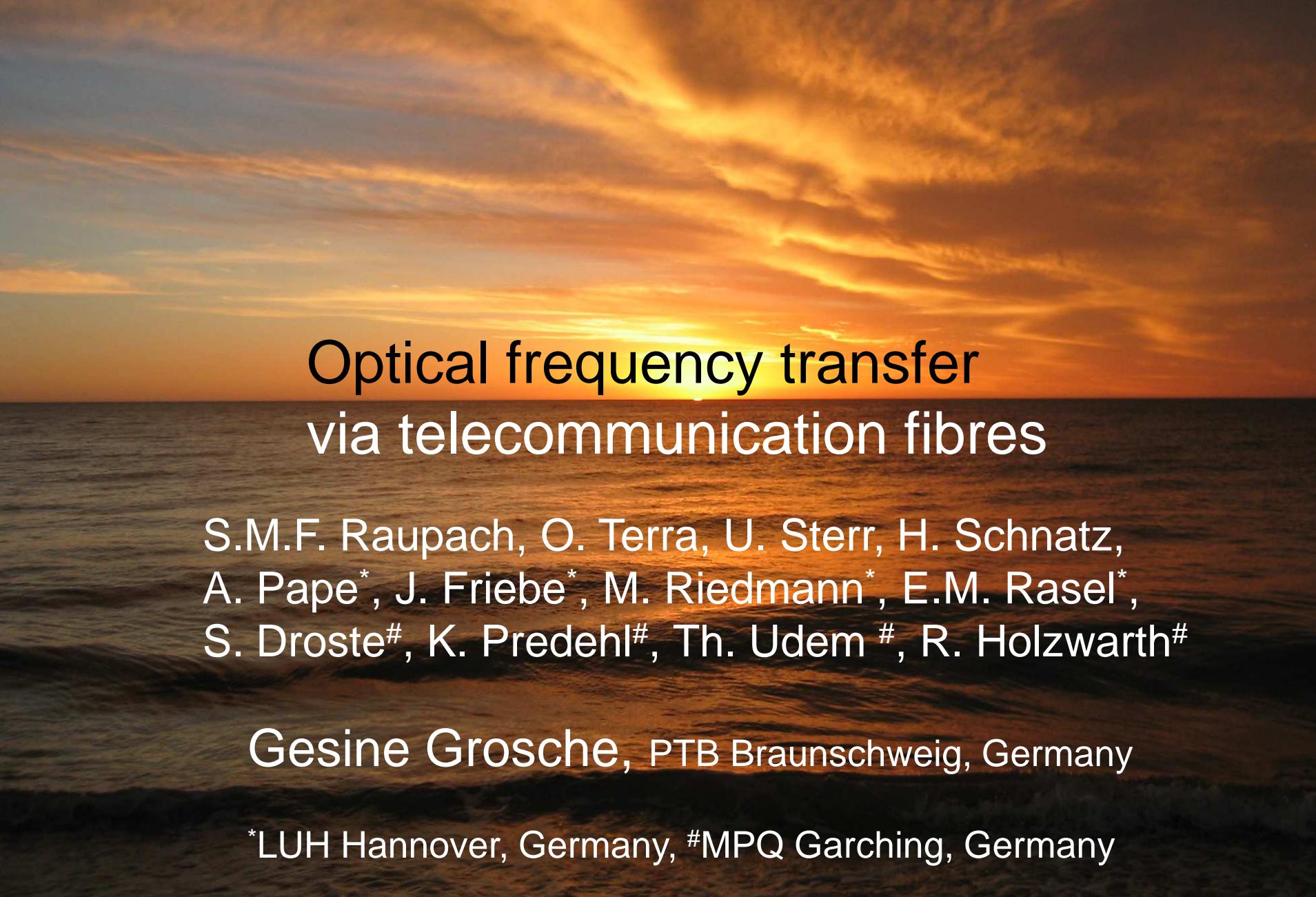


20.11.2012, „Optical Networks for Accurate Time and Frequency Transfer“
International workshop, EMRP-project NEAT-FT. Hoofddorp, The Netherland



Optical frequency transfer via telecommunication fibres

S.M.F. Raupach, O. Terra, U. Sterr, H. Schnatz,
A. Pape*, J. Friebe*, M. Riedmann*, E.M. Rasel*,
S. Droste#, K. Predehl#, Th. Udem #, R. Holzwarth#

Gesine Grosche, PTB Braunschweig, Germany

*LUH Hannover, Germany, #MPQ Garching, Germany

Applications of frequency dissemination

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

- a) dissemination of the unit of length / remote calibration:

$$\delta\lambda/\lambda = \delta\nu/\nu \approx 10^{-6} \dots 10^{-10}$$

- b) compare optical frequency standards (over long distances)

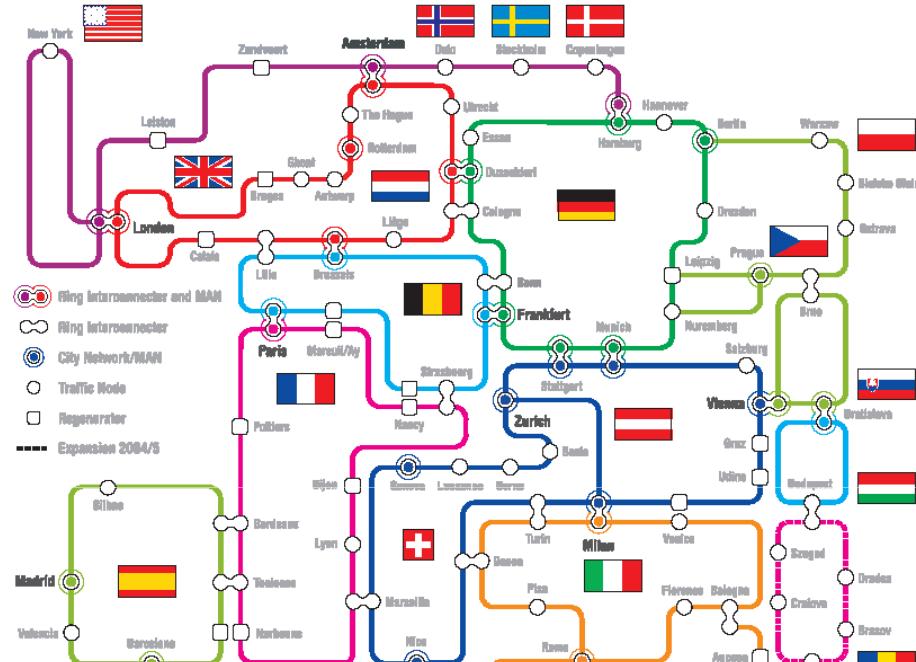
fundamental constants (m_p/m_e , α)
 $\delta\nu/\nu \approx 10^{-13} \dots 10^{-18}$

- 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 & synchronization – telescopes, accelerators, geodesy, LIGO; frequency as a „probe“- GR, SR
 $\delta\nu/\nu \approx 10^{-12} \dots 10^{-20} \dots ?$

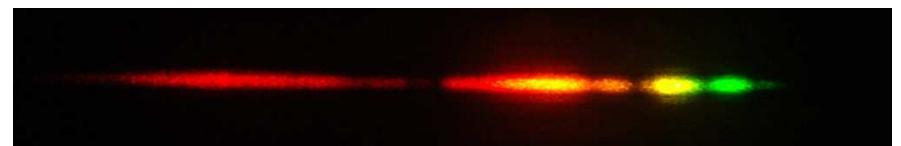
Basics

Optical fibre networks: advantages



- existing infrastructure:
fibre networks across Europe,
optically transparent; amplifiers
- low attenuation: **25 dB/ 100 km**
for radiation **at 1,55 µm** (200 THz)
- protected, low noise:
buried, underground fibre
broadcasting - DCF77

- many active and passive components
optical telecommunications
- femtosecond modelocked lasers:
frequency combs at 1,55 µm



Challenge 1: delay variations, „phase noise“

Problem: thermal variation and mechanical perturbations
change path length: refractive index n changes

Fiber type	λ (nm)	Temperature coefficient (ps (K km) $^{-1}$)
SMF-28	1550	36.80
	1310	37.97
SMF-DS	1550	38.67
LEAF	1550	37.97

$$dn/dT \sim 10^{-5}/K$$

$U(\tau) \sim 4$ ns for
 $L=100$ km
and $\Delta T = 1$ K
($\tau = 500\mu s$)

$$\begin{aligned}\Delta v(t) &= \frac{1}{2\pi} \frac{d}{dt} \Delta \phi_{fibre}(t) \\ &= \frac{d}{dt} \left(\frac{nL}{\lambda} \right) \approx \frac{L}{\lambda} \frac{dn}{dt}\end{aligned}$$

Solution: bi-directional links to detect and correct noise

- mirror at remote end
- “repeater”, slave laser locked to incoming signal
- two-way approach: simultaneous transmission in both directions

Asymmetry ?!

Challenge 2: signal to noise ratio

Problem

- attenuation 25 dB/ 100 km 400 km → 100 dB
- reflections at splices/ connectors
- scattering (Brillouin, Rayleigh)

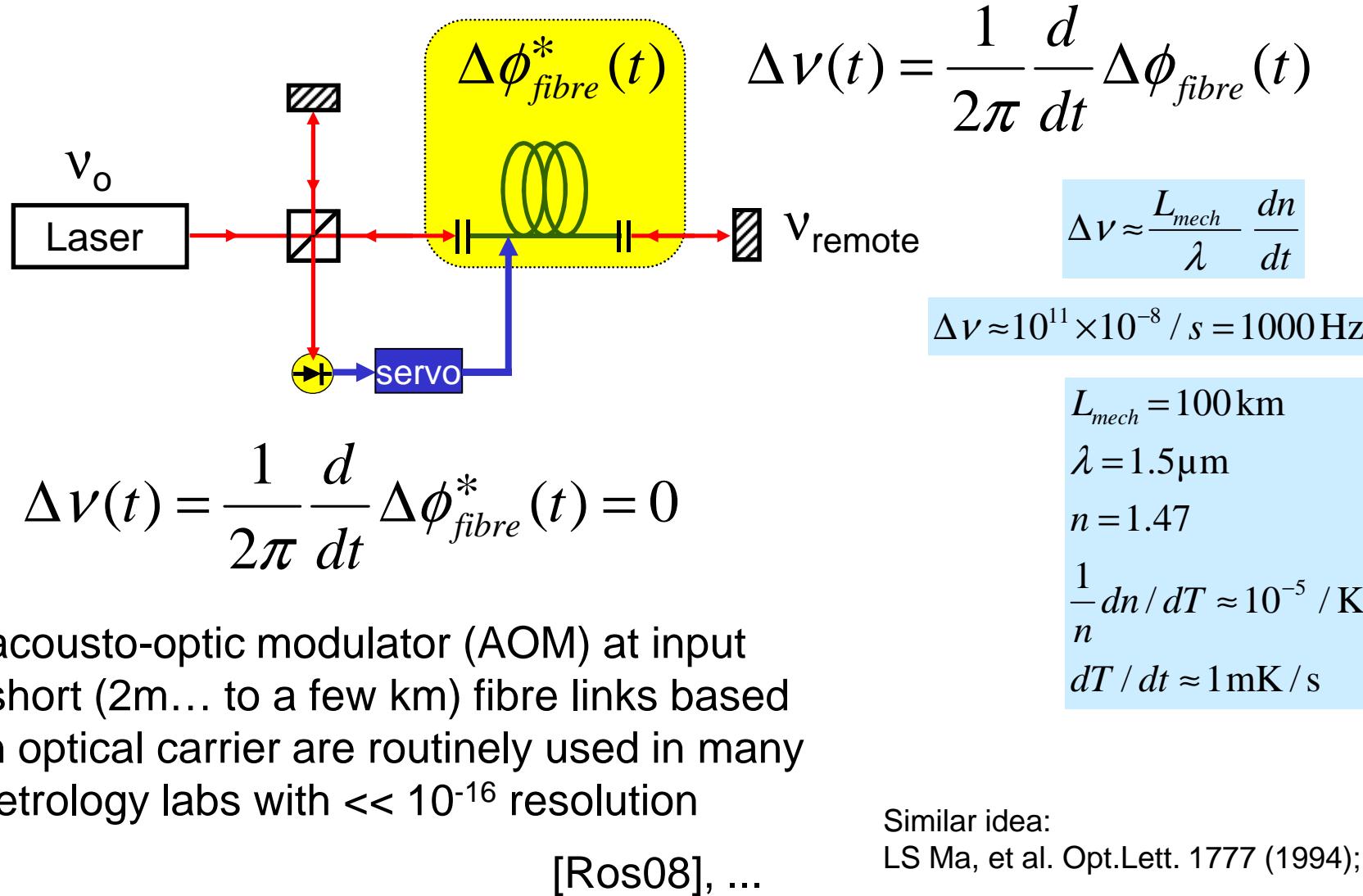
$$\sigma_y(\tau) = \frac{\sqrt{3 S_\phi \Delta f}}{2\pi\nu_0 \tau}$$


Solutions

- amplify – Erbium doped fibre amplifiers, Fibre Brillouin amplification, ...
- regenerate – “repeater”, slave laser locked to incoming signal
- filter – optical filters, heterodyne detection, phase-locked-loops ...

Amplified noise ?!

