Physikalisch-Technische Bundesanstalt
Braunschweig und Berlin
Nationales Metrologieinstitut

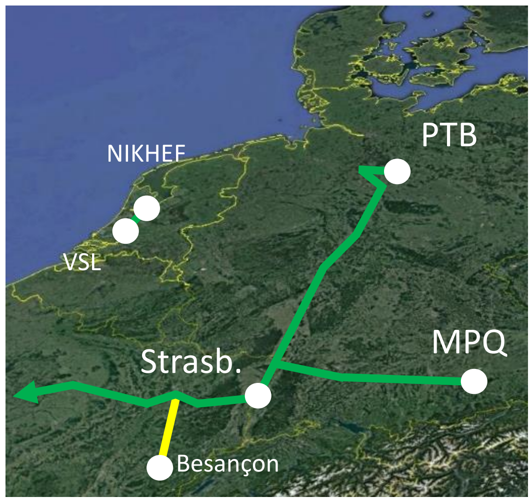
Frequency dissemination and remote frequency comparisons

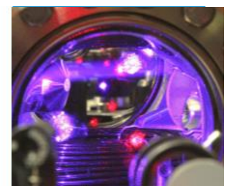
update 10/2018 PTB-KIT-MPQ fibre link.

Gesine Grosche, AG 4.34

& nat. and internat. partners

Andreas Koczwara, Dr. Sebastian Koke
Dr. Alexander Kuhl, Dr. Thomas Waterholter
Dr. Erik Benkler (part-time)





„Reminder“ - Interferometric Fibre Links (IFL) in a nutshell

Applications of frequency transfer

Transfer the stability and accuracy of a frequency reference to a different location

a) dissemination of the unit of length / remote calibration:
$\delta\lambda/\lambda = \delta\nu/\nu \approx 10^{-6} \ldots 10^{-10}$

b) compare optical frequency standards (over long distances)
fundamental constants (m_p/m_e, α)
$\delta\nu/\nu \approx 10^{-13} \ldots 10^{-18}$

c) use one ultra-stable „master“-laser for many experiments
remote spectroscopy, remote µ-wave synthesis:
short-term instability $\sigma_\nu < 10^{-15}$ (1s)

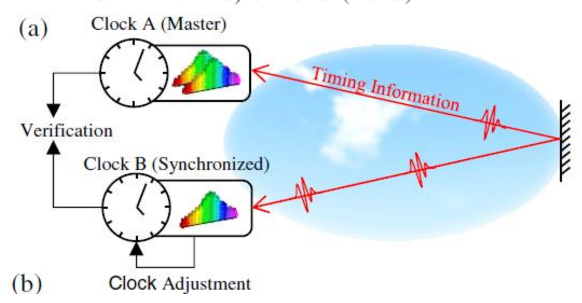
d) remote sensing & syntonization – radio telescopes, geodesy, accelerators, LIGO; frequency as a „probe“- GR, SR; $\delta\nu/\nu \approx 10^{-12} \ldots 10^{-20}$ …?

e) characterise & validate other frequency (time) transfer methods

4.34 G. Grosche „Frequenzmessungen über Glasfaser “

Frequency comparison methods

JEAN-DANIEL DESCHÊNES *et al.*
PHYS. REV. X **6**, 021016 (2016)



Satellite Link
10^{-11}(1s)-10^{-16}(few d)

Lab A

Atomic clocks

Stability(1s) 10^{-15}-10^{-16}
Accuracy 10^{-17}-10^{-18}

Transportable Clocks
FOM 4x10^{-16}(1d)
Sr 10^{-16}(500s)

Lab B

Time-frequency metrology

High-precision physics

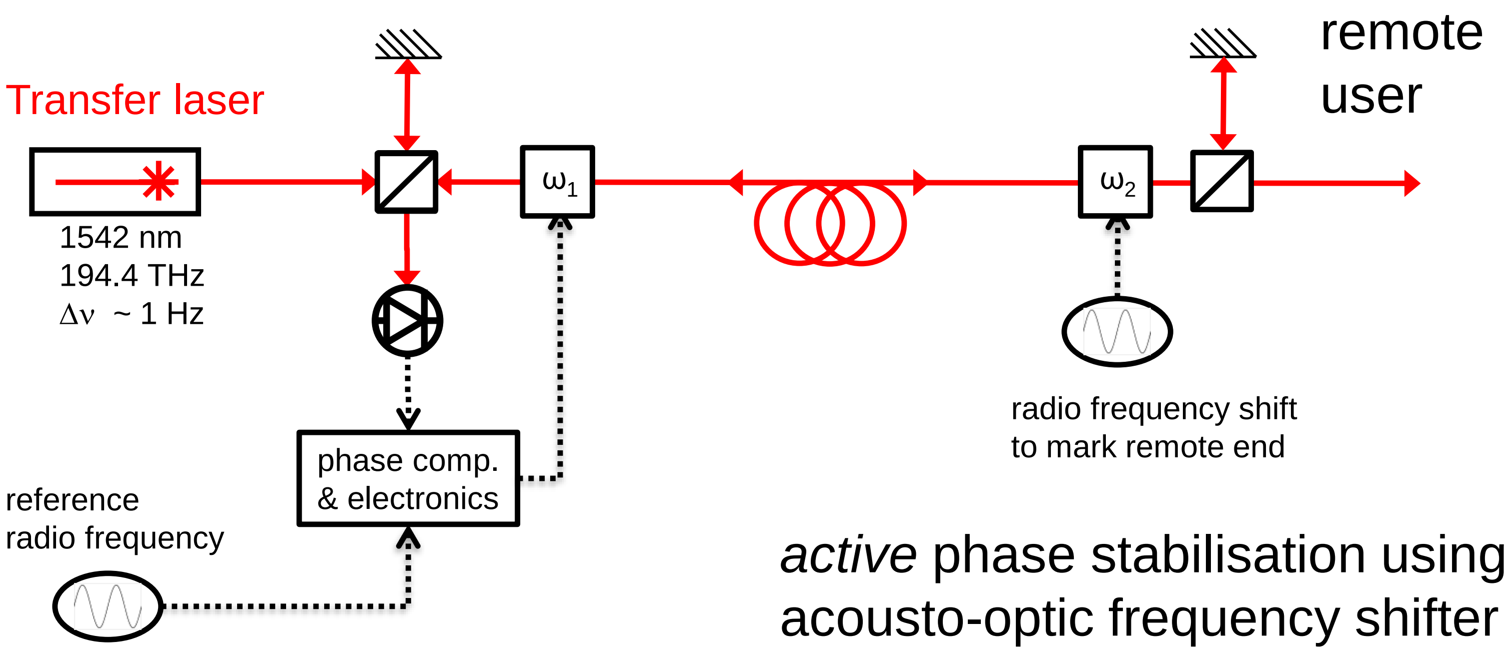
Optical Fiber Link
Rapid development since 10 years
10^{-14}(1s)-<10^{-18}(1d)

quote from:

[Anne Amy-Klein, tutorial EFTF 2018]

Interferometric optical fibre links

:= optical fibre link with fixed optical phase at remote („far“) end
relative to
a local reference point.



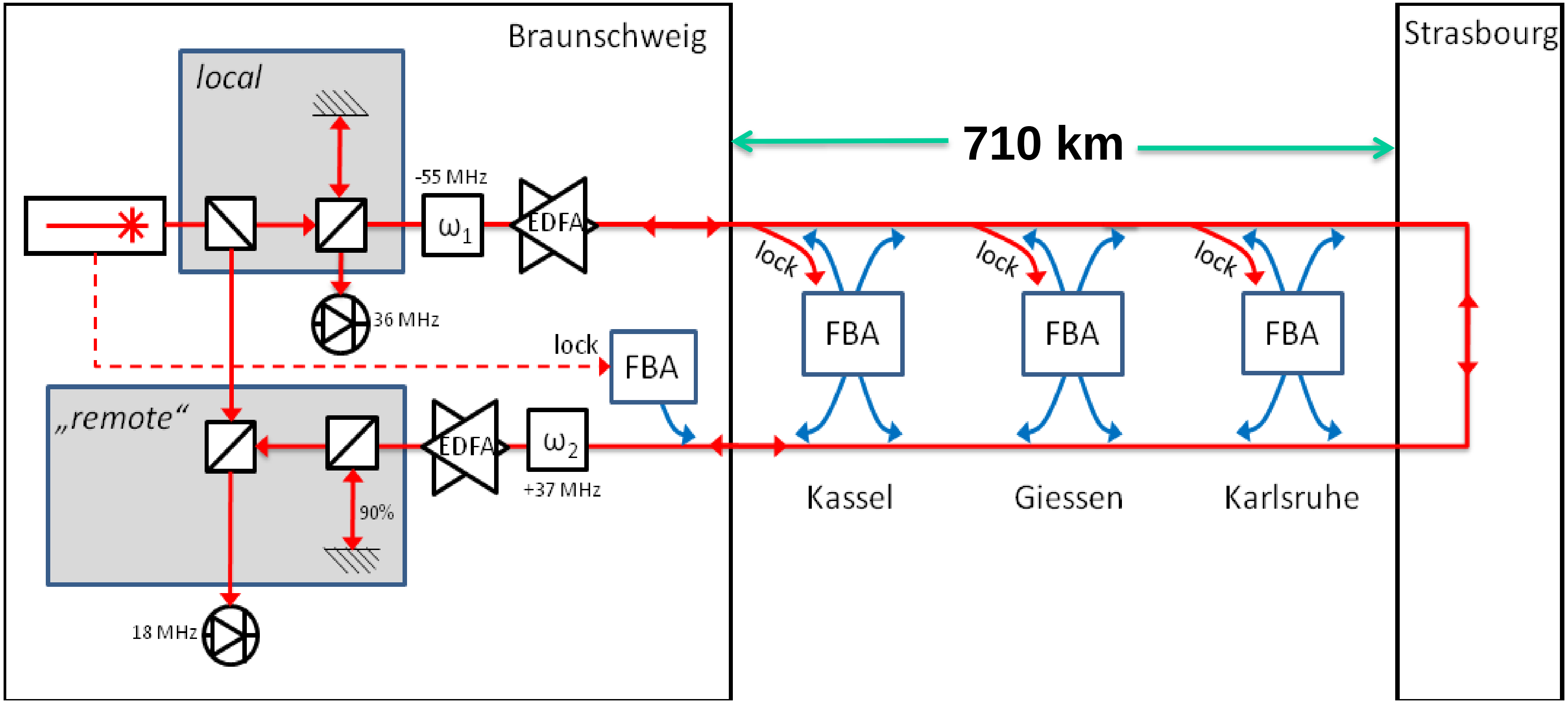
active phase stabilisation using
acousto-optic frequency shifter

Foreman et al. RevSci Inst. (2007)
Grosche et al. CLEO , paper CMKK1 (2007)
*Williams et al., J. Opt. Soc. Am. B **25** 1284 (2008) …*

„bi-directional“: light propagates in both directions, same optical path
assume reciprocity of forward and backward propagation

