Comparison of clocks using optical fiber links: recent results and future projects

Harald Schnatz, PTB

Physikalisch-Technische Bundesanstalt, Braunschweig, Germany

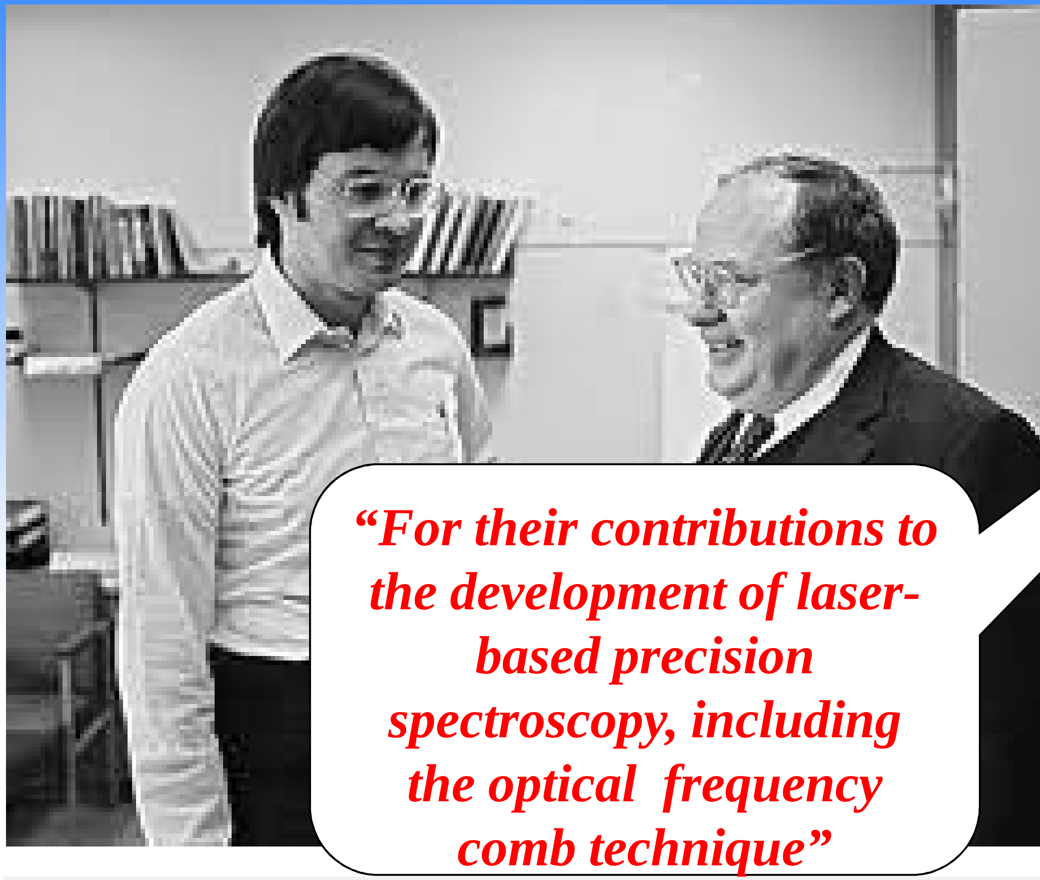
on behalf the JRP *NEAT-FT* of EURAMET

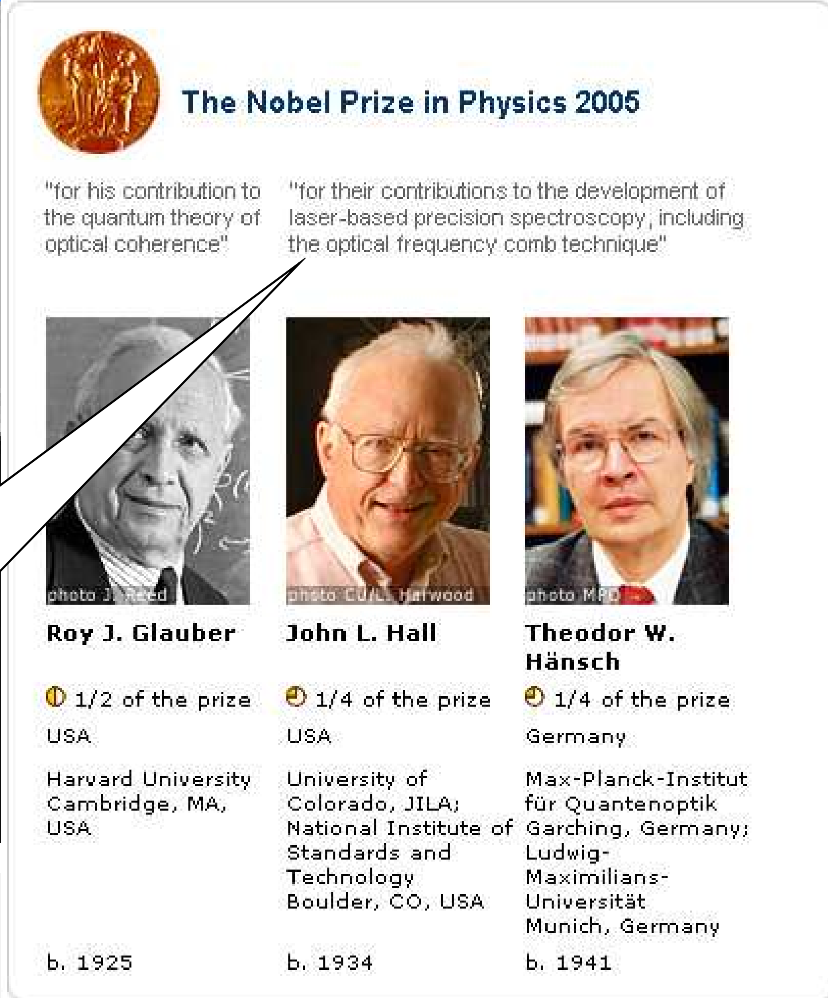
7th Customer Empowered Fibre (CEF) Networks workshop, CESNET, Prague, Sept. 2012

Comparison of clocks using optical fiber links:

- **Motivation**
- **Optical fiber links**
- **Results of the first real long-haul link (920 km)**
- **Joint research project NEAT-FT**
- **Summary & Outlook**

“Never measure anything but frequency!”

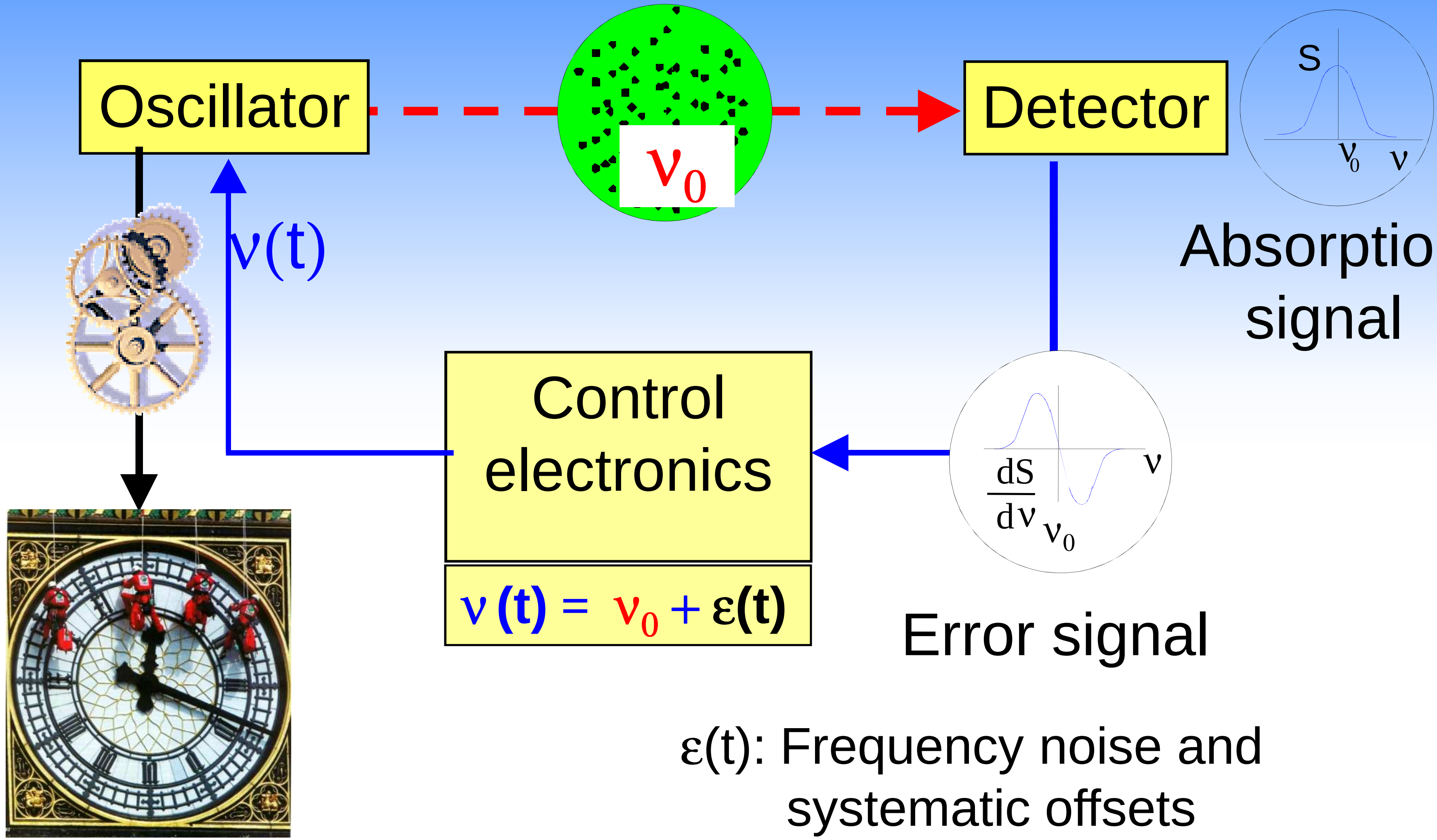




Arthur Schawlow’s advice to his students.

