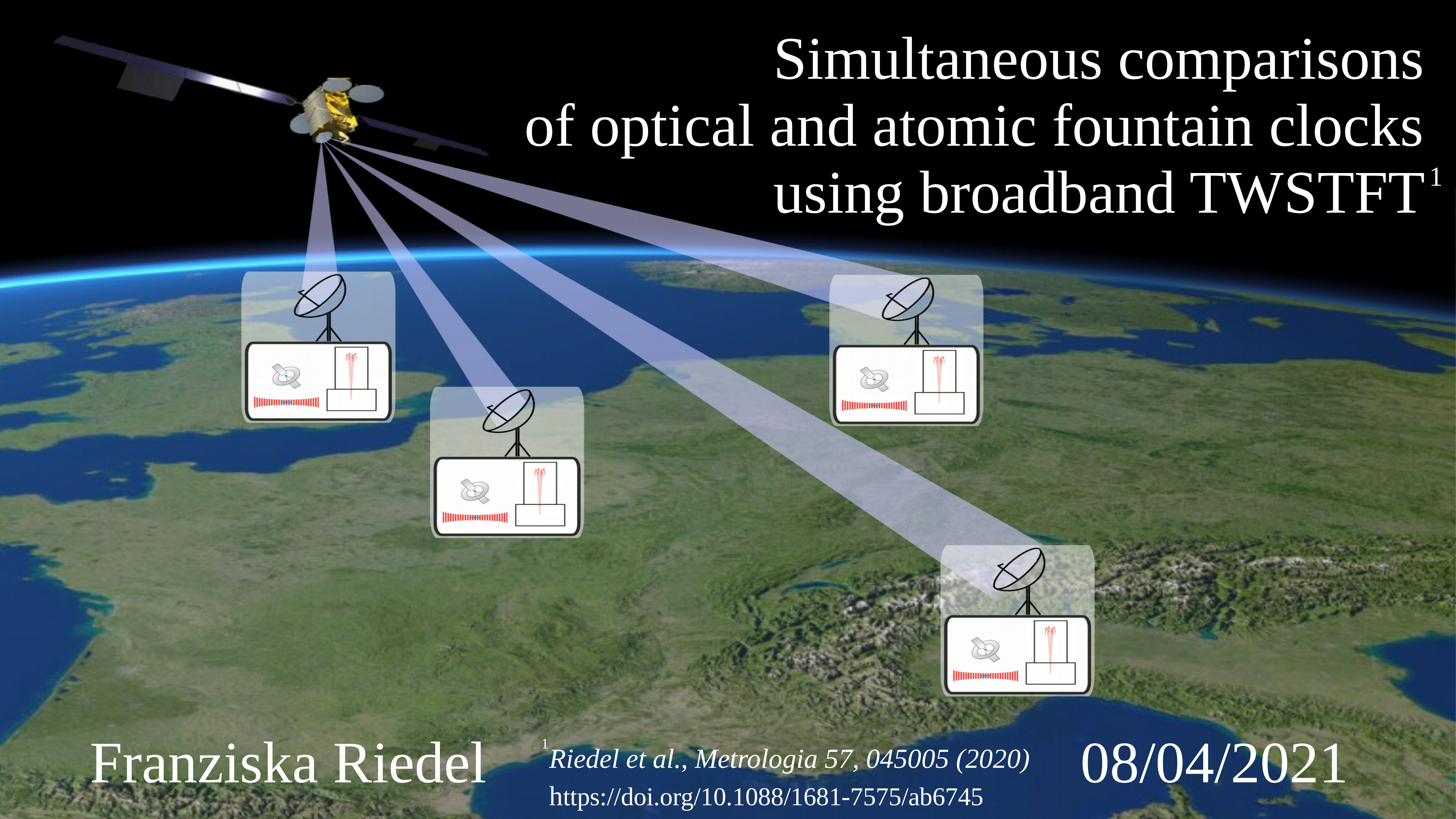
Simultaneous comparisons of optical and atomic fountain clocks using broadband TWSTFT[1]



Franziska Riedel

[1] *Riedel et al., Metrologia 57, 045005 (2020)*

https://doi.org/10.1088/1681-7575/ab6745

08/04/2021

Outline

Introduction

Frequency comparison with satellites: **T**wo-**W**ay **S**atellite **T**ime and **F**requency **T**ransfer (TWSTFT)

Planning and execution of the clock comparison campaign

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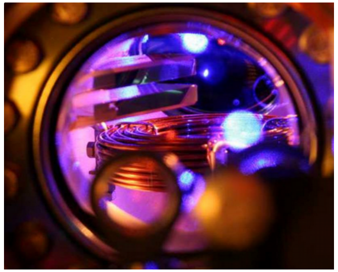
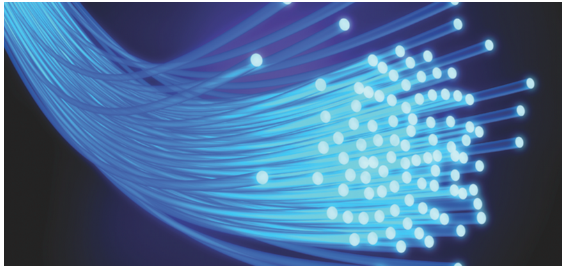
EMRP-project ITOC: “International Timescales with Optical Clocks”



Contents: local comparisons between optical clocks, absolute frequency measurements, assess information about implementing optical clocks in timescales ...

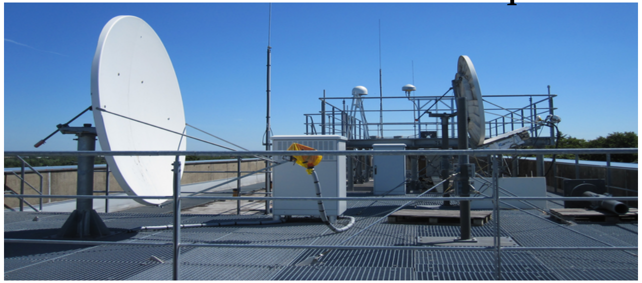
… remote comparisons!

Optical fibers



limited in availability

Satellite-based techniques



limited in uncertainty

Remote comparisons: using satellites

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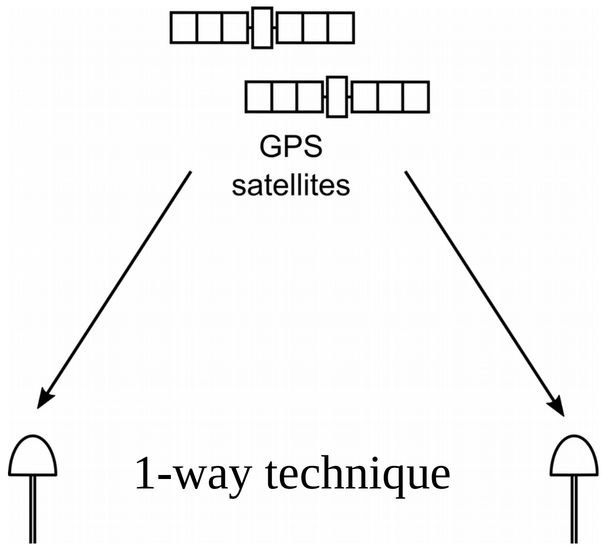
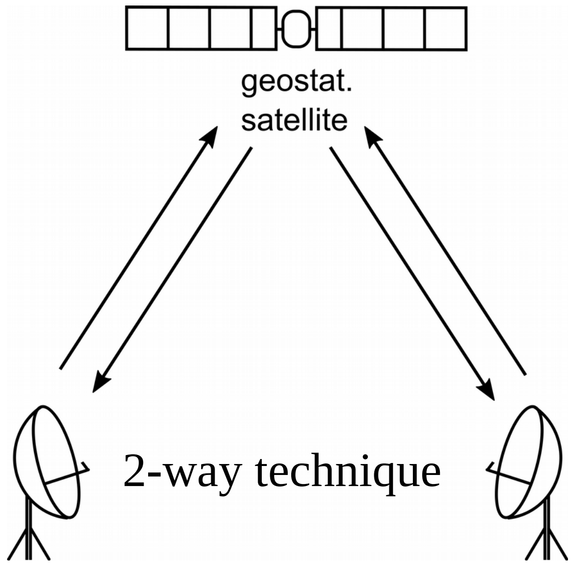
Navigation satellites:



Geostationary satellites:



Precise Point Positioning (PPP): best openly available technique

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

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

→ try out highest modulation bandwidth possible with equipment

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Two-Way Satellite Time and Frequency Transfer

