Physikalisch-Technische Bundesanstalt
Braunschweig and Berlin
National Metrology Institute

European Time and Frequency Services

Why are optical T/F services so popular?

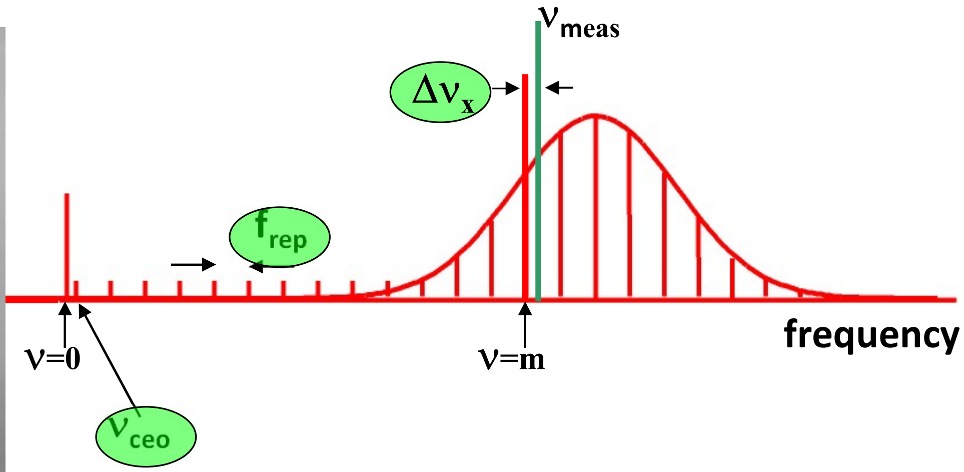
Problems to be solved and use cases

H. Schnatz, on behalf of CloNetS DS
Clock Network Services Design Study

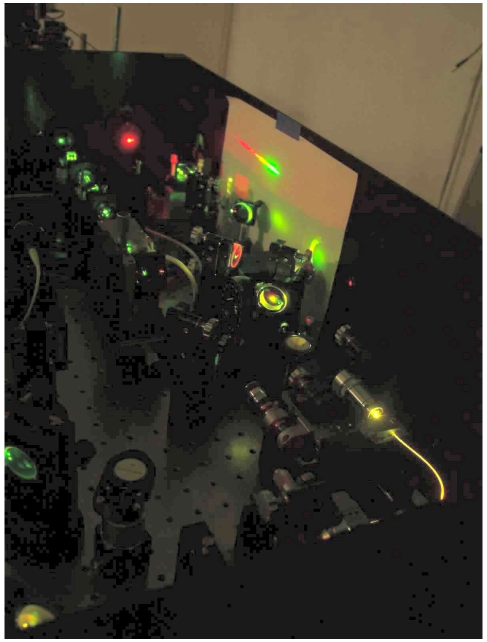
Why are optical T/F services so popular?

Frequency is the most precise measurable quantity

"Never measure anything but frequency!"
was the advice of A. Schawlow to his students