Atomic Frequency Standard / Clock

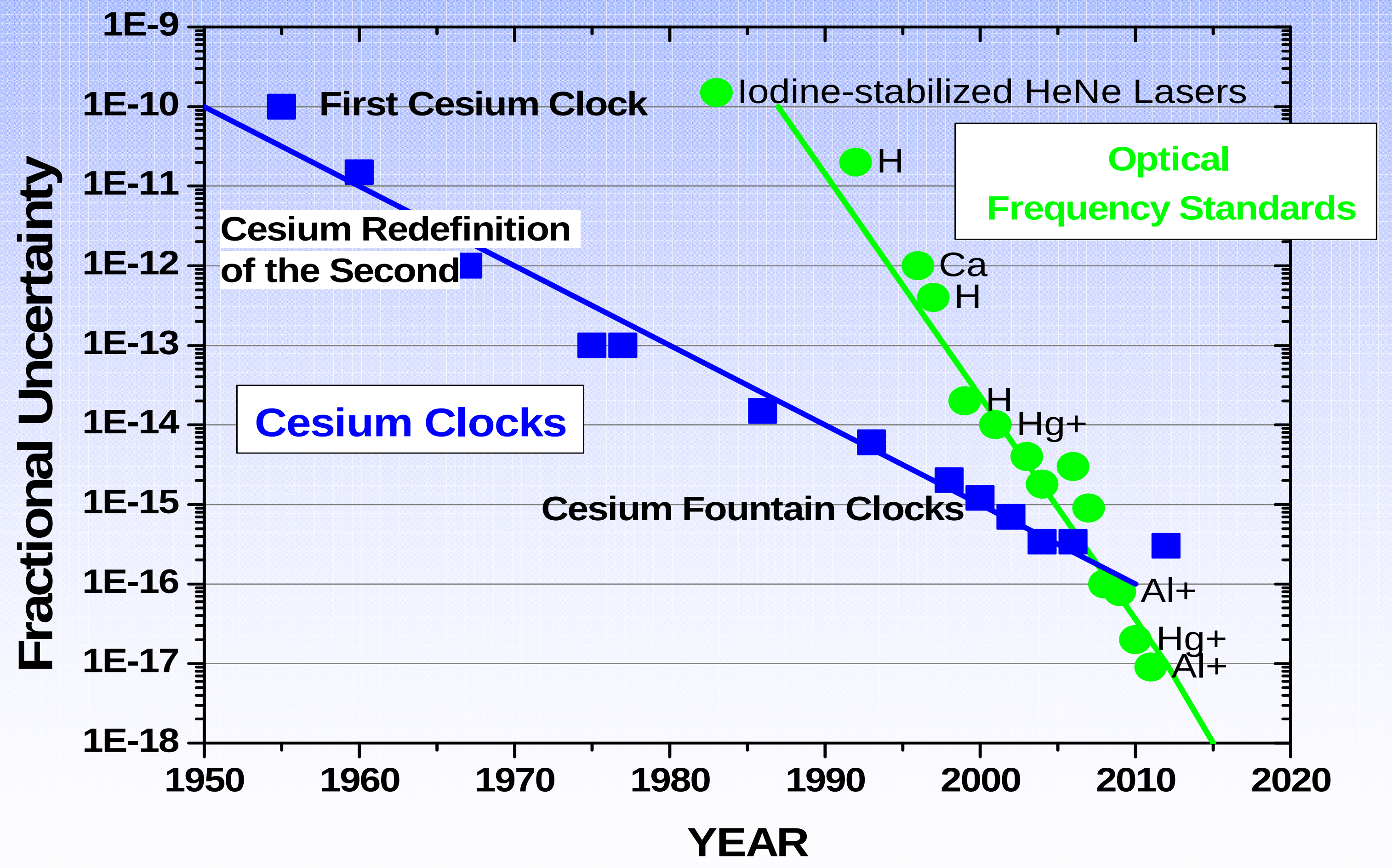
ν_0: „undesturbed“ transition frequency



$\varepsilon(t)$: Frequency noise and systematic offsets

Uncertainty of optical and Cs clocks

PTB



C.W. Chou et al. PRL **104**, 070802 (2010)

"Never measure anything but frequency!"

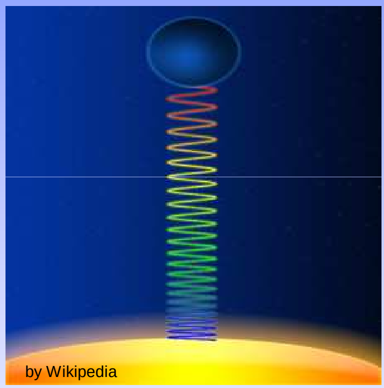
PTB

- The transition frequency of an atom realized by an atomic clock is the most stable and precisely known physical quantity.
- All at the same, this transition frequency is affected by
  - Magnetic fields → Zeeman shift
  - Electrical fields → Stark shift
  - Temperature → Black body shift
  - Velocity → Doppler shift
  - Time dilation → 2^{nd} order Doppler shift
  - Gravitational potential → red shift
  - Grand Unification → are fundamental constants stable?

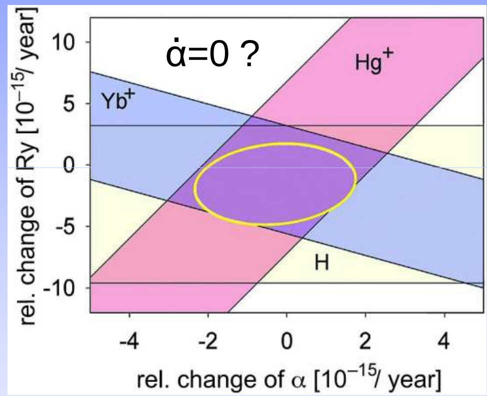
Who needs (better) clocks?

Precise tests of fundamental physics

Gravitational red shift

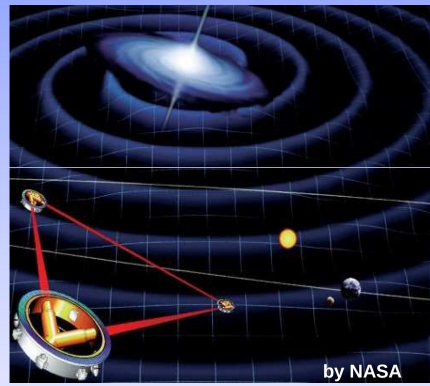


„Constancy“ of fundamental constants



Peik et al., PRL, 2004, 93/17

Gravitational wave detection



Tests of SRT

Fundamental constants

Tests of GRT

Redefinition of the “s”

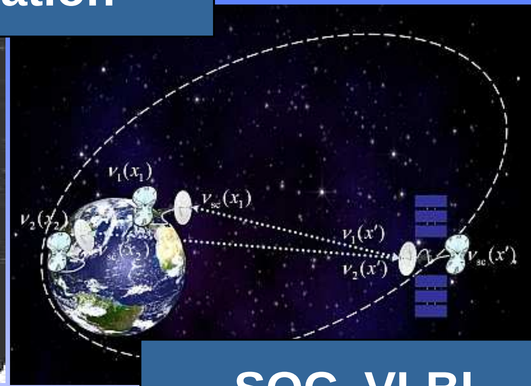
Dimensional Metrology

Who needs (better) clocks?

