# ELSTAB (Electronic Delay STABilized System) - precise time and frequency transfer over optical fiber with autonomous calibration

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# Introduction

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## Set goal:

**A continuous precise RF time and frequency transfer over optical fiber**


**A specialised system of electronic-optic converteres is required**

## Main issues that need to be addressed:

1. Unknown and variable propagation delay – daily and seasonal changes
   (required returning the signal or employment another system for calibration)
2. Forward and backward transmission in pair of fibers in telecom network
   (asymmetry of the length of fibers - preferred single fiber tranmission)
3. Forward and backward transmission in the same fiber requires different optical wavelengths
   (if $\lambda_F = \lambda_B$ – mutual interference, backward scaterring, reflections = increased noise and false detections)
4. Chromatic dispersion (D) dependent on: wavelength, length of fiber and temperature
   (e.g. at 1550 nm: D = 17 ps / (nm · km) and $\partial D/\partial T$ ± 4 $fs\,/\,(nm \cdot km \cdot K)$ = stability $\lambda_F$, $\lambda_B$ is relevant)
5. Required specialised bi-directional optical amplifiers

# Basic concepts of RF TF transfer proposed by AGH

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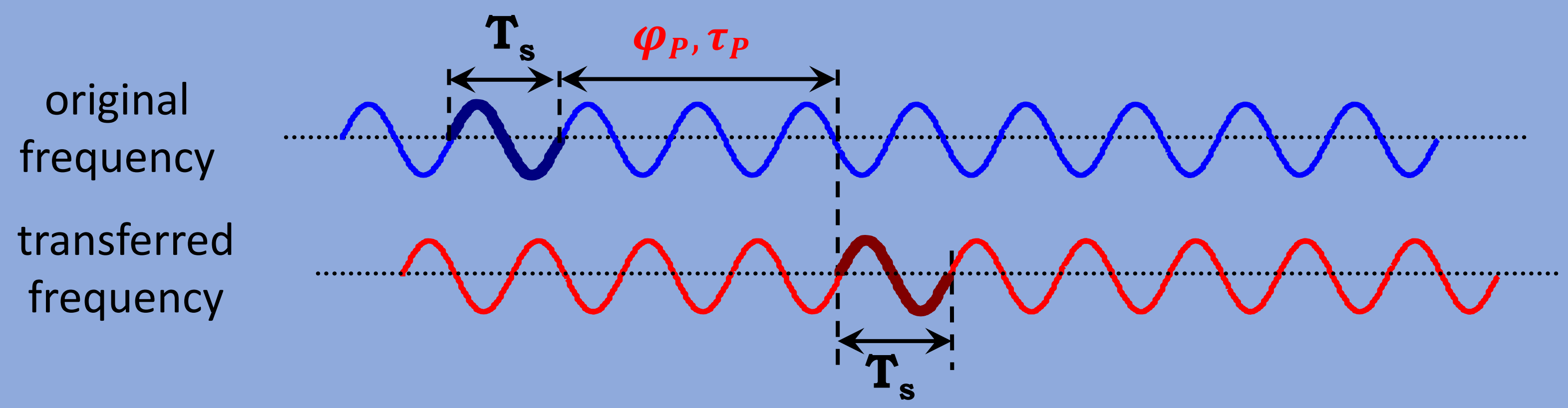
## Employing Electronic Delay Lines for delay stabilization

### *Frequency distribution*




$$\frac{d\varphi_T}{dt} = \frac{d\varphi_O}{dt}$$

$$\Downarrow$$

$$\varphi_P = \text{const}$$

$$\Downarrow$$

$$\tau_P = \text{const}$$

### *Time distribution*


***$\tau_P$ = const***
***and***
***KNOWN***

AGH

***Courtesy of AGH***

# ELSTAB – Electronic Delay Stabilized System

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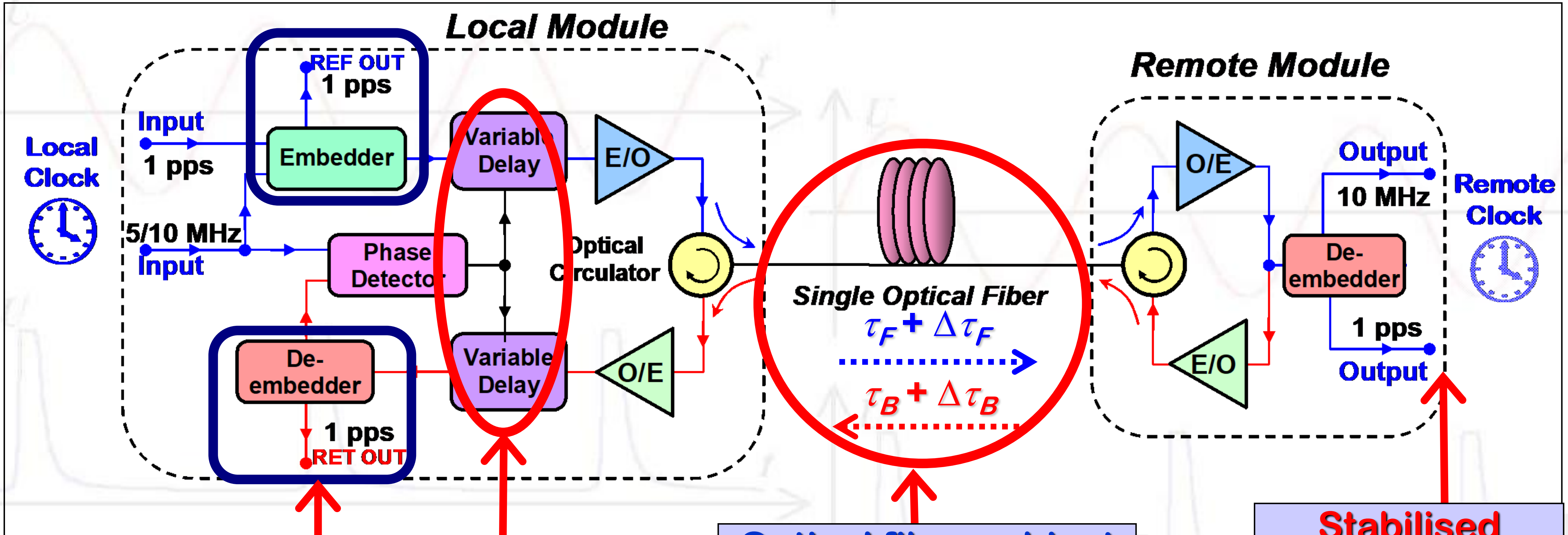