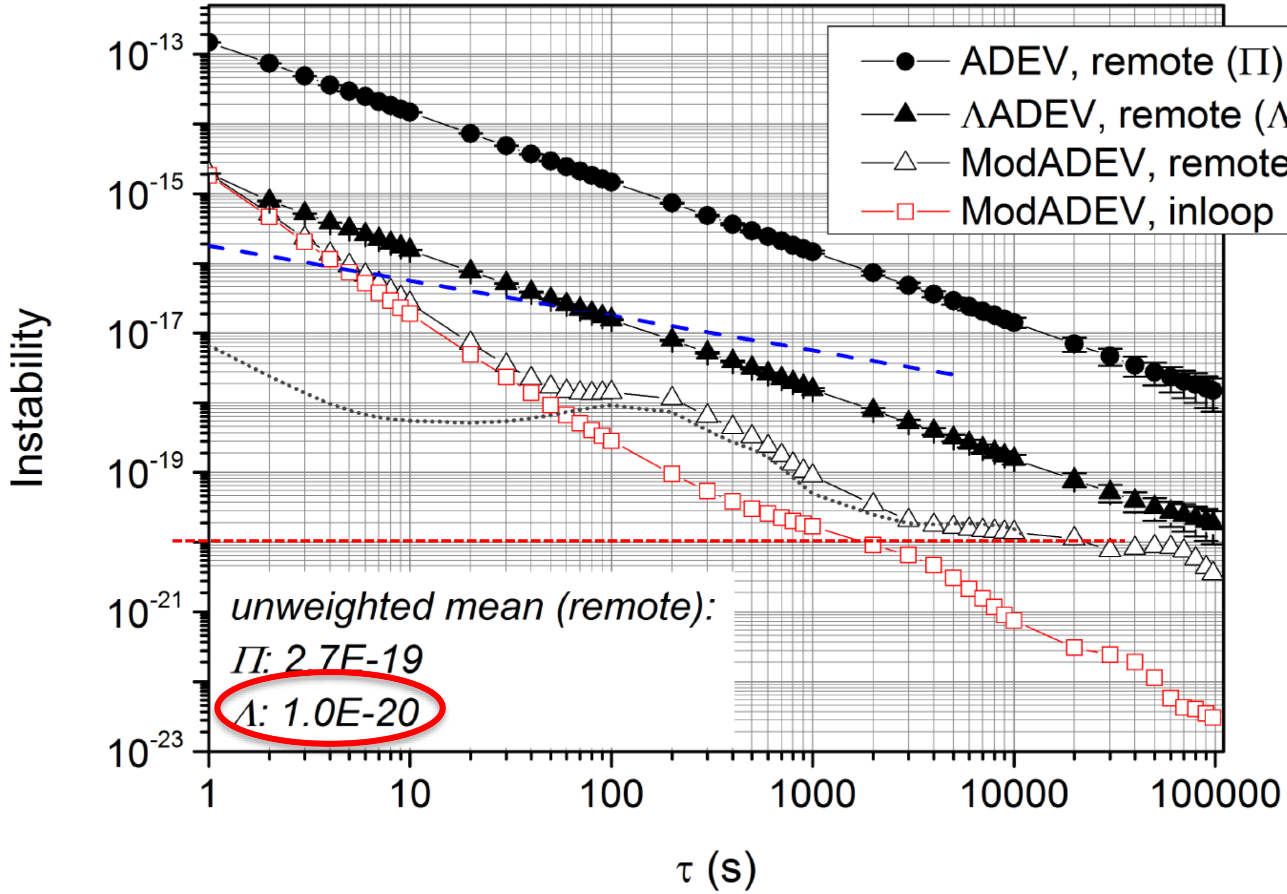
Tests involve loops: here 1400 km PTB-Strb-PTB

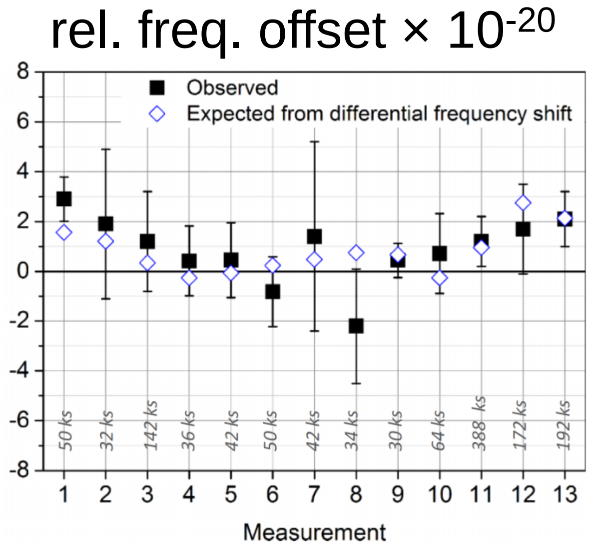
Field test of cascaded fibre Brillouin modules (FBA) in 1400 km loop: PTB-Strb-PTB, total attenuation > 300 dB:



S. Raupach, A. Koczwara and G. Grosche: „Brillouin amplification supports 10^{-20} accuracy in optical frequency transfer…“; Phys Rev A **92**, 021801(R) (2015) editors‘ suggestion

Test results: instabililty/ uncertainty (1400 km)



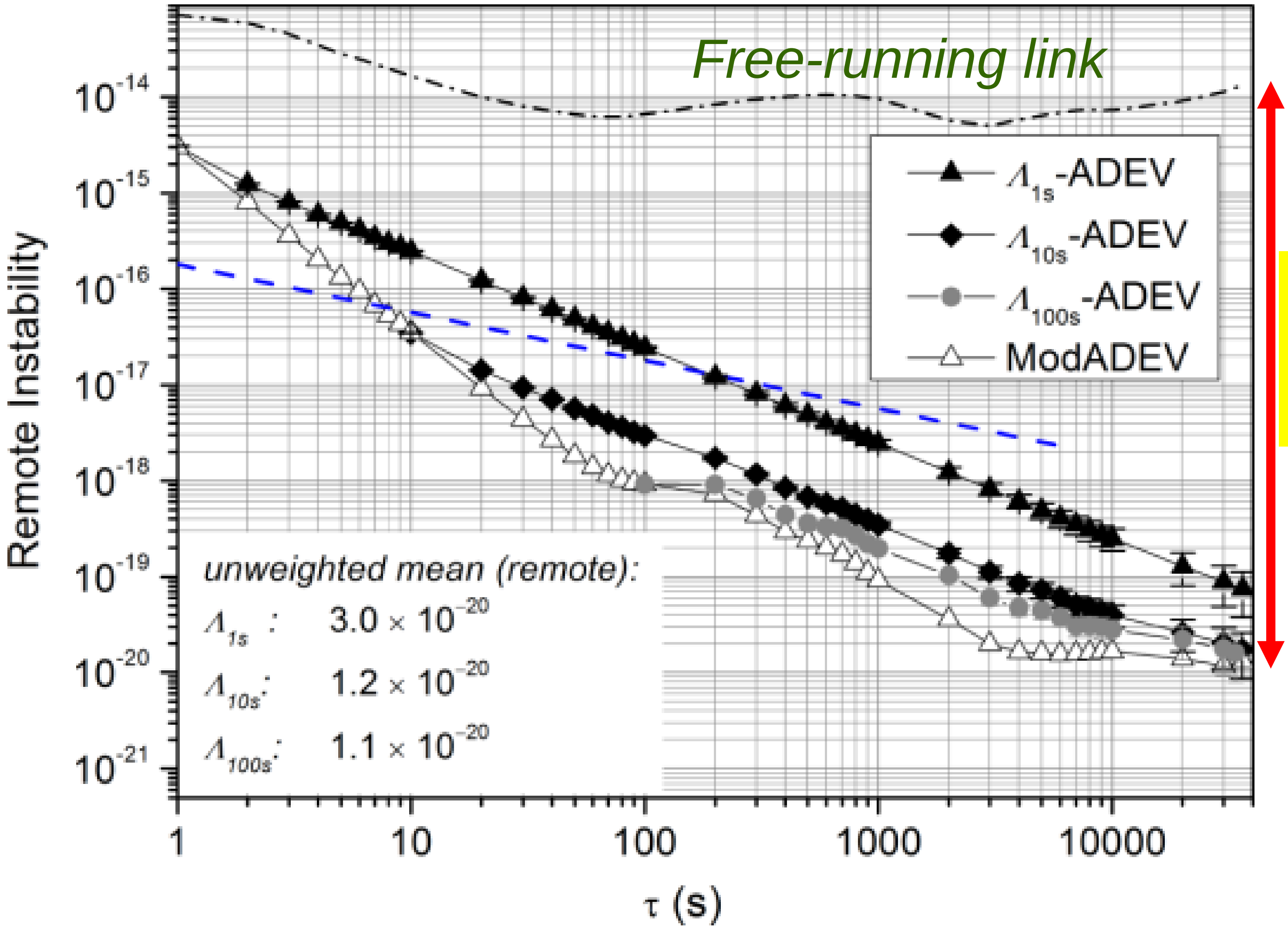


1400 km PTB-Strb-PTB loop link with FBA: excellent properties of FBA

- continuous measurements – no cycle slips/ signal interruptions
- unprecedented instability and accuracy

S. Raupach, A Koczwara and G. Grosche: „Brillouin amplification supports 10^{-20}…“ PRA 92, 021801(R) (2015)

Noise suppression. Λ_ns ADEV



fluctuations suppressed by factor ~ 10^6

S. Raupach, A Koczwara and G. Grosche: „Brillouin amplification supports 10^{-20}…", PRA 92, 021801(R) (2015)

CCTF „Roadmap“ SI/ clock validation and clock development

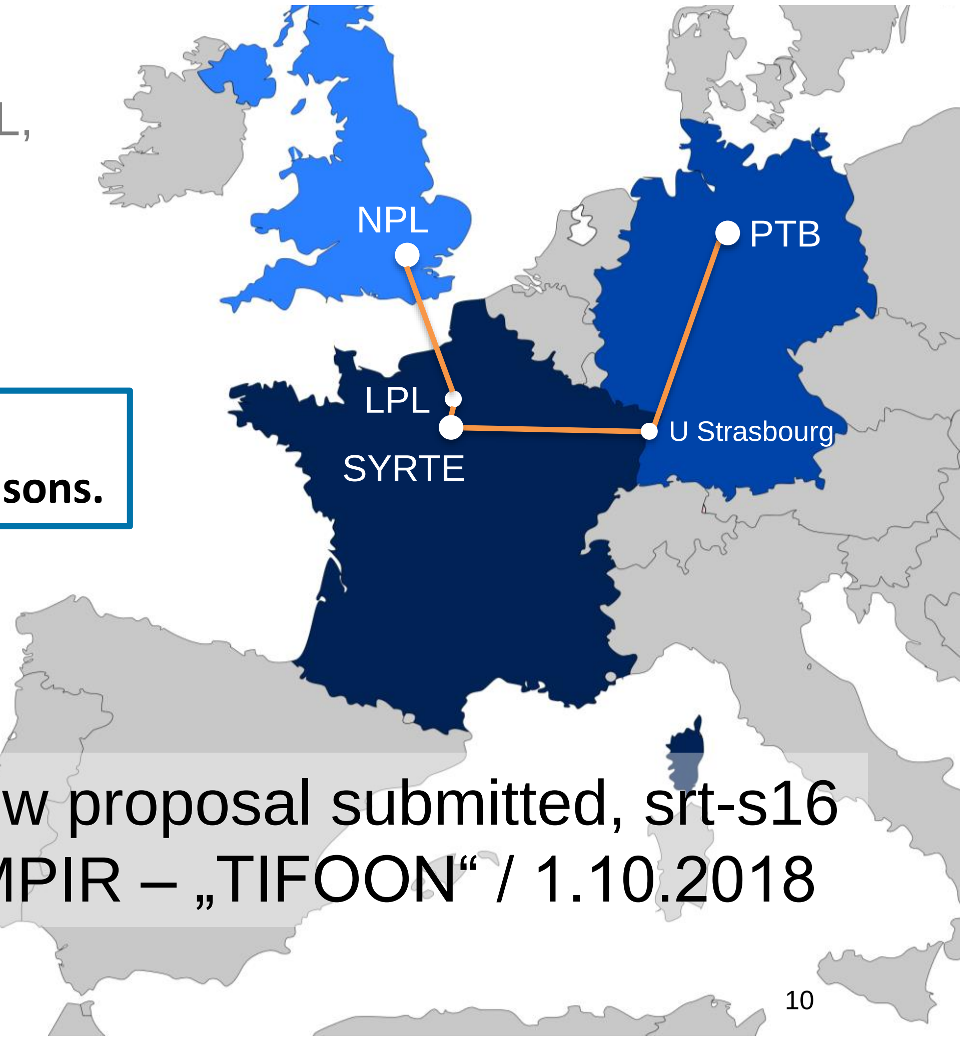
AG 4.34 - European fibre link

S. Koke[1], J. Kronjäger[2], E. Cantin[3], O. Lopez[3], A. Kuhl[1], T. Waterholter[1], E. Benkler[1], A. Amy-Klein[3], P.-E. Pottie[4], and G. Grosche[1]

[1] PTB [2] NPL National Physical Laboratory [3] LPL Laboratoire de physique des lasers [4] l'Observatoire de Paris SYRTE Systèmes de Référence Temps-Espace

EMPIR-project „OFTEN“

WP 1 (S. Koke): Enable & perform comparisons of optical clocks (OC) at NPL, SYRTE, and PTB via **joint fibre link** with
fractional instability $< 10^{-17}$
& uncertainty $< 10^{-17}$



NPL-SYRTE-PTB fibre link is established and we performed 1st tri-national clock comparisons.