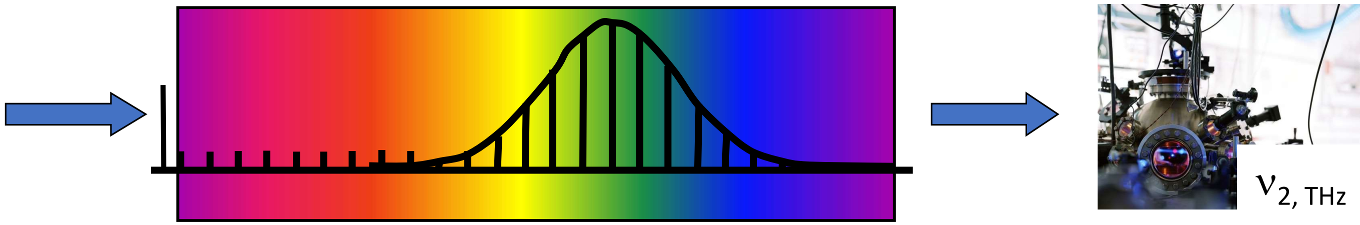


$$\nu_{meas} = \nu_{ceo} + m\, f_{rep} + \Delta\nu_X$$



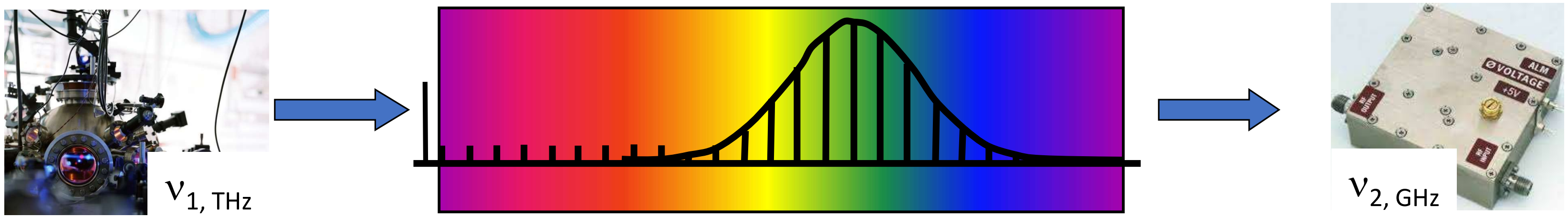
Purpose of Frequency Comb

From microwaves to optical references



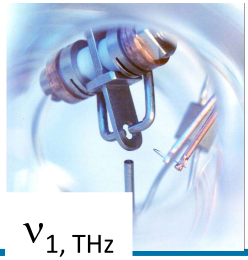
multiply

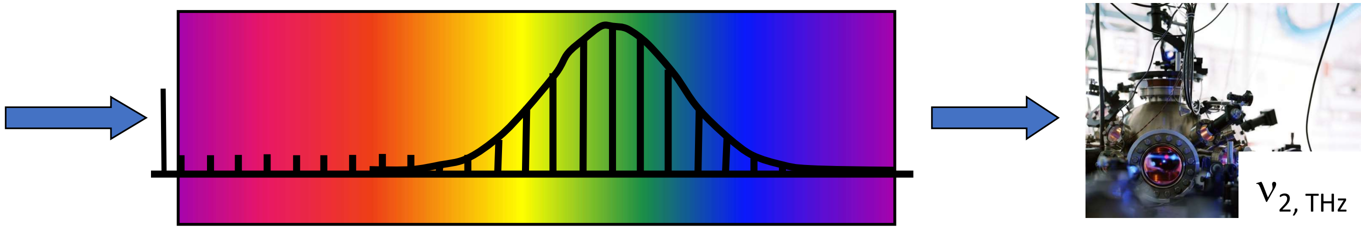
From optical to microwave references



divide

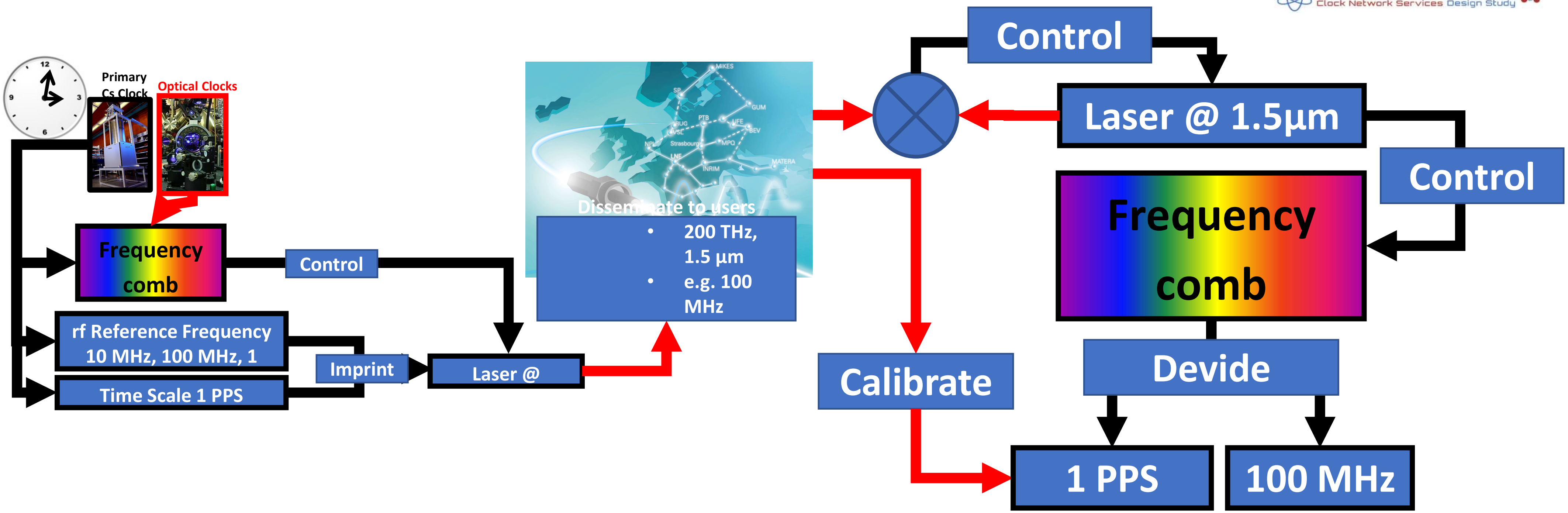
From optical to optical references





compare

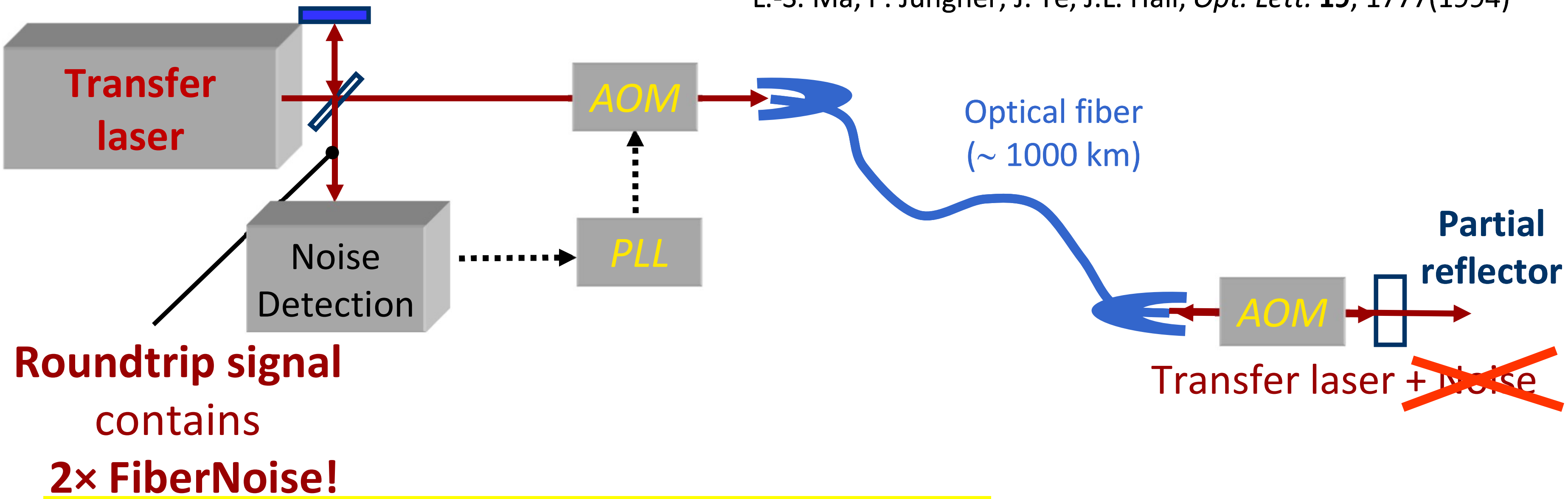
Dissemination of Reference Signals via Optical Fibers



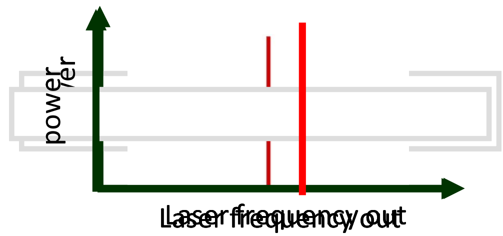
Stabilisation of the transmission channel

Compensation of frequency fluctuations due to length fluctuations:*

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



This scheme requires fully bi-directional operation!

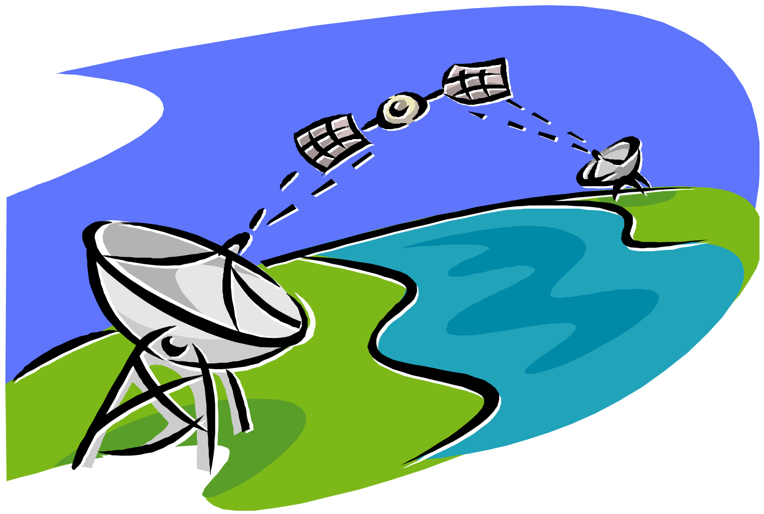


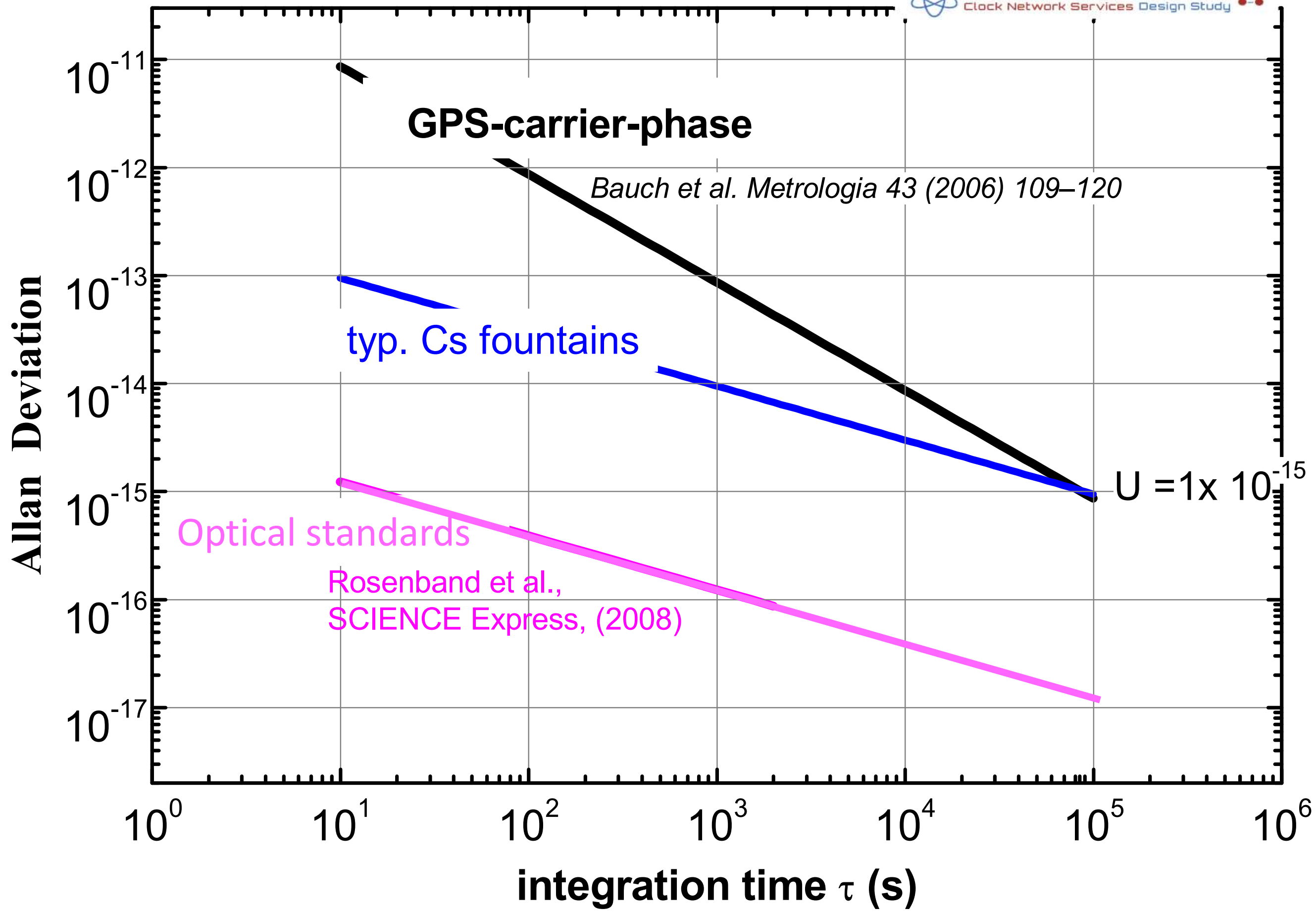
*Foreman et al. Rev. Sci Inst. **78** 021101 (2007); Williams et al., J. Opt. Soc. Am. B **25** 1284 (2008) …*