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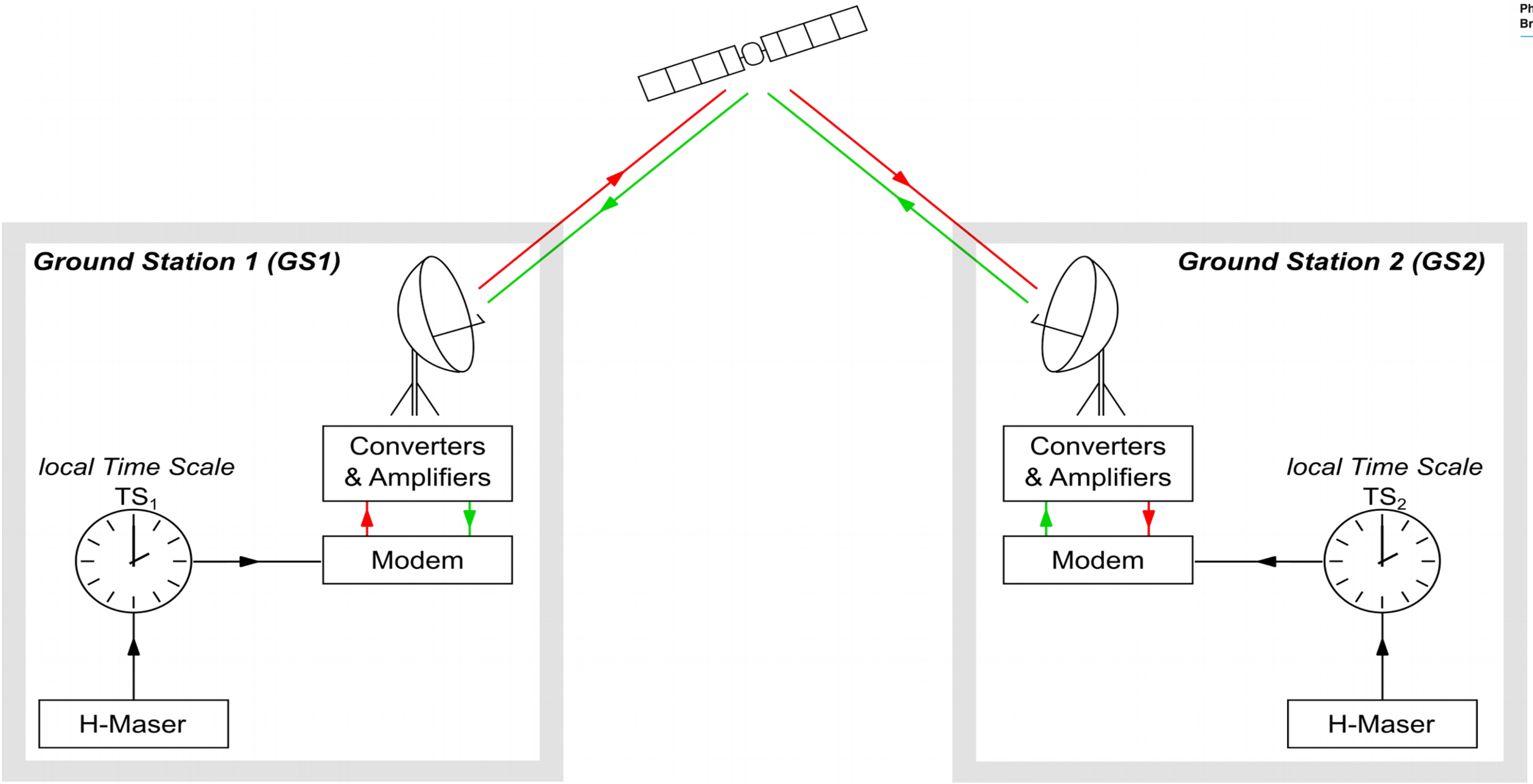
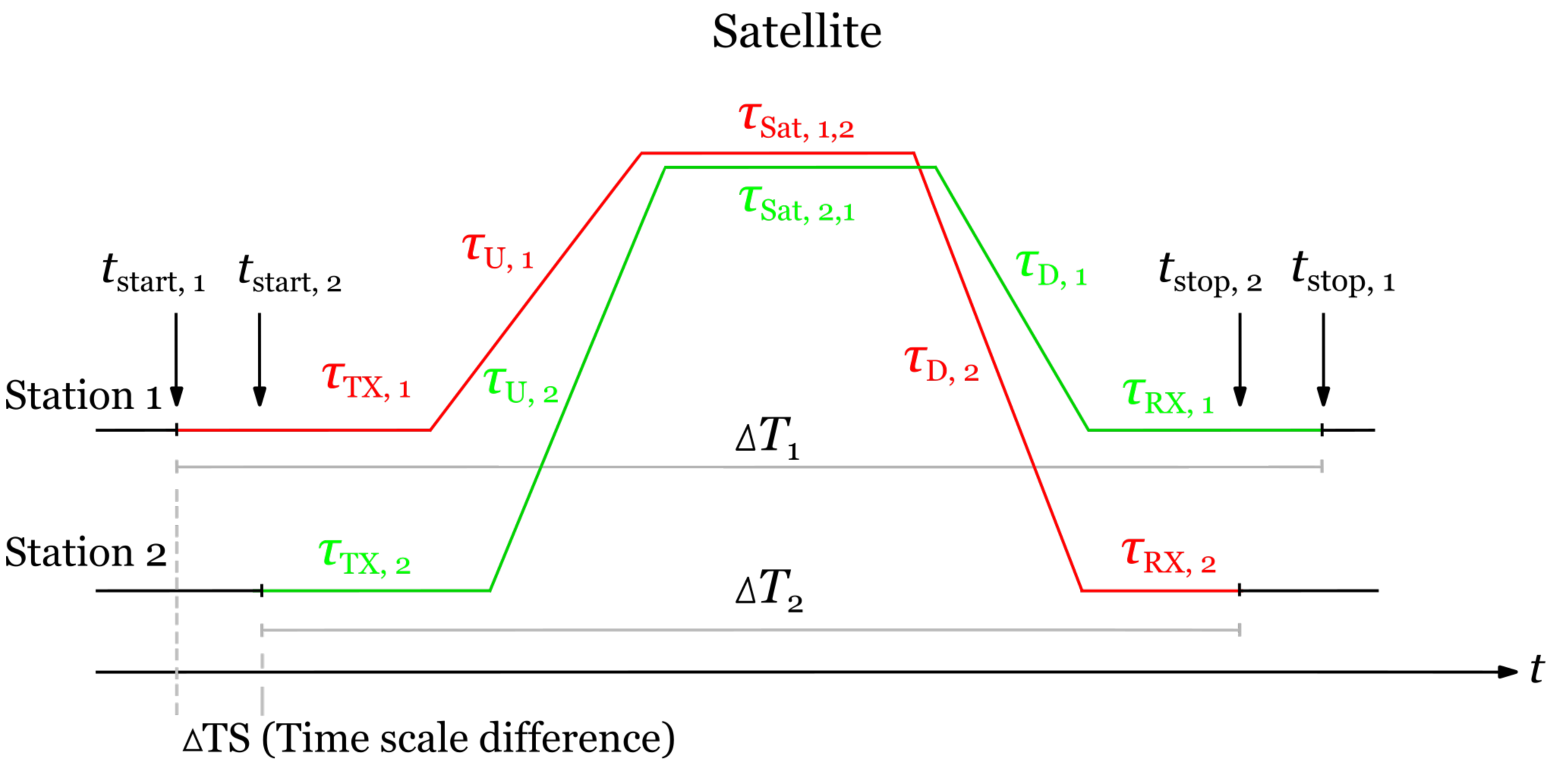


Two-Way Satellite Time and Frequency Transfer



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

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

Two-Way Satellite Time and Frequency Transfer

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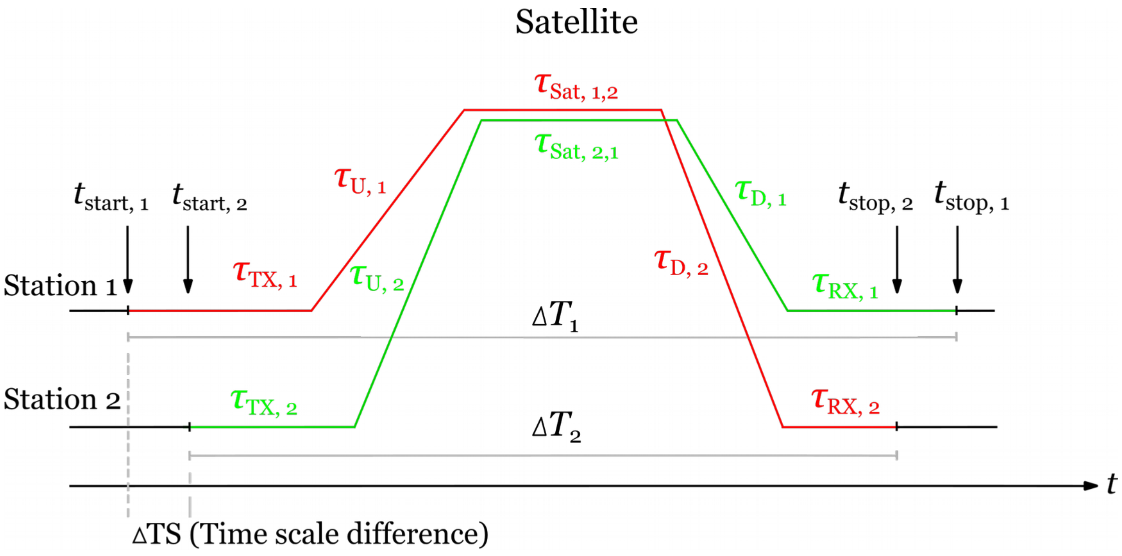


$$\Delta T_1 = \Delta TS + \tau_{TX,2} + \tau_{U,2} + \tau_{21} + \tau_{D,1} + \tau_{RX,1}$$

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

$$\Delta TS = \tfrac{1}{2}\,[\Delta T_1 - \Delta T_2 - (\tau_{sat,\,2,1} - \tau_{sat,\,1,2}) - (\tau_{U,2} - \tau_{D,2}) - (\tau_{D,1} - \tau_{U,1}) - (\tau_{TX,2} + \tau_{RX,1} - \tau_{TX,1} - \tau_{RX,2})]$$

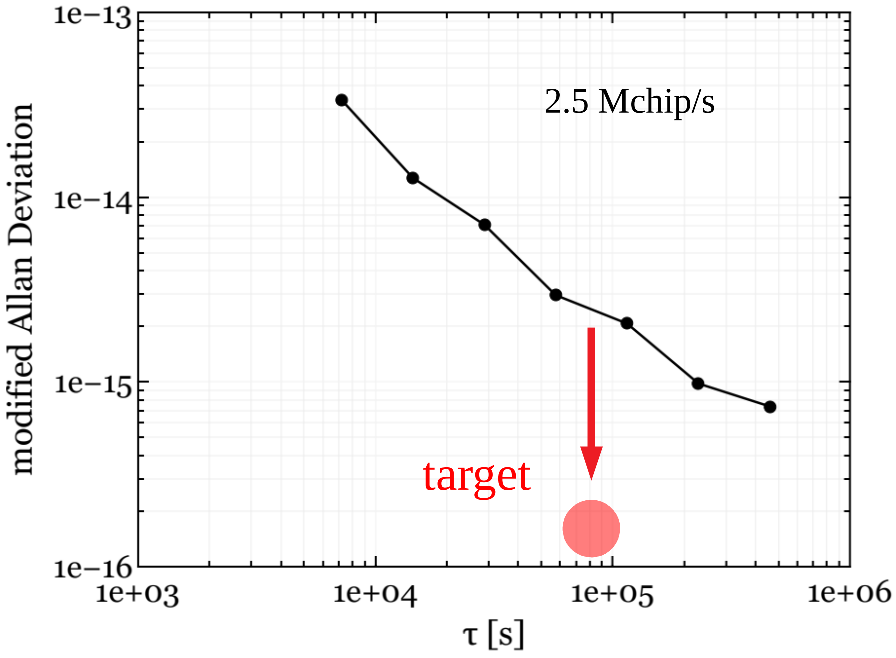
$= 0$ for reciprocal path

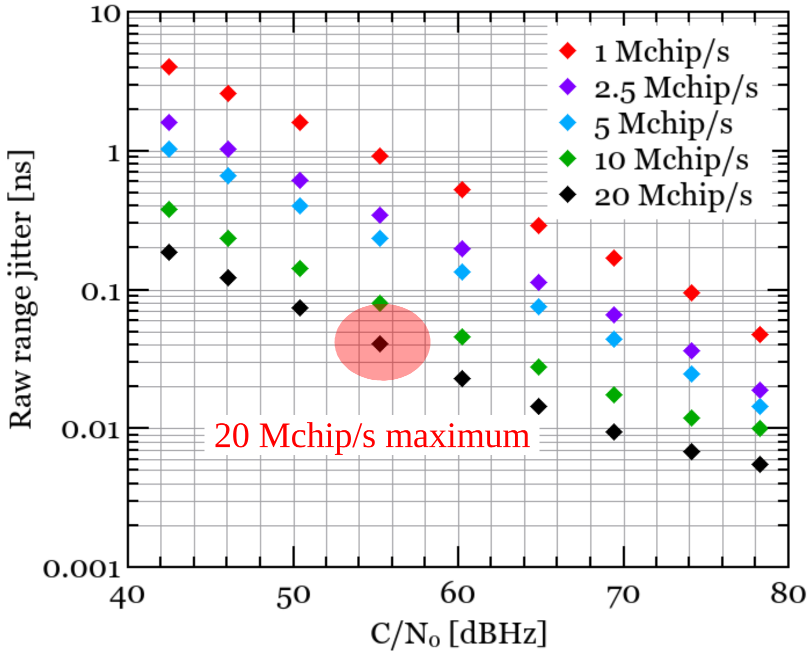
$=$ const. (calibrated)

