Long distance fiber link

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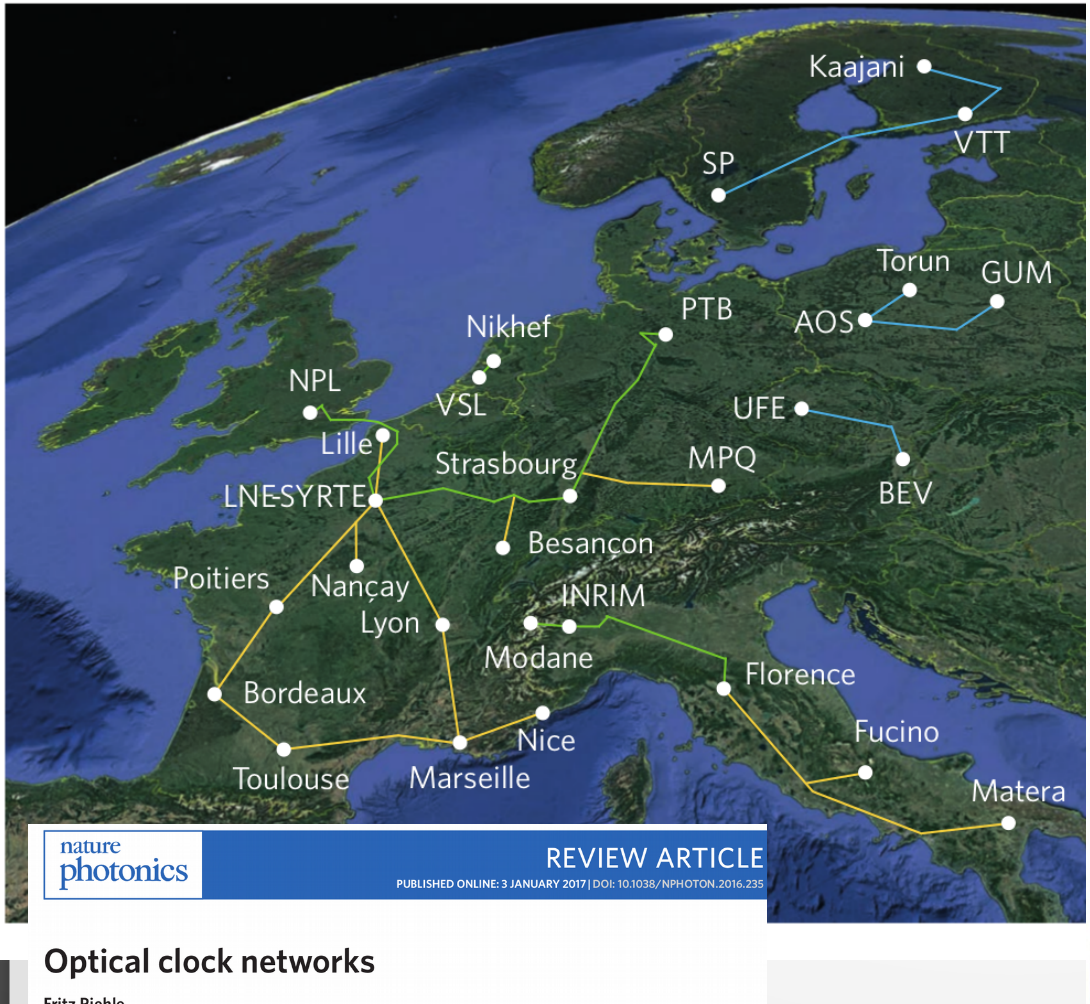
ACES Workshop, TU München, October 22nd 2018

Outline

- What we are talking about?
- Applications
- Noise cancellation principle, Experimental Setup
- Results
- Conclusion
- Plans

Long fiber links

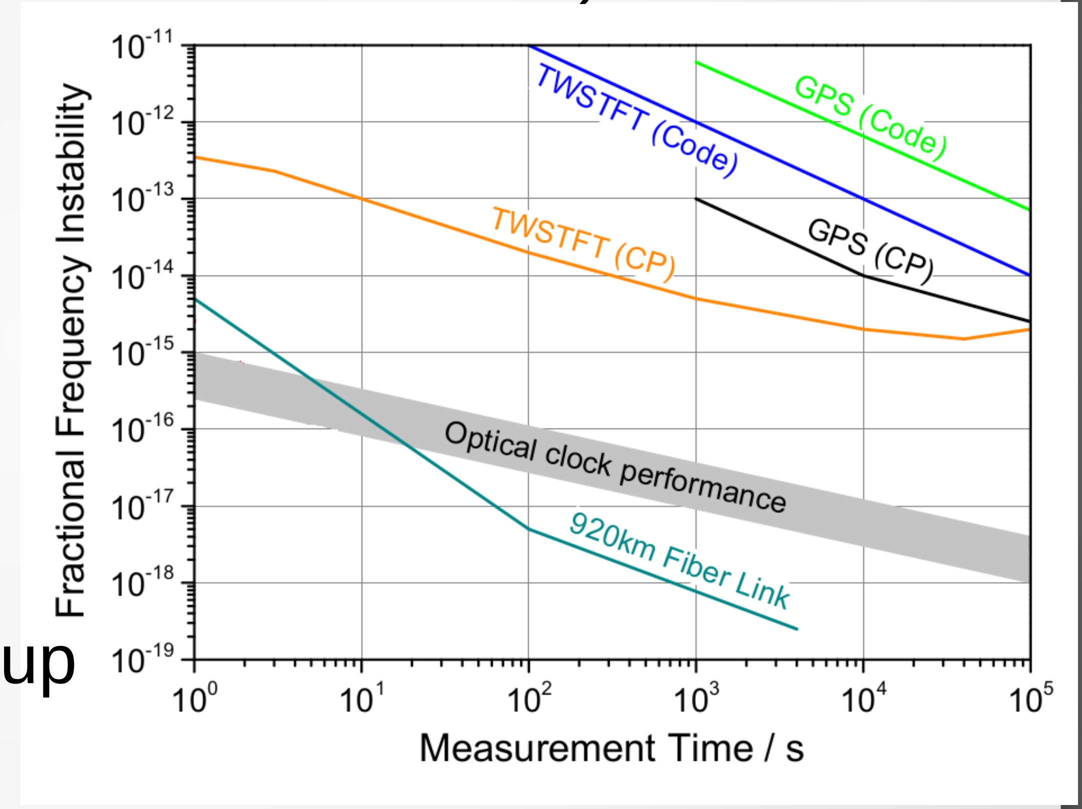


Also in Japan, USA, China, Australia….

Dark or public fiber

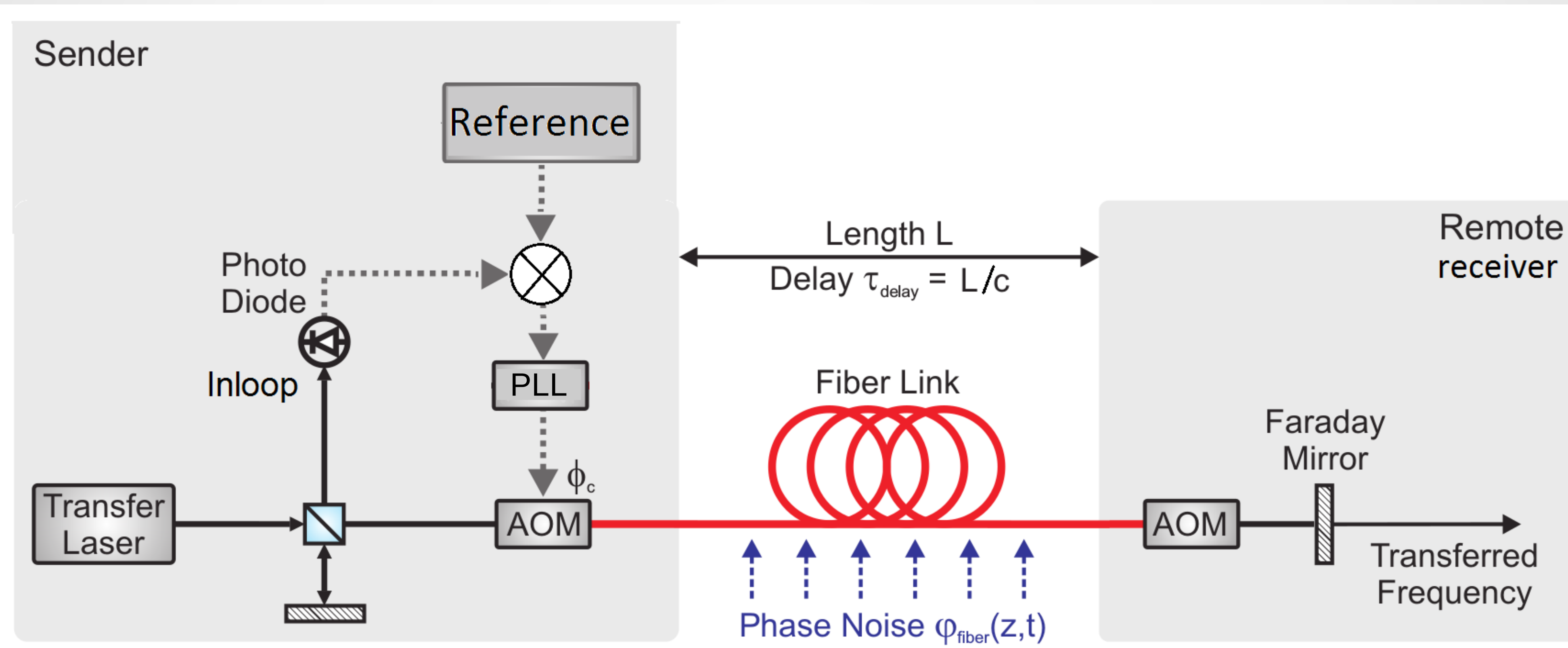
Applications

- Frequency transfer (precision measurements)
- Time transfer
- Clock Comparison
- Gravitational Shift
- Sagnac effect
- Earthquake detection
- Even between parts of setup



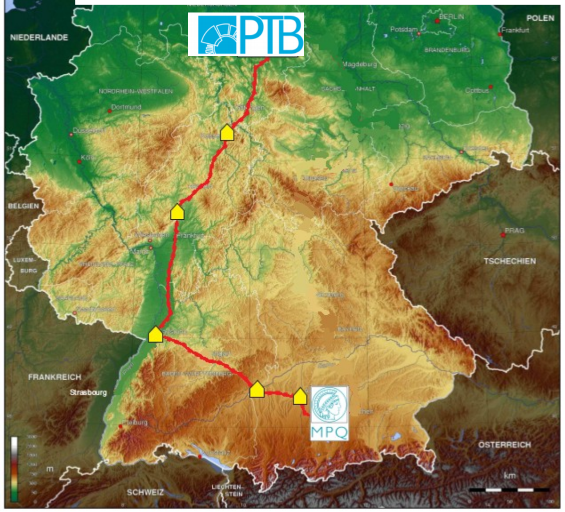
[1] S.Droste, PhD Thesis

Stabilization Principle

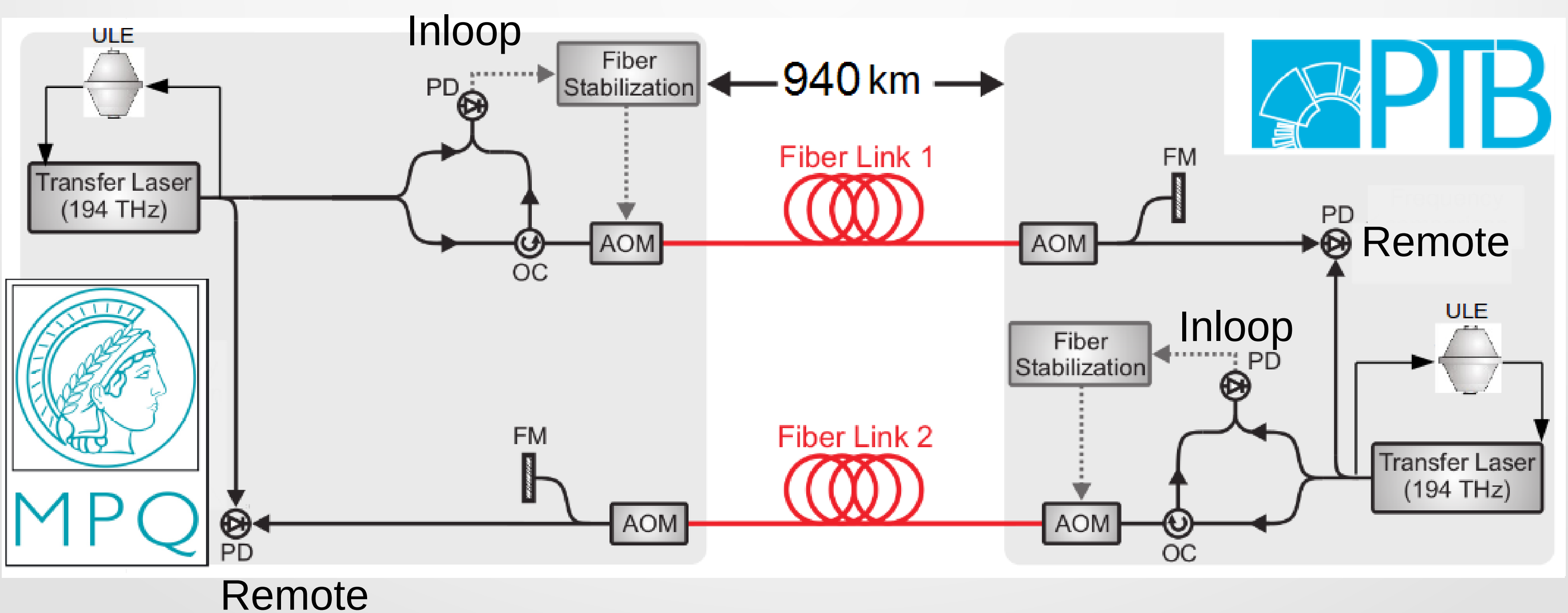


Experimental Setup

Thomas Waterholter, Alexander Kuhl, Sebastian Koke, Gesine Grosche

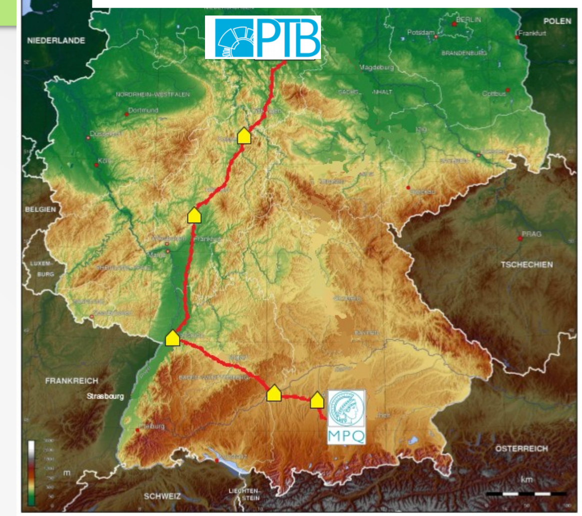


- λ = 1.5 µm, 940 km, 2 fibers
- Attenuation 0.23 dB/km, total attenuation > 225 dB
- Delay 10 ms, bandwidth 50 Hz
- ULE cavity
- «Antiparallel» configuration → Cross-checks!

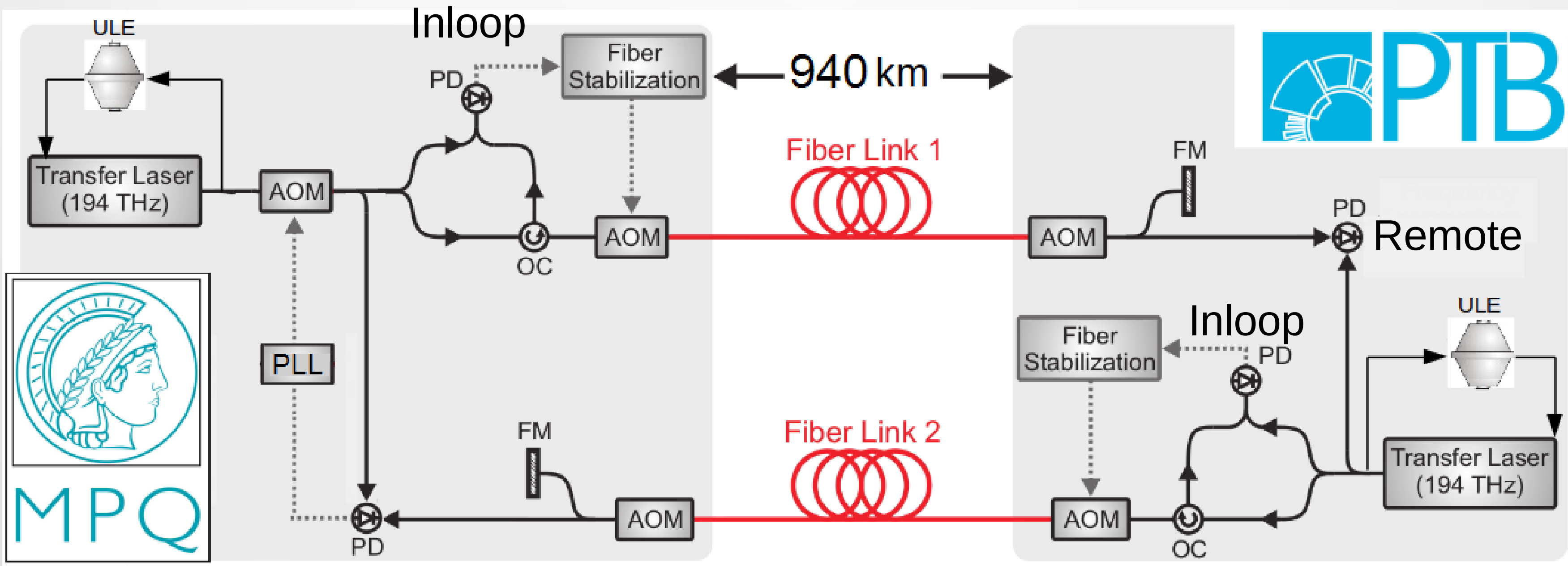


Experimental Setup

Thomas Waterholter,
Alexander Kuhl,
Sebastian Koke,
Gesine Grosche



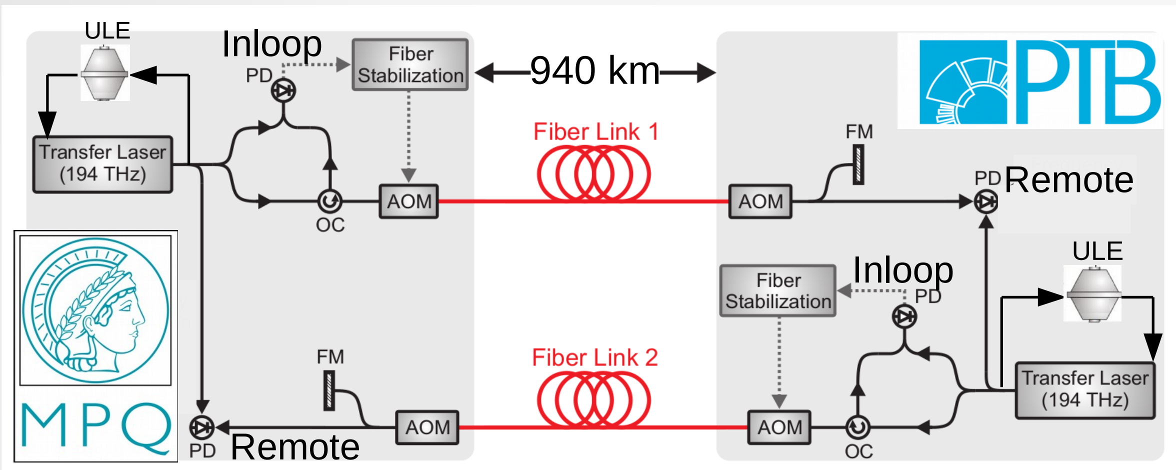
- Locking to upcoming light:
  - ULE drift compensation
  - Reliability of the whole link
- (Locking to Comb which is locked to Maser or Optical Clock)



