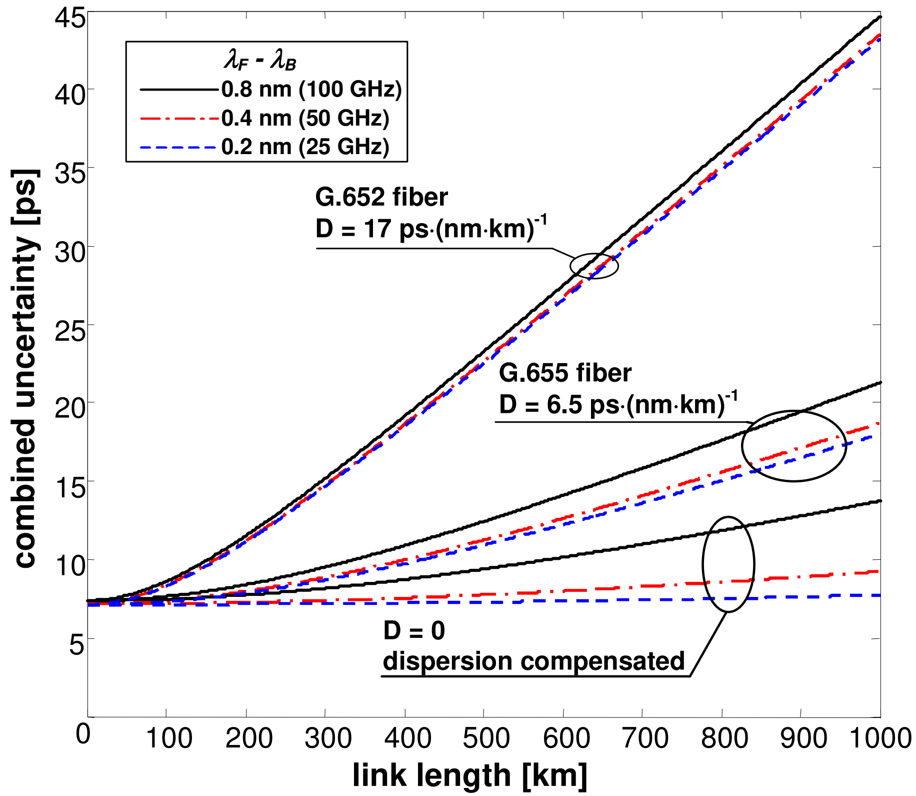
Local & remote modules asymmetry:

$$\tau_C = \left(2\tau_{REF\to OUT} - \tau_{REF\to RET}\right)\Big|_{\substack{SHORT\\PATCHCORD}}$$

Fully automated calibration is on the way!

ELSTAB
uncertainty budget

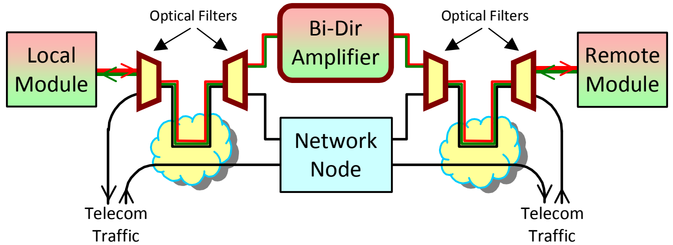
	uncertainty source	sensitivity coefficient	standard uncertainty: length independent	standard uncertainty: length dependent	uncertainty budget: 50 km	uncertainty budget: 500 km
1	$\tau_{UTC(k)\to REF}$	1	5 ps	-	5 ps	5 ps
2	$\tau_{REF\to RET}$	0.5	5 ps	-	2.5 ps	2.5 ps
3	τ_C	0.5	7.2 ps	-	3.6 ps	3.6 ps
4	D_T	$0.5(\lambda_F-\lambda_B)$	5 ps/nm	$\frac{\partial D/\partial T\cdot\Delta T\cdot L}{\sqrt{12}}$	2.1 ps	6.1 ps
5	τ_{BIR}	0.5	-	$LDV\cdot\sqrt{L}$	0.2 ps	0.6 ps
6	$\lambda_F-\lambda_B$	$0.5D_T$	5 pm	-	2.1 ps	21.2 ps
7	A_E	$2\omega/c^2$	-	$10^{-3}\cdot A_E$	0.2 ps	2 ps
				Combined uncertainty:	**7.3 ps**	**23.2 ps**