Astronomy

Navigation

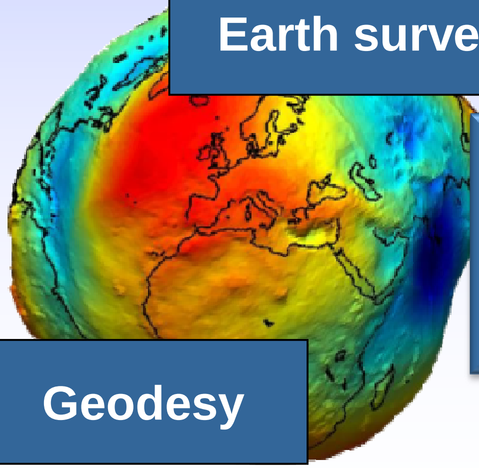
Galileo, GPS



SOC, VLBI

Accelerators

Earth survey

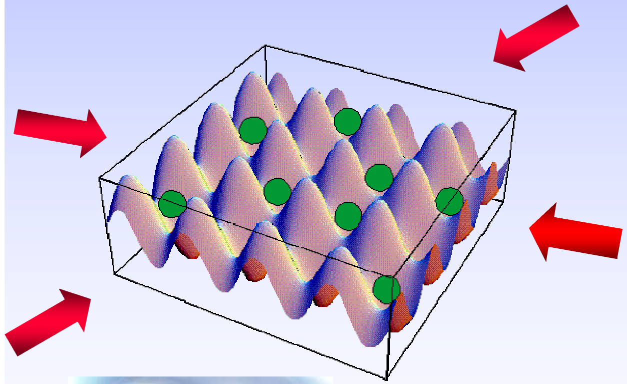


Geodesy

seismics, natural resources, hydrological water inventory, melting of the polar ice caps

Example: Special Theory of Relativity

Moving a clock with 3 m/s shifts its relative frequency by $v/c=10^{-8}$ (1st. order Doppler)



Time Dilation (2nd. order Doppler)
The residual motion of a trapped particle (@ T=100 mK) corresponds to $(v/c)^2 \approx 10^{-16}$

Example: General Theory of Relativity

1m height difference
between two clocks corresponds to a relative frequency shift of 10^{-16}

Optical Clocks and Relativity
C. W. Chou, D. B. Hume, T. Rosenband, D. J. Wineland
Science Vol. 329. no. 5999, pp. 1630 – 1633, (2010)

Example: General Theory of Relativity

PTB

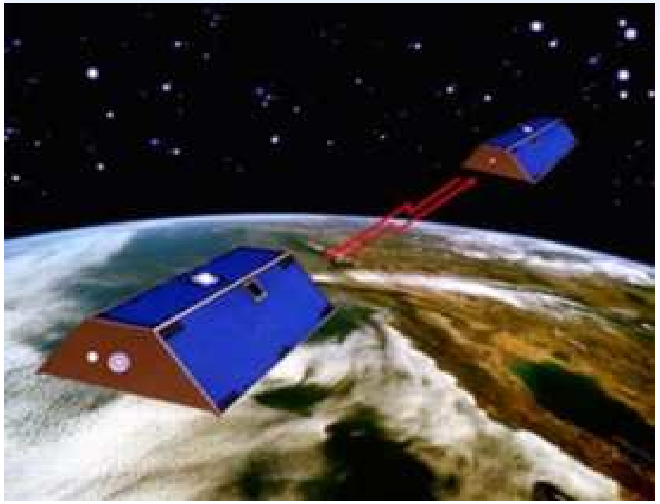
The frequency of a transportable Sr lattice clock (429 THz) at the Sphinx laboratory (3580m) at the Jungfraujoch would be shifted by ≈150 Hz compared to a clock in Braunschweig (75 m).