**Possible calibration during operation of the link**

**Optical fiber subject to change Delay**

**Stabilised propagation Delay**

**Electronic Variable Delay Lines**

$$\Delta\tau_F \approx \Delta\tau_B$$

$$\Delta\tau_{DF} \approx \Delta\tau_{DB}$$

$$\Delta\tau_{DF} + \Delta\tau_F = \Delta\tau_{DB} + \Delta\tau_B \approx 0$$

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*Courtesy of AGH*

# Coupled Electronic Delay Lines and obtained stability

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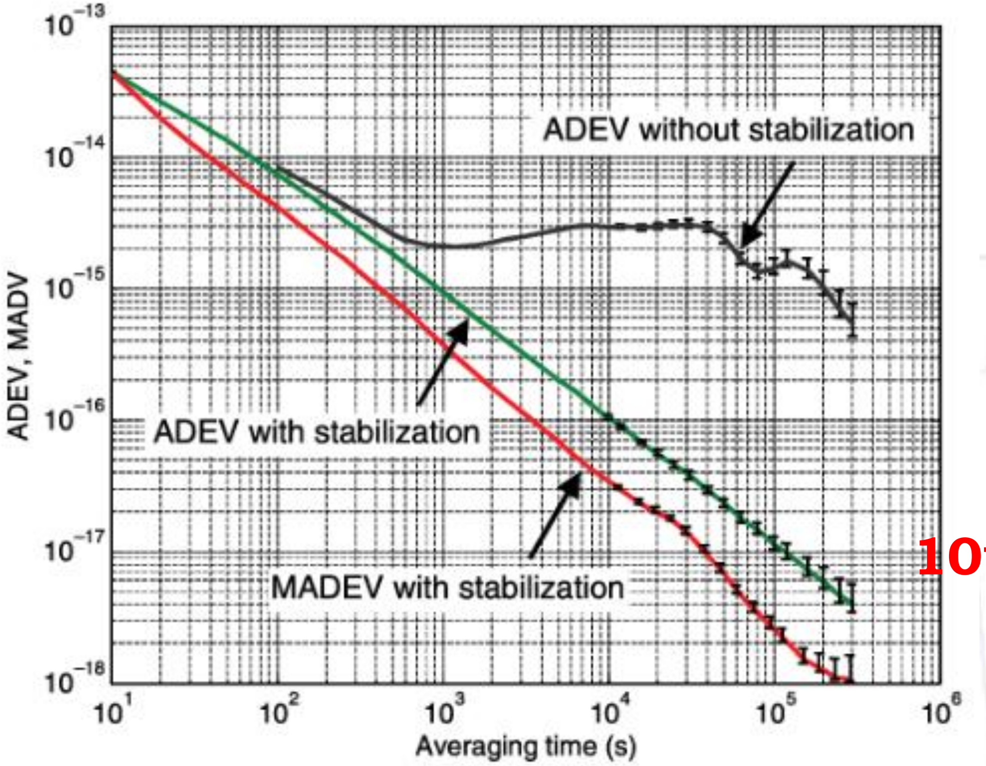
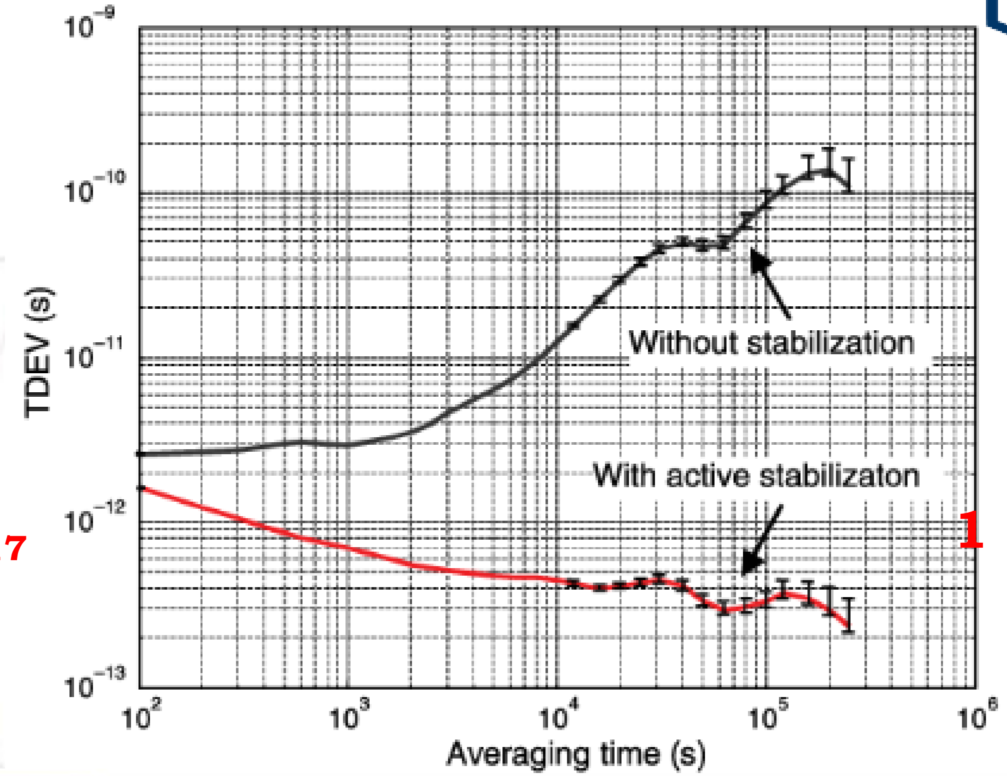



$10^{-17}$




**60 km link**

**1 ps**

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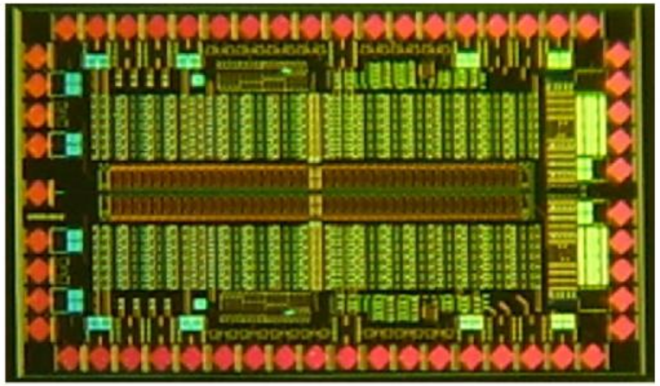
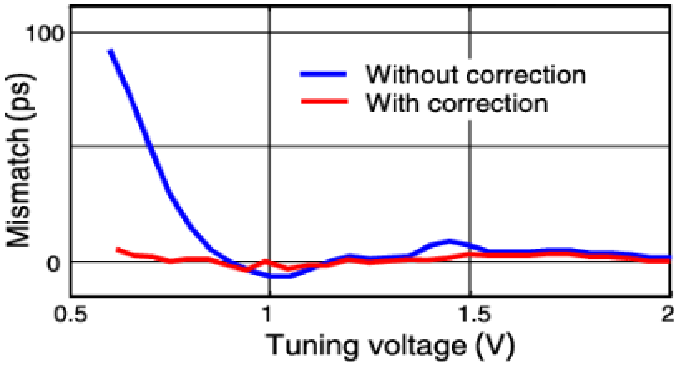
*Courtesy of AGH*



1.3mm× 2mm custom designed electronic integrated circuit containing the coupled delay lines




