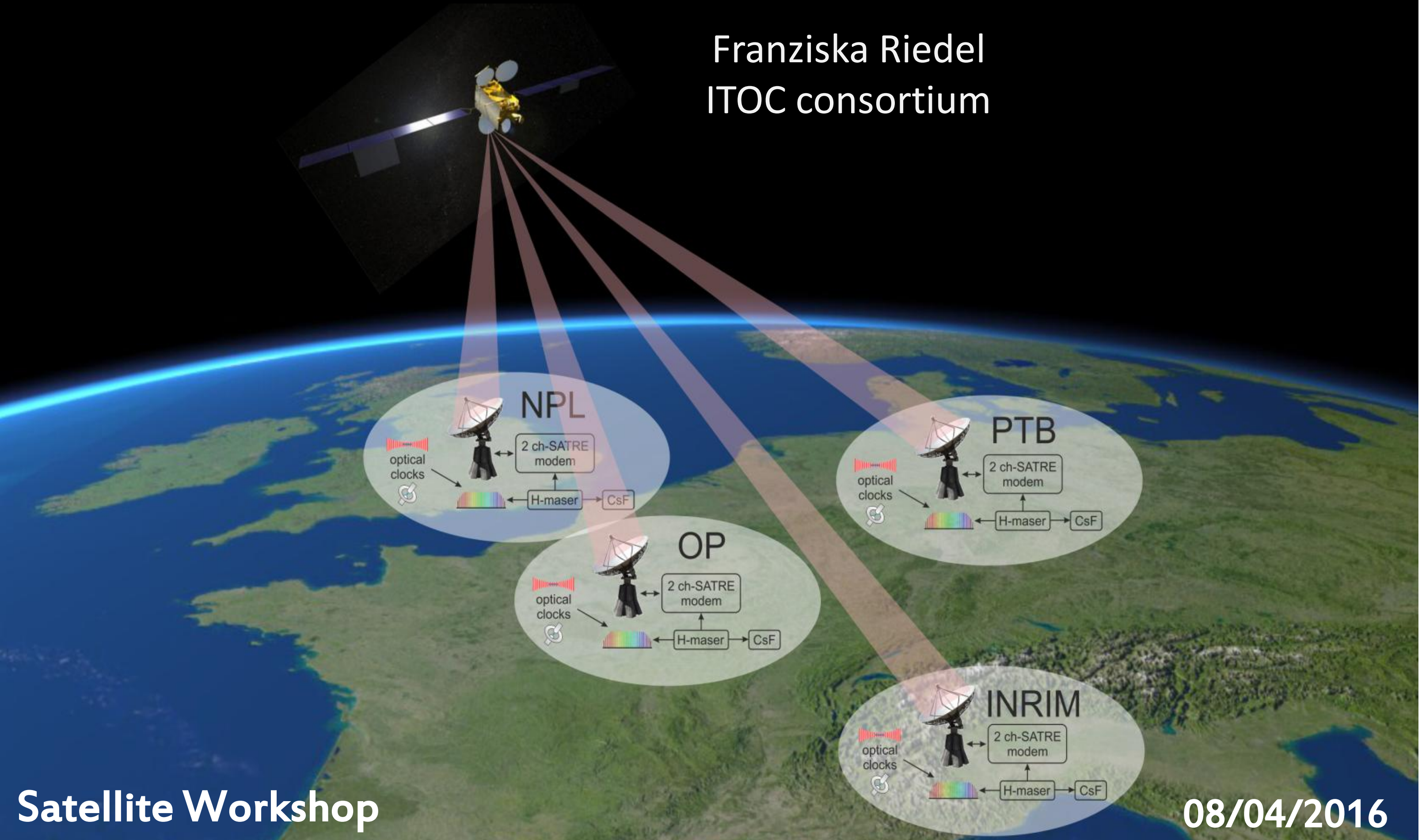
Remote optical and fountain clock comparison using broadband TWSTFT and GPS PPP

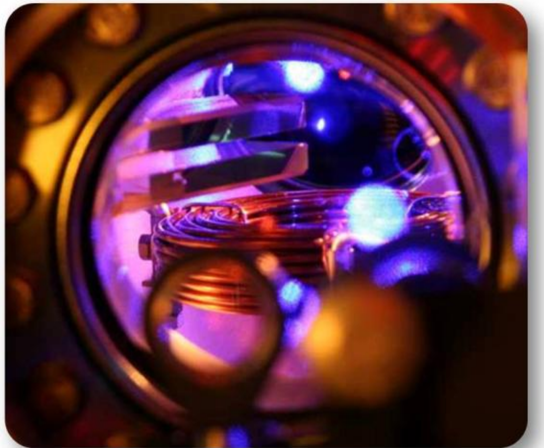
Highlight Talk
International Timescales with Optical Clocks