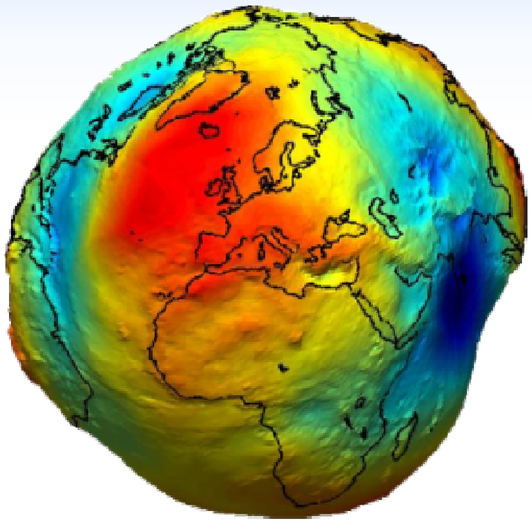
100 cm

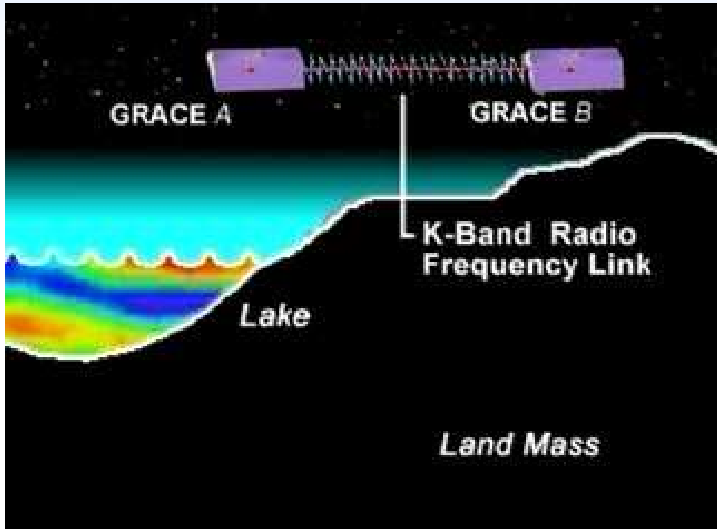
Example: Earth Survey from space

GOCE (Gravity Field and steady-state Ocean Circulation Explorer) launched 2002

GRACE (Gravity Recovery And Climate Experiment) launched 2009



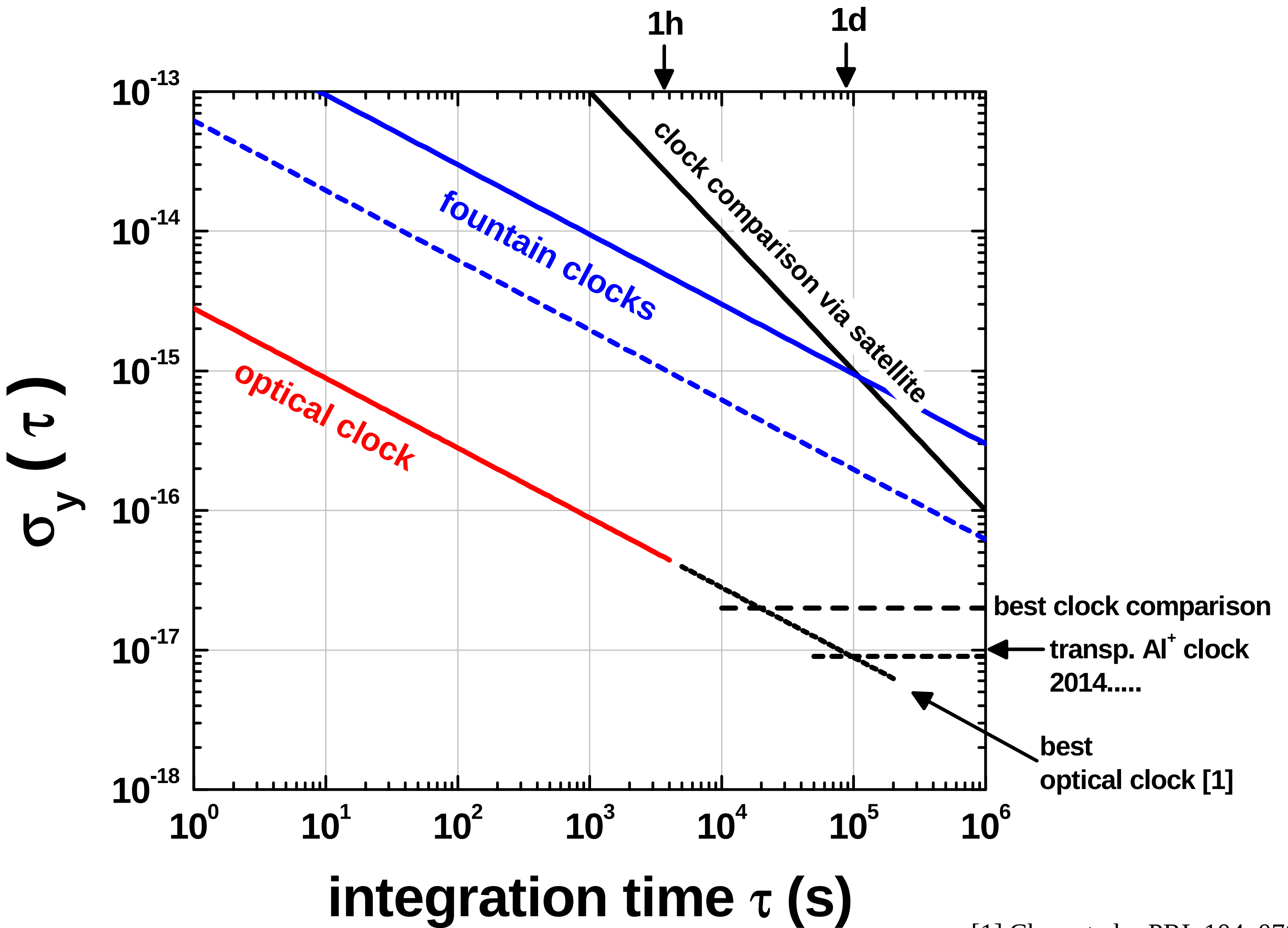




- **Clocks are ideal sensors to measure tiny effects with high precision.**

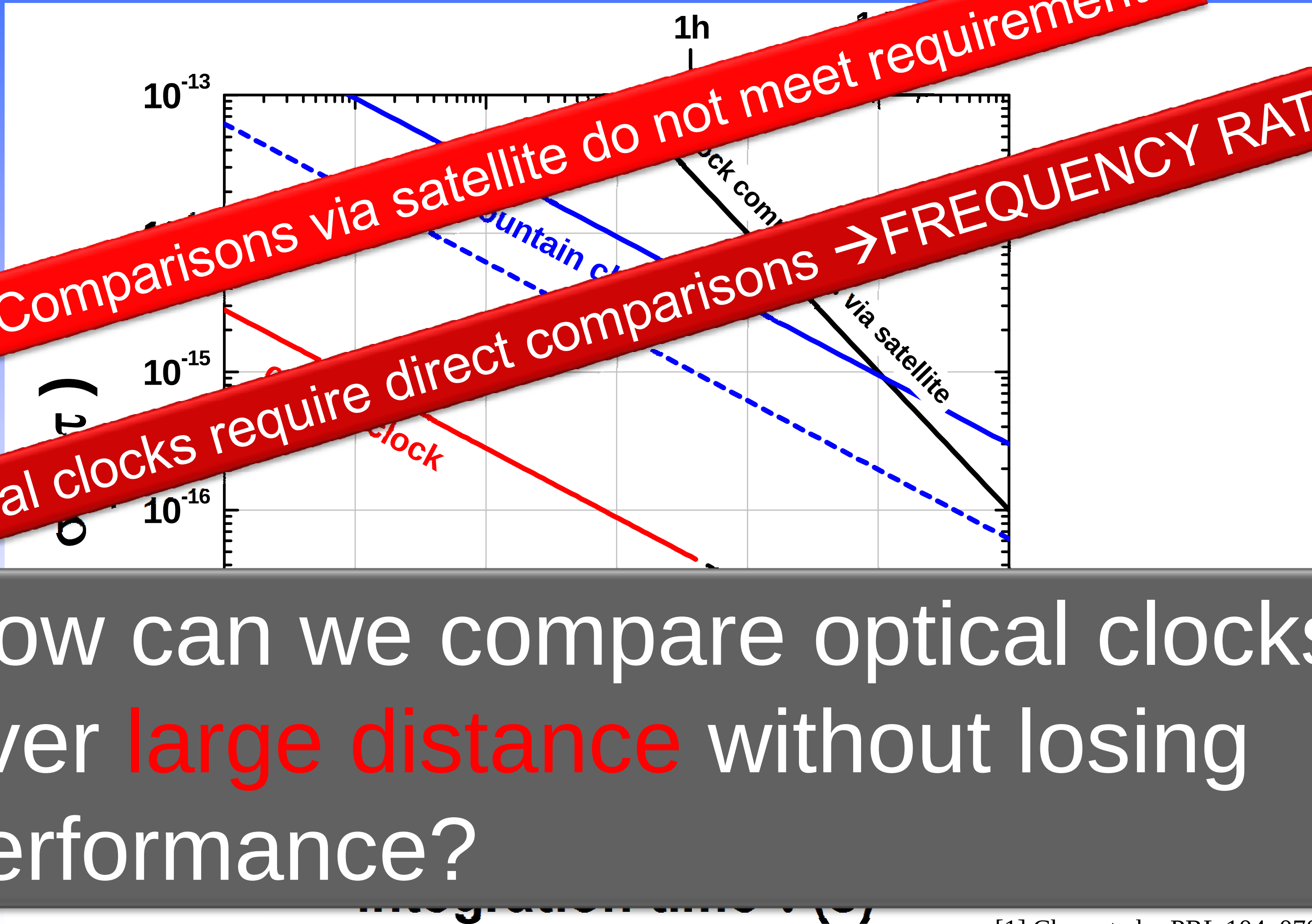
- **This mostly requires a frequency comparison between two clocks.**

Clock comparisons



[1] Chou et al., PRL 104, 070802 (2010)

Clock comparisons



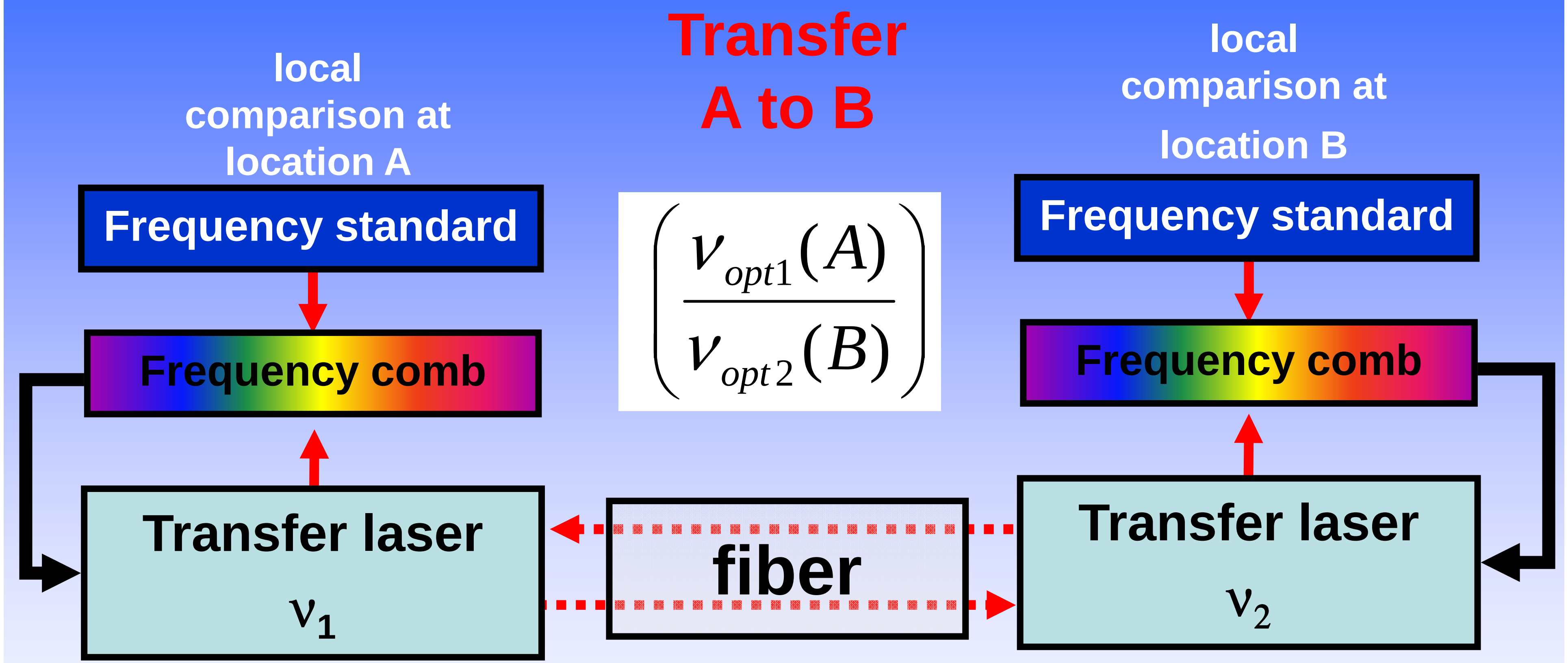
Comparisons via satellite do not meet requirements

Optical clocks require direct comparisons →FREQUENCY RATIO

How can we compare optical clocks over large distance without losing performance?