Remote

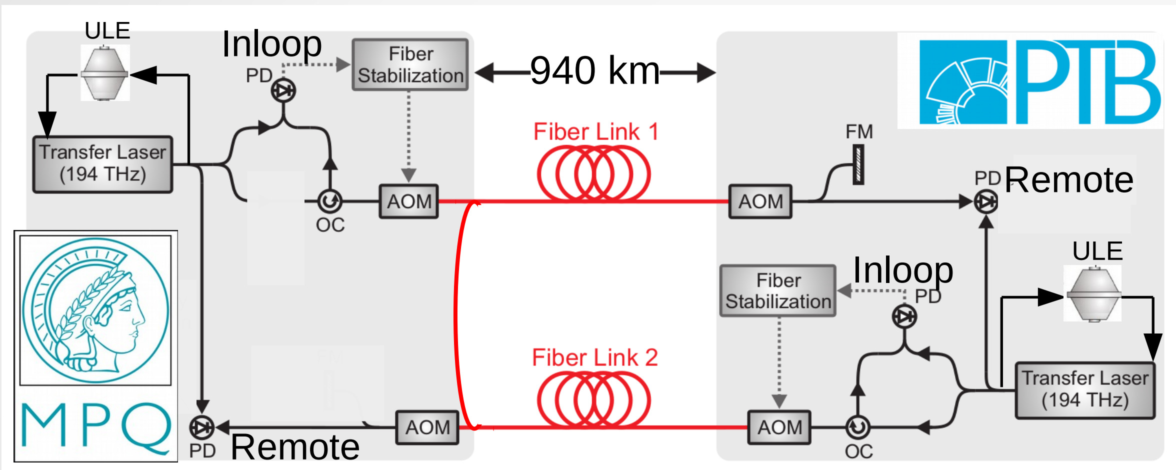
Experimental Setup: Options

- «Giant loop» configuration



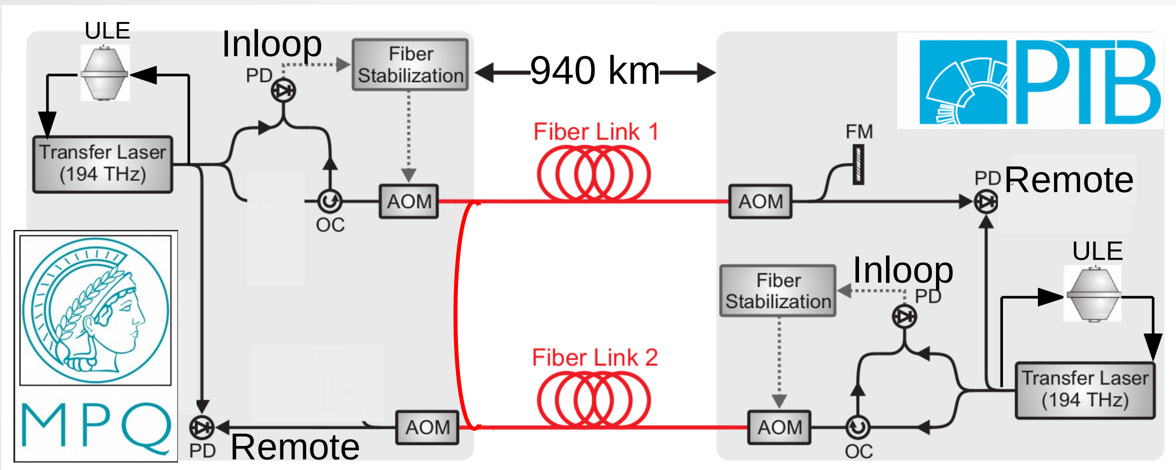
Experimental Setup: Options

- «Giant loop» configuration



Experimental Setup: Options

- «Giant loop» configuration



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Eavesdropping time and frequency: phase noise cancellation along a time-varying path, such as an optical fiber

Gesine Grosche

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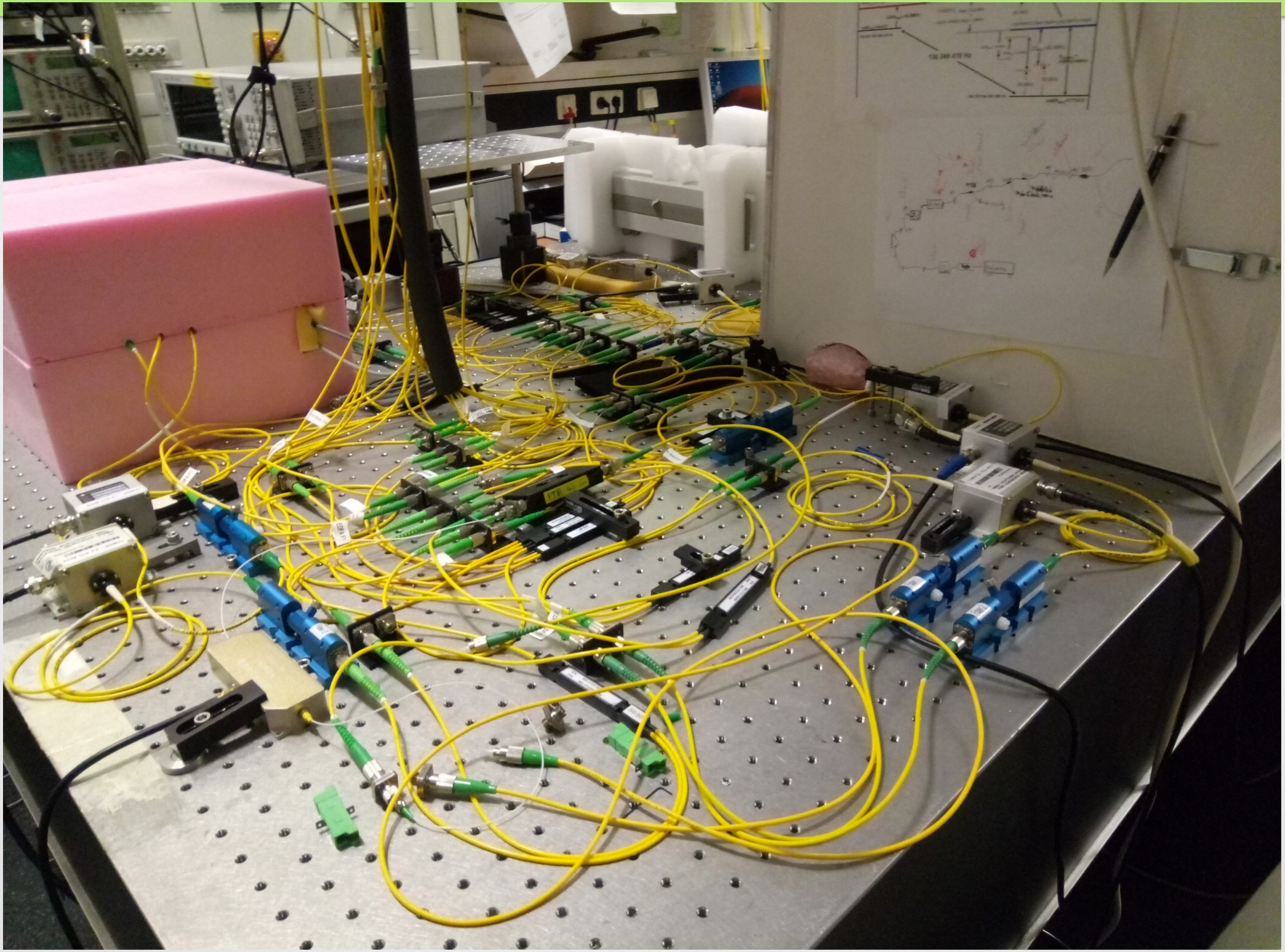
Single-mode optical fiber is a highly efficient connecting medium used not only for optical telecommunications but also for the dissemination of ultrastable frequencies or timing signals. Ma *et al.* [Opt. Lett. **19**, 1777 (1994)] described a measurement and control system to deliver the same optical frequency at *two* places, namely the two ends of a fiber, by eliminating the "fiber-induced phase-noise modulation, which corrupts high-precision frequency-based applications." I present a simple detection and control scheme to deliver the same optical frequency at *many* places anywhere along a transmission path, or in its vicinity, with a relative instability of 1 part in 10^{19}. The same idea applies to radio frequency and timing signals. This considerably simplifies future efforts to make precise timing or frequency signals available to many users, as required in some large-scale science experiments.

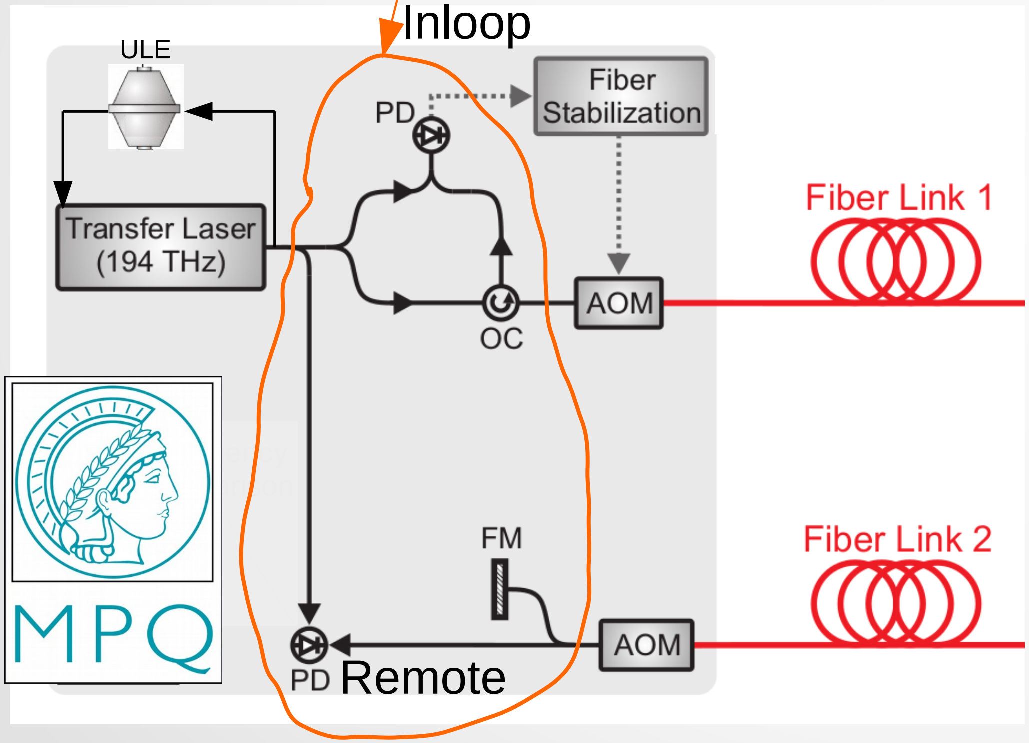
OCIS codes: (060.2360) Fiber optics links and subsystems; (060.2840) Heterodyne; (120.3940) Metrology.
http://dx.doi.org/10.1364/OL.39.002545

Experimental Setup



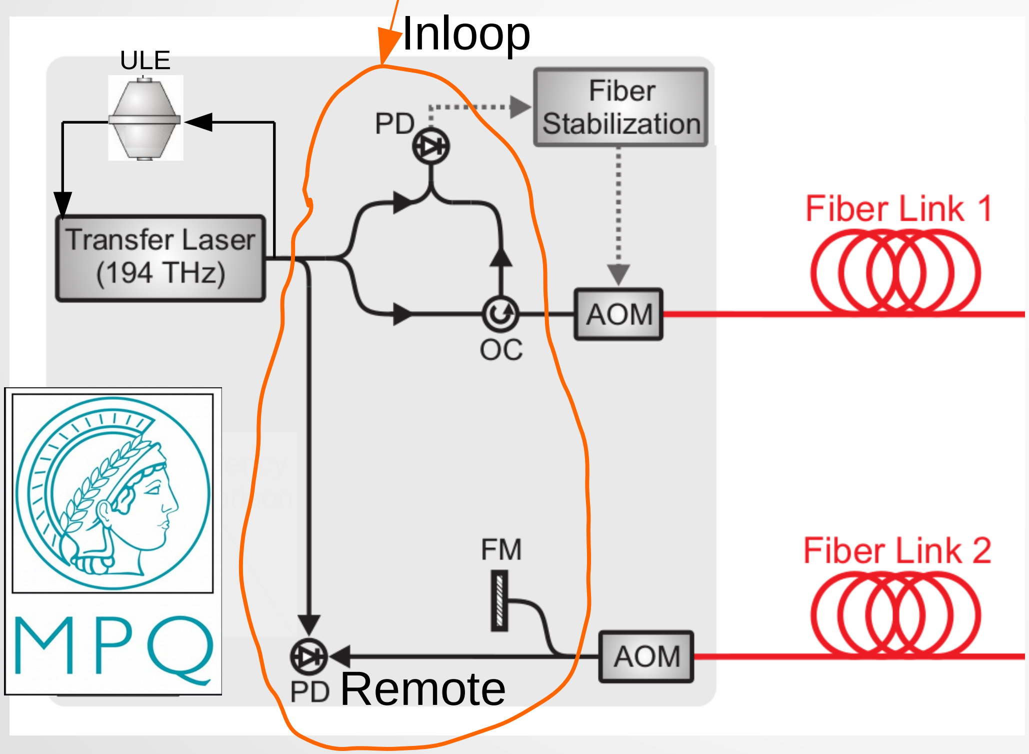
Experimental Setup

Termostabilized box

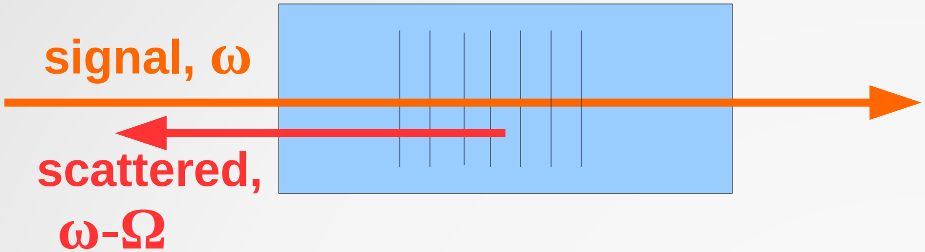


Experimental Setup

Termostabilized box

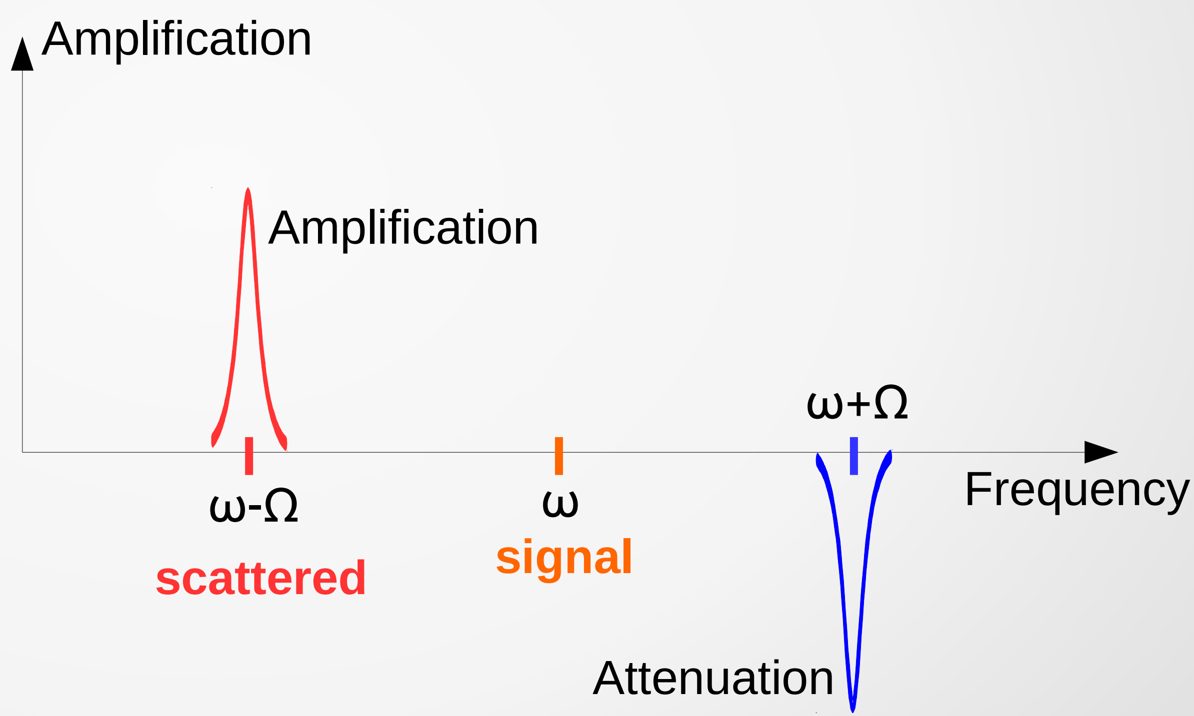


Stimulated Brillouin scattering

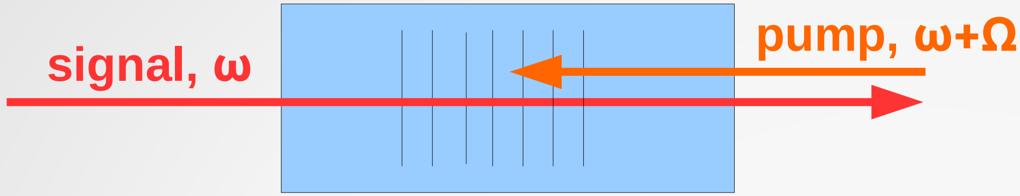


$$\frac{\Omega}{V_s} = 2\frac{\omega n}{c}$$

- Two waves: ω-Ω and ω+Ω
- Ω ~ 11 GHz
- About 4 mW



Fiber Brillouin amplification



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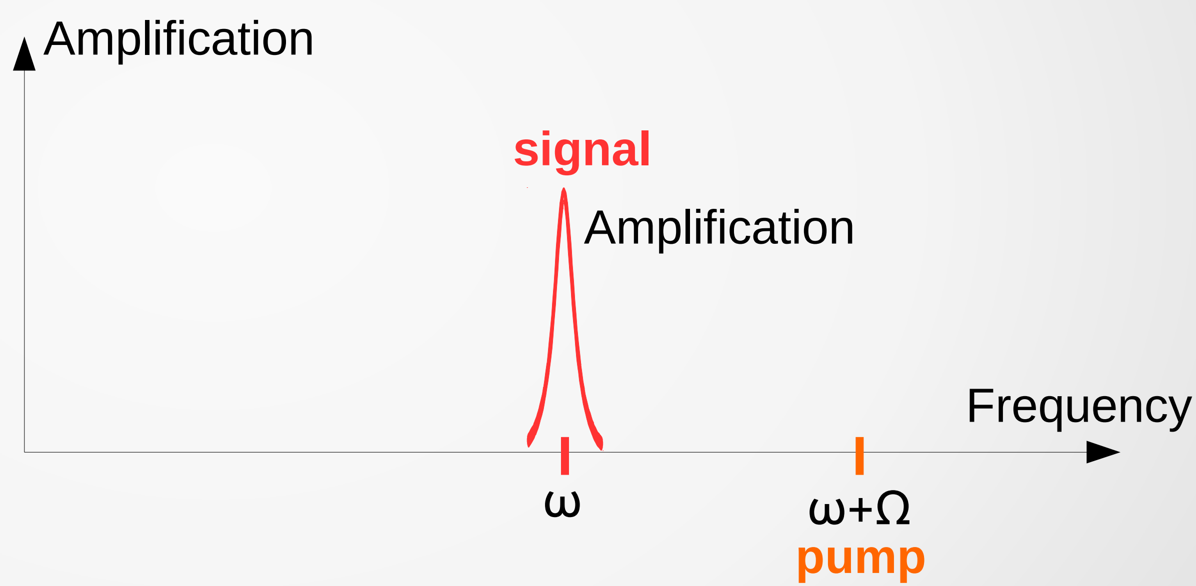
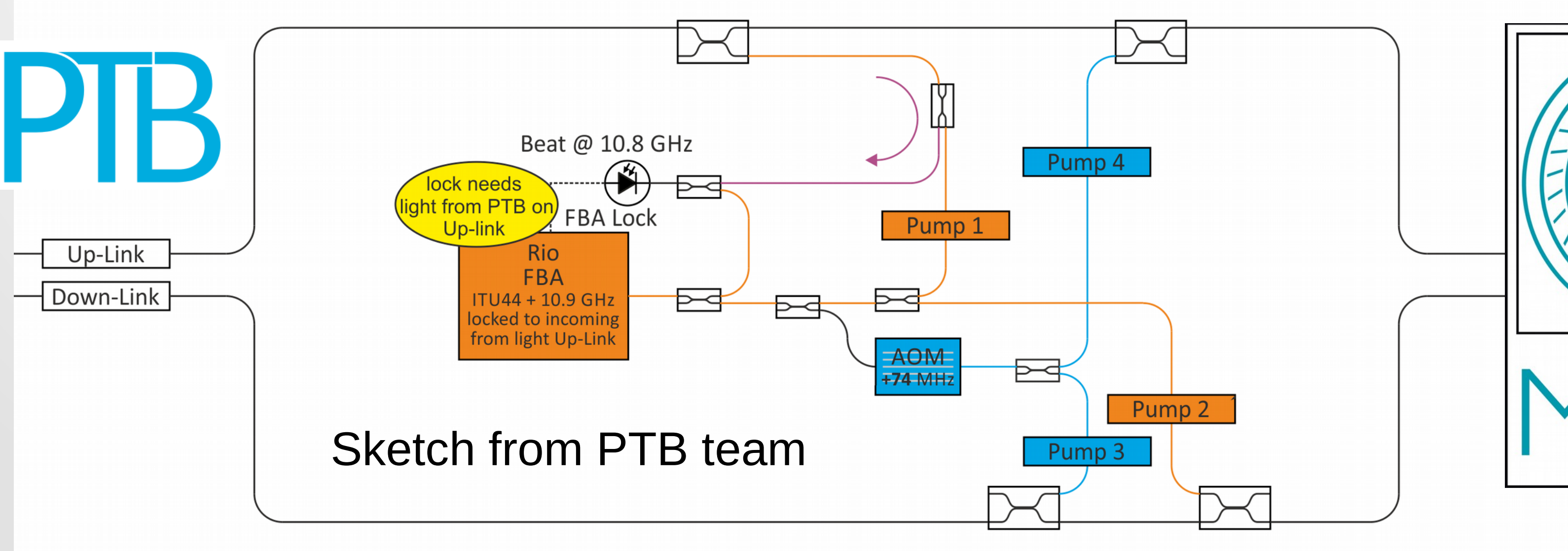