Franziska Riedel
ITOC consortium



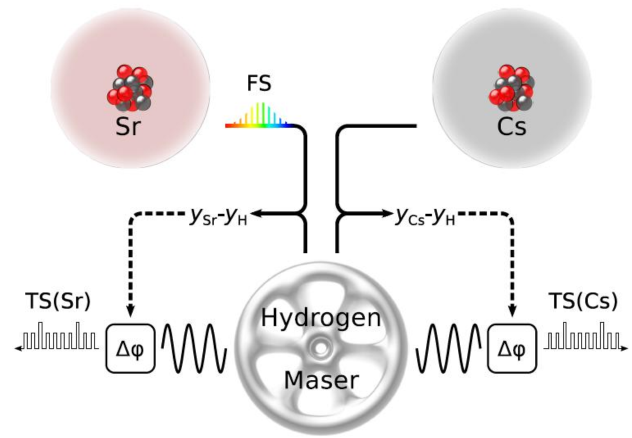
Satellite Workshop
08/04/2016
Optical clocks : quantum engineering and international timekeeping

Motivation



Optical clocks:
orders of magnitude more accurate and stable

Demonstration of steering local timescales with optical clocks



Grebing et al., arXiv:1511.03888

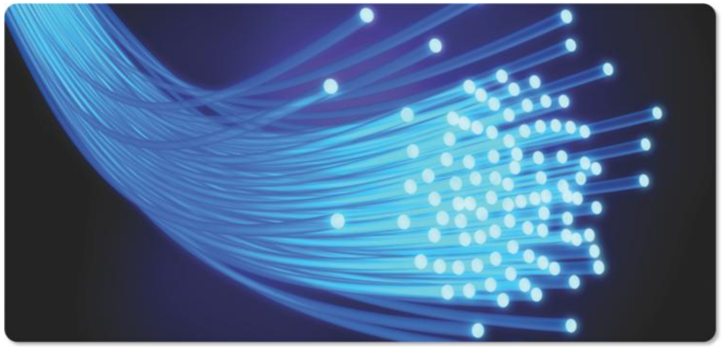
UTC(k)

Performance of links contributing to UTC?

UTC(k)

UTC

Motivation



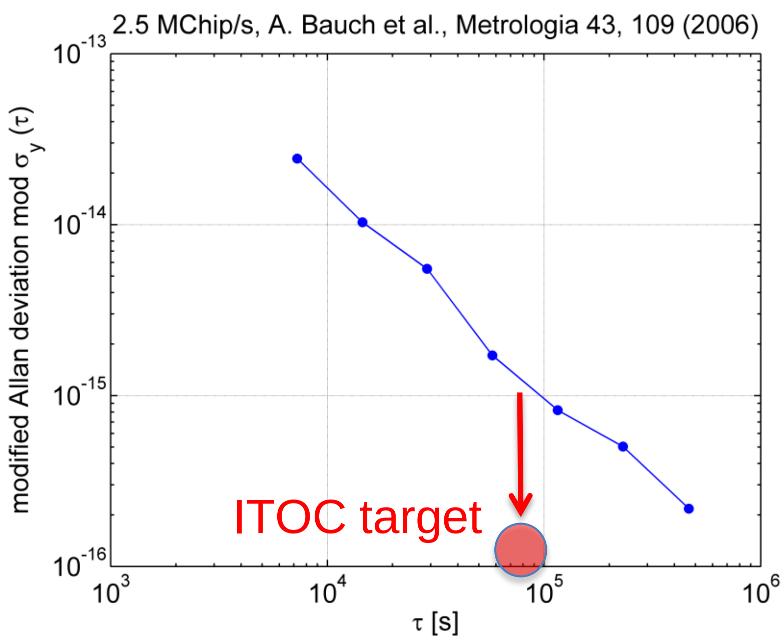
Optical fibers:

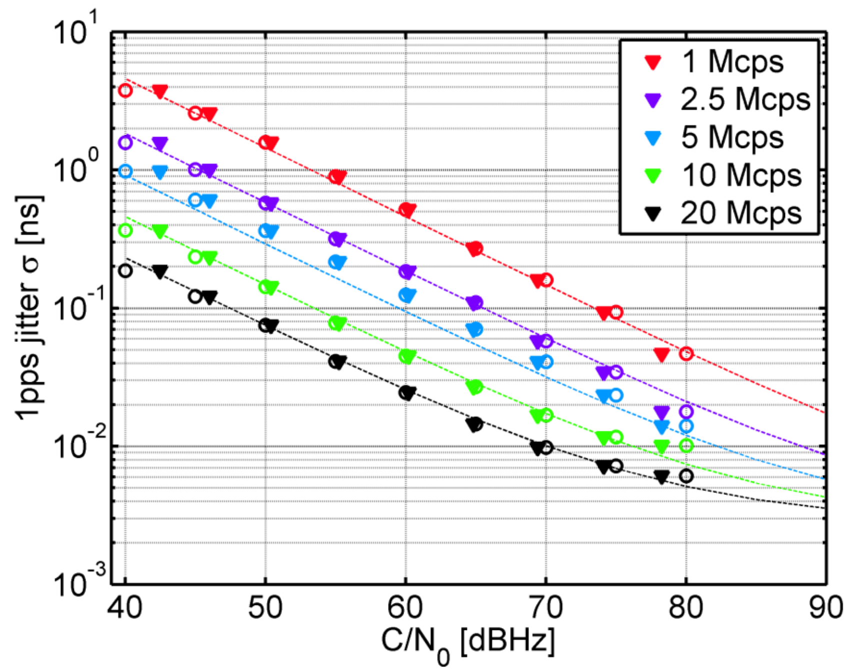
Not yet available for simultaneous comparisons on international/intercontinental scale

Currently used techniques:
GPS and TWSTFT

TWSTFT currently with 2.5 / 1 Mchip/s modulation bandwidth

Effect of higher chiprate



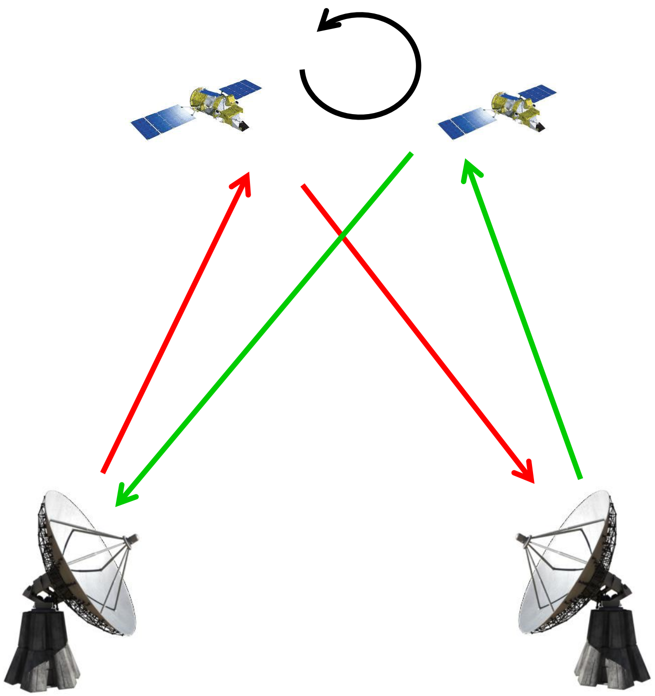


Main TWSTFT target in ITOC: Instability of 10^{-16} @ 1 day

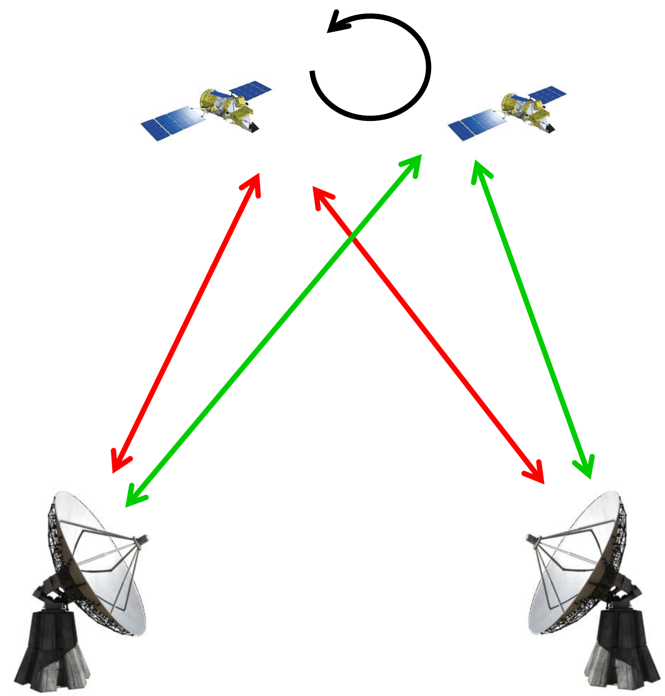
But with lower statistical uncertainty ...