Measured mismatch of the coupled delay lines

observed residual non-compensated phase fluctuations: **<15 ps p-p**

# Long fiber link instability with ELSTAB system

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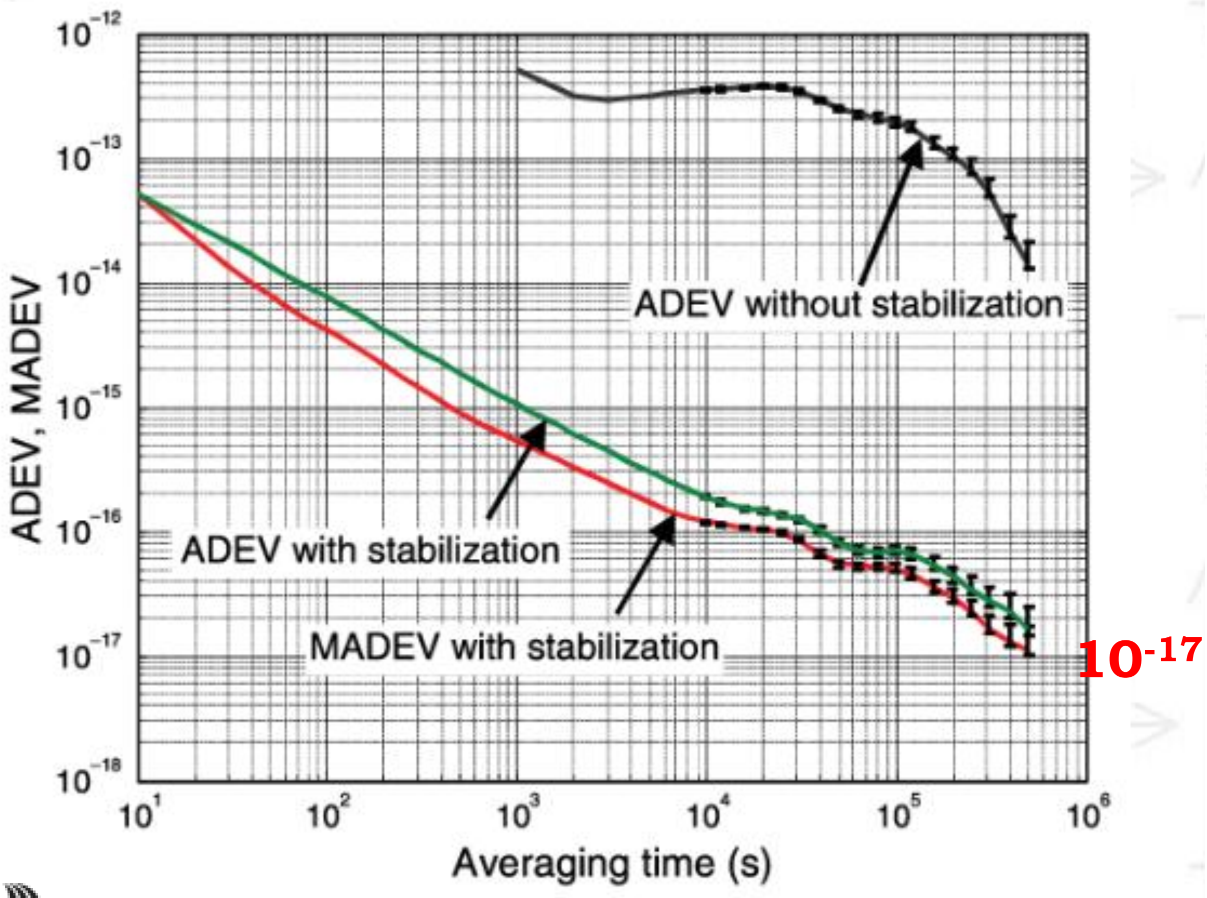
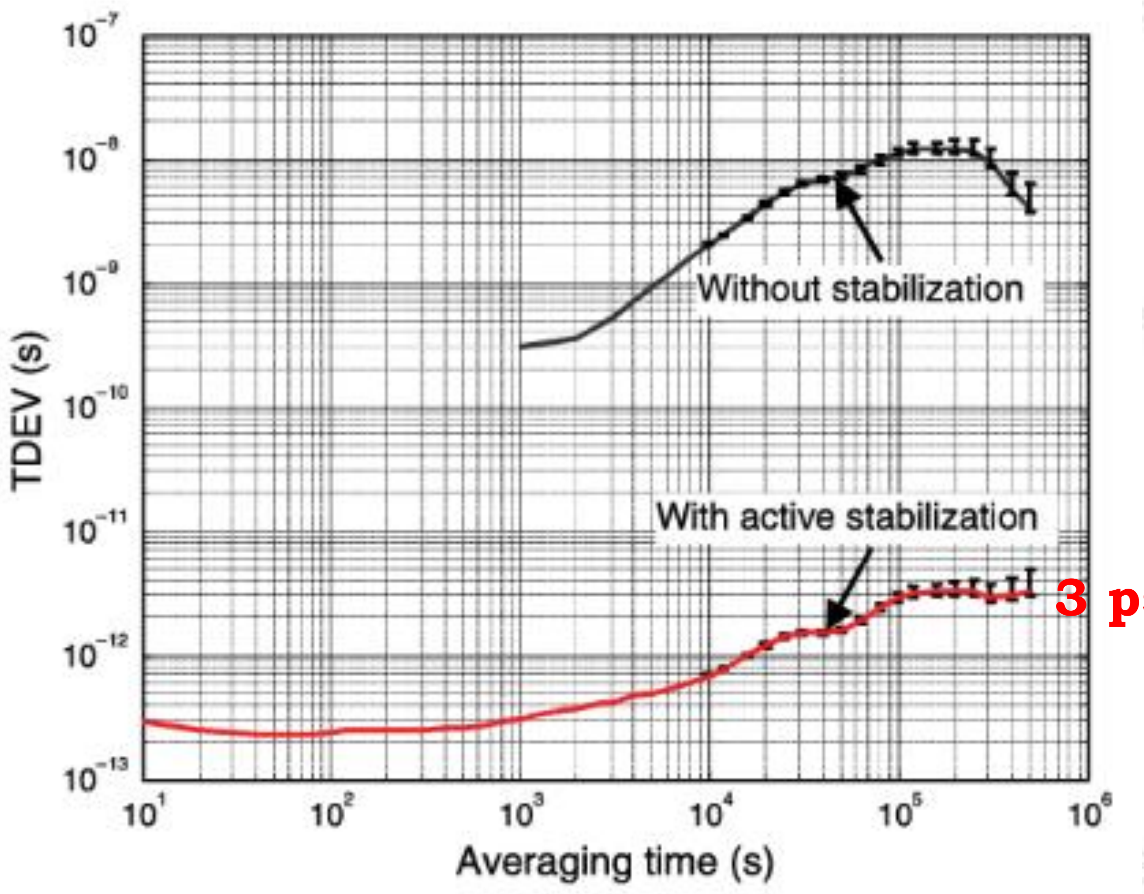
## 615 km link




$10^{-17}$




3 ps

Instability in **615-km**-long fiber link (with 11 bi-directional amplifiers) in 2016
(observed residual non-compensated **30 ps p-p** phase fluctuations)

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**Note:** Now, **phase fluctuations** are independent of the length of the link and **do not exceed 15 ps p-p**.