Compensation of phase fluctuations



2. Noise suppression Experimental implementation

$$\nu_{\text{remote}} = \nu_0 + f_{\text{synth}} / 2$$

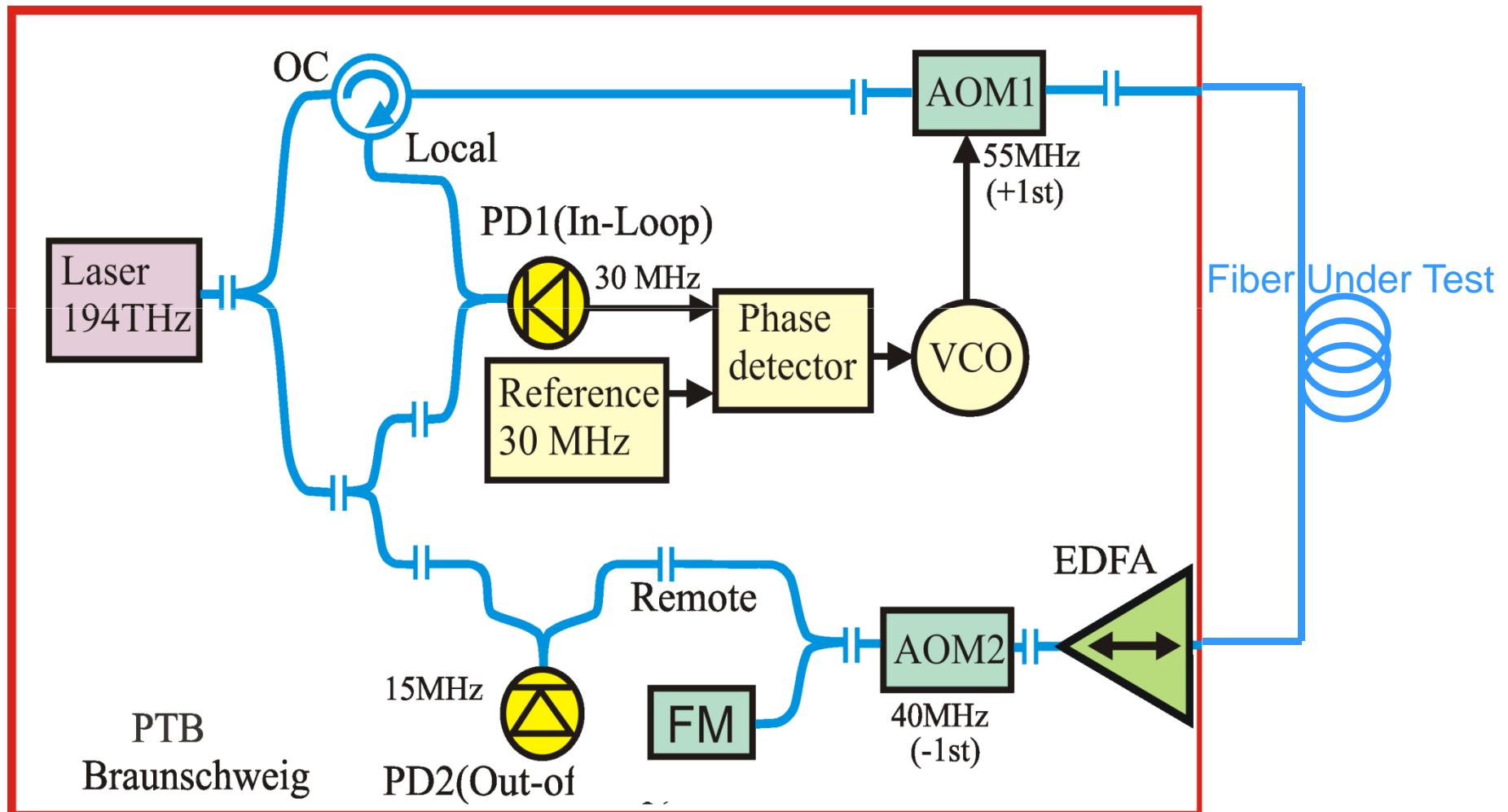
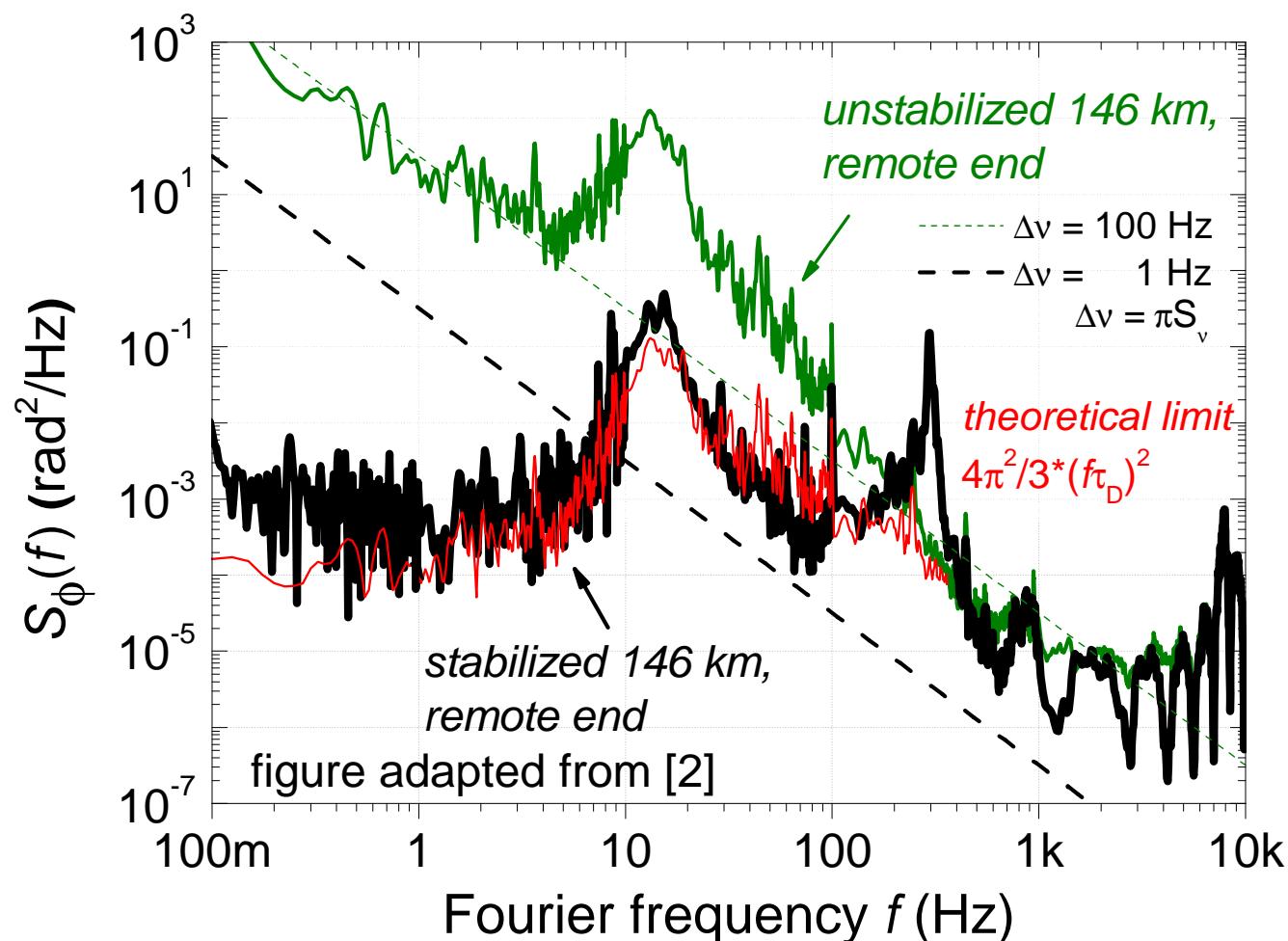


figure adapted O. Terra, G. Grosche, K. Predehl et al. Appl. Phys B 97, 541 (2009)

146 km link: „delay limit“ of fibre noise suppression



$$S_{remote}(f) = 4\pi^2/3 \cdot (f\tau_D)^2 \cdot S_{fiber}(f) \quad [1]$$

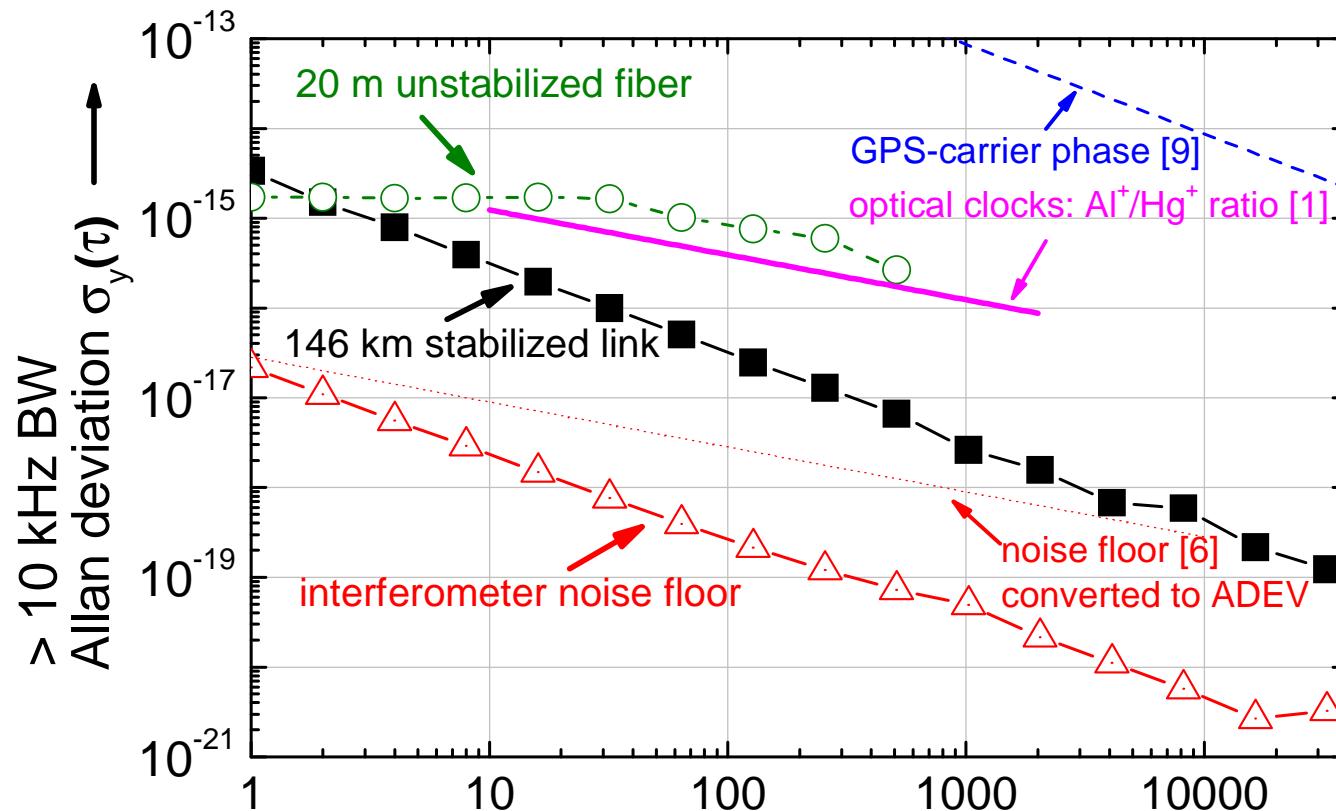
good PASSIVE stability of fibre is important !

[1] P.A. Williams *et al.* JOSAmB **25** 1284 (2008)

[2] G. Grosche, O. Terra, K. Predehl *et al.* Opt. Lett. (2009)

First section of German fibre network

PTB → Uni Hanover → PTB, 146 km stabilized



$$\sigma_y = 3 \times 10^{-15} / \tau s^{-1}$$

integration time τ (s) →

equiv.timing jitter ~ 3 fs

rel. uncertainty: < 10^{-19}

=> Application: 73 km link to IQ labs

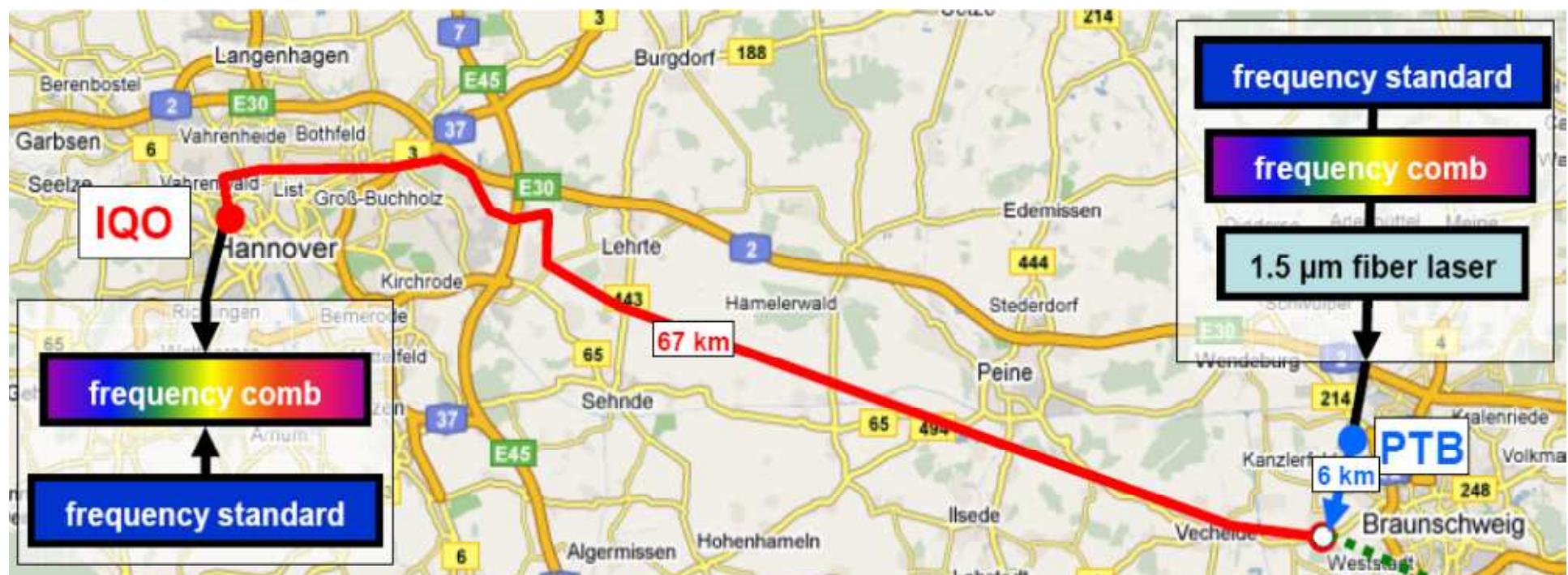
$\sigma_y \sim L^{3/2}$ L = fiber length

=> estimate $\sigma_y = 5 \times 10^{-14} / \tau s^{-1}$ for 900 km



Applications

3. Remote measurements - via Braunschweig-Hanover fibre link



- Mg optical frequency standard measurement
 - long term accuracy
- Mg clock laser improvement
 - short term instability
- Hydrogen maser „calibration“; reference for GNSS

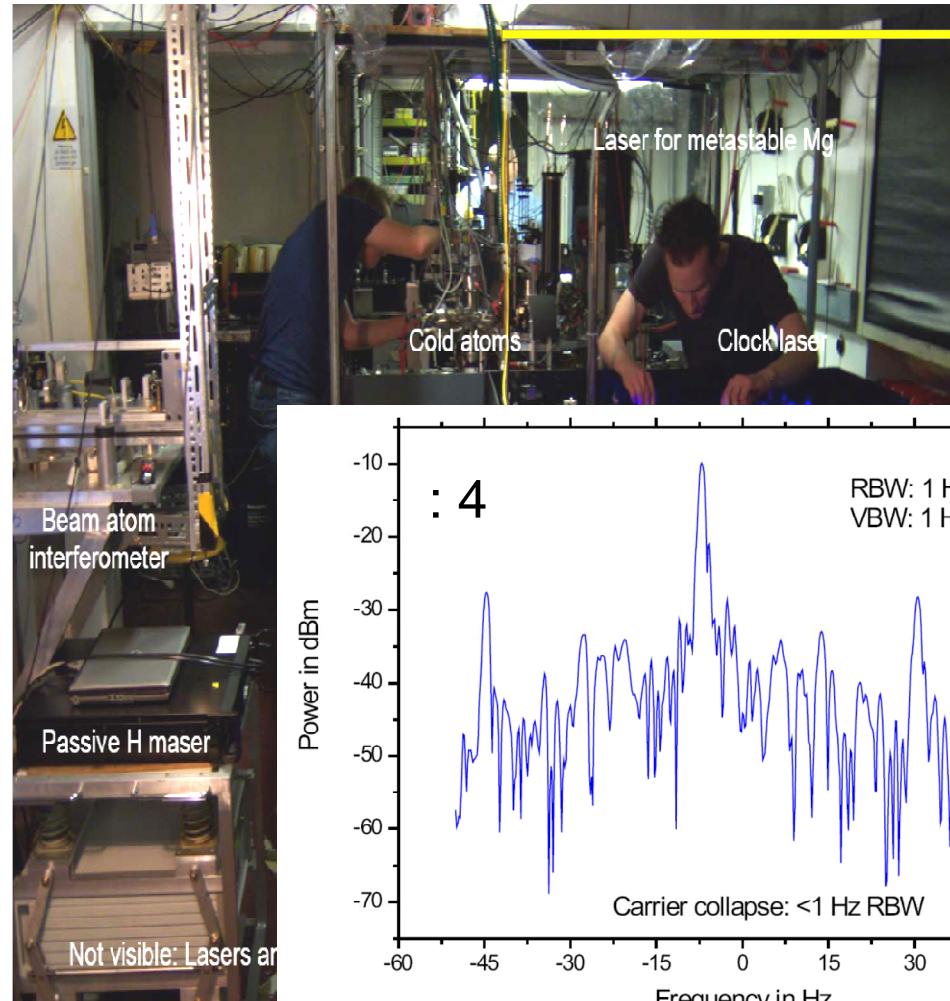
„Remote frequency measurement of the $^1S_0 \rightarrow ^3P_1$ transition in ...“
Jan Friebe, ...GG,..E.M.Rasel; *New J. Phys.* 13, 125010 (2011)