Fiber Brillouin Amplifiers

- Bandwidth ~20 MHz
- Frequency lock is required → difficult!
- Polarization matters → difficult!
- 2 amplifiers in labs + 4 along the link
- Remote control from PTB

PTB

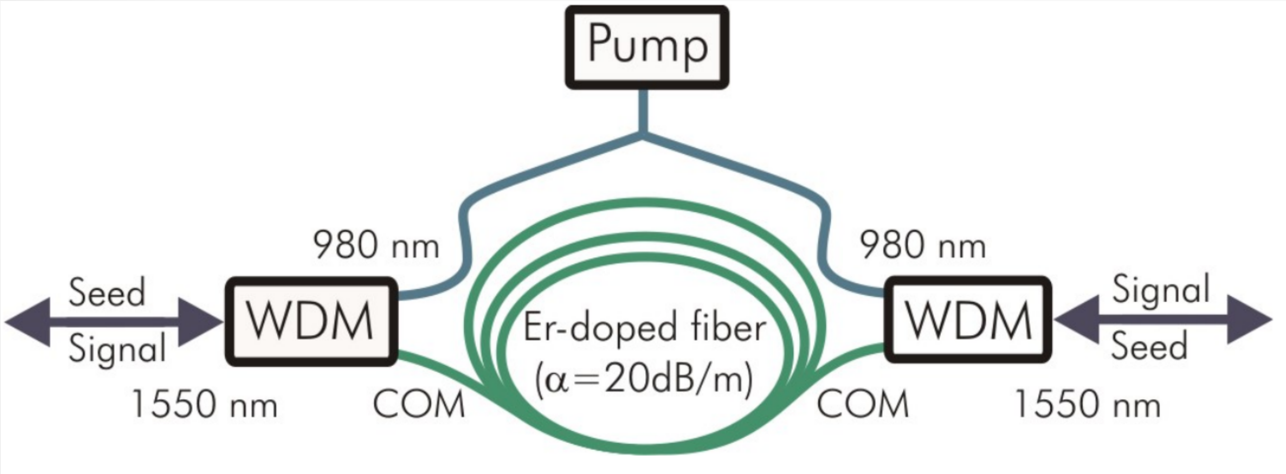


Sketch from PTB team

MPQ

Erbium Doped Fiber Amplifiers

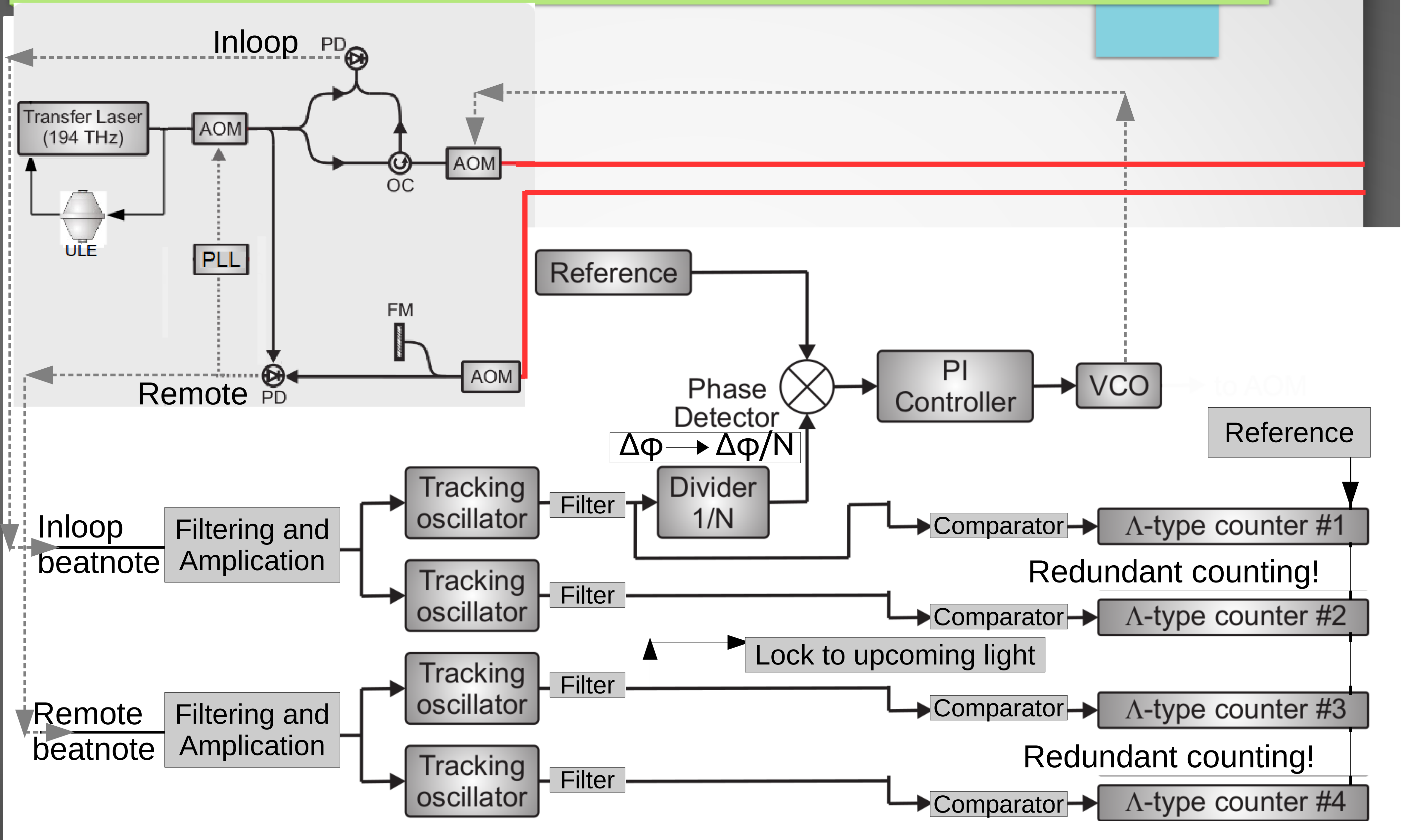
- Bandwidth ~13 GHz
- Bidirectional
- 4 units in labs + 1 along each link (totally 2)
- Remote control from MPQ



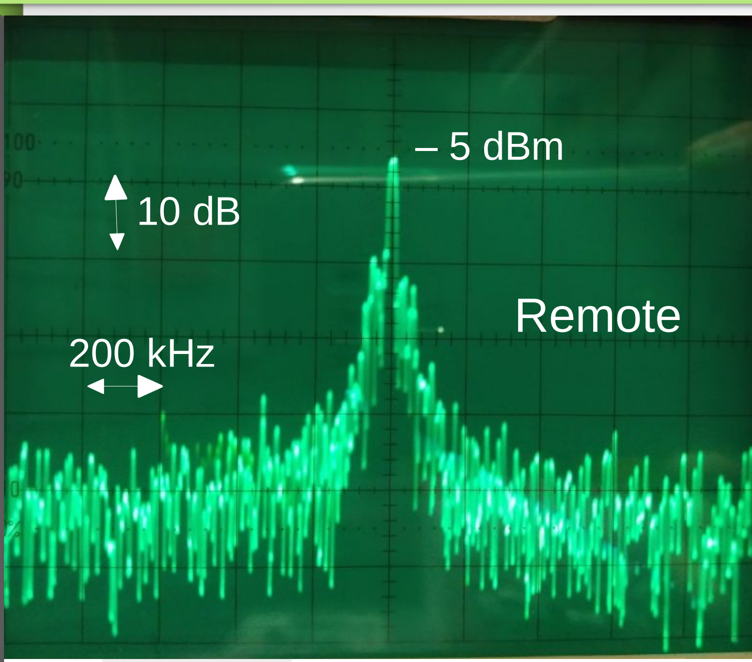
Amplifiers

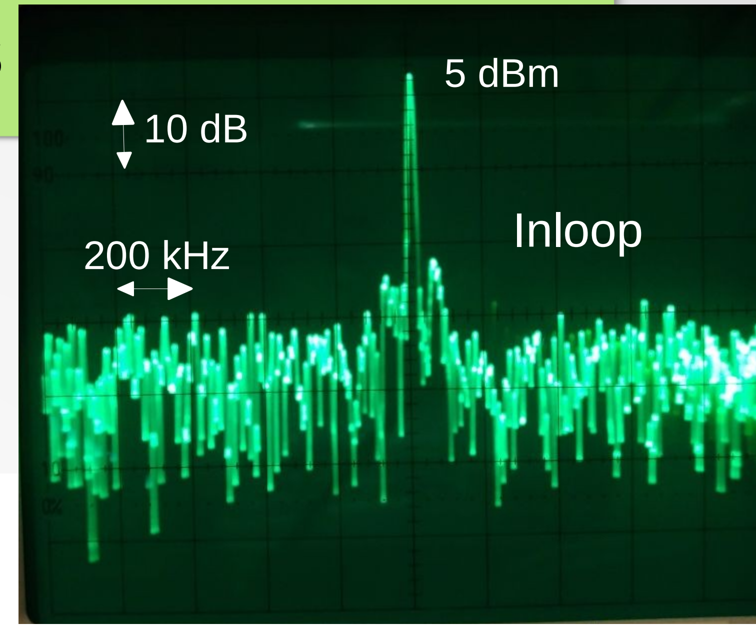
DÄNEMARK
NIEDERLANDE
POLEN
BELGIEN
TSCHECHIEN
FRANKREICH
ÖSTERREICH
SCHWEIZ
PTB
MPQ

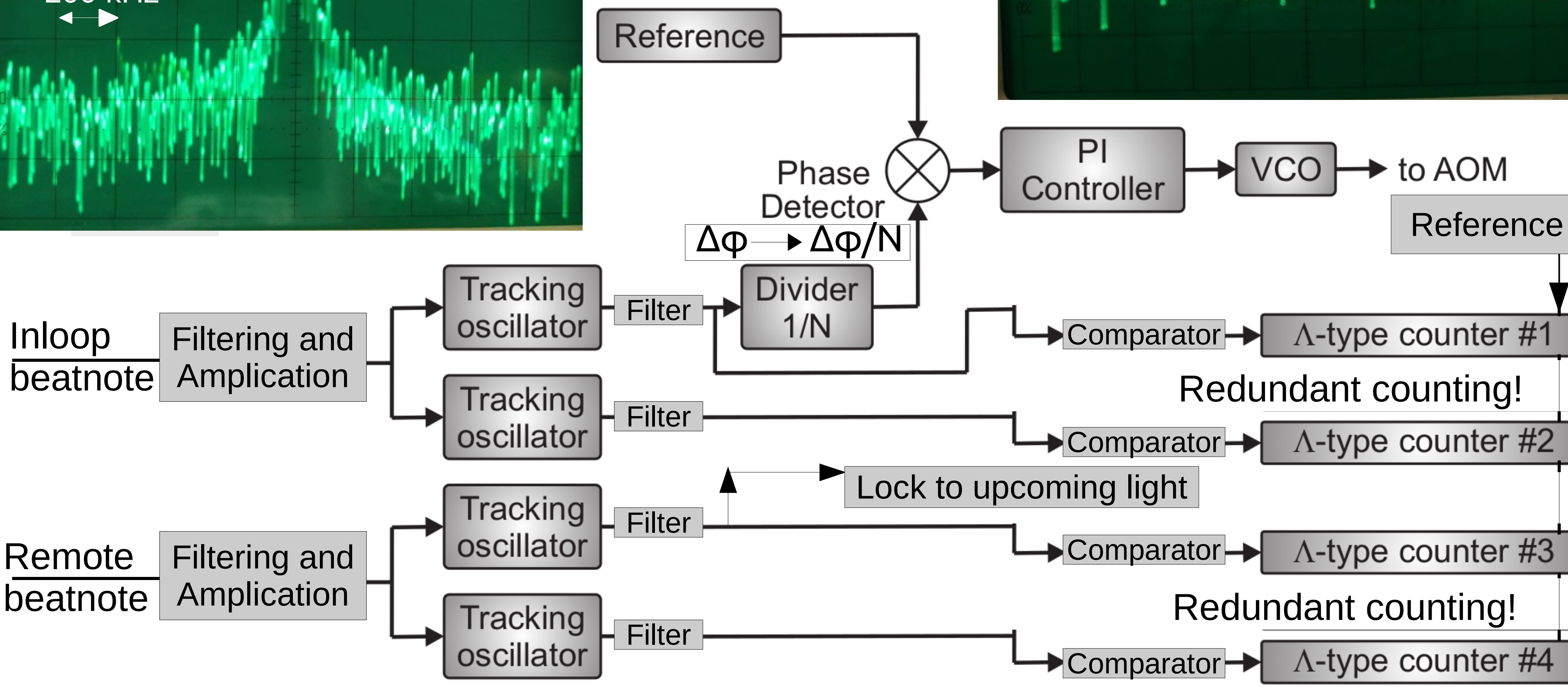
Locking and counting of beatsignals



Locking and counting of beatsignals







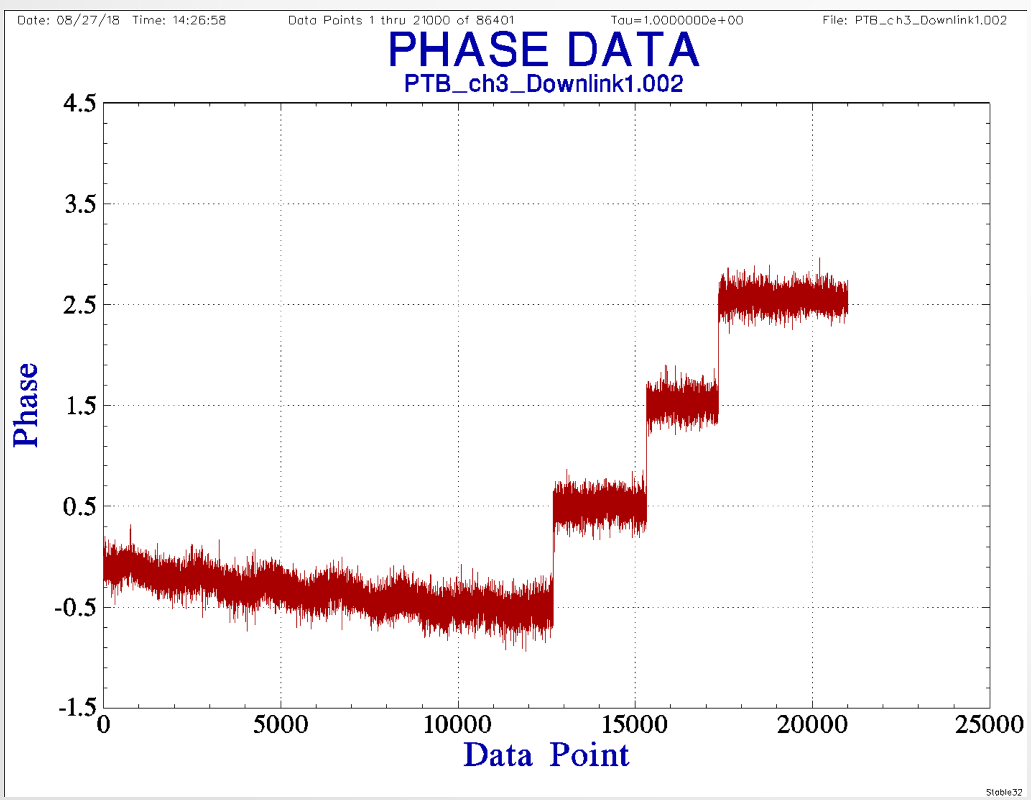
Validation criteria

Problem: cycle-slips!