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# A completed ELSTAB set

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Remote Module for reception

Local Module for transmission


Bidirectional Amplifiers (every 60-80 km)

# Fiber delay stabilization idea – in details

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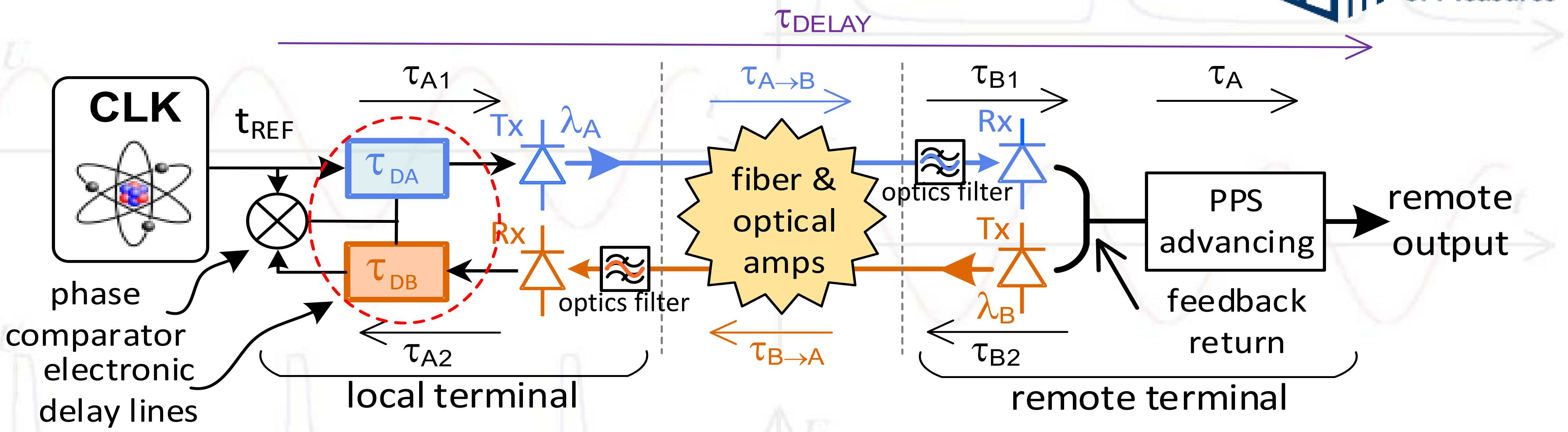


$$T_{RT} = \underbrace{\tau_{A1} + \tau_{A\to B} + \tau_{B1}}_{\tau_{Forward}} + \underbrace{\tau_{B2} + \tau_{B\to A} + \tau_{A2}}_{\tau_{Backward}} + \tau_A$$

$$\tau_{Forward} \approx \tau_{Backward}$$

$$T_{DELAY} = \tau_{A1} + \tau_{A\to B} + \tau_{B1} + \tau_A$$

$$T_{DELAY} \approx \tau_{Forward} \approx \tau_{Backward}$$

$$T_{DELAY} = T_{RT}/2 + (\tau_{A1} - \tau_{B1} + \tau_{A2} - \tau_{B2})/2 + \tau_A + (\tau_{A\to B} - \tau_{B\to A})/2$$

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# Sources of fiber link asymmetry - $\Delta\tau_L$

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$T_{DELAY} = T_{RT}/2 +$ → „round-trip” delay – stabilized and known

$+ (\tau_{A1} - \tau_{B1} + \tau_{A2} - \tau_{B2})/2 + \tau_A$ → terminals asymmetry ($\Delta\tau_T$), constant and known

$+ (\tau_{A\to B} - \tau_{B\to A})/2$ → link (fiber) asymmetry ($\Delta\tau_L$), dependent on the fiber length, wavelengths and lasers used

$(\tau_{A\to B} - \tau_{B\to A}) =$

*Sagnac effect* — *fiber birefringence* — *chromatic dispersion*

$$\Delta\tau_L = \frac{4\omega A}{c^2} + LDV\sqrt{L} + D \cdot L \cdot \Delta\lambda_{A\leftrightarrow B}$$

**Note:** **The last term is the most significant.**

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# Sagnac effect

$$\Delta\tau_{Sagnac} = \pm 2 \cdot \omega \cdot A_E / c^2$$

$\omega$ - rotation speed of Earth

$A_E$ - area of equatorial projection of the Surface swept by the vector extending from the center of Earth and moving along the fiber link

$c$ - speed of light in vacuum

$\pm$ - sign '+' applied for the movement in East direction, sign '-' for the West direction

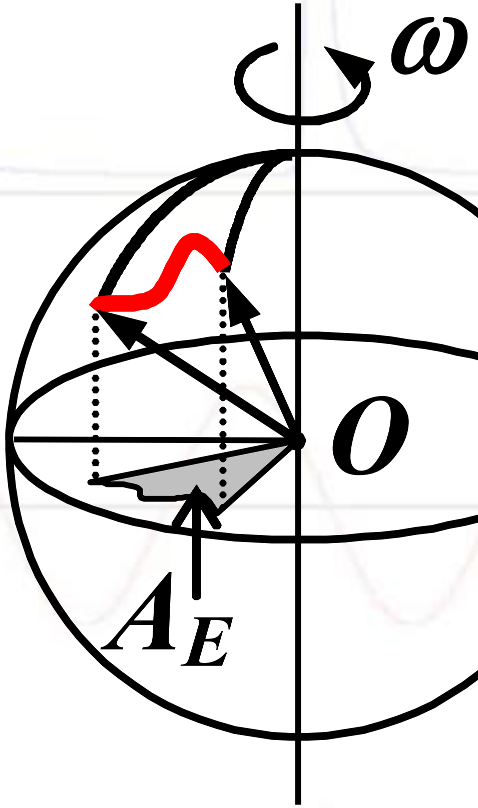



Illustration of the $A_E$ component in the formula for Sagnac correction (red curve – examplary fiber route)

Max value = <5 ns/1000 km (along the equator)