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

Modem performance: measurements at high bandwidth

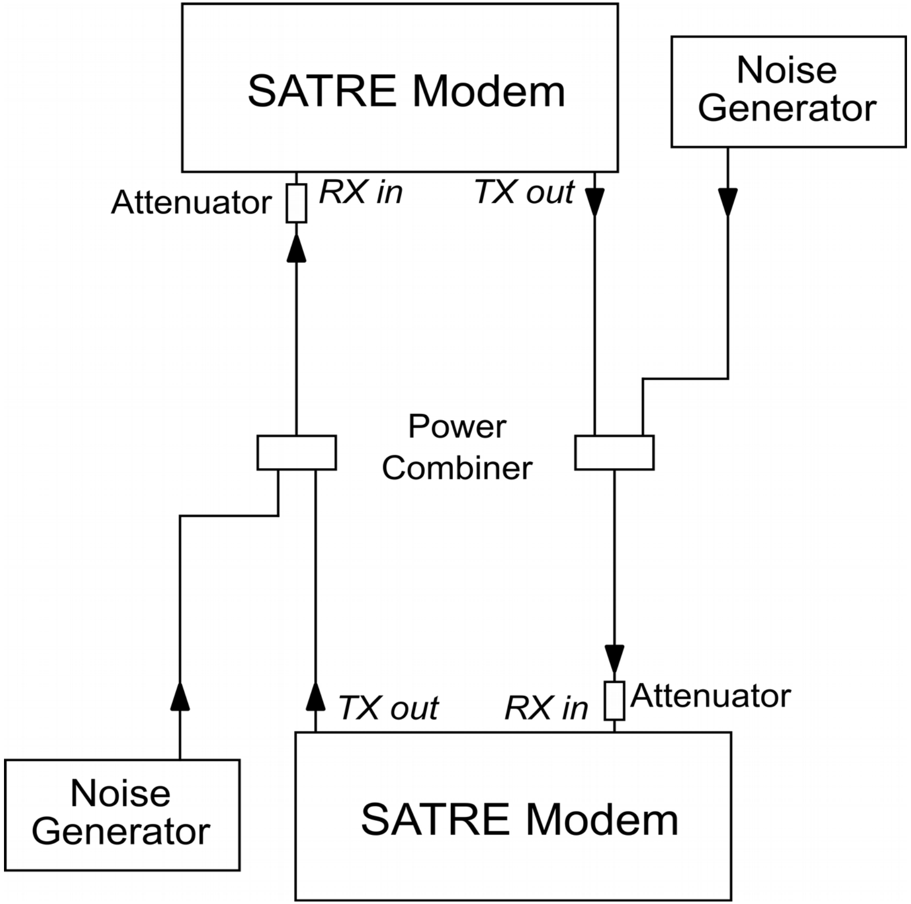
Each laboratory: modem from same manufacturer

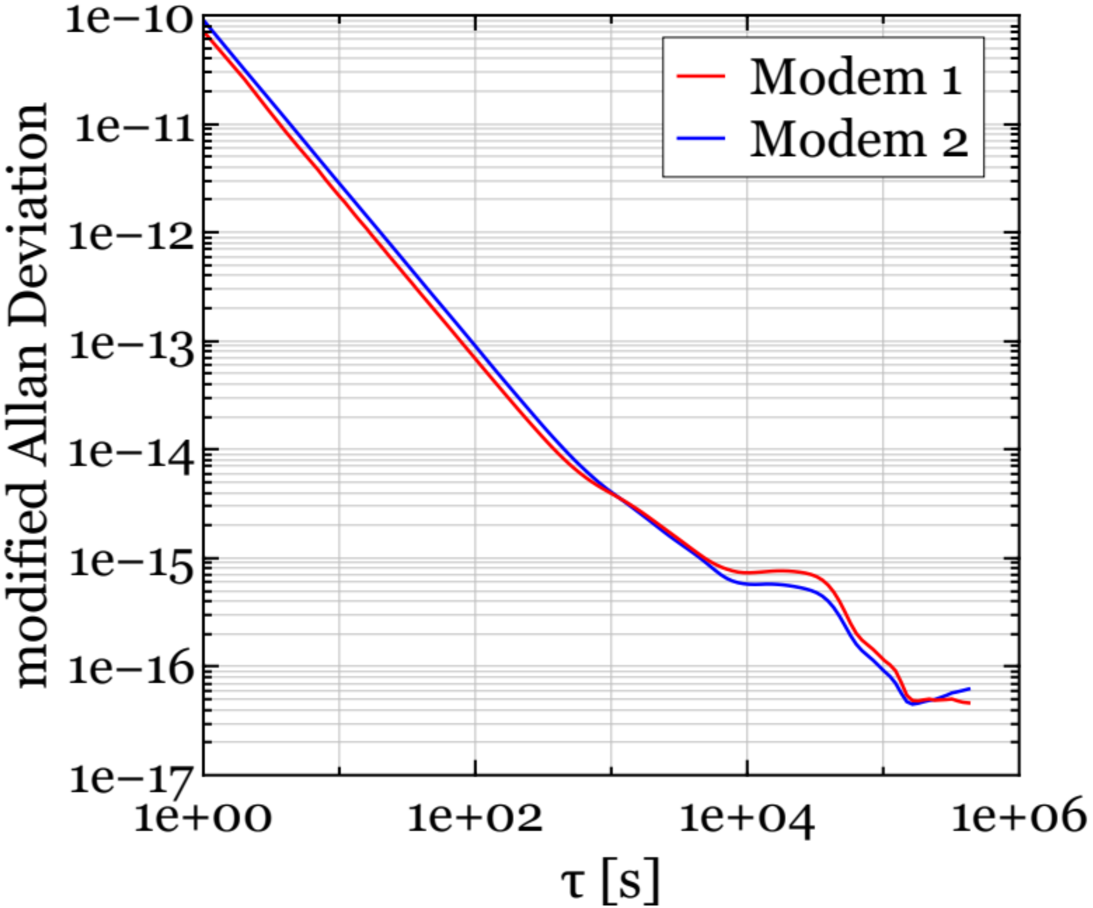




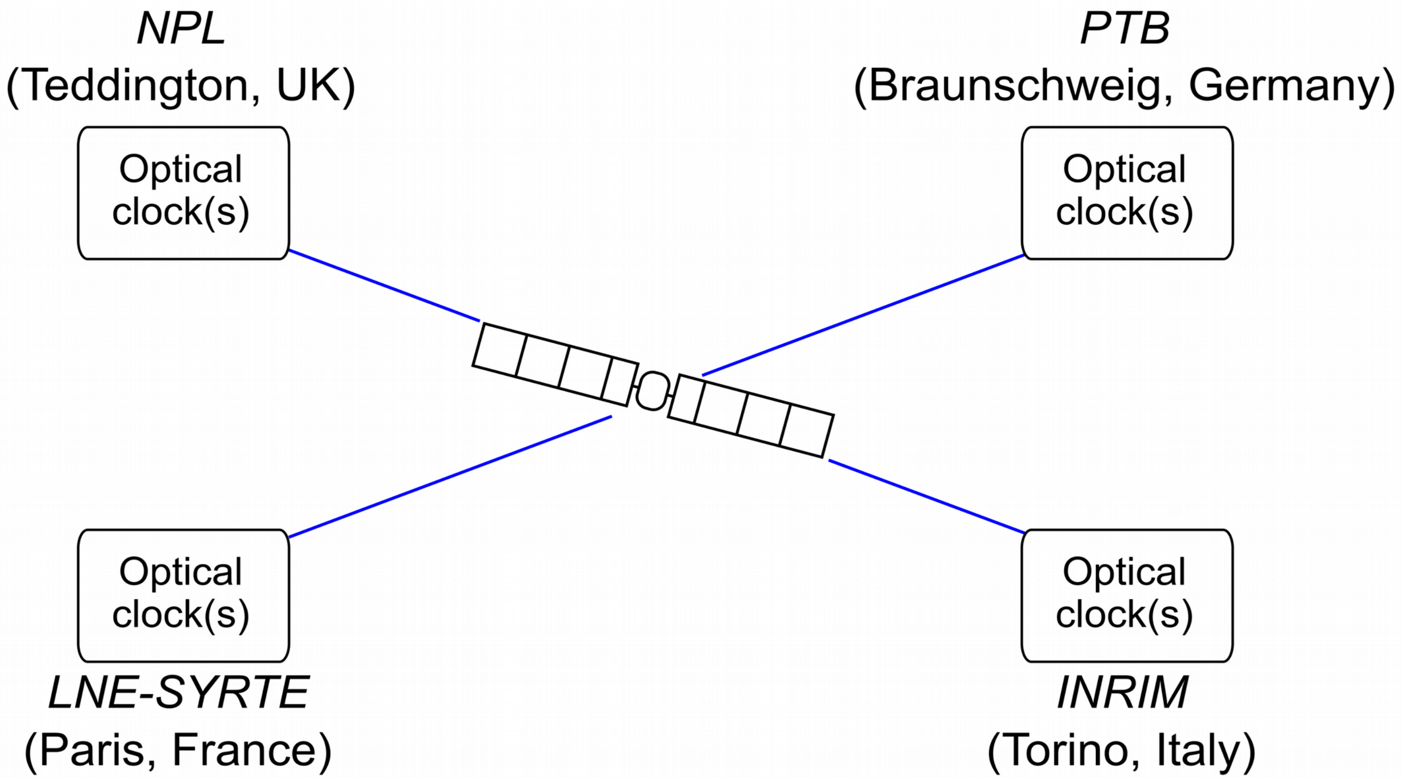
D. Piester et al. IEEE TUFFC 55, 9 (2008), pp. 1906–1912

