AKADEMIA GÓRNICZO-HUTNICZA
IM. STANISŁAWA STASZICA W KRAKOWIE

Time and frequency transfer via optical fiber

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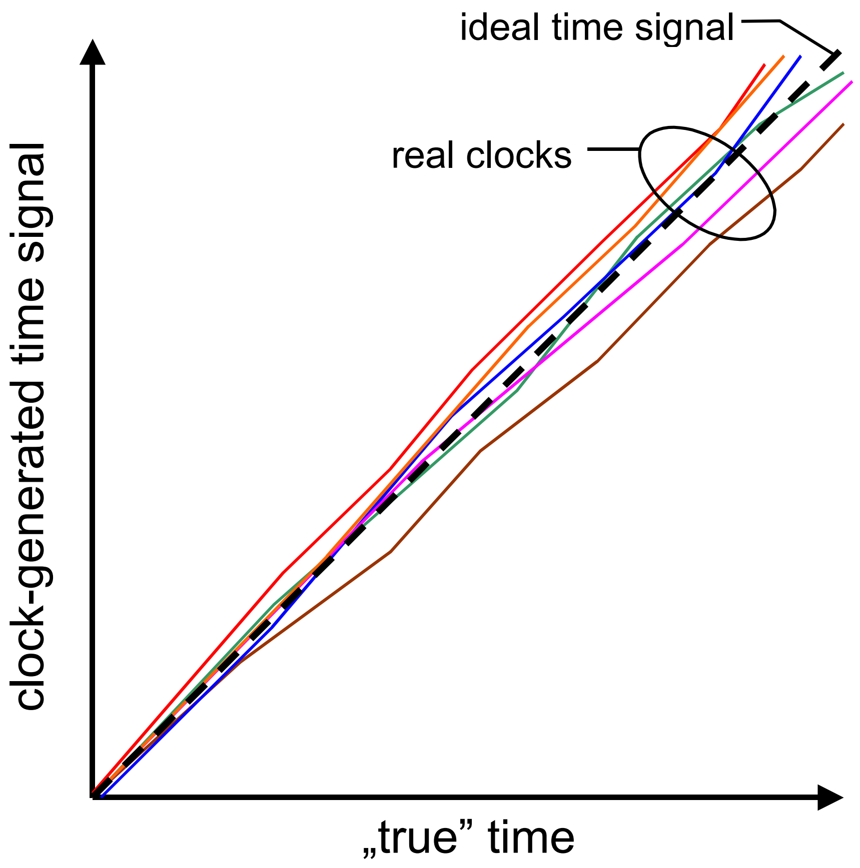
AGH

Introduction



The most precise time scale may be derived processing the signals from many clocks.

Introduction

Main kinds of precise clocks:

- Rubidium clock
- Cesium atomic clock
- Cesium fountain atomic clock
- Hydrogen maser
- Optical clock

Time scales:

TAI - International Atomic Time (Temps Atomique International)
UTC - Coordinated Universal Time
TA(PL) - Polish Atomic Time
UTC(PL) – Polish official time based on UTC

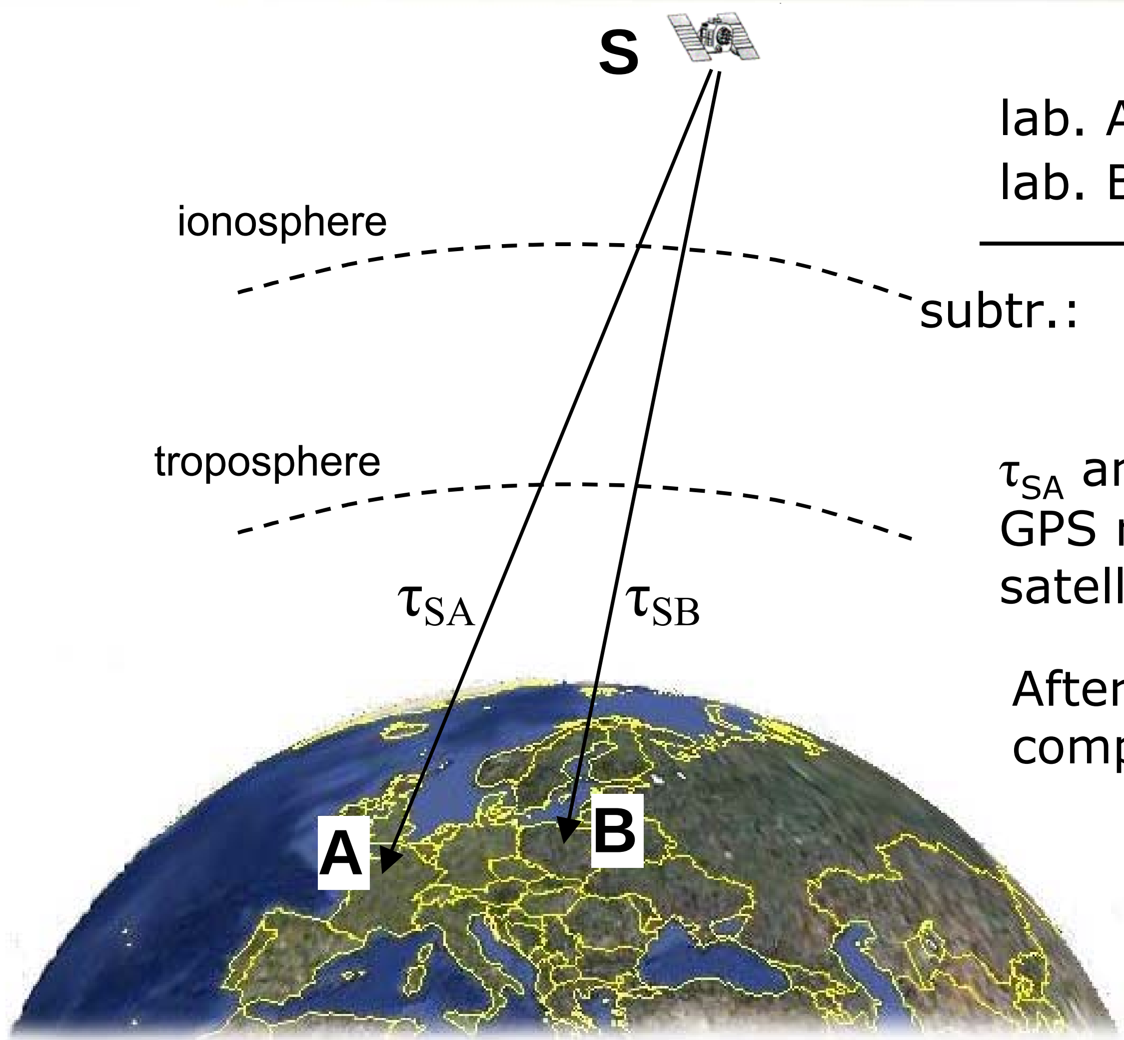
Problem:

Atomic time scale is derived from comparisons of many clocks located in **remote** laboratories.

⇩

The comparisons are affected by
varying propagation delays
of time signals transmitted between laboratories.

GPS Common-View clocks comparison



lab. A: ClockA – (ClockS – τ_{SA})
lab. B: ClockB – (ClockS – τ_{SB})

subtr.: ClockA – ClockB + (τ_{SA} - τ_{SB})

τ_{SA} and τ_{SB} are estimated by GPS receivers basing on known satellite position

After 1-day averaging the comparison uncertainty is ~ 10 ns.