[1] S.Droste, PhD Thesis

Criterium	Threshold
Difference of redundantly counted f_{Beat} at MPQ	$<$ 0.2 Hz
Difference of both f_{Beat} and its nominal frequency at MPQ	$<$ 1 Hz

For stabilized link

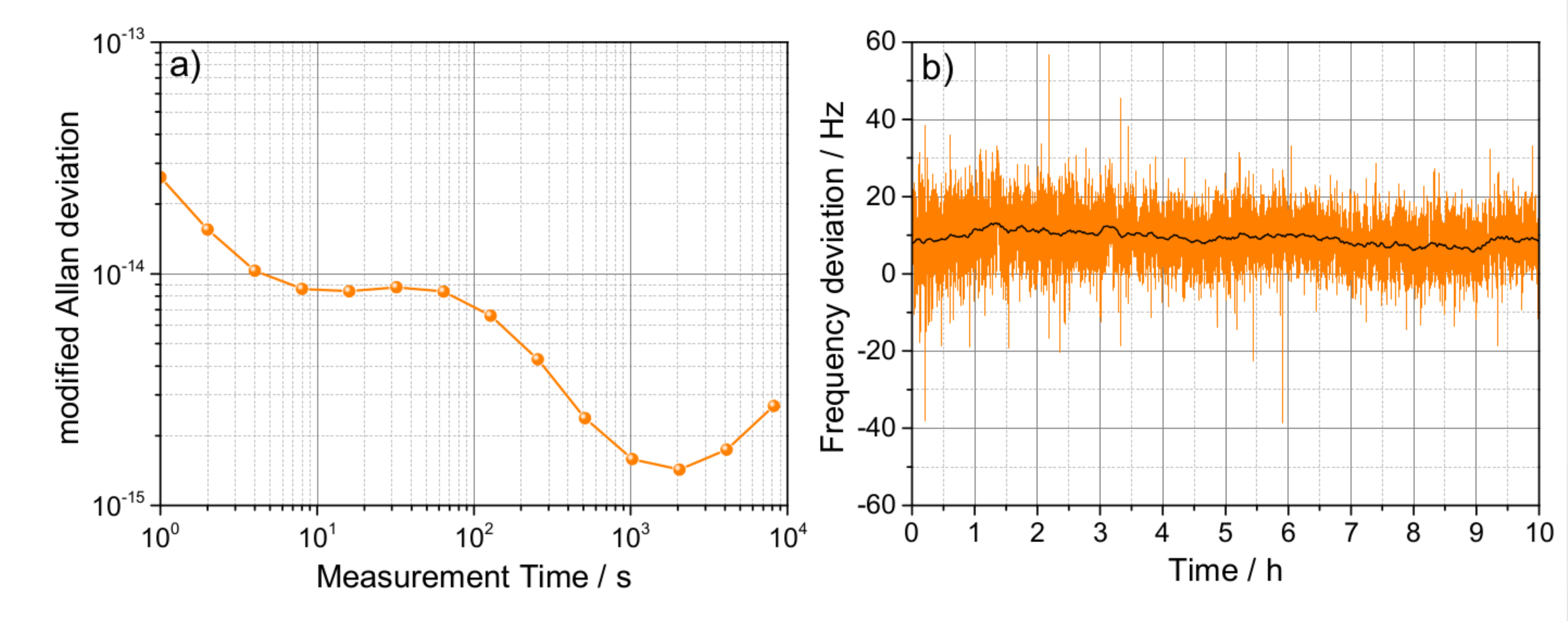


Data from PTB team

MPQ-PTB link

Free-running link

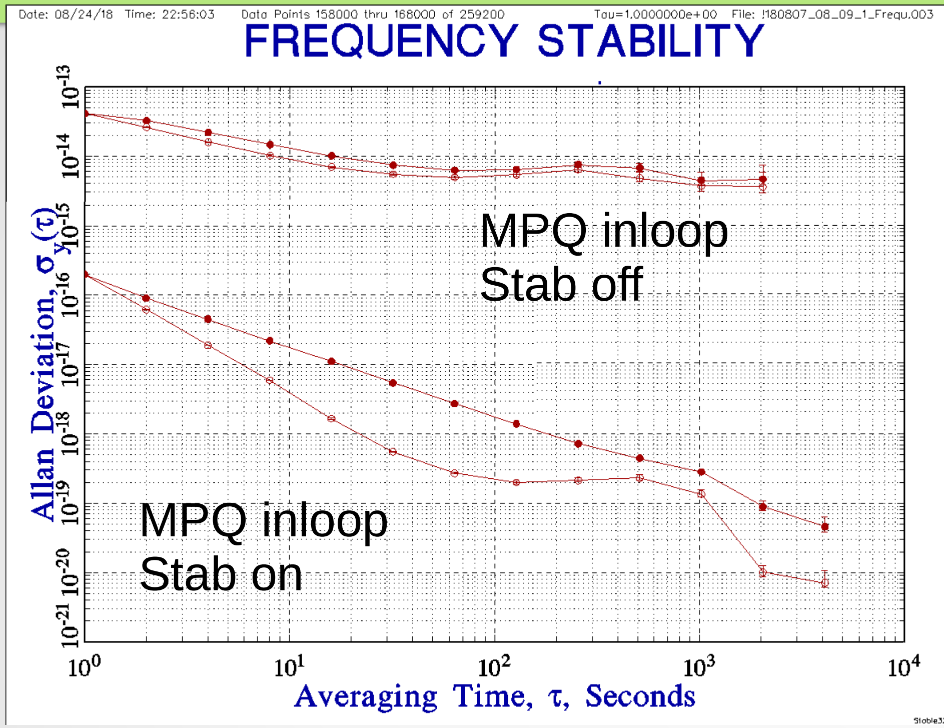
Doppler Shift

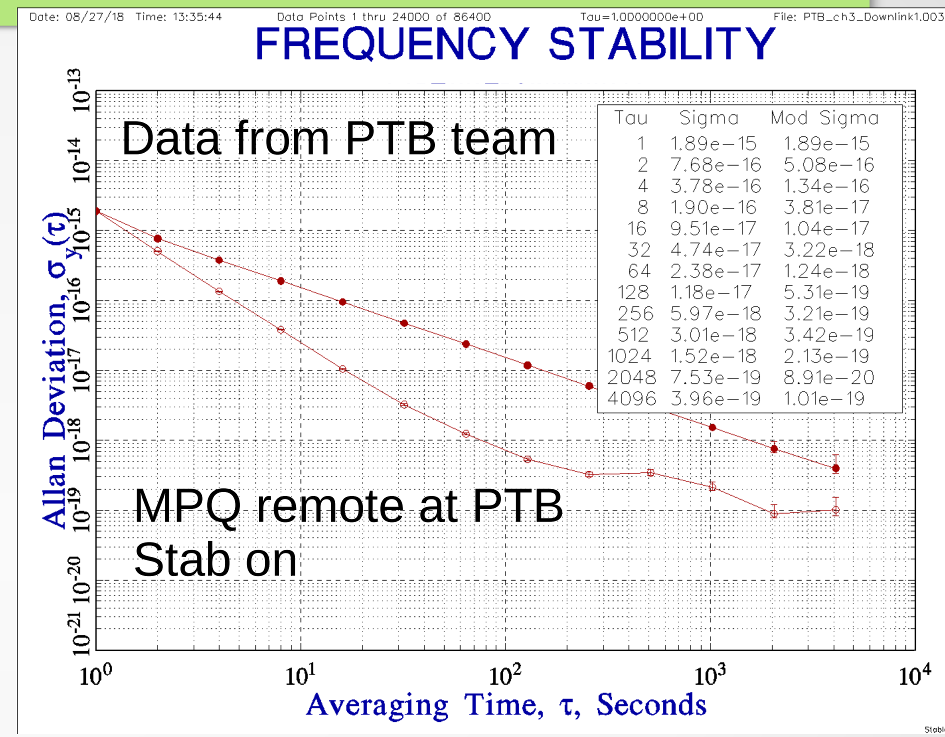


$\Delta\nu \sim \pm\, 10$ Hz

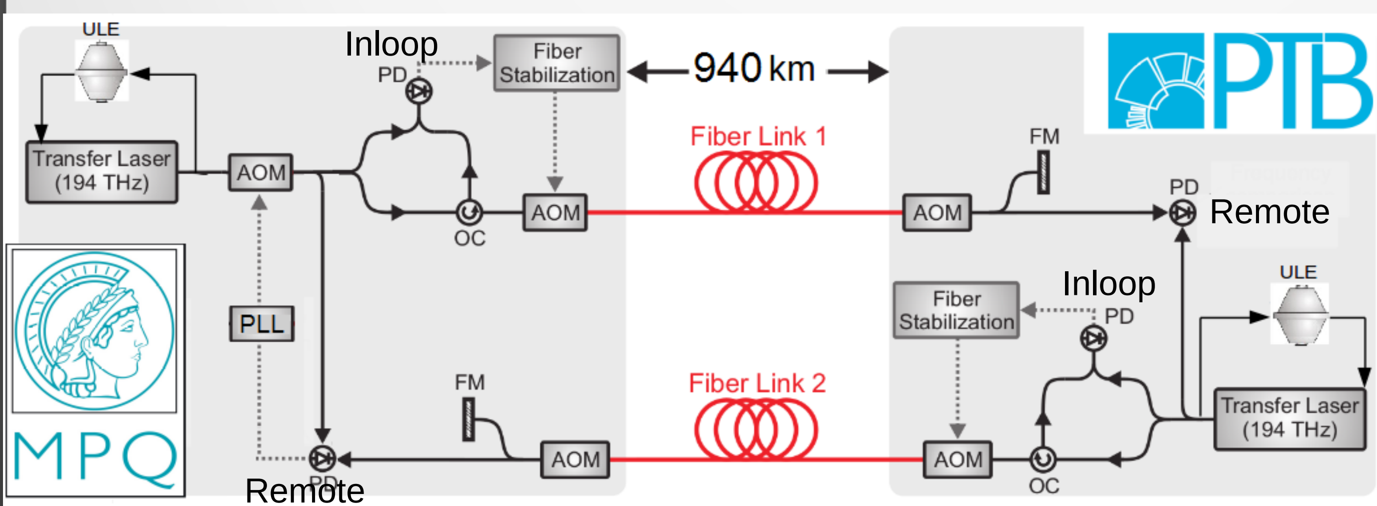
[1] S.Droste, PhD Thesis

980 km MPQ-PTB and PTB-MPQ link



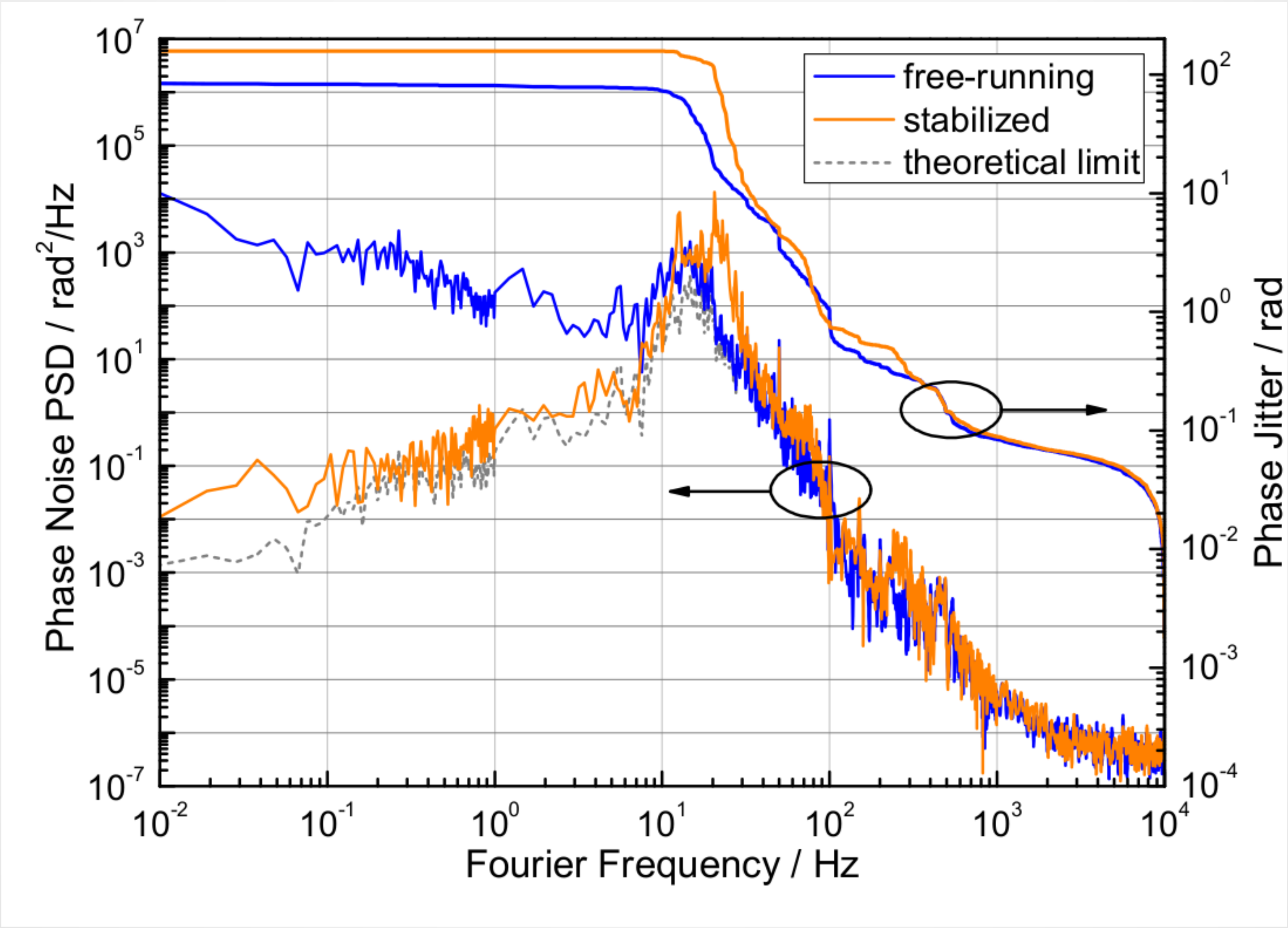


Tau	Sigma	Mod Sigma
1	1.89e−15	1.89e−15
2	7.68e−16	5.08e−16
4	3.78e−16	1.34e−16
8	1.90e−16	3.81e−17
16	9.51e−17	1.04e−17
32	4.74e−17	3.22e−18
64	2.38e−17	1.24e−18
128	1.18e−17	5.31e−19
256	5.97e−18	3.21e−19
512	3.01e−18	3.42e−19
1024	1.52e−18	2.13e−19
2048	7.53e−19	8.91e−20
4096	3.96e−19	1.01e−19



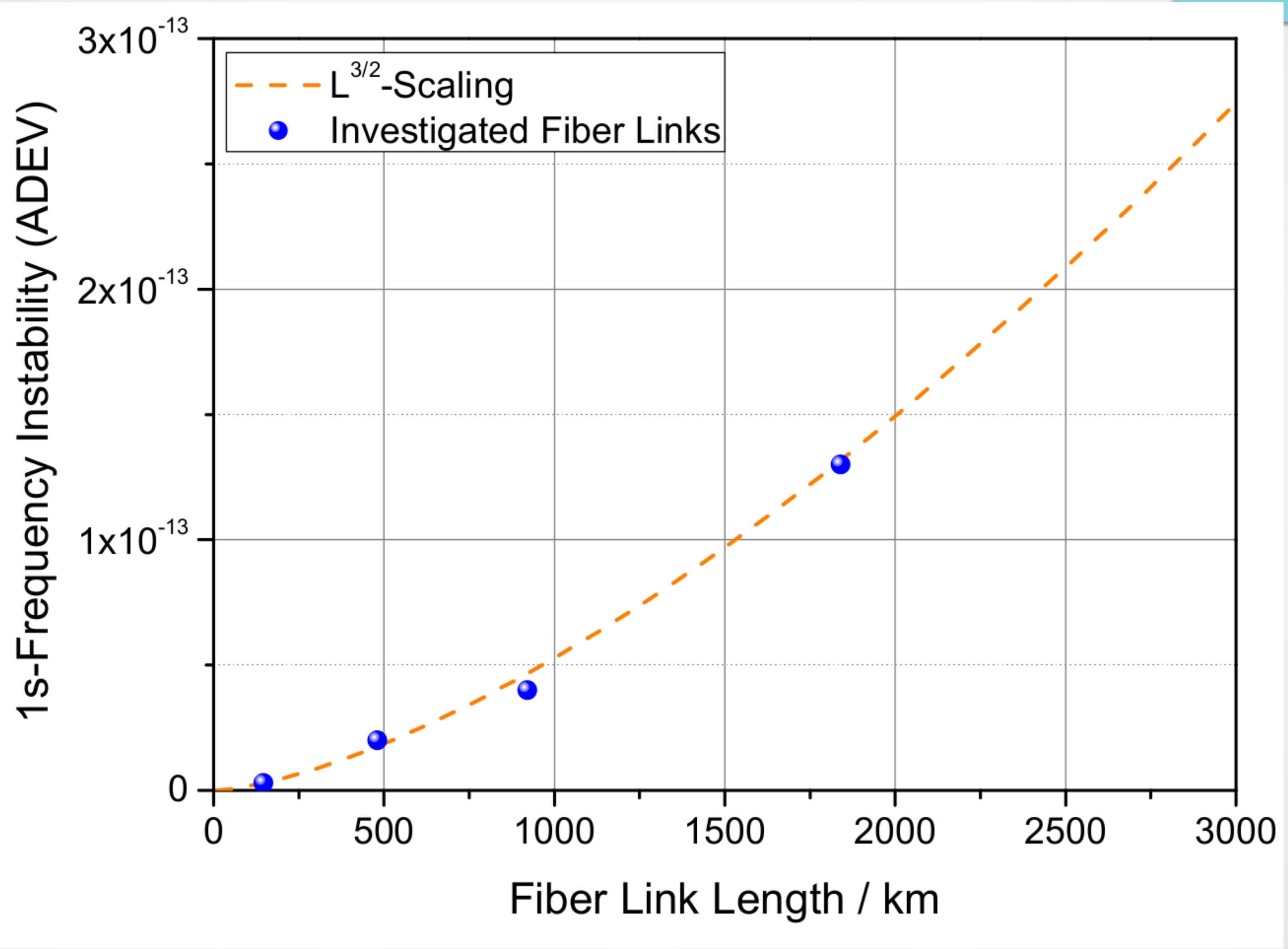
- White phase and f^1
- Allan Deviation: stability
- Accuracy 1.22×10^{-19}