Clock comparison campaigns to date

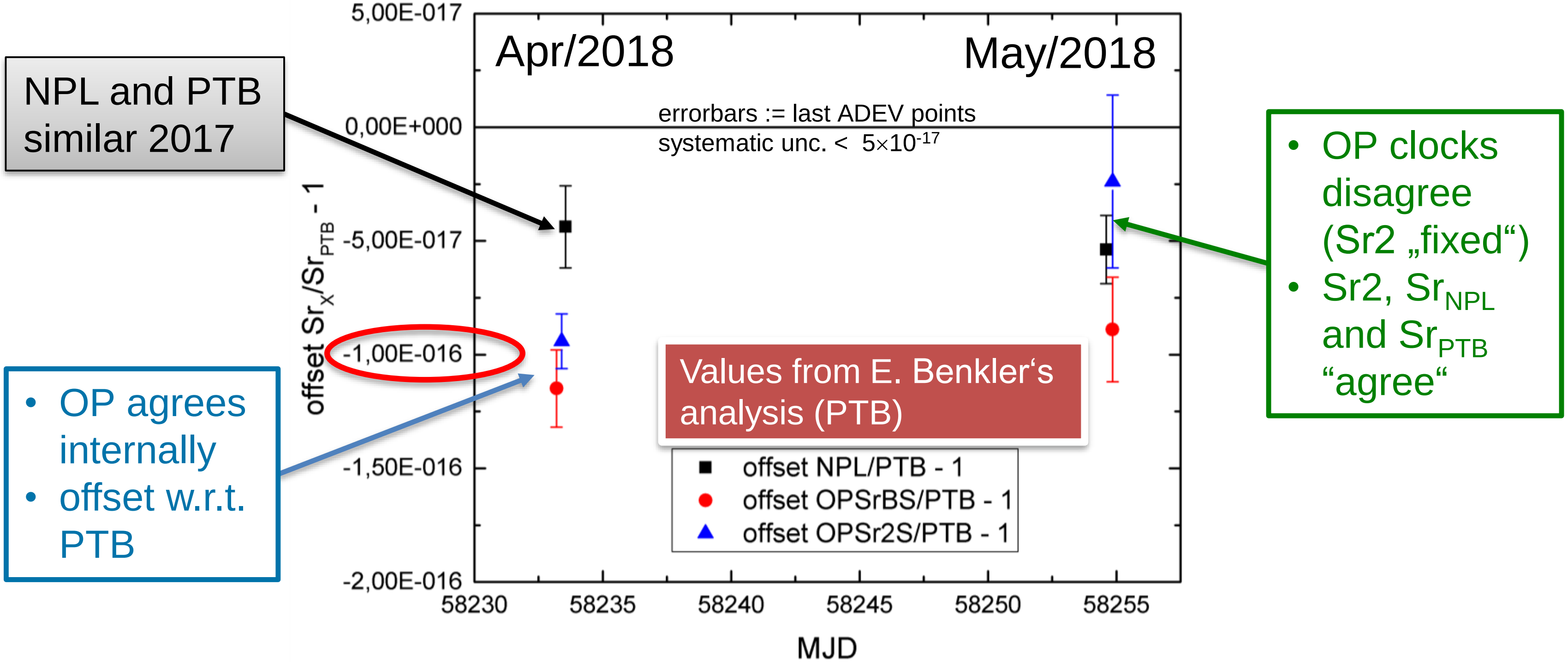
- June 2017, duration: 5 weeks
- 9 OC + 3 CsFs, **Sr_{transp} in Paris !**
- April & May 2018, < 1 week
- 6 OC (Yb^+, Sr)

New proposal submitted, srt-s16
EMPIR – „TIFOON“ / 1.10.2018

EFTF contribution and 24 April 2018- UTC(DE); 4.34 G Grosche

WP1 in OFTEN: Clock comparison 2018

Sr clocks in Europe:



Two clocks can locally agree and yet – *may* be wrong.
International comparisons help discover inconsistencies.

Question: could we use transportable clocks to check consistency ? „Redundant" blind measurements ?

Adapted from OFTEN 3rd PM – WP1, S. Koke

Chronometric levelling / „relativistic geodesy“ using clocks and IFLs

d) remote sensing & synchronization … geodesy:

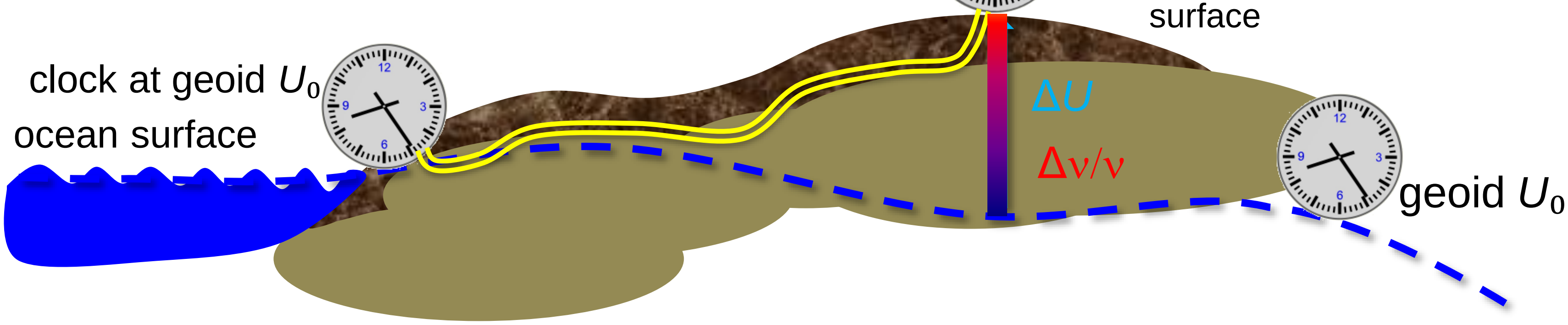
- chronometric levelling

Vermeer, Rep. of the Finnish Geod. Insti. **83**, 1 (1983)
Bjerhammar, Bull. Geodesique **59**, 207 (1985), NOAA tech report (1986)

Relativistic geodesy lends itself to the following new definition of the geoid:

The relativistic geoid is the surface nearest to mean sea level on which precise clocks run with the same speed.

Gravitational red shift for height determination ?



light experiences gravitational red shift; height:

$$H_P = \frac{U_P - U_O}{\bar{g}} = \frac{c^2}{\bar{g}} \frac{\Delta\nu}{\nu}$$

$\Delta\nu/\nu = 10^{-18}$ for $\Delta H = 0.01$ m

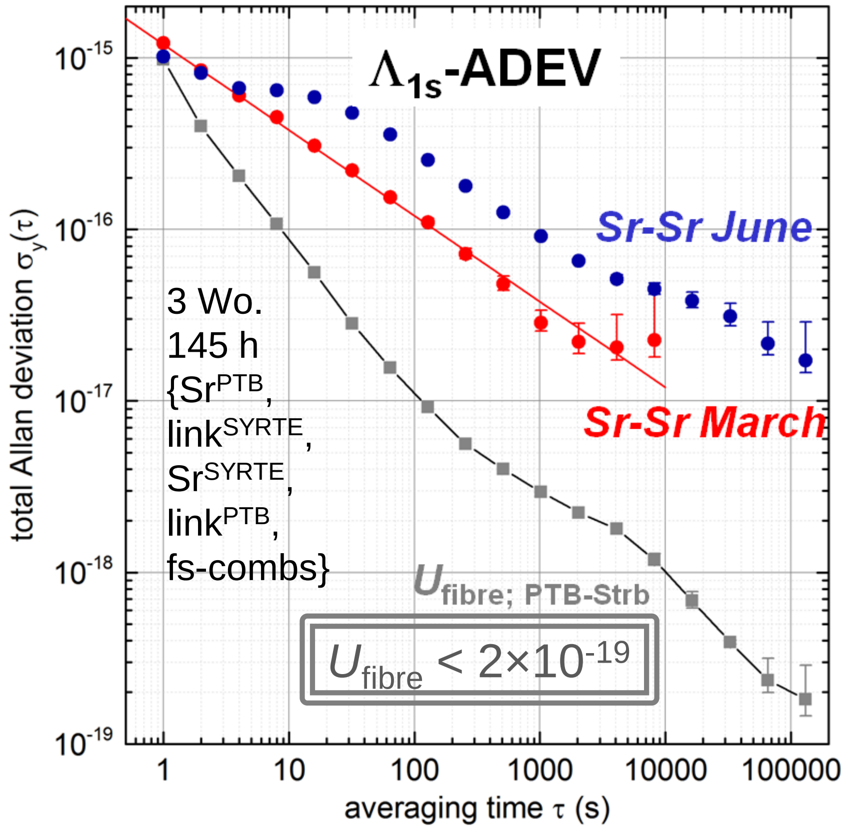
=> calculate height H_p from apparent clock frequency difference

European links (IFL) connecting clocks

SYRTE-Strasb-SYRTE
1480 km, 420 dB
3 RLS, 16 EDFA

PTB-Strasb-PTB
1400 km; 300 dB
3 FBA

Comparison Sr^{PTB} : Sr^{SYRTE} via IFL (6/2015)



FBA := fibre Brillouin amplifier module

S.M.F. Raupach, A. Koczwara and G. Grosche, in Opt. Exp. (2014) and PhysRev A (2015)

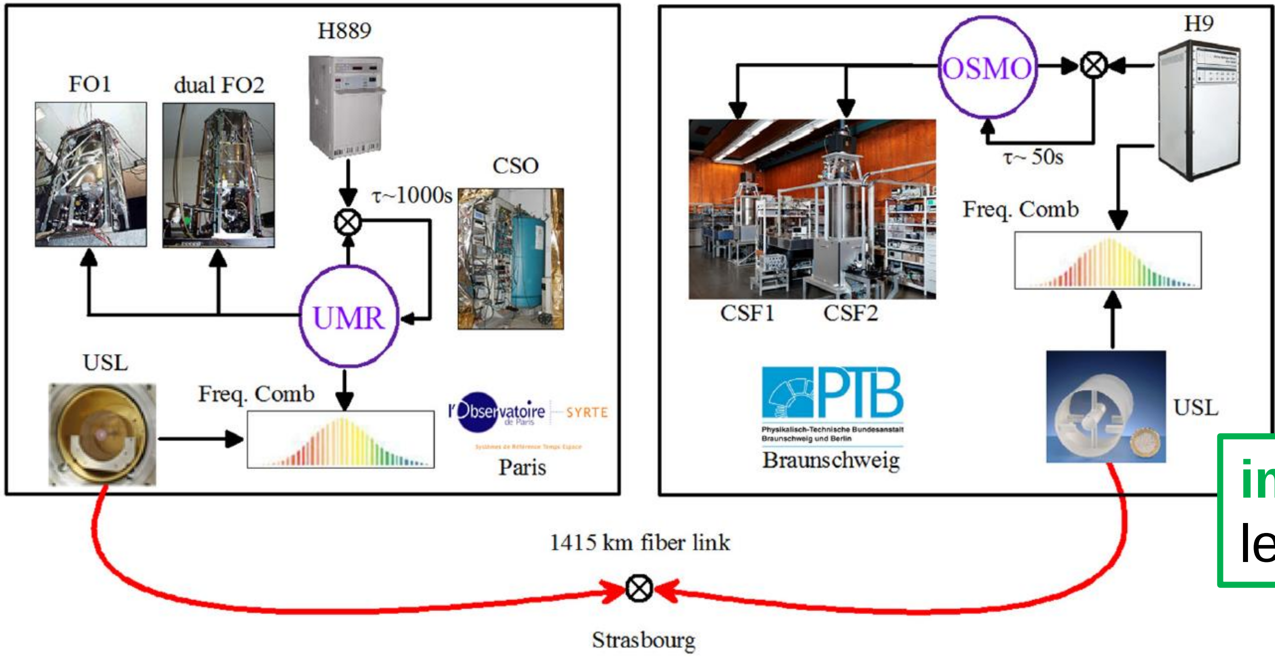
$$|\nu(Sr^{PTB}) - \nu(Sr^{SYRTE})|/\nu(Sr) = (4.5 \pm 5.0) \times 10^{-17}$$

imo: chronometric levelling at $U_{\Delta H}$ ~ 0.5 m

C. Lisdat, G. Grosche, N. Quintin *et al*; Nature Comm. (2016)

Further examples chronometric levelling

First international comparison of fountain primary frequency standards via a long distance optical fiber link