$(\tau_{A\rightarrow B} - \tau_{B\rightarrow A})$ =

$$\Delta\tau_{Sagnac\_RoundTrip} = \pm \frac{4\omega A_E}{c^2}$$

**Note:** For Round Trip, asymmetry of Sagnac correction is a doubled value of correction in one direction

# Birefringence effect (Polarisation Mode Dispersion)

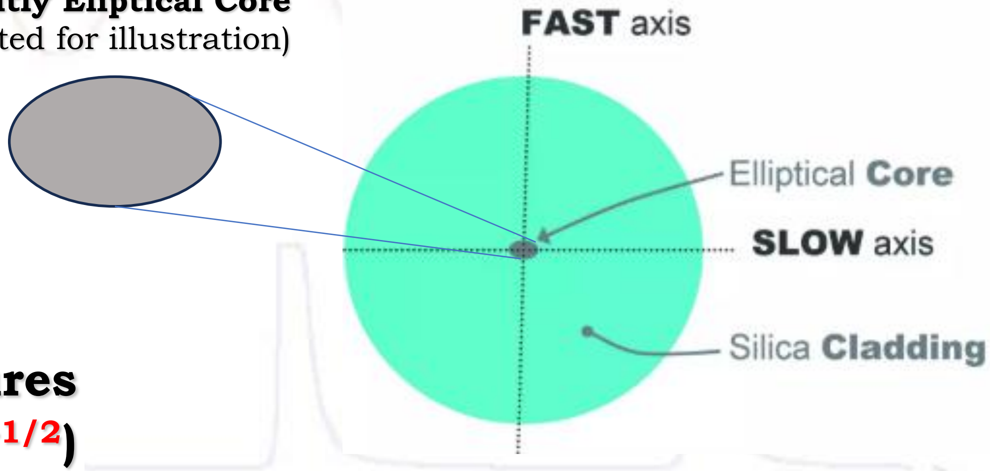
**The birefringence of the fibre is caused by some residual ellipticity of the core of the fibre resulting from manufacturing imperfections, the strain affecting the fibre, etc, and results in a dependence of the speed of the propagating optical wave on its state of polarization.**

$$\Delta\tau_{PMD} = LDV\sqrt{L}$$

***LDV*** - **Link Design Value quoted by fiber manufactures (typicaly: from 0.02 ps / km$^{-1/2}$ to 0.08 ps / km$^{-1/2}$)**

***L*** – **Length of fiber link (in km)**

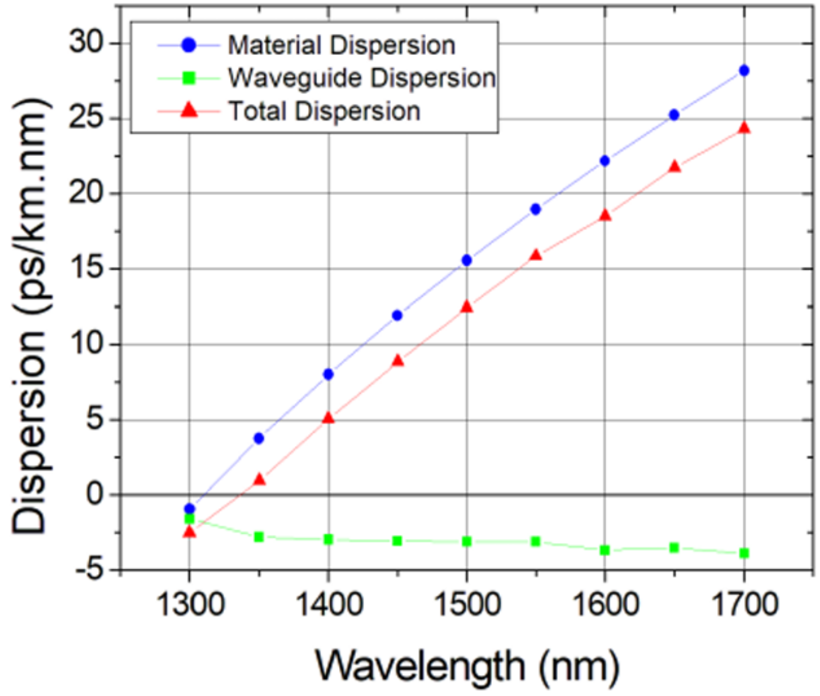
**Slightly Eliptical Core**
(picture exaggerated for illustration)




*https://fibercore.humaneticsgroup.com/*

**Note: Typically, negligibly small (less than 1-2 ps)**

# Chromatic dispersion




https://iopscience.iop.org/article/10.1088/1742-6596/2426/1/012026/pdf

$$\Delta\tau_{CD} = \mathrm{D} \cdot L \cdot \Delta\lambda_{A\leftrightarrow B}$$

**$D$ – Chromatic Dispersion (c. 17 ps / (km· nm) at 1550 nm)**

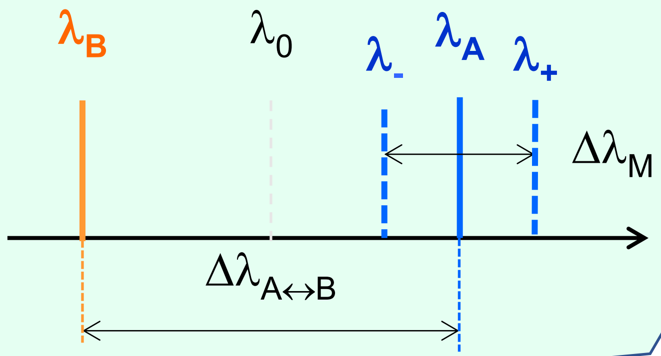
**$L$ – Length of fiber link (in km)**

**$\Delta\lambda_{A\leftrightarrow B}$ – Lasers wavelength difference between forward and backward directions (typ. 0.8 nm for ELSTAB)**

Determination $\Delta\tau_{CD}$ with ELSTAB:

- temporarily open the feedback loop
- change one laser wavelength by a known value $\Delta\lambda_M$
- measure related round – trip delay change $\Delta\tau_M$

$$\Delta\tau_{CD} = \Delta\tau_M \frac{\Delta\lambda_{A\leftrightarrow B}}{\Delta\lambda_M}$$




*Courtesy of AGH*

**Note: This is an extra method offered by ELSTAB.**

# Examplary uncertainty budget for ELSTAB link

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## GUM-AOS 420 km link

| | determined quantity | estimate | sensitivity coefficient | standard uncertainty | uncertainty contribution | |
|---|---|---|---|---|---|---|
| 1 | $\tau_{UTC(PL)\rightarrow REF}$ [a] | 420.17 ns | 1 | 100 ps | 100 ps | TIC – measurement with SR620 |
| 2 | $\tau_{REF\rightarrow RET}$ [a] | 4 093 944.73 ns | 0.5 | 100 ps | 50 ps | TIC – measurement with SR620 |
| 3 | $\tau_{\Delta\lambda}$ [b] | 2.950 ns | 0.5 | 19 ps | 9.5 ps | Chromatic dispersion |
| 4 | $\tau_{S}$ [c] | -1.686 ns | 0.5 | 5 ps | 2.5 ps | Sagnac effect |
| 5 | $\tau_{B}$ [d] | 0 ns | 0.5 | 1.2 ps | 0.6 ps | Birefrigence effect |
| 6 | $\tau_{H}$ [e] | 26.565 ns | 0.5 | 8.8 ps | 4.4 ps | Hardware delay |
| | $\tau_{UTC(PL)\rightarrow OUT}$ | 2 047 406.45 ns | complex uncertainty: | | 112.3 ps | $U \approx 0.22$ ns |

Calibration of propagation delay dominated by TIC uncertainty.