Two-Way Satellite Time and Frequency Transfer (TWSTFT)

lab. A: ClockA – (ClockB – τ_{BSA})
lab. B: ClockB – (ClockA – τ_{ASB})

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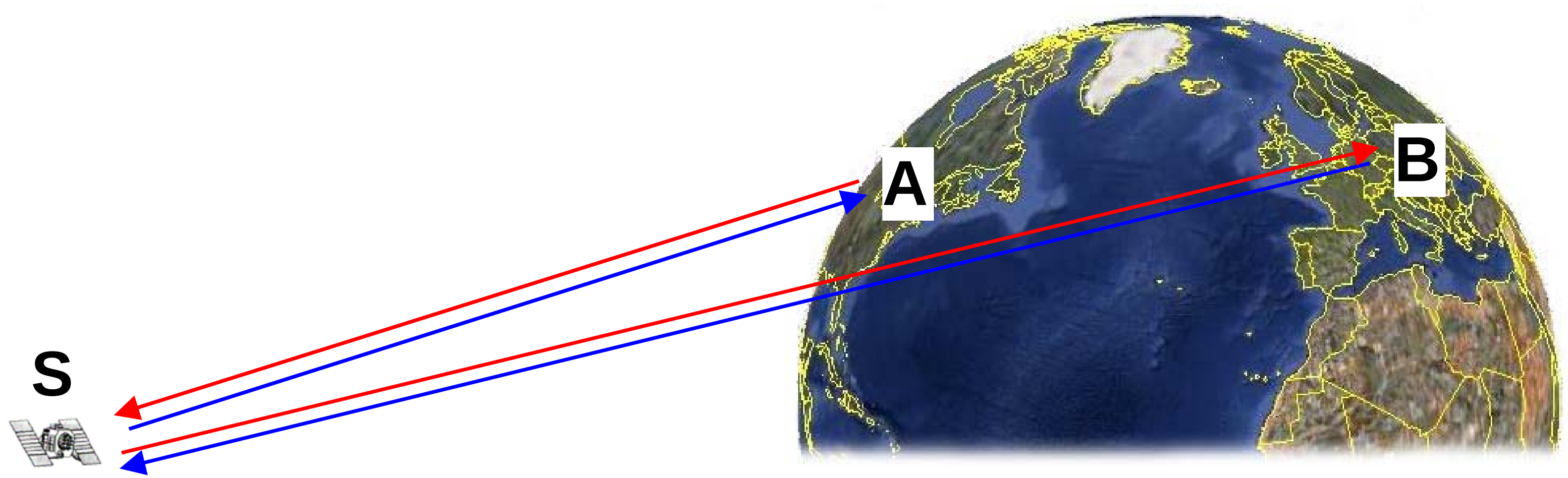
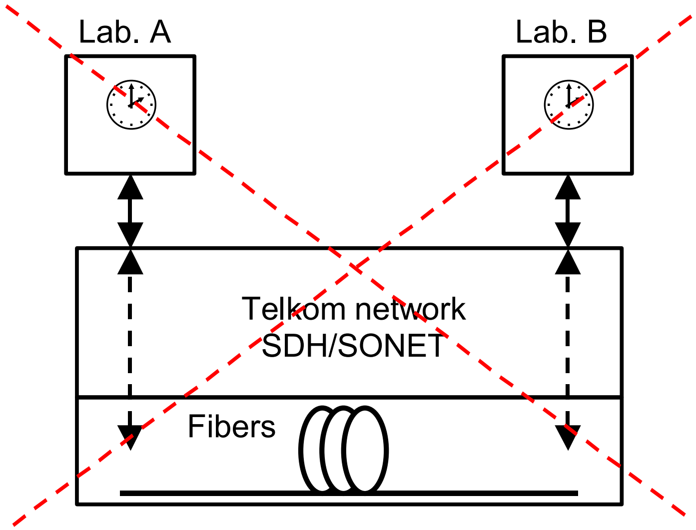
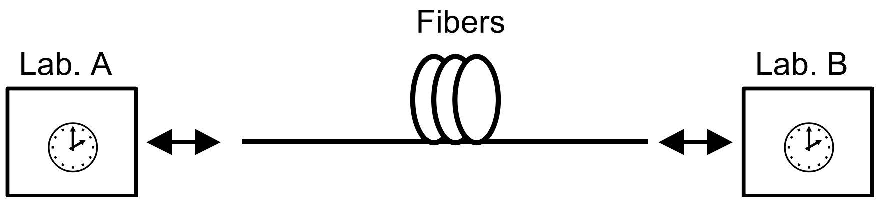
subtr.: ClockA – ClockB + (τ_{BSA} - τ_{ASB})/2

After averaging and many corrections the comparison uncertainty is ~ 1 ns.



Our activity in fiber-optic time/frequency transfer



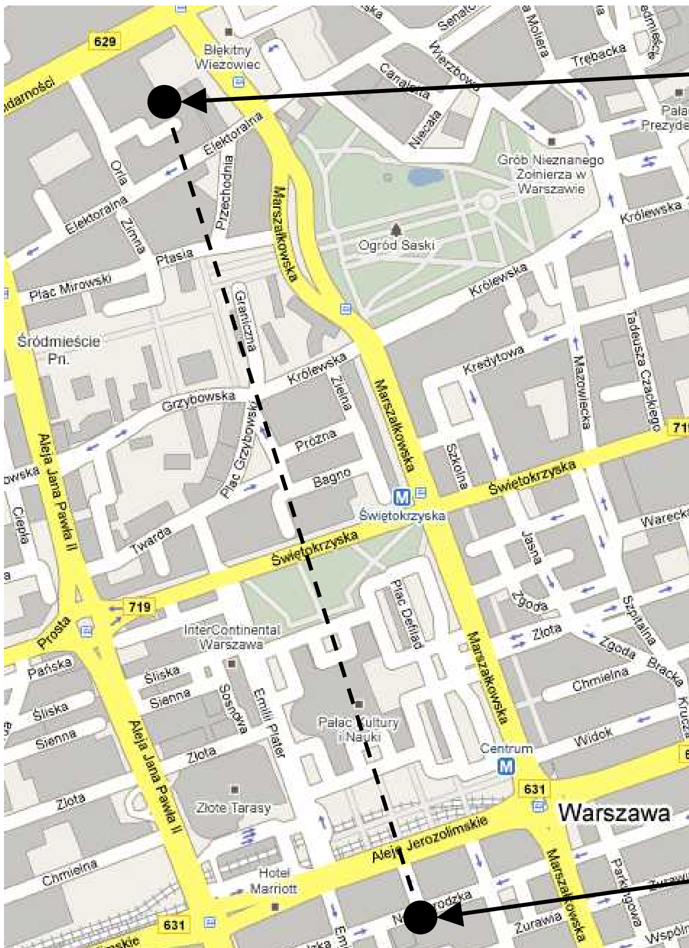


research – determining basic accuracy limitations of the fiber-optic transfer of time/frequency signals,

design – development of transmitters, receivers, optical amplifiers etc. dedicated for time/frequency transfer systems.

Practical needs in Poland

1. Point-to-point connections between some institutions in Warszawa



Główny Urząd Miar
Lab. Czasu i Częstotliwości
W-wa, ul. Elektoralna

Our time/frquency transfer system

TPSA
Primary Reference Clock
W-wa, ul. Nowogrodzka

Practical needs in Poland

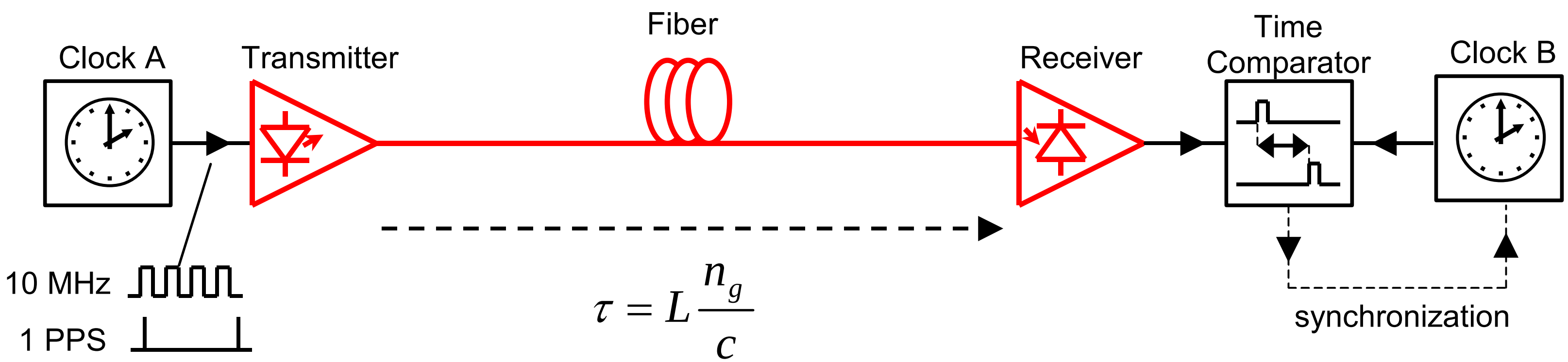
2. Network between atomic clocks in Warszawa metropolitan area

Institution		Clocks
GUM (Warszwa, Elektoralna)	-	3 Cs + 1HM
TPSA (Warszawa, Obrzeźna)	-	2 Cs
TPSA (Warszawa, Nowogrodzka)	-	2 Cs
IŁ (Warszawa, Miedzeszyn)	-	2 Cs
CWOM (Warszawa, Radiowa)	-	1 HM
CWOM (Zielonka k/Warszawy)	-	1 Cs
ITR (Warszawa, Ratuszowa)	-	1 Cs

Practical needs in Poland

3. Long-haul connections

First approach: unidirectional time/frequency transfer



$$\tau = L\frac{n_g}{c}$$

$$\Delta\tau = \frac{L}{c}\frac{\partial n_g}{\partial T}\Delta T + \frac{Ln_g}{c}\frac{\partial L}{L\partial T}\Delta T + \frac{L}{c}\frac{\partial n_g}{\partial \lambda}\Delta\lambda$$

Fundamental accuracy limit: temperature dependence of the fiber propagation delay.