Phase Noise Power Spectral Density



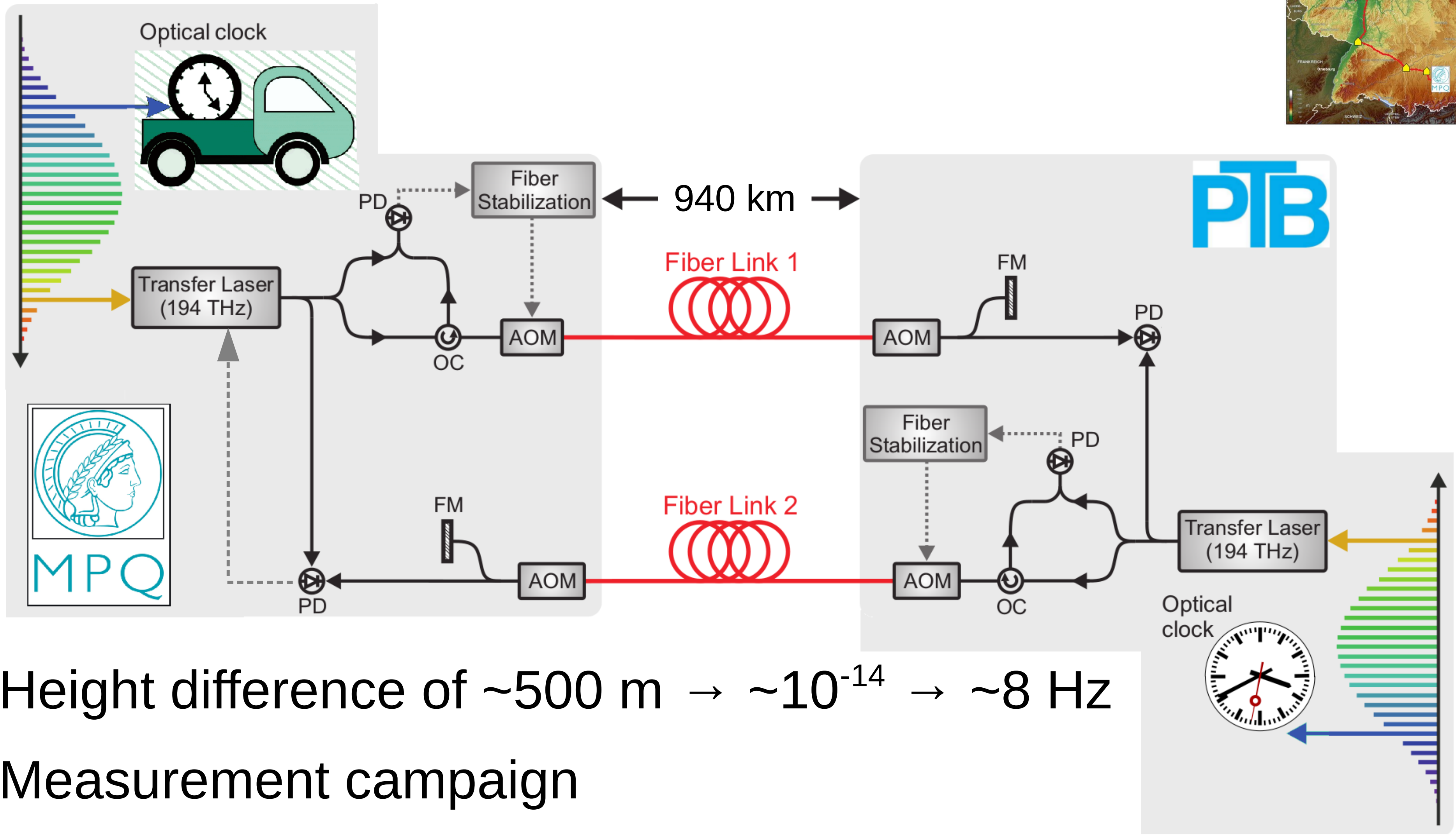
[1] S.Droste, PhD Thesis

Scaling



[1] S.Droste, PhD Thesis

Gravitational shift measurement



Height difference of ~500 m → ~10^{-14} → ~8 Hz

Measurement campaign

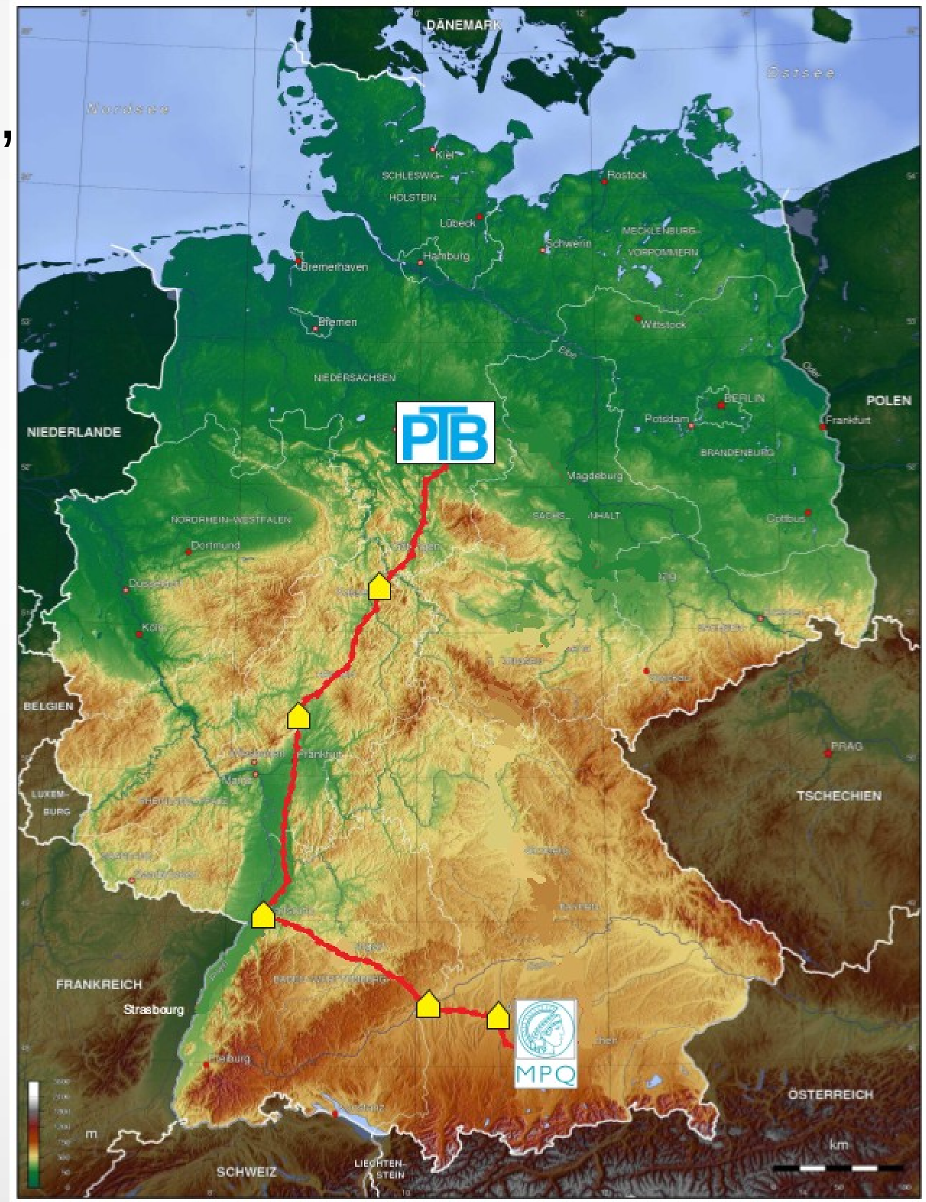
10th of September - 20th of October 2018

Conclusion

- Optical fiber links
- New MPQ-PTB-MPQ link is working!

Plans

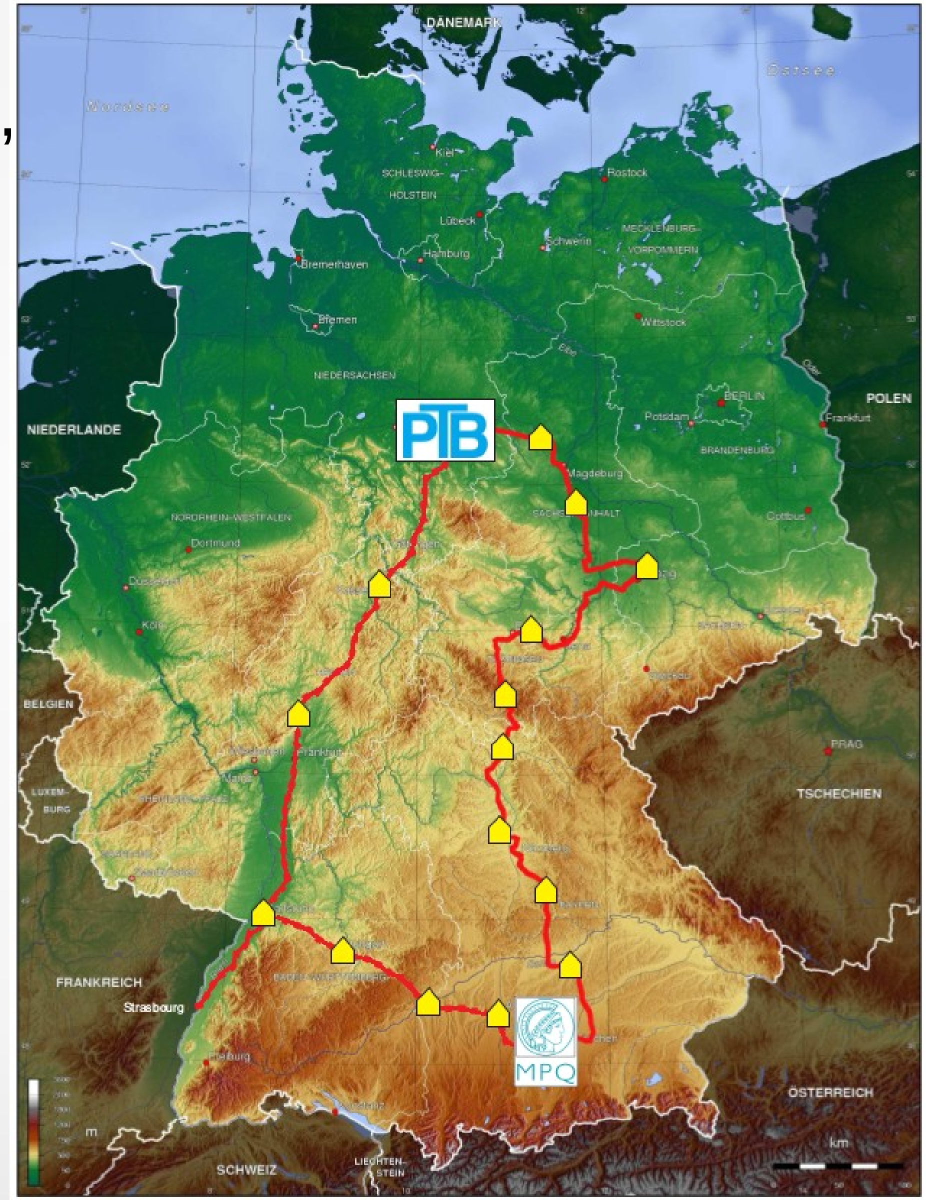
- Analyse data from Campaign, continue if necessary
- Optimizations and improvements



- Sagnac effect
- Time transfer

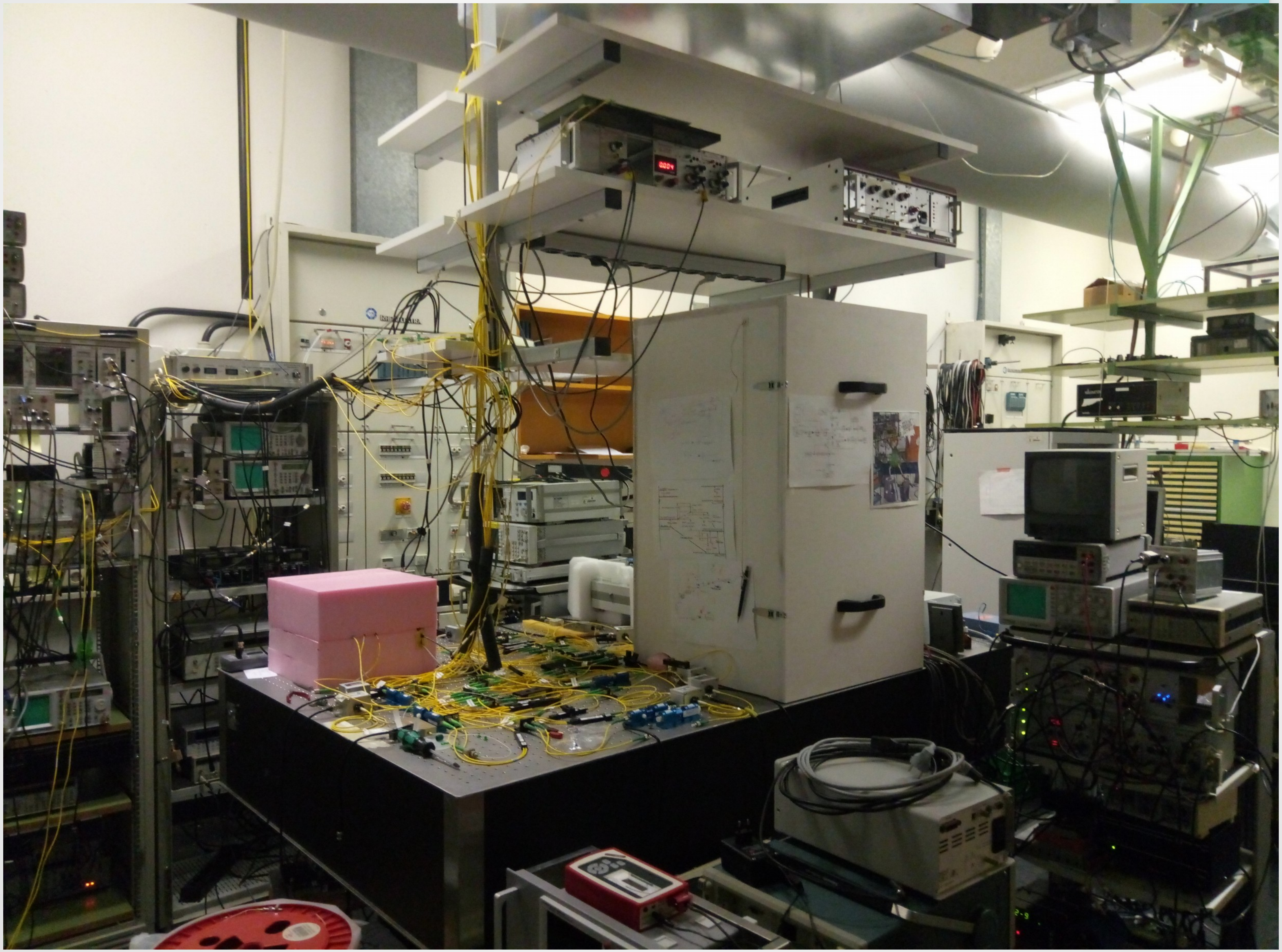
Plans

- Analyse data from Campaign, continue if necessary
- Optimizations and improvements

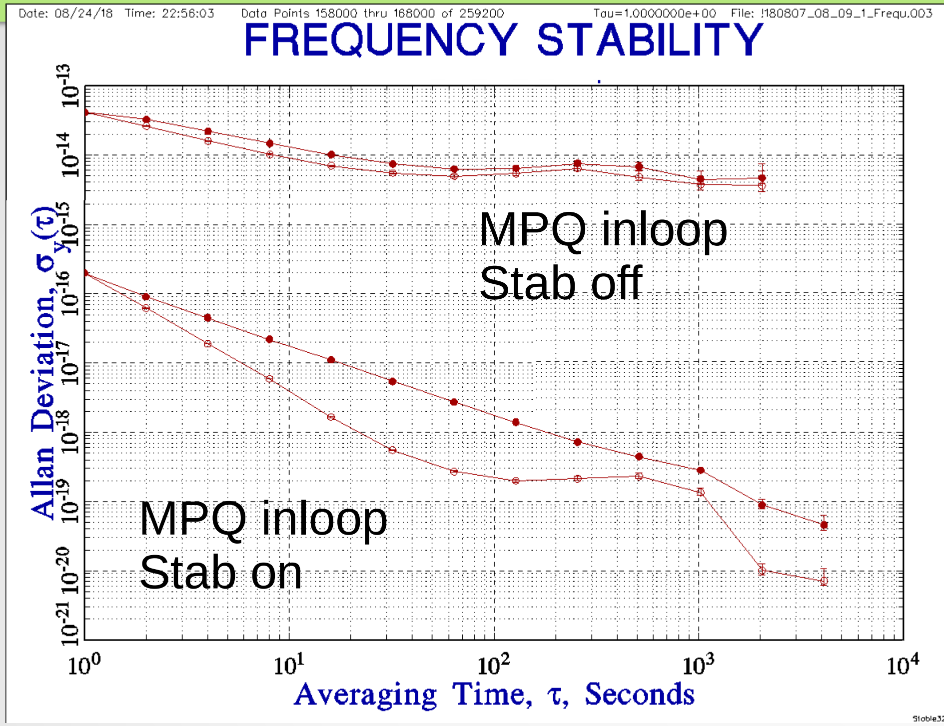


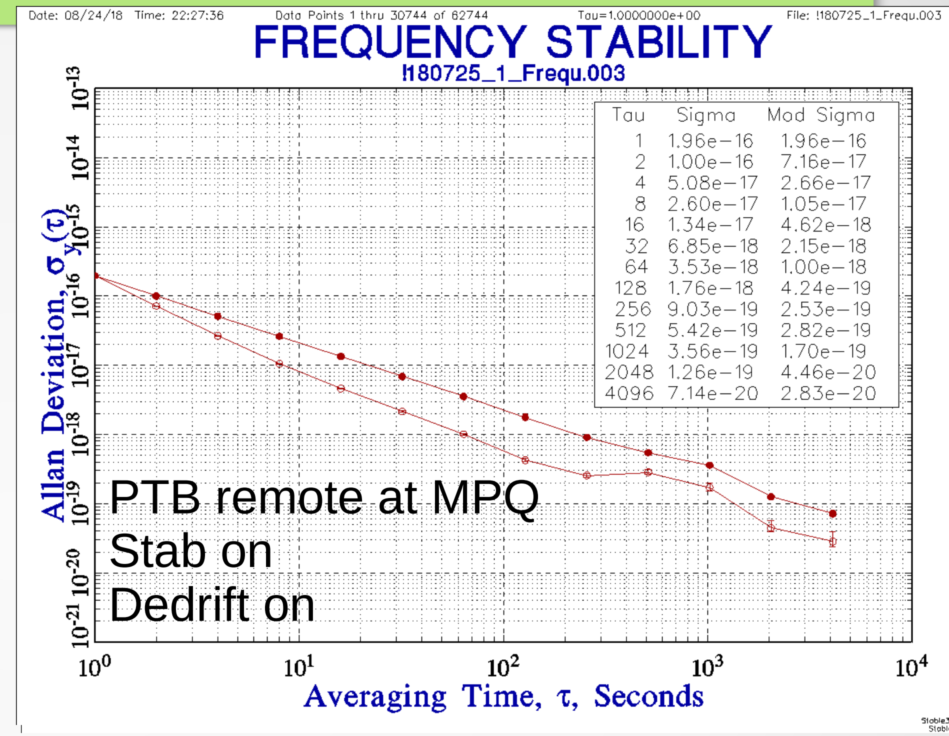
- Sagnac effect
- Time transfer

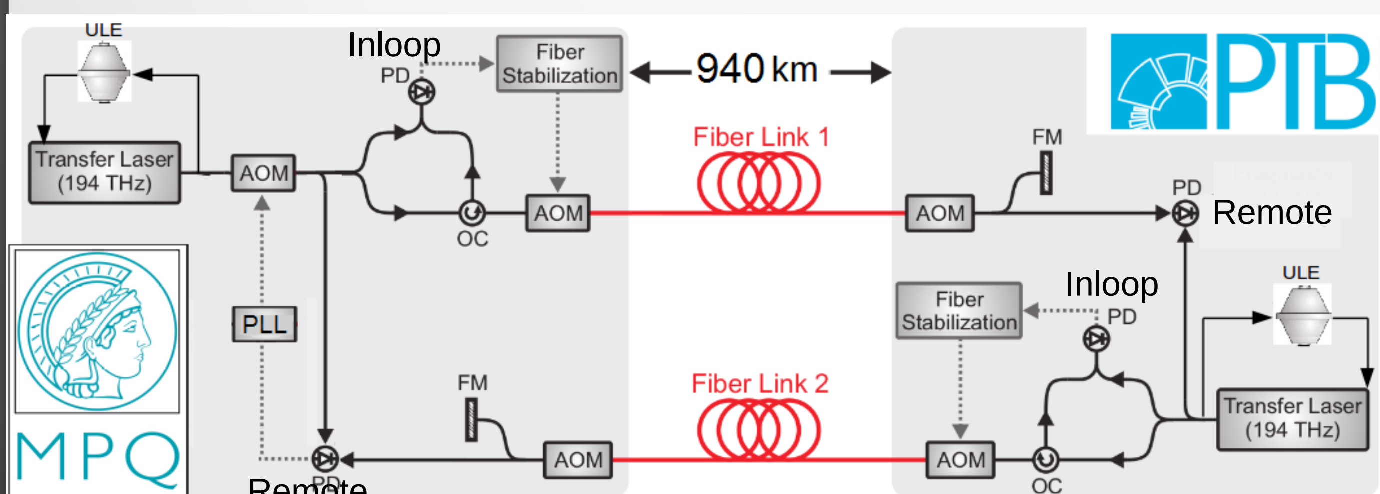
Thank you for your attention!