Use Cases and Problems to be solved

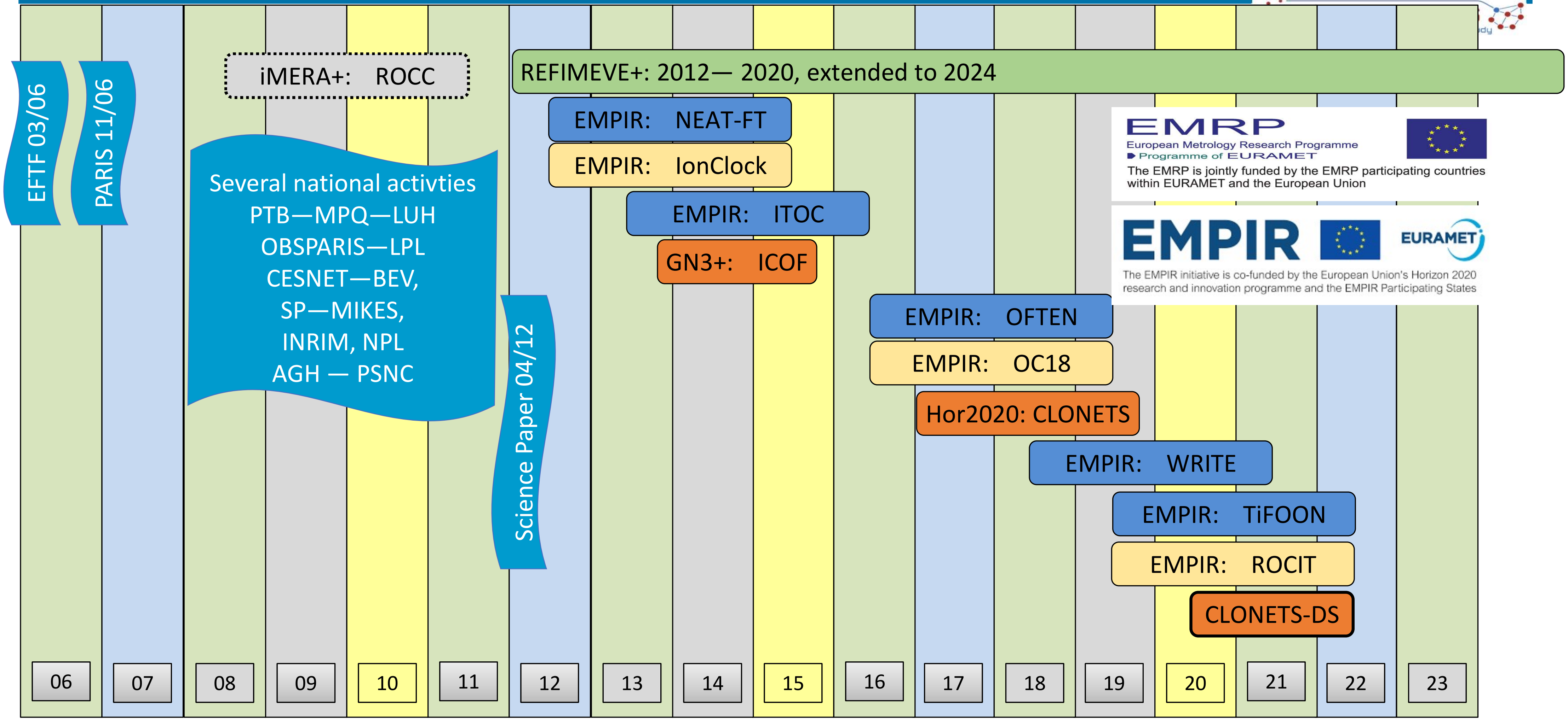
Problems to be solved and use cases

Frequency Transmission via Satellite & Fibers

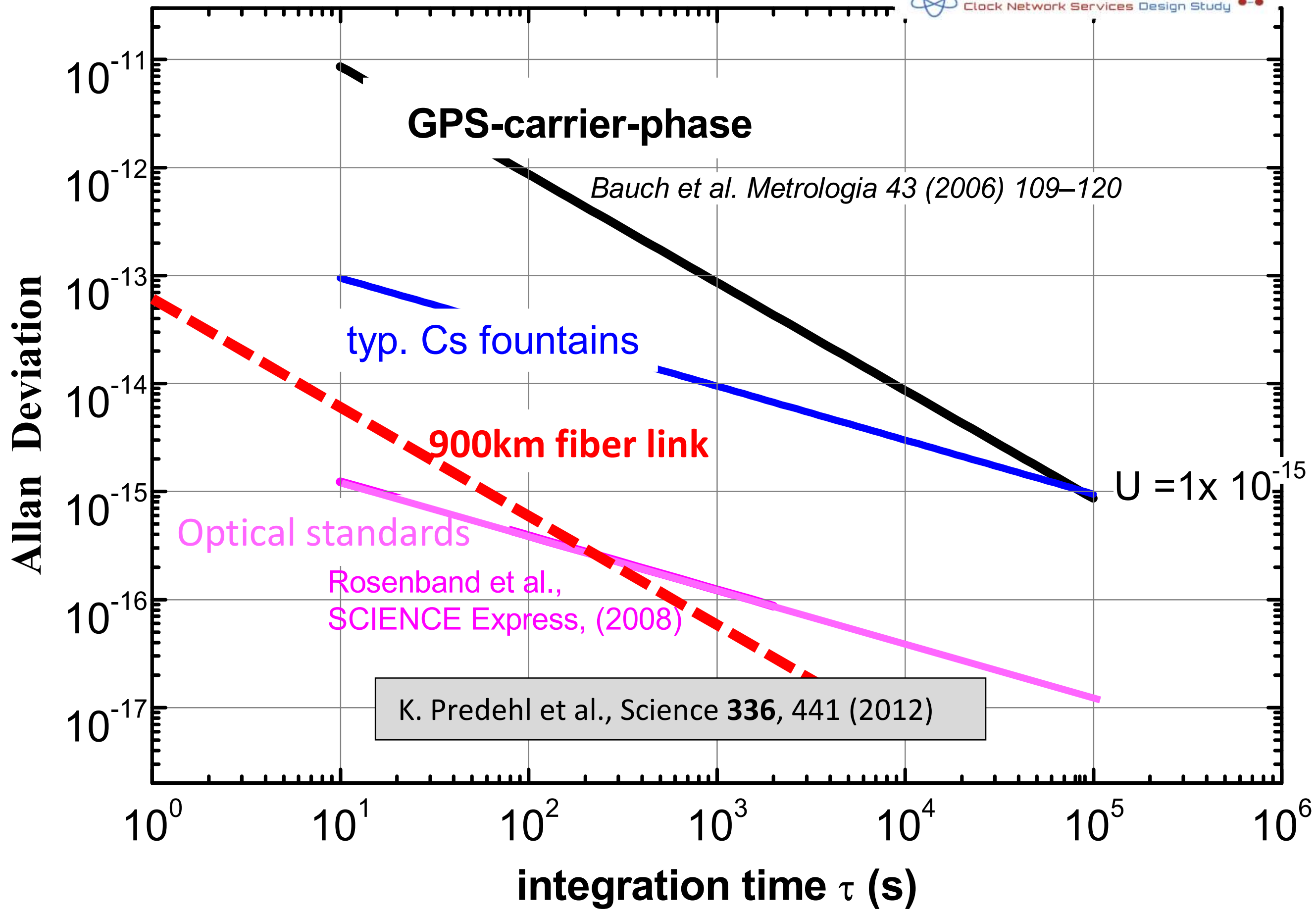




Overview: T&F Fiber Projects

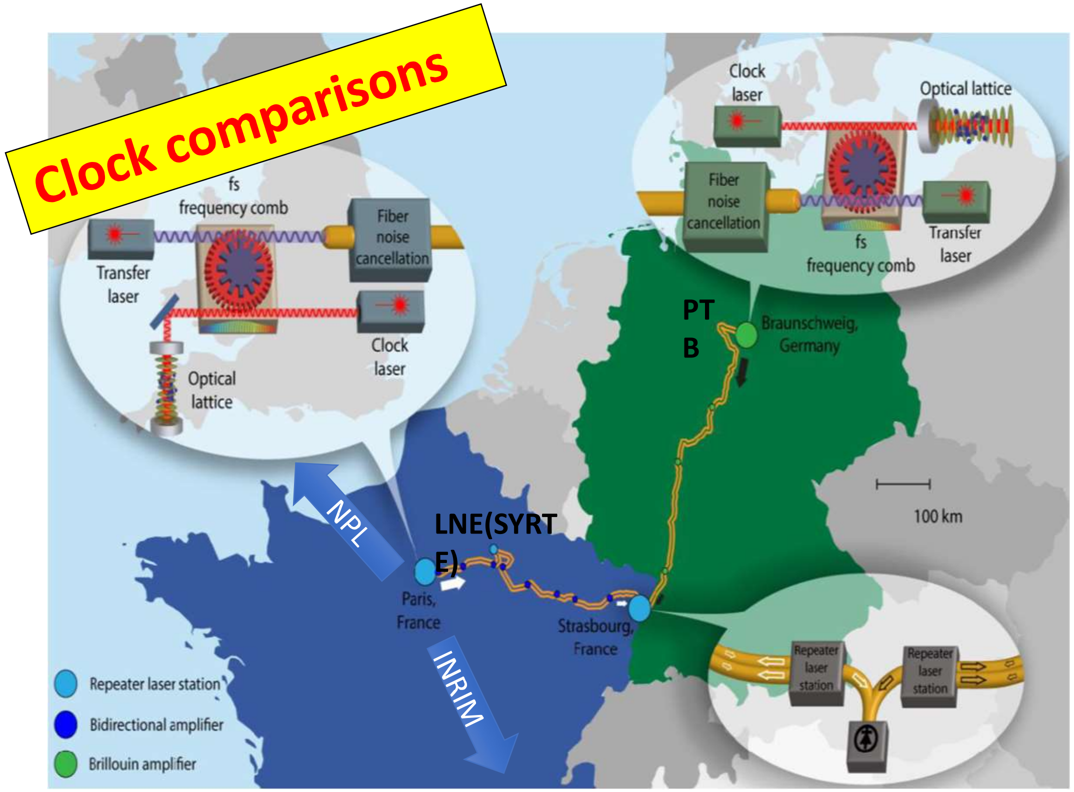


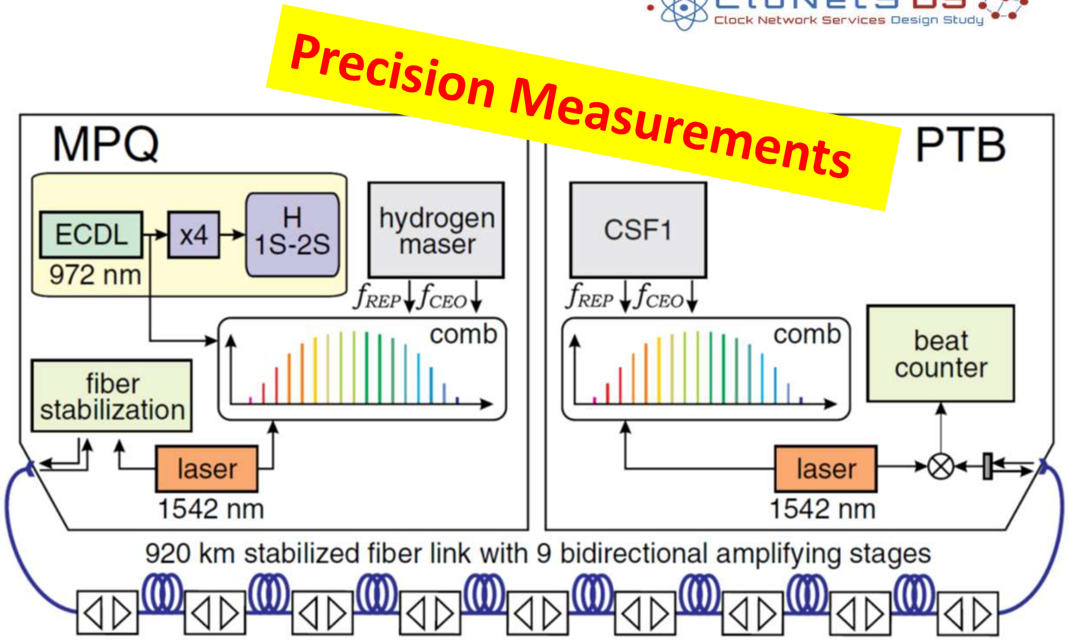
Frequency Transmission via Satellite & Fibers



Optical fibres & optical standards make new time and frequency transfer capabilities possible!