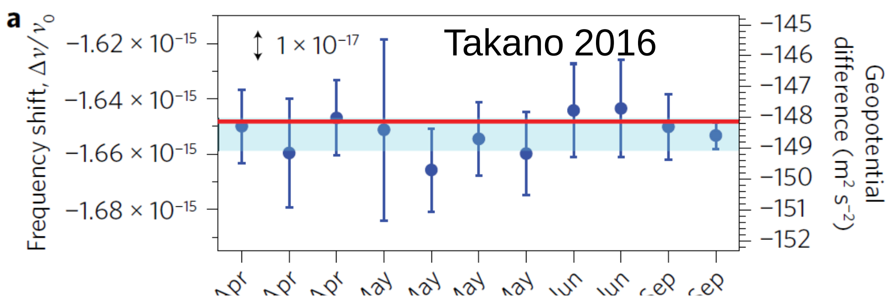


(a) Local Comp.	Diff. [10^{-16}]
CSF2 – CSF1	−2.4
FO1 – FO2-Cs	−1.8
FO1 – FO2-Rb	−2.9
FO2Cs – FO2-Rb	−0.2
(b) Distant Comp.	**Diff.**
CSF1 – FO1	2.7
CSF1 – FO2-Cs	0.6
CSF1 – FO2-Rb	1.2
CSF2 – FO1	−0.1
CSF2 – FO2-Cs	−1.8
CSF2 – FO2-Rb	−1.9

J. Guena, S. Weyers, M Abgrall *et al*; Metrologia (2017)

imo: chronometric levelling at $U_{\Delta H}$ ~ 4 m

- **T. Takano, M. Takamoto, I. Ushijima *et al*; *Geopotential measurement with synchronously linked optical lattice clocks*, Nat. Phot. (2016) $U_{\Delta H}$ ~ 0.05 m**
- **J. Grotti, S. Koller, et al, *Geodesy and metrology with a transportable optical clock*, Nat. Phys. (2018). $U_{\Delta H}$ = ?**
- **Campaign 2017 with transportable clock in Paris.**



Goals to support future experiments

using frequency comparisons via IFL:

- extend range (distance)
- connect locations of geodetic interest (non-NMI)
- connect several locations simultaneously
- enable ***fast*** measurements: ***U*** ~ 5E-18 adequate.

  aim for 1E-18

Disseminate height (differences) to labs with OFS

New connection/ interferometric fibre link PTB-KIT-MPQ (940 km)

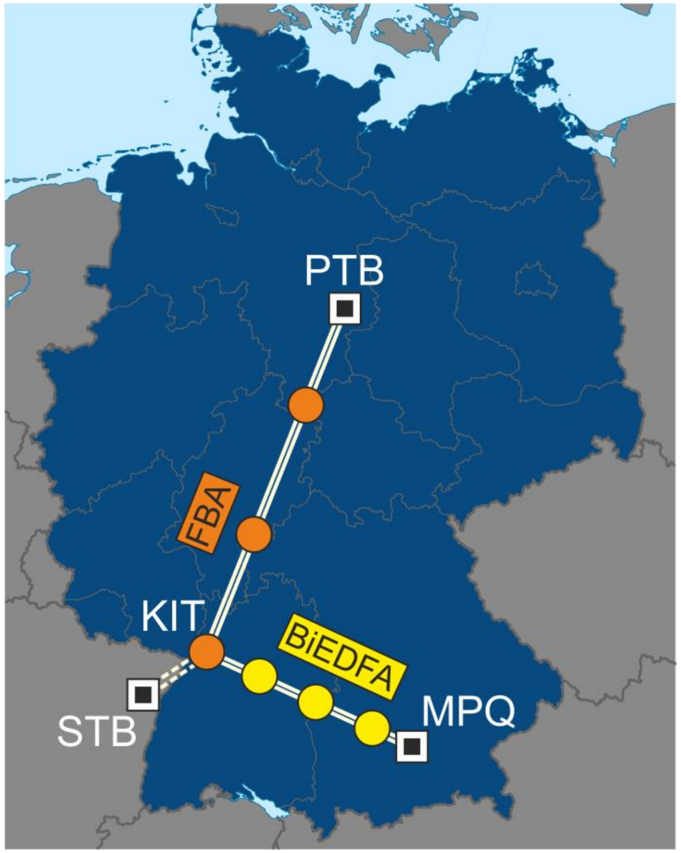
New IFL PTB-KIT-MPQ

- **goal 2018: „equip Karlsruhe node to operate new IFL“**
- **reality:**

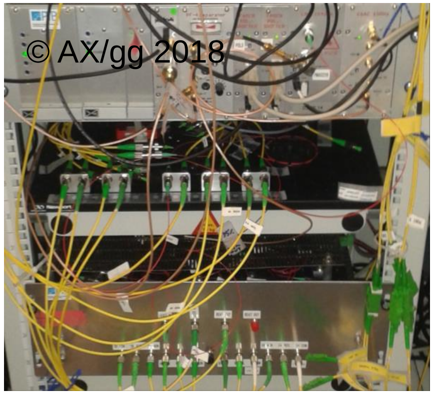
4/2018

U (PTB-KIT-PTB) < 10^{-19}

U (MPQ-KIT-MPQ) >> 10^{-18}

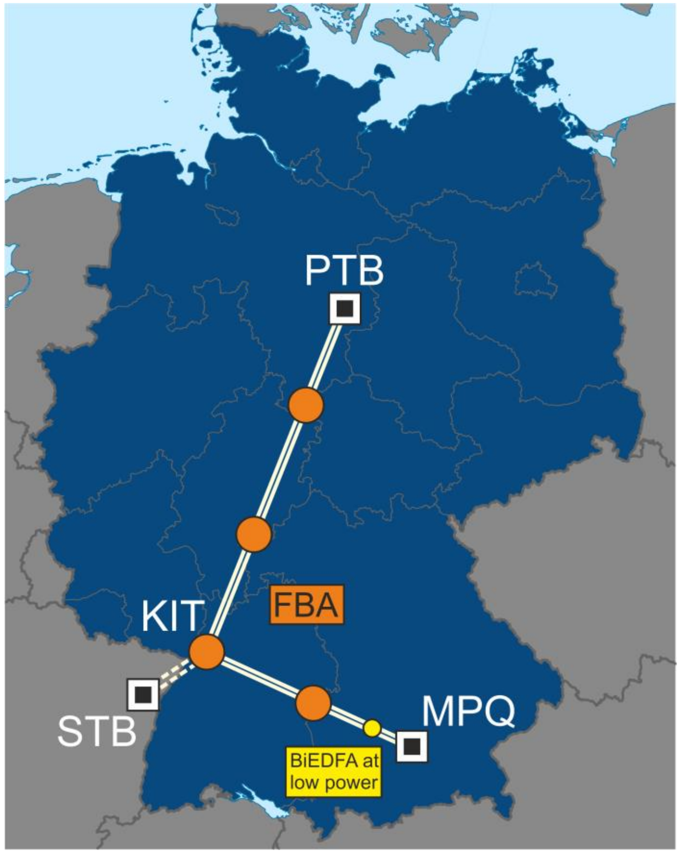


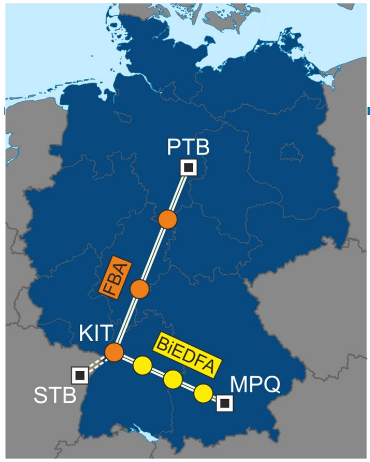
solution (4/2018): adapt and **insert FBA-module** in MPQ-KIT section



now

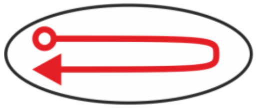
***U* (PTB-MPQ-PTB) < 10^{-19}**





new IFL PTB-KIT-MPQ

Three possible configurations:



Continuous loop PTB-MPQ-PTB via KIT

„Antiparallel“, stabilize PTB->MPQ and MPQ->PTB

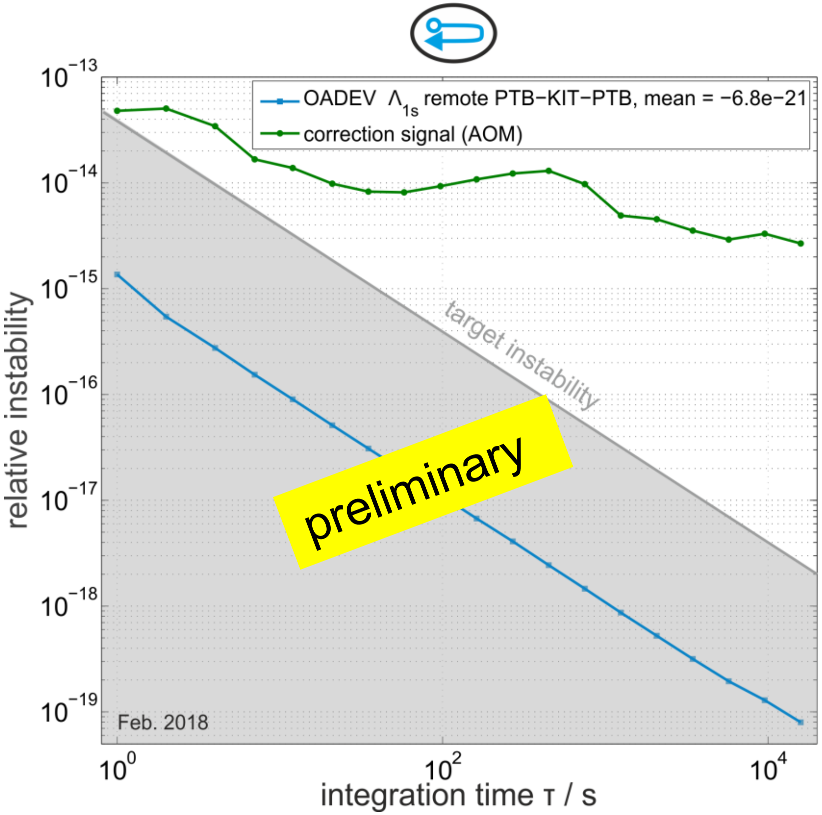
Connect two stabilized loops (extraction at KIT)

Fibre link: two segments, „node“ at KIT

First test separate „loops“

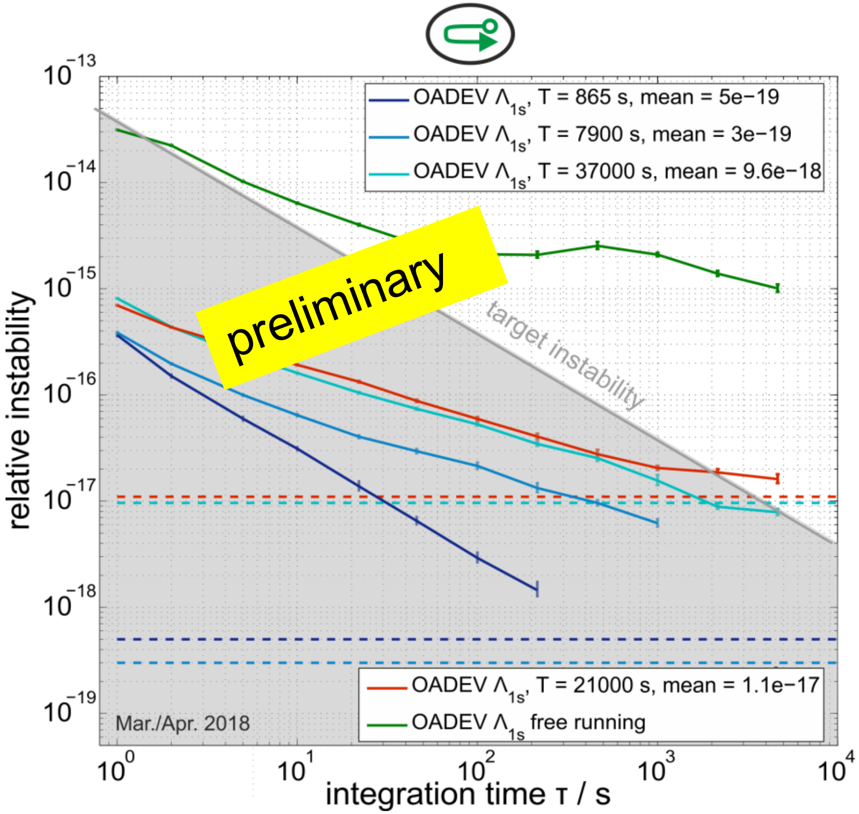
PTB-KIT: 600 km, 3 FBAM;