„Long-distance remote comparison of ultrastable optical ...“
Andre Pape ... GG; *Opt. Exp.* 18, 21477 (2010)

fig. adapted from O.Terra, PhD Dissertation, LU Hanover 2010

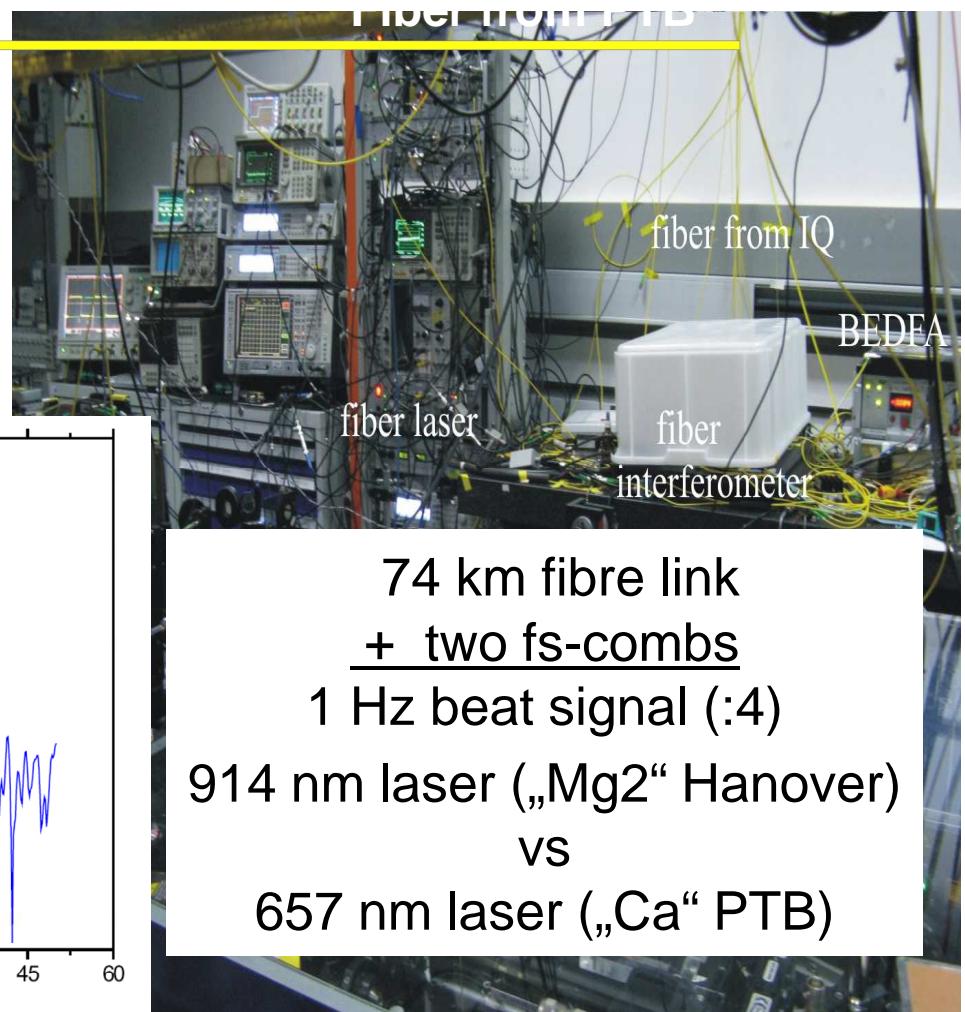
Remote spectroscopy: improving an optical clock laser

Mg-clock at IQ, University Hanover



74 km

PTB, Braunschweig

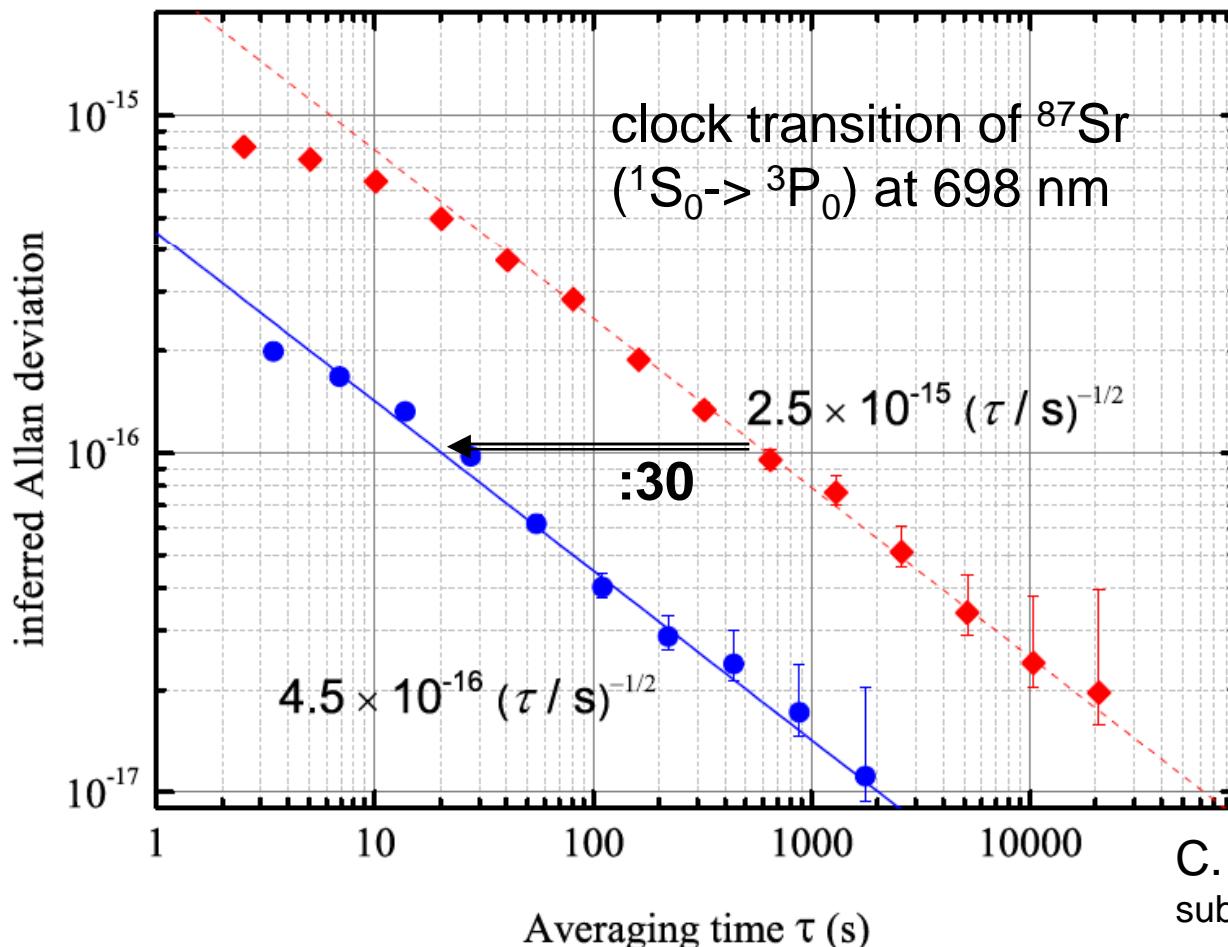


O. Terra, G. Grosche, W. Ertmer, J. Fribe, T. Legero, B. Lipphardt, A. Pape, K. Predehl, E. Rasel, M. Riedmann, U. Sterr, T. Wübbena und H. Schnatz:
"Frequency measurement of a magnesium frequency standard using a commercial telecommunication fiber link", **Proc. SPIE**, Vol. 7431, 74310B (2009);
A. Pape, O. Terra, J. Fribe, M. Riedmann, T. Wübbena, E. M. Rasel, K. Predehl, T. Legero, B. Lipphardt, H. Schnatz, and G. Grosche,
"Long-distance remote comparison of ultrastable optical frequencies with 10^{-15} instability in fractions of a second," **Opt. Express** **18**, 21477-21483 (2010)

~~Future application: remote spectroscopy~~

Several clocks with one laser source

- a. Synchronous read-out [Takamoto *et al.* Nature Phot. (2011)]
- b. Synchronous read-out, multi-wavelength
- c. Master-Slave configuration, multi-wavelength



Sr lattice clock instability
(from interleaved data)

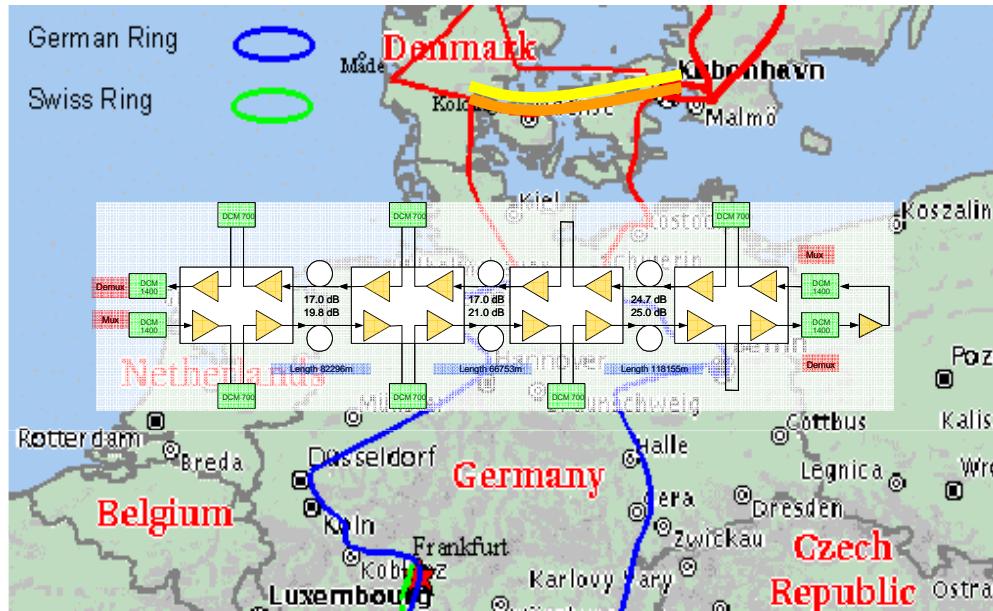
red: Sr-clock laser (ULE)
blue: $1.54\mu\text{m}$ laser (Si-cavity) as master laser

Figure adapted from

C. Hagemann, *et al.*, CPEM 2012
subm. to IEEE Trans. Inst. Meas. (2012)

Applications without dedicated dark fibre ?

1) hitch-hike entirely on telecom equipment (EDFAs) => uni-directional

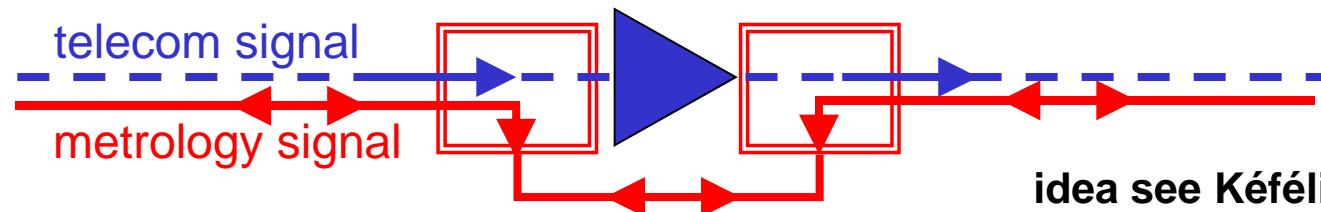


- 534 km live fiber link, Teledanmark
 - 16 channel DWDM, 200 GHz spacing
- Metrology signal between **active channels**; fibre losses: 124.5 dB;
8 dual-stage telecom amplifiers

OK for wavelength dissemination
OK for telecommunication, too !

G.Grosche *et al.* paper CTuH4, CLEO (2004) &
D.A.Humphreys *et al.*, IEE Proc. Optoelectron. (2006)