Typical values for Ge-doped silica fiber (after: K.T.V. Grattan, B. T. Meggitt, *Optical fiber sensor technology vol. 3*, Kluwer 1999) :

$$\frac{\partial n_g}{\partial T} = 11 \cdot 10^{-6}\ [1/^\circ C]$$

$$\frac{\partial L}{L \partial T} = 0.55 \cdot 10^{-6}\ [1/^\circ C]$$

⇒ $\Delta\tau$ **= 39 ps/(°C·km)**

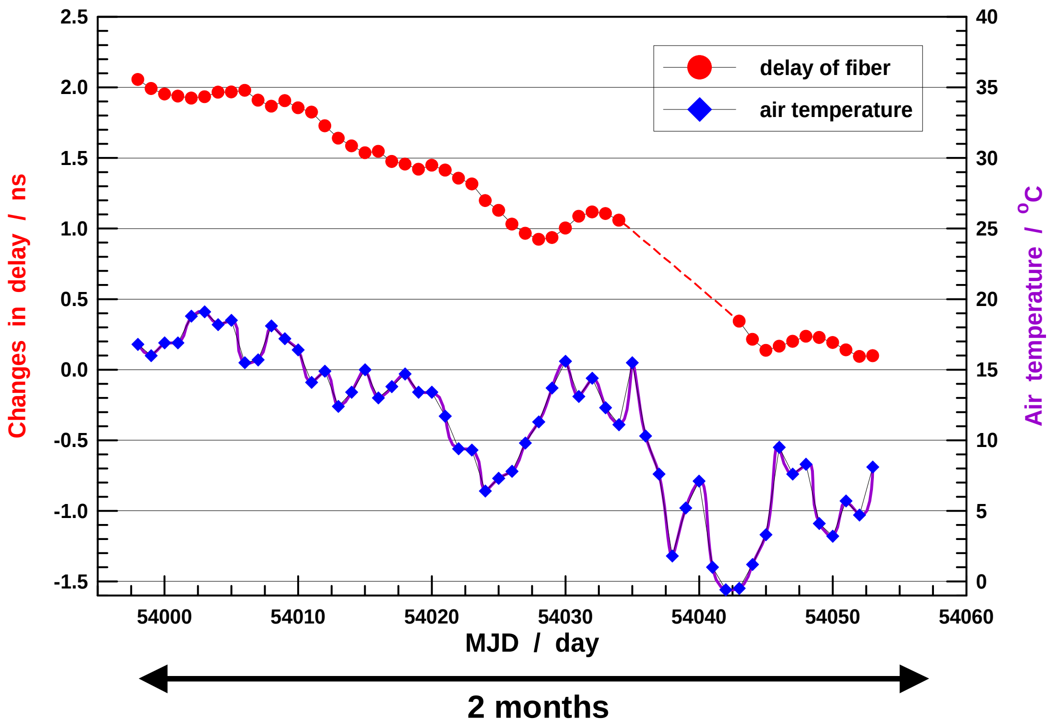
Our measurements results:

Fiber type	Fiber length [km]	λ [nm]	Temperature sensitivity [ps/(°C·km)]
SMF-28	12	1550	**36.80**
		1310	**37.97**
SMF-DS	20	1550	**38.67**
LEAF	20	1550	**37.97**

For 10 km long fiber:

diurnal temperature variations ~1°C ➡ Δτ ~ 0.4 ns

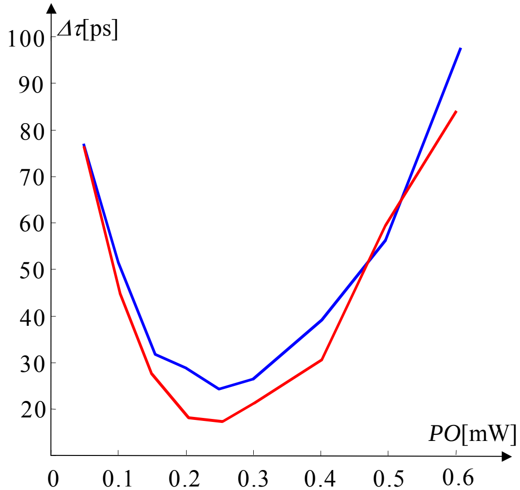
seasonal temperature variations ~20°C ➡ Δτ ~ 8 ns

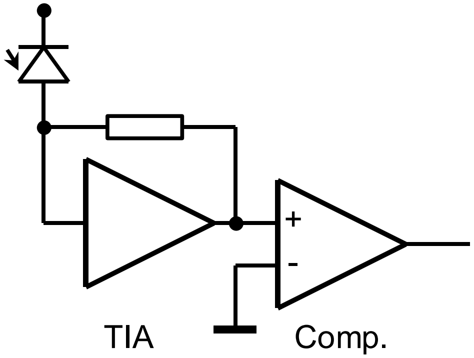


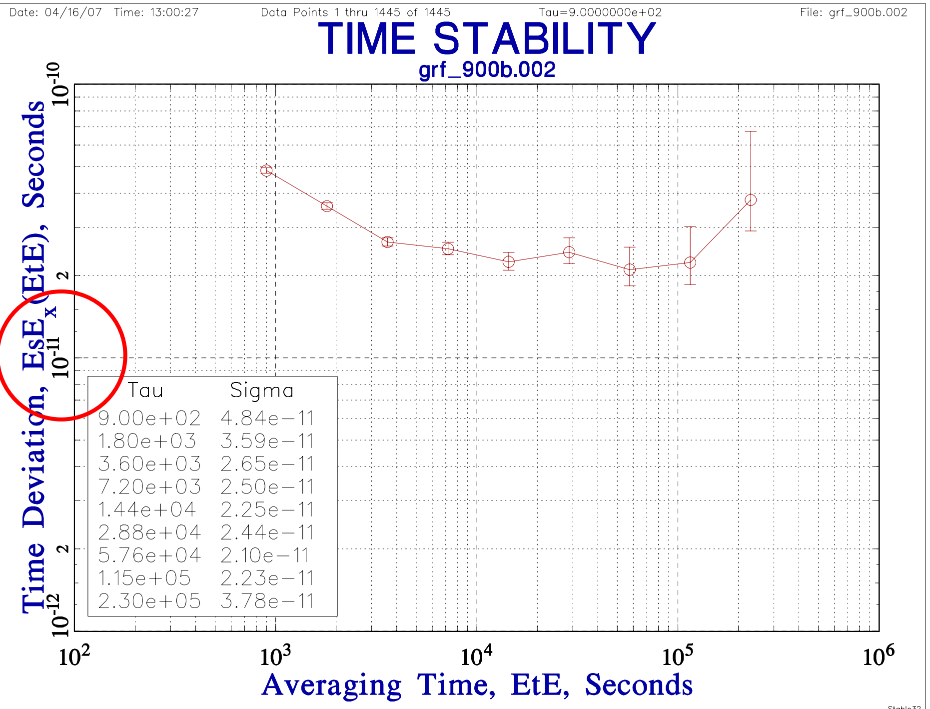
Two-month measurement of 6 km-long fiber propagation delay variation (by Laboratorium Czasu i Częstotliwości, Główny Urząd Miar)

Additional impairments by transmitter and receiver electronics (our actual design) :

- temperature sensitivity of transmitter: < 0.2 ps/°C,
- temperature sensitivity of receiver: < 1 ps/°C,
- receiver level sensitivity: < 20 ps/dB,
- long term (ageing) propagation variations ???

