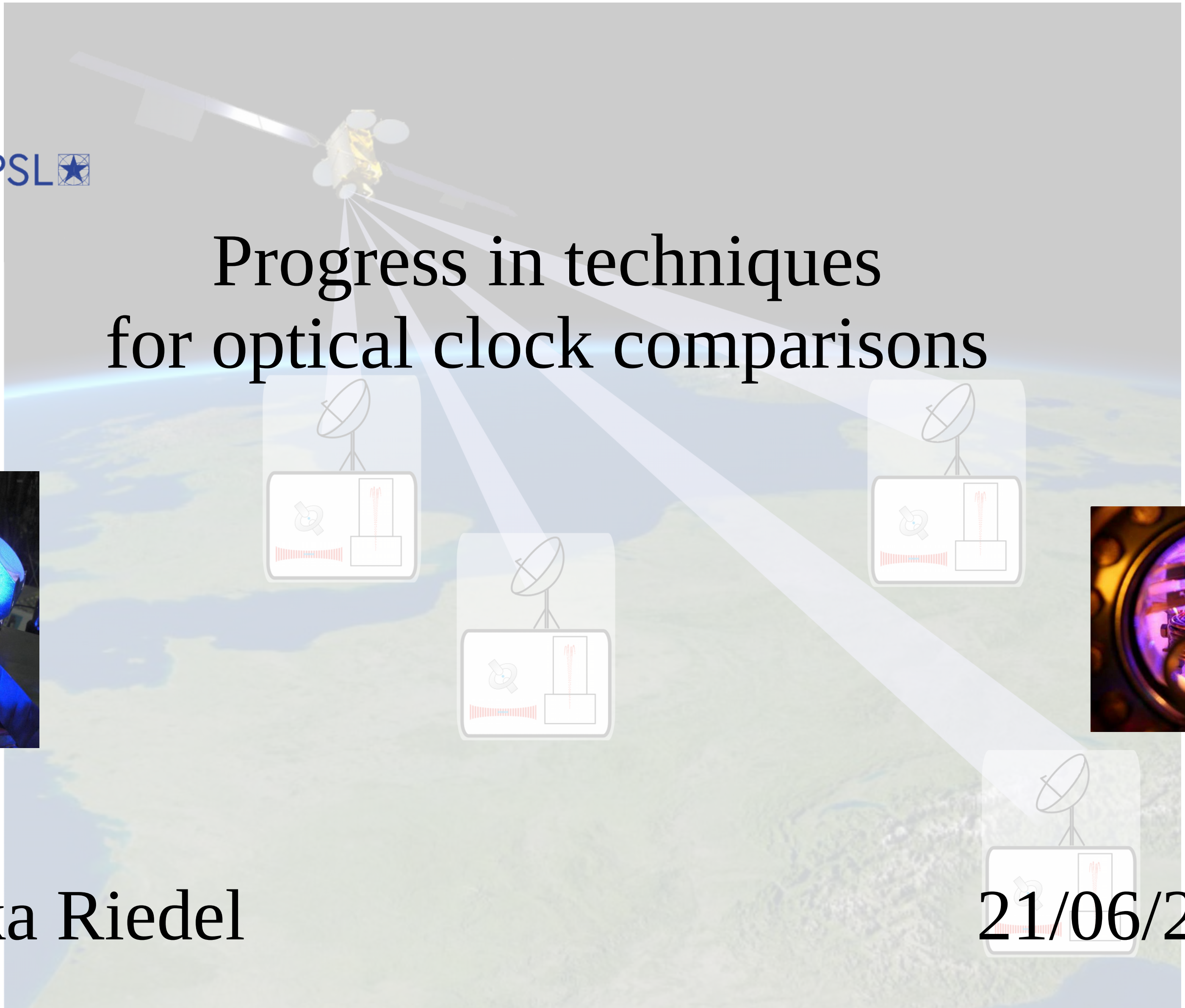
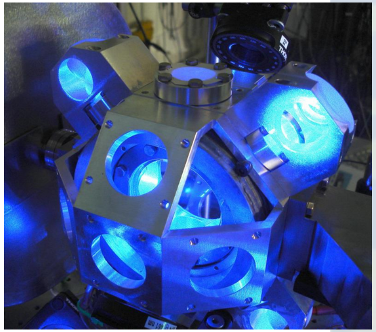
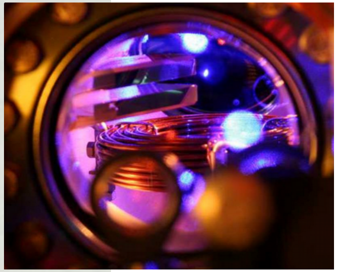


Progress in techniques for optical clock comparisons





Franziska Riedel

21/06/2021

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First simultaneous international comparison of optical clocks*:

- planning and execution
- data analysis
- results

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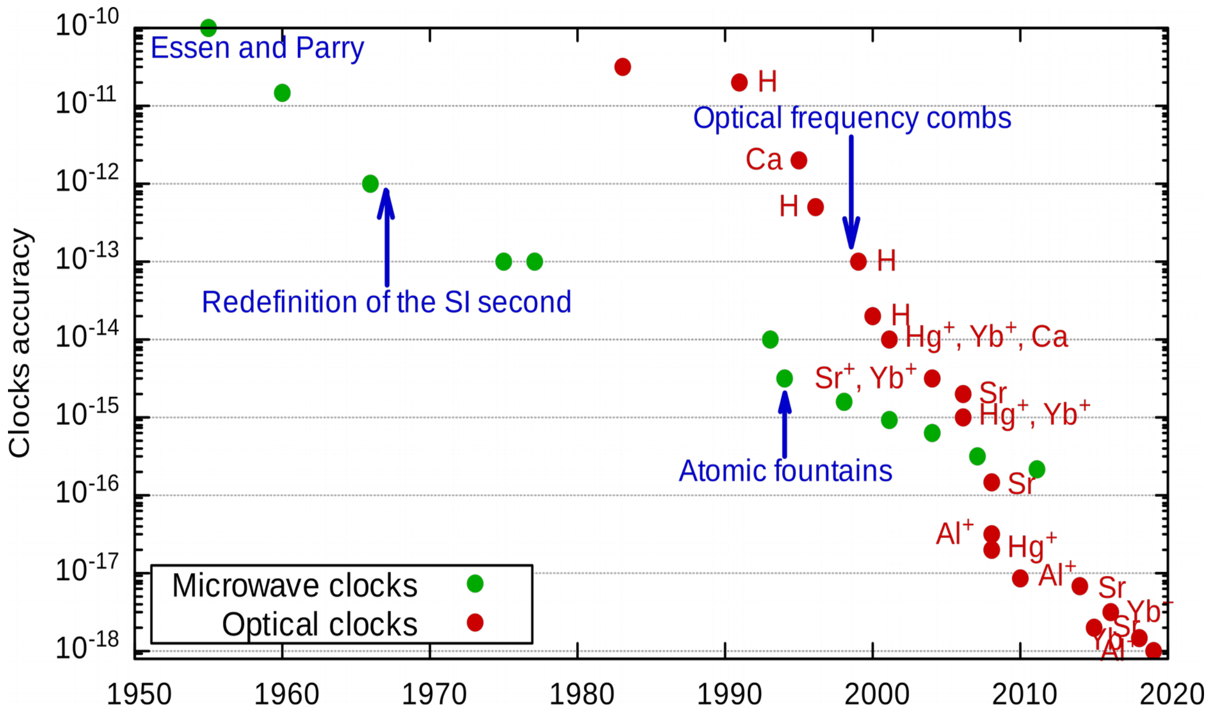
* Details on this campaign can be found in: *Riedel et al., Metrologia 57, 045005 (2020);* https://doi.org/10.1088/1681-7575/ab6745

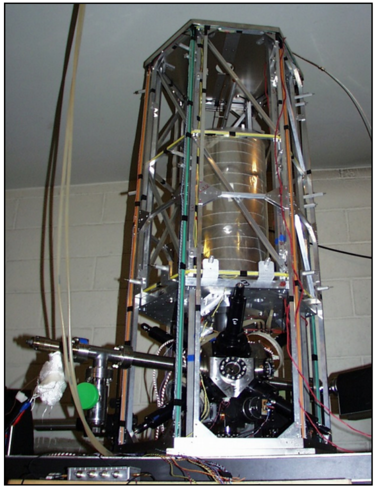
LNE
Le progrès, une passion à partager

SYRTE l'Observatoire de Paris | PSL

Introduction – Atomic Clocks

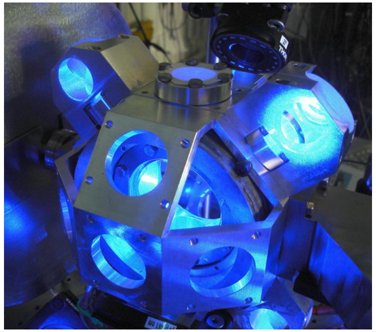
PTB
Physikalisch-Technische Bundesanstalt
Braunschweig und Berlin



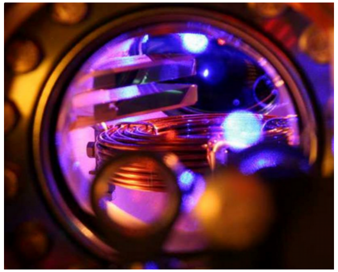


Fountain at SYRTE

Fountain at PTB



Sr clock (trap) at SYRTE



Sr clock (trap) at PTB

Introduction – Comparison Techniques

Transportable clocks

Optical fibers

Satellite-based techniques

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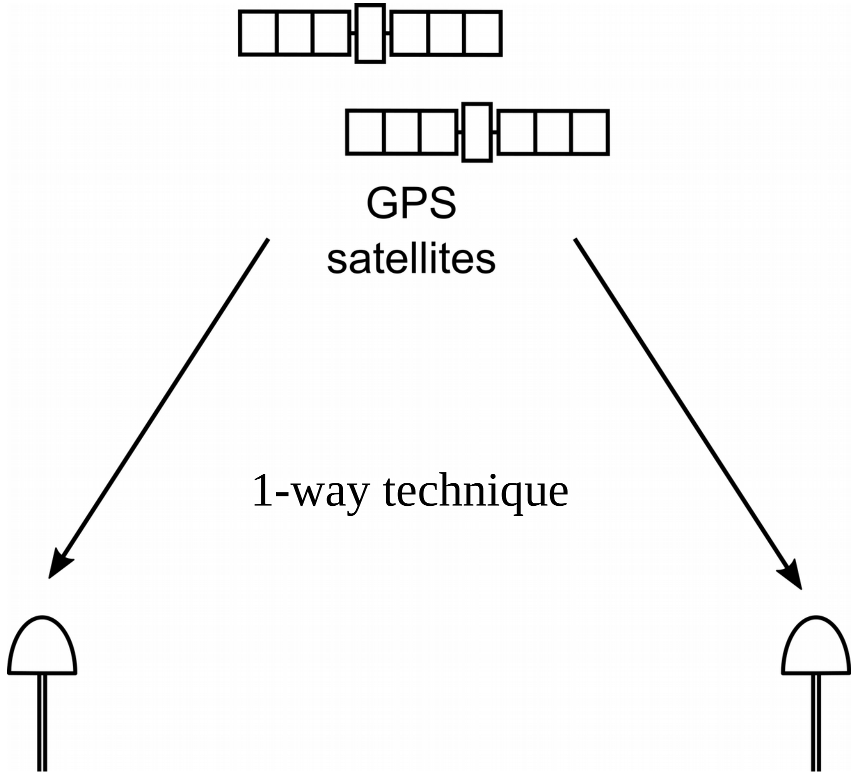
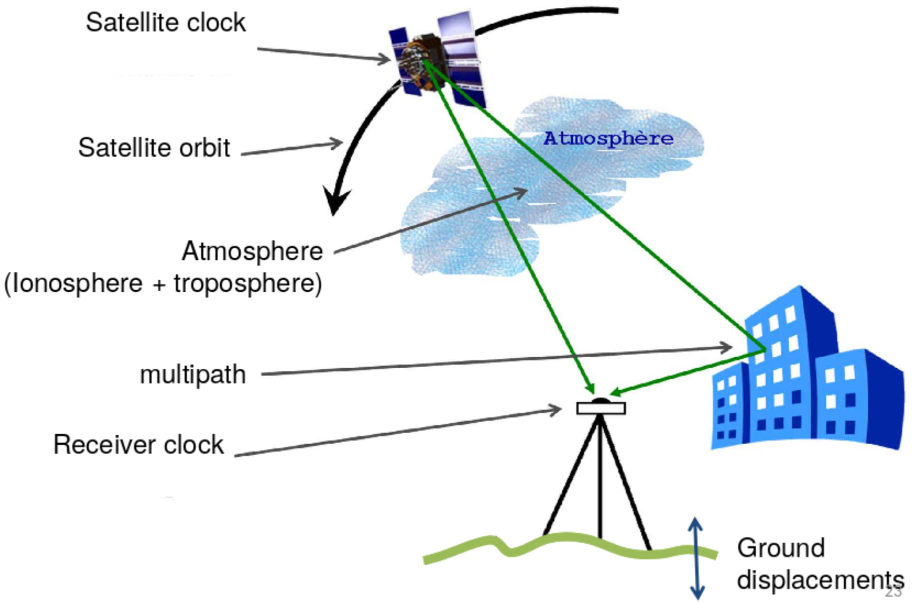
Satellite-based comparison techniques: GNSS (Global navigation satellite system)