$$\tau_{IN\rightarrow OUT} = \frac{1}{2}\tau_{REF\rightarrow RET} + \tau_{IN\rightarrow REF} + \frac{1}{2}\left(\tau_{FIB\_F} - \tau_{FIB\_B}\right) + \frac{1}{2}\tau_{H}$$

# Examplary uncertainty budget for ELSTAB link

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## A possible improvement with better TIC

| | determined quantity | estimate | sensitivity coefficient | standard uncertainty | uncertainty contribution |
|---|---|---|---|---|---|
| 1 | $\tau_{UTC(PL)\rightarrow REF}$ (a) | 1159.682 ns | 1 | 10 ps | 10 ps |
| 2 | $\tau_{REF\rightarrow RET}$ (a) | 4 217 484.702 ns | 0.5 | 10 ps | 5 ps |
| 3 | $\tau_{\Delta\lambda}$ (b) | 2.834 ns | 0.5 | 19 ps | 9.5 ps |
| 4 | $\tau_S$ (c) | -1.686 ns | 0.5 | 5 ps | 2.5 ps |
| 5 | $\tau_B$ (d) | 0 ns | 0.5 | 1.2 ps | 0.6 ps |
| 6 | $\tau_H$ (e) | 47.76 ns | 0.5 | 8.8 ps | 4.4 ps |
| | $\tau_{UTC(PL)\rightarrow OUT}$ | 2 109 926.487 ns | total uncertainty: | | 15.5 ps |

$U \approx 31$ ps

Output signals 1 pps/ 10 MHz – can be advanced with ps resolution.

# ELSTAB = Calibration available on request

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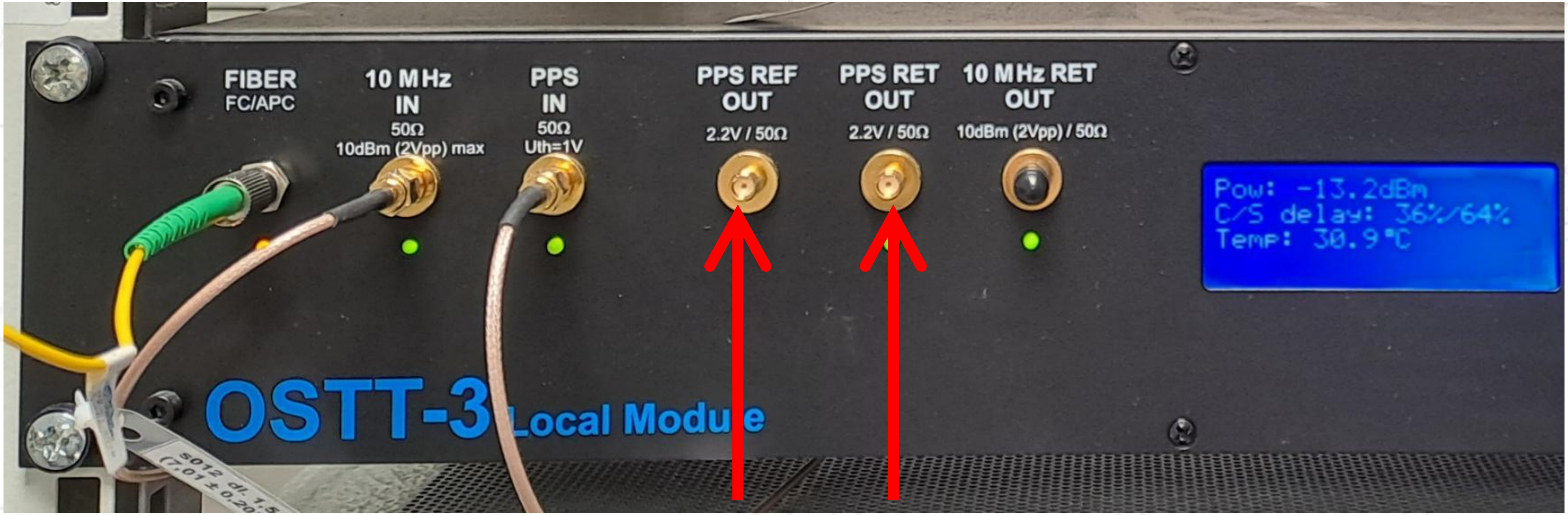
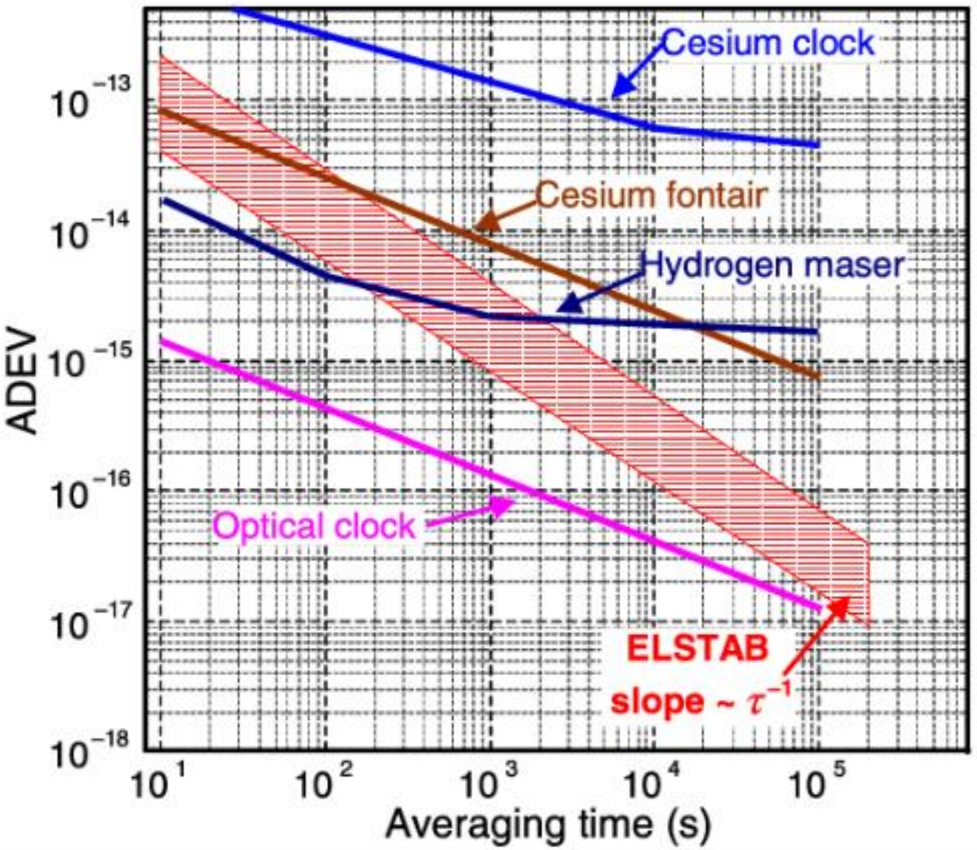



**TIC**

Propagation delay of the link can be measured during operation the link at Local Module outputs (with Time Interval Counter, High Speed Oscilloscope) – between PPS REF OUT and PPS RET OUT