2) bi-directional link: go around uni-directional telecom equipment



Optical add-drop multiplexers (OADM) = filters

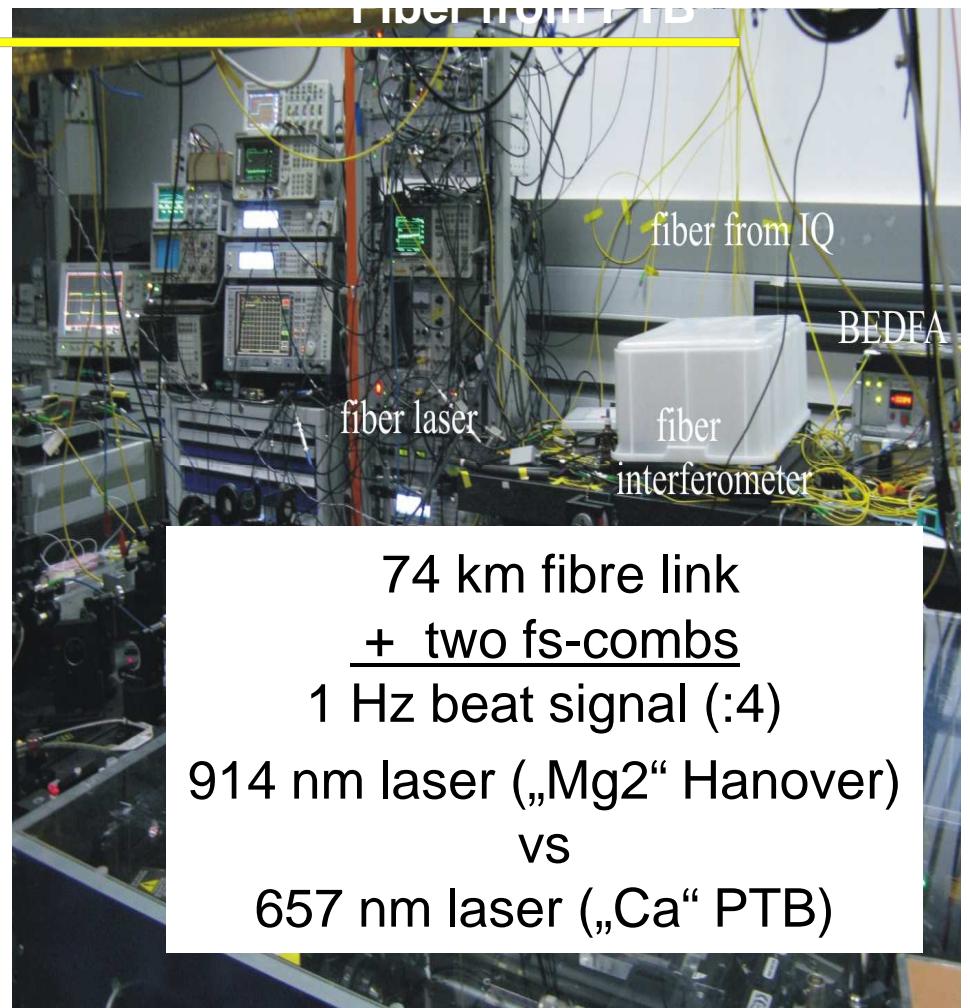
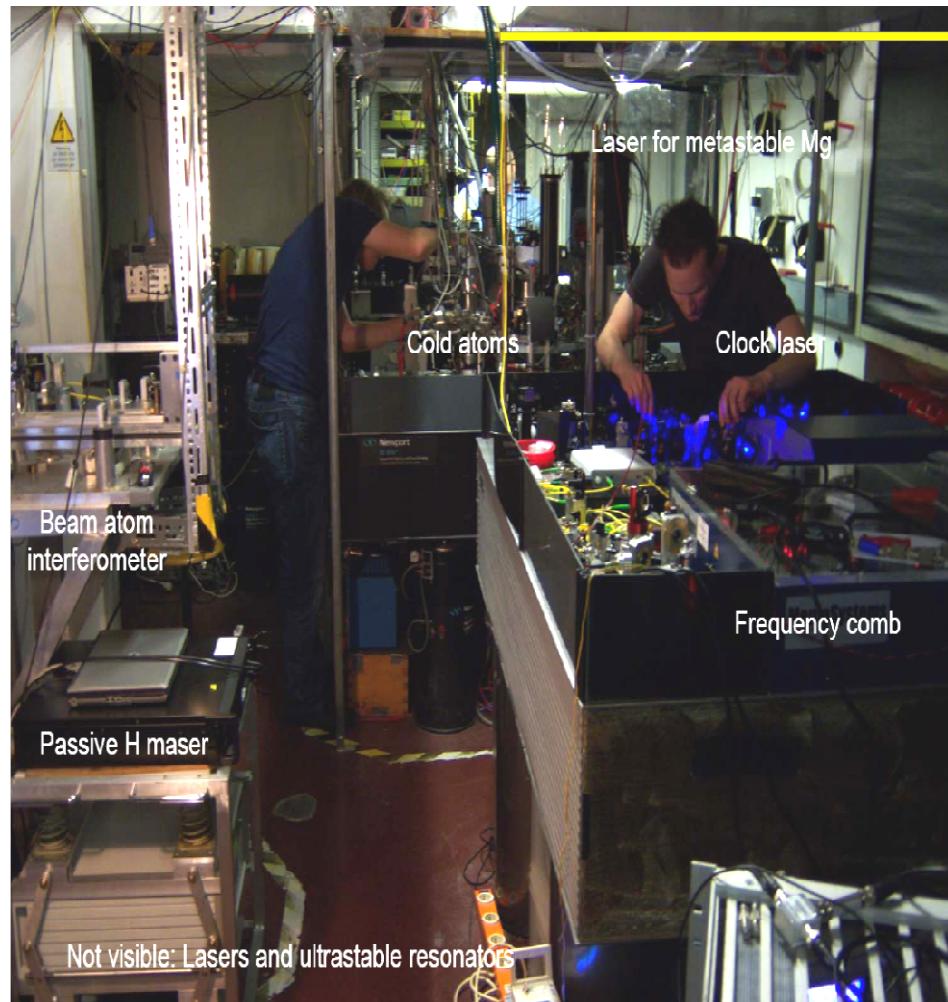
idea see Kéfélian *et al.*
Opt. Lett. 34, 1573 (2009)

One fibre link per remote user?

Mg-clock at IQ, University Hanover

74 km

PTB, Braunschweig



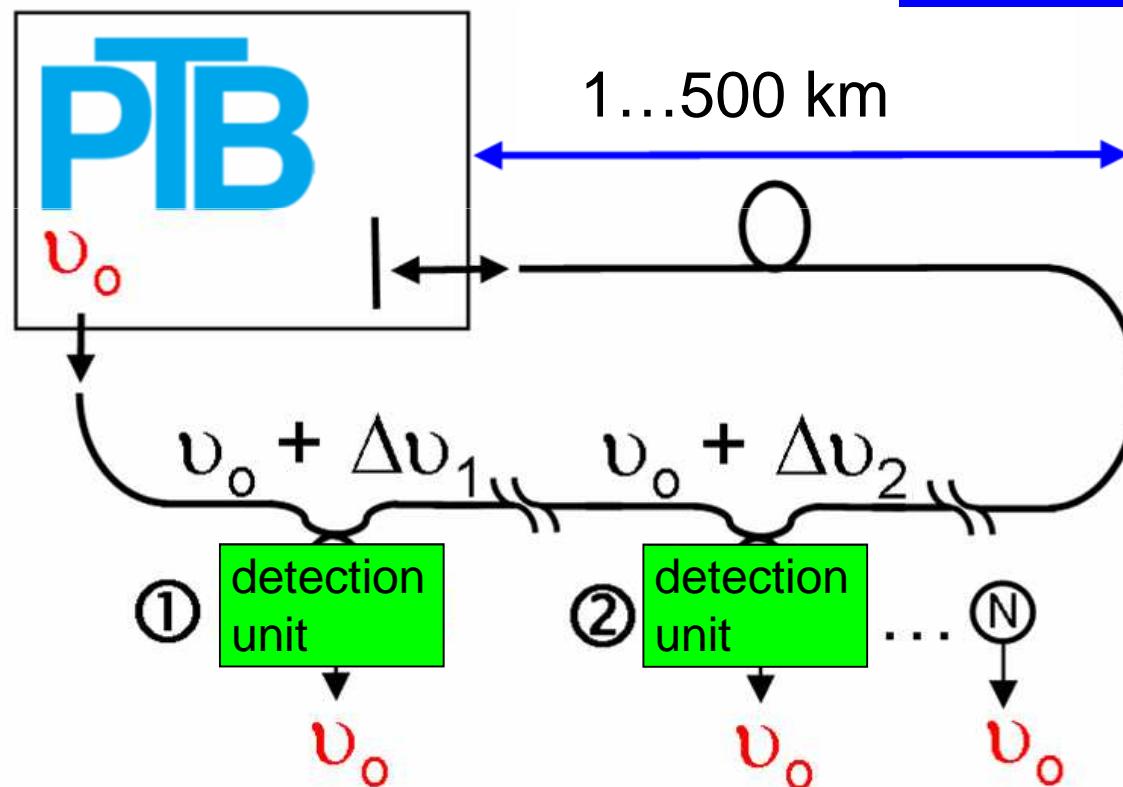
74 km fibre link
+ two fs-combs
1 Hz beat signal (:4)
914 nm laser („Mg2“ Hanover)
vs
657 nm laser („Ca“ PTB)

O. Terra, G. Grosche, W. Ertmer, J. Fribe, T. Legero, B. Lipphardt, A. Pape, K. Predehl, E. Rasel, M. Riedmann, U. Sterr, T. Wübbena und H. Schnatz:
"Frequency measurement of a magnesium frequency standard using a commercial telecommunication fiber link", **Proc. SPIE**, Vol. 7431, 74310B (2009);
A. Pape, O. Terra, J. Fribe, M. Riedmann, T. Wübbena, E. M. Rasel, K. Predehl, T. Legero, B. Lipphardt, H. Schnatz, and G. Grosche,
"Long-distance remote comparison of ultrastable optical frequencies with 10^{-15} instability in fractions of a second," **Opt. Express** **18**, 21477-21483 (2010)

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

Gesine Grosche, PTB

=> WP1 NEAT-FT



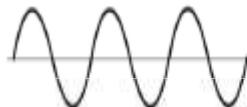
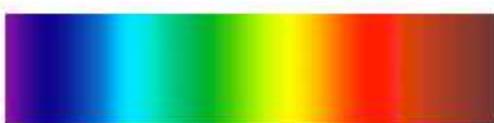
Modulated signals

Comparison

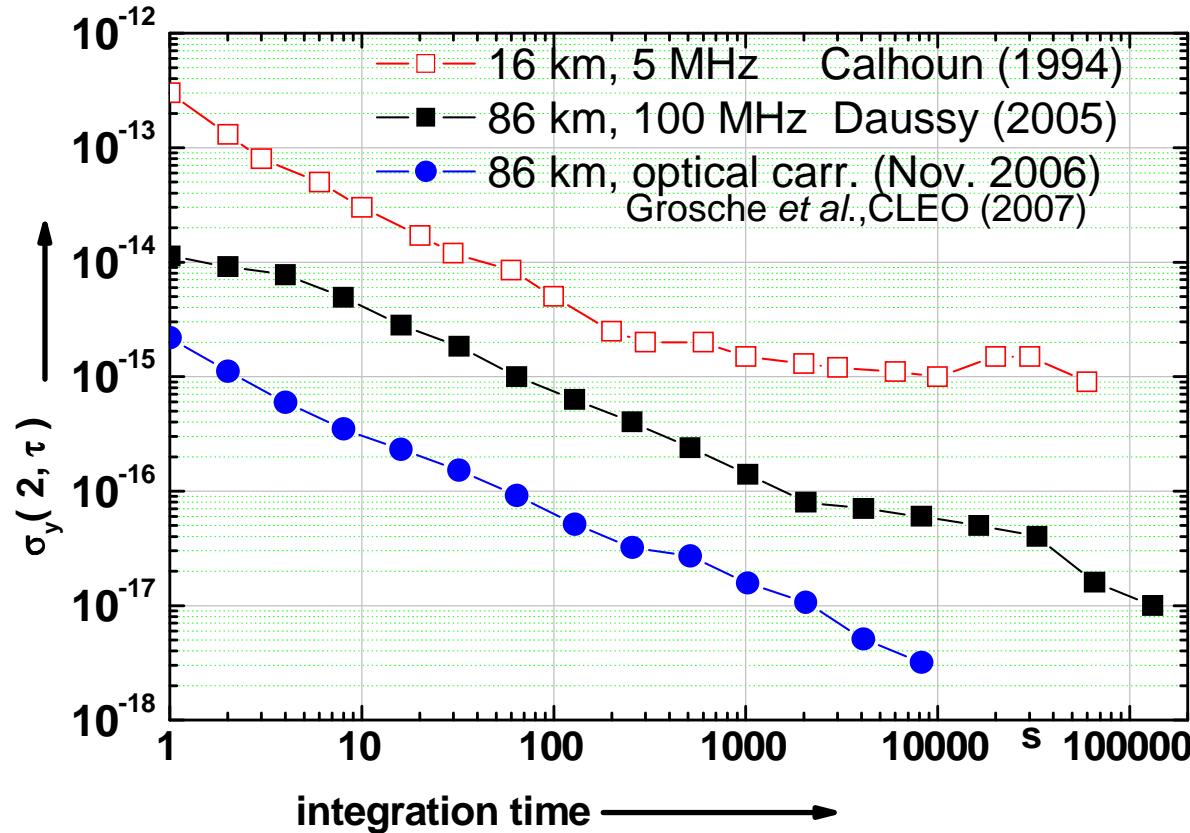


source: G. Marra, BIPM workshop 2011,
http://www.bipm.org/en/events/advanced_time_frequency/

Frequency transfer techniques over fibre

Transfer technique	Type	Comments
Single optical carrier 	optical	Narrow opt. BW, can be used on networks carrying internet traffic -> currently the technique of choice for long-haul frequency transfer.
Intensity modulated opt. carrier 	microwave	Narrow opt. BW, suitable for long-haul transfer. Microwave only
Optical frequency comb 	optical and microwave	Large bandwidth -> needs dark fibre or many ITU channels -> unsuitable for long-haul transfer

Direct modulation vs optical carrier



$$\sigma_y(\tau) = \frac{\sqrt{3S_\phi^{\text{white}} \Delta f}}{2\pi\nu_0\tau}$$

$$P_{rf}^{\text{direct}} \propto P_{\text{SigOpt}}^2$$

$$P_{rf}^{\text{het}} \propto P_{\text{SigOpt}} \cdot P_{\text{LOOpt}}$$

Excellent **passive** stability of buried fibre links – $10^{-14} \dots 10^{-15}$