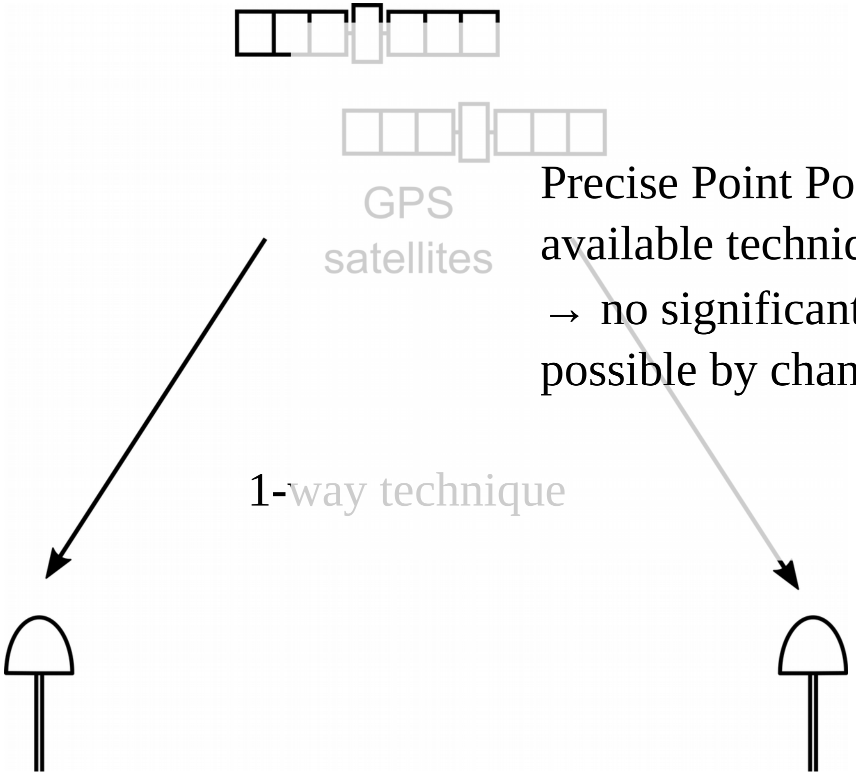


Observation modeling



by courtesy of Pascale Defraigne

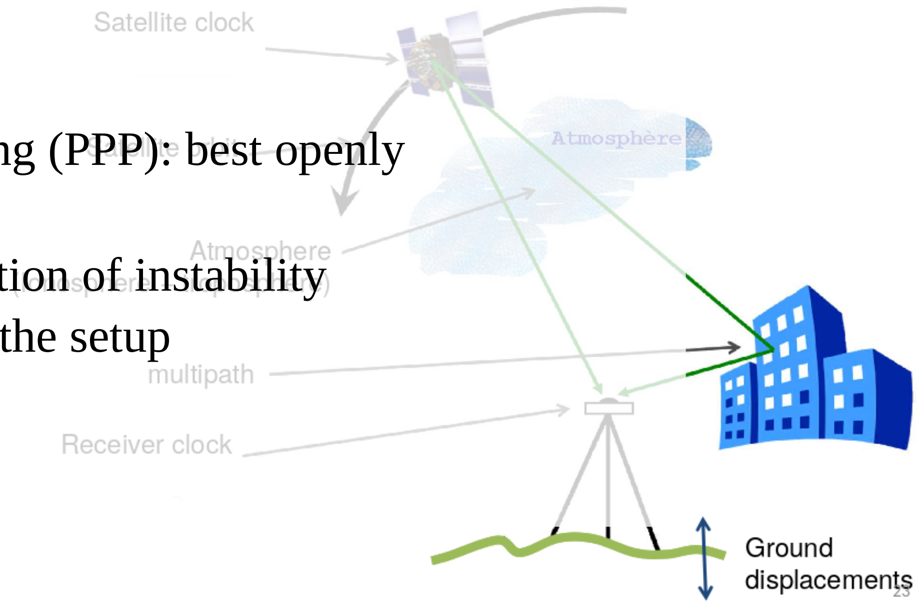
Satellite-based comparison techniques: GNSS (Global navigation satellite system)



Precise Point Positioning (PPP): best openly available technique

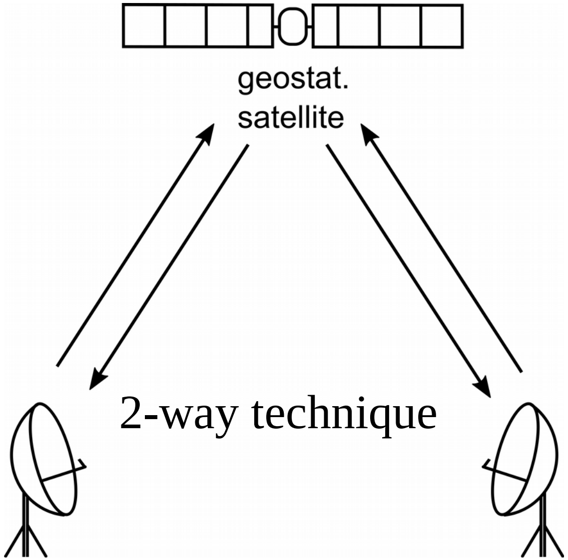
→ no significant reduction of instability possible by changes in the setup

Observation modeling



by courtesy of Pascale Defraigne

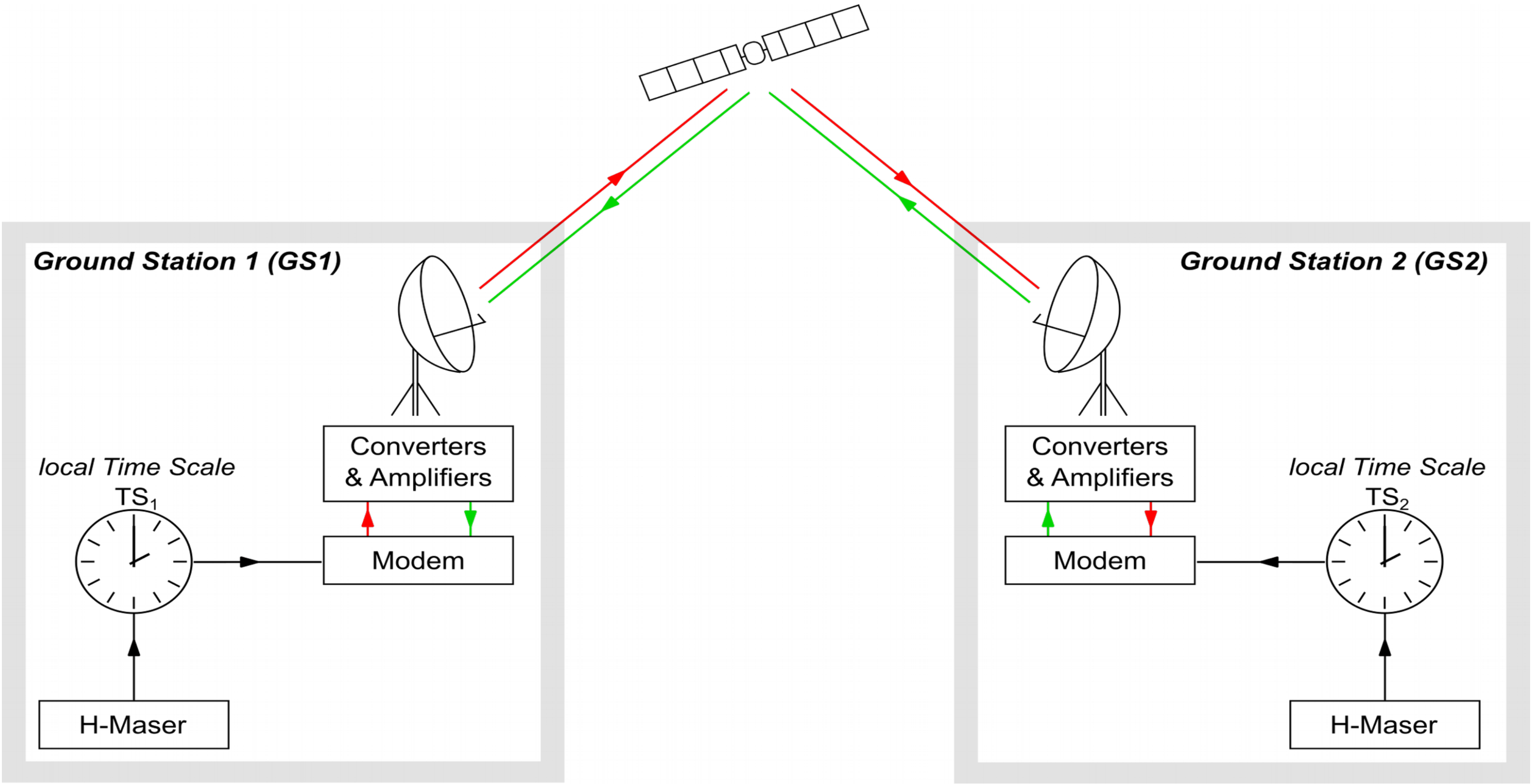
Satellite-based comparison techniques: Geostationary satellites



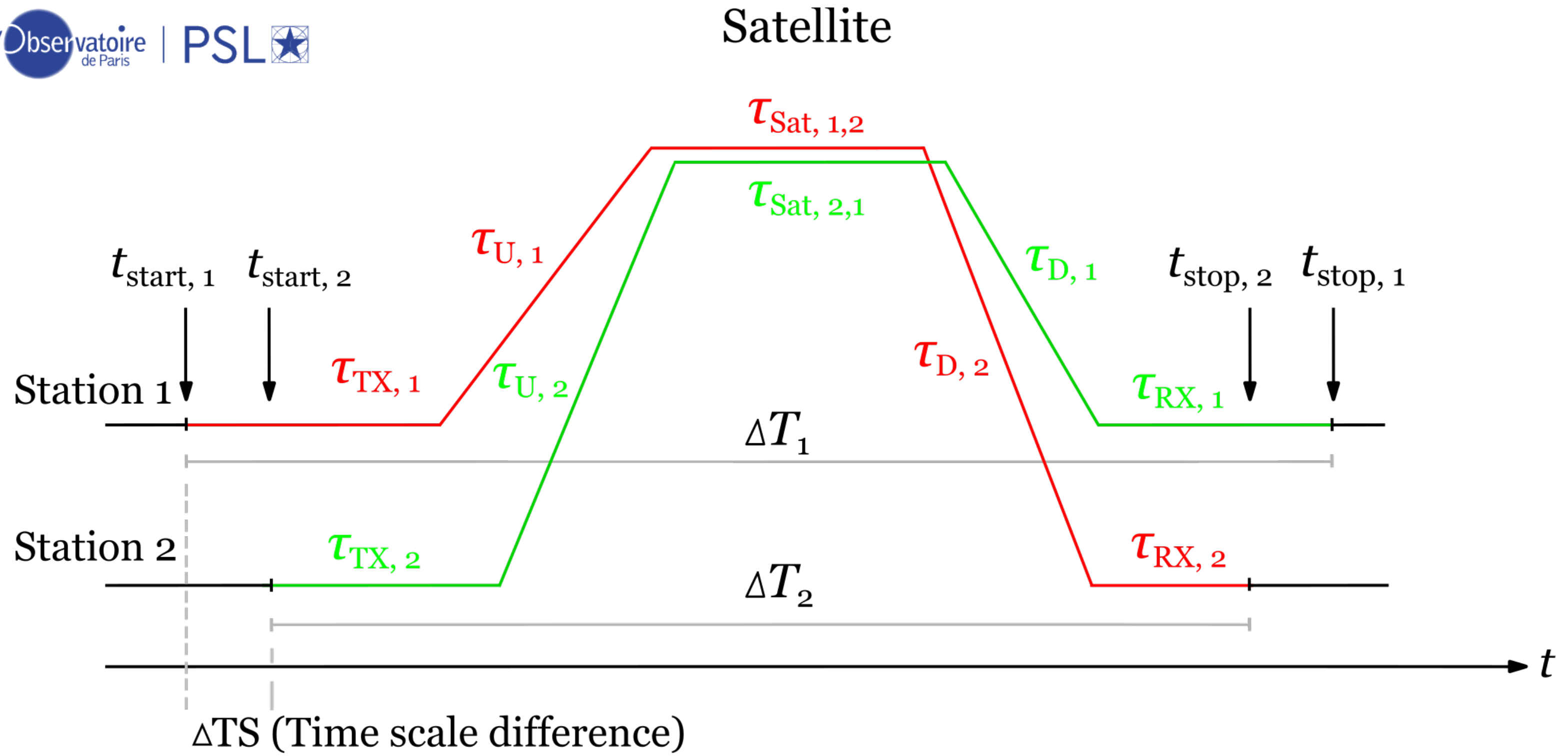
Instability depends significantly on signal properties set by the station (signal power, modulation bandwidth)

→ try out highest modulation bandwidth possible with equipment

Two-Way Satellite Time and Frequency Transfer (TWSTFT)