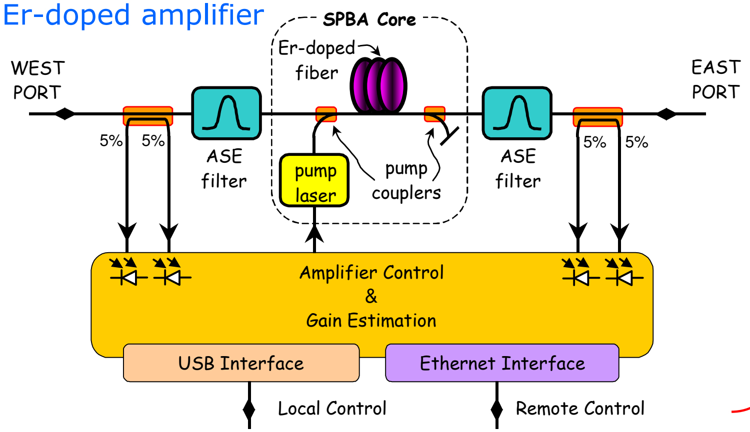
ELSTAB
long-distance transfer (>~100km)

Dark fiber

Dark channel



Bi-directional
Er-doped amplifier



Best options:

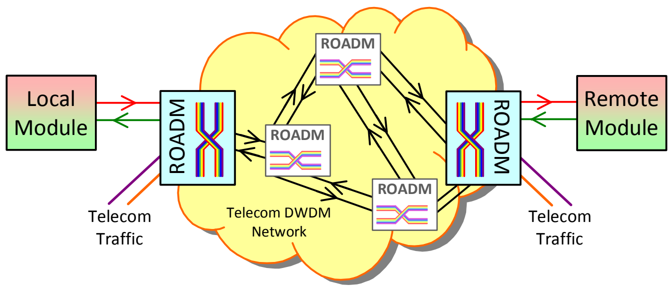
dark fiber
or
dark channel

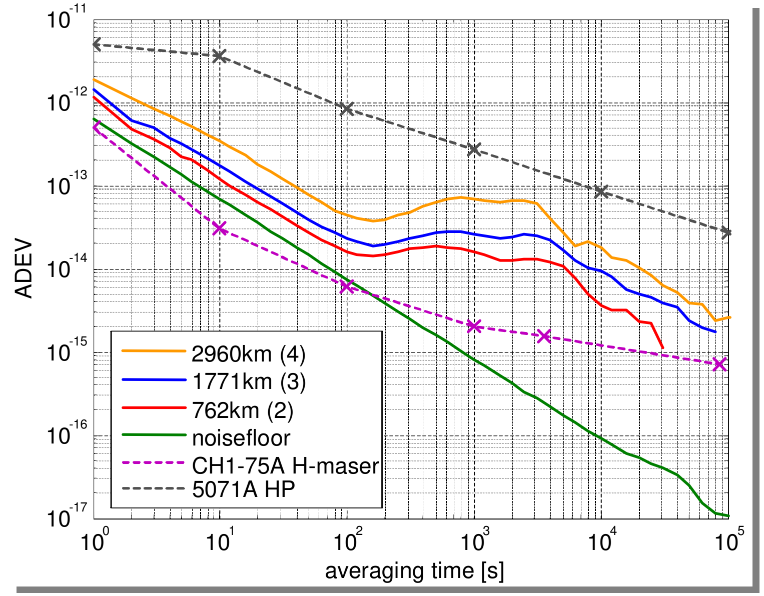
Alternate option:

optical DWDM
alien λ

cost:
lost of time transfer autocalibration

performance degradation due to unpredictable fiber link asymmetry

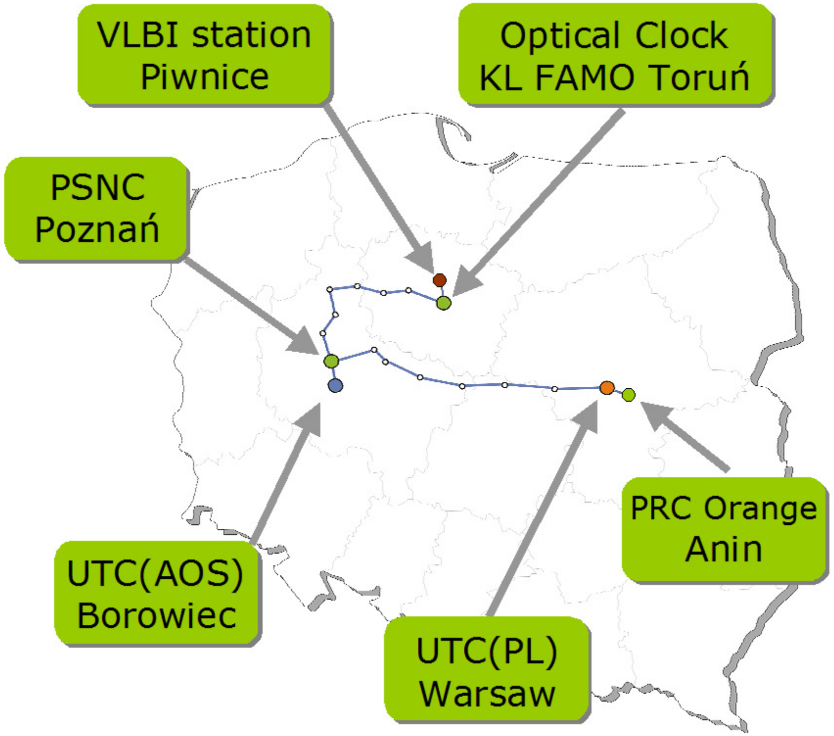




Examples of ELSTAB DWDM performance

ELSTAB - implementations
links in Poland

OPTIME project



GUM – AOS link:

420 km of fiber, 117 dB total loss,

operational since January 2012,

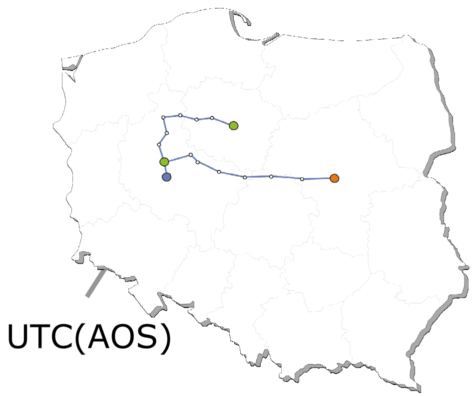
UTC(AOS) - UTC(PL) continuously reported to BIPM, also available online: http://www.optime.org.pl/node/47

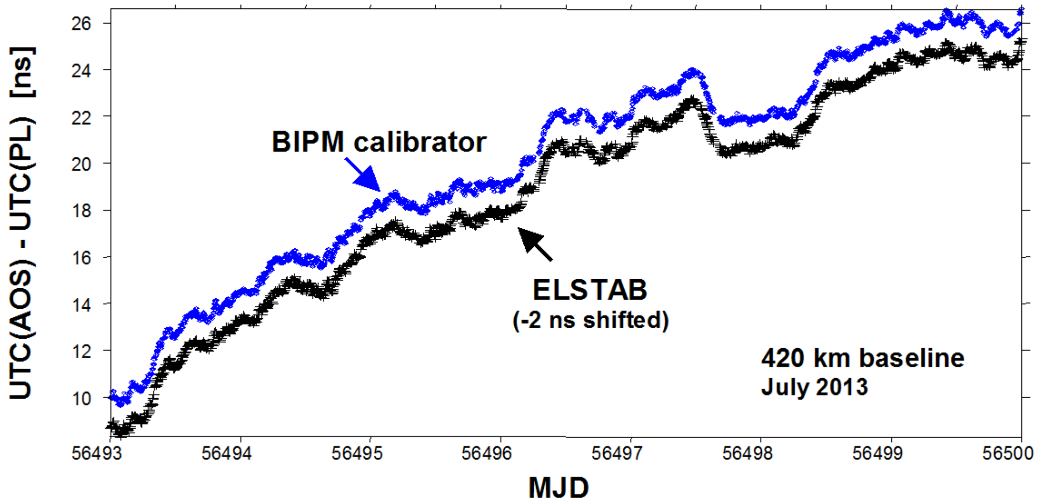
AOS – FAMO link:

330 km of fiber, 85 dB total loss,

operational since December 2014, used for absolute measurements of Polish strontium clock

ELSTAB system
side by side with BIPM METODE calibrator

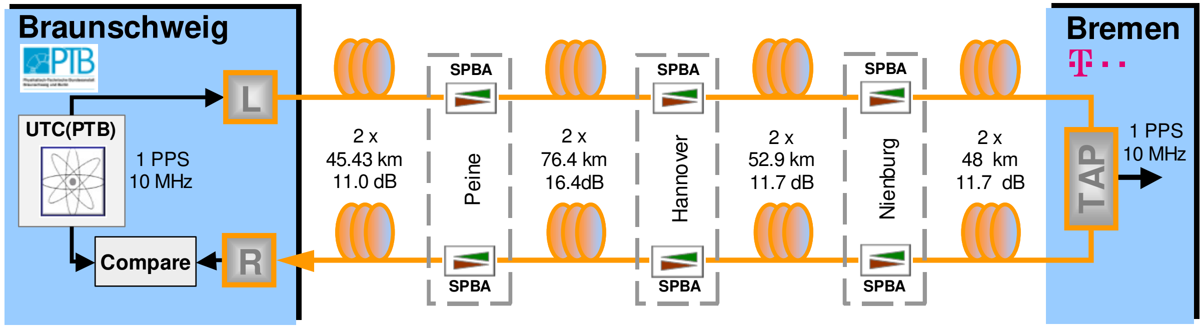




The UTC(AOS) versus UTC(PL) calibration obtained with ELSTAB and METODE ***differs by 0.7 ns****, when calibration uncertainties estimated for both systems are 0.12 ns and 0.8 ns, respectively.*

ELSTAB - implementations

Optical Time Transfer (OTT) with Deutsche Telekom & PTB (PoC I)

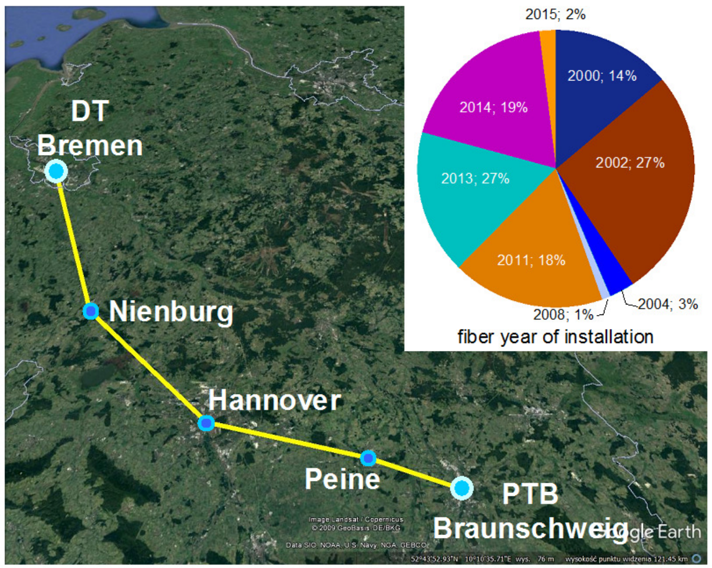


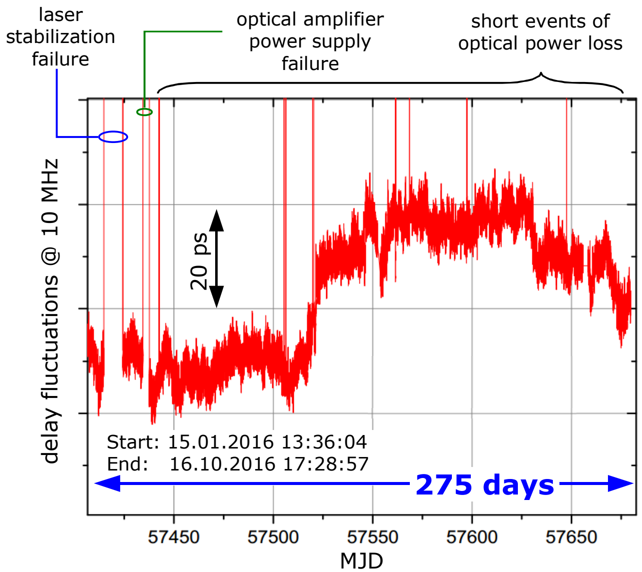
Goals of Proof of Concept experiment:

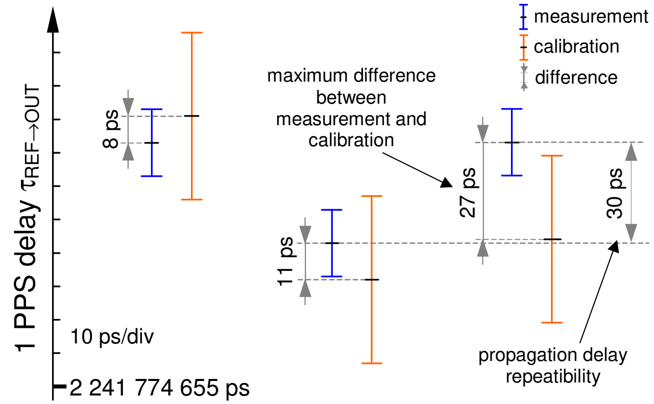
evaluate potential feasibility of OTT using ELSTAB technology for supervision of network synchronization

test ELSTAB long-term operation on Deutsche Telekom fiber network

test time transfer between PTB and Deutsche Telekom







Date	10.07.2015	11.12.2015	21.06.2016
Measurement [ps]	2 241 774 726±10	2 241 774 696±10	2 241 774 724±10
Calibration [ps]	2 241 774 734±25	2 241 774 685±25	2 241 774 697±25

ELSTAB - implementations

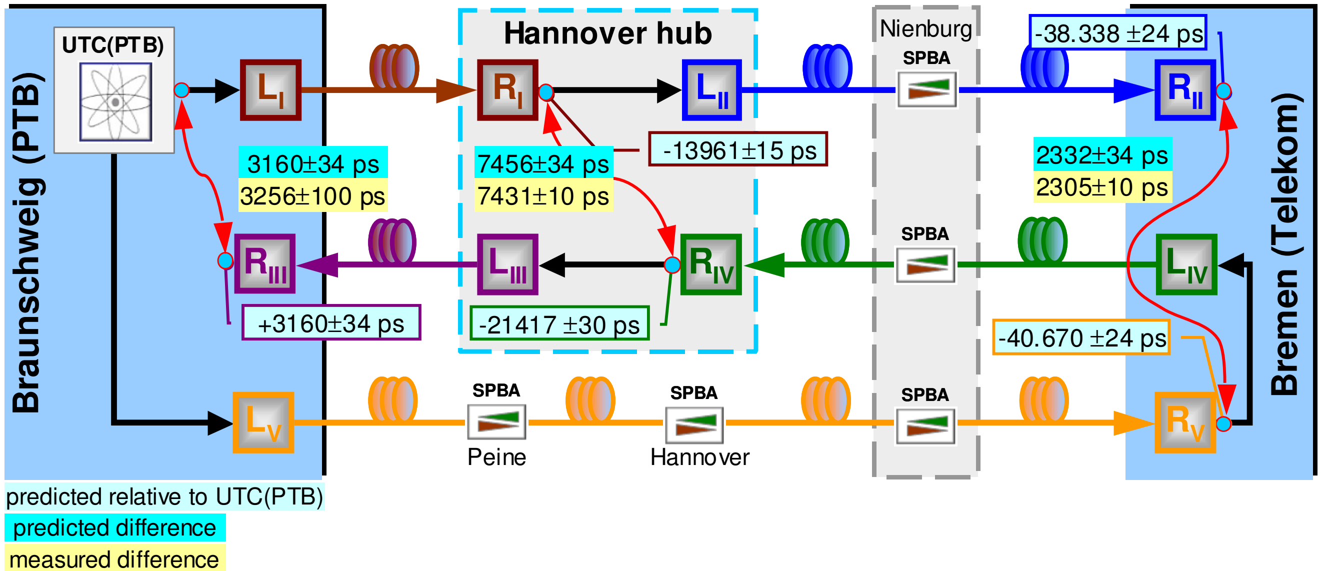
OTT with Deutshe Telekom & PTB (PoC II)