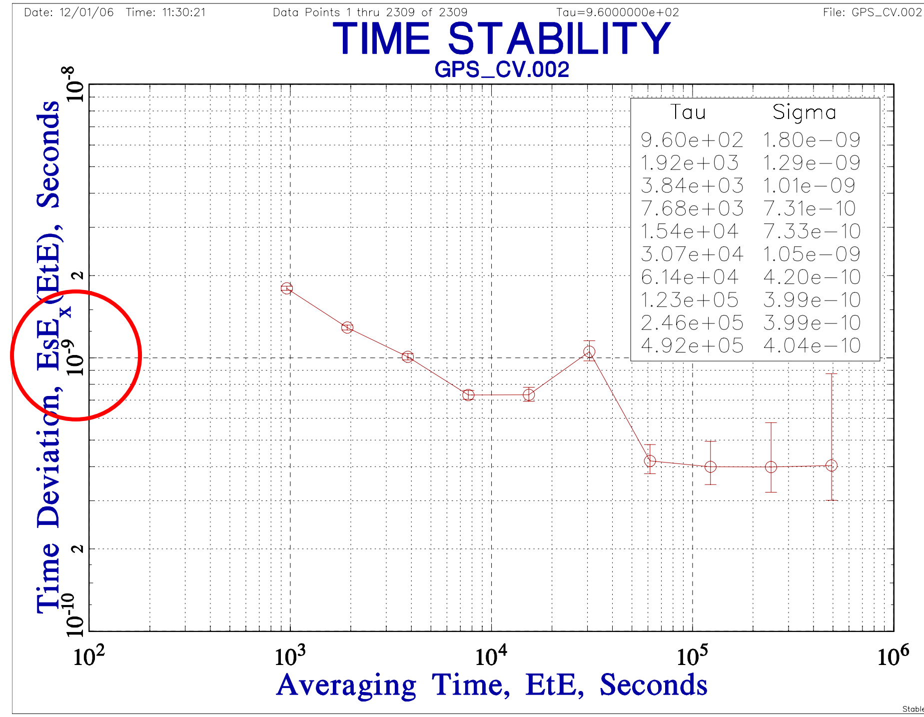






Comparison accuracy for 3 km-long unidirectional fiber transfer

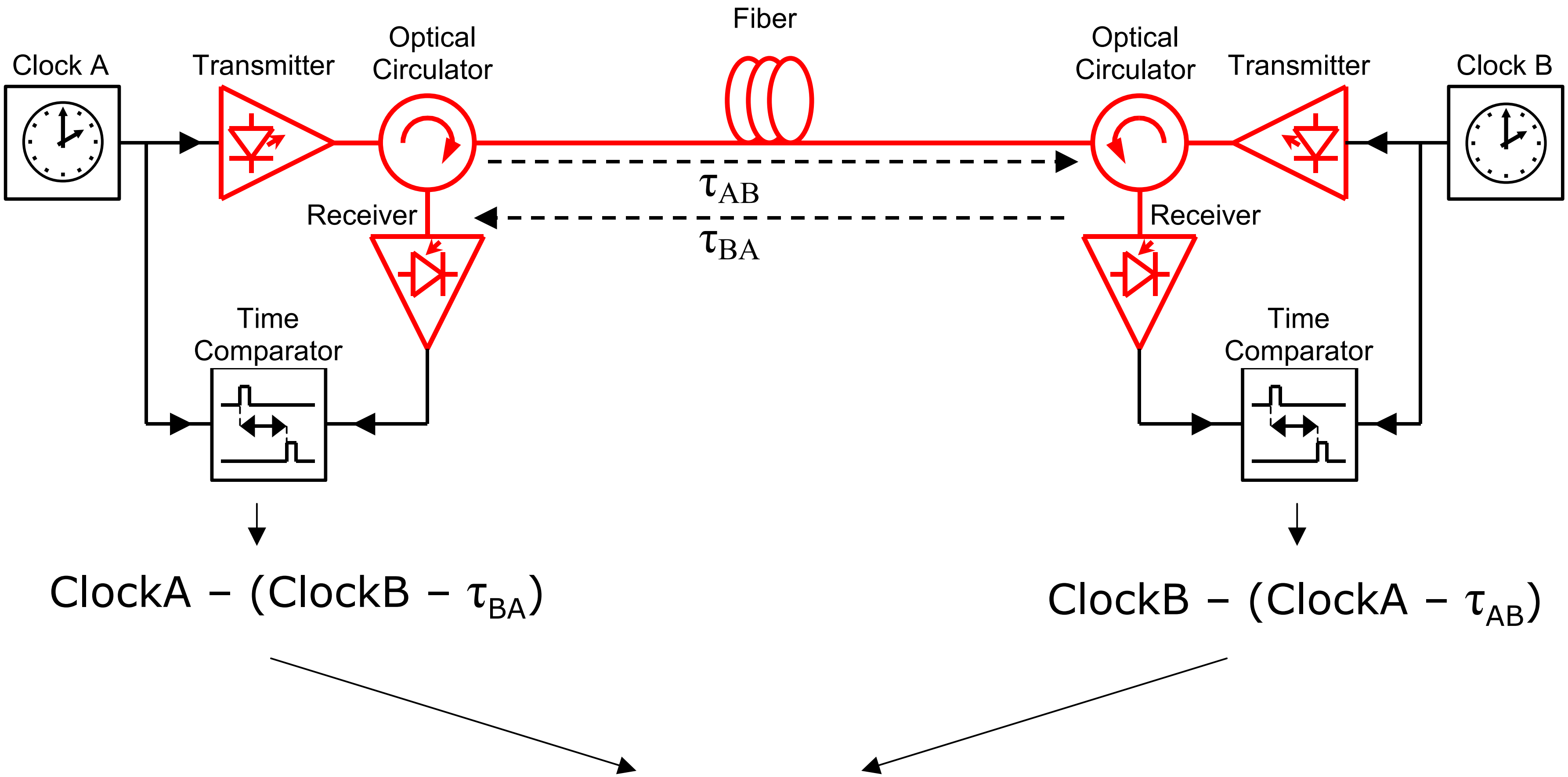
(by Laboratorium Czasu i Częstotliwości, GUM)



Comparison accuracy for GPS Common-View system

(by Laboratorium Czasu i Częstotliwości, GUM)

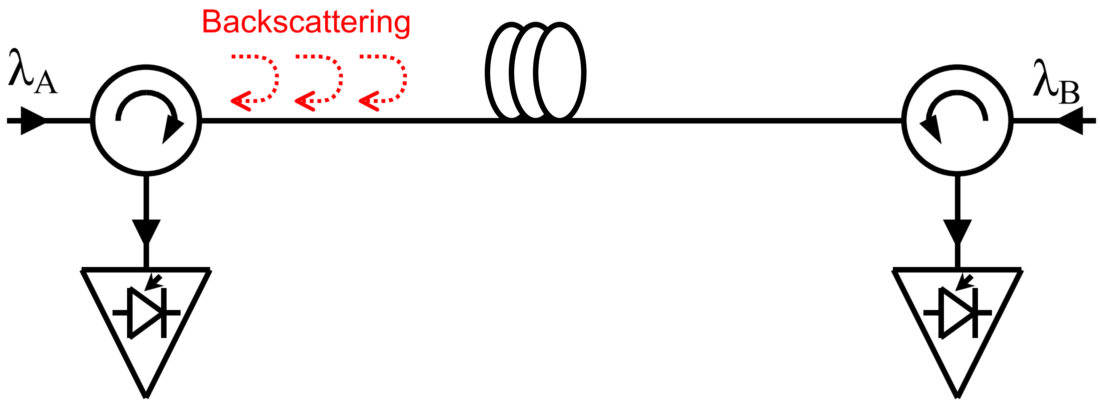
Second approach: bidirectional time/frequency transfer