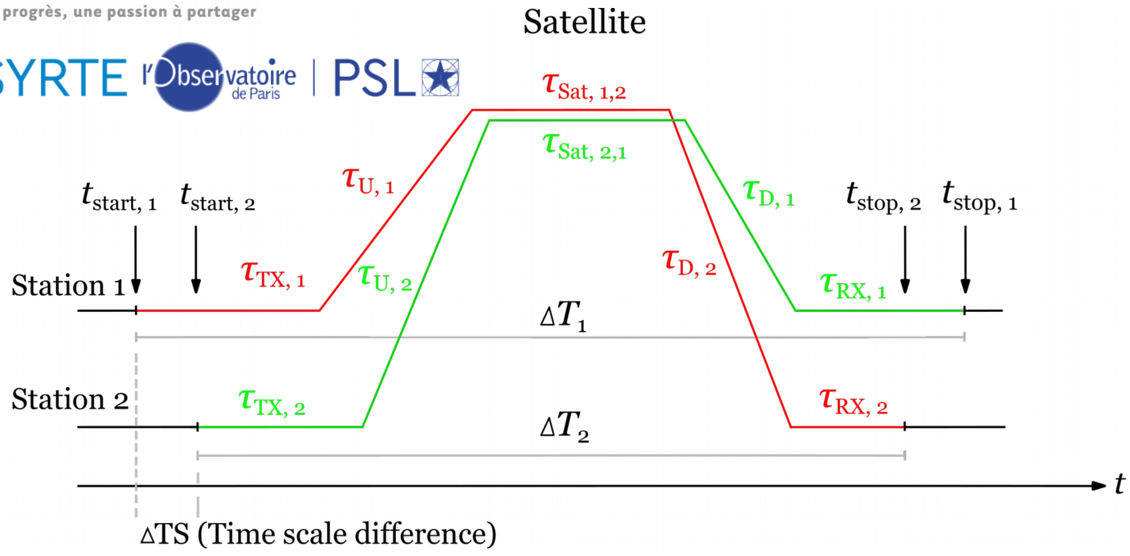
Two-Way Satellite Time and Frequency Transfer



$$\Delta T_1 = \Delta TS + \tau_{TX,2} + \tau_{U,2} + \tau_{21} + \tau_{D,1} + \tau_{RX,1}$$

$$\Delta T_2 = -\Delta TS + \tau_{TX,1} + \tau_{U,1} + \tau_{12} + \tau_{D,2} + \tau_{RX,2}$$

Two-Way Satellite Time and Frequency Transfer



$$\Delta T_1 = \Delta TS + \tau_{TX,2} + \tau_{U,2} + \tau_{21} + \tau_{D,1} + \tau_{RX,1}$$

$$\Delta T_2 = -\Delta TS + \tau_{TX,1} + \tau_{U,1} + \tau_{12} + \tau_{D,2} + \tau_{RX,2}$$

$$\Delta TS = \tfrac{1}{2}\,[\Delta T_1 - \Delta T_2 \underbrace{- (\tau_{sat,\,2,1} - \tau_{sat,\,1,2}) - (\tau_{U,2} - \tau_{D,2}) - (\tau_{D,1} - \tau_{U,1})}_{=\,0 \text{ for reciprocal path}} \underbrace{\cancel{- (\tau_{TX,2} + \tau_{RX,1} - \tau_{TX,1} - \tau_{RX,2})}}_{=\,\text{const. (calibrated)}}]$$

Frequency comparison: only $d(\Delta TS)/dt \;\rightarrow\; d\tau_x/dt$

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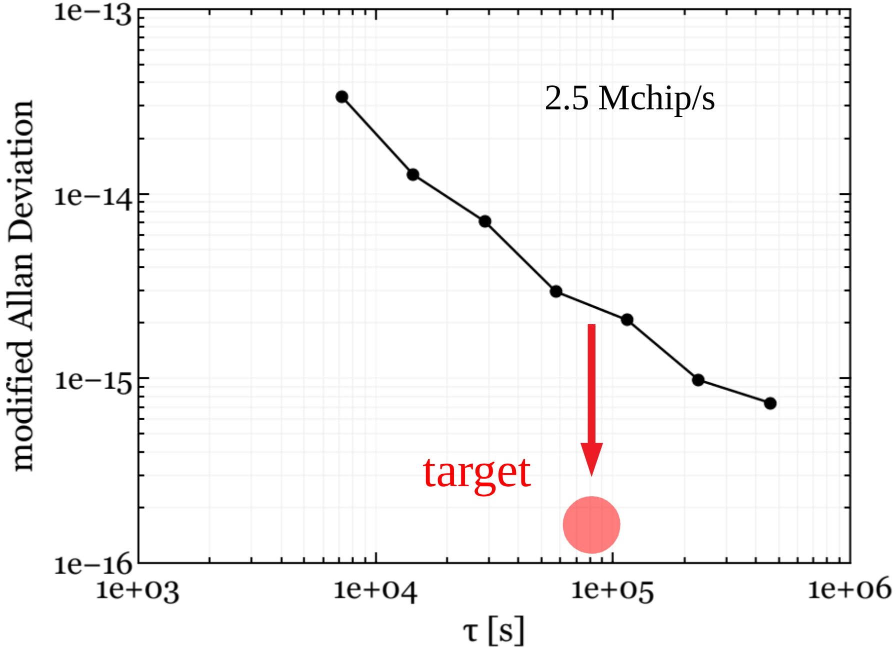
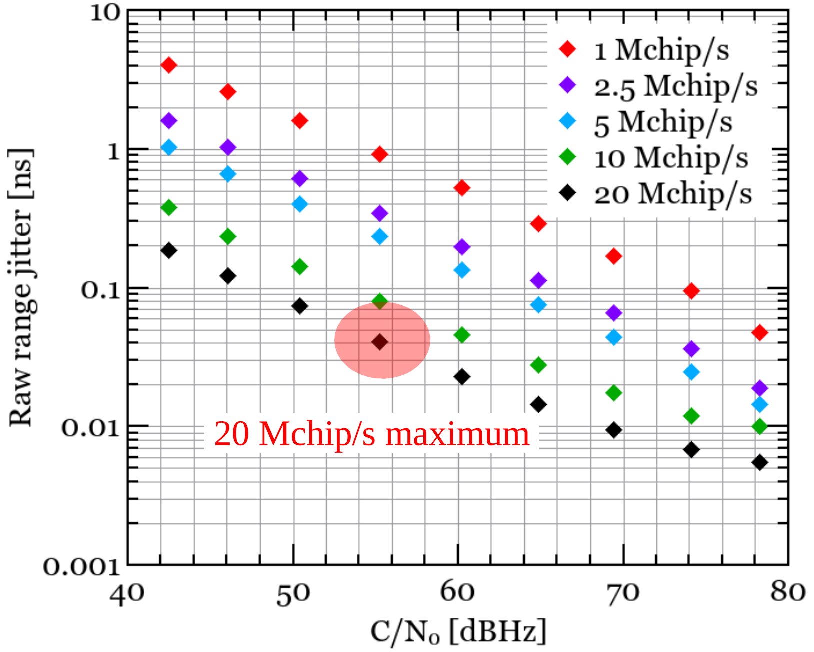
Measurements at high bandwidth

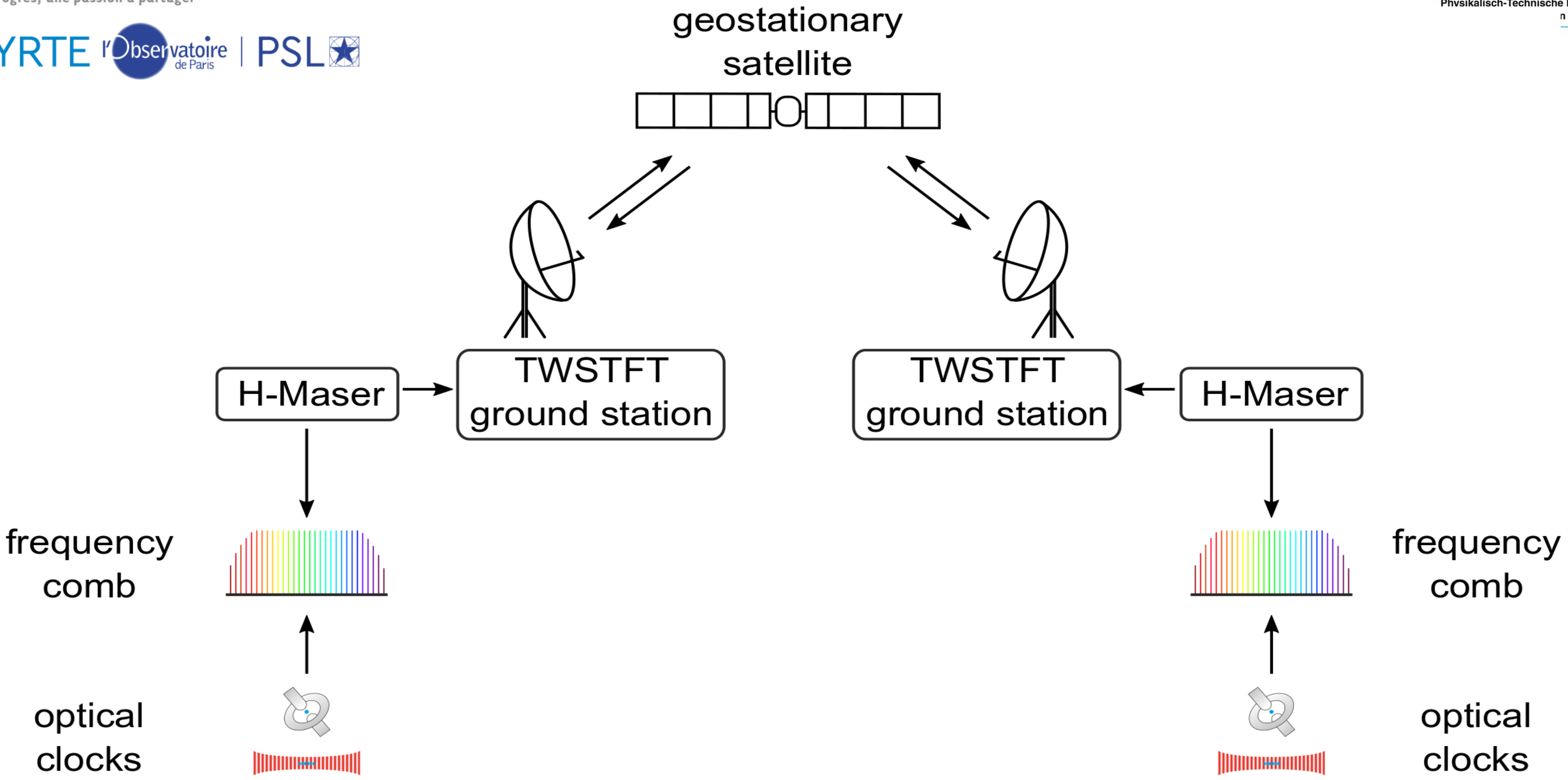
Each laboratory: modem from same manufacturer



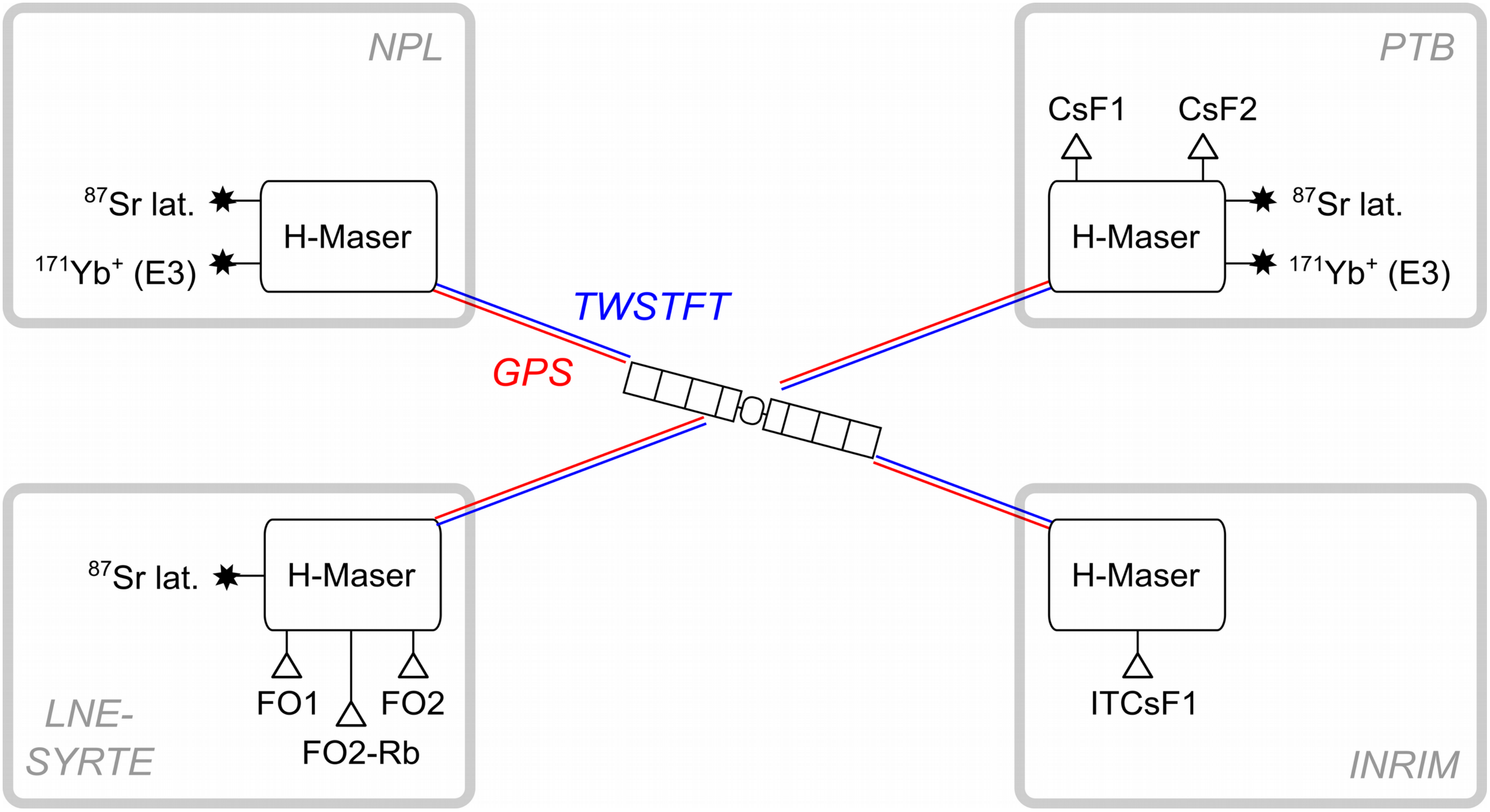
D. Piester et al. IEEE TUFFC 55, 9 (2008), pp. 1906–1912