Advantages of optical carrier approach

improved resolution and lower short term instability

constant intensity: less AM/PM conversion, fewer non-linear processes

longer distance: less attenuation for signal with heterodyne detection

1 GHz and 9.15 GHz rf transfer over 86 km

Adapted from O. Lopez et al. APB 98, 723 (2010) and references therein

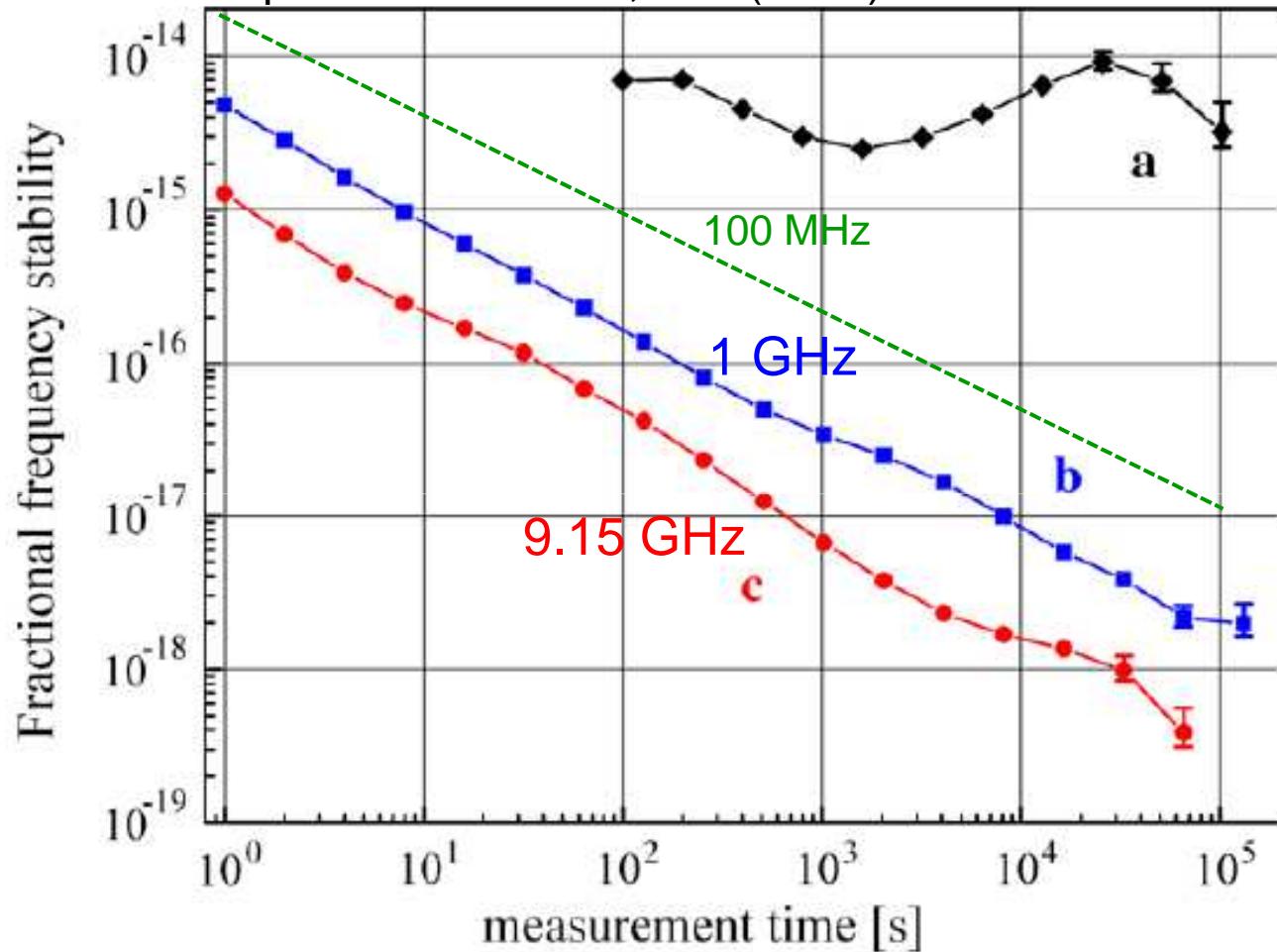
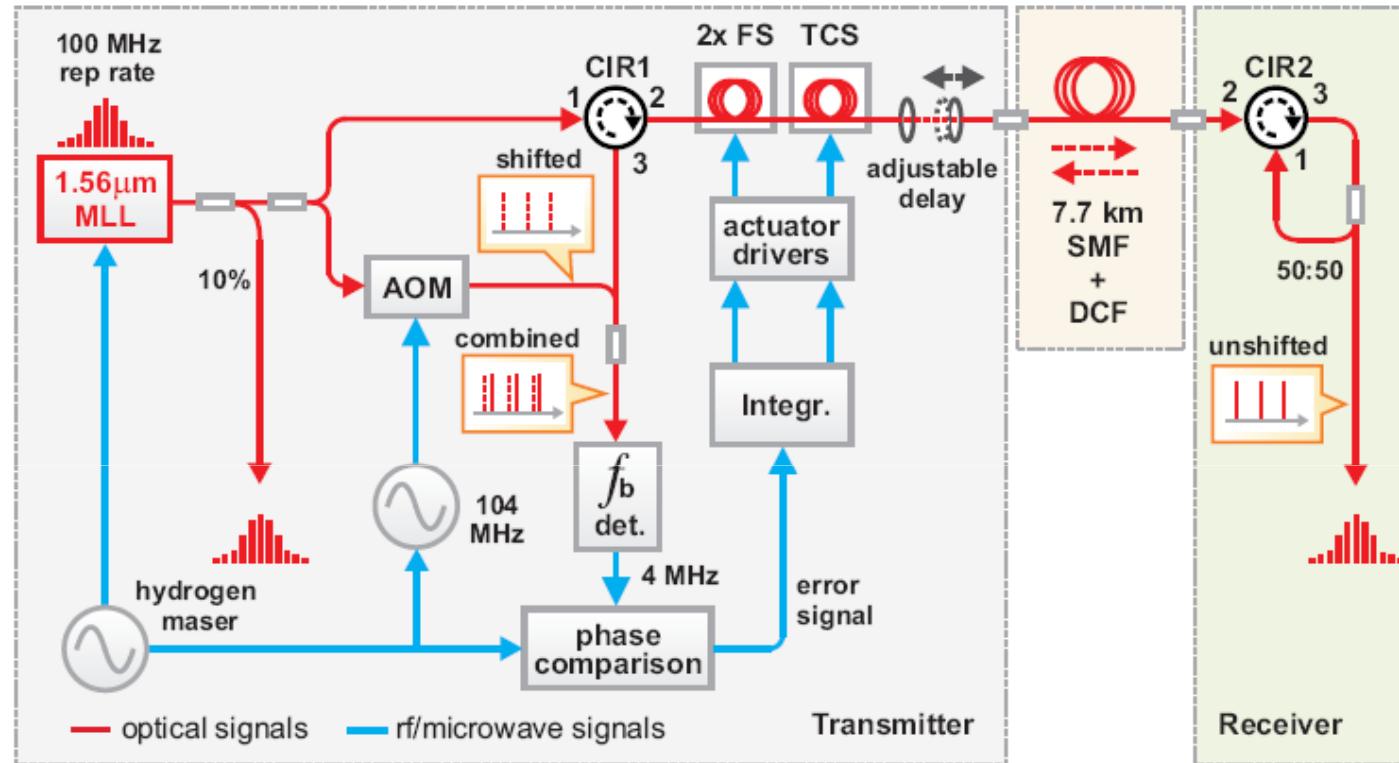


Fig. 4 Fractional frequency stability of (a) the free-running 86-km link (*black diamonds*), (b) the 1-GHz compensation system [11] (*blue squares*) and (c) the compensated link at 9.15 GHz (*red circles*, 15-Hz measurement frequency bandwidth)

$f_0 = 1 \text{ GHz}$ in [Lop08]=O. Lopez et al., EPJD 77, 064701 (2008)
 $f_0 = 9.15 \text{ GHz}$ in [Lop10]=O. Lopez et al. APB 98, 723 (2010)

Optical phase detection for 7.7 km link

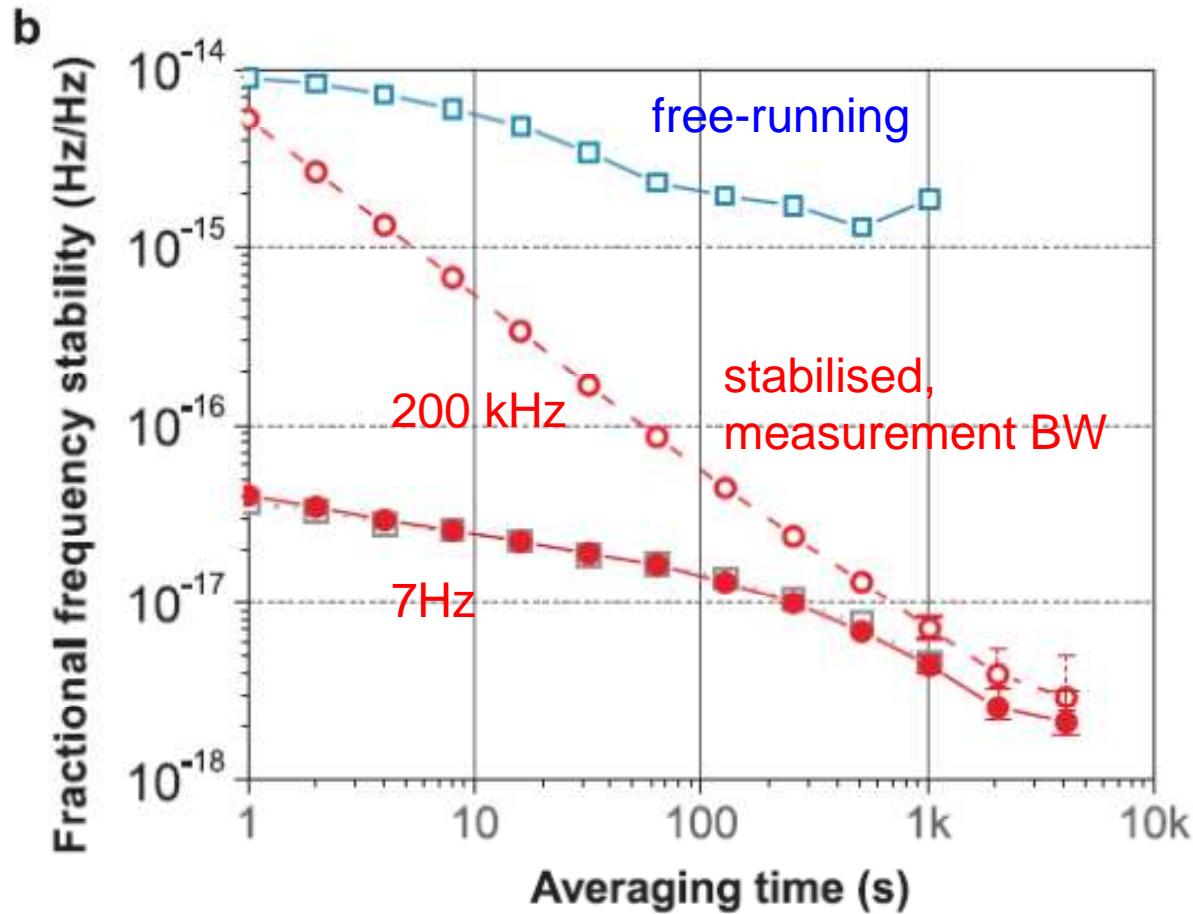
figure from [Mar12]= G. Marra et al. Opt. Exp. **20**, pp. 1775 (2012)



- beat comb lines with (AOM-shifted) local comb – c.f. optical carrier
- See also: optical phase detection for rf-distribution, e.g.
[Mus06]= Musha et al. APB **82**, 555 (2006)

Single optical mode stability for 7.7 km link

figure adapted from [Mar12] = G. Marra et al. Opt. Exp. **20**, pp. 1775 (2012)



instability of one comb mode: beat ultrastable laser with local fs comb and user-end fs comb; see measurement noise floor.

Modulated signals

=> **Time transfer**

WP3,WP4 NEAT-FT

=> poster G. Marra (NPL, WP3-leader NEAT-FT)

=> next talk by Anne Amy-Klein



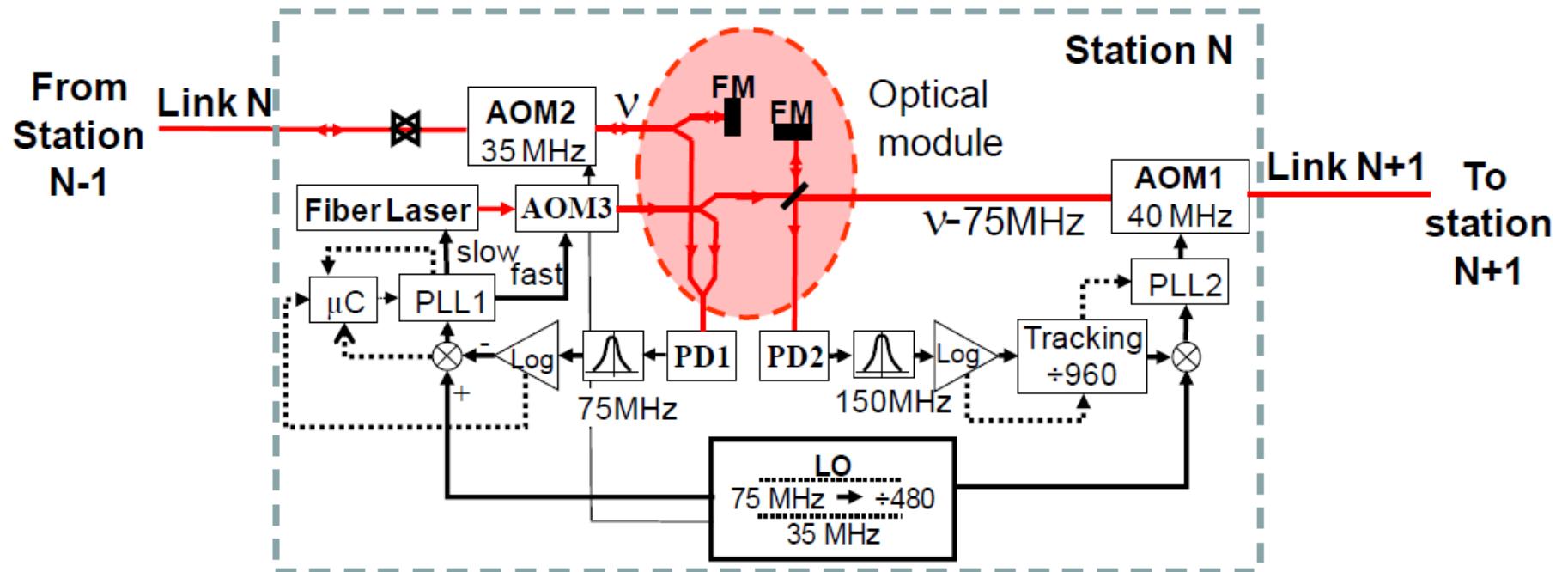
Signal amplification and regeneration

Long distance links – alternative approach

Subdivide the link into sections

[lop10]:= O. Lopez et al., Optics Express **18** (16) 16849 (2010)

„Cascaded multiplexed optical link on a Telecommunication network for frequency dissemination“



Scheme of the Nth repeater station, FM: Faraday mirror, PD: photodiode, LP: local RF oscillator, AOM: acousto-optic modulator, Log: logarithmic amplifier, μ C: microcontroller, PLL: phase-locked loop. (source: fig.1 and figure caption in ref. [lop10])

Erbium-doped fibre amplifiers

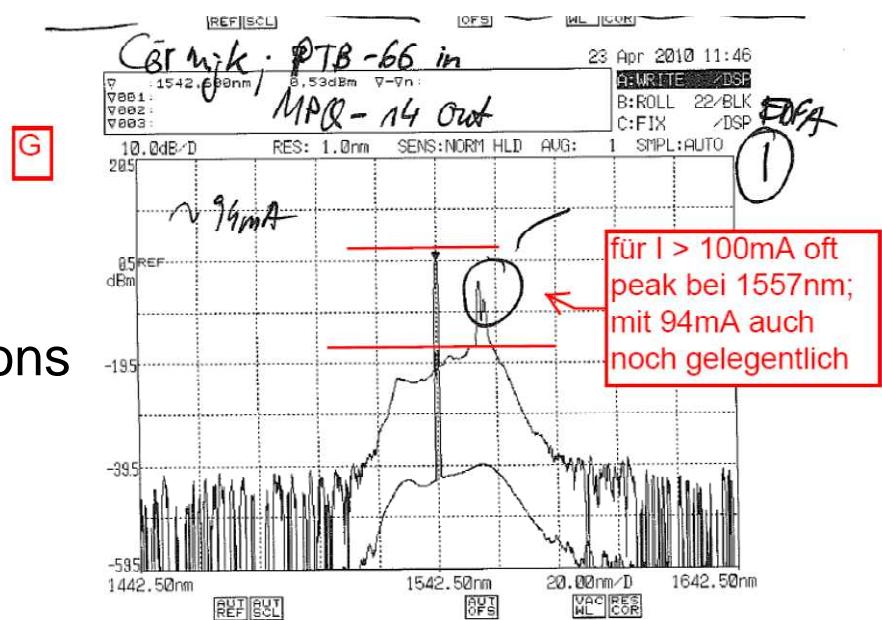
- each EDFA to compensate ~ 20-25 dB loss (212 dB / 9)
- bi-directional for phase noise compensation

Erbium-doped fibre amplifiers

a) Lasing effects (reflections)
– gain limited typ. < 20 dB

b) Same gain medium for both directions
– crosstalk, gain limit

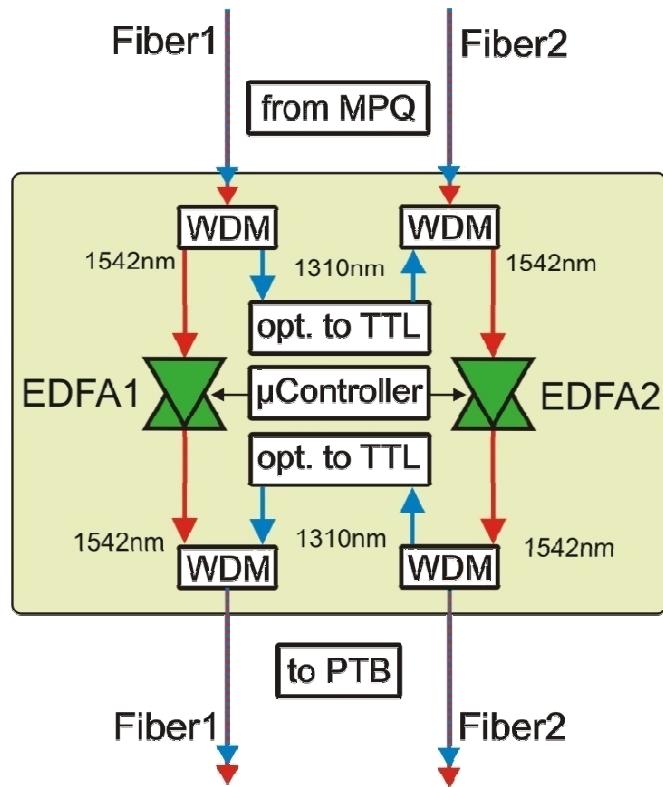
c) EDFA spacing ~ 100 km.