SATRE Modem tests: long-term instability at $C/N_0 = 55$ dBHz





Goal: clock comparison with high-bandwidth TWSTFT



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

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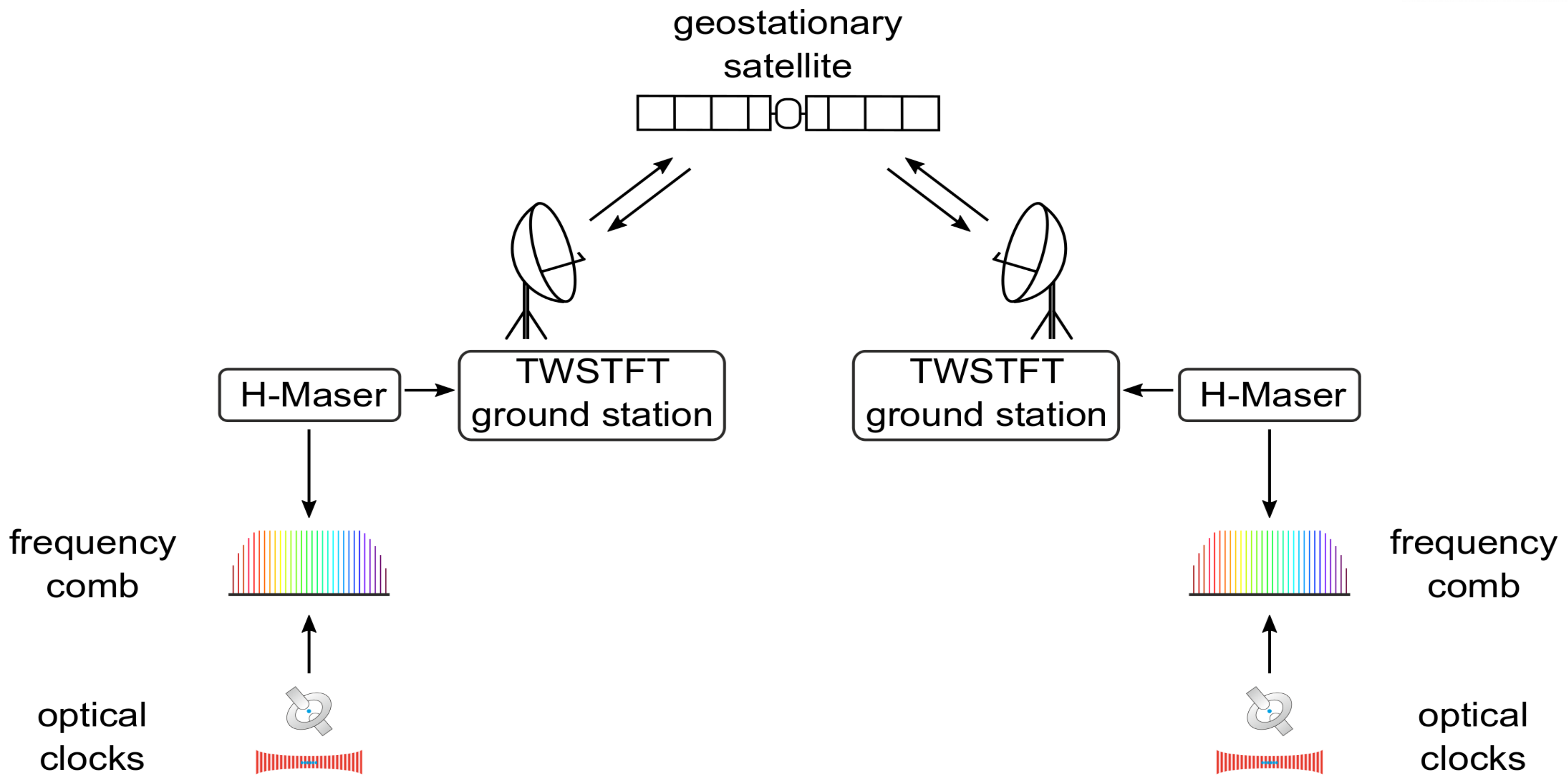
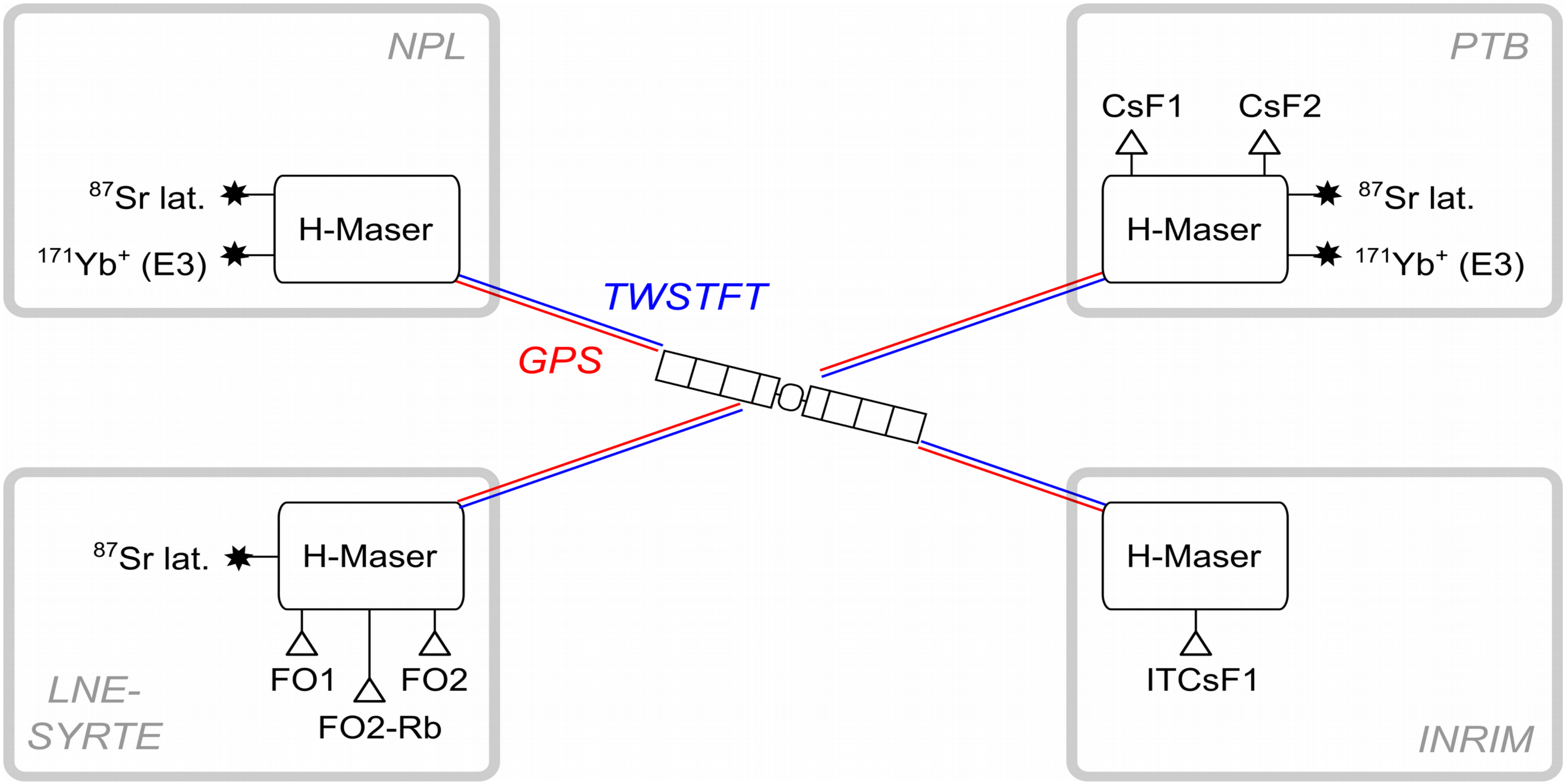
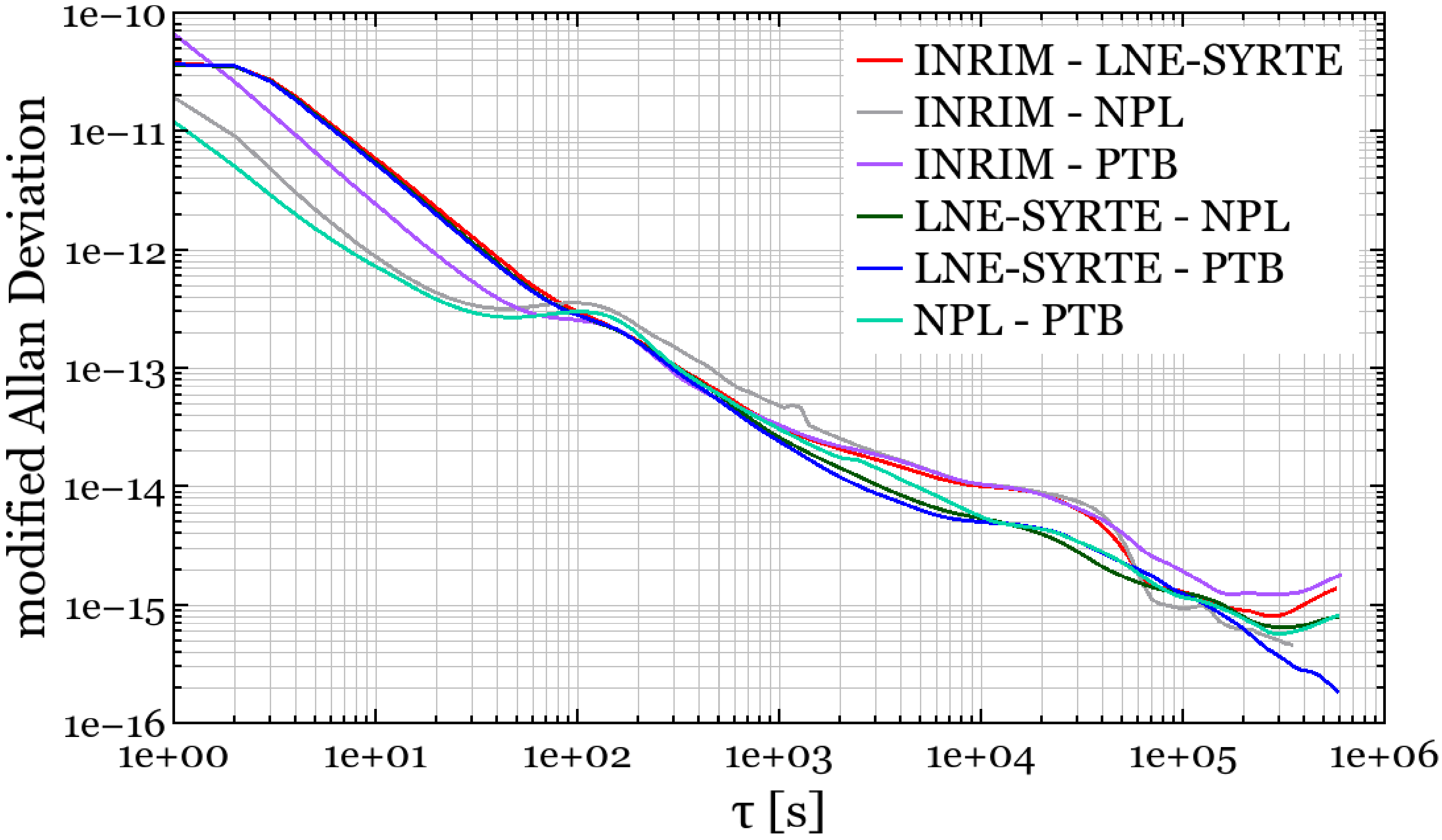
Comparison of optical clocks: Setup