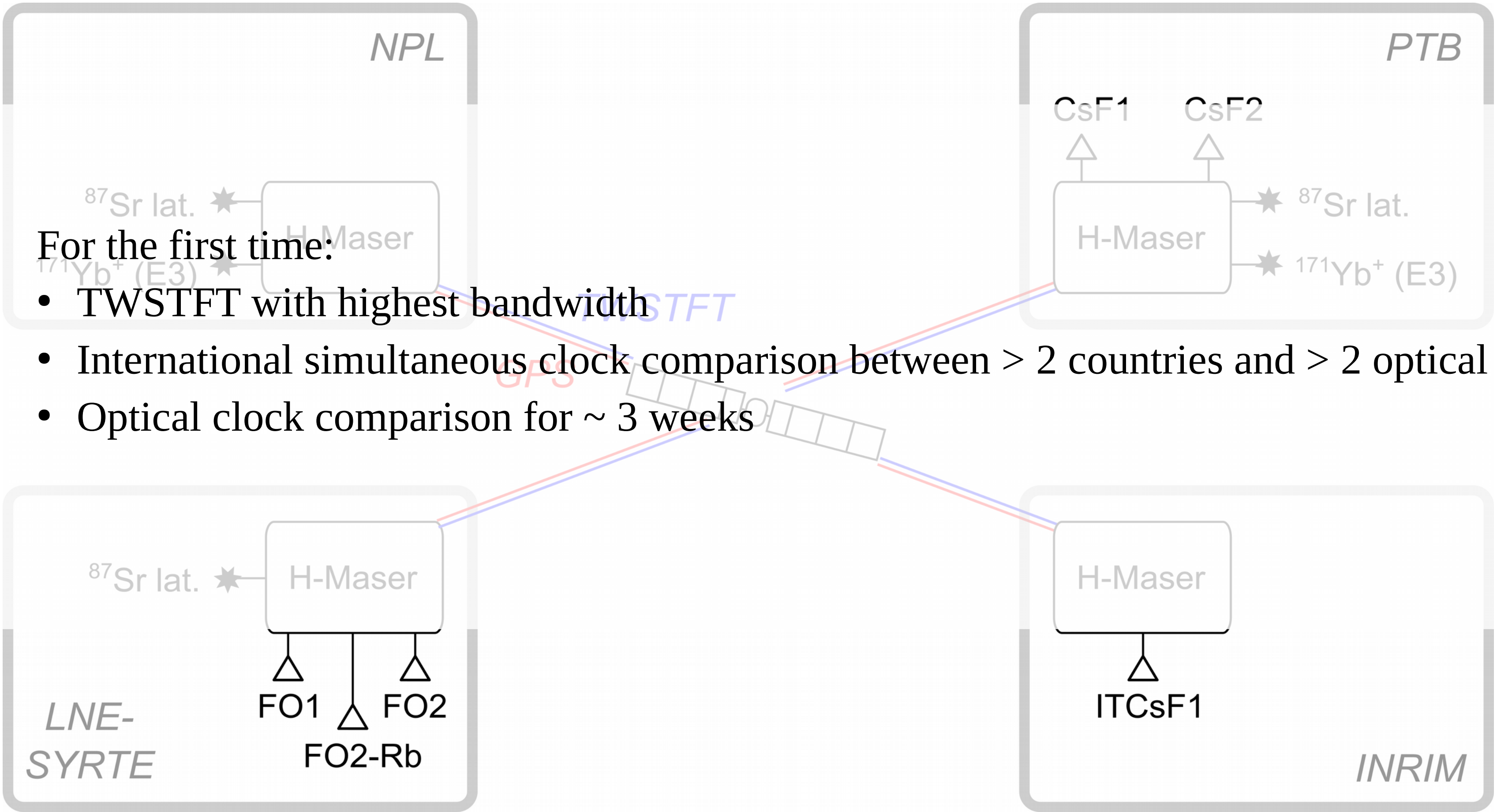
Comparison of optical clocks: Setup



Clock comparison campaign: overview



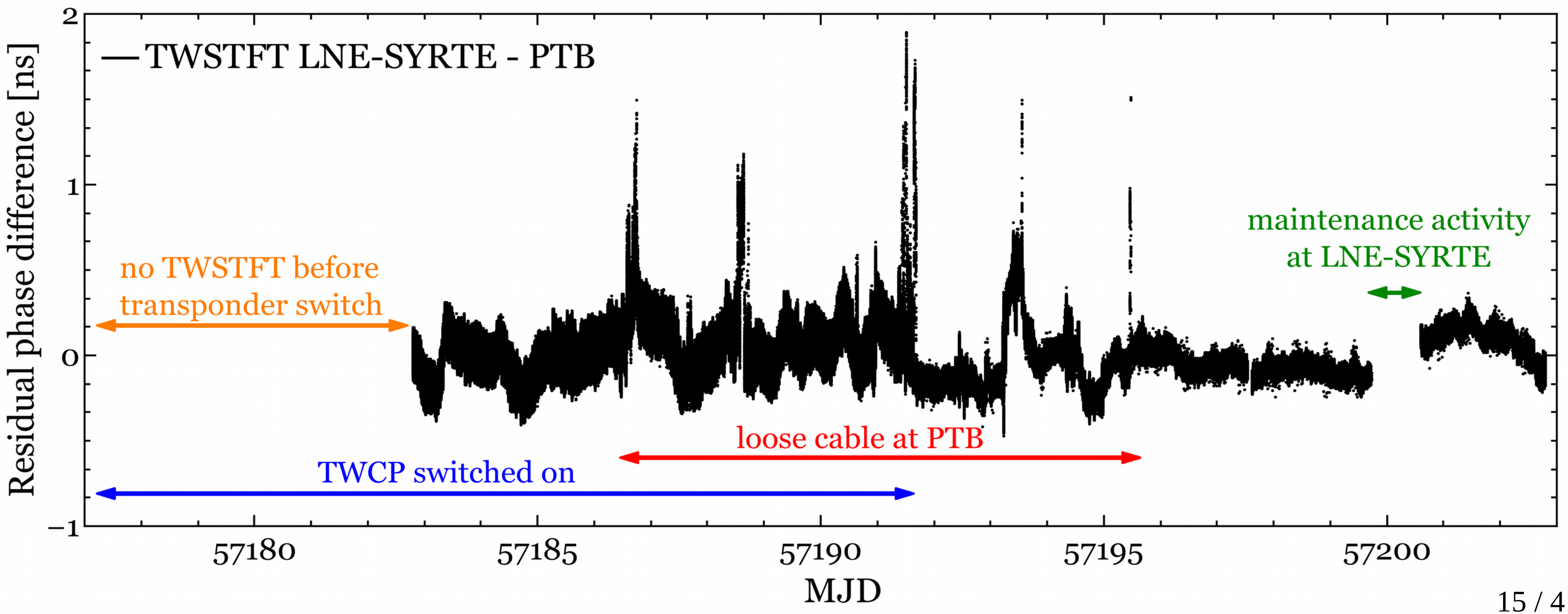
Clock comparison campaign: overview



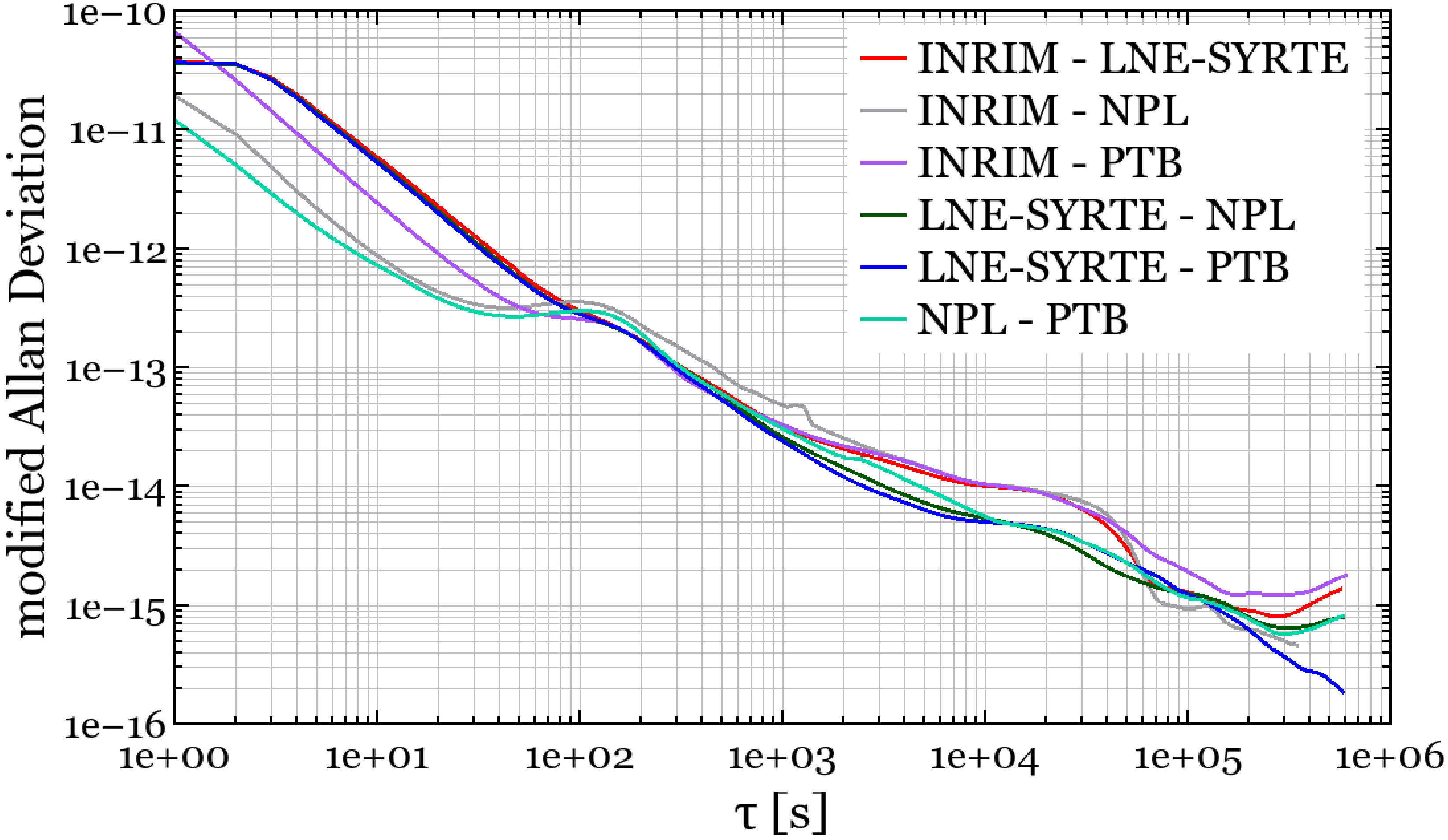
For the first time:

- TWSTFT with highest bandwidth
- International simultaneous clock comparison between > 2 countries and > 2 optical clocks
- Optical clock comparison for ~ 3 weeks

Unforeseen difficulties: TWSTFT link LNE-SYRTE-PTB



TWSTFT instability (H-Maser comparison)