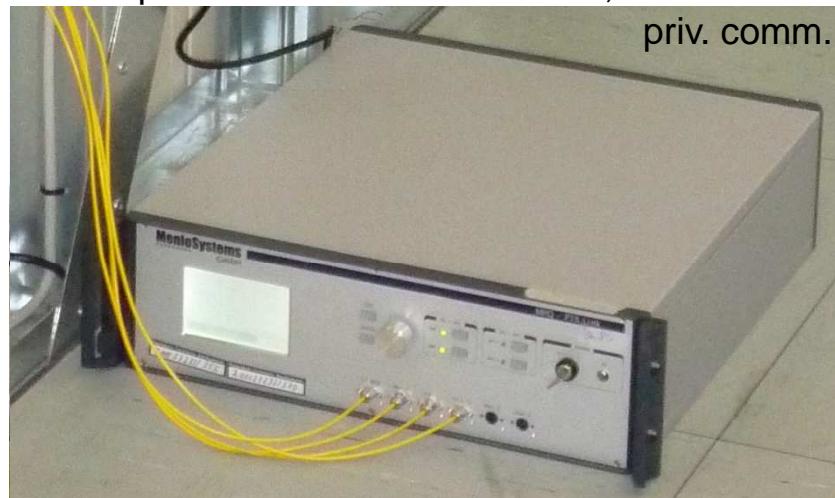
Bi-directional amplifiers in series => highly nonlinear system...

Bi-directional EDFA: remote control

- Remote communication via 1310 nm modulated signal
- adjust gain (pump current), 18 bi-directional EDFAs



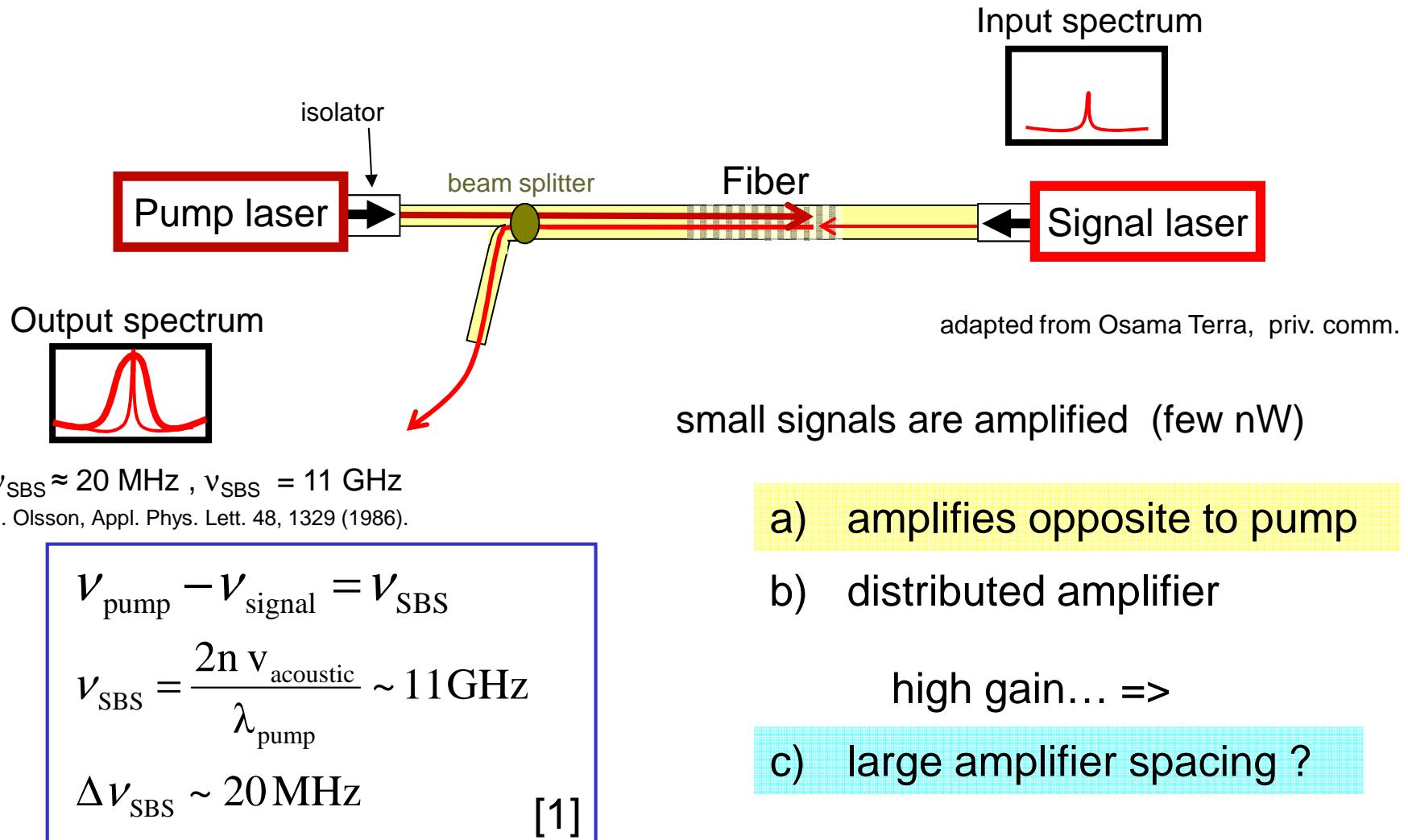
figures adapted from Katharina Predehl, Osama Terra
priv. comm.



Problem: lasing effects
=> gain limited < 20 dB
=> 40 dB excess link loss

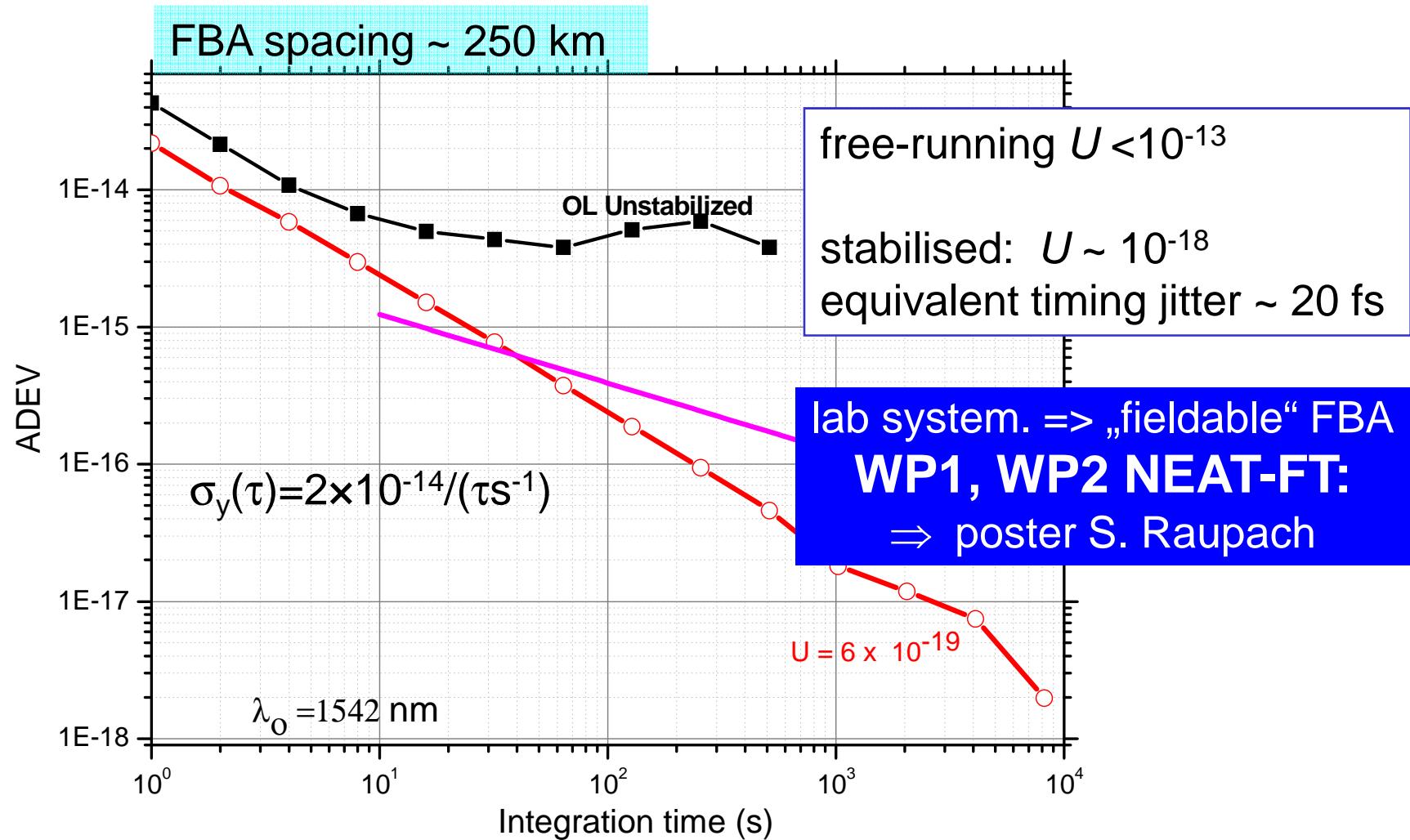
- Works well up to distances of 80-100 km

Alternative: fibre Brillouin amplification (FBA)



[1] Ferreira *et al.*, „Analysis of the gain and noise characteristics of fibre Brillouin amplifiers“, Opt. & Quantum Electronics **26**, 35-44 (1994) and references therein

Brillouin amplification in a stabilised 480 km link

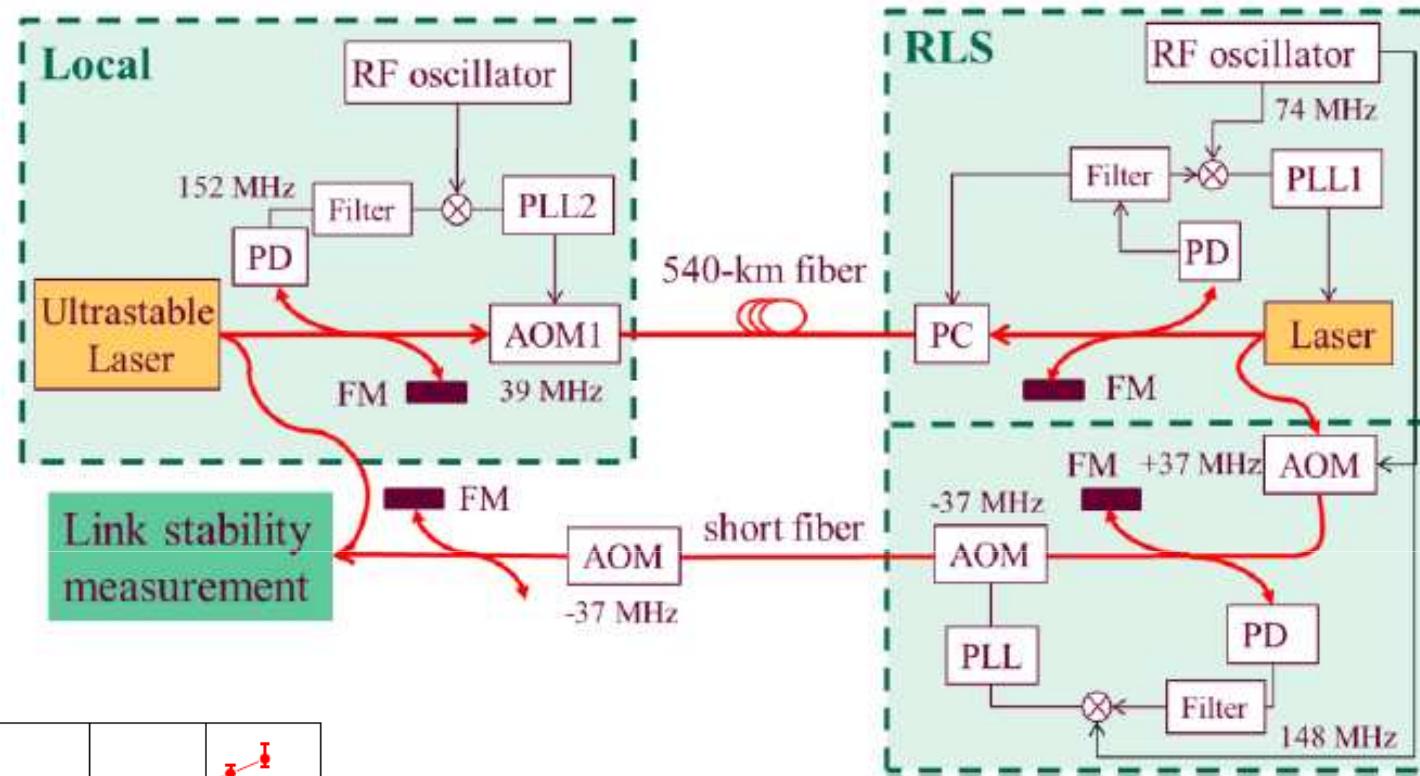


O. Terra, G. Grosche, H. Schnatz: *Brillouin amplification in phase coherent transfer of optical frequencies over 480 km*, Optics Express **18**, 16102 (2010)

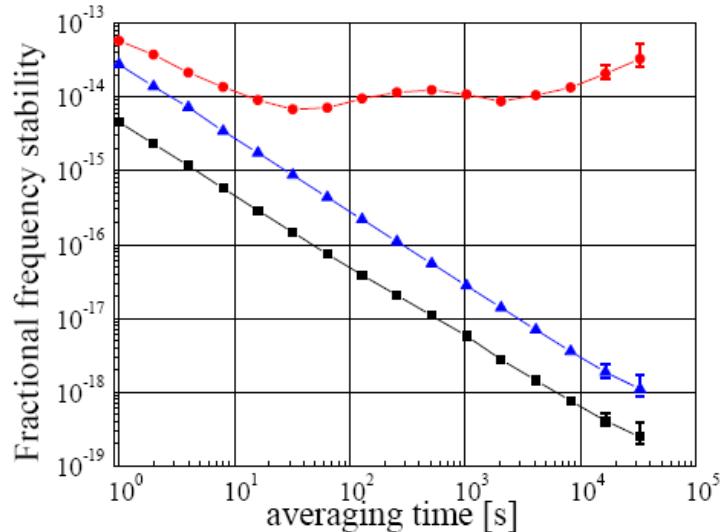
540 km link with repeater station (Paris group):

“Ultra-stable long distance optical frequency distribution using the Internet fiber network”

figures and results:
Olivier Lopez et al.;
Opt. Exp. 20, 23518
(2012)



optical link, FM : Faraday mirror, PD : photodiode, PC: polarization optic modulator, PLL : phase-lock loop.