Time and Frequency metrology





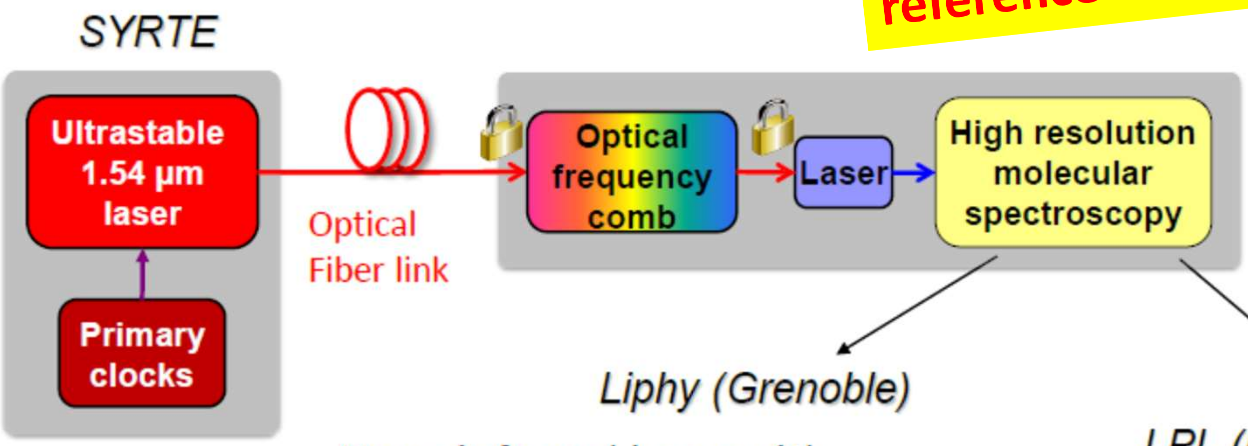
Matveev et al., PRL 110, 230801 (2013)

- Frequency Instability Sr^{PTB}-Sr^{SYRTE}: 2×10^{-17} (2000 s)
- Agreement of distant clocks: $(4.7 \pm 5) \times 10^{-17}$

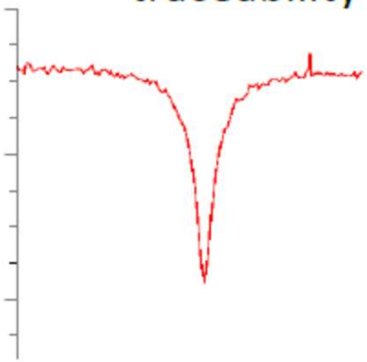
- Hydrogen 1S-2S: $\nu_{1S\text{-}2S}$= 2466 061 413 187 018 (11) Hz
- Relative uncertainty: 4.5×10^{-15}