[1] Chou et al., PRL 104, 070802 (2010)

Comparing remote clocks



$$\left(\frac{\nu_{opt1}(A)}{\nu_{opt2}(B)}\right)$$

$$\left(\frac{\nu_{opt1}}{\nu_1}\right)_A \qquad \nu_1(A)/\nu_2(B) \qquad \left(\frac{\nu_2}{\nu_{opt2}}\right)_B$$

Technical requirements

PTB

- Signal attenuation →
  select low loss fiber: 0.2 dB/km
  in-line bi-directional amplifiers: EDFA
- Stimulated Brillouin Scattering SBS →
  keep input power below threshold: 5 mW
- High isolation against environmental noise (thermal, acoustic, seismic, etc.) →
  use fiber buried under ground
- Coherence of transmitted frequency →
  use highly stable cw laser
- Optical path length changes $\Delta\lambda$ →
  compensate $\Delta\lambda$ by Δf using AO frequency shifter

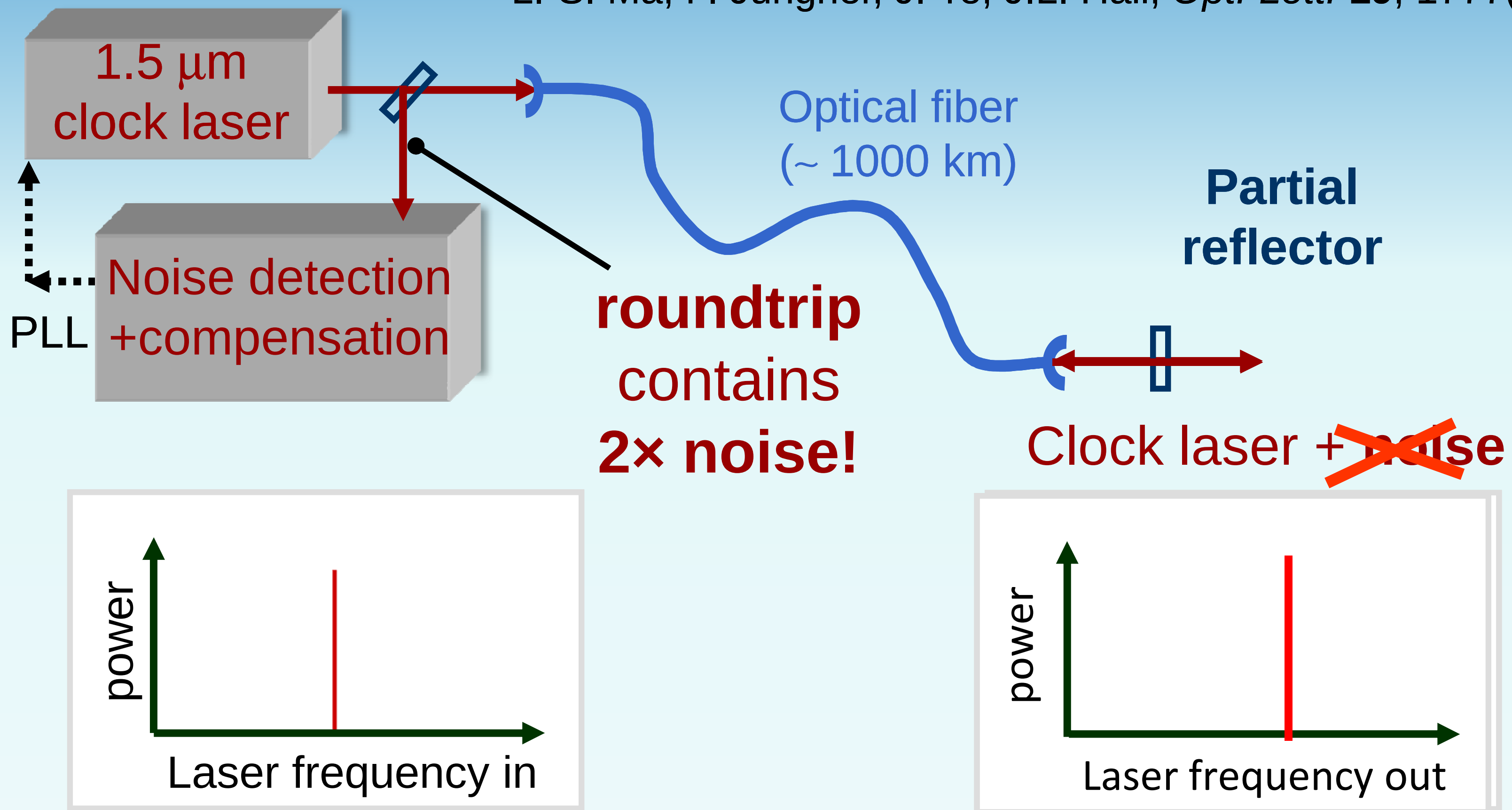
– **Needs bi-directional operation of the link**

Optical path length stabilization

PTB

Compensation of frequency fluctuations due to length fluctuations:*

*L.-S. Ma, P. Jungner, J. Ye, J.L. Hall, *Opt. Lett.* **19**, 1777(1994)



Slide with courtesy of Jeroen Koelemeij
LaserLaB VU University, j.c.j.koelemeij@vu.nl

Some details of the 920 km link

PTB

- 2 *dark* fibers (ITU-T G.652)

  n ~ 1.4681 at 1550 nm

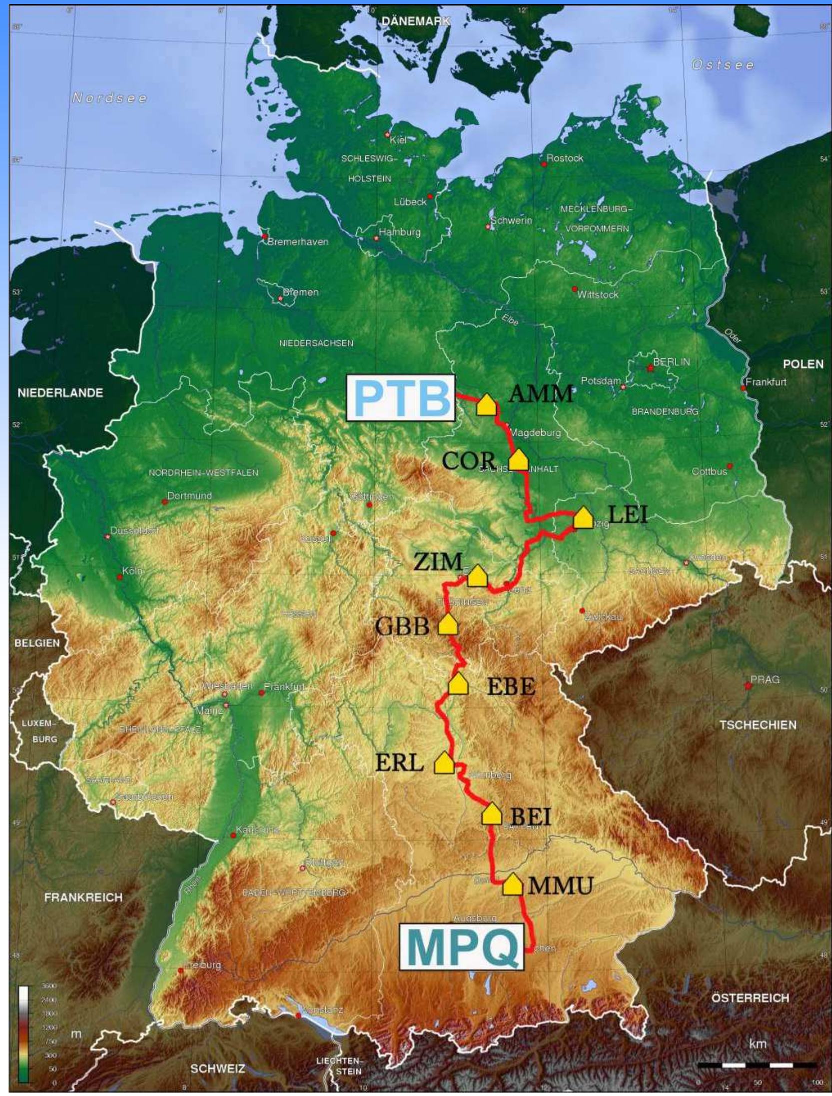
  A~ 0.23 dB/km

  CD~18 ps/(nmkm)

DFN Deutsches Forschungsnetz

GasLINE

- Total fiber length 920 km
- Total one way loss >200 dB
- Access to the link at
  - 7 telecom containers
  - 2 computing centers



Noise Cancelation Limit

PTB

Limited by:

1. Laser noise
2. Out of loop fiber
3. Delay unsuppressed fiber noise

$$S_{\Phi}^{remote}(f) = \frac{4\pi^2}{3} \cdot \left[f \cdot \frac{nL}{c} \right]^2 \cdot S_{\Phi}^{fiber}(f)$$