1200 km PTB-KIT-PTB loop



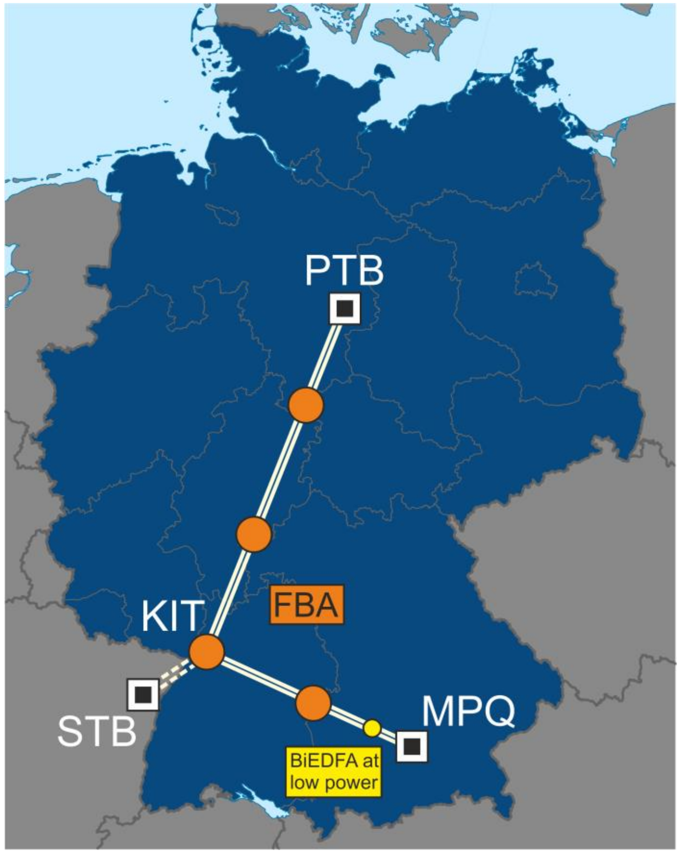
MPQ-KIT: 340 km, 3 bi-EDFA

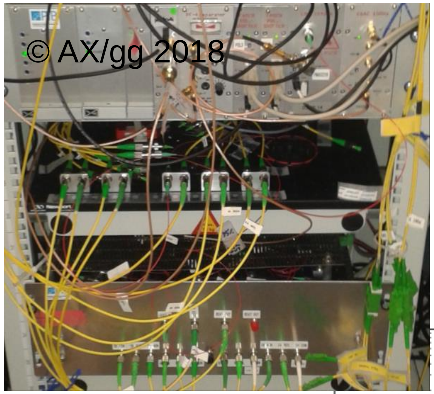
680 km MPQ-KIT-MPQ loop

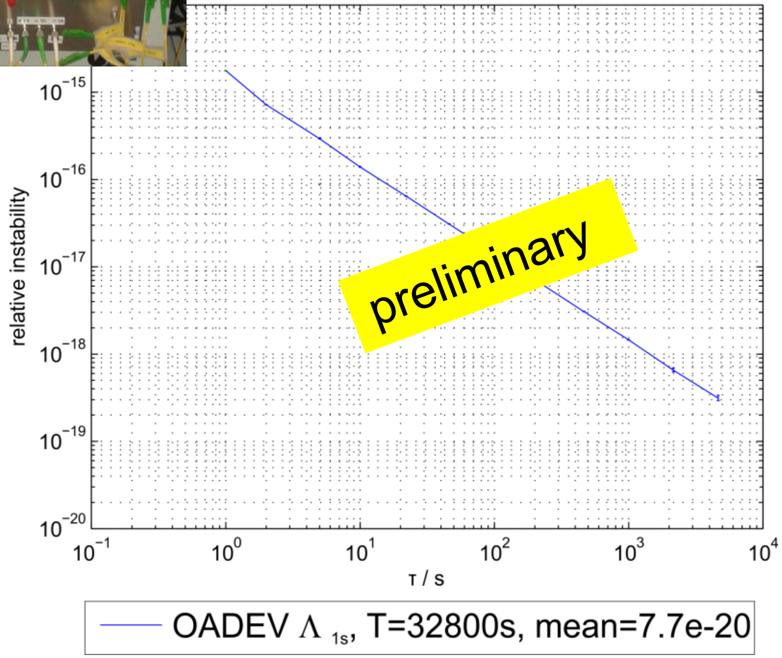


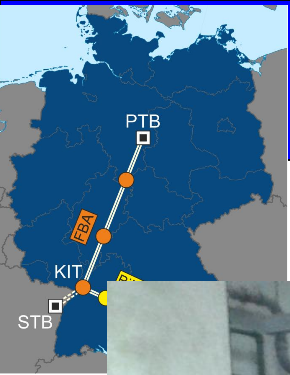
Insert FBA module in Ulm

adapt and insert FBA-module in MPQ-KIT section







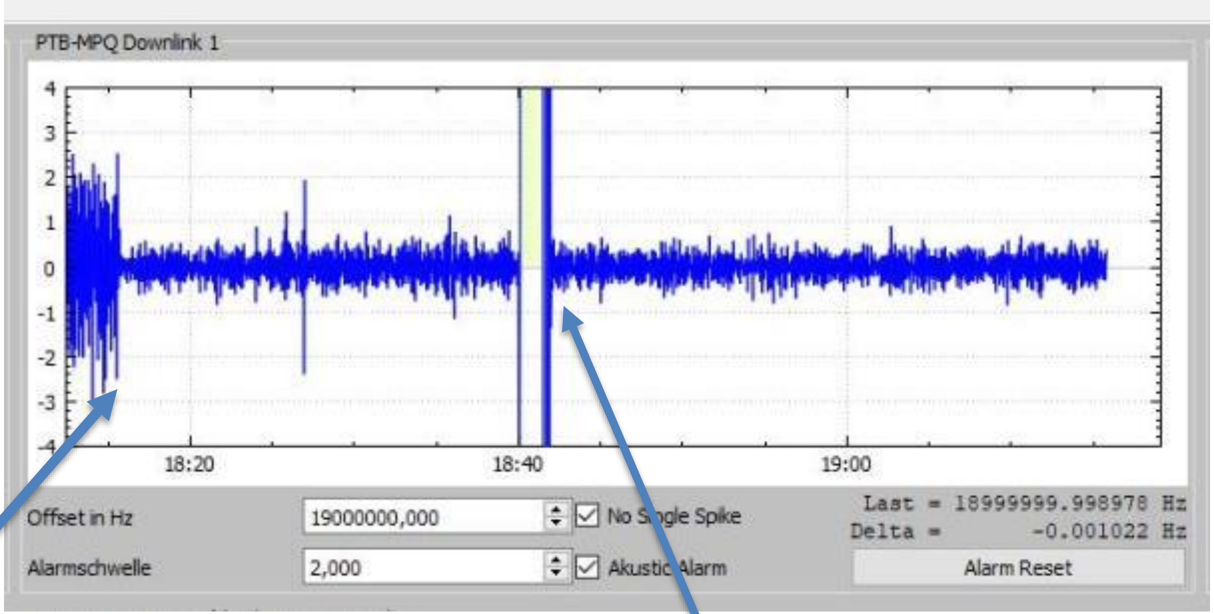


Cope with challenging environments

Kassel – location of FBA

On-line *remote* optimisation: laser at MPQ

Optimise repeater laser lock at MPQ



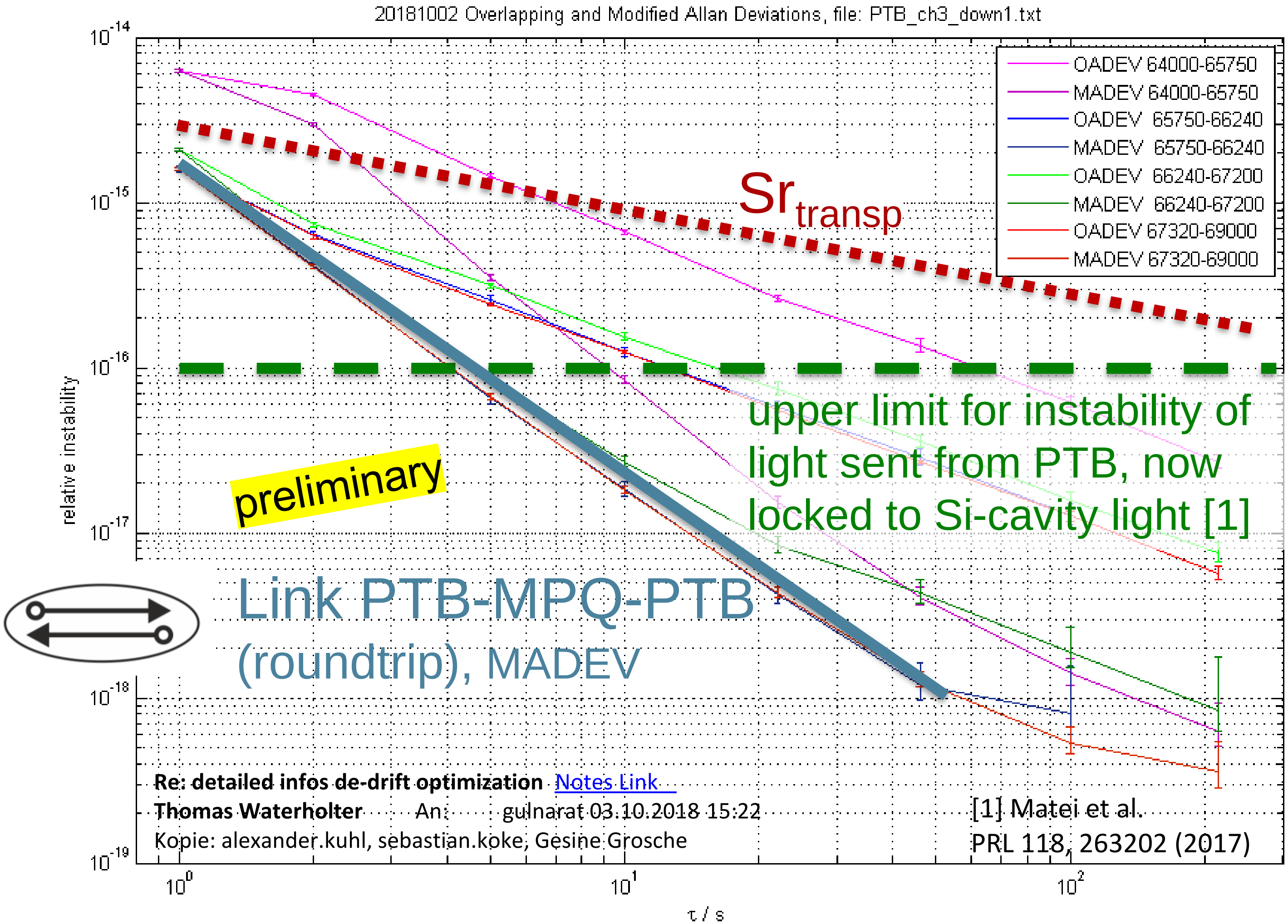
Von: gulnarat@rzg.mpg.de
An: Gesine.Grosche@ptb.de
Kopie: alexander.kuhl@ptb.de, sebastian.koke@ptb.de, thomas.waterholter@ptb.de
Datum: 02.10.2018 21:48
Betreff: Re: dedrift modification ... not so good ...

Dear Gesine!