Clock comparison campaign: overview



Clock comparison campaign: TWSTFT instability



Clock comparison campaign: TWSTFT and GPS PPP

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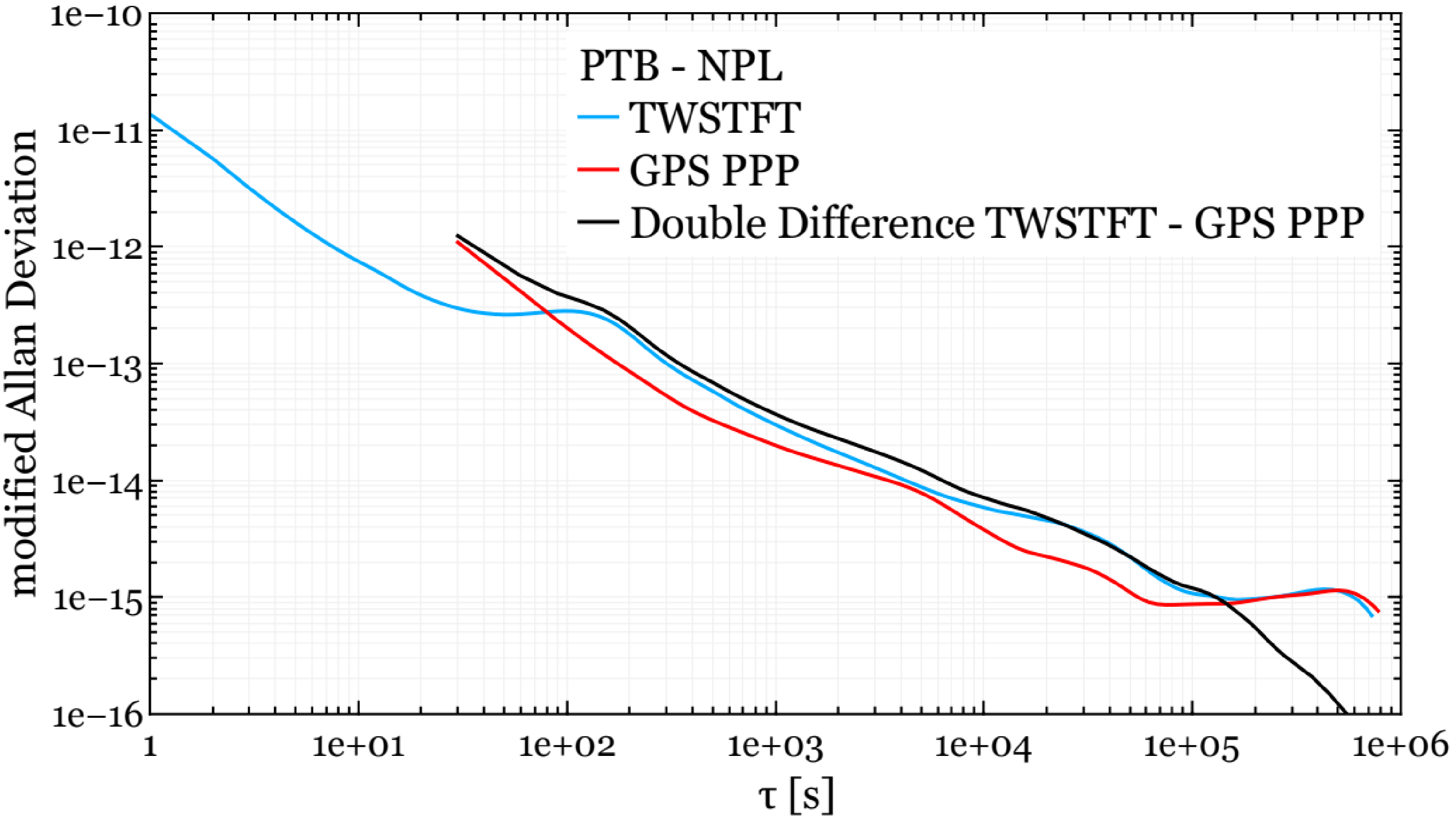

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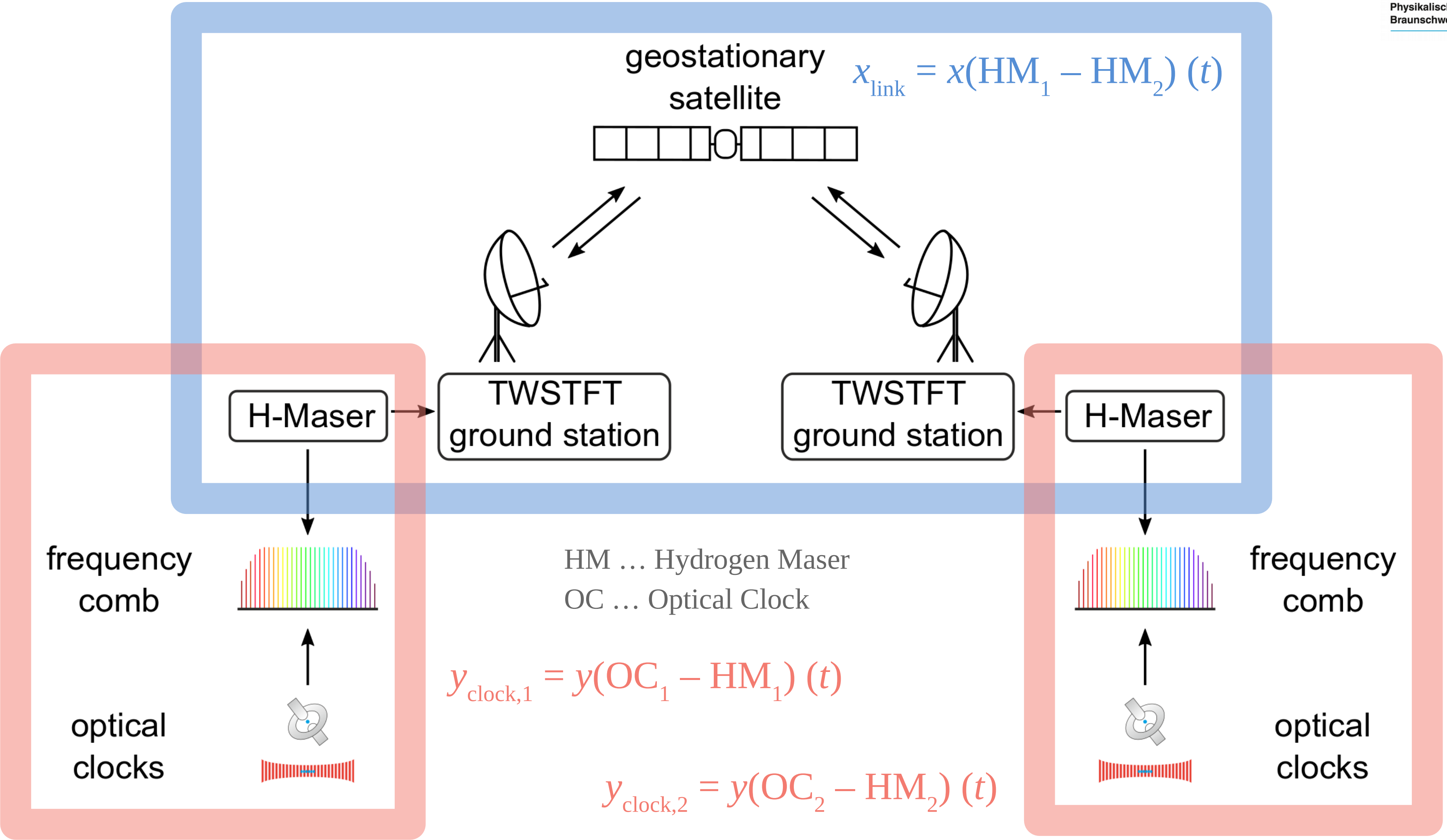
Calculate relative frequency differences of optical clocks



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

HM … Hydrogen Maser
OC … Optical Clock

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

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

Calculate relative frequency differences of optical clocks

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

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

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

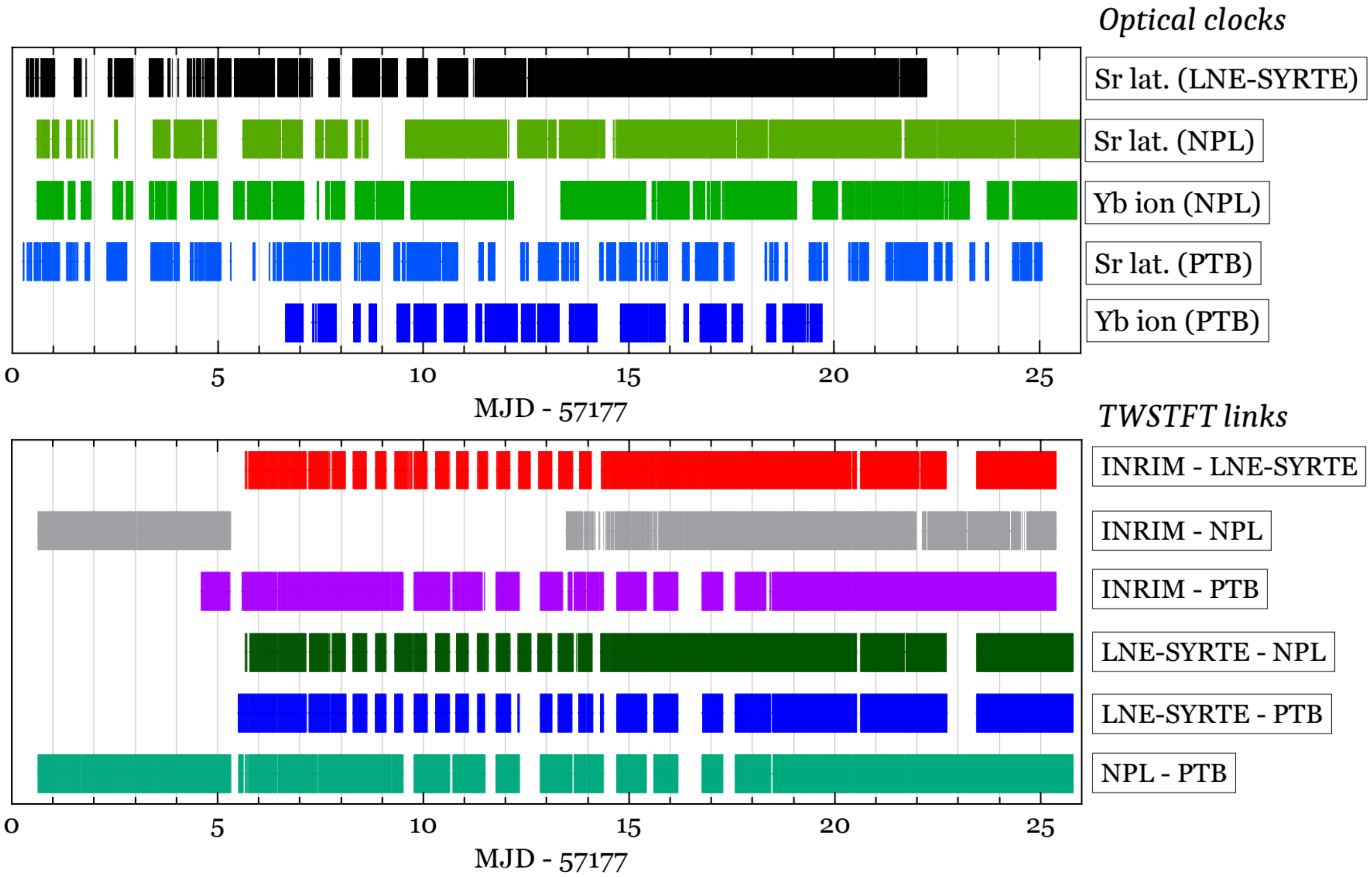
$$y_{\mathrm{clock,1}}(t) = y(\mathrm{OC}_1 - \mathrm{HM}_1)\,(t)$$