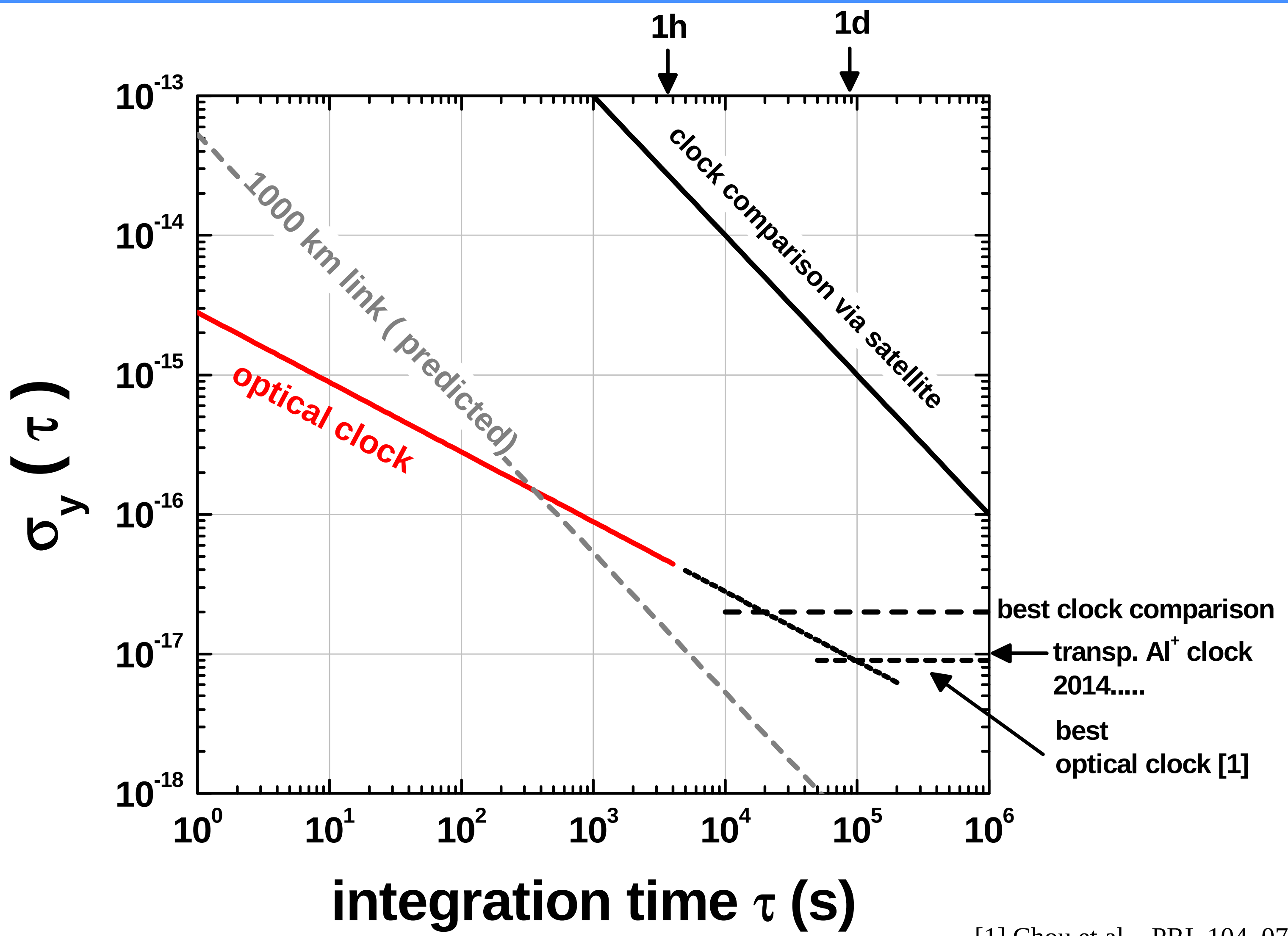
P. A. Williams et al., *J Opt. Soc. Am. B* ***25*** , 1284 (2008)

Assuming: $S_{\Phi}^{fiber}(f, L) \propto L \quad \Rightarrow$

$S_{\Phi}^{remote}(f, L) \propto L^3$

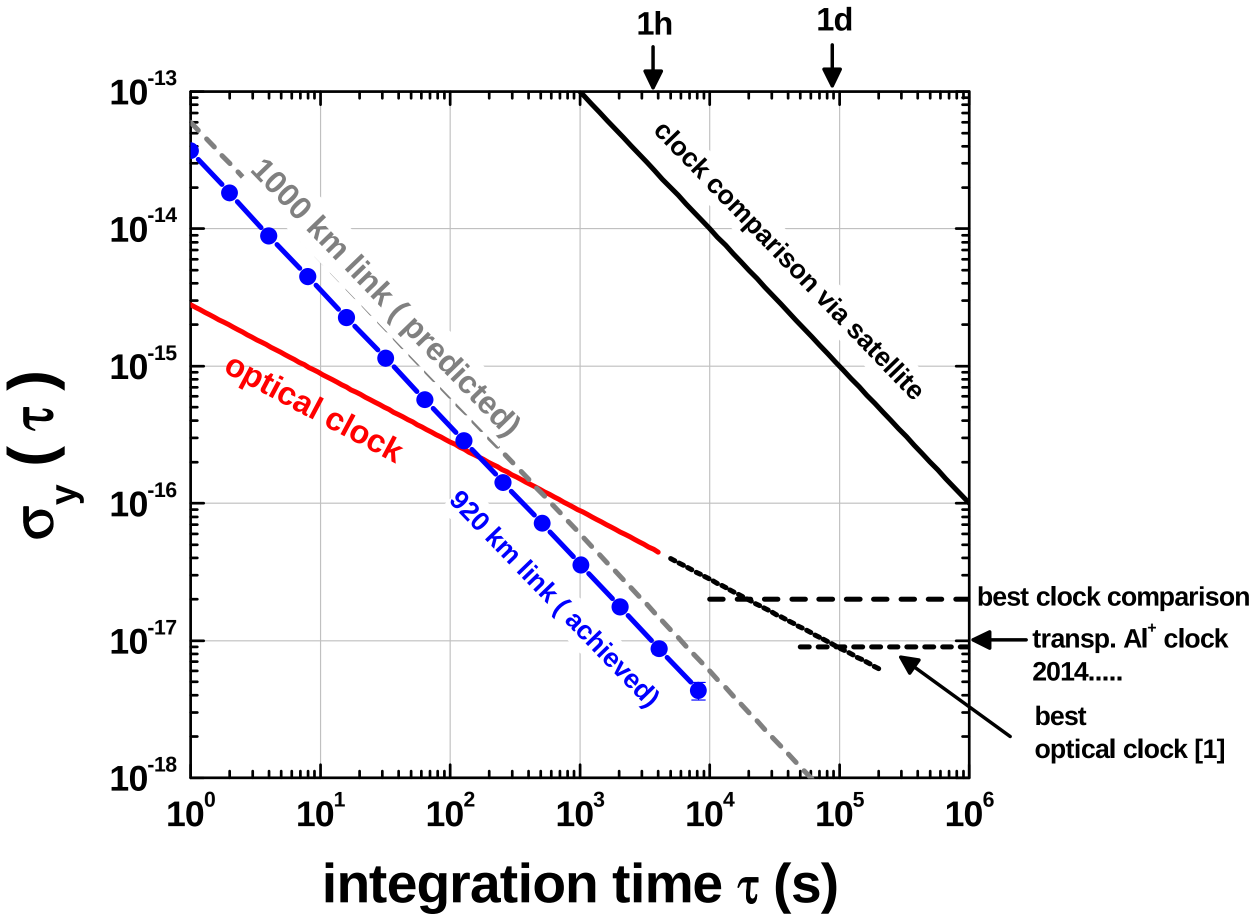
$$ADEV(D,\tau) \approx 2 \cdot \times 10^{-14} \times \sqrt{\left(D/_{480\,km} \right)^3 \cdot 1/_{\tau}}$$

Clock comparisons



[1] Chou et al., PRL 104, 070802 (2010)