Yes, at 18:15 I have removed the first capacitor from my low-pass, at 18:24 I have removed the second capacitor (totally were 3 of them). At 18:42 I have switched back to the previous configuration (fron PTB's PFK to our Digital phase detector + Lockbox).
Kind regards, Gulnara

Despite contruction work in Kassel, 40°C in Ulm etc.:

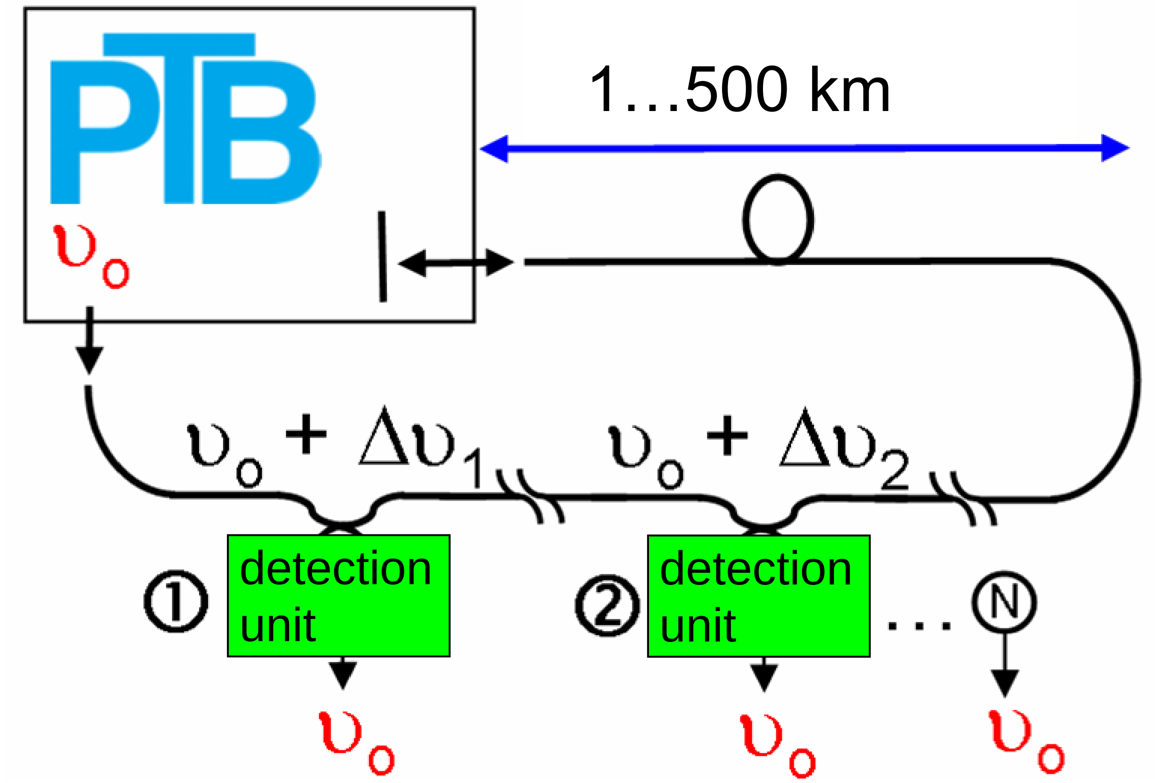
Instabilities of link, of reference frequency and of Sr_{transp}



Remote comparison of Sr_{transp} with Yb^+ and Sr_{stat} @PTB in progress.

What next? Outlook and more questions

Dissemination of frequency references to *many* locations along an optical telecommunication fiber

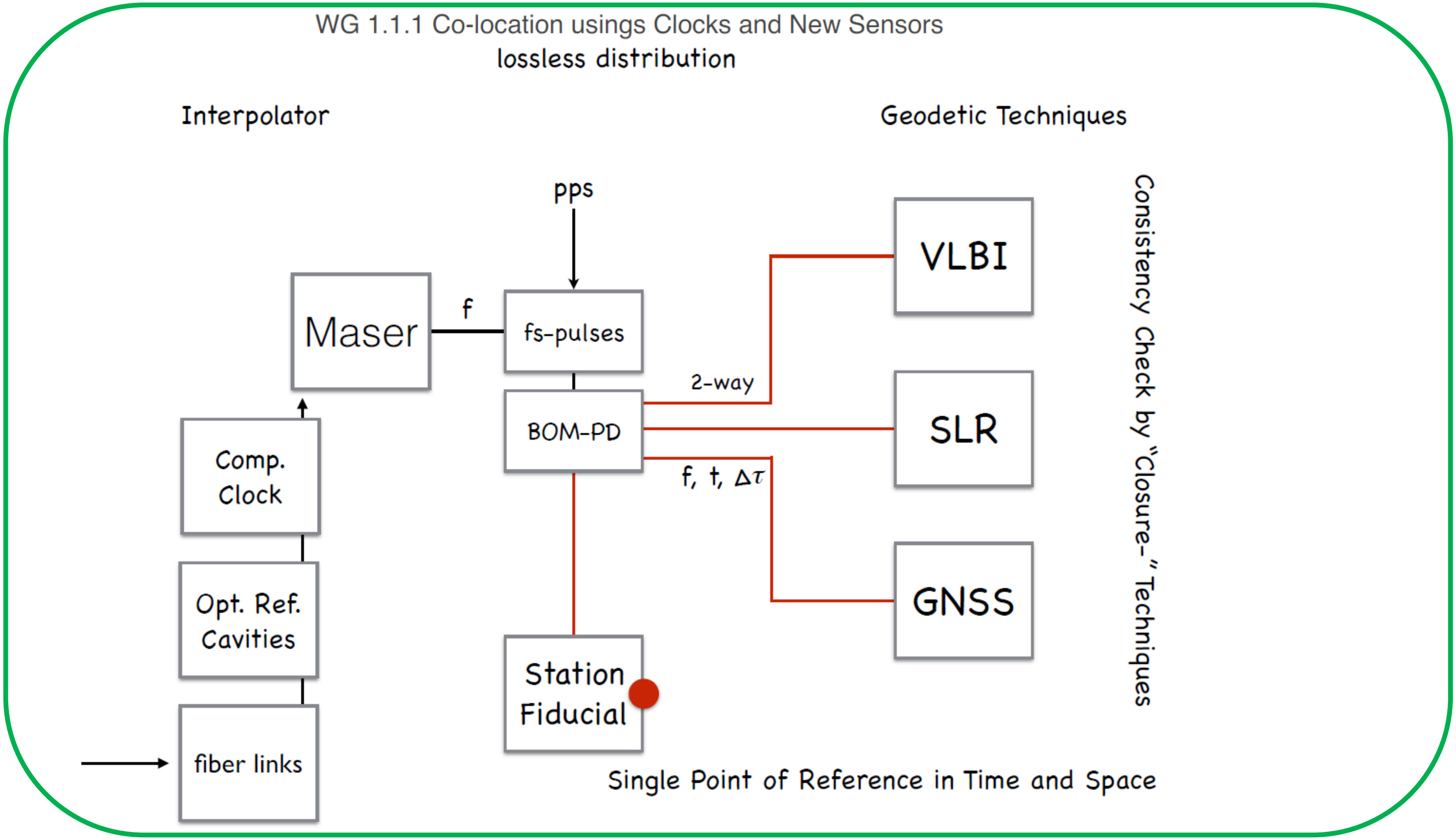


Patent PTB/G. Grosche DPMA 10 2008 062 139 (2008 applic.), granted (2013)
more: G. Grosche „*Eavesdropping time and frequency*...“, Opt. Lett. **39** (2014)

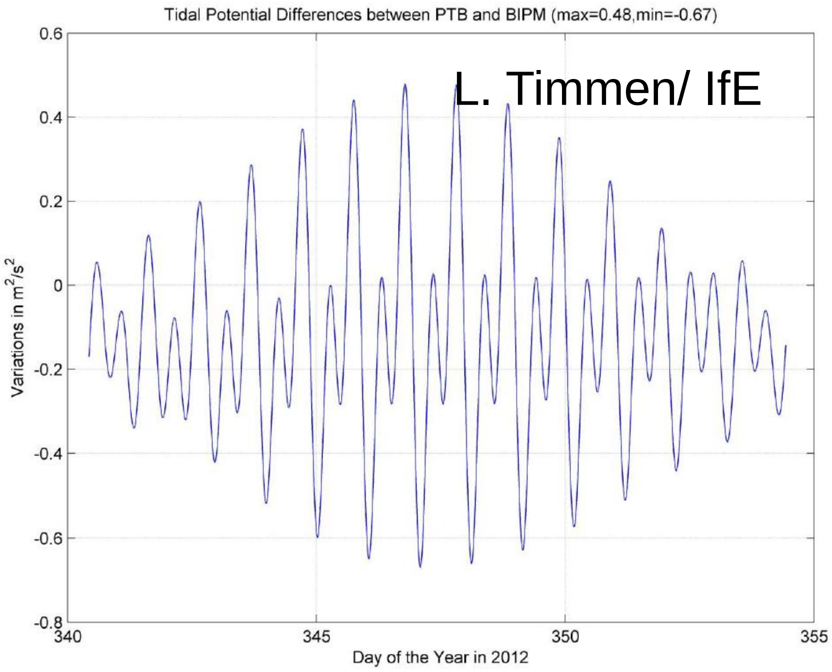
Coordination of space geodetic techniques

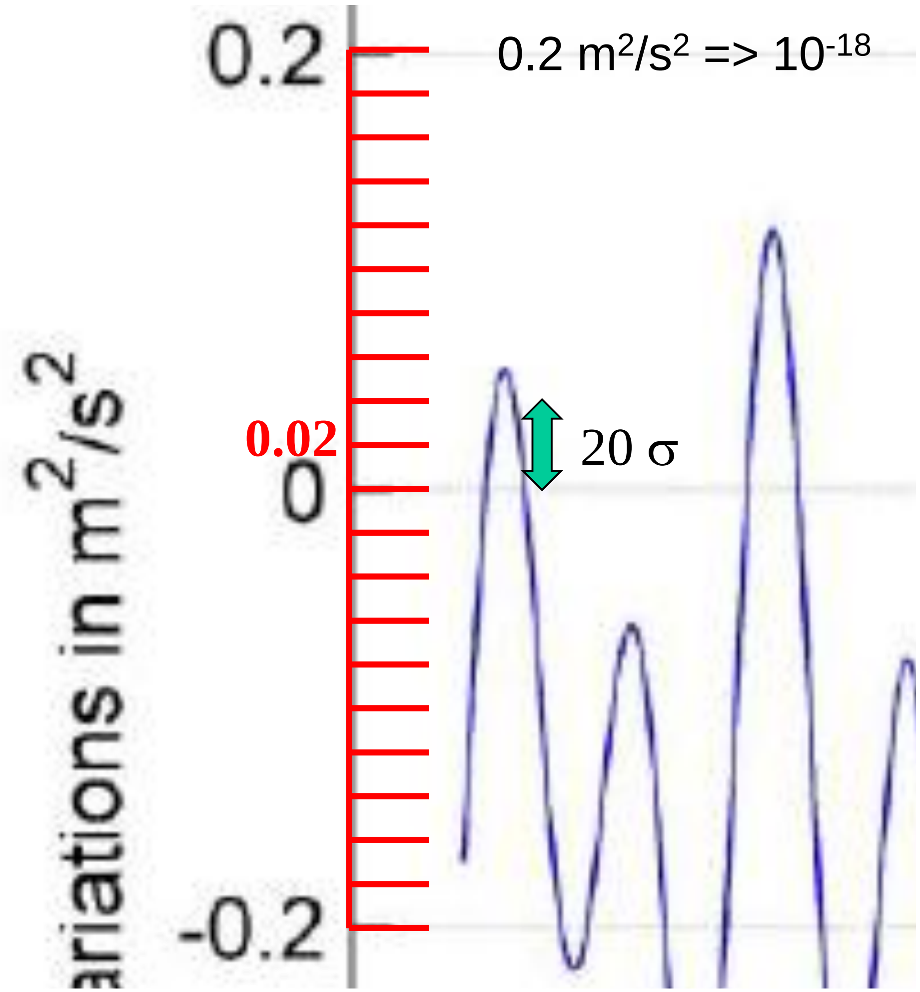
U. Schreiber, Wettzell

IAG: Sub-commission 1.1. Coordination of Space geodetic techniques:



Tidal potential (differences)





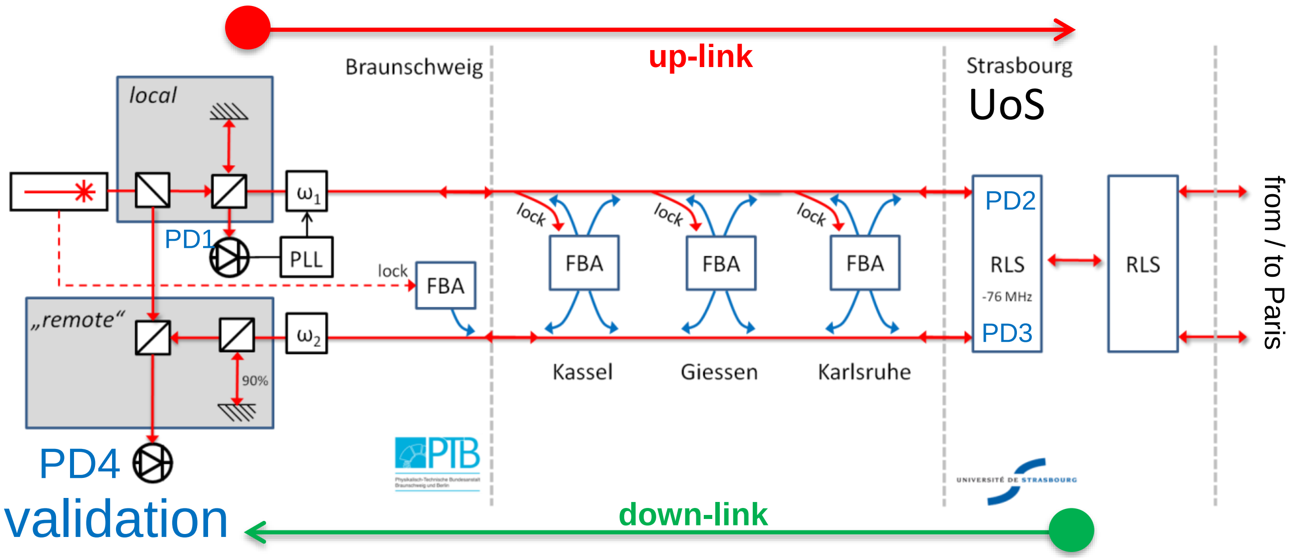
What is informative for „geodesy“ ?