- 540 km link $3 \times 10^{-14}/(\tau s^{-1})$ ADEV (full bw) on a „difficult“ link
- fully automated opto-electronic station

=> WP1, WP2 NEAT-FT

How good is the link?

Characterising and monitoring ultra-long links

920 km optical link PTB – MPQ Garching

- A **pair** of 900 km dark fibres
600 km geographical distance
- Round-trip delay 10 ms
- Predicted $\sigma_y(\tau) = 5 \times 10^{-14} / (\tau s^{-1})$
- Attenuation > 200 dB one-way
- **9 Container** stations with EDFA
- An optical communication channel allows for remote access to the EDFAs
- At each end: one fibre Brillouin amplifier (FBA)



fig. adapted from Osama Terra, priv. comm.

Optimization

1. Reflections cause lasing

additional EDFA in
Großbreitenbach

2. ASE saturates the EDFAs

reduce EDFA gain in most
containers

Solution:

1. Clean Connectors

adjust frequency scheme:
move noise away from signal

+ Index matching gel

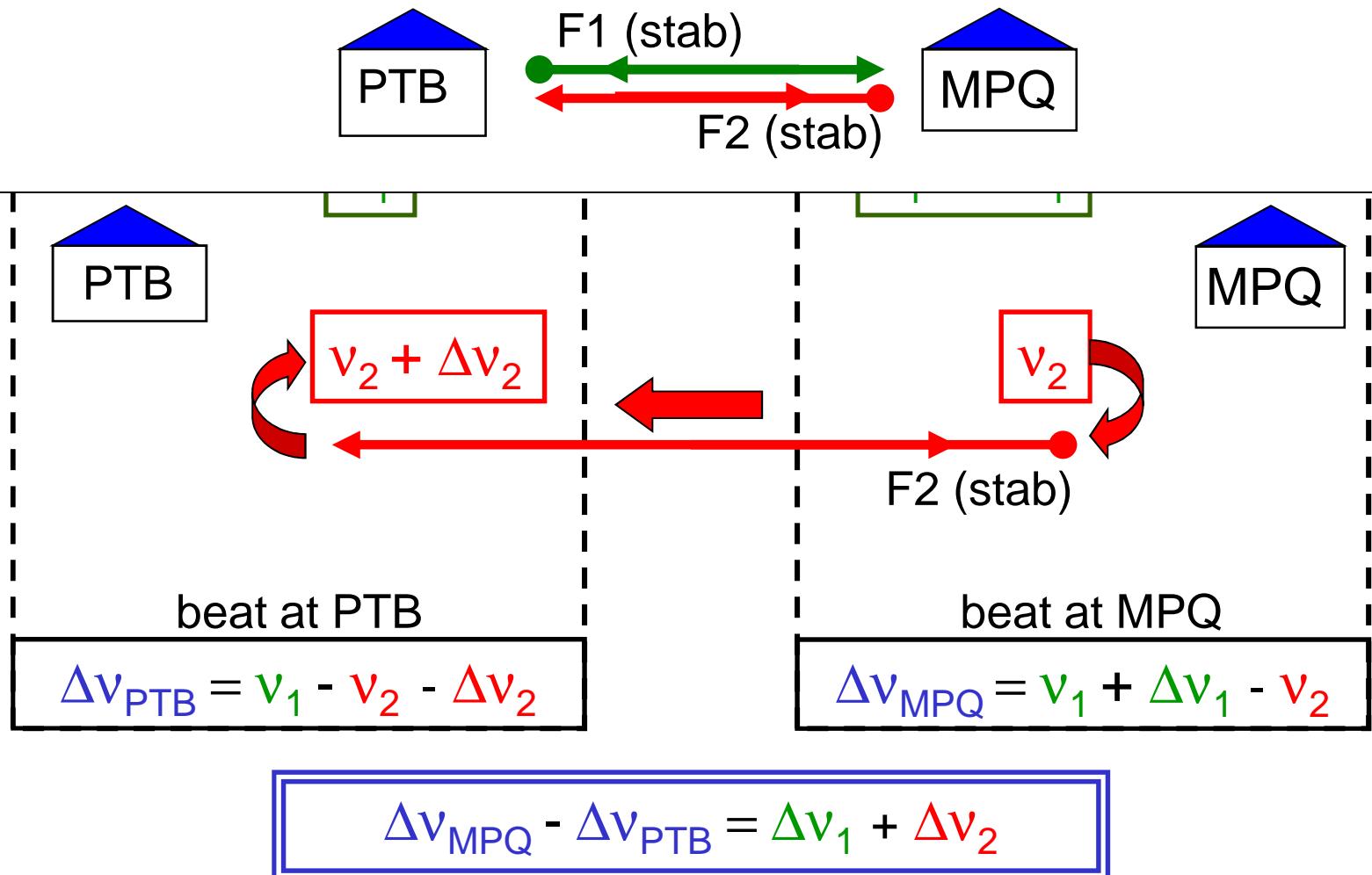
2. Optical bandpass filters (100 GHz)

reduce complexity of set-up

Use a Brillouin amplifier at the remote end to boost the inloop signal!

How to check link at level of best optical clocks - or below? $U \sim 10^{-17}$?!

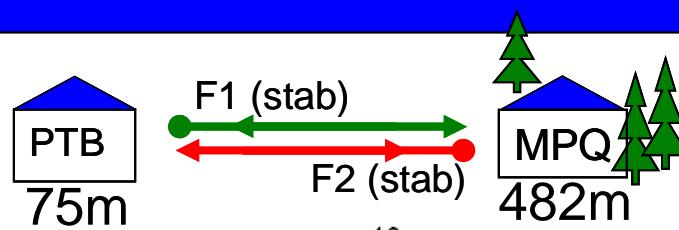
Testing the fibre link performance – with two stabilised fibres forming a loop



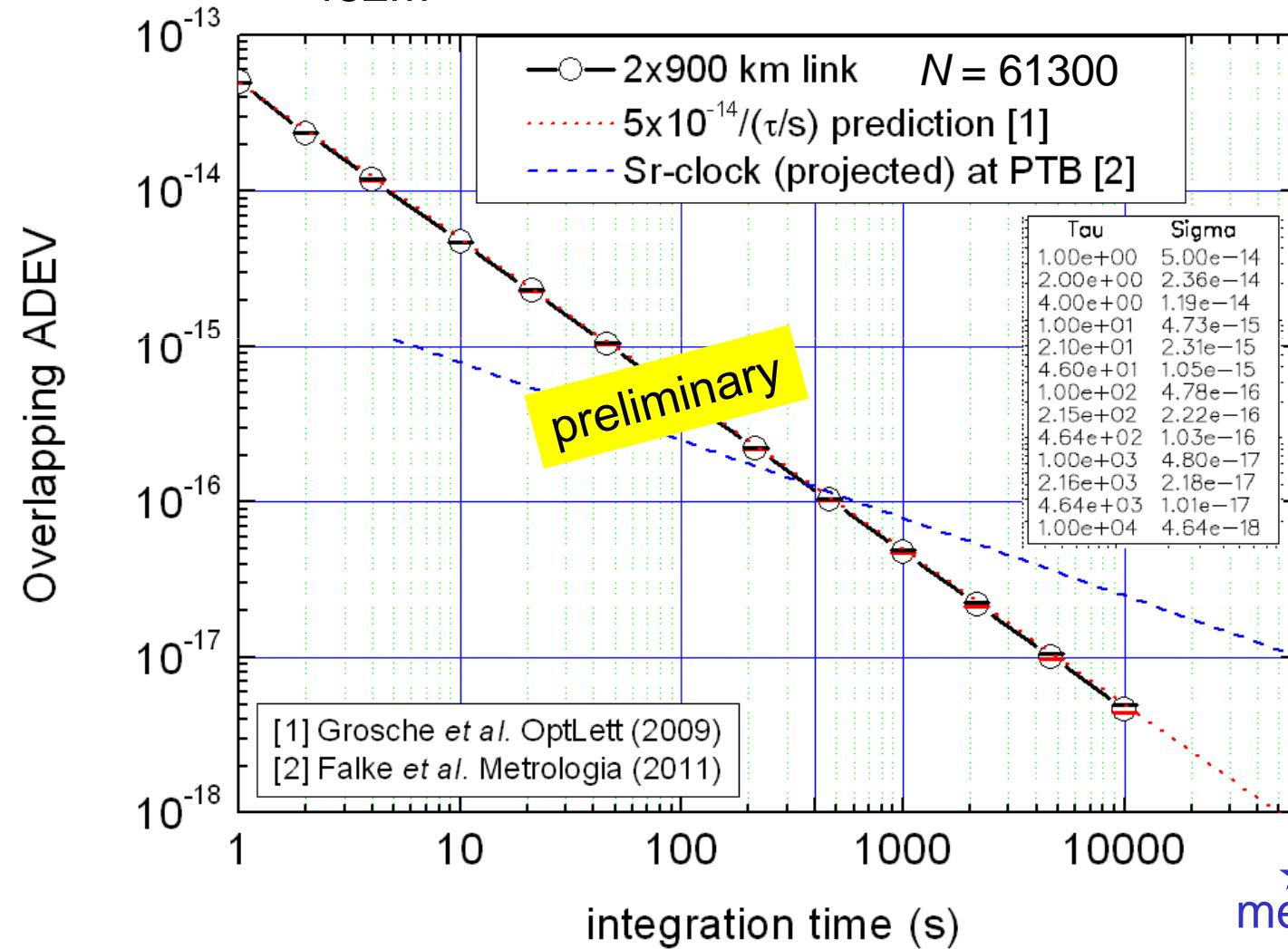
virtual loop gives ***sum of frequency shifts*** incurred in F1 and F2

$$\Delta v_i = \Delta v_{i_fibrenoise} + \Delta v_{i_gravitational\ redshift} + \dots$$

2 x 900 km loop: instability (ADEV, full BW)



Different gravitational potential: $\Delta v/v = g \Delta h/c^2$
 $\Delta v/v \sim 10^{-16}/\text{m}$; $\Delta v_{\text{PTB/MPQ}} = 8.5 \text{ Hz} (4 \times 10^{-14})$