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

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

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

Calculate relative frequency differences of optical clocks



Calculate relative frequency differences of optical clocks

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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

Calculate relative frequency differences of optical clocks

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$$\bar{y} = \sum_{i=1}^{n} w_i \cdot y_i \quad \text{with} \quad \sum_{i=1}^{n} w_i = 1$$

gaps: $y(t_i) = [] \rightarrow w(t_i) = 0$

Uncertainty? $u = \sqrt{u^2_{A,clocks} + u^2_{A,link} + u^2_{B,clocks} + u^2_{B,link}}$

$u_{B,\,link}$: contributions estimated from the temperature measured during the campaign

u_A = square root of estimator for variance of the mean $s^2_{\bar{y}}$

$$s^2_{\bar{y}} = \sum_{i=1}^{n} w_i^2 \sum_{i=1}^{n} w_i (y_i - \bar{y})^2$$

But:

non-white noise on data, gaps on data: biased estimator for standard deviation of the mean

Calculate relative frequency differences of optical clocks

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reduced biased:

$$s_{\bar{y}}^2 = R_0 \sum_{i=1}^{n} w_i^2 + 2 \sum_{l=1}^{l_\text{cut}} R_l \sum_{j=1}^{l_\text{cut}} w_j w_{j+l}$$

with

$$R_l = \frac{\sum_{i=1}^{N-l} \sqrt{w_i w_{i+l}} (y_i - \bar{y})(y_{i+l} - \bar{y})}{\sum_{i=1}^{N-l} \sqrt{w_i w_{i+l}}}$$

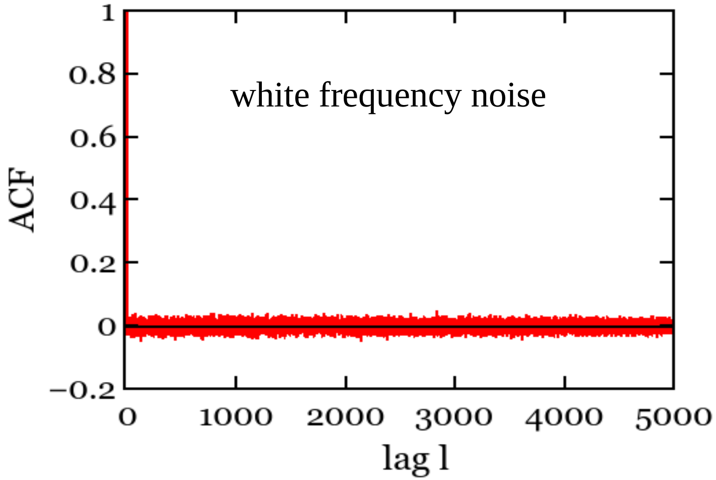
Autocorrelation function (ACF)

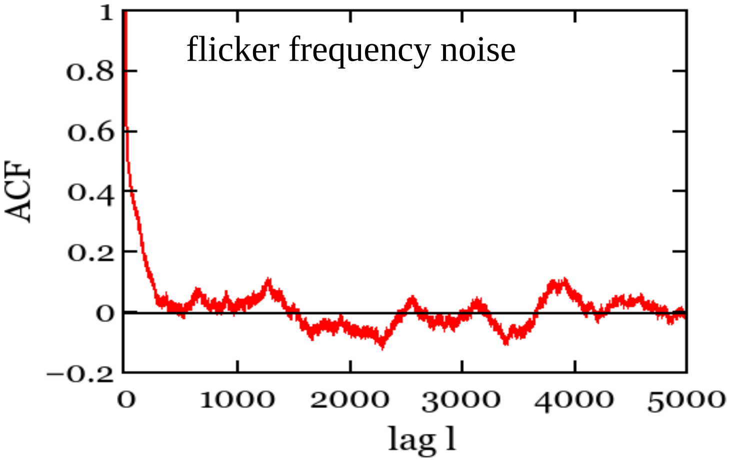
$$r_l = \frac{R_l}{R_0}$$

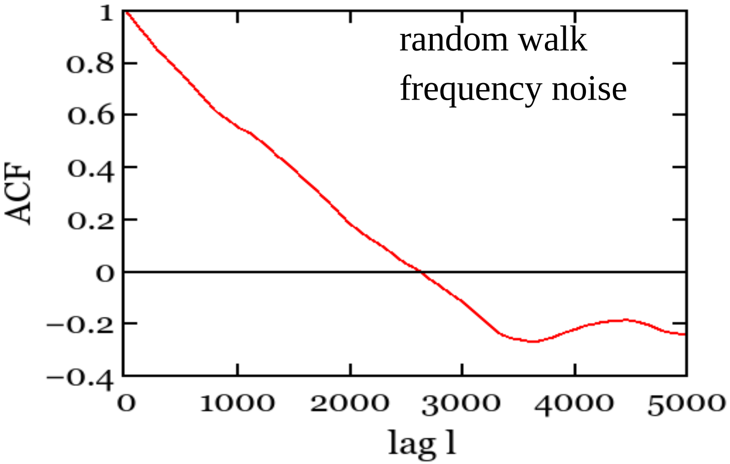
ACF, normalized

Calculate relative frequency differences of optical clocks

Autocorrelation function (of relative frequency data) at different noise types







Calculate relative frequency differences of optical clocks

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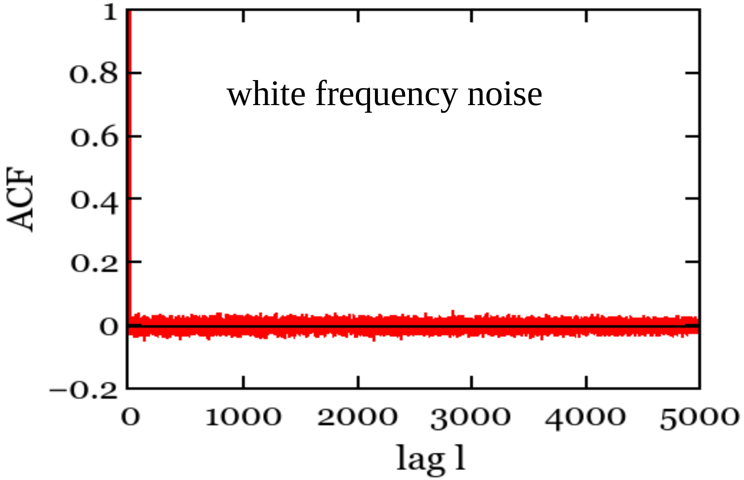
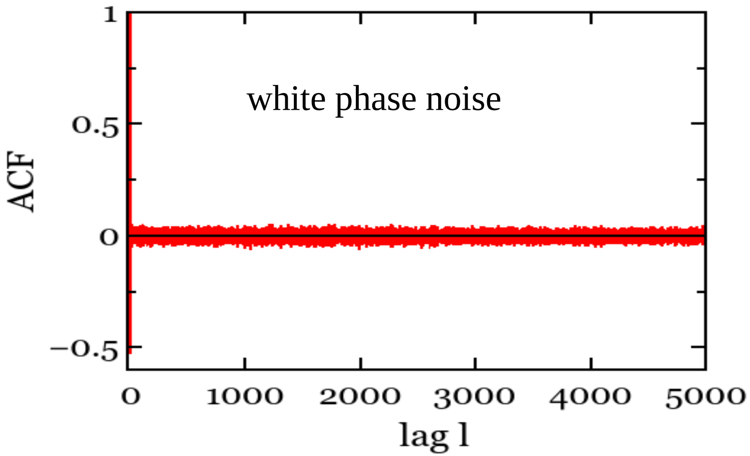
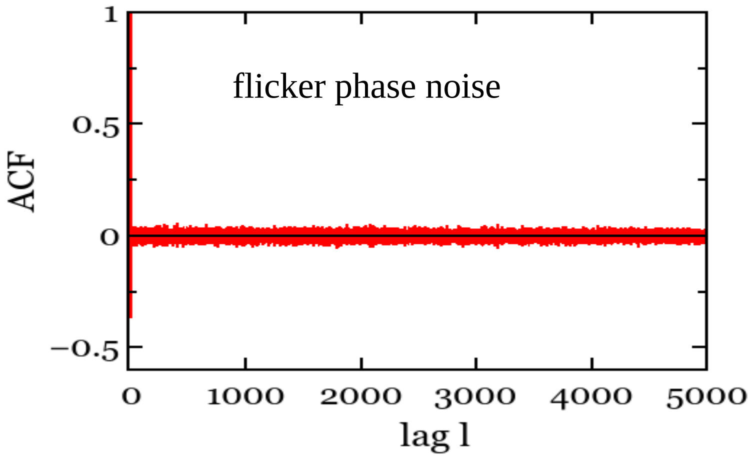
Autocorrelation function (of relative frequency data) at different noise types



$$s_{\bar{y}}^2 = R_0 \sum_{i=1}^{n} w_i^2 + 2 \sum_{l=1}^{l_{\text{cut}}} R_l \sum_{j=1}^{l_{\text{cut}}} w_j w_{j+l}$$