Link Instability & Clock Comparisons

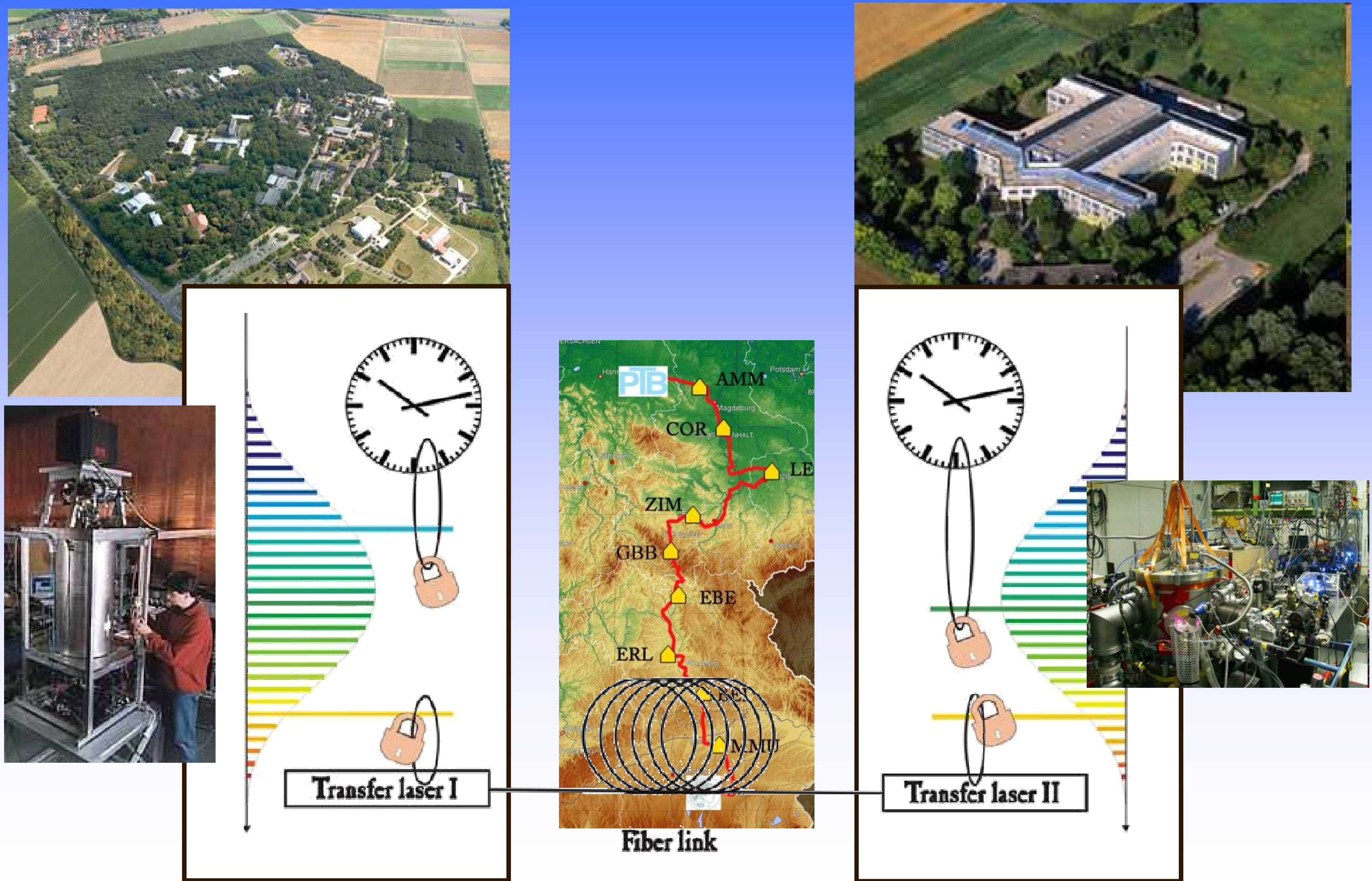


Accuracy: $(\nu_{out} - \nu_{in}) / \nu_{in} < 0.7\ (3.7) \times 10^{-19}$ (<100µHz)

K. Predehl et al., Science, **336**, 441 (2012)

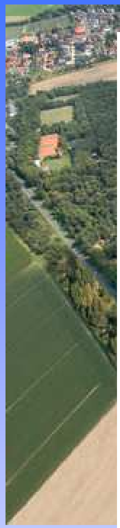
[1] Chou et al., PRL 104, 070802 (2010)

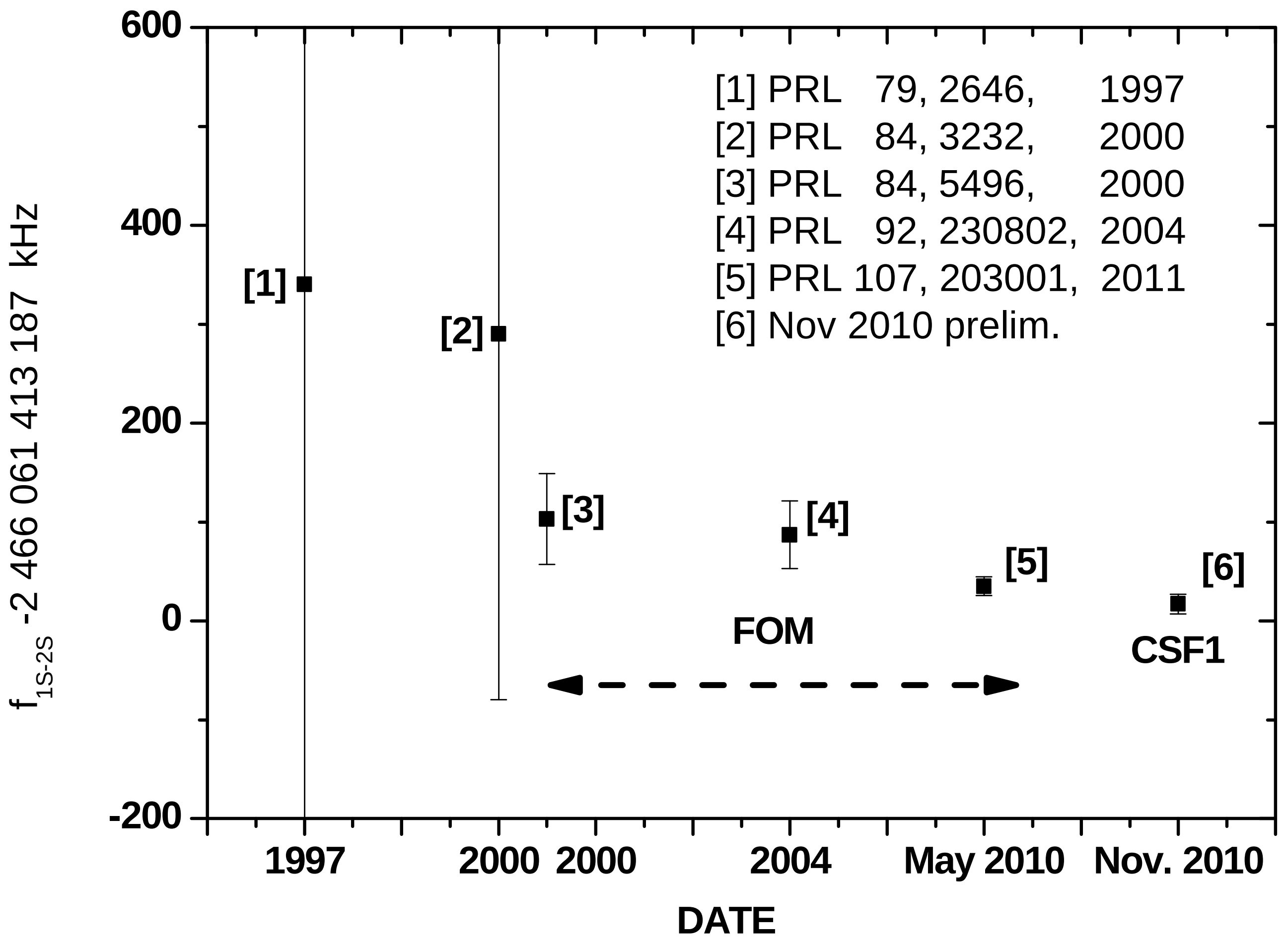
1S-2S Frequency measurement

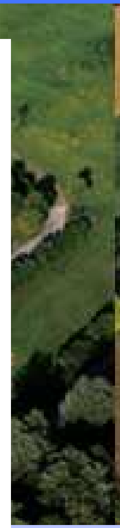


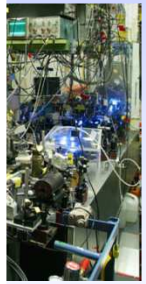
[5] Ch. G. Parthey et al., PRL, 107, 203001 (2011).

1S-2S Frequency measurement









[5] Ch. G. Parthey et al., PRL, 107, 203001 (2011).