980 km MPQ-PTB and PTB-MPQ link



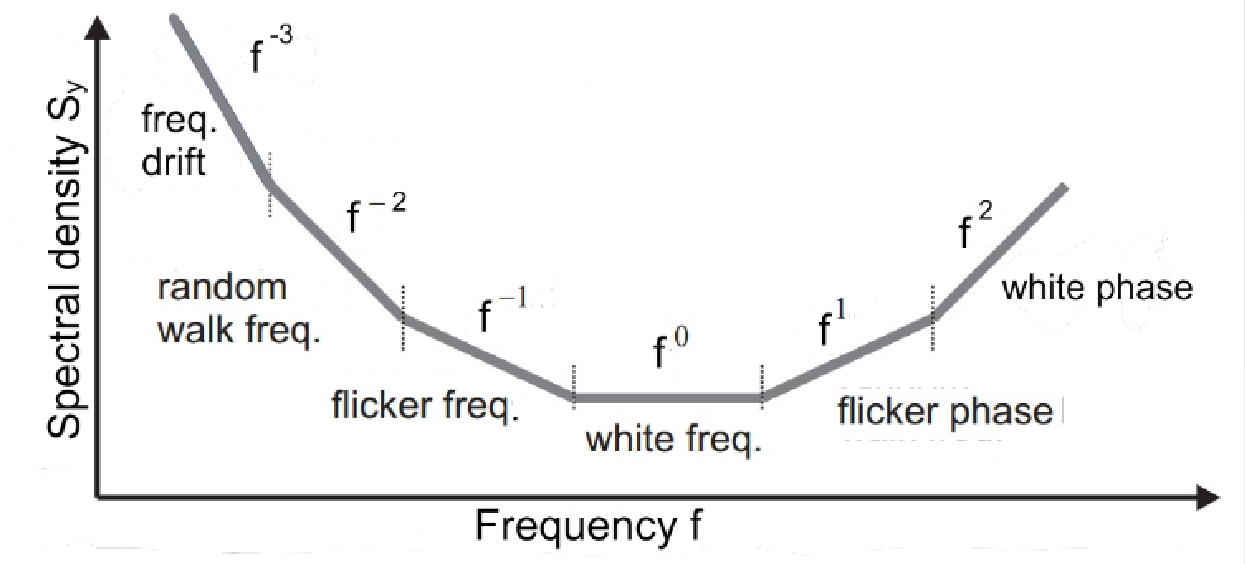


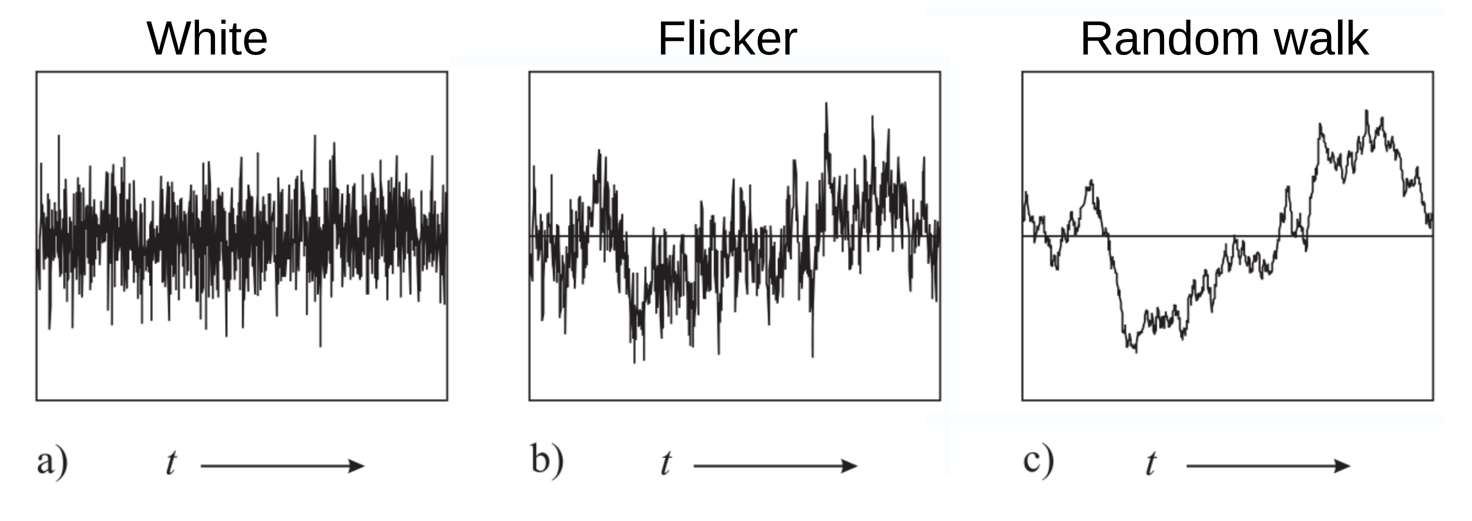


- Allan Deviation: stability
- Accuracy 1.22×10^{-19}

Types of noises. Power spectral density

$$S_y(f) = \sum_{\alpha=-2}^{2} h_\alpha f^\alpha.$$

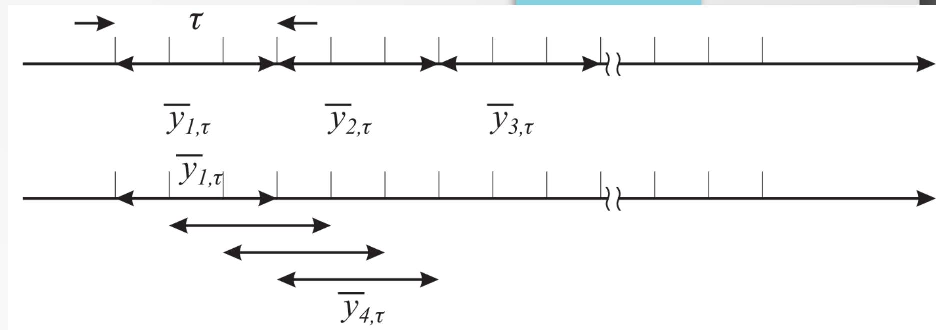




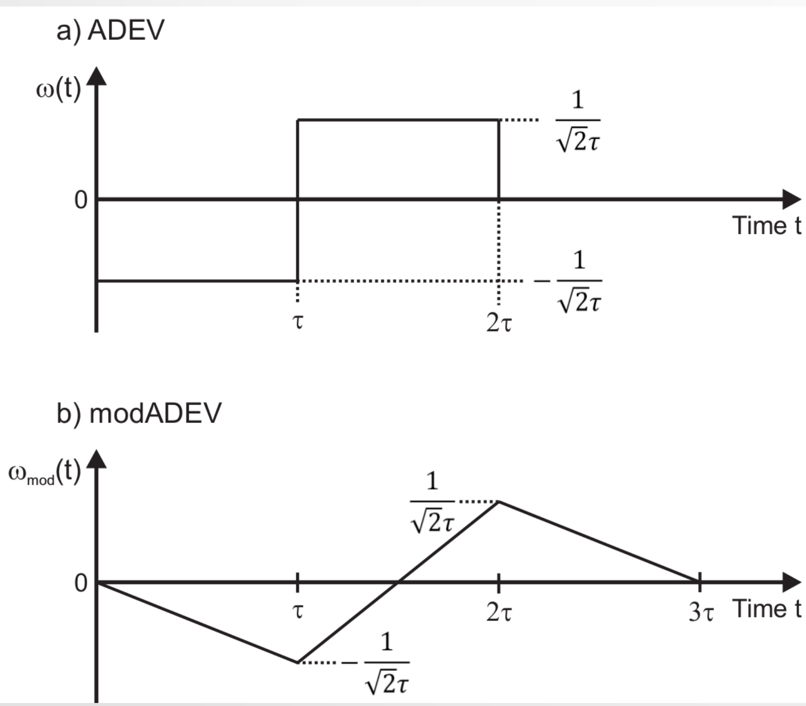
Measure. Allan Deviation

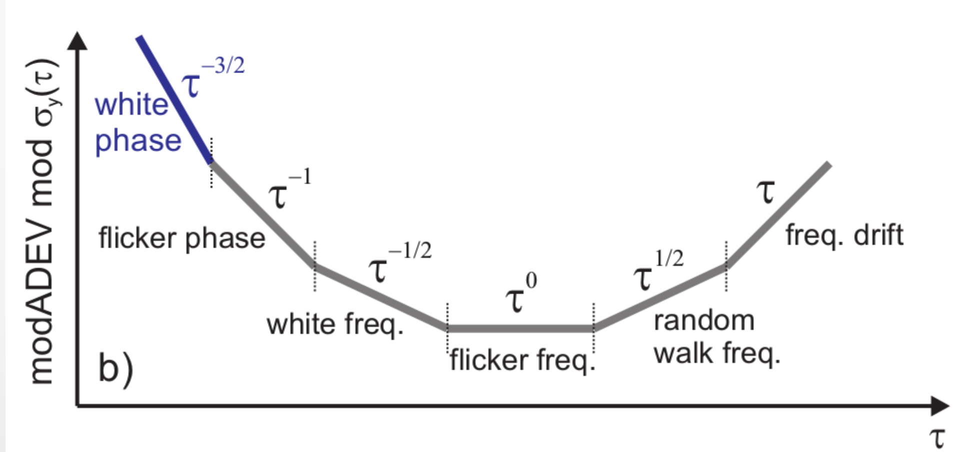
Allan deviation $\sigma_y(\tau) = \sqrt{\frac{1}{2}\left\langle (\bar{y}_{i+1} - \bar{y}_i)^2 \right\rangle}$

$$y(t) \equiv \frac{\Delta\nu(t)}{\nu_0}$$



Overlapping Allan deviation





Π- and Λ-counters. Relationships between different Allan deviations

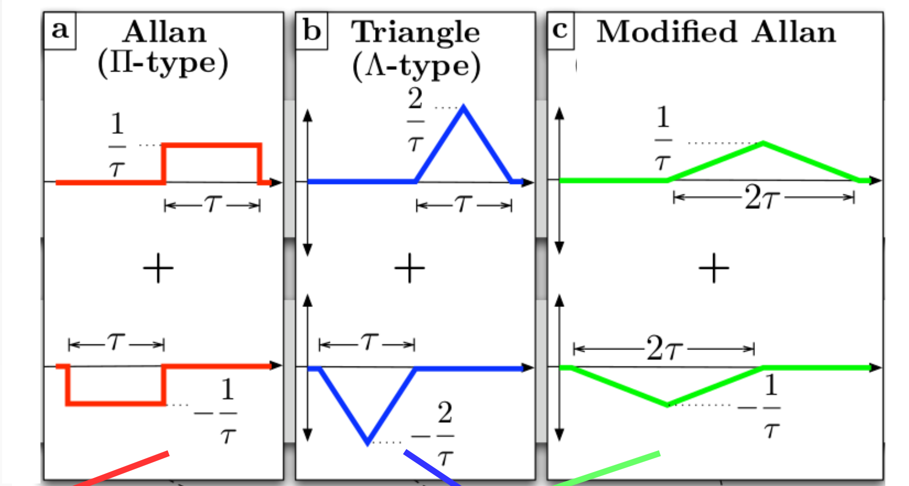
Report modes of our K+K counters:

- Phase

  (or Frequency) → • Π-counter

- Phase Average

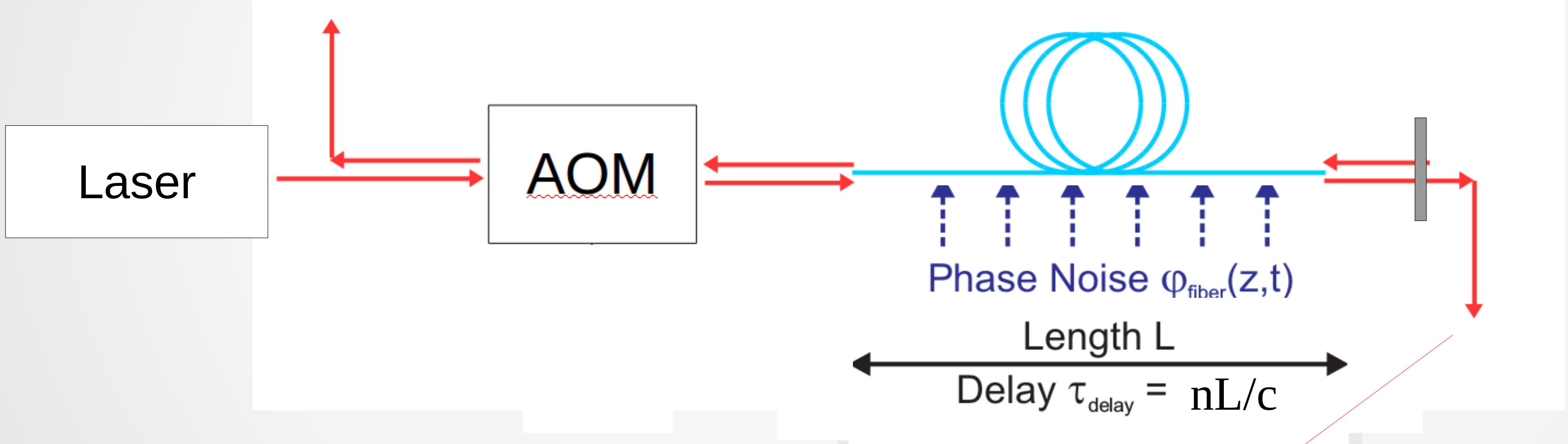
  (or Frequency Average) → • Λ-counter



Noise Type	$S_y(f)$	Allan (σ_A^2)	Modified Allan	Triangle
White phase noise	$h_2 f^2$	$\frac{3\,f_H}{4\,\pi^2}\,h_2\tau^{-2}$ $= \sigma_A^2(\tau)$	$\frac{3}{8\,\pi^2}\,h_2\tau^{-3}$ $= \frac{1}{2\,f_H\tau}\,\sigma_A^2(\tau)$	$\frac{2}{\pi^2}\,h_2\tau^{-3}$ $= \frac{8}{3\,f_H\tau}\,\sigma_A^2(\tau)$
Flicker phase noise	$h_1 f$	$\frac{1.038+3\,ln(2\,\pi\,f_H\,\tau)}{4\,\pi^2}\,h_1\tau^{-2}$ $= \sigma_A^2(\tau)$	$\frac{3\,ln(\frac{256}{27})}{8\,\pi^2}\,h_1\tau^{-2}$ $= \frac{3.37}{3.12+3\ln\pi f_H\tau}\,\sigma_A^2(\tau)$	$\frac{6\,ln(\frac{27}{16})}{\pi^2}\,h_1\tau^{-2}$ $= \frac{12.56}{3.12+3\ln\pi f_H\tau}\,\sigma_A^2(\tau)$
White frequency noise (Random walk phase noise)	h_0	$\frac{1}{2}h_0\tau^{-1}$ $= \sigma_A^2(\tau)$	$\frac{1}{4}h_0\tau^{-1}$ $= 0.50\,\sigma_A^2(\tau)$	$\frac{2}{3}h_0\tau^{-1}$ $= 1.33\,\sigma_A^2(\tau)$
Flicker frequency noise	$h_{-1}f^{-1}$	$2\,ln(2)\,h_{-1}$ $= \sigma_A^2(\tau)$	$2\,ln(\frac{3\,3^{11/16}}{4})\,h_{-1}$ $= 0.67\,\sigma_A^2(\tau)$	$(24\,ln(2) - \frac{27}{2}\,ln(3))\,h_{-1}$ $= 1.30\,\sigma_A^2(\tau)$
Random walk frequency noise	$h_{-2}f^{-2}$	$\frac{2}{3}\,\pi^2\,h_{-2}\,\tau$ $= \sigma_A^2(\tau)$	$\frac{11}{20}\,\pi^2\,h_{-2}\,\tau$ $= 0.82\,\sigma_A^2(\tau)$	$\frac{23}{30}\,\pi^2\,h_{-2}\,\tau$ $= 1.15\,\sigma_A^2(\tau)$
Frequency Drift ($\dot{y} = D_y$)	-	$\frac{1}{2}D_y^2\tau^2$	$\frac{1}{2}D_y^2\tau^2$	$\frac{1}{2}D_y^2\tau^2$

Inloop and Remote signals

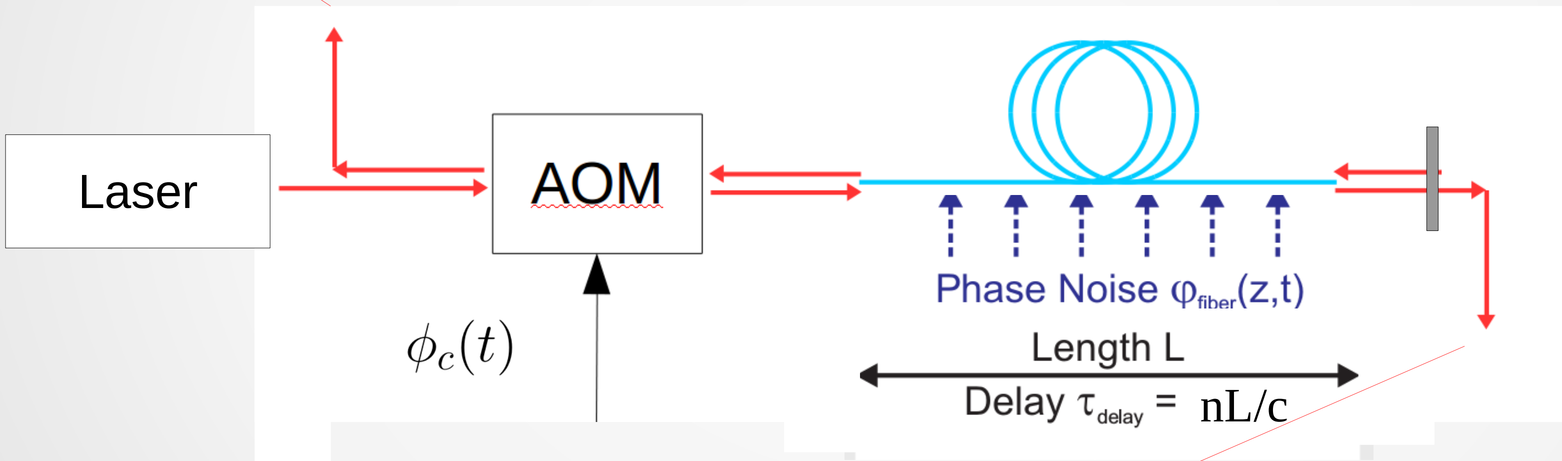
$$\varphi_{fiber,RT}(t) = \int_0^L \left(\delta\varphi(z, t - \frac{z}{c}) + \delta\varphi(z, t - (2\tau_{delay} - \frac{z}{c}))\right) dz$$



$$\varphi_{fiber}(t) = \int_0^L \delta\varphi(z, t - (\tau_{delay} - \frac{z}{c}))\ dz$$

Inloop and Remote signals

$$\varphi_{inloop}(t) = \varphi_{fiber,RT}(t) - \left(\phi_c(t) + \phi_c(t - 2\tau_{delay})\right) = 0.$$

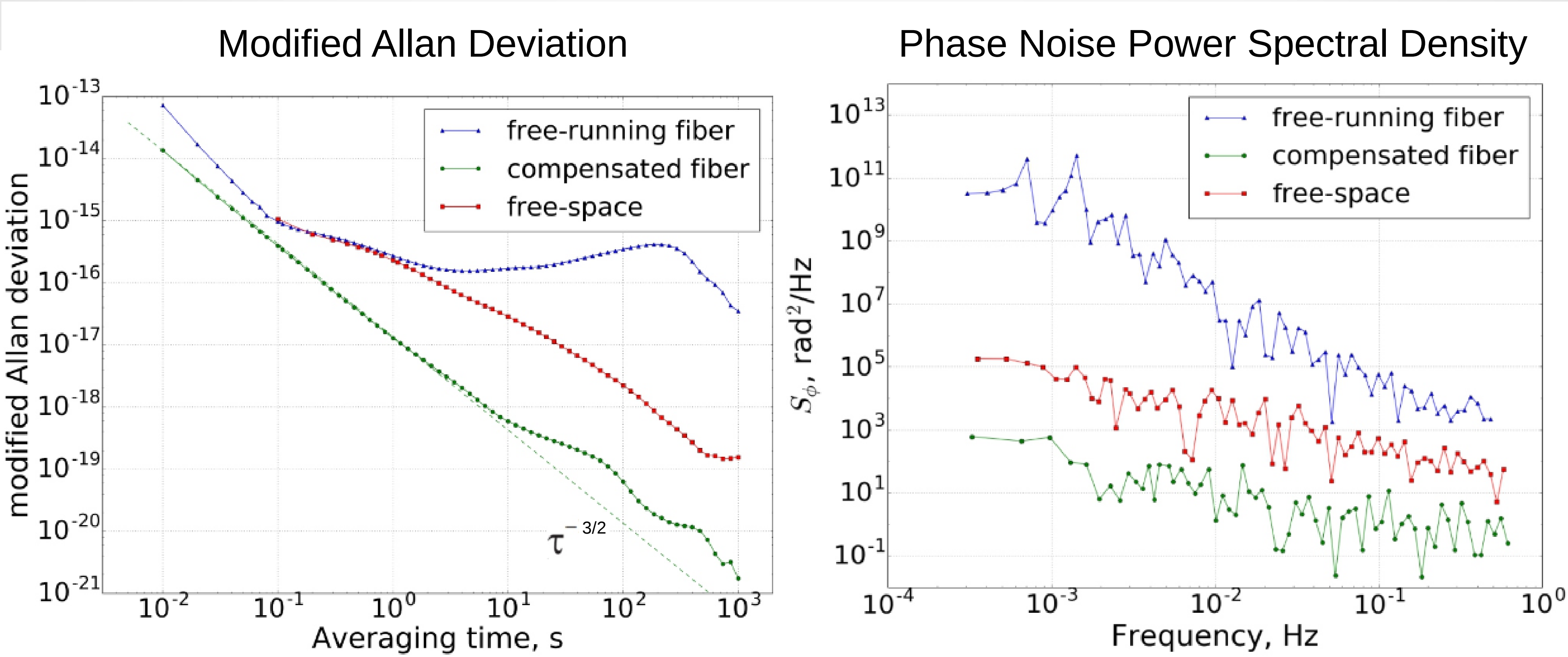


$$\varphi_{remote}(t) = \varphi_{fiber}(t) - \phi_c(t - \tau_{delay}) = \frac{L}{c}\frac{d\varphi}{dt}.$$