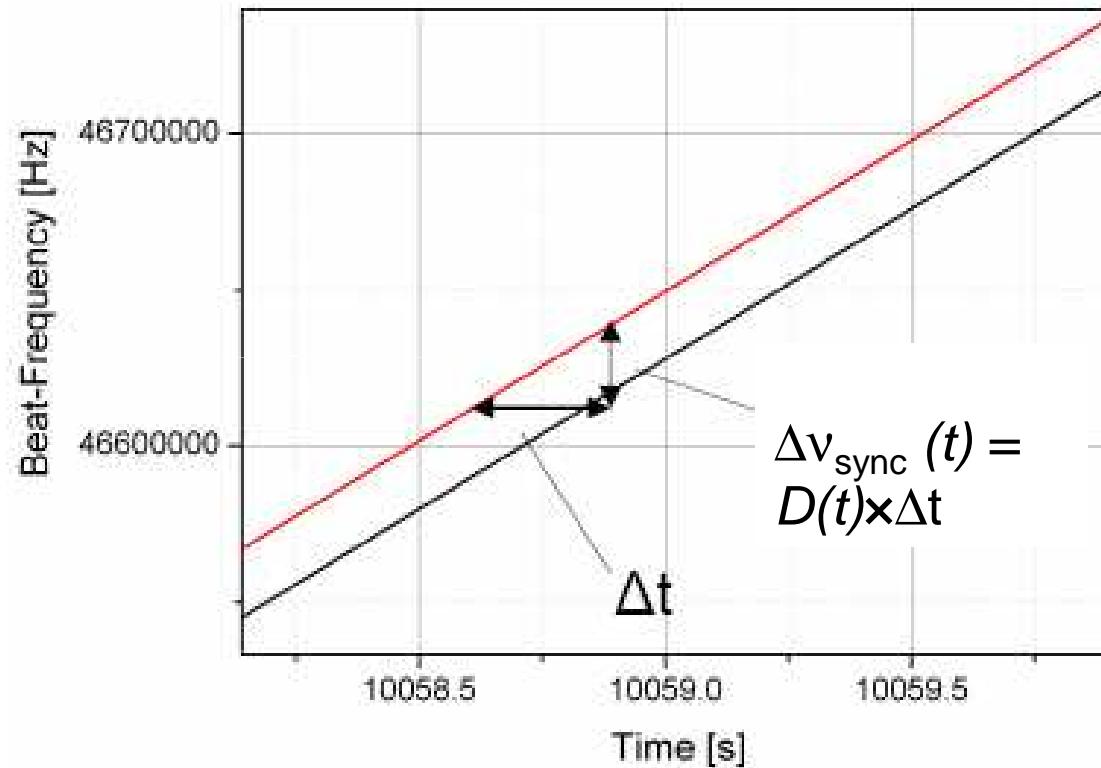


Accuracy revisited: synchronisation offset Δt

Input frequencies (lasers) at PTB and MPQ drift differently

drift difference $D(t) := d/dt (\nu_1 - \nu_2)$

$$\Delta\nu_{\text{sync}}(t) = D(t) \times \Delta t$$



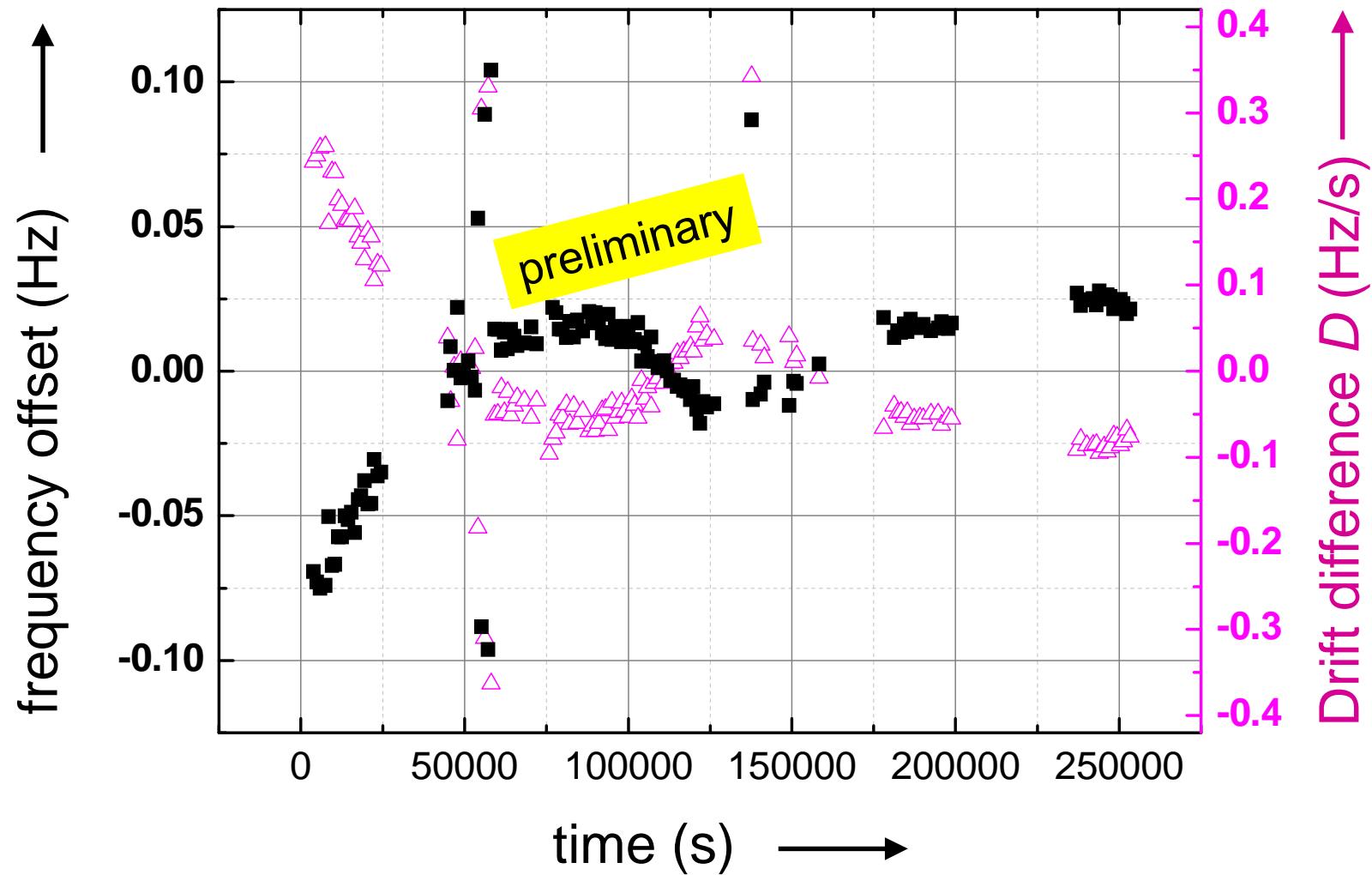
for $D(t) = D = 100 \text{ mHz/s}$ and $\Delta t = 100 \text{ ms}$

$$\Delta\nu_{\text{sync}} = 10 \text{ mHz} \Rightarrow 5 \times 10^{-17};$$

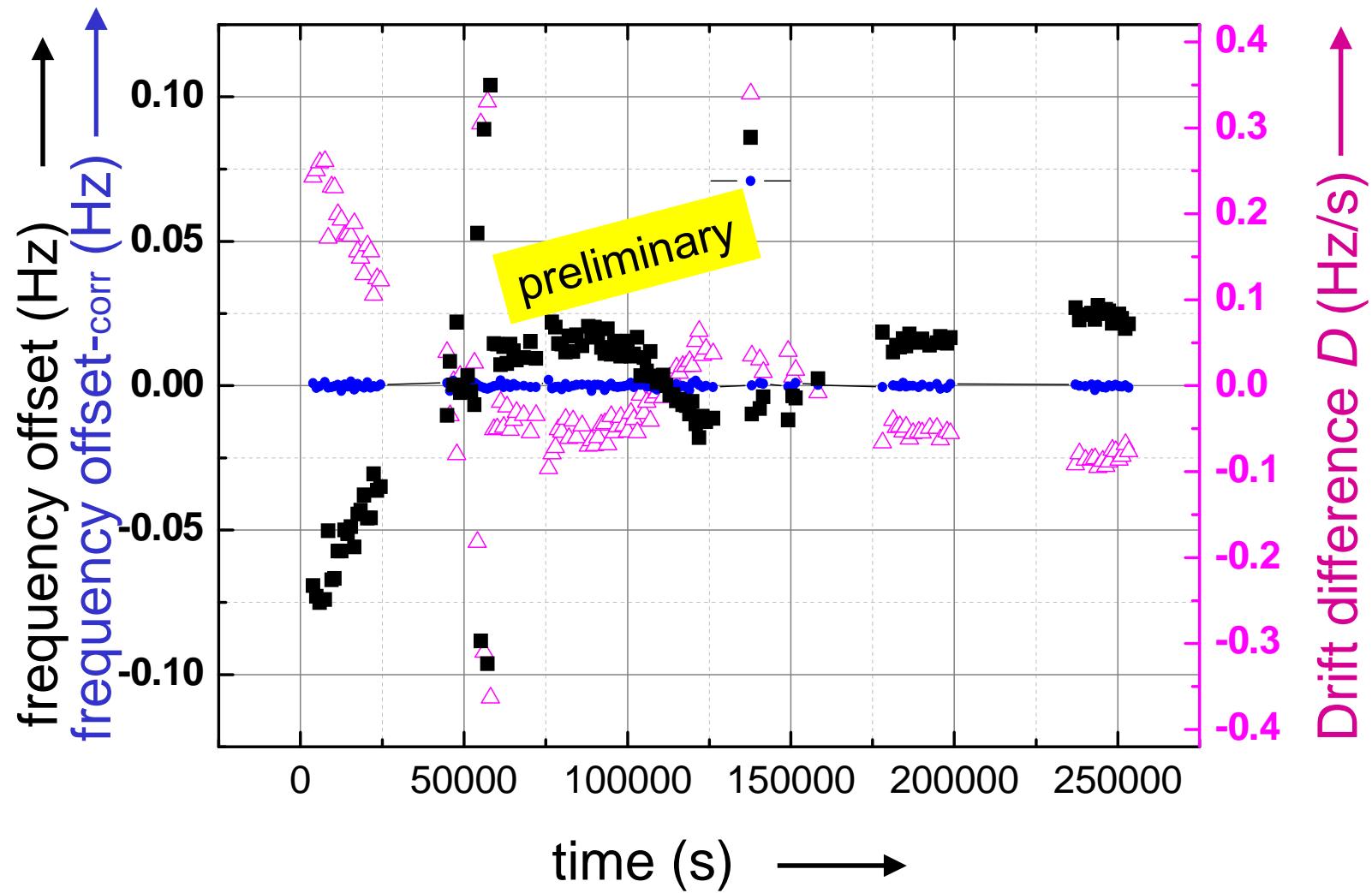
measure Δt by applying *artificial* drift difference $D^{\text{ext}} \gg D$

Solution: measure drift and Δt , apply correction

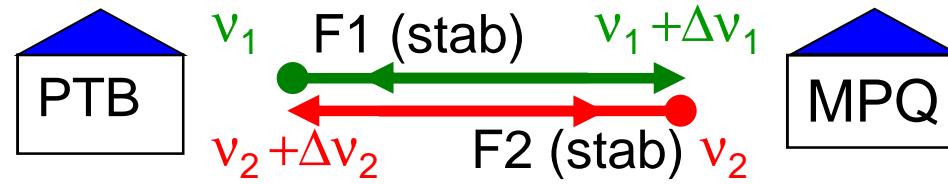
Δ counter: overlapping multiple averages within gate period of 1s
130 blocks of 1000s duration each; arithmetic mean of each block.



... it works



Uncertainty of frequency transmission



	mean (mHz/s)	sdev (mHz/s)
rel. drift $D := \frac{d}{dt} (v_1 - v_2)$	-0.6	100

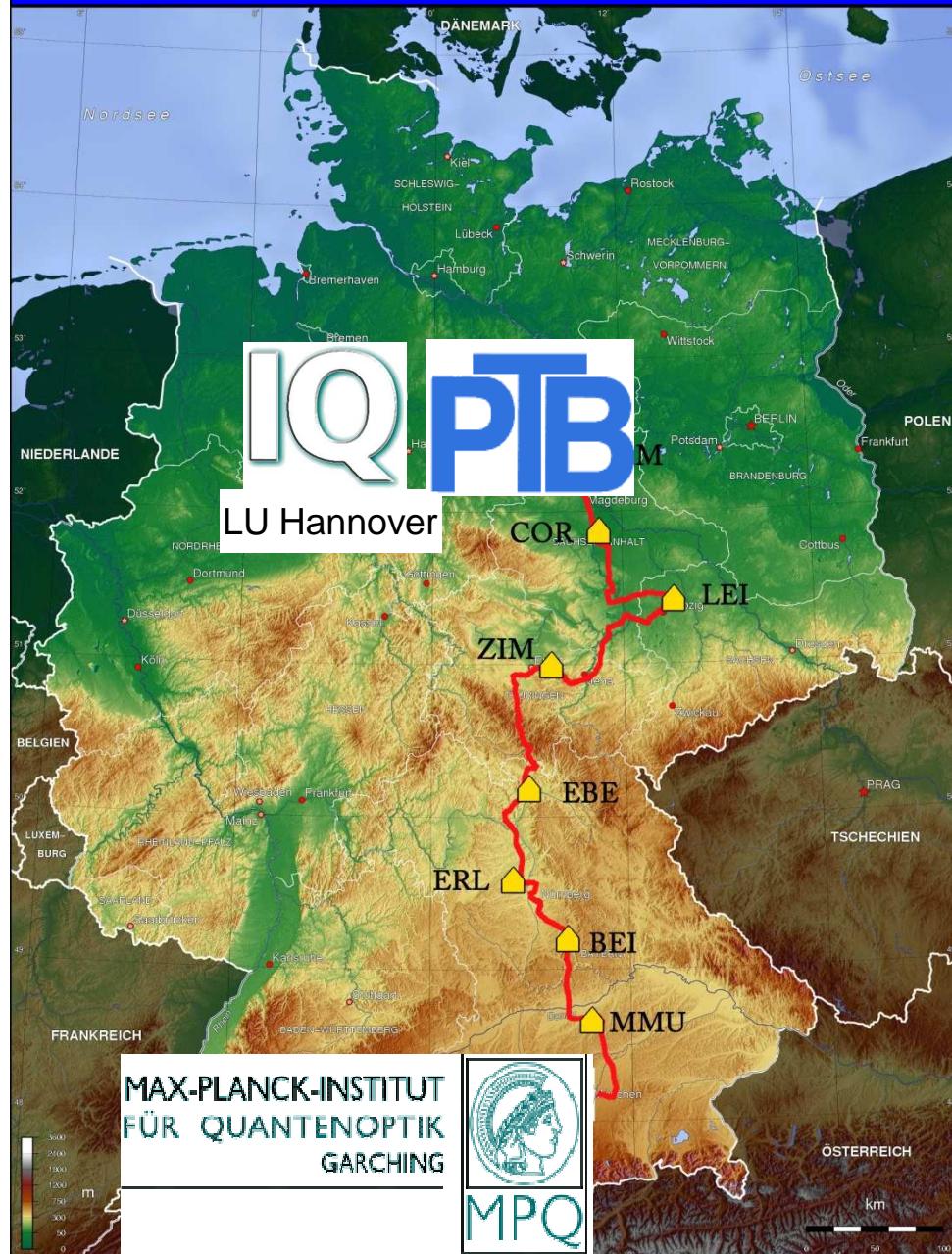
$$\Delta v_{\text{sync}}(t) = D(t) \times \Delta t$$

130 blocks of 1000s duration each; overall arithmetic mean.

$\Delta v_1 + \Delta v_2$	mean (mHz)	sdev (mHz)	mean (relative)	sdev (relative)	$U := \text{sdev}/\sqrt{130}$
uncorrected	0.151	32	7.7×10^{-19}	1.6×10^{-16}	1.4×10^{-17}
corrected	-0.026	0.76	1.3×10^{-19}	3.9×10^{-18}	3.4×10^{-19}

see also: K. Predehl, G. Grosche, S.M.F. Raupach *et al.*, **Science 336, 441 (2012):**
 “A 920-Kilometer Optical Fiber Link for Frequency Metrology at the 19th Decimal Place”

Σ A brief summary...



- 1000 km scale network of phase-stabilised dark fibre links
 - PTB Brauns.- IQ Hannover 2x 73km
 - PTB Brauns.- MPQ Garching 2x 920 km
- Noise suppression
 - close to theory; $\sigma(\tau, L) := \text{full BW ADEV}$
 - $\sigma(\tau, L) = 1.5 \times 10^{-15} / (\tau s^{-1}) \times (L / 100\text{km})^{3/2}$
 - accuracy (noise floor, loop) $< 10^{-19}$
 - accuracy (split loop, synch.) $< 5 \times 10^{-19}$
- Used for remote measurements:
 - optical clock measurement (Mg)
 - remote laser characterisation (Mg/Ca)
 - Hydrogen (1S-2S)
- Amplification
 - 146 km PTB-IQ-link one EDFA
 - 480 km link with fibre Brillouin amplifiers
 - 900 km PTB-MPQ link using 2x 9 bi-directional EDFAs + 2 FBA
- How to get to Paris?



Cooperation fibre link



Klaus Ullmann †
Christian Grimm

DFN
Deutsches
Forschungsnetz

Fa. Gasline

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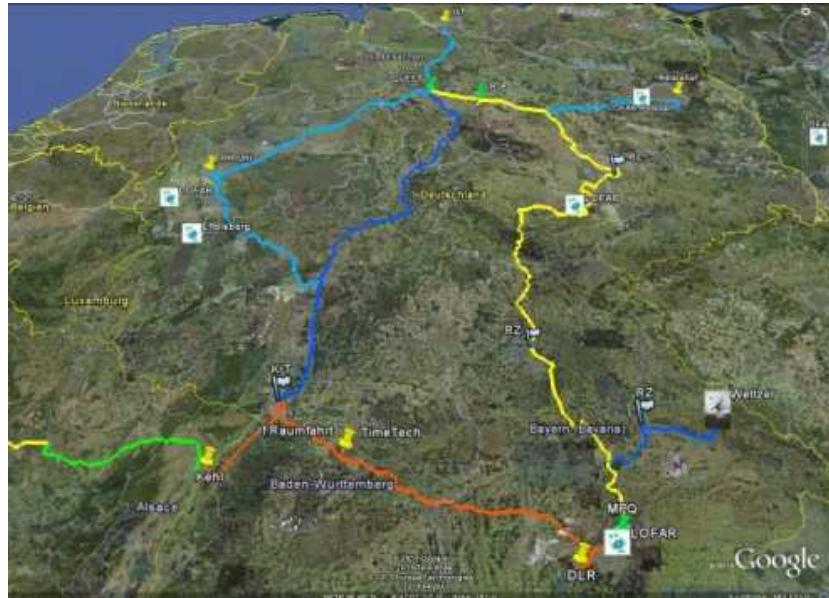


PTB (Germany), BEV (Austria), INRIM (Italy)
MIKES (Finland), NPL (UK), OBSPARIS (France), SP (Sweden)
UFE (Czech Rep.), VSL (The Netherlands)

Future work (at PTB)

Frequency distribution to many locations;
amplifier technology, timing distribution; robust systems.
gravitational potential: $\Delta v/v = g \Delta h/c^2$

Link NMI (Braunschweig – Paris)



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=> CRC Geodesy