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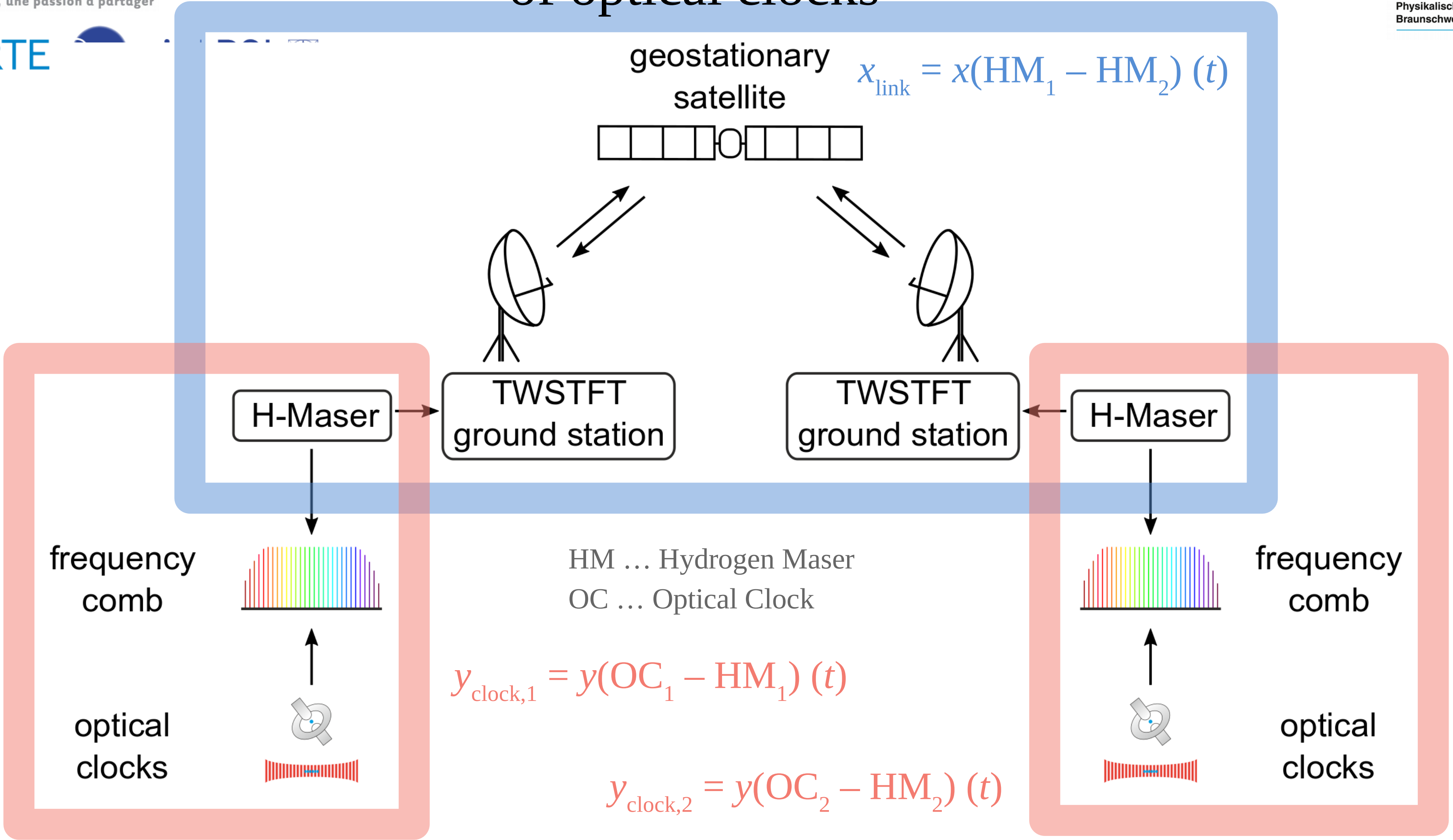
Calculate relative frequency differences of optical clocks



$x_{\text{link}} = x(\text{HM}_1 - \text{HM}_2)\,(t)$

HM … Hydrogen Maser
OC … Optical Clock

$y_{\text{clock},1} = y(\text{OC}_1 - \text{HM}_1)\,(t)$

$y_{\text{clock},2} = y(\text{OC}_2 - \text{HM}_2)\,(t)$

Calculate relative frequency differences of optical clocks

$$x_{\text{link}}(t) = x(\text{HM}_1 - \text{HM}_2)\,(t)$$

$$y_{\text{clock},1}(t) = y(\text{OC}_1 - \text{HM}_1)\,(t)$$

$$y_{\text{clock},2}(t) = y(\text{OC}_2 - \text{HM}_2)\,(t)$$

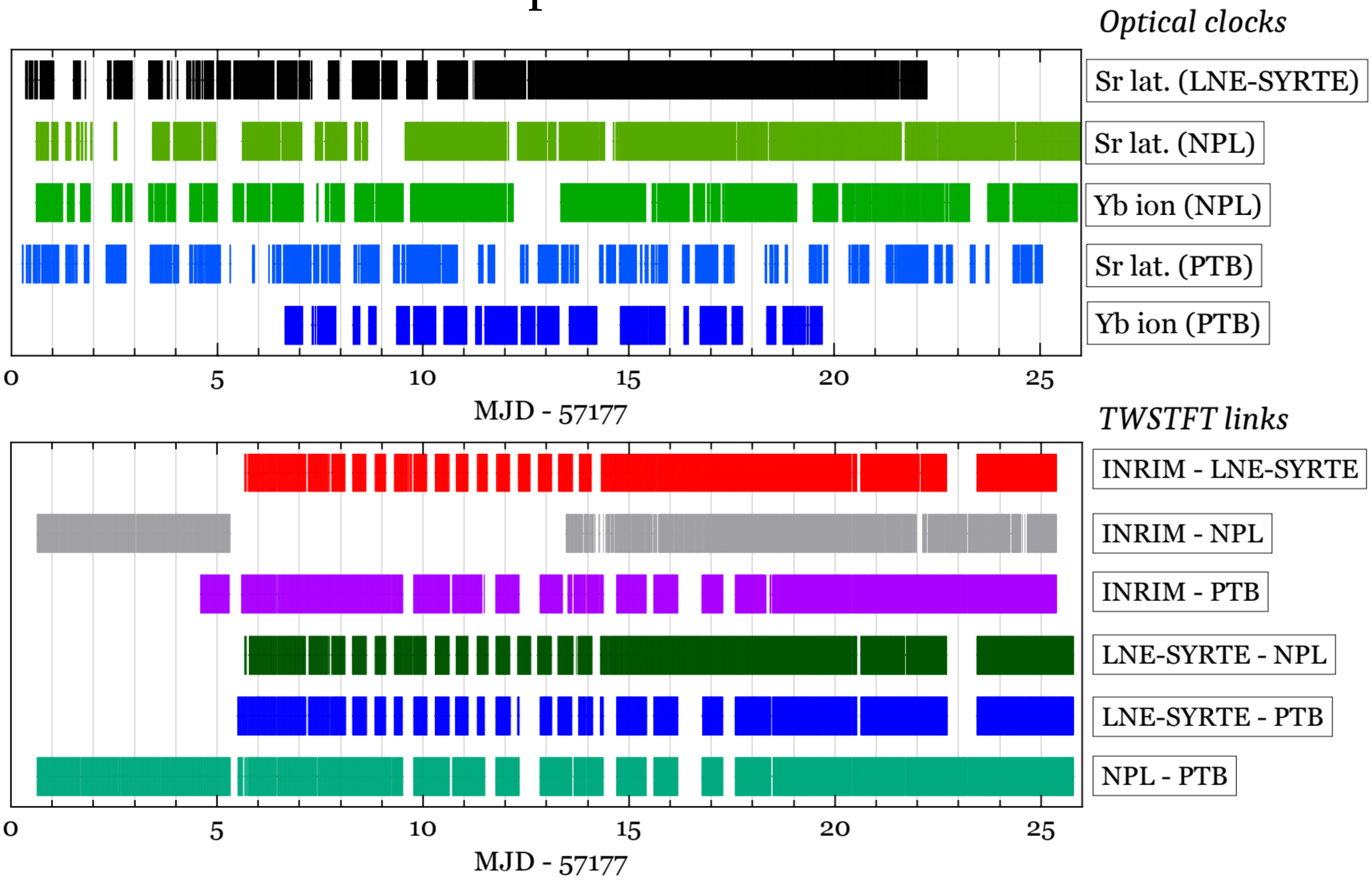
$$y_{\text{link}}(t) = \frac{x_{\text{link}}(t + \frac{\Delta t}{2}) - x_{\text{link}}(t - \frac{\Delta t}{2})}{\Delta t}$$

$$= y(\text{HM}_1 - \text{HM}_2)(t)$$

$$\rightarrow\ y(\text{OC}_1 - \text{OC}_2)\,(t) = y_{\text{clock},1}\,(t) - y_{\text{clock},2}\,(t) + y_{\text{link}}(t)$$

But: $y_{\text{clock},x}\,(t)$ dominated by noise of HM, $y_{\text{link}}(t)$ by phase noise of link

Calculate relative frequency differences of optical clocks



Calculate relative frequency differences of optical clocks

Find a compromise for:

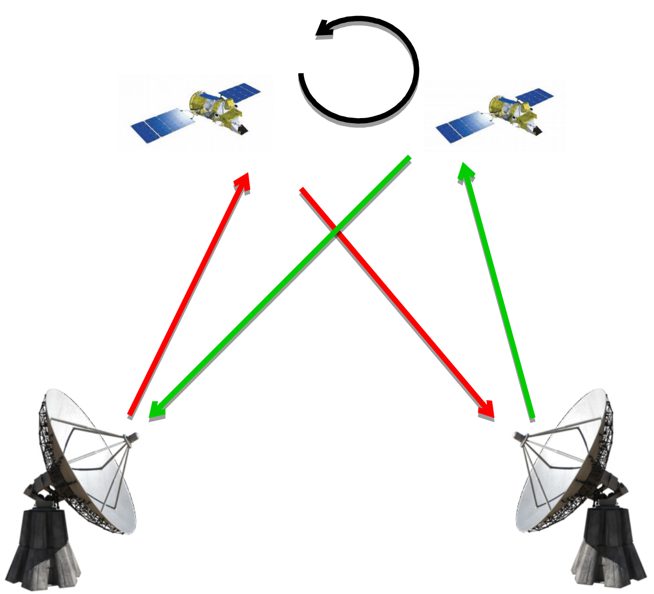
- Minimize phase noise on link data with pre-averaging
- Use only overlapping data to have the HMs cancel out
- Discard as few data as possible

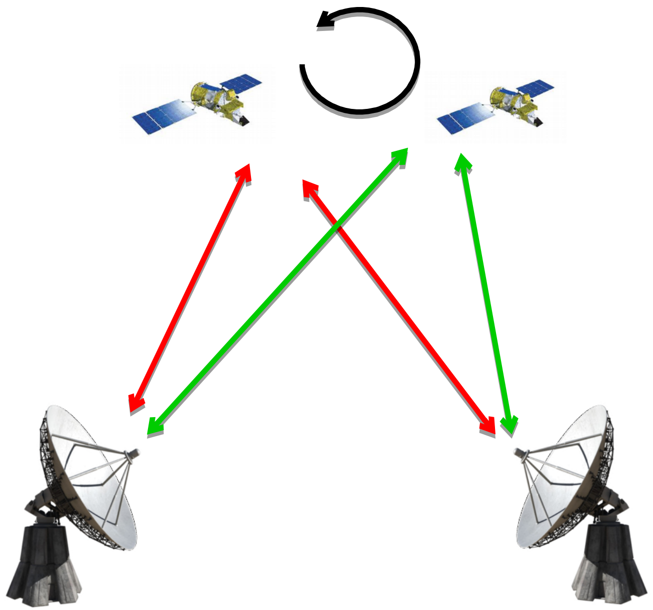
→ obtain $y(\mathrm{OC}_1 - \mathrm{OC}_2)\,(t) = y_{\mathrm{clock},1}\,(t) - y_{\mathrm{clock},2}\,(t) + y_{\mathrm{link}}(t)$

→ calculate weighted mean

Geometric and relativistic effects: impact on station and satellite

→ caused by residual motion of satellite





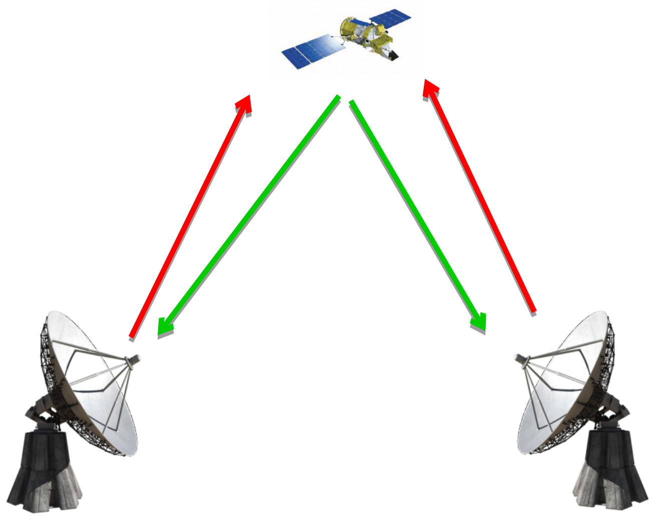
Variation of path length delay:
leads to non-reciprocity of uplink/downlink path
→ introduce delay in ground stations

Variation of the Sagnac effect
→ calculate corrections afterwards,
based on satellite position and velocity

Ionospheric correction

Ionospheric delay:

- frequency dependent
  → correction based on up- and downlink frequencies
- take into account TEC (Total Electron Content) and its variation with time



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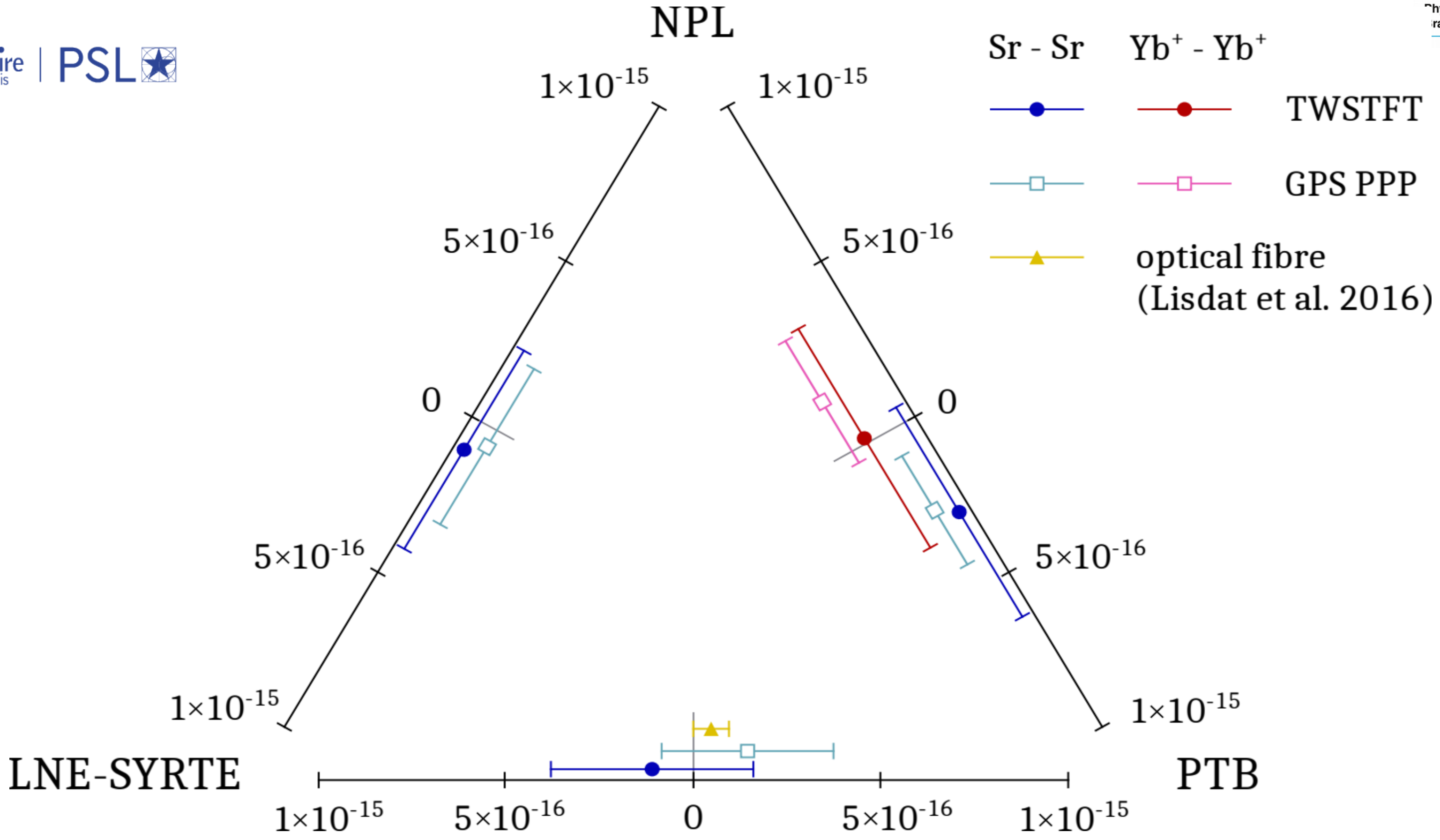
Results for optical clocks (same type)

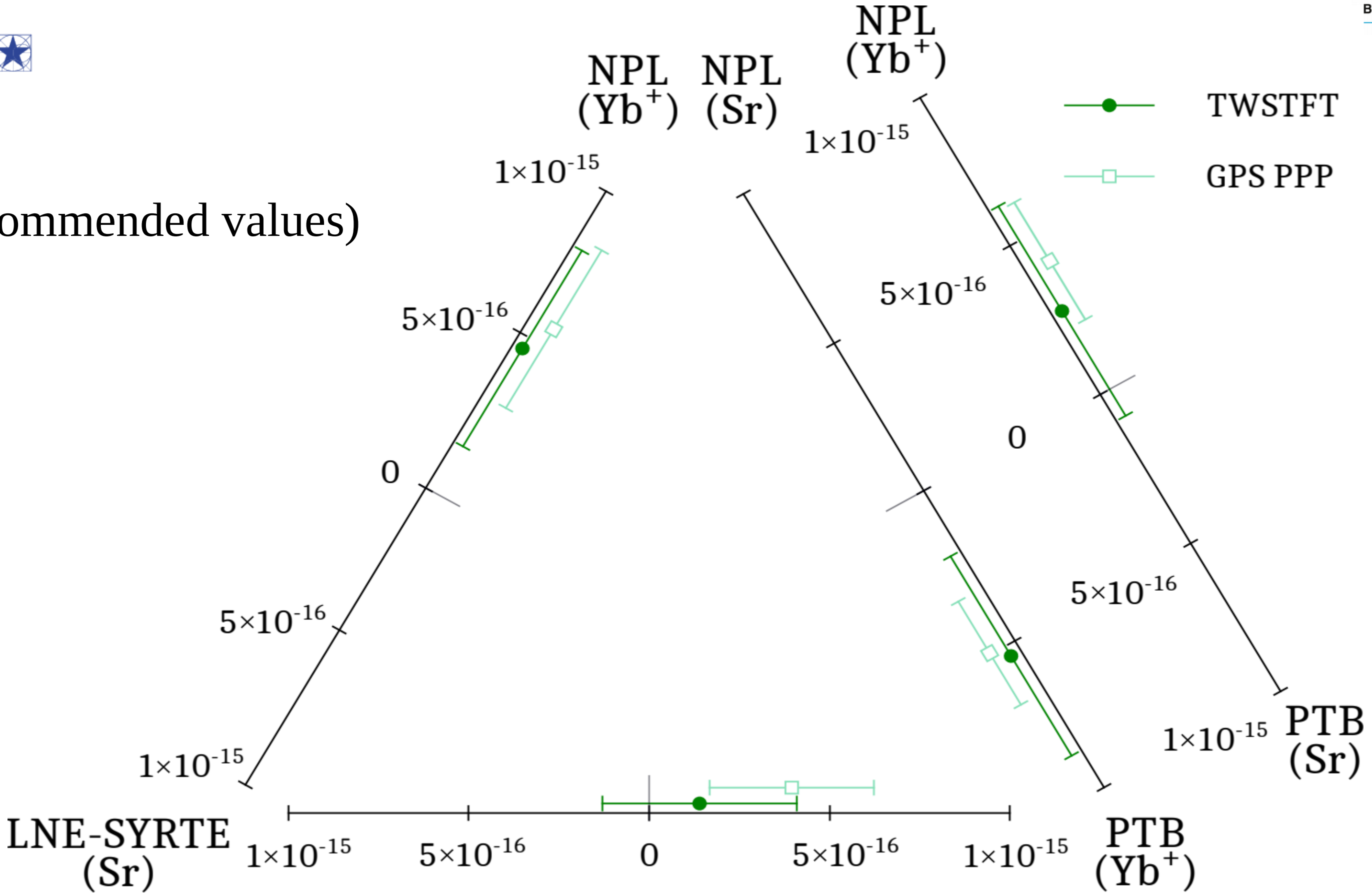


Different clocks: agreement, but slight offset in Sr (NPL) indicated

Different techniques: agreement

Results for optical clocks (different type)

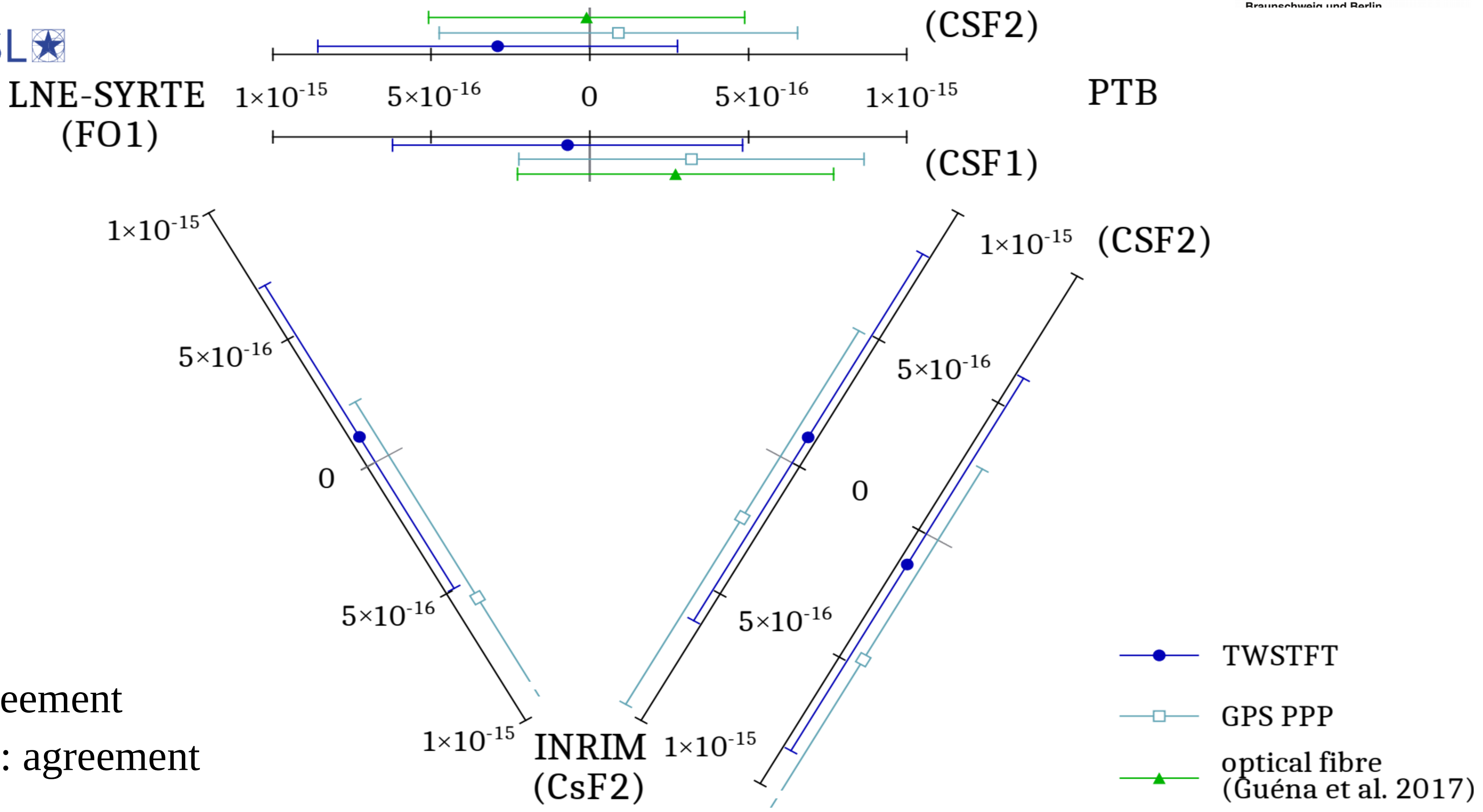
("0" = CIPM 2017 recommended values)



Different clocks: agreement (combined uncertainty), but systematic offset

Different techniques: agreement

Results for fountain clocks (part 1)