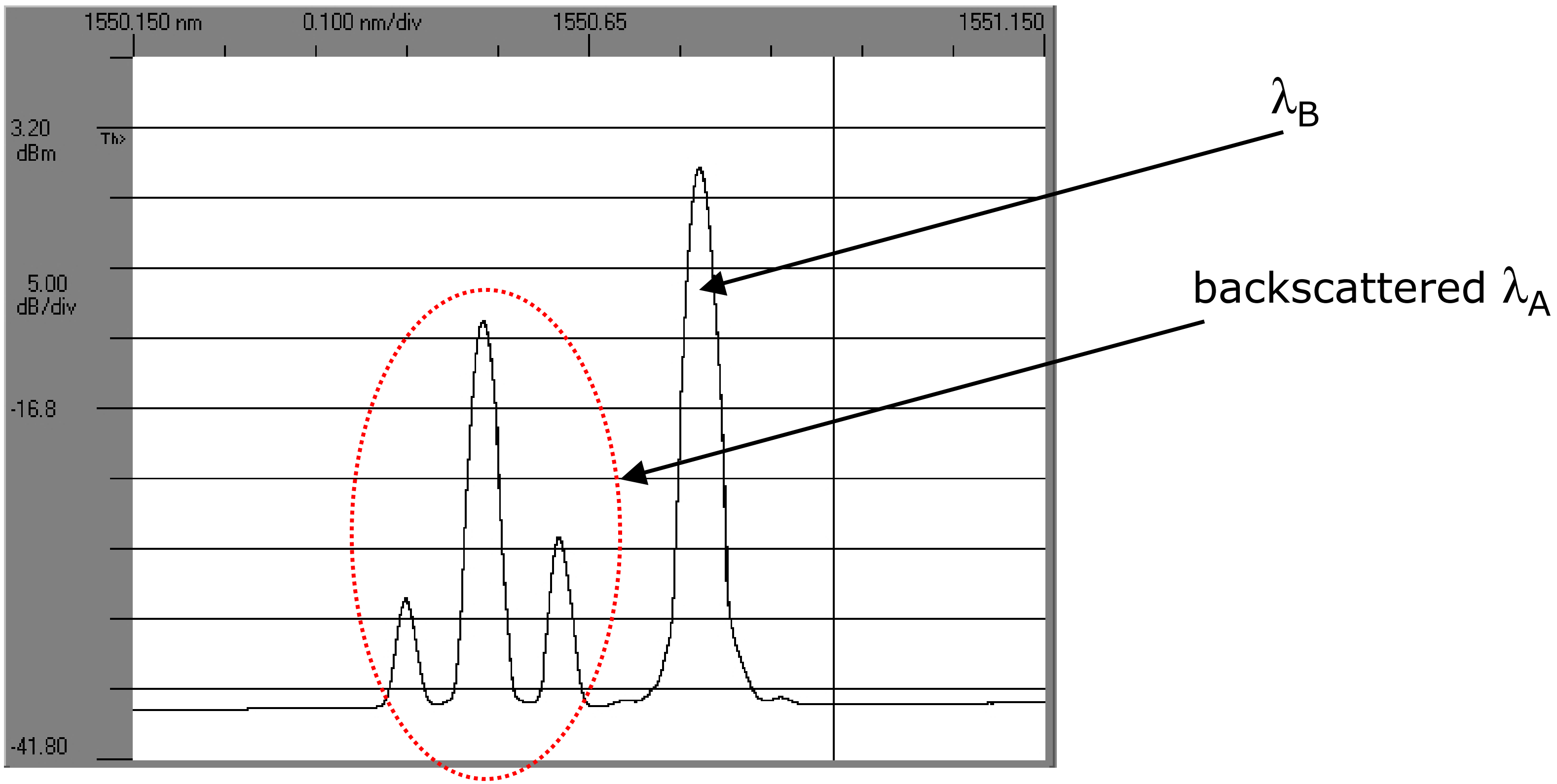


$ClockA - (ClockB - \tau_{BA})$

$ClockB - (ClockA - \tau_{AB})$

subtracting : $ClockA - ClockB + (\tau_{BA} - \tau_{AB})/2$

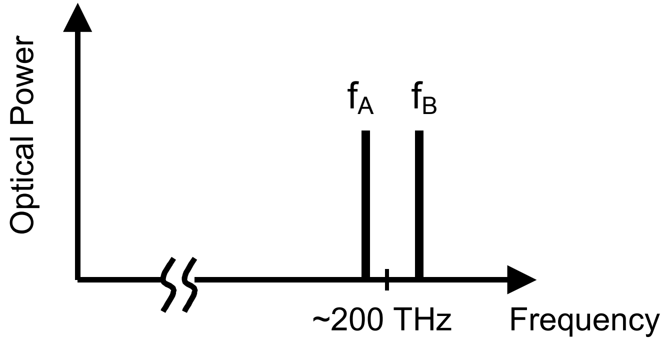




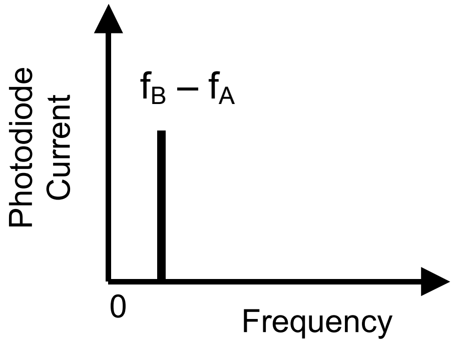
Optical spectrum at the receiver input

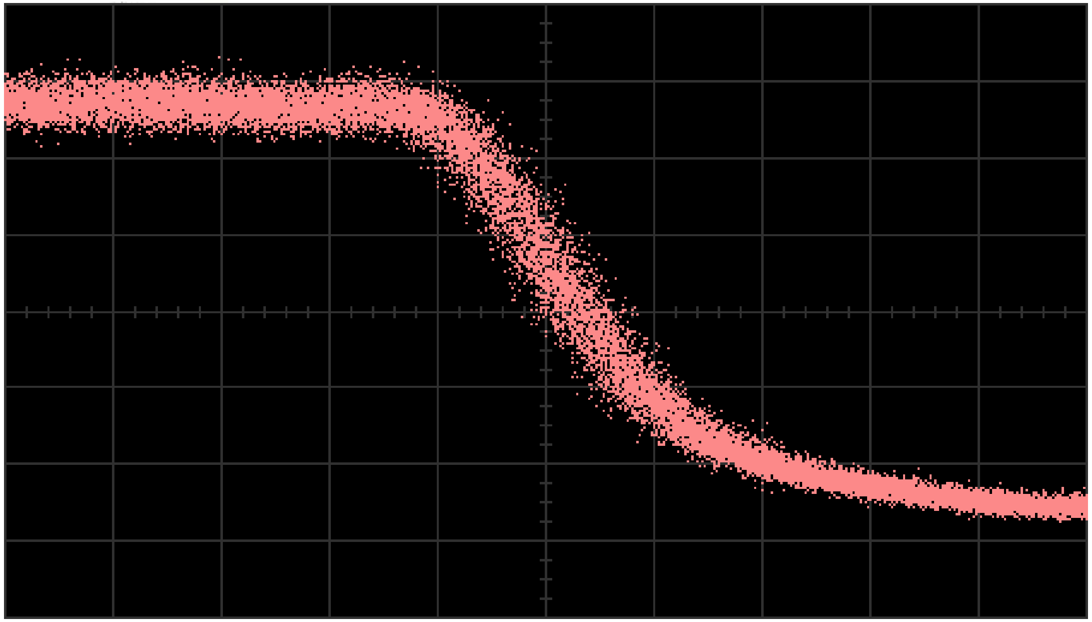
In bidirectional transmission backscattered light interacts (mixes) with received signal thus it is necessary to detune λ_A from λ_B .

Photodiode input:

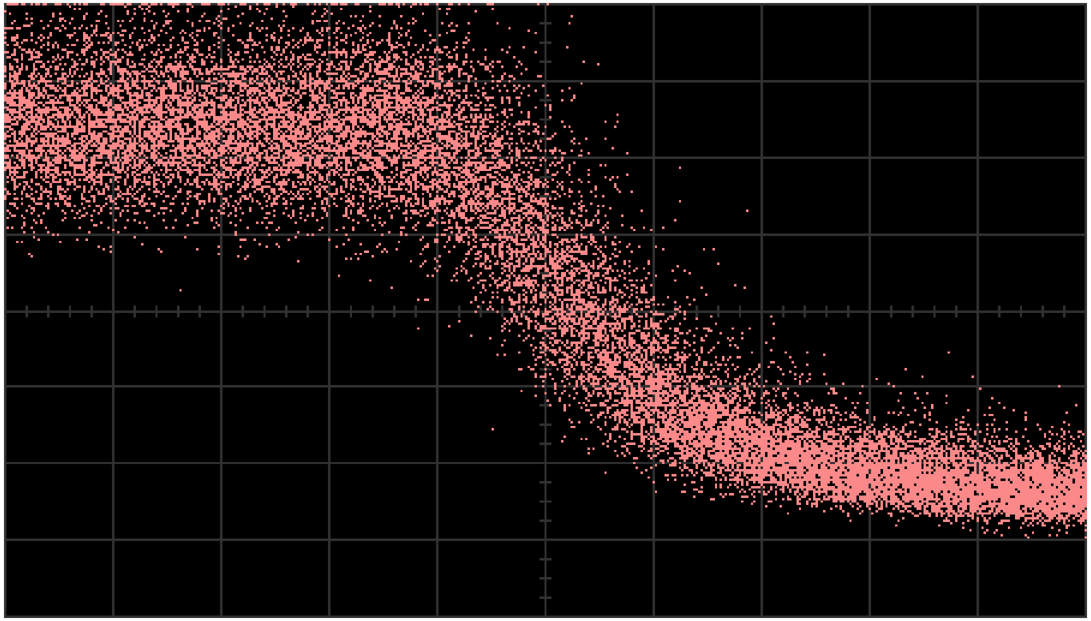


Photodiode output:

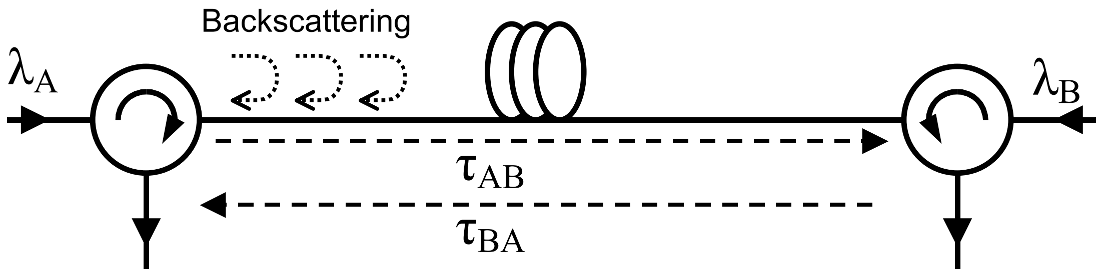




$$\left|\lambda_A - \lambda_B\right| \geq 0.4\,\mathrm{nm}\ (50\,\mathrm{GHz})$$



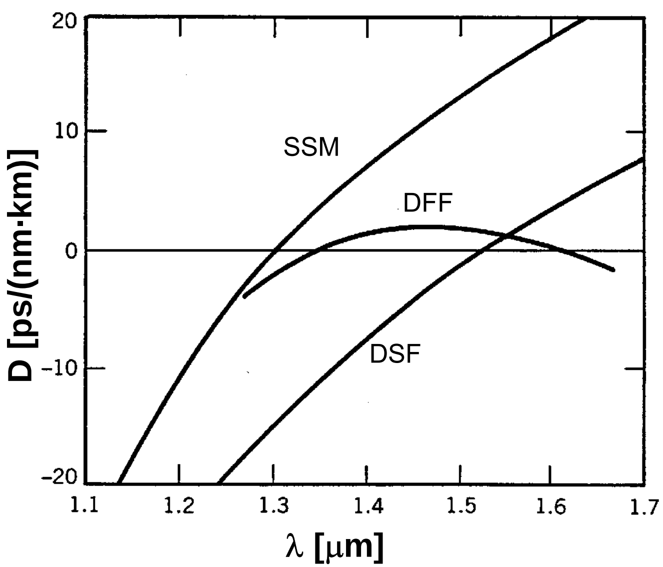
$$\lambda_A = \lambda_B$$

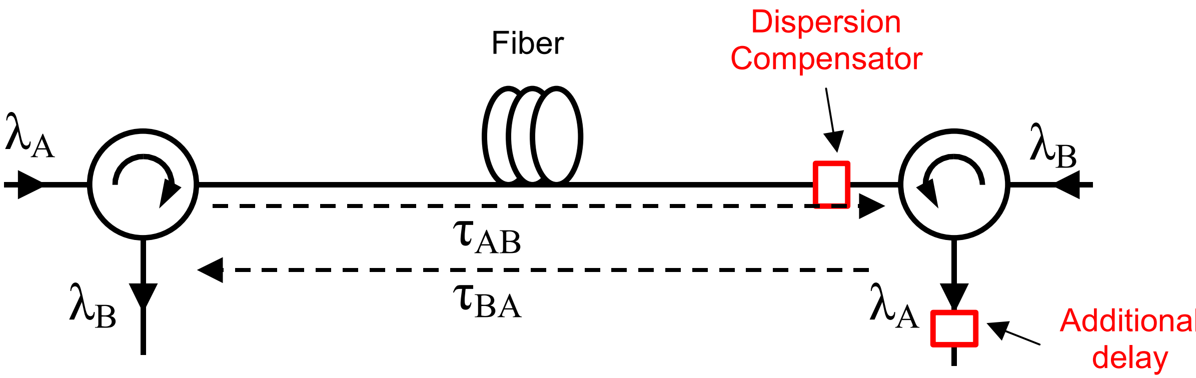


$$\tau_{AB} = \tau_{BA} \ ???$$

$\lambda_A \neq \lambda_B \Rightarrow$ chromatic dispersion manifests

$$D = \frac{\Delta\tau}{L\Delta\lambda}$$





$$\tau_{AB} - \tau_{BA} = LD(\lambda_A - \lambda_B)$$

For **100 km long fiber**, Δλ=0.4 nm, D=17 ps/(nm·km) ➨ $\boldsymbol{\tau_{AB} - \tau_{BA} = 680}$ **ps**

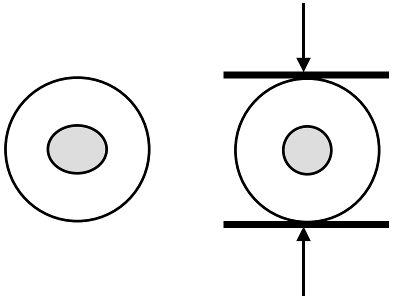
D depends on temperature !!!

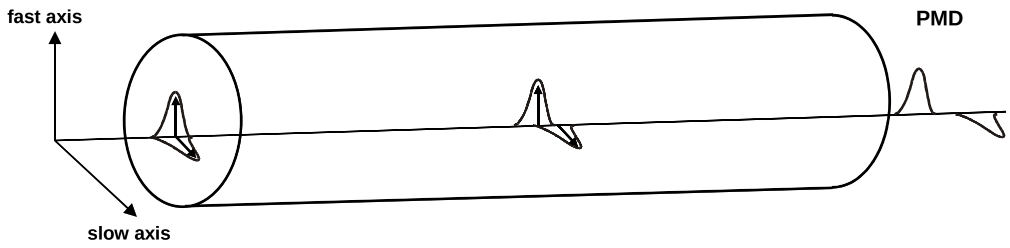
$$\frac{dD}{dT} \sim -1.5 \ldots -4 \cdot 10^{-3} \, \mathrm{ps/(nm \cdot km \cdot C)}$$

For **100 km long fiber**, Δλ=0.4 nm, ΔT=20°C ➨ $\boldsymbol{\Delta(\tau_{AB} - \tau_{BA}) \sim 3}$ **ps**

For bidirectional clock comparisons the impact of the fiber temperature is ~ $2 * 10^4$ times smaller than for unidirectional scheme.