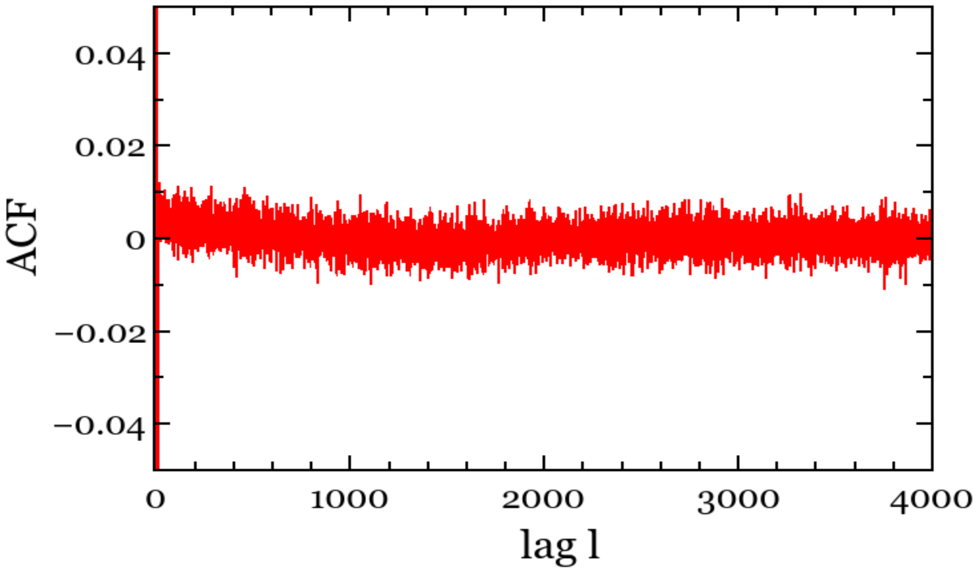




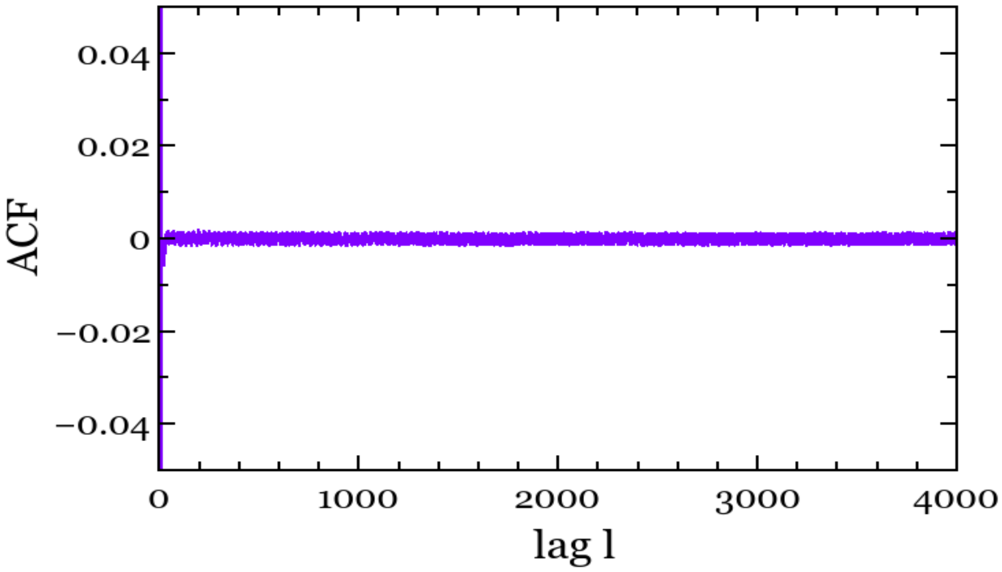
Calculate relative frequency differences of optical clocks

Autocorrelation function of relative frequency data from clock comparisons

$y(\mathrm{OC} - \mathrm{HM})$



$y(\mathrm{OC}_1 - \mathrm{OC}_2)$



$l_{\mathrm{cut}} = 4000$

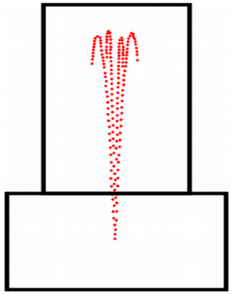
Clock comparison campaign: Other comparisons

Fountain clocks:

different requirements for calculation

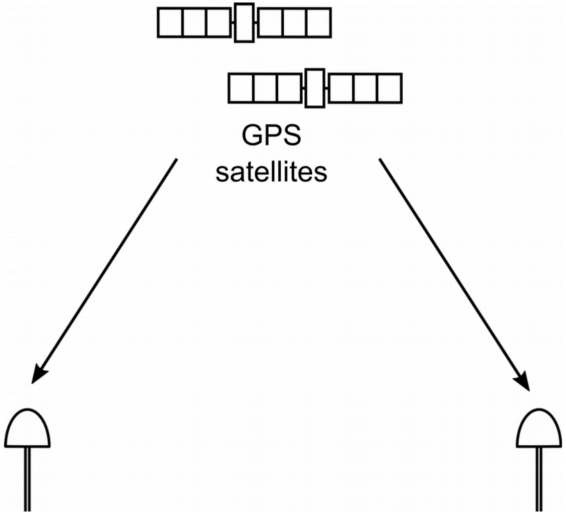
→ pre-average each set of data over certain interval,

use $u_{A,\ link}$ of optical clock comparison



GPS:

same as TWSTFT, but on 30s interval



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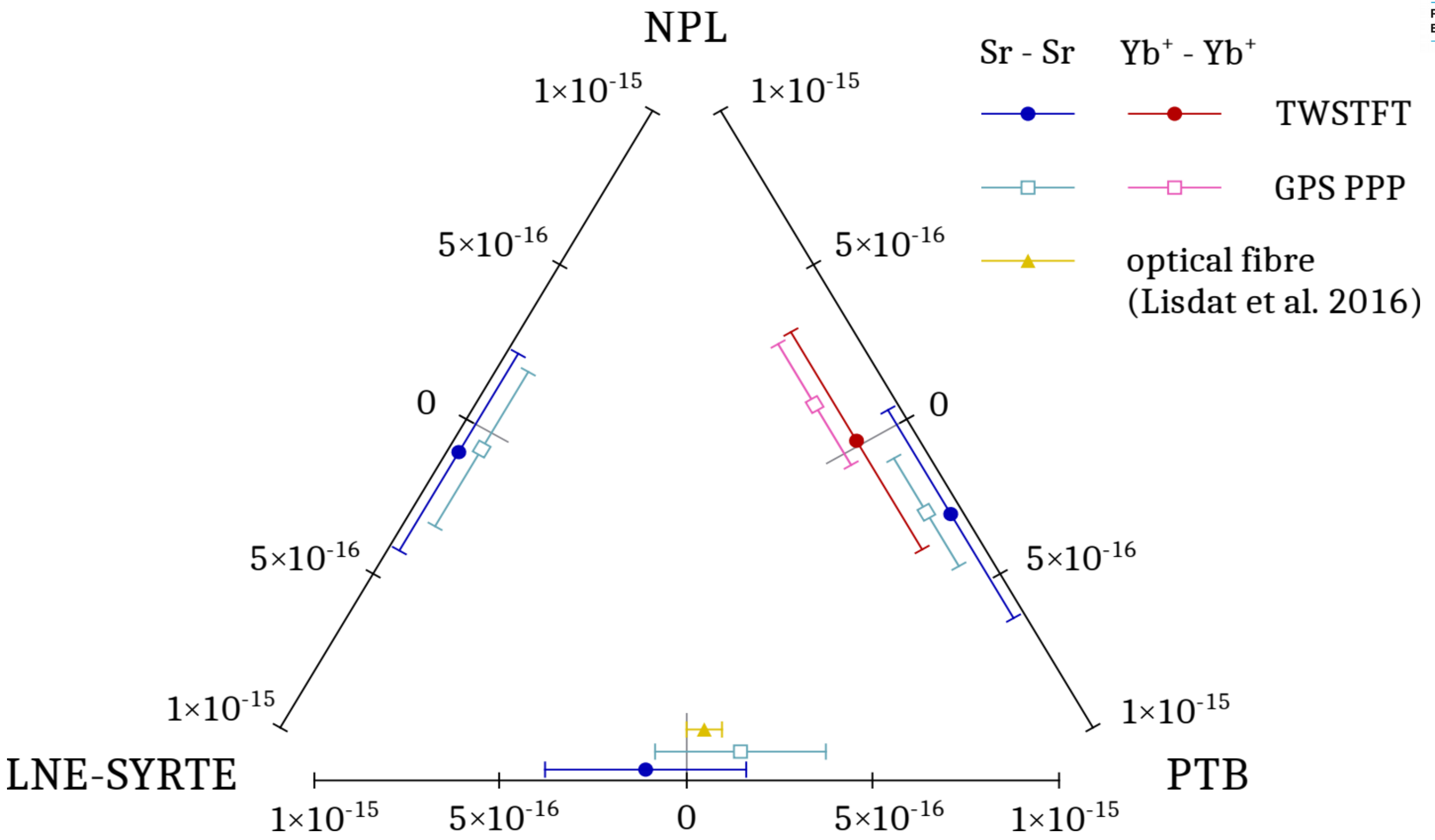
Results for optical clocks (same type)