- GNSS frequency link characterisation.
- Anything directly observable (using U_{transfer} ~2E-20)??
- Fibre-loop Sagnac ?? (derivative of earth rotation)
- Fibre links as giant (integrating) sensor ?
- Mobile clocks ?
- Free-space links, connections with IFL-networks ?

Merci !

Setup of PTB–UoS link: 700 km ×2

Cascaded phase-stabilized fibre link:



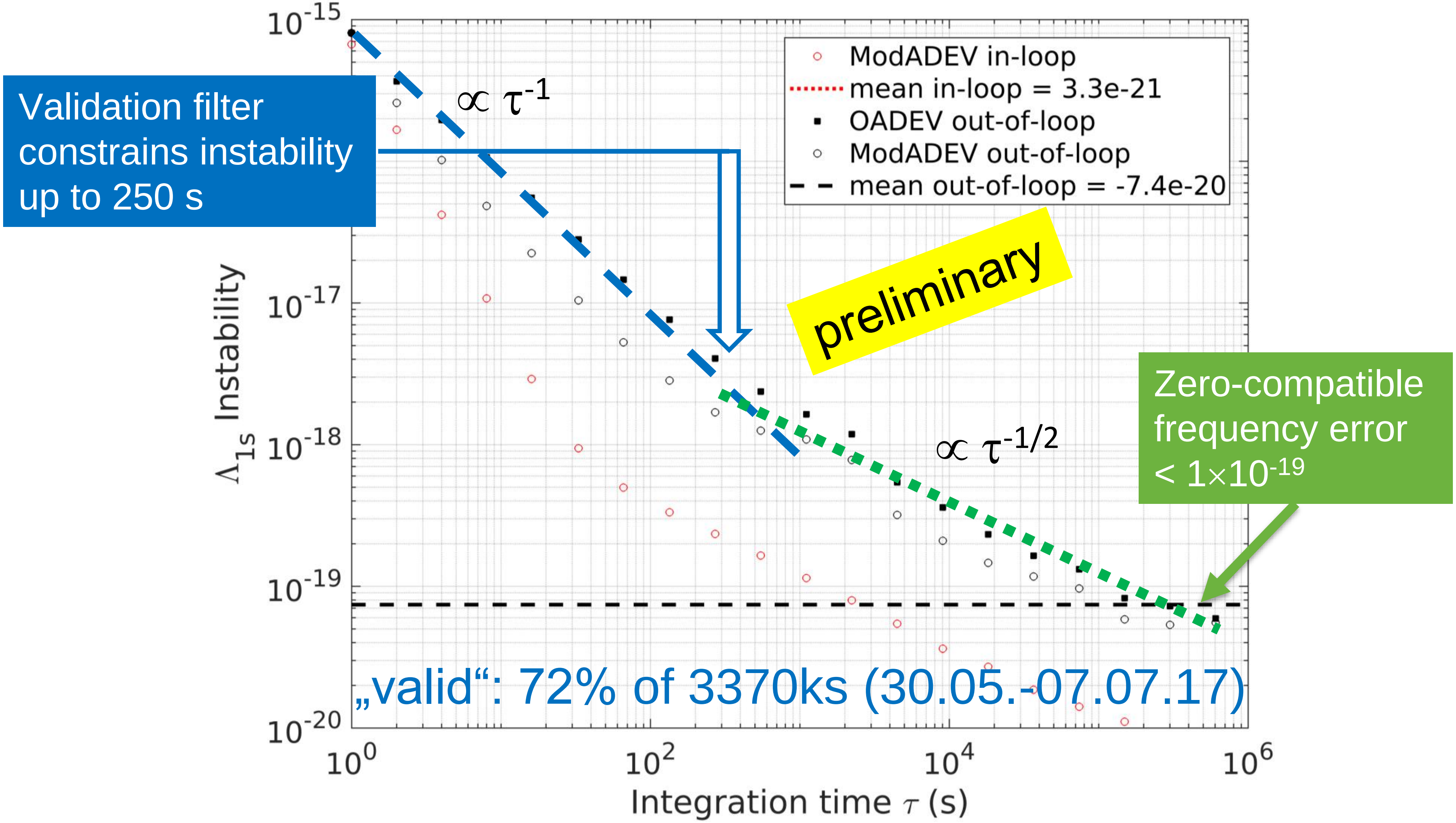
- 3 in-field FBA-modules: narrowband, amplitude stable, direction sensitive
- terminated by RLS: signal extraction @ UoS for remote clock comparisons
- out-of-loop validation: uplink **plus** downlink (each stabilised individually) on PD4
  → frequency offset PD4 gives upper limit for the frequency offset @ UoS
- el. tracking + dead-time-free Λ_{1s}-counting

[based on S Koke et al.: EFTF 2018, A1L-B 7135]

Validated data – PTB–UoS link: 700 km ×2

1. integrity check & 2. validation (1000 samples of 1s): „$u_{link} < u_{clocks}$"

| Mean FF(1000s) | $\leq 5\times10^{-18}$ & OADEV(τ=250s) $\leq 6\times10^{-18}$

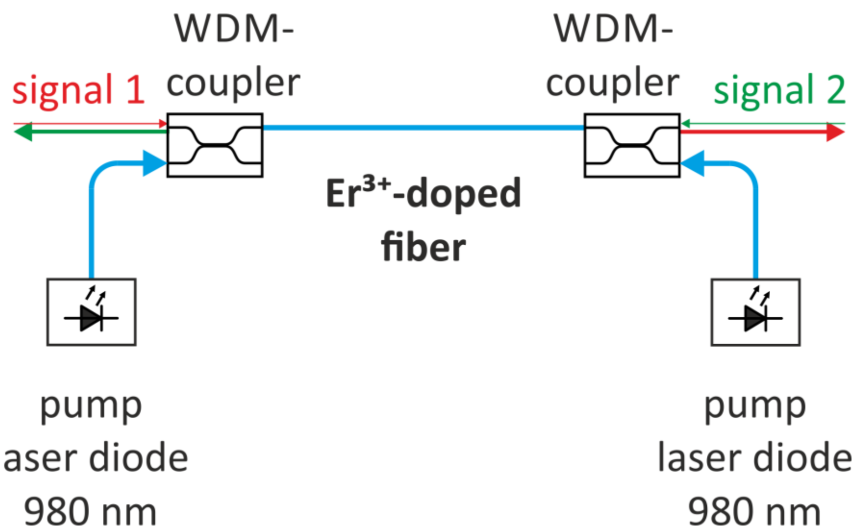


[based on S Koke et al.: EFTF 2018, A1L-B 7135]

Verstärkertechnik im Vergleich biEDFA / FBA

bidirectional EDFA

- broadband amplifier
- max. gain: 15-20 dB
- bidirectional

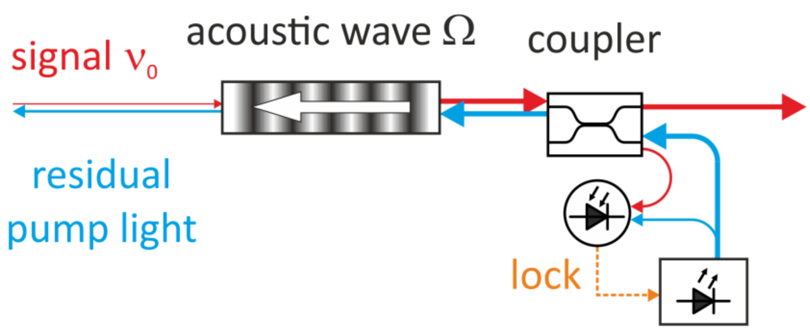


⇒ sensitive to reflections /
Rayleigh scattering

⇒ „glitches“ / signal loss

fibre Brillouin amplifier

- narrow bandwidth (~10 MHz)
- max. gain: > 45 dB
- direction sensitive, pump counterprop. signal



scattering of pump photons at acoustic phonons,
$\Omega = \nu_{Pump} - \nu_0 = 11$ GHz

pump
laser diode
$\nu_0 + 11$ GHz

⇒ ***insensitive*** to reflections /
Rayleigh scattering

Fibre Brillouin modules development

S. Raupach (A. Koczwara) joined fibre activity in 12/2010

by 2/2011: PTB-MPQ link factor 10 lower uncertainty

Each module amplifies four signals

- Offset Lock @ 11 GHz
- Pump stabilization
- Remote control of polarization
- Autonomous operation

stable amplitude;
gain > 40 dB, depends on frequency and pump direction

⇒ allows us to reduce susceptibility to Rayleigh back scatter (c.f. EDFA).

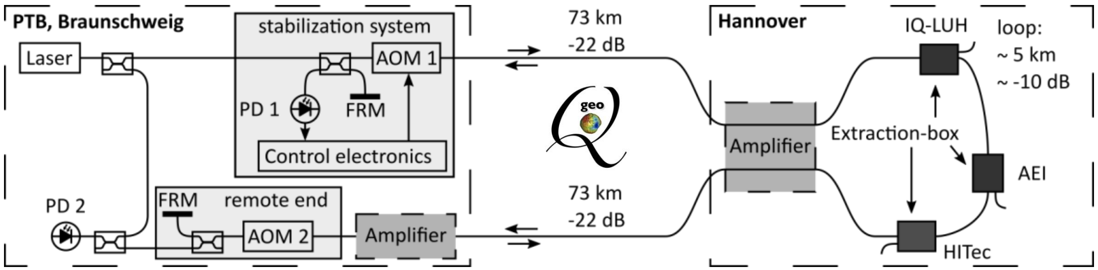
⇒ high gain even in bi-directional configuration.