Polarization-mode dispersion





In nowadays fibers $\mathrm{PMD} \sim 0.1\,\mathrm{ps}/\sqrt{\mathrm{km}}$

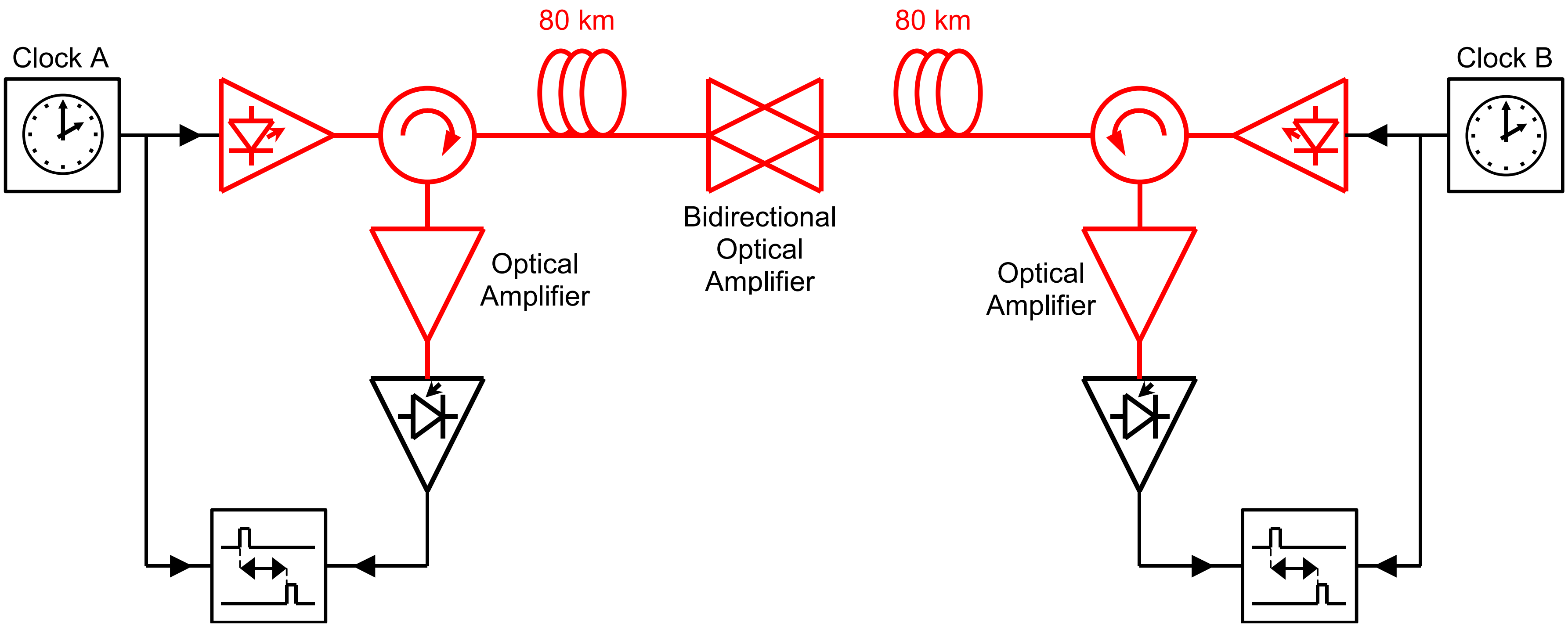
For 100 km long fiber ➡ **$\Delta\tau_P$ ~ 1 ps**

In older instalations may be 10 × greater !

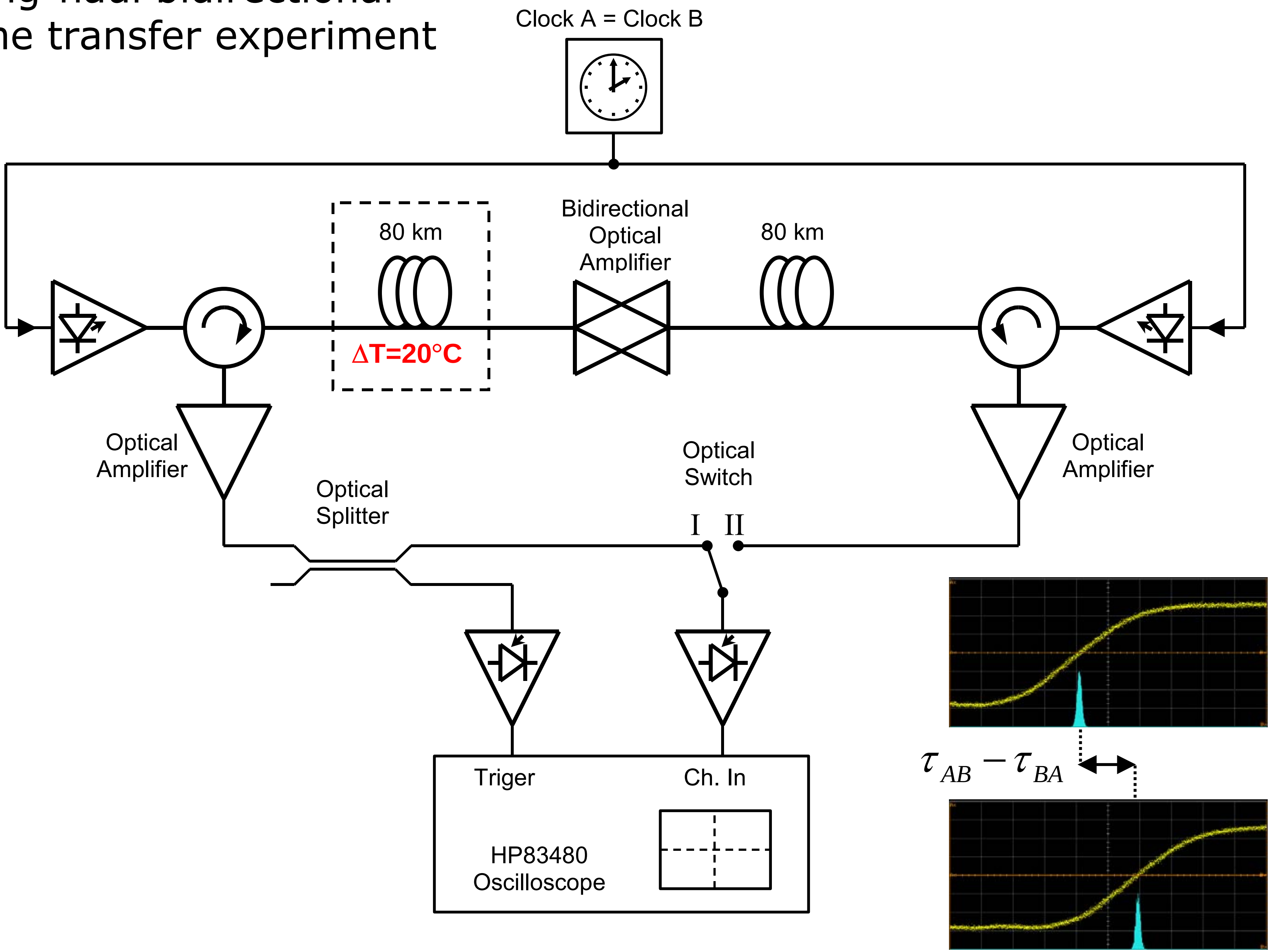
Additional possible impairments in bidirectional transmission:

- transmitter and receiver electronics,
- optical paths asymmetry in optical amplifiers, filters etc.

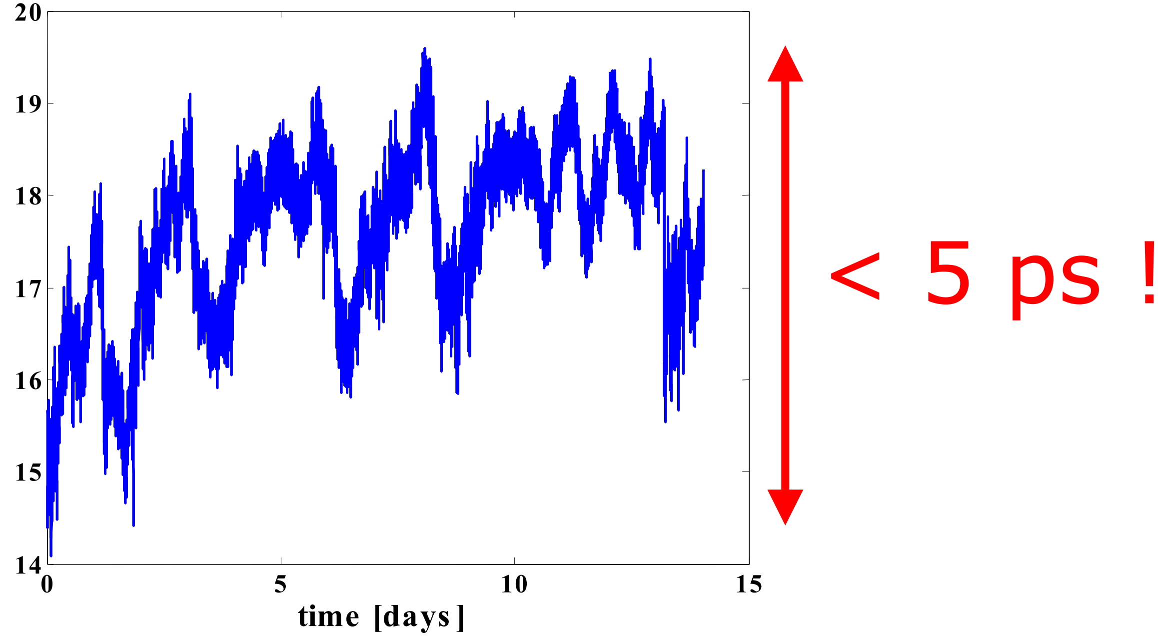
Long-haul bidirectional time transfer experiment