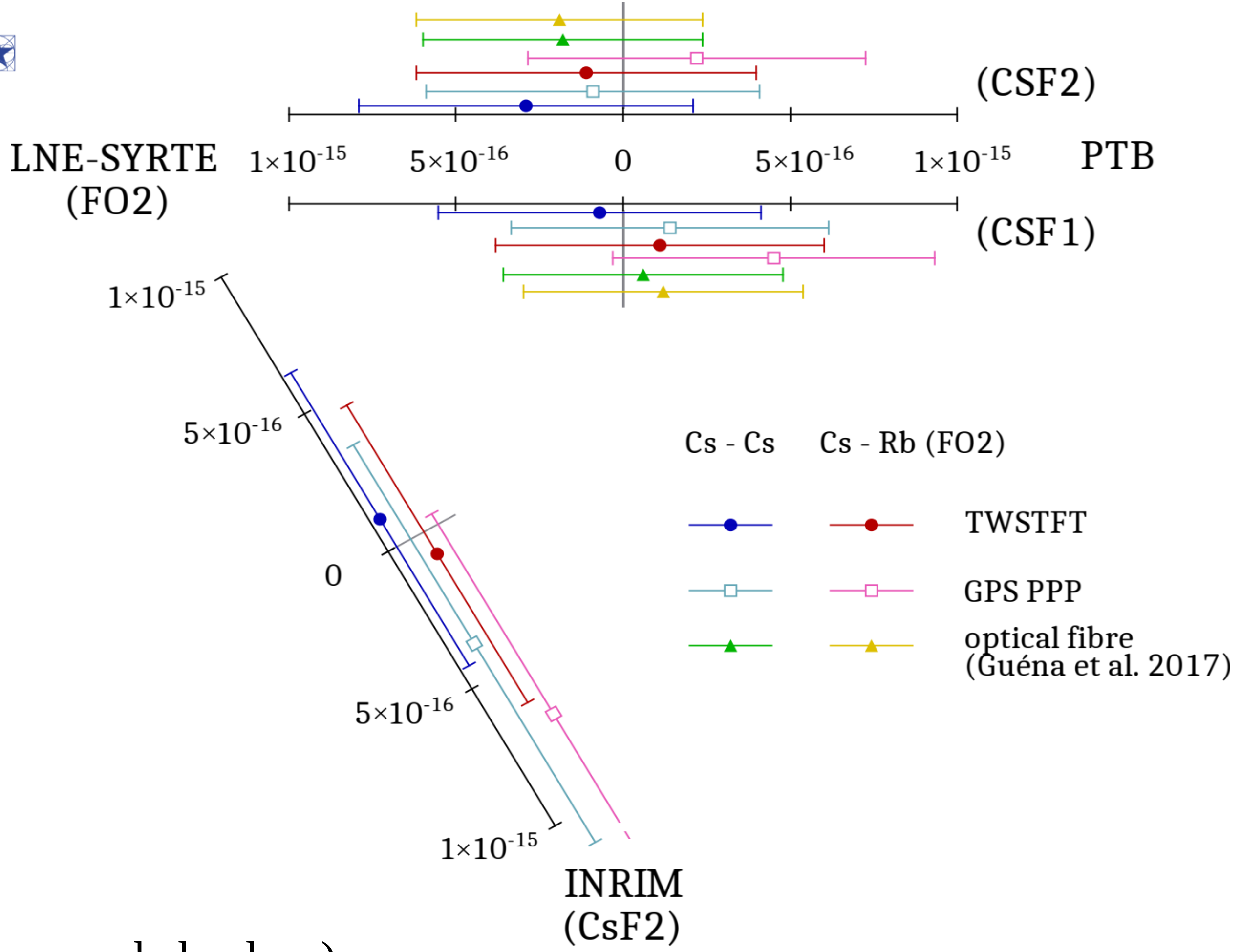


Fountain clocks: agreement

Different techniques: agreement

Larger uncertainties: larger contributions by the clocks to u_A and u_B

Results for fountain clocks (part 2)



Comparisons with Rb:

(“0” = CIPM 2017 recommended values)

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Recent improvements in satellite-based techniques

Digital modem development:

- Software defined radio (SDR) receiver, code-based digital receiver for daily operations, developed by TL
- Software ranging system (SRS), digital modem capable of both code-based and carrier-based transfer, developed by NICT
- both at low chip rates only so far

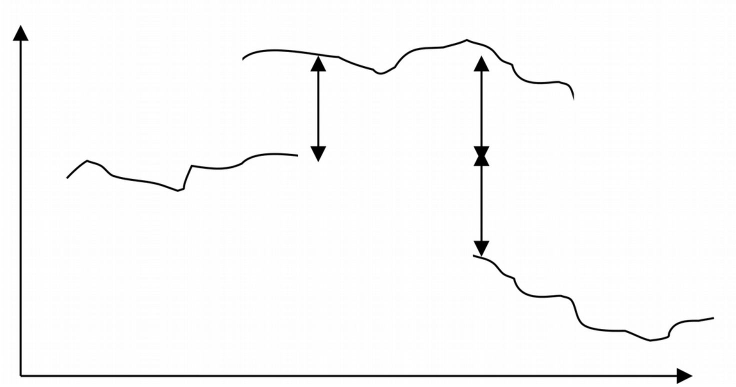
First results comparing SRS and SDR with analog TWSTFT and GPS PPP *:

- Comparison between UTC(OP) and UTC(PTB) for approx. 80 days
- Both SDR and SRS are comparable, and better than analog TWSTFT (all in code-based operation)
- GPS PPP shows lower instability at averaging times of up to a few days (uses carrier-phase in addition to code-phase)
- All techniques are limited by the instability of the UTC(k) time scales for long averaging times

* From: Thanh Thai et. al, “Code- and carrier-phase based TWSTFT Experiment between INRiM, LNE-SYRTE and PTB”, presentation at ION PTTI 2021

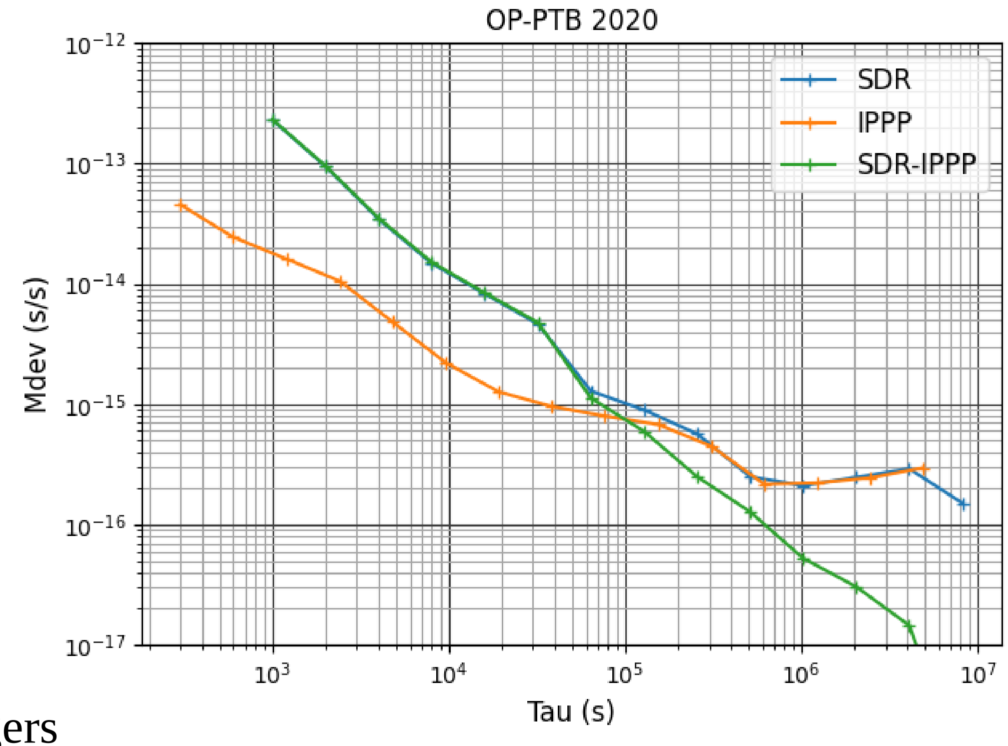
Recent improvements in satellite-based techniques

Classical PPP: combination of code and phase
ambiguities of phase defined by code noise



IPPP = Integer PPP

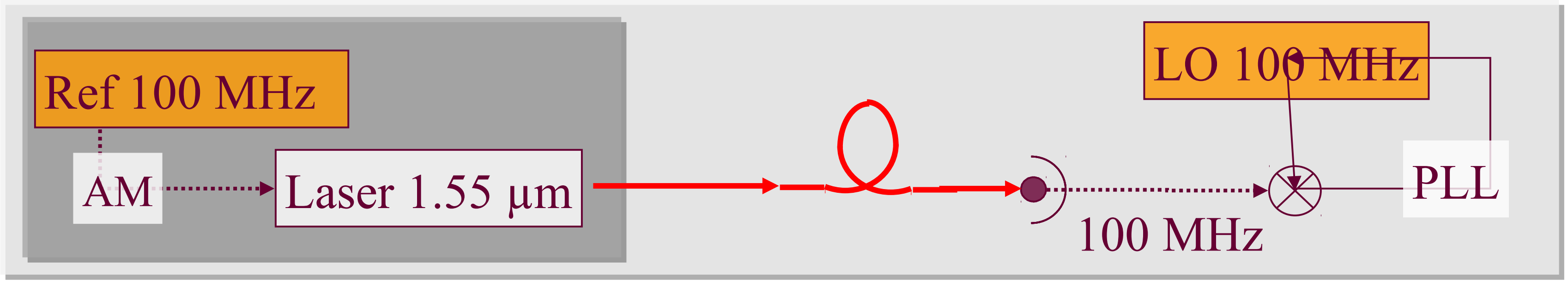
→ ambiguities for solutions are estimated as integers



From: G. Petit & F. Meynadier, “IPPP links for UTC: comparison to existing techniques”, presentation at ION PTTI 2021

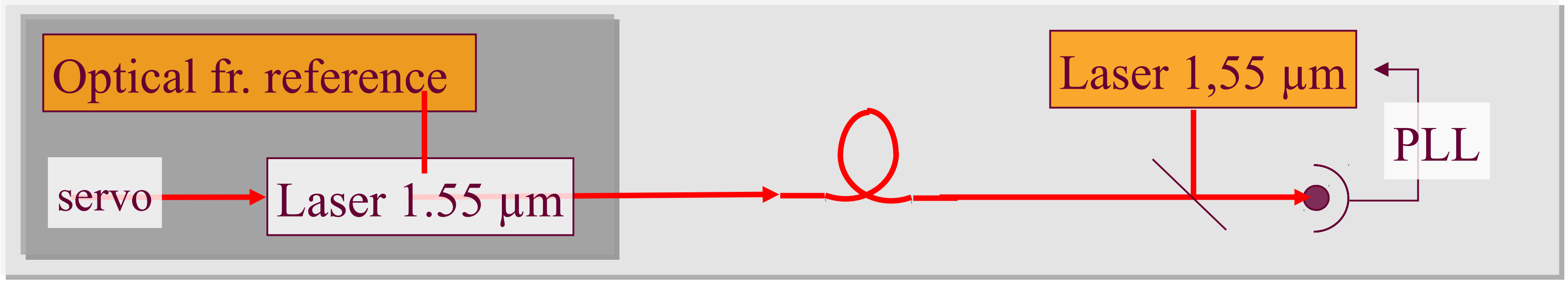
Optical fibers

- RF or MW transfer (100 MHz to 10 GHz)
  - Amplitude modulation of the optical carrier



- Direct transfer of an optical frequency
  - Well-suited to optical clocks comparison

pictures by courtesy of P.E. Pottie/A. Amy-Klein



Optical fibers

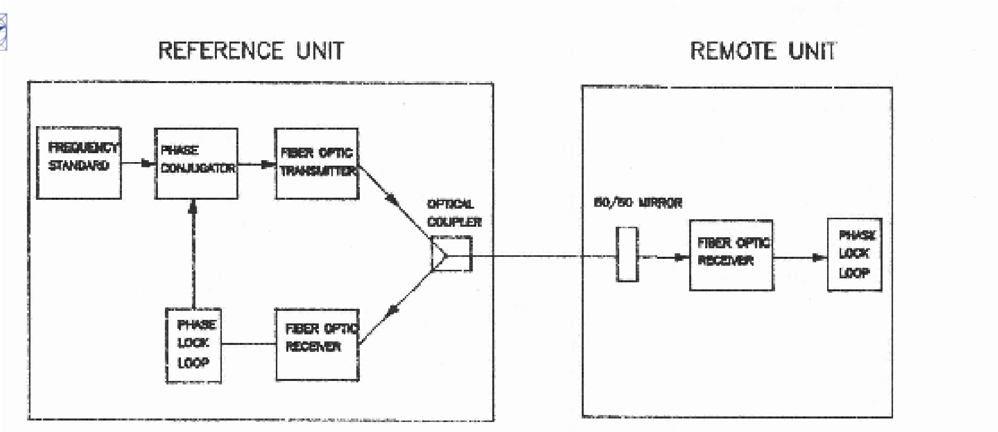


FIGURE 3. FIBER OPTIC FREQUENCY DISTRIBUTION SYSTEM

Basic principle:
L. E. Primas *et al.*, Proc. 20th PTTI, Vienna, VA, 29 Nov - 1 Dec 1988(1988)