Time and Frequency metrology

reference frequencies for users



Near-infrared laser with traceability to primary standards

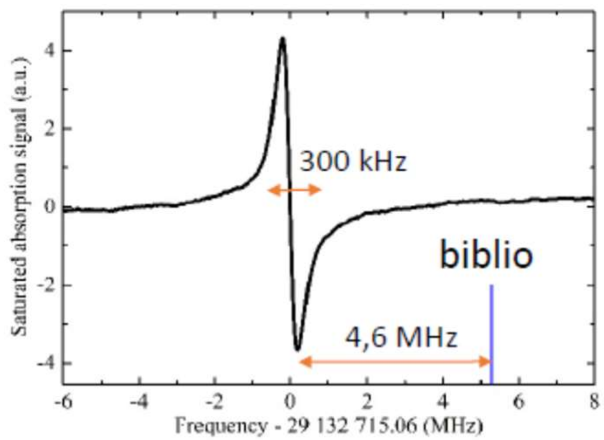


Absorption line of methane

-> Atmospheric studies

With courtesy of Liphy

Methanol absorption line



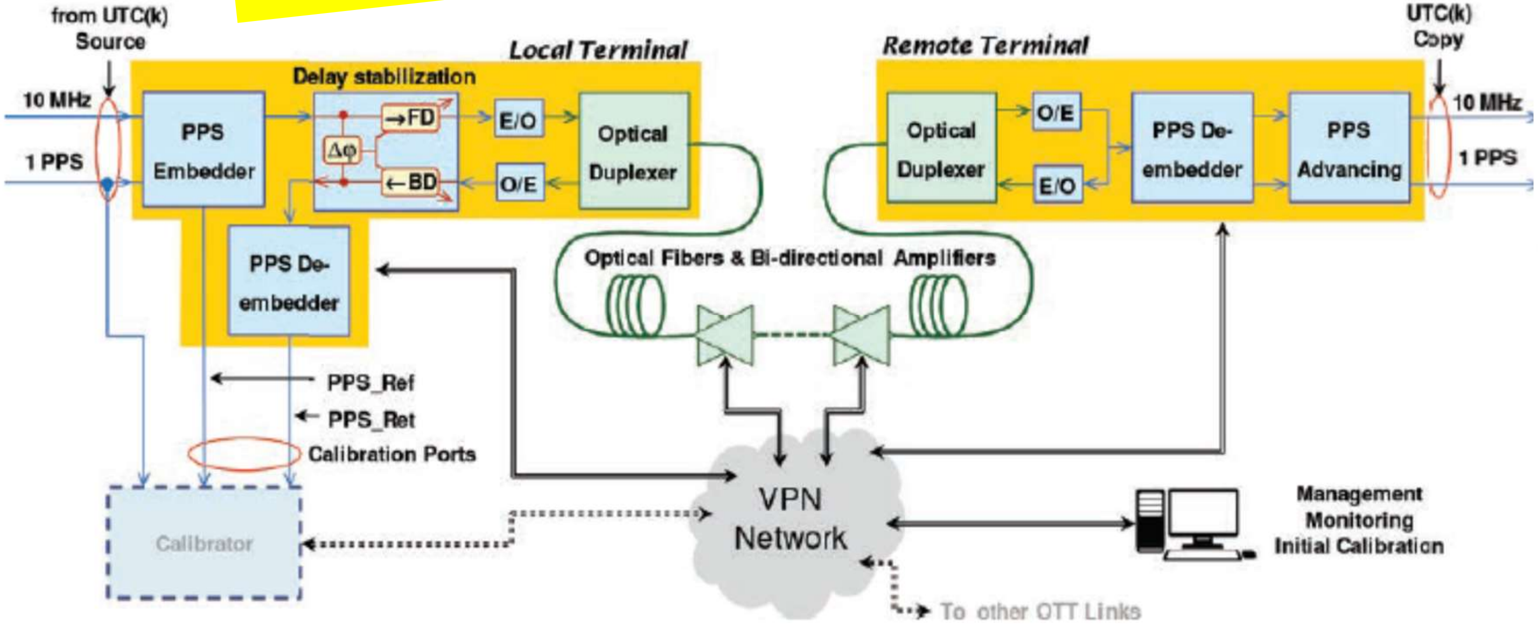
Spectroscopy of Methanol with Quantum Cascade Laser emitting at 10 µm
It copies the stability of SYRTE reference with traceability to primary standards
-> Atmospheric studies and astrophysical interest

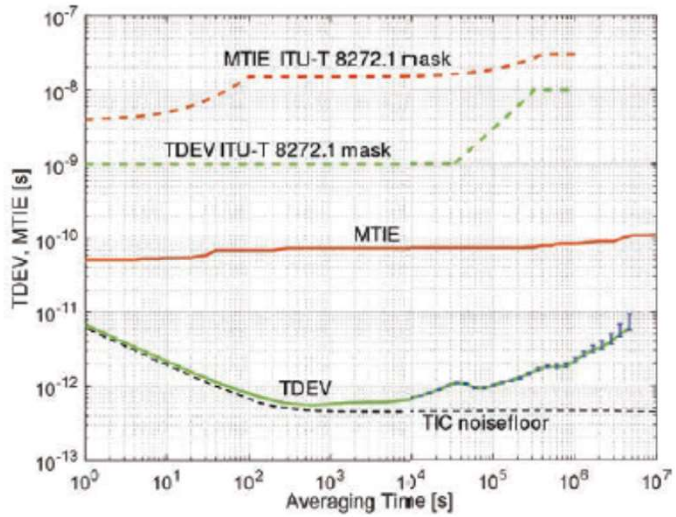
Argence Nature Photon 2015, Santagata, Optica 2018

Slide shown by A. Amy-Klein @ TiFOON workshop
The REFIMEVE optical fibernetwork, Anne Amy-Klein, LPL, Université Sorbonne Paris Nord and CNRS

Time and Frequency metrology

Better time scales





- Timing Jitter @ ps-level
- Accuracy @ 10 – 30 ps -level

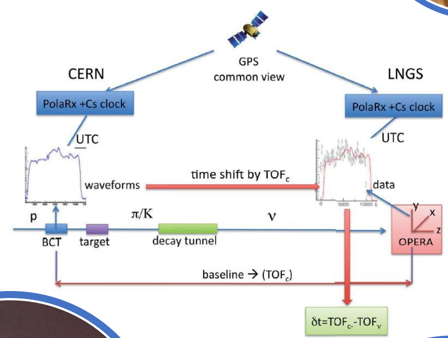
Śliwczyński, Ł..; Krehlik, P.; Imlau, H.; Ender, H.; Schnatz, H.; Piester, D. & Bauch, A.
Fiber-Based UTC Dissemination Supporting 5G Telecommunications Networks
IEEE Communications Magazine, **2020**, *58*, 67-73

Better Timescales

- Back-up system for GNSS (*ground clocks*)
  - In July 2019 Galileo had failed for 11 days due to ground clocks.
  - December 14, *2020* had failed for 6 hours due *an anomaly in the time determination function of the ground segment of the system."*
- GNSS vulnerable to spoofing
  - US Executive Order 13905, Strengthening National Resilience Through Responsible Use of Positioning, Navigation, and Timing Services
- Neutrinos faster than light?