Delay-unsuppressed noise $S_{remote}(f) = \frac{1}{3}(f\,\tau_{delay})^2 S_{fiber}(f).$

Results

Even for 5 m fiber:

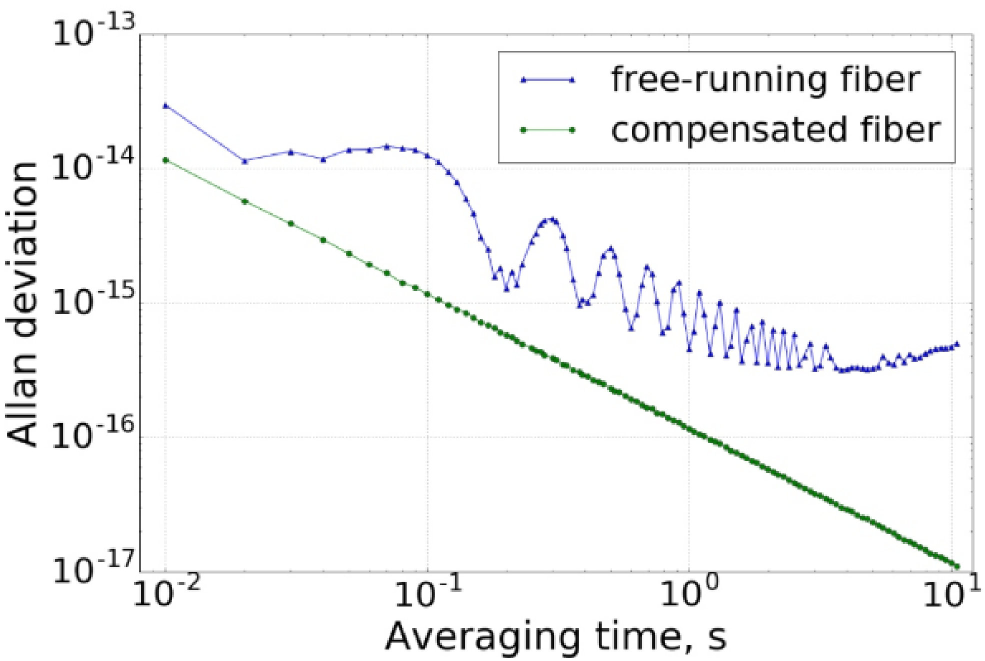


White phase noise

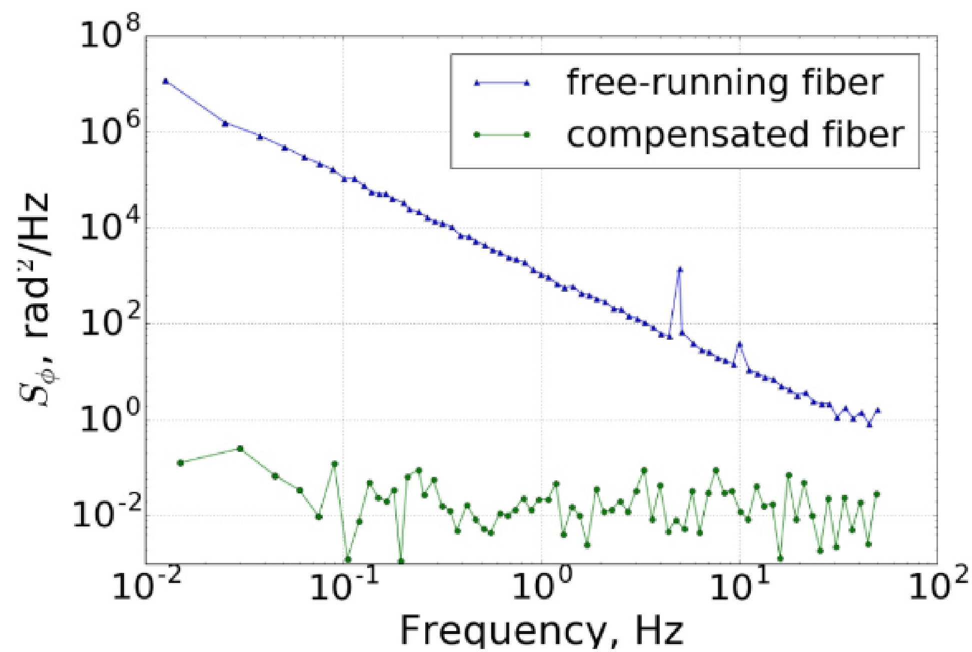
5 Hz mechanical perturbations

Even for 5 m fiber:

Allan Deviation



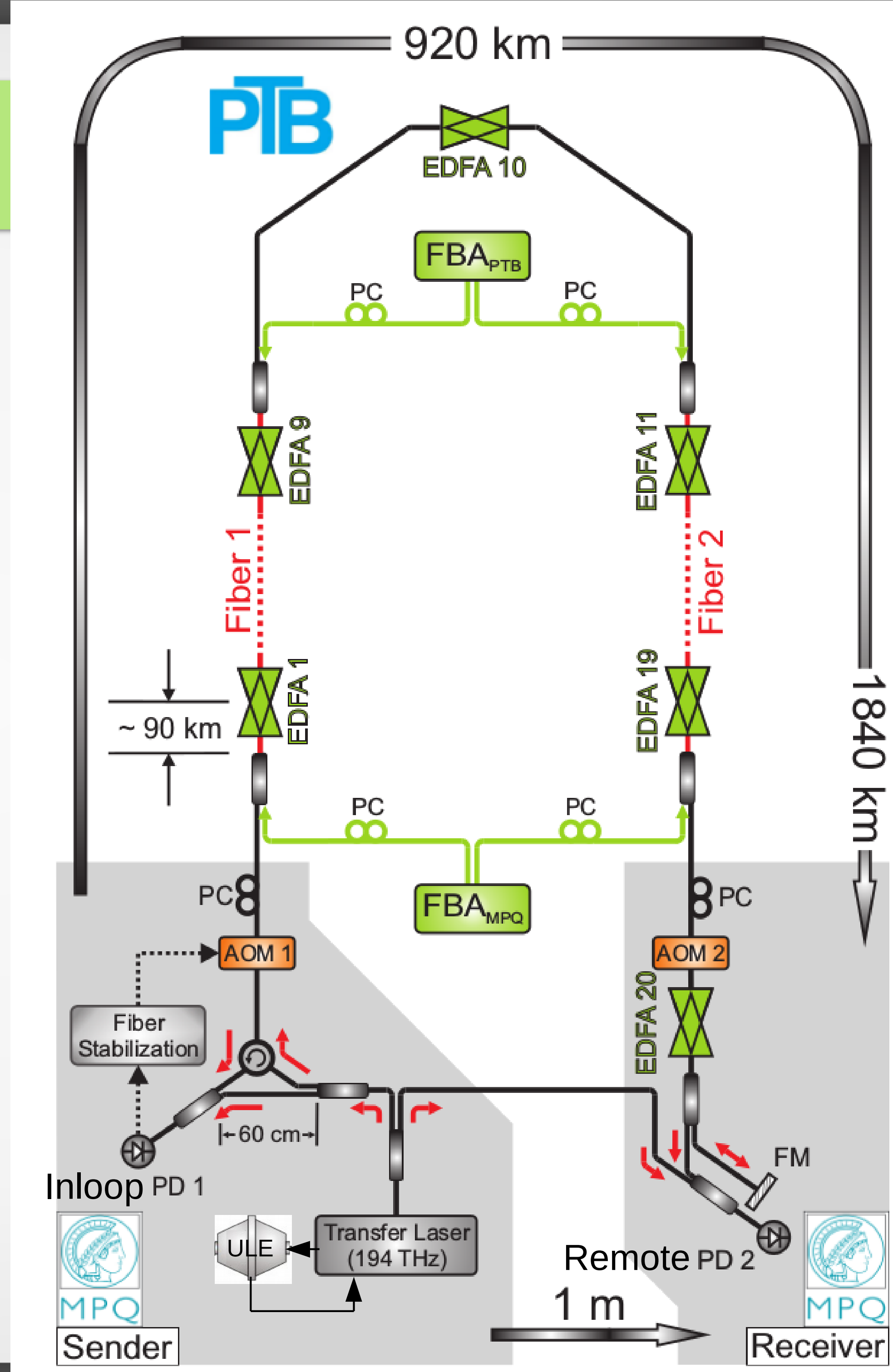
Phase Noise Power Spectral Density



Experimental Setup

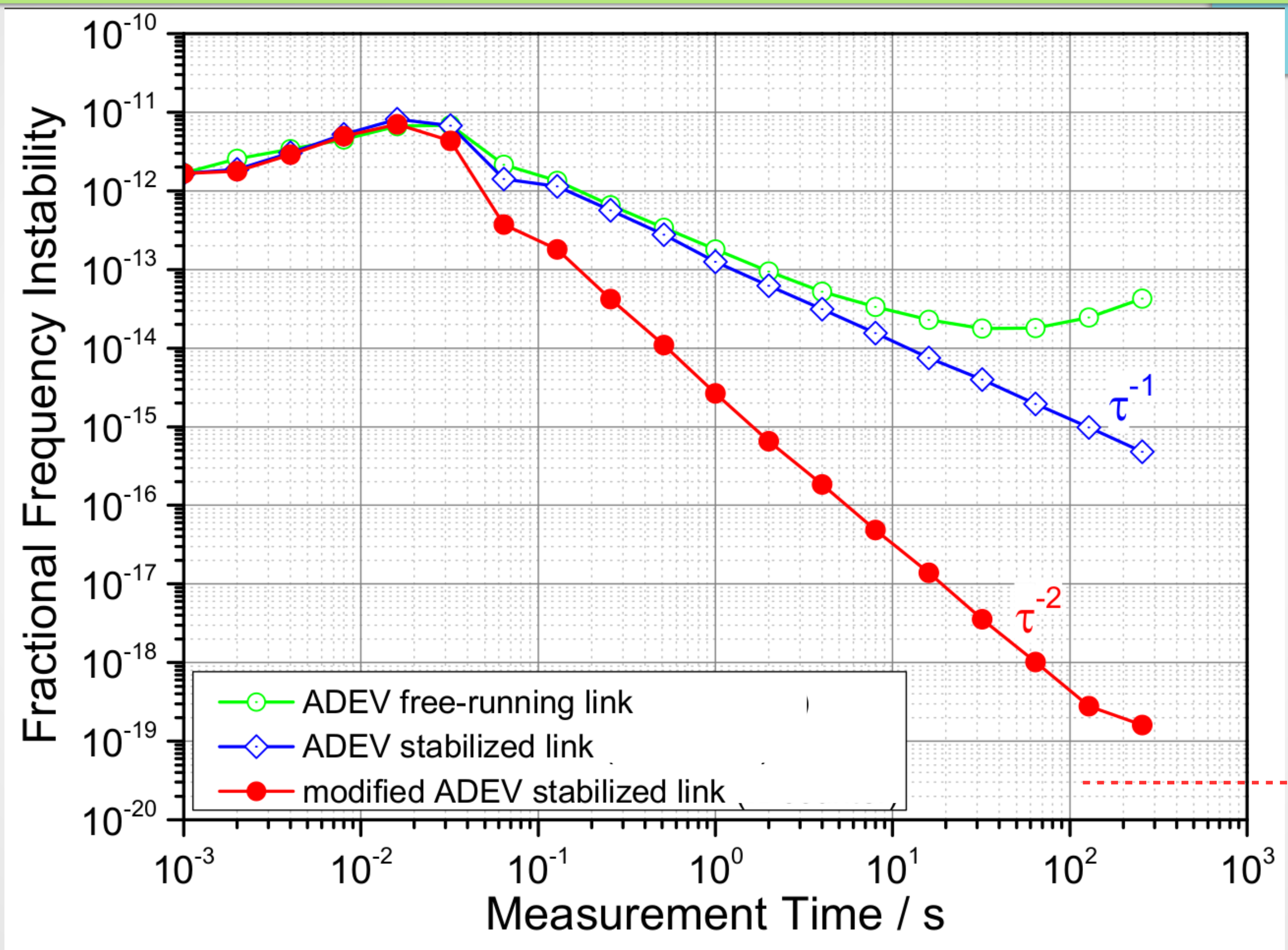
- Attenuation 0.23 dB/km
- Total attenuation > 420 dB

- ULE cavity
- Delay 18 ms
- Bandwidth 27 Hz



[1] S.Droste, PhD Thesis

1840 km MPQ-PTB-MPQ link. Stability



Remote

expected flicker frequency noise floor

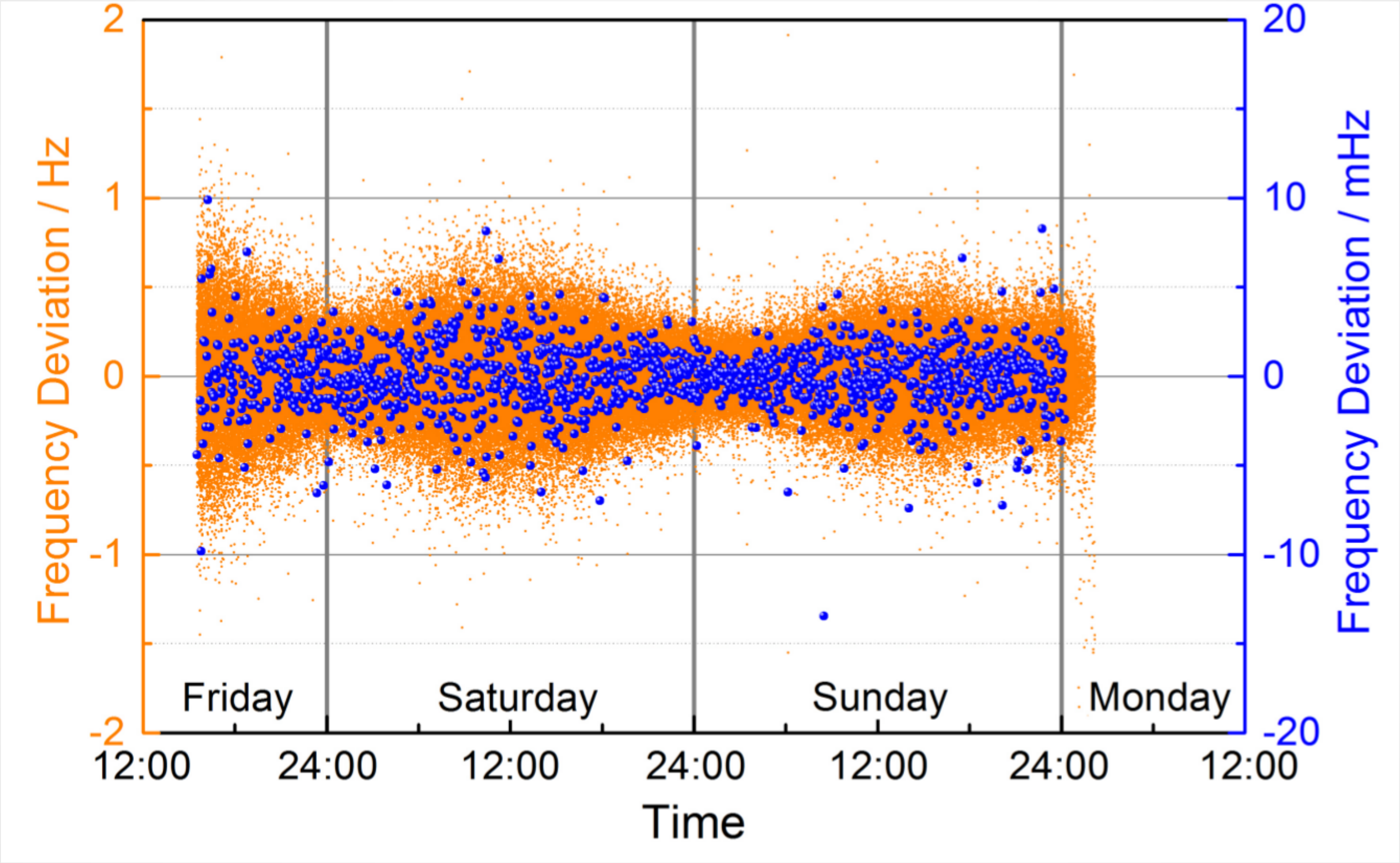
(1) undetected cycle slips,
(2) the noise of the transfer laser,
(3) the noise floor of the interferometer.

Short term instability: 2.7×10^{-15} in 1 s

Long term instability: $< 10^{-18}$ after ~70 s

[1] S.Droste, PhD Thesis

1840 km MPQ-PTB-MPQ link. Accuracy



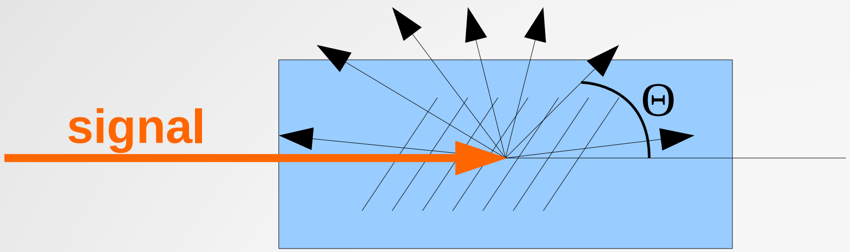
$$\left(-0.1 \pm 2.6\right) \cdot 10^{-19}$$

[1] S.Droste, PhD Thesis

Extended noise analysis

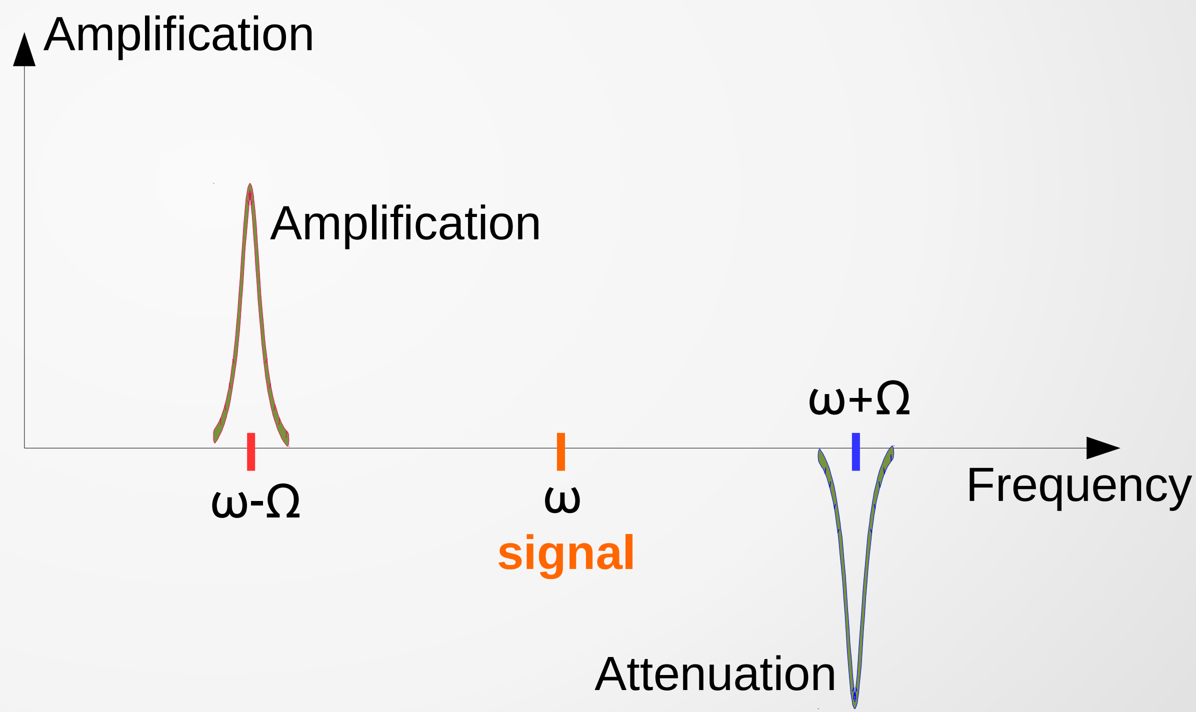
Noise Type	$S_y(f)$	$S_\phi(f)$	$\sigma_y^2(\tau)$	mod $\sigma_y^2(\tau)$
Random walk freq.	$h_{-2}f^{-2}$	$\nu_0^2 h_{-2} f^{-4}$	$\frac{2\pi^2 h_{-2}}{3}\tau$	$\frac{11\pi^2 h_{-2}}{20}\tau$
Flicker frequency	$h_{-1}f^{-1}$	$\nu_0^2 h_{-1} f^{-3}$	$2\ln(2)h_{-1}$	$2\ln(1.59)h_{-1}$
White frequency	$h_0 f^0$	$\nu_0^2 h_0 f^{-2}$	$\frac{h_0}{2}\tau^{-1}$	$\frac{h_0}{4}\tau^{-1}$
Flicker phase	$h_1 f^1$	$\nu_0^2 h_1 f^{-1}$	$\frac{(3.12+3\ln(\pi f_h \tau))h_1}{4\pi^2}\tau^{-2}$	$\frac{3\ln(9.48)h_1}{8\pi^2}\tau^{-2}$
White phase	$h_2 f^2$	$\nu_0^2 h_2 f^0$	$\frac{3 f_h h_2}{4\pi^2}\tau^{-2}$	$\frac{3h_2}{8\pi^2}\tau^{-3}$
f^1-noise	$h_3 f^3$	$\nu_0^2 h_3 f^1$	$\frac{3 f_h^2 h_3}{8\pi^2}\tau^{-2}$	$\frac{(9.64+10\ln(\pi f_h \tau))h_3}{16\pi^4}\tau^{-4}$
f^2-noise	$h_4 f^4$	$\nu_0^2 h_4 f^2$	$\frac{f_h^3 h_4}{4\pi^2}\tau^{-2}$	$\frac{10 f_h h_4}{16\pi^4}\tau^{-4}$
f^3-noise	$h_5 f^5$	$\nu_0^2 h_5 f^3$	$\frac{3 f_h^4 h_5}{16\pi^2}\tau^{-2}$	$\frac{10 f_h^2 h_5}{32}\tau^{-4}$
f^4-noise	$h_6 f^6$	$\nu_0^2 h_6 f^4$	$\frac{3 f_h^5 h_6}{20\pi^2}\tau^{-2}$	$\frac{10 f_h^3 h_6}{48\pi^4}\tau^{-4}$