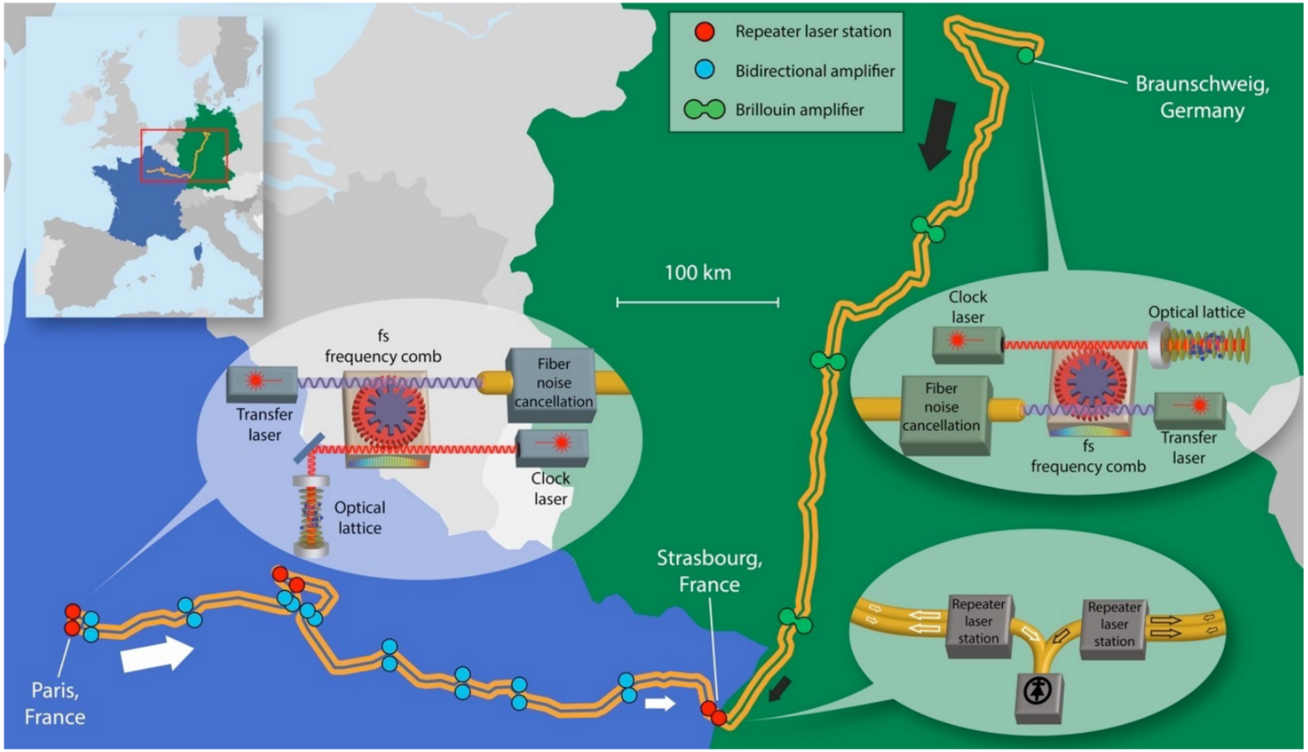
Noise: different types of amplifiers, repeater stations

Availability: balance costs and performance

...

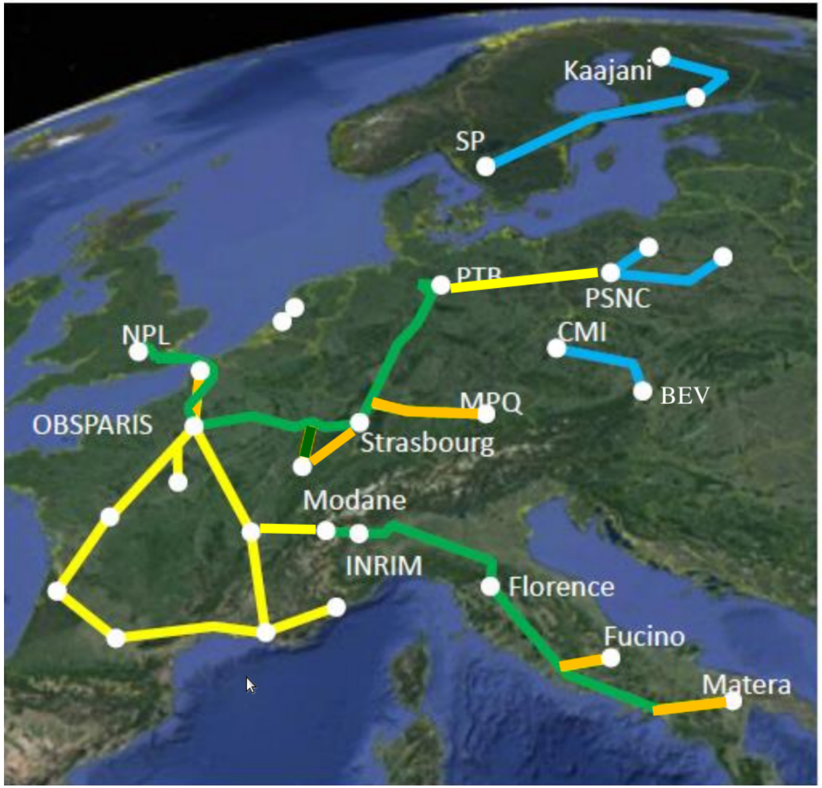
Optical fibers

Sr-Sr comparison between PTB and SYRTE
→ first international fiber link for frequency comparisons



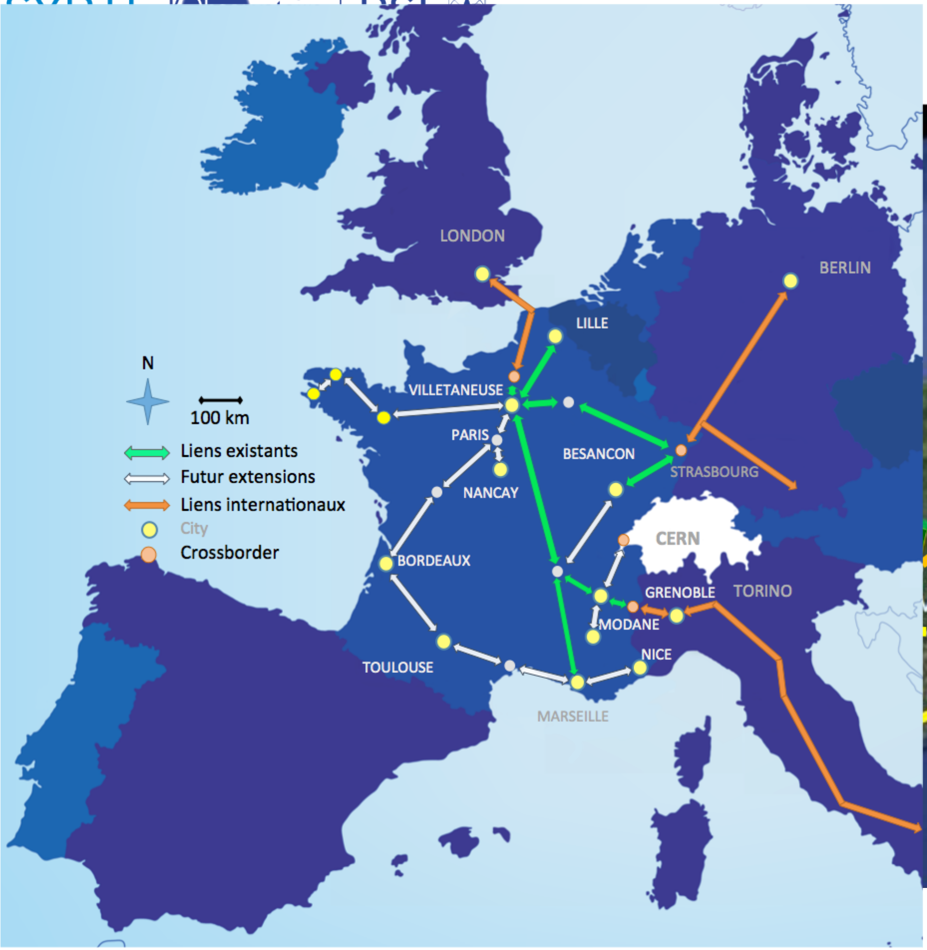
C. Lisdat et al, Nature Comm. 2016

Optical fibers



pictures by courtesy of P.E. Pottie/A. Amy-Klein

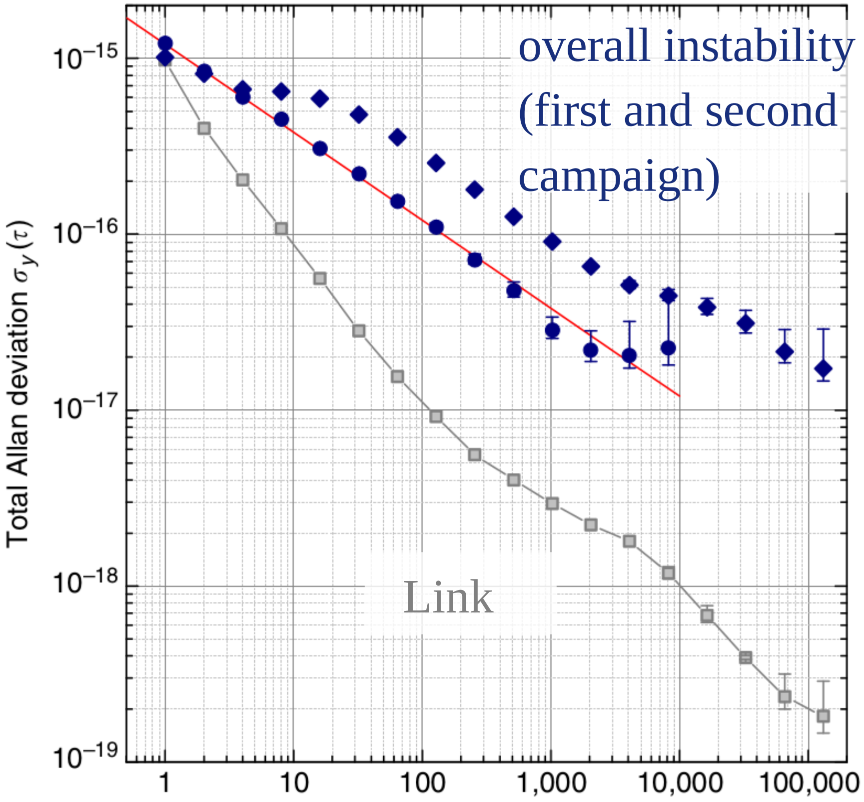
Optical fibers

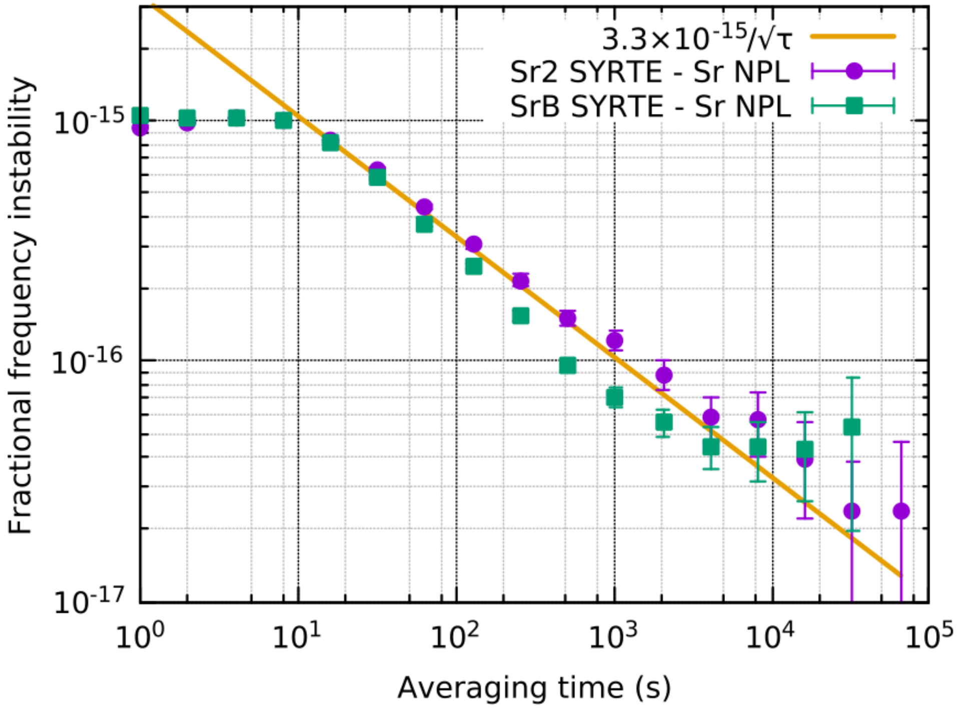


pictures by courtesy of P.E. Pottie/A. Amy-Klein

Optical fibers

C. Lisdat et al, Nature Comm. 2016





P. Delva et al, PRL 2017

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Summary

- Optical clocks new generation of atomic clocks for broad field of applications: remote comparisons necessary!
- First simultaneous international optical clock comparison carried out
  → using broadband TWSTFT and GPS PPP
  → uncertainty limited by links + gaps (HMs do not cancel out perfectly)
  → Uncertainty of low 10^{-16} achieved, proof of improvements on TWSTFT
- Results for clock types of same type agree with each other
- Results of clocks of different type agree with CIPM 2017 recommended values, but indicate an offset
  → advantage of simultaneity

Suitable techniques for optical clock comparisons

- Comparison via optical fibers:
  Best uncertainty/instability,
  Network set up in Europe, but still limited baselines available
- Transportable optical clocks:
  limitation in uncertainty and operation due to technical compromises,
  only subsequent measurements
- Satellite-based techniques:
  – GPS integer PPP (iPPP): lower instability than PPP for averaging times > a few hours
  – TW Carrier Phase: superior to all other satellite-based techniques at short averaging times up to a few hours, but averages with $\tau^{-1/2}$
  – digital TWSTFT with SDR or SRS: some systematic effects can be suppressed, lower instabilities observed at low chip rates
- Other techniques: free space links, VLBI

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+ input from SYRTE/BIPM/ORB colleagues for this presentation

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EMRP
European Metrology Research Programme
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Thank you for your attention!