J. High Energ. Phys. **2012,** 93 (2012).
https://doi.org/10.1007/JHEP10(2012)093

- Time distribution networks for critical infrastrucutre
  - markets in Financial Instruments (*MiFID II*) - *Directive*



Synchronization of mobile networks

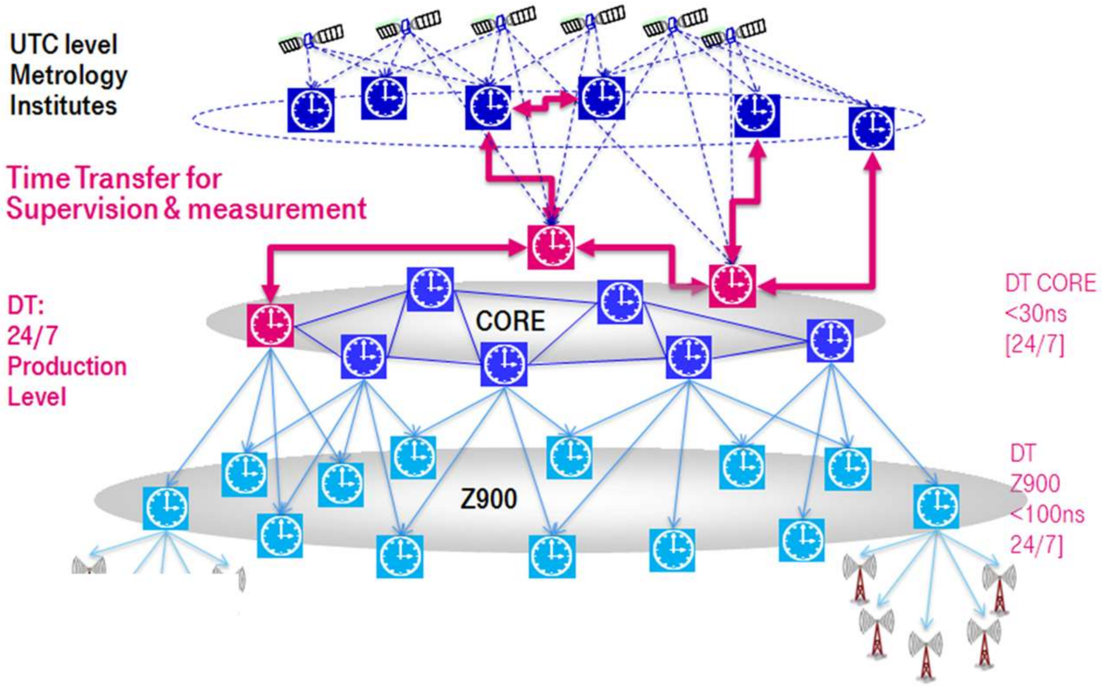
Enhanced Primary Clocks and Time Transfer
Synchronization network supervision need Time Transfer

A cnPRTC based core network needs supervision which should be …

- … independent from GNSS to be able to detect any GNSS anomaly or problem
- … accurate and precise enough for ±30 ns network requirement at backbone level

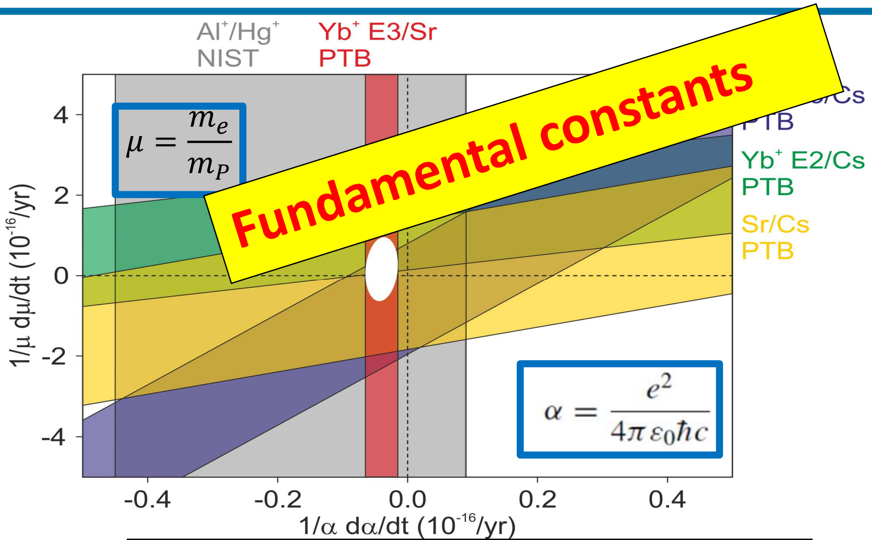
Options:

1. GNSS common view allows ≈ 10 ns
2. High accuracy Time Transfer for providing remote reference



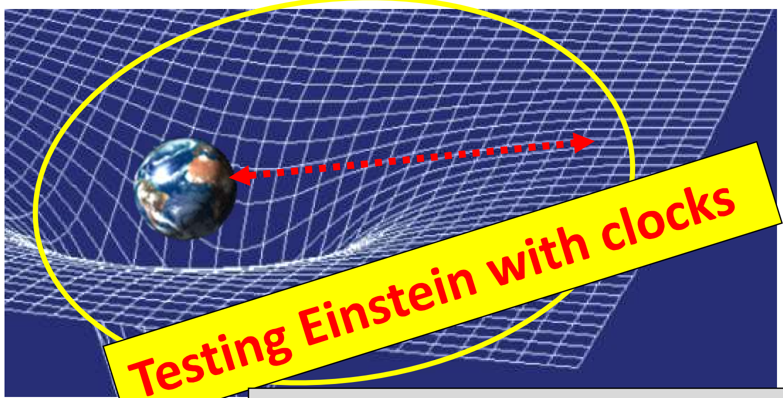
Slide shown by H. Imlau, D Telekom @ TiFOON workshop Time and frequency in Telecommunication: requirements, methods and architecture

Test of fundamental Theories



Fundamental constants

N. Huntemann *et al.,* Phys. Rev. Lett. 113, 210802 (2014)



Testing Einstein with clocks

P. Delva, *et al.;* PRL 118, 221102 (2017)

Searches for dark matter

B.M. Roberts, *et al.;* New J. Phys. 22 (2020) 093010

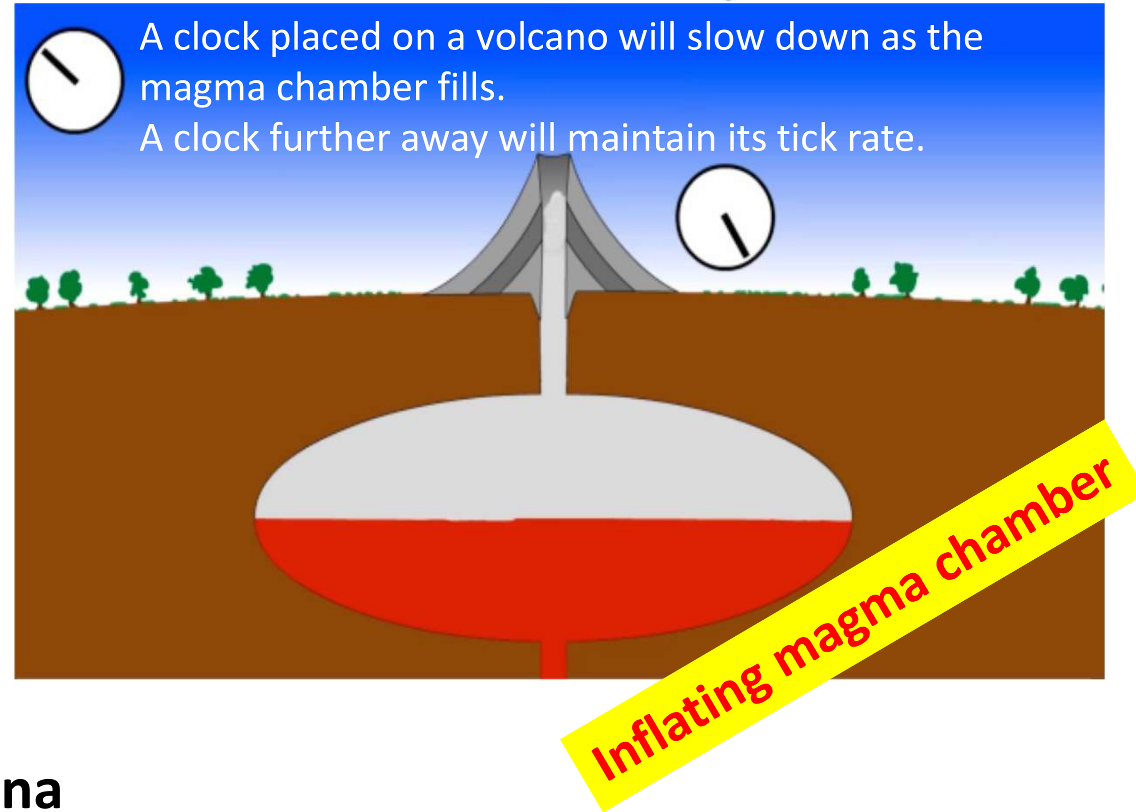
- Variations of the fine structure constant: $< 5 \times 10^{17}$ (@ 10^3s)