Stimulated Brillouin scattering

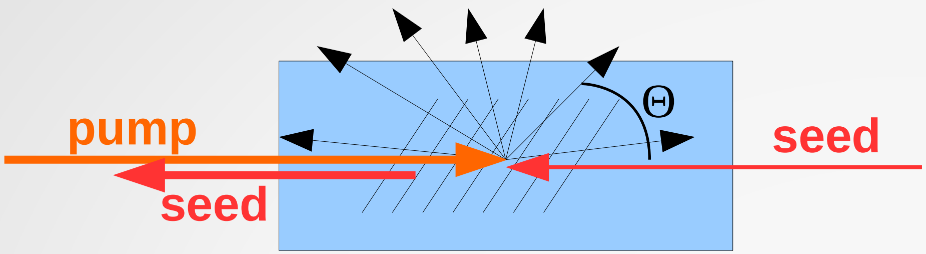


$$\frac{\Omega}{V_s} = 2\frac{\omega n}{c}\sin\frac{\Theta}{2}$$

- Only Θ = Π: backwards
- Two waves: ω-Ω and ω+Ω
- Ω ~ 11 GHz
- About 4 mW



Stimulated Brillouin scattering



$$\frac{\Omega}{V_s} = 2\frac{\omega n}{c}\sin\frac{\Theta}{2}$$

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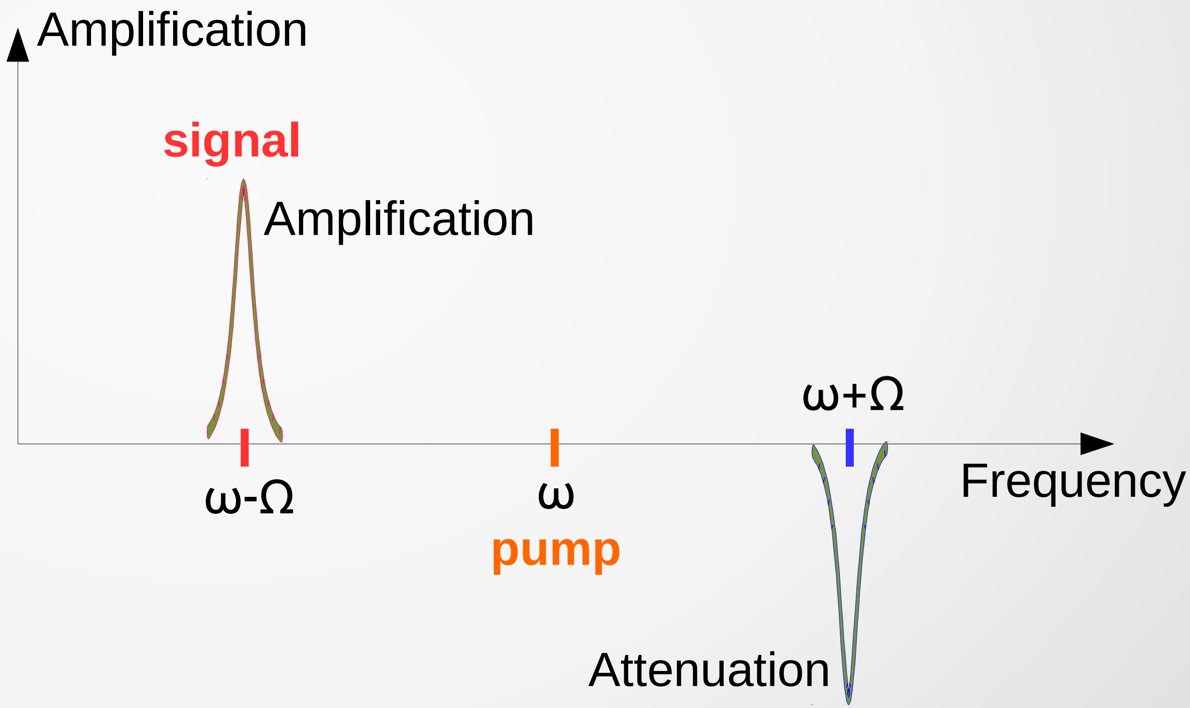
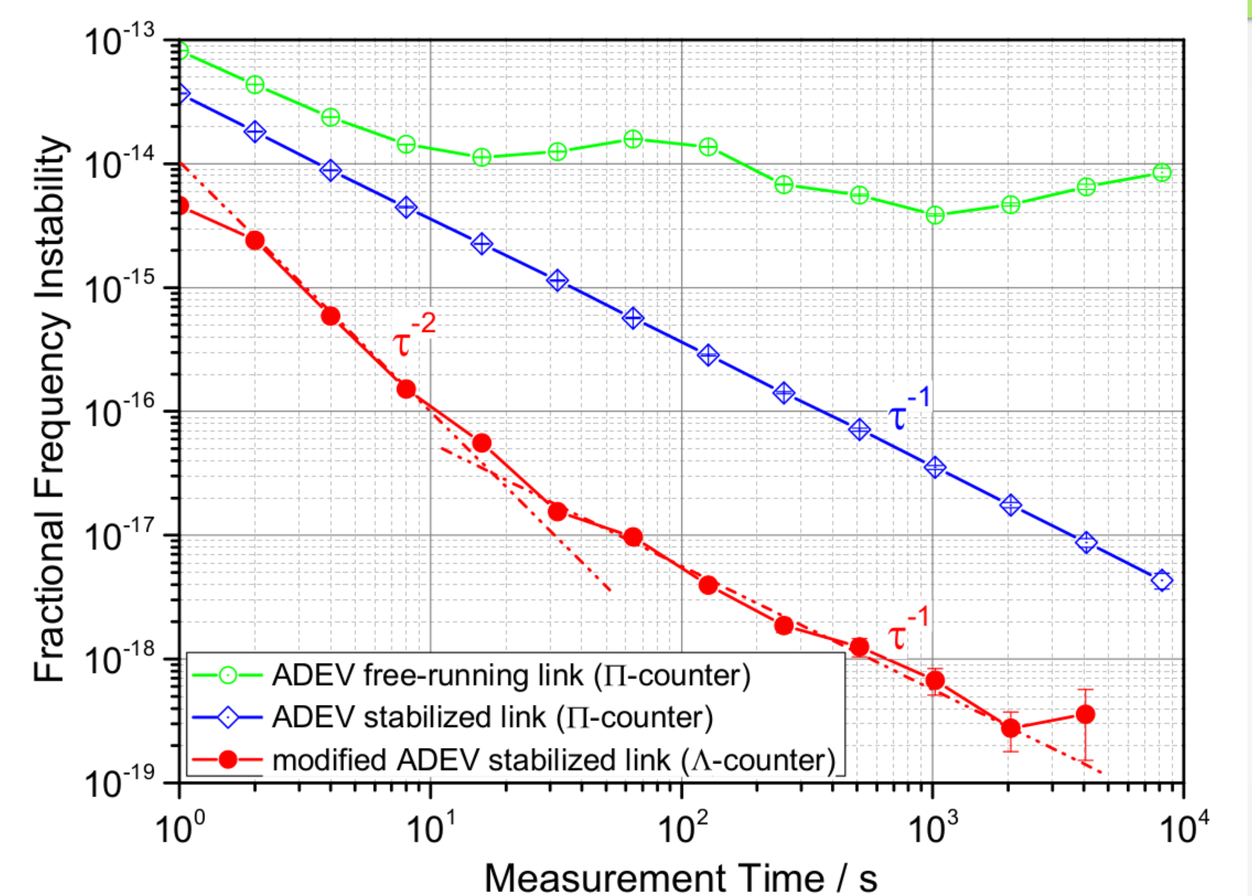


920 km MPQ-PTB



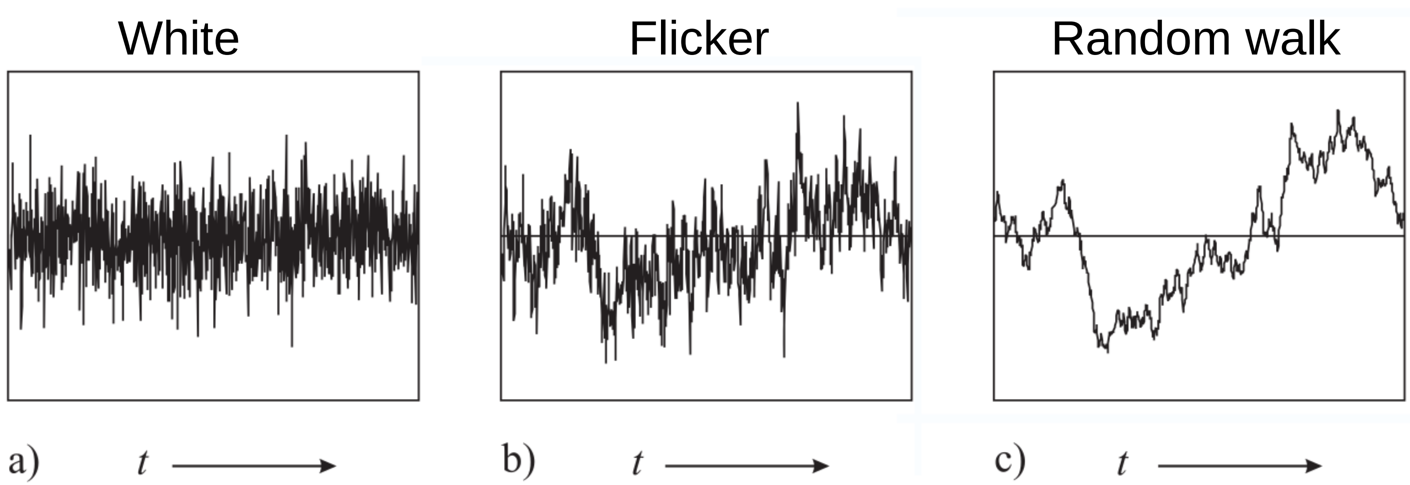
Criterium	Threshold
Difference of redundantly counted $f_{Beat,F1}$ at PTB	$<$ 0.2 Hz
Difference of redundantly counted $f_{Beat,F2}$ at MPQ	$<$ 0.2 Hz
Difference of both $f_{Beat,F1}$ and its nominal frequency at PTB	$<$ 1 Hz
Difference of both $f_{Beat,F2}$ and its nominal frequency at MPQ	$<$ 1 Hz

[1] S.Droste, PhD Thesis

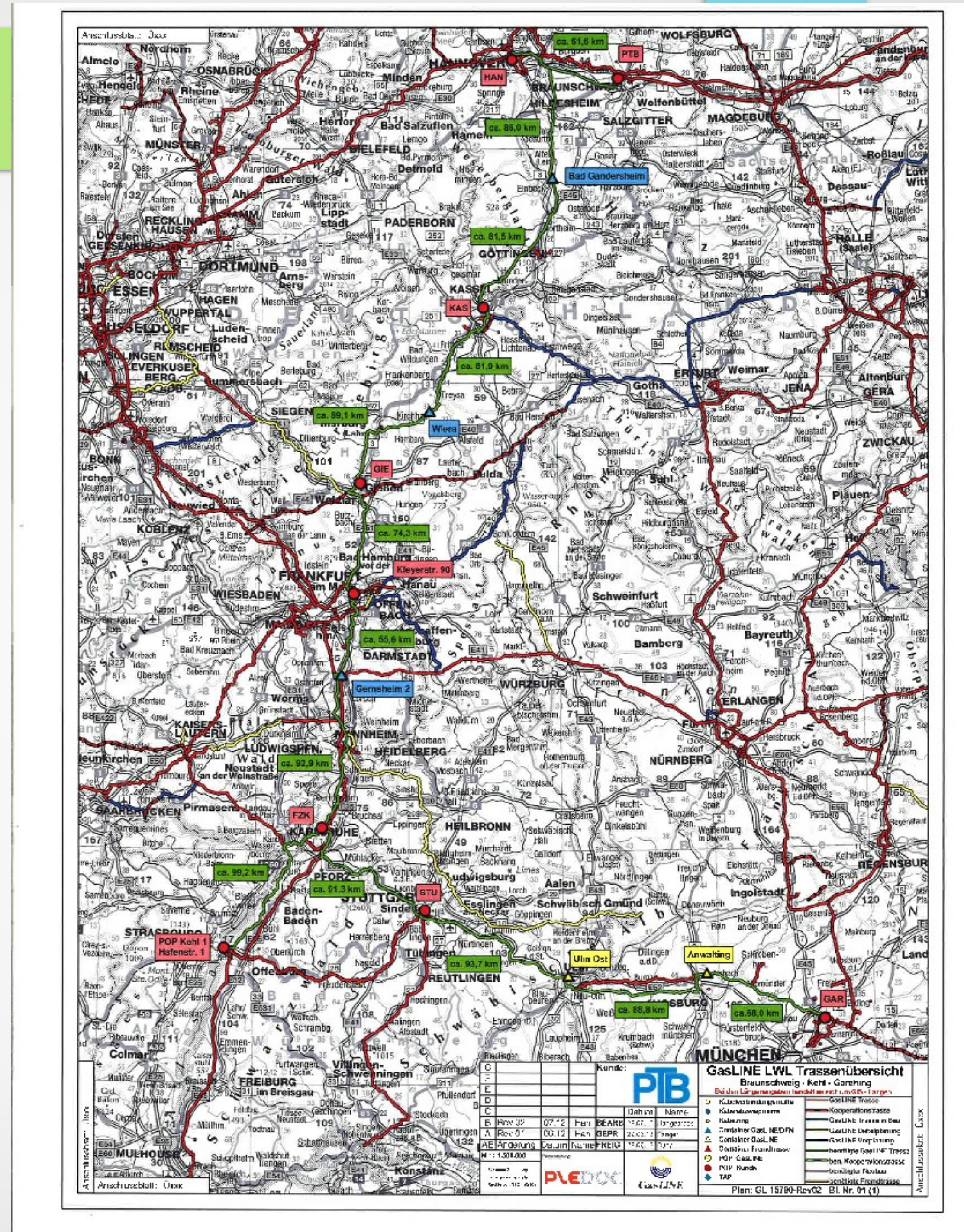
Noise types

Тип шума	Происхождение	S_ϕ	S_y	σ_y	Mod σ_y
Случайные уходы частоты	Окружающая среда	$\propto f^{-2}$	$\propto f^{-4}$	$\propto \tau^{\frac{1}{2}}$	$\propto \tau^{\frac{1}{2}}$
Фликкер-шум частоты	Компоненты стандарта частоты	$\propto f^{-1}$	$\propto f^{-3}$	const	const
Белый шум частоты	Дробовой шум, тепловой шум	const	$\propto f^{-2}$	$\propto \tau^{-\frac{1}{2}}$	$\propto \tau^{-\frac{1}{2}}$
Фликкер-шум фазы	Электроника	$\propto f^{1}$	$\propto f^{-1}$	$\propto \tau^{-1}$	$\propto \tau^{-1}$
Белый шум фазы	Окружающая среда	$\propto f^{2}$	const	$\propto \tau^{-1}$	$\propto \tau^{-\frac{3}{2}}$

$S_y(f)$	$S_\phi(f)$	Type of noise	$\sigma_y^2(\tau)$
$h_{-2}f^{-2}$	$\nu_0^2 h_{-2} f^{-4}$	Random walk of frequency noise	$(2\pi^2 h_{-2}/3)\tau^{+1}$
$h_{-1}f^{-1}$	$\nu_0^2 h_{-1} f^{-3}$	Flicker frequency noise	$2h_{-1}\ln 2\tau^0$
$h_0 f^0$	$\nu_0^2 h_0 f^{-2}$	White frequency noise (Random walk of phase noise)	$(h_0/2)\tau^{-1}$
$h_1 f$	$\nu_0^2 h_1 f^{-1}$	Flicker phase noise	$h_1[1.038 + 3\ln(2\pi f_h \tau)]/(4\pi^2)\tau^{-2}$
$h_2 f^2$	$\nu_0^2 h_2 f^0$	White phase noise	$[3h_2 f_h/(4\pi^2)]\tau^{-2}$



Map



HANNOVER
HAN
PTB
BRAUNSCHWEIG
WOLFSBURG
HILDESHEIM
SALZGITTER
MAGDEBURG
ca. 61,6 km
ca. 85,0 km
Bad Gandersheim
ca. 81,5 km
GÖTTINGEN
KASSEL
KAS
ca. 81,9 km
Wiera
ca. 89,1 km
GIE
ca. 74,3 km
Kleyerstr. 90
FRANKFURT
ca. 55,6 km
DARMSTADT
Gernsheim 2
MANNHEIM
HEIDELBERG
ca. 92,9 km
FZK
KARLSRUHE
ca. 99,2 km
ca. 91,3 km
STUTTGART
BTU
POP Kehl 1
Hafenstr. 1
ca. 93,7 km
Ulm Ost
Anwalting
ca. 88,8 km
ca. 58,0 km
GAR
MÜNCHEN
DORTMUND
ESSEN
WIESBADEN
WÜRZBURG
NÜRNBERG
ERLANGEN
Bamberg
Schweinfurt
HEILBRONN
REUTLINGEN
Tübingen
FREIBURG
im Breisgau
ERFURT
JENA
GERA
ZWICKAU
Plauen
REGENSBURG
Ingolstadt
Augsburg
PADERBORN
BIELEFELD
OSNABRÜCK
MÜNSTER
Bad Salzuflen
SIEGEN
KOBLENZ
BONN
KAISERSLAUTERN
SAARBRÜCKEN
LUDWIGSHAFEN
STRASBOURG
Konstanz
MULHOUSE
Colmar
Kunde:
PTB
GasLINE LWL Trassenübersicht
Braunschweig - Kehl - Garching
PLEDOC
GasLINE
Plan: GL 15790-Rev02 Bl. Nr. 01 (1)

Experimental Setup