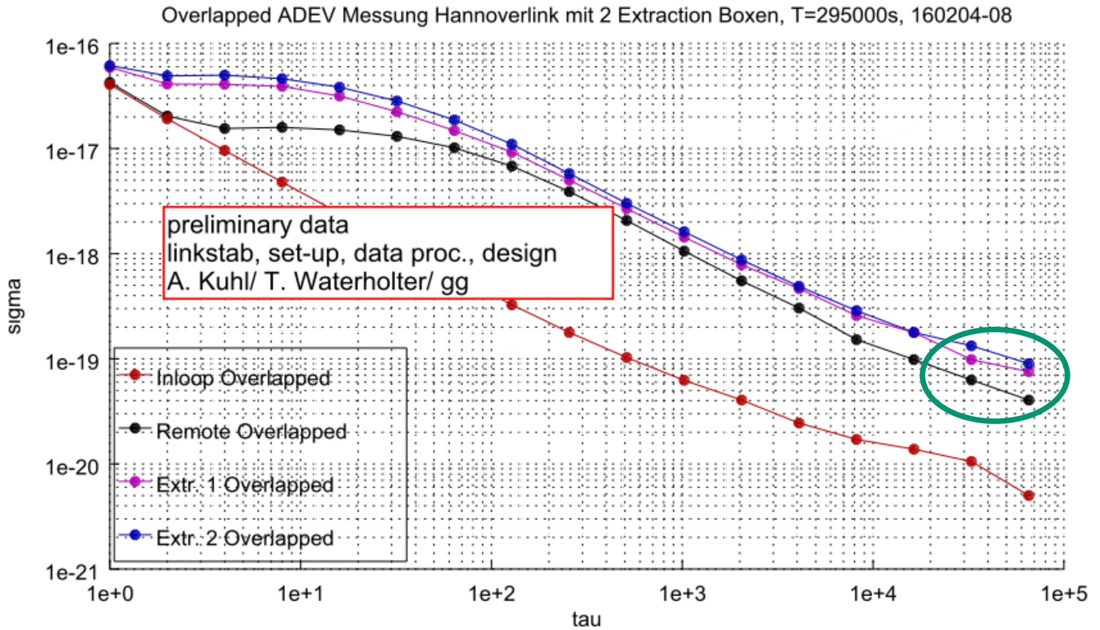
More details (FBA) see:

S.M.F. Raupach, A. Koczwara and G. Grosche: „Optical frequency transfer via a 660 km underground fiber link using a remote Brillouin amplifier“ Opt.Exp **22**, 26537-26547 (2014)

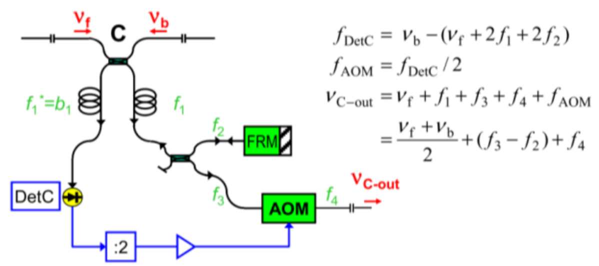
Developing regional network PTB/ Uni-Hannover (IQ, AEI, HiTec)

Simultaneous dissemination to **several** locations





G. Grosche, Opt. Lett. **39**, 2545 (2014)



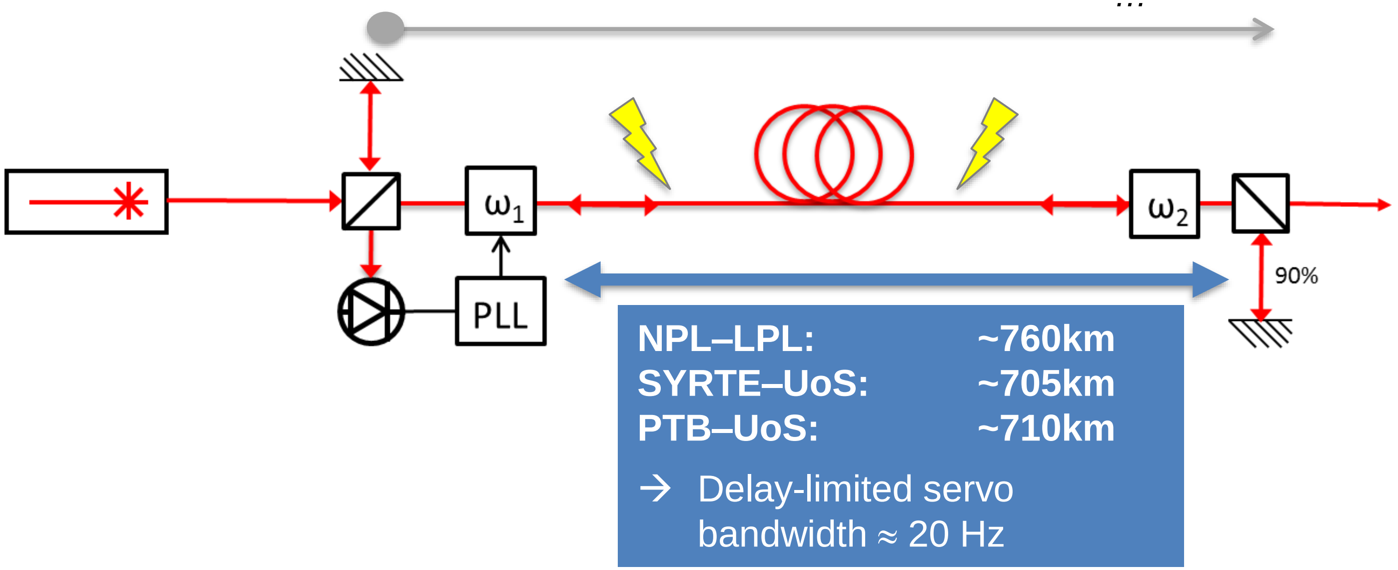
→ for 24/7 operation

→ measure OFS Mg (IQ)

Compensation of fibre noise

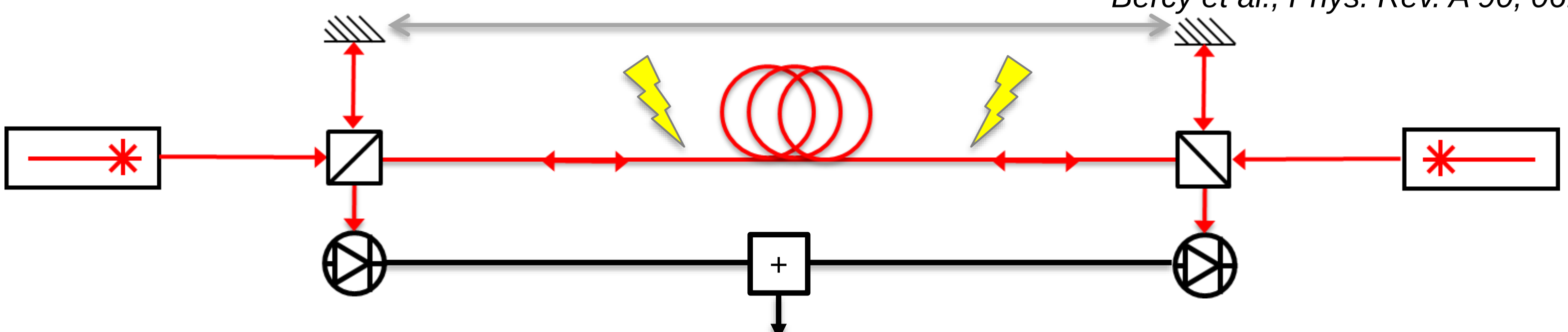
Active phase stabilization:

Foreman et al. Rev. Sci Inst. 78, 021101 (2007)
Williams et al., JOSA B 25, 1284 (2008)
…



Two-way link: (like TW-satellite)

fibre-based e.g.
Calosso et al., Opt. Lett. 39, 1177-1180 (2014)
Bercy et al., Phys. Rev. A 90, 061802(R) (2014)



fibre phase noise cancelled up to delay limit

[based on S Koke et al.:]

Amplification: > 20 dB attenuation/ 100 km

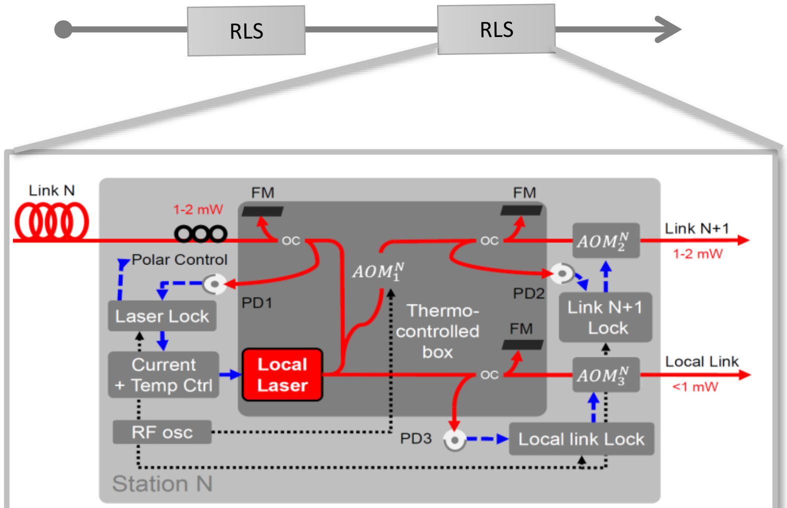
Repeater Laser Station (RLS):

intermediate phase-lock of narrowband laser to weak metrological signal

Foreman et al., Phys. Rev. Lett. 99, 153601 (2007)

→ link = cascade of stablized subsections

→ **enhanced fibre phase noise rejection + signal refreshing**



Chiodo, et al., Opt. Expr. 23, 33927 (2015)

Main amplification techniques used:

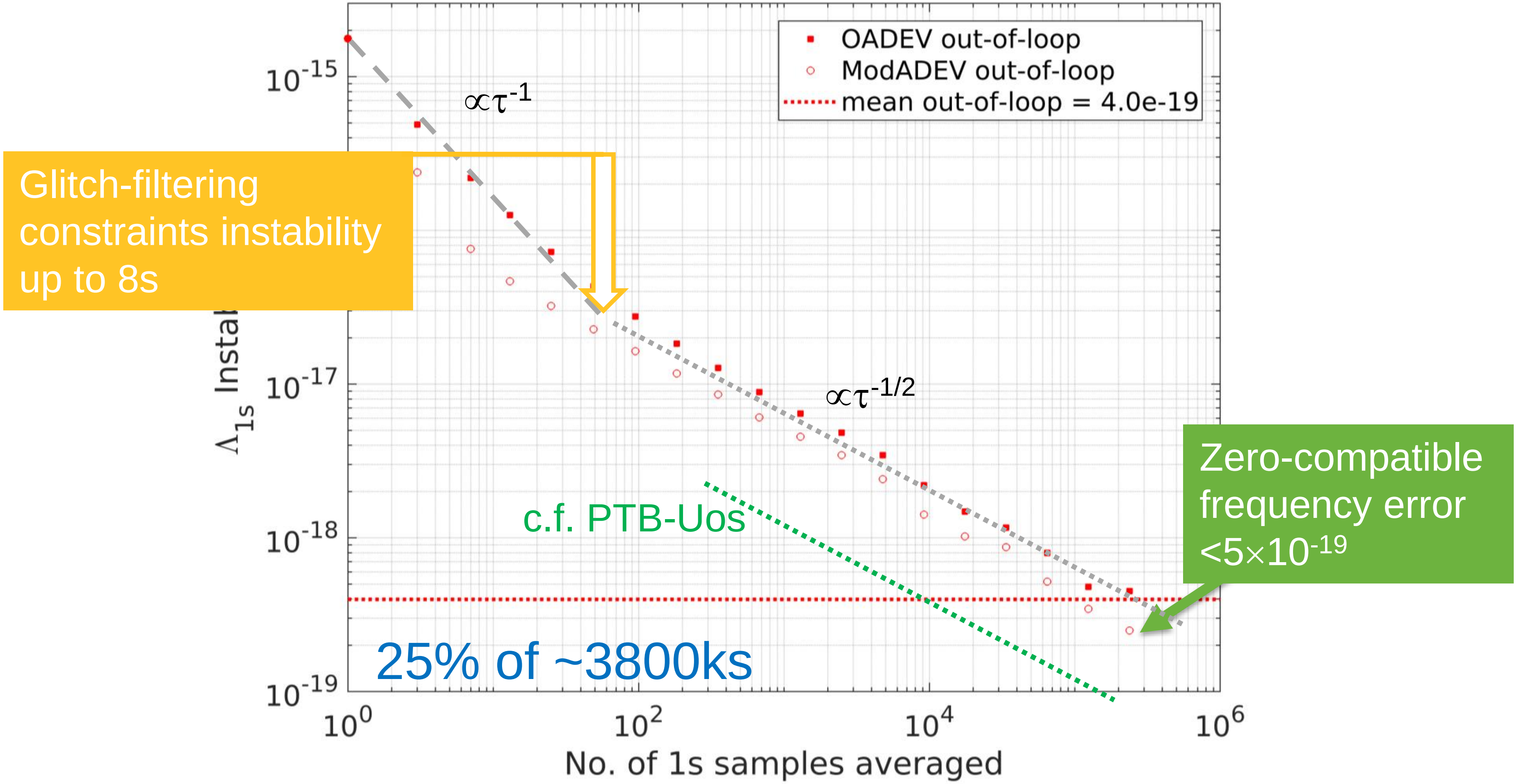
– bidirectional Erbium-doped fibre amplifier (bi-EDFA)

– fibre Brillouin amplifier (FBA)

[based on S Koke et al.: EFTF 2018, A1L-B 7135]

Roundtrip Instability

Concatenated glitch-filtered data set 760 km ×2 NPL-LPL



→ Scaling of instability continues far beyond the filtering-set constraints

→ Frequency dissemination over ALFA has no systematic bias

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