Geophysics with ground-based atomic clocks

- R. Bondarescu, *et al.;* **Geophysical applicability of atomic clocks: direct continental geoid mapping,** *Geophys. J. Int.* (2012) **191,** 78–82

- M. Bondarescu, *et al.;* **The Potential of Continuous, Local Atomic Clock Measurements for Earthquake Prediction and Volcanology,** *EPJ Web of Conferences,* **2015**, *95*, 04009

- R. Bondarescu, *et al.;* **Ground-based optical atomic clocks as a tool to monitor vertical surface motion,** *Geophys. J. Int.* (2015) **202,** 1770–1774



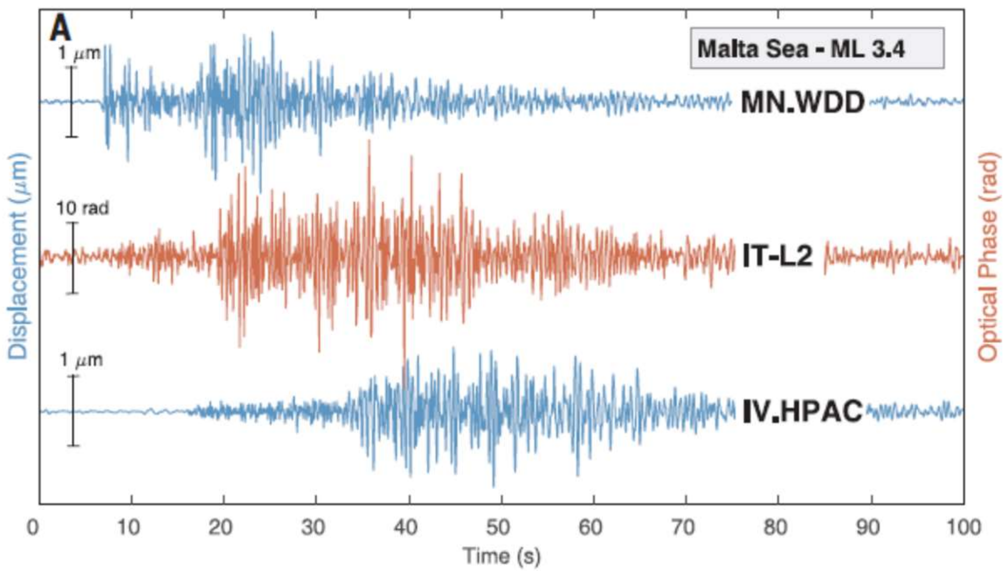
➢ **Inflating magma chamber, Example Etna**

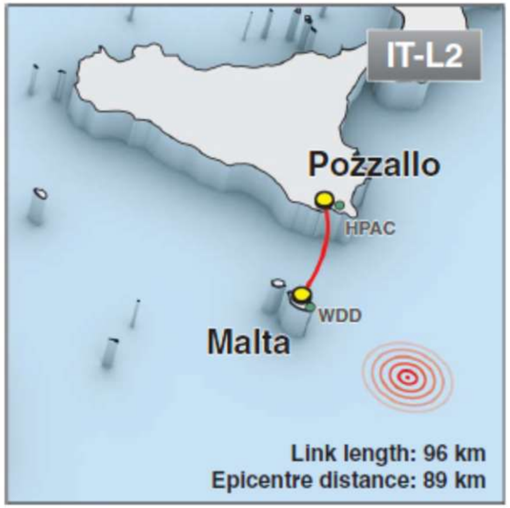
➢ **Solid Earth tides→ requires large separation of clocks/ continental scale**

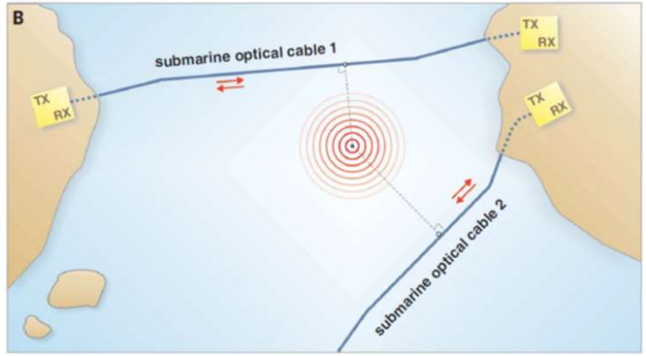
Geophysics with ground-based atomic clocks

CloNetS DS
Clock Network Services Design Study

Earthquake detection



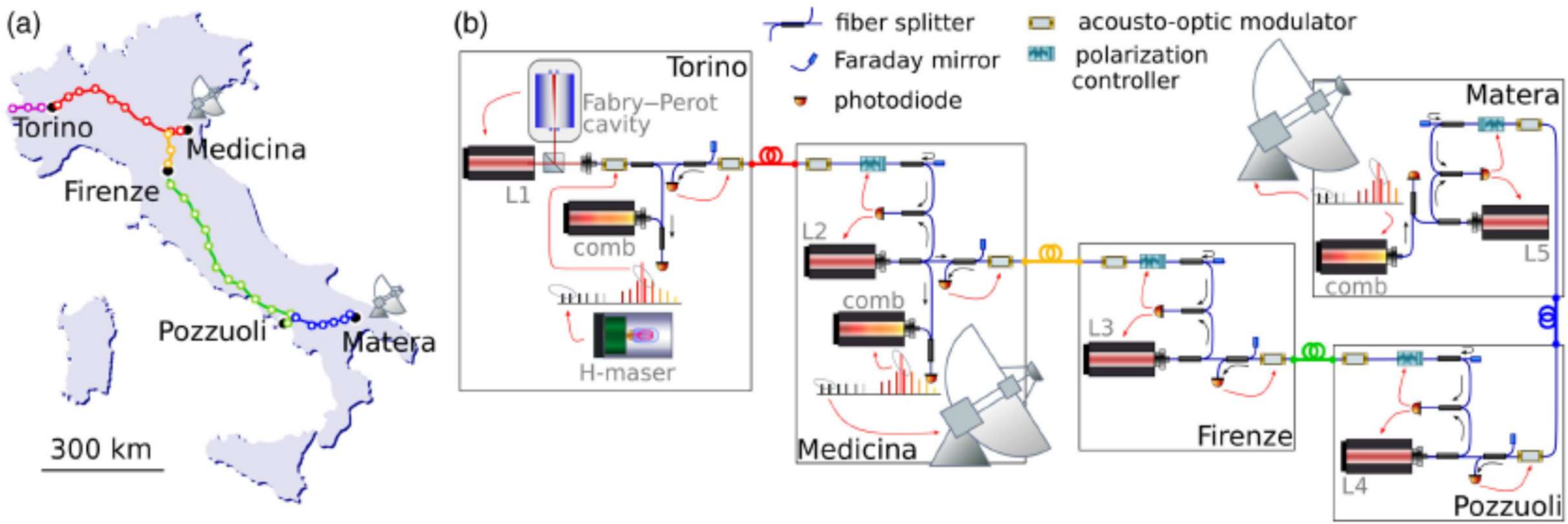




Marra, G.; et al.; Ultrastable laser interferometry for earthquake detection with terrestrial and submarine cables *Science*, **2018**, *361*, 486-490