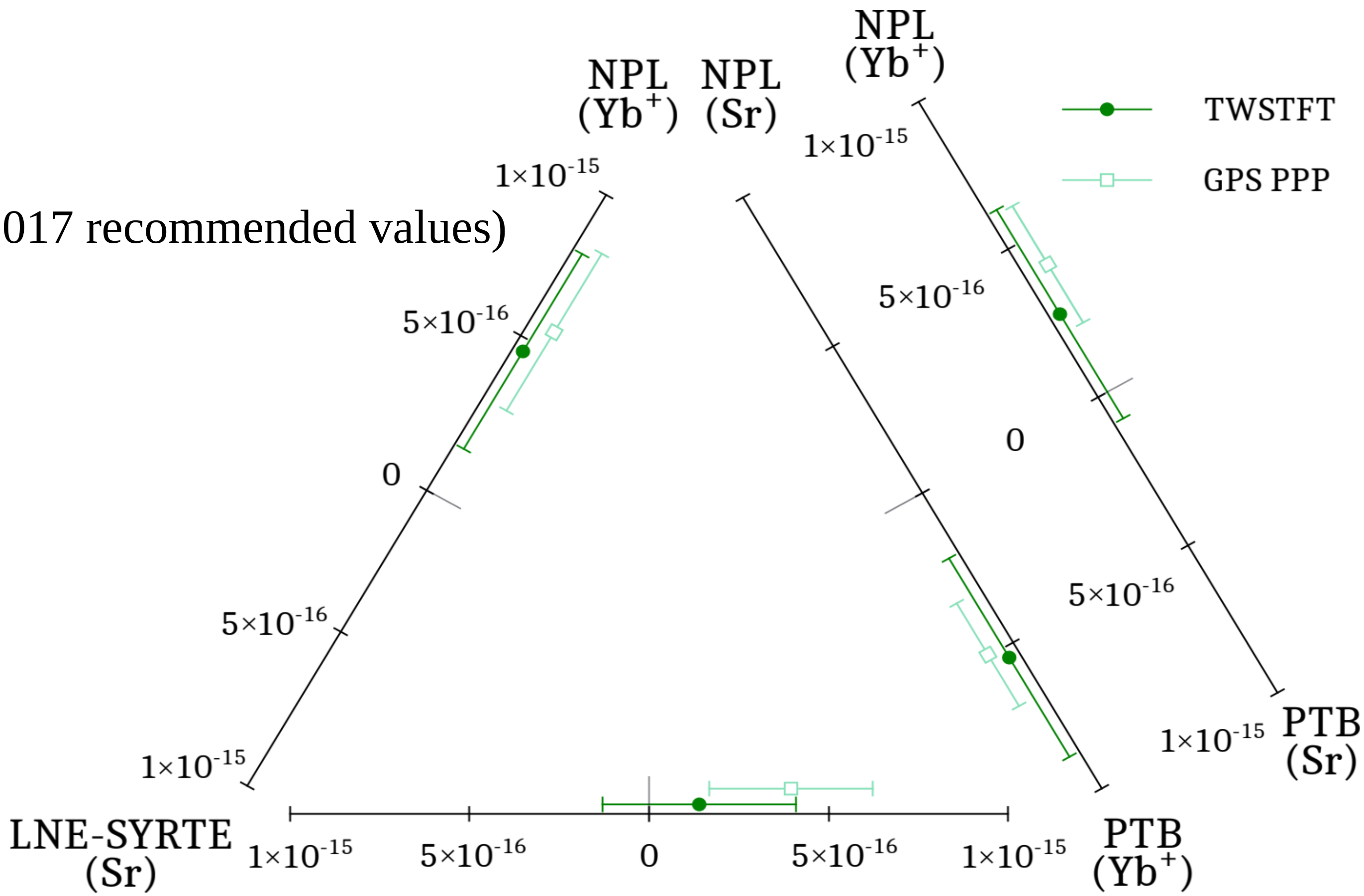


Different clocks: agreement, but slight offset in Sr (NPL) indicated

Different techniques: agreement

Results for optical clocks (different type)

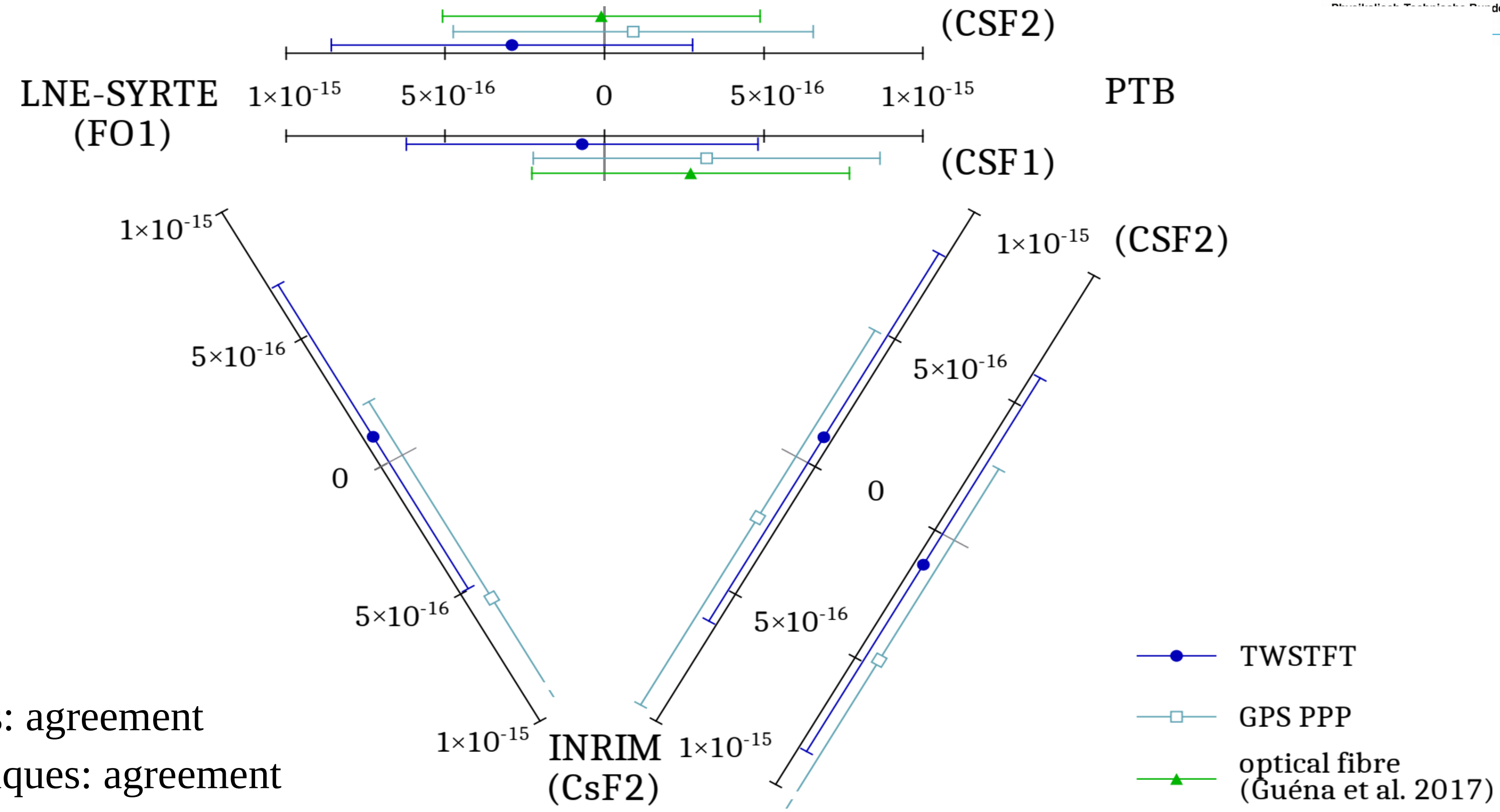
("0" = CIPM 2017 recommended values)



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

Different techniques: agreement

Results for fountain clocks (part 1)

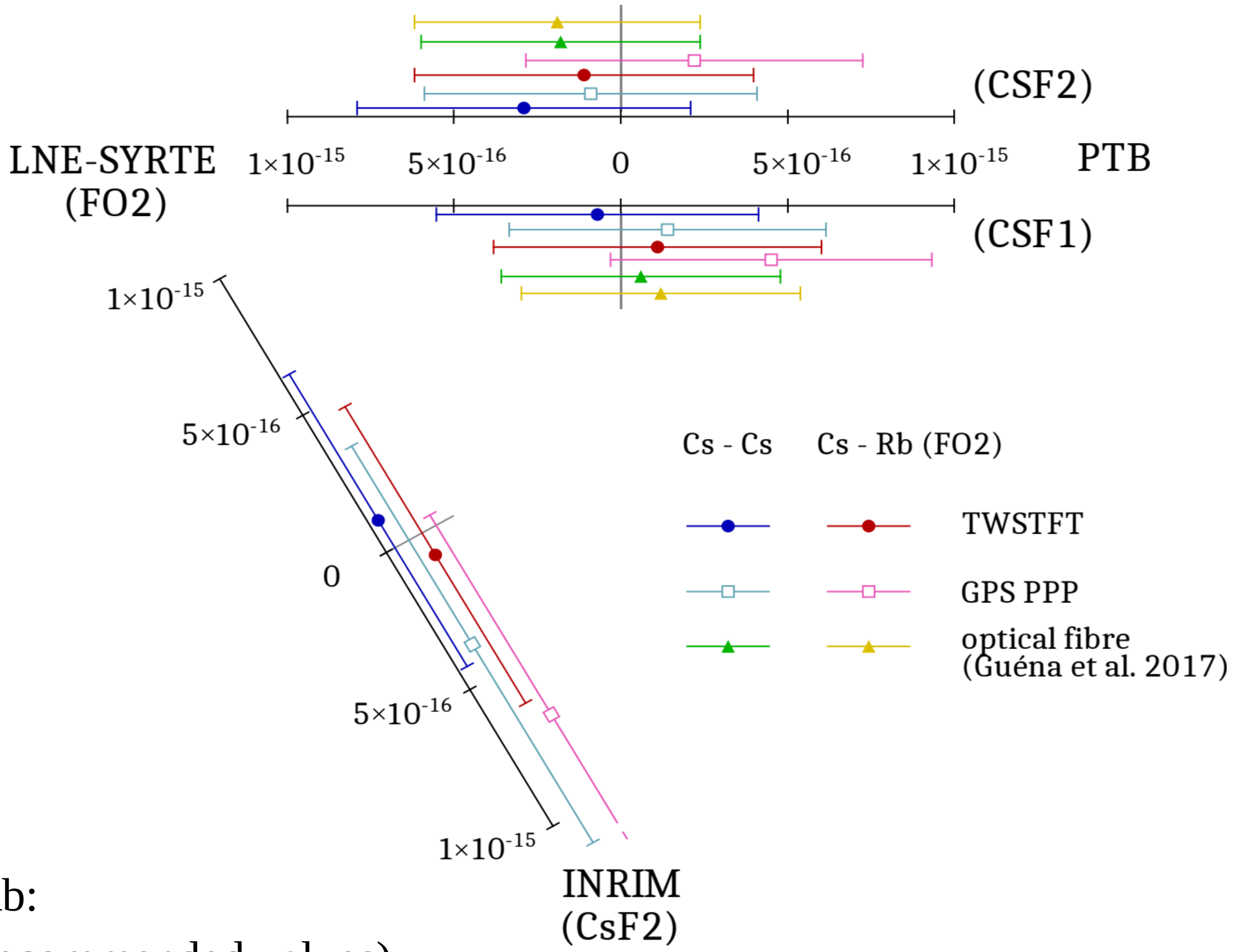


Fountain clocks: agreement

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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Summary

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- First simultaneous international optical clock comparison (> 2 clocks)
- Characterization of TWSTFT equipment, Analysis of effects impacting precise TWSTFT measurements

  → Corrections (relativistic/ionospheric) required for uncertainty of $1\cdot10^{-16}$ or lower
- TWSTFT improves respectively with higher chip rate
- Development of analysis procedure taking into account gaps and correlation
- Limitations:

  – disturbances increasing noise/gaps on data (clocks and links)

  – determination of u_B
- 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

Outlook: suitable techniques for clock comparisons

- Comparison via optical fibers:
  Network set up in Europe, but still only very 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 $\tau^{-1/2}$
  – TWSTFT with SDR (software-defined radio): some systematic effects can be suppressed, lower instabilities observed at low chip rates

Acknowledgements

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EMRP
European Metrology Research Programme
Programme of EURAMET
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Thank you for your attention!

NPL National Physical Laboratory

LNE Le progrès, une passion à partager

l'Observatoire de Paris SYRTE Systèmes de Référence Temps-Espace

INRiM Istituto Nazionale di Ricerca Metrologica

MIKES Centre for metrology and accreditation

TIMETECH

NICT

Observatoire royal de Belgique

Bureau International des Poids et Mesures