# ELSTAB – the main features




1. Stability – Adev ~$10^{-17}$@1day, TDev ~1 ps
2. Calibration of propagation delay – measured at Local Module outputs and available on request.
3. Output signals 1 pps/ 10 MHz – can be advanced (reduced link delay) with ps resolution (phase of 1 pps v. 10 MHz fixed).
4. Chromatic dispersion – can be measured at Local Module outputs.
5. Excelent mismatching delay lines – better than 15 ps peak-to-peak

6. New options are incoming – Dispersion Insensitive, ToDay transmission

# UTC(PL) dissemination via optical fiber: ELSTAB links

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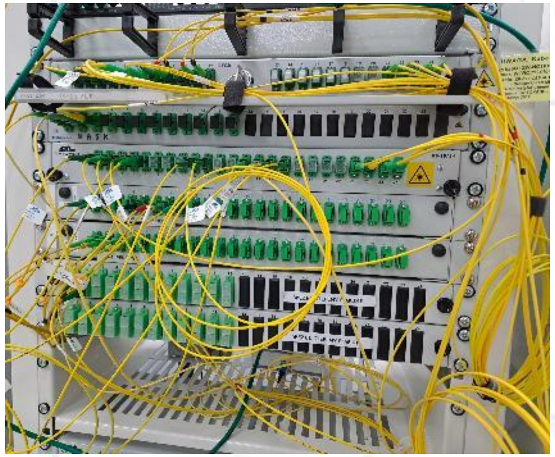
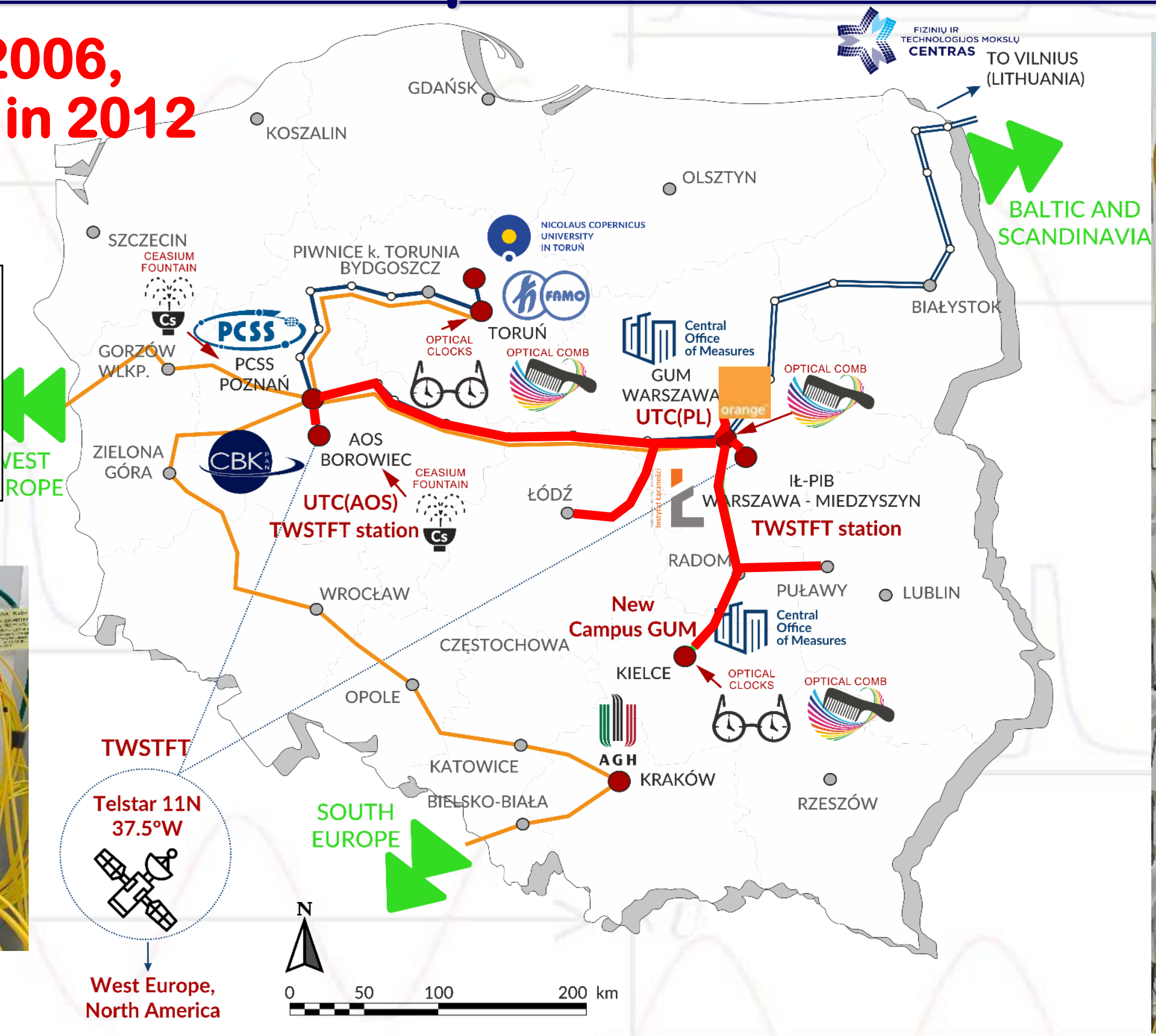
**First steps in 2006,
first ELSTAB link in 2012**