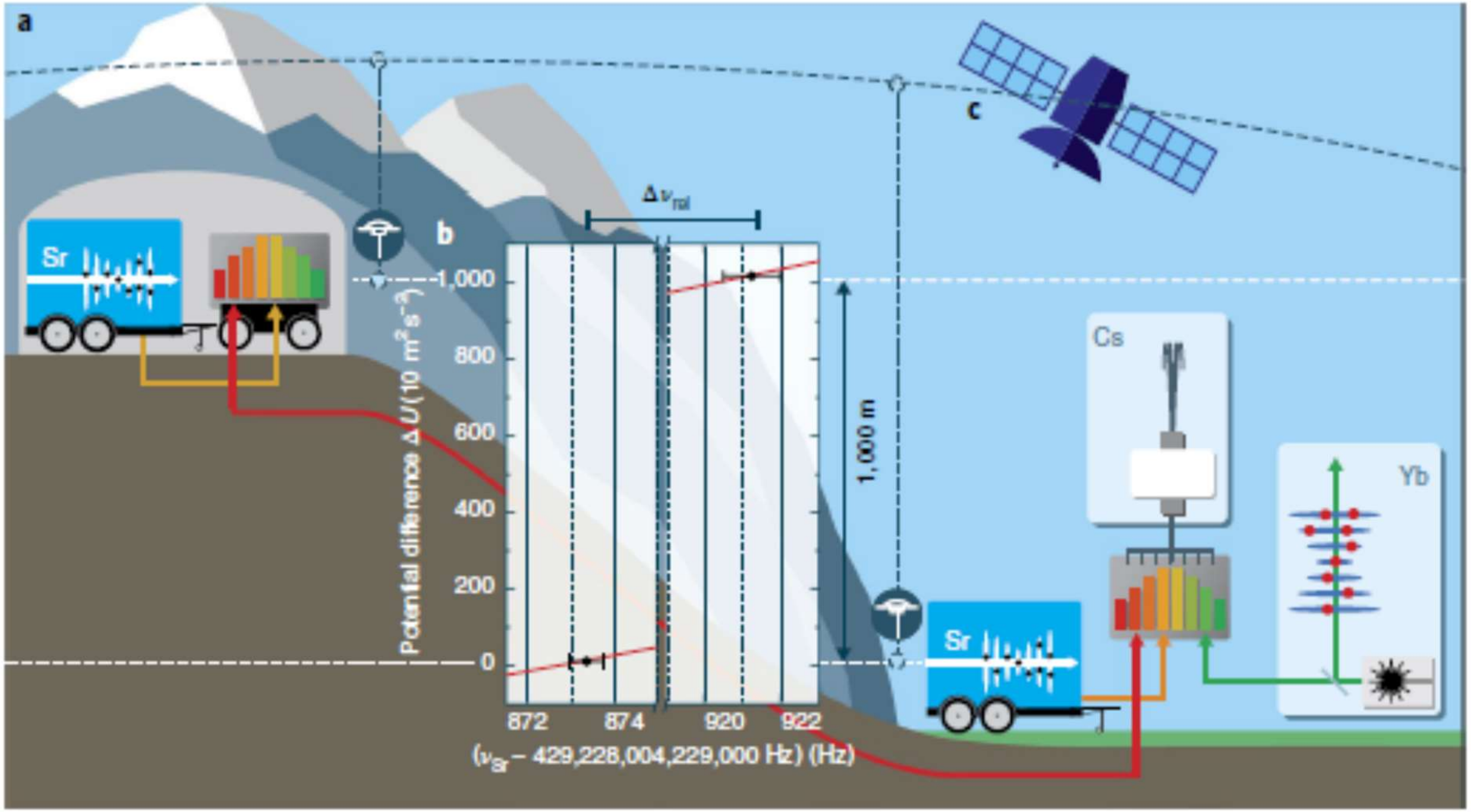
Syntonisation of astrophysical observatories

Talk of P. Boven, today



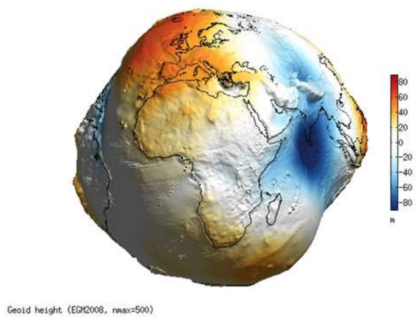
Clivati, C.; et al.; Common-clock very long baseline interferometry using a coherent optical fiber link, *Optica,* **2020**, *7*, 1031-1037

Geodesy with ground-based atomic clocks



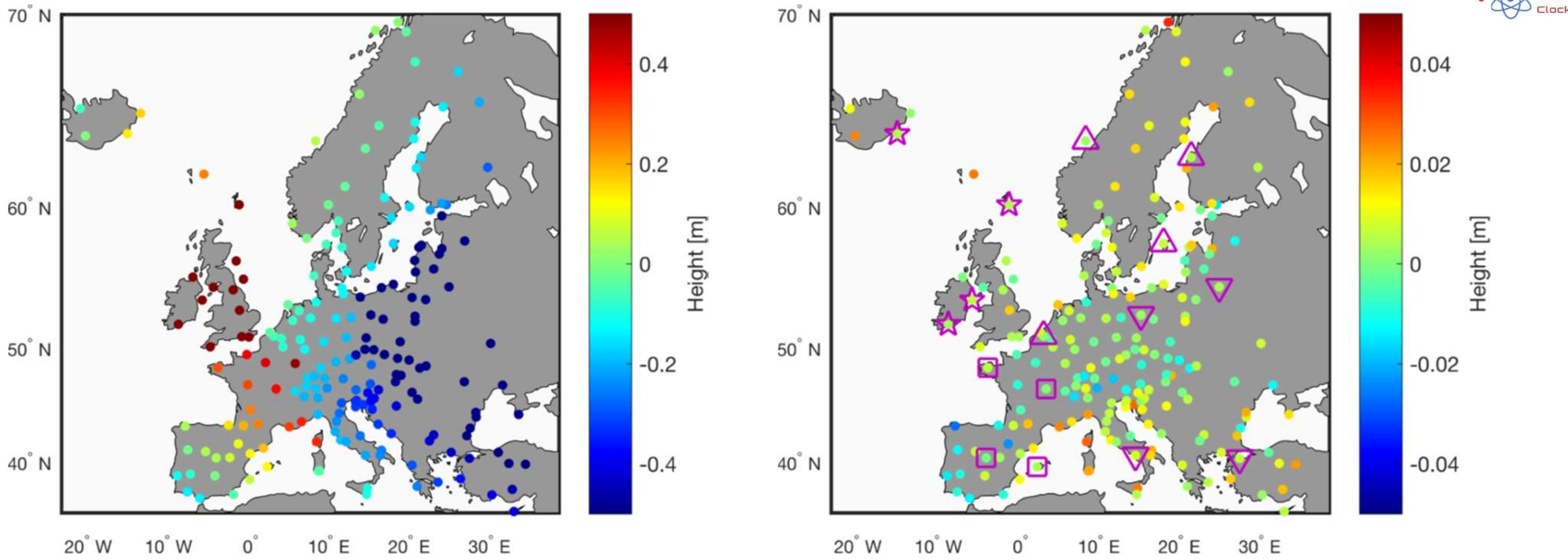
Gravitational red shift

$$\frac{\Delta\nu}{\nu}=\frac{U_P-U_0}{c^2}$$



Grotti, J.; *et al.;* Geodesy and metrology with a transportable optical clock, *Nature Physics,* **2018**, *14*, 437-441

Clocks for Unifying Height Systems



Clocks are powerful in obtaining height differences between distant points.

This makes them appropriate for height system unification,by identifying:

- discrepancies (offsets) between different height datums;
- systematic distortions of national/regional levelling networks.

Slide shown by J. Müller @ TiFOON workshop
Application of clock measurements in geodesy
J. Müller, IFE, Leibniz Univ. Hanover

Requirements on link infrastructure:

- **Transmission based on dark fiber or dark channel**
  - **availability of the same ITU channel** through the whole network.
    - ideally ITU-channel 44
    - attenuation as low as possible   typically 20dB/100km
    - low PMD: PMD-Coefficient better than 0.5 ps / km$^{1/2}$.

- **Bi-directional operation is indispensible**
  - fiber pair in the **same** fiber bundle

- **fibers in underground conduct**
  with good thermal and seismic isolation

Requirements on link infrastructure:

- **APC connectos/ E2000 to eliminate back reflections**
- **Possibility to implement dedicated equipment**
- **Access to containers guarantied**
- **Signal:**

  ultrastable, single frequency, optical carrier

  2 AM Lasers $\pm$ 12.5 or $\pm$ 25 GHz from optical carrier, providing

  - Rf signal: 10MHz, 100 MHz, or 1GHZ
  - Timing signal: 1 PPS

Problems to be solved

- Sustainable access to dark fiber or channel
- Traceability to SI system
- Redundancy
- Interoperability throughout Europe
- Management of the network
- Stakeholder involvement
- Sustainable financial support

CloNetS DS

Clock Network Services Design Study

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