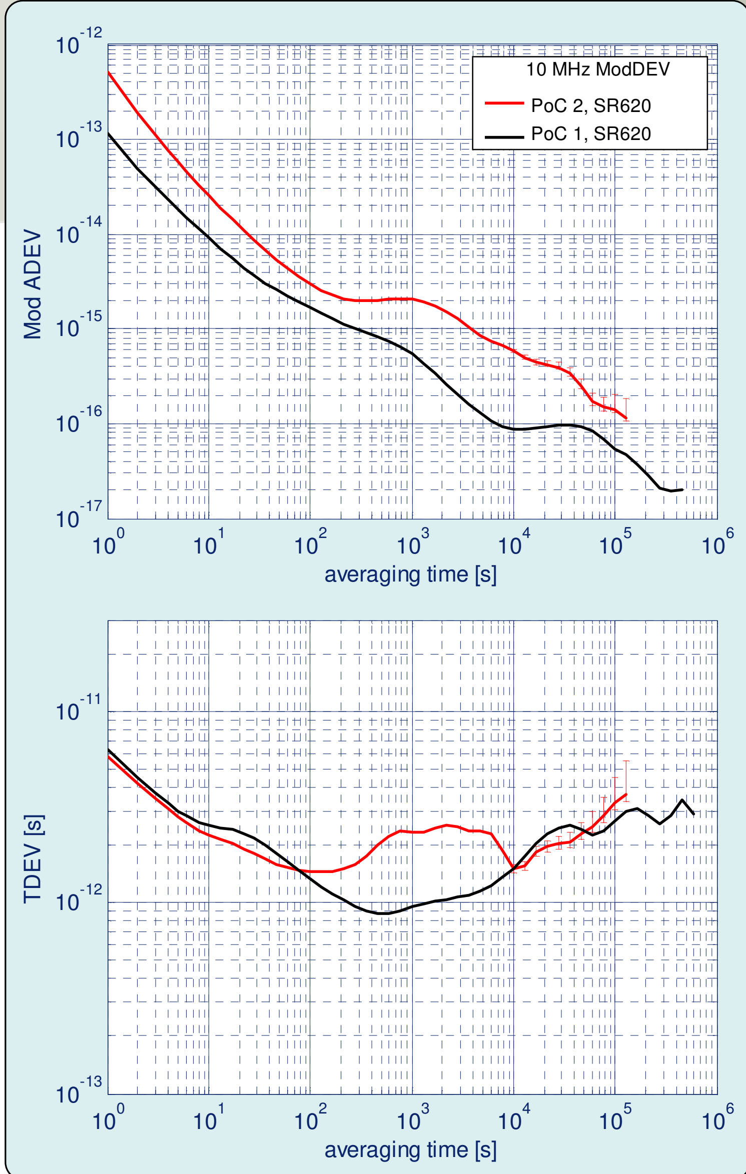
In Phase II:

the experimental PoC I link has been upgraded to operational link

a hub in Hannover has been created for future expansion of the link

extensive calibration tests were performed thanks to redundantt architecture of PoC II link





Summary

- In last few years great interest is observed in fiber optic time and frequency transfer, international initiatives on pan-European scale are undertaken to create a working fiber network for such purposes
- Such initiatives joins various groups of institutions from NRENs, telecom, metrological/academic labs and industry
- The main driving force now is high-end metrology and science, but created technology may be successfully deployed for telecom and industrial needs
- ELSTAB is an example of available technology that offers high-performance and reliable dissemination of frequency and UTC-traceable time
- Typical ELSTAB performance shows ADEV of 2…3$\times 10^{-13}$@1s, decreasing with the slope τ^{-1} with increasing observation interval and time calibration uncertainty of 20…50 ps (depending on distance and fiber type)
- ELSTAB has been successfully tested in the field over the distances up to 500 km and over even longer distances in the lab
- ELSTAB technology is continuously evolving in a direction to improve its performance on one hand and to transform it into a plug-and-play (by implementing automatic time transfer calibration) system on the other

Thank you for your attention

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