**<0.5 ns**
**timing accuracy v. UTC(PL)**






# Examplary on-line results for ELSTAB link

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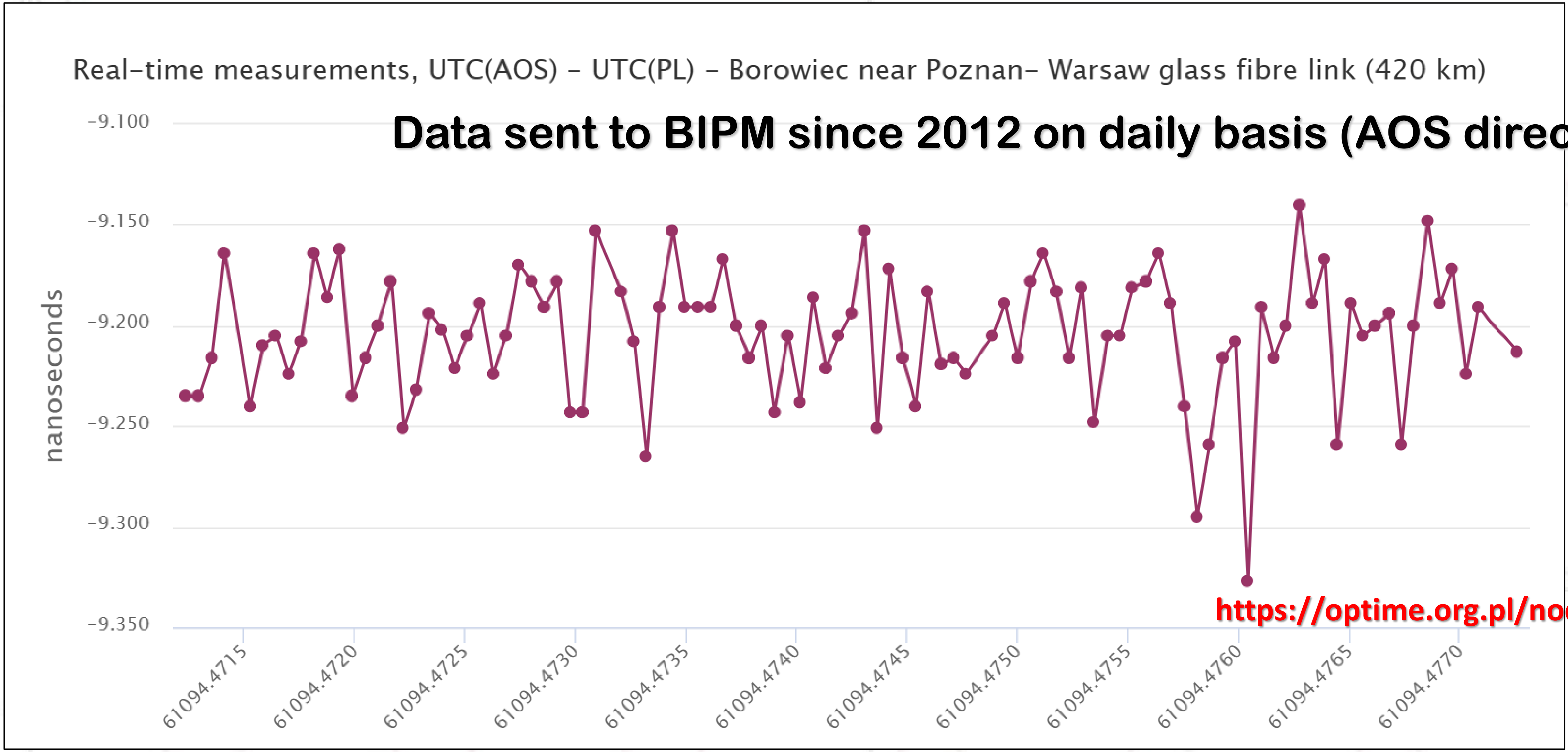


**Data sent to BIPM since 2012 on daily basis (AOS directory)**

https://optime.org.pl/node/47

# List of relevant publications on ELSTAB technology

Central Office of Measures


1. P. Krehlik at al.:"**ELSTAB—Fiber-Optic Time and Frequency Distribution Technology: A General Characterization and Fundamental Limits**," in IEEE Trans. on UFFC, vol. 63, no. 7, pp. 993-1004, July 2016, doi: 10.1109/TUFFC.2015.2502547
2. Ł. Śliwczyński at al., "**Calibrated optical time transfer of UTC(k) for supervision of telecom networks**," *Metrologia*, vol. 56, 2019, Art. no. 015006, doi: 10.1088/1681-7575/aaef57.
3. Ł. Śliwczynski at al.: "**Dissemination of time and RF frequency via a stabilized fibre optic link over a distance of 420 km**," *Metrologia*, vol. 50, pp. 133–145, 2013
4. Ł. Śliwczyński at al.: "**Picoseconds-Accurate Fiber-Optic Time Transfer With Relative Stabilization of Lasers Wavelengths**," in J. Lightwave Techn., vol. 38, no. 18, pp. 5056-5063, 15 Sept.15, 2020, doi: 10.1109/JLT.2020.2999158.
5. Ł. Śliwczyński at al.: „**Optical fibers in time and frequency transfer**", MST, vol. 21, no. 7, p. 075302, Jul. 2010, doi: 10.1088/0957-0233/21/7/075302
6. P. Krehlik at al.: „**Fiber-Optic Joint Time and Frequency Transfer With Active Stabilization of the Propagation Delay**", IEEE Trans. on Instrum. and Meas., vol. 61, no. 10, Oct. 2012, doi: 10.1109/TIM.2012.2196396
7. Ł. Śliwczyński at al.: „**Active Propagation Delay Stabilization for FiberOptic Frequency Distribution Using Controlled Electronic Delay Lines**", IEEE Trans. on Instrum. and Meas., vol. 60, no. 4, Apr 2011, doi: 10.1109/TIM.2010.2090696
8. Ł. Śliwczyński at al.: „**Frequency Transfer in Electronically Stabilized Fiber Optic Link Exploiting Bidirectional Optical Amplifiers**", IEEE Trans. on Instrum. and Meas., vol. 61, no. 9, Sep. 2012, doi: 10.1109/TIM.2012.2188663

# List of relevant publications on ELSTAB technology - 2

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9. Ł. Śliwczyński i J. Kołodziej: „**Bidirectional Optical Amplification in Long-Distance Two-Way FiberOptic Time and Frequency Transfer Systems**”, IEEE Trans. on Instrum. and Meas., vol. 62, no. 1, p. 253–262, Jan. 2013, doi: 10.1109/TIM.2012.2212504
10. Ł. Śliwczyński at al.: “**Synchronized lasermodules with frequency offset up to 50 GHz for ultra-accurate long-distance fiber optic time transfer links**,” J. Lightwave Techn., vol. 40, pp. 2739 – 2747, 2022, doi: 10.1109/JLT.2022.3147591
11. Z. Jiang at al., "**Comparing a GPS time link calibration with an optical fibre self-calibration with 200 ps accuracy**," 2015, Metrologia 52 384–91, DOI 10.1088/0026-1394/52/2/384
12. Ł. Śliwczyński et al., "**Fiber-Optic Time Transfer for UTC-Traceable Synchronization for Telecom Networks**," in IEEE Communications Standards Magazine, vol. 1, no. 1, pp. 66-73, March 2017, doi: 10.1109/MCOMSTD.2017.1600766ST
13. Ł. Śliwczyński et al., "**Fiber-Based UTC Dissemination Supporting 5G Telecommunications Networks**," in IEEE Communications Magazine, vol. 58, no. 4, pp. 67-73, April 2020, doi: 10.1109/MCOM.001.1900599
14. Ł. Śliwczyński at al., "**Modeling and Optimization of Bidirectional Fiber-Optic Links for Time and Frequency Transfer**," in IEEE Trans. on UFFC, vol. 66, no. 3, pp. 632-642, March 2019, doi: 10.1109/TUFFC.2018.2889186
15. P. Krehlik at al., "**Electrical Regeneration for Long-Haul Fiber-Optic Time and Frequency Distribution Systems**," in IEEE Trans. on UFFC, vol. 68, no. 3, pp. 899-906, March 2021, doi: 10.1109/TUFFC.2020.3016610
16. P. Krehlik at al., "**Optical Multiplexing of Metrological Time and Frequency Signals in a Single 100-GHz-Grid Optical Channel**," in IEEE Trans. on UFFC, vol. 68, no. 6, pp. 2303-2310, June 2021, doi: 10.1109/TUFFC.2021.3053430

# Thank you for your attention

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