Summary

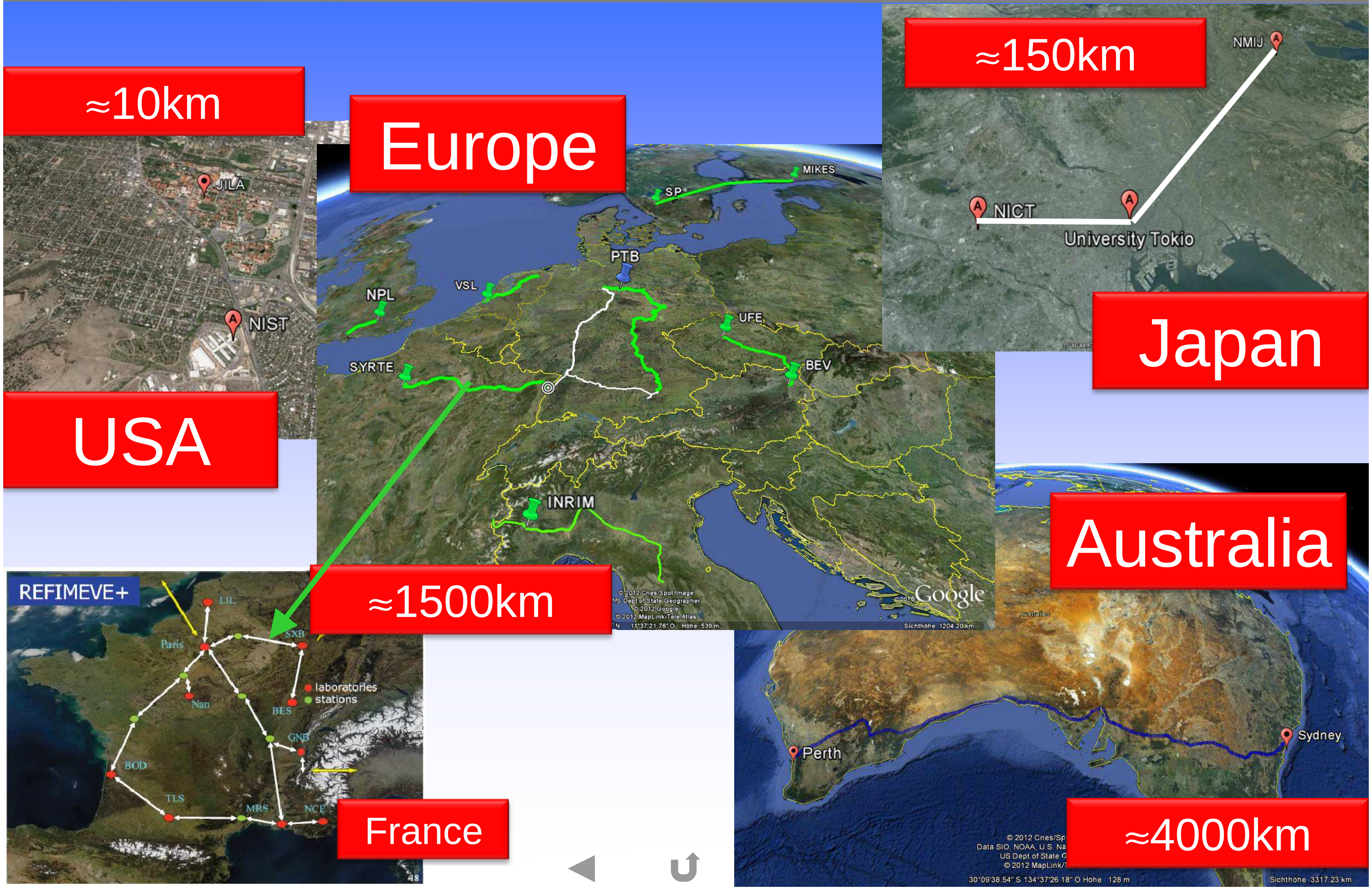
PTB

- We have set up a ***phase stabilized, fully optical*** fiber link for remote clock comparison across Germany.
- The system shows ***stable long term operation*** (>weeks!),
- is highly competitive to satellite based techniques.
- Best performance of **ANY** technique demonstrated to date

  10^{-18} in 10 000 s over 920 km

- Comparision capability factor of 10 better than ANY existing clock
- There seems to be no fundamental limits to run even longer links

International fiber link projects



NEAT-FT: Accurate time & frequency comparison and dissemination through telecommunication networks

EURAMET European Association of National Metrology Institutes

JRP-Coordinator

PTB, Germany

Funded JRP-Participants

BEV, Austria

MIKES, Finland

OBSPARIS, France

UFE, Czech Republic

INRiM, Italy

NPL, United Kingdom

SP, Sweden

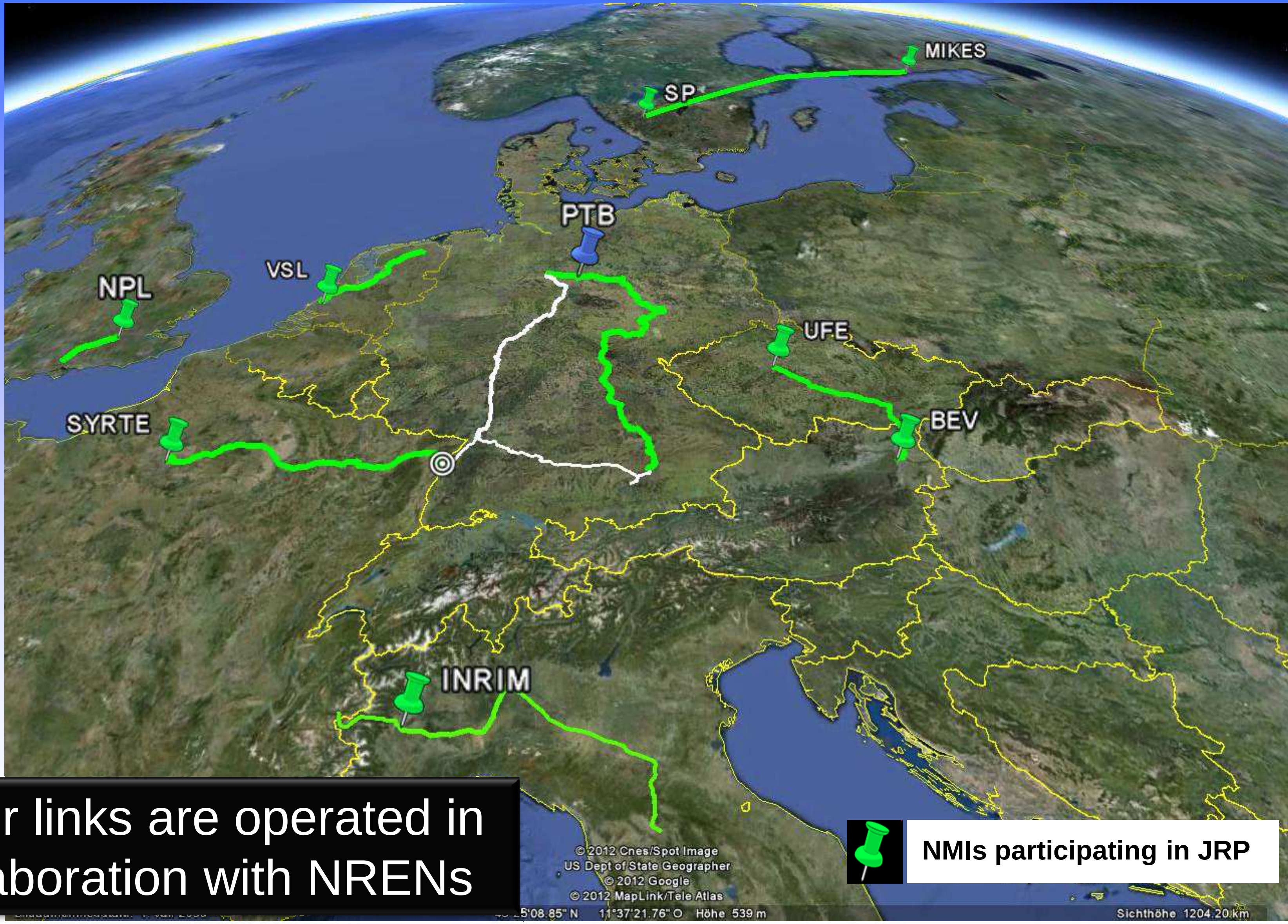
VSL, The Netherlands

Unfunded JRP-Participants

CESNET, Czech Republic

The JRP is supported by 38 stakeholders from industry, national agencies, and academia, including non-European NMIs.

NEAT-FT Participants



Fiber links are operated in collaboration with NRENs

NEAT-FT Participants

Workshop

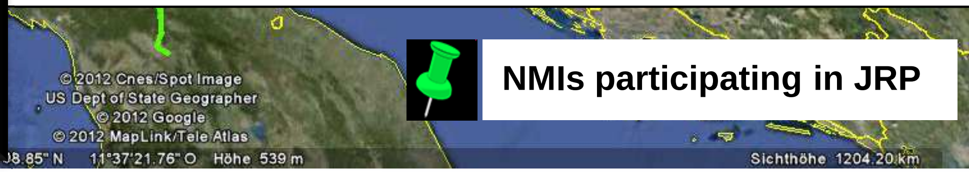
Optical Networks for Accurate Time and Frequency Transfer

20-21 November 2012

Venue: Van der Valk Hotel, Schiphol A4
Hoofddorp, The Netherlands

More information coming soon on
http://www.ptb.de/emrp/neatft_home.html

Fiber links are operated in collaboration with NRENs



NMIs participating in JRP

Outlook

PTB

- Establishing a European network for frequency and time dissemination will require further support by National Research & Education Networks (NREN) or fiber providers.

- Optical fiber links will find broad applications in fundamental and applied science.

The Vision of 2020