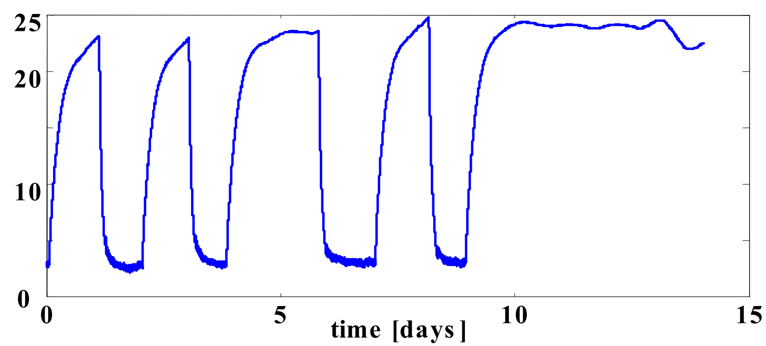
Long-haul bidirectional time transfer experiment



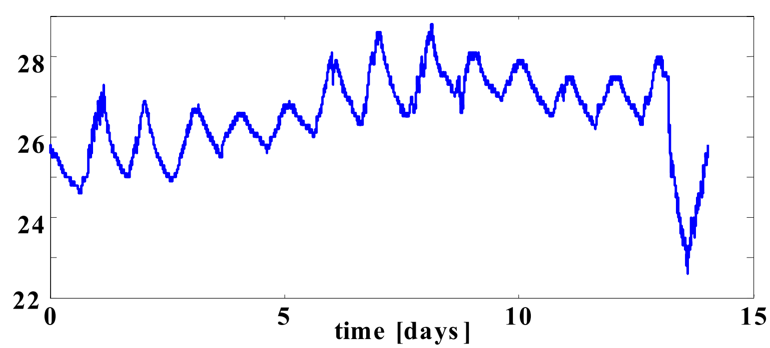
$\tau_{AB} - \tau_{BA}$ [ps]



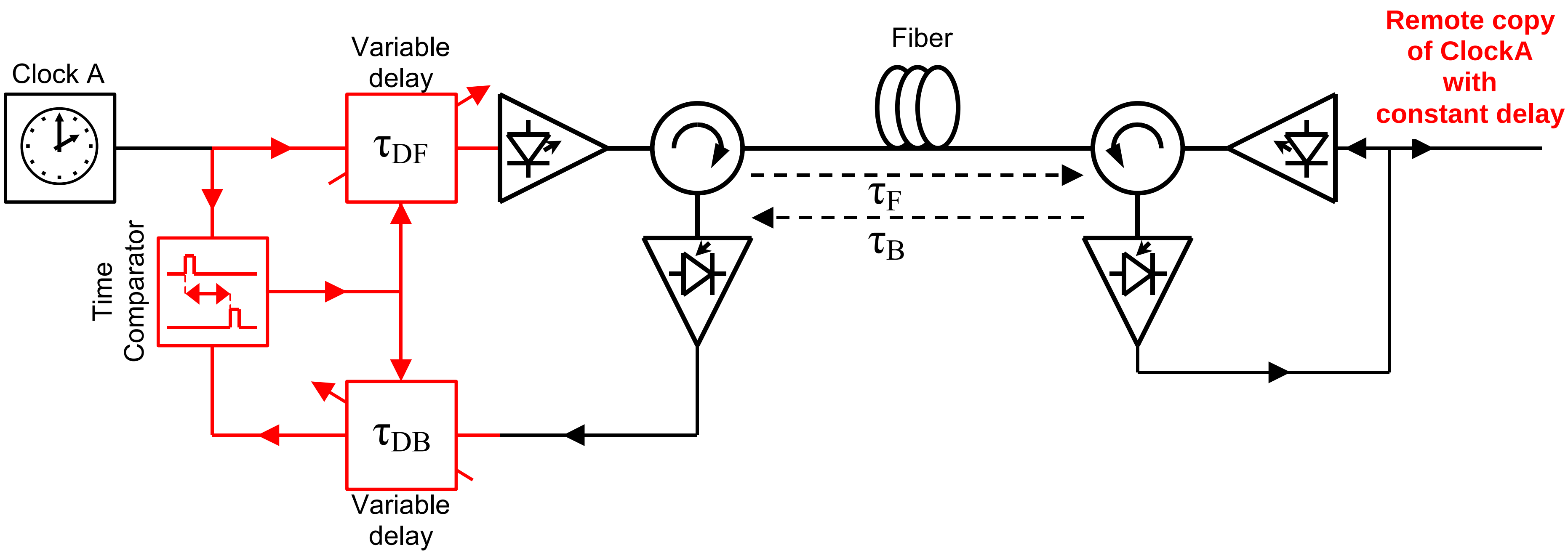
chamber temperature [C deg.]



lab. temperature [C deg.]

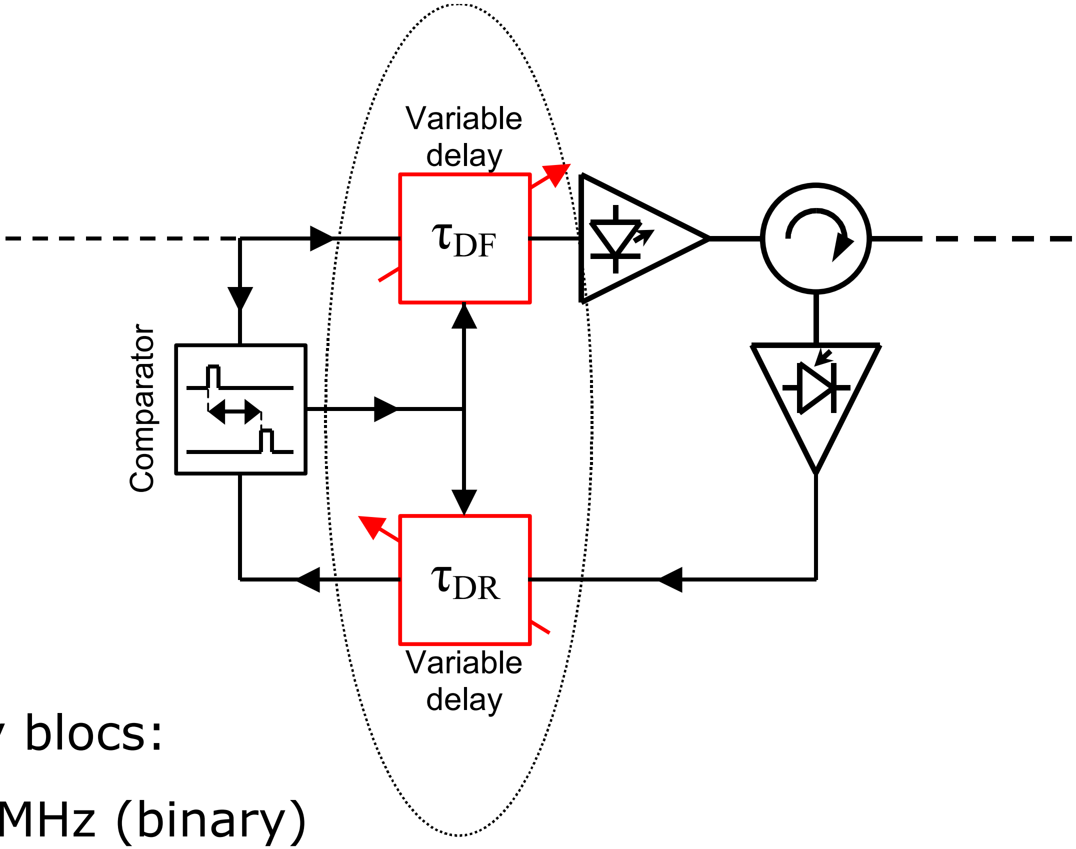


Third approach: time/frequency transfer with active delay stabilization



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

$$\Rightarrow \quad \tau_{DF} + \tau_F = \text{const}$$



Demands on variable delay blocs:

- input signal: 1PPS or 10 MHz (binary)
- monotonic tuning
- no glitches
- continuous tuning or small tuning steps; ~ 20 ps
- tuning range ~ 100 ns (for 30 km fiber length)
- excellent matching: τ_{DF} - τ_{DB} < 20 ps

Conclusions

- Time/frequency transfer in „black fiber" (i.e. not via telkom network layers) offers better results than GPS-based time transfer or clock comparisios.
- Unidirectional transmission gives exellent results for short links (up to few km); for longer links the main limitation is the temperature dependence of the fiber propagation delay.
- Bidirectional transmission allows few-ps-range accuracy of clocks comparisons even for long-haul links; the main limitation is the temperature dependence of the fiber chromatic dispersion and (in older fibers) the polarization-mode dispersion.
- Active delay stabilization would offer the constant propagation delay even for long links; the limiting factor seems to be the design of the matched variable delay blocks.