... corrections must be taken into account

Effects caused by satellite motion:



Variation of path length:
leads to non-reciprocity of uplink/downlink path



Daily variation of the Sagnac effect

See poster by S. Shemar this afternoon

ITOC TWSTFT campaigns

20 Mchip/s TWSTFT:

Lease of a full Ku-band transponder (36 MHz) on SES ASTRA 3B for two campaigns

SES your satellite company

1) 24.-31. October 2014: Link test

Equipment and performance test

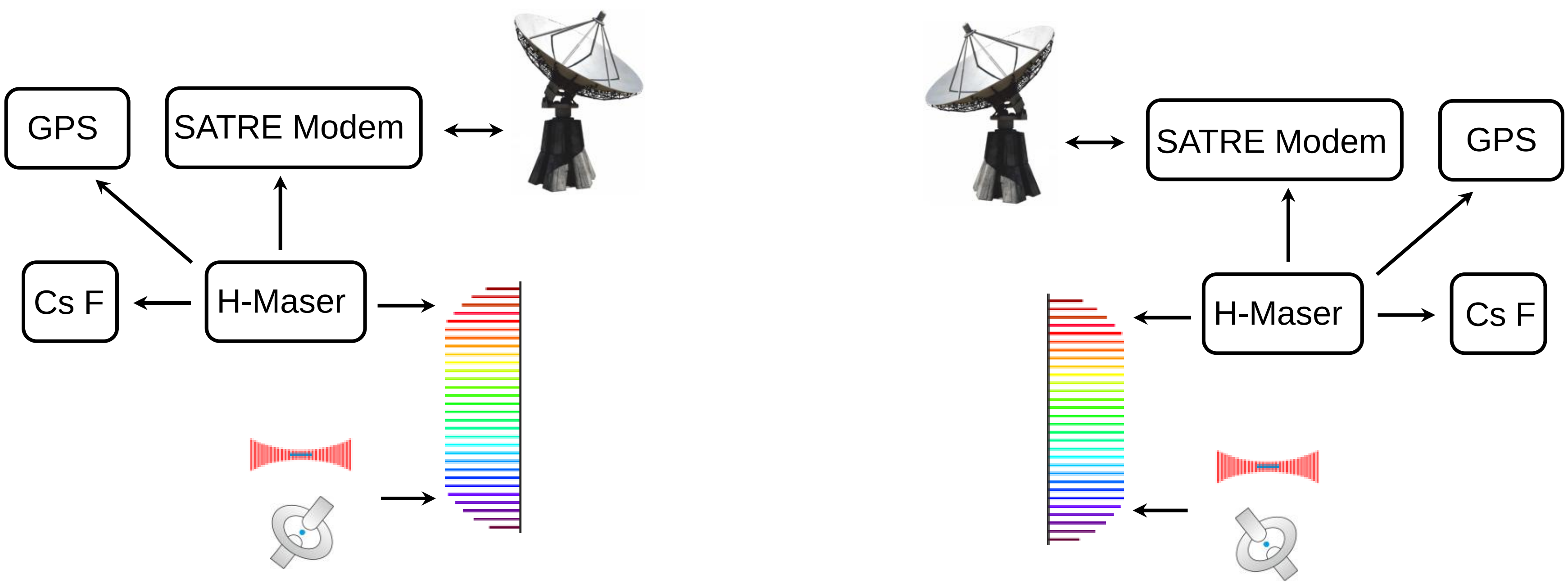
ITOC TWSTFT campaigns

20 Mchip/s TWSTFT:

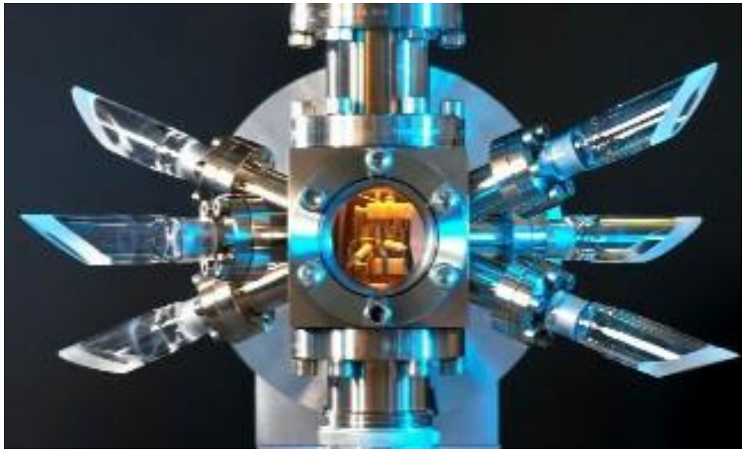
Lease of a full Ku-band transponder (36 MHz) on SES ASTRA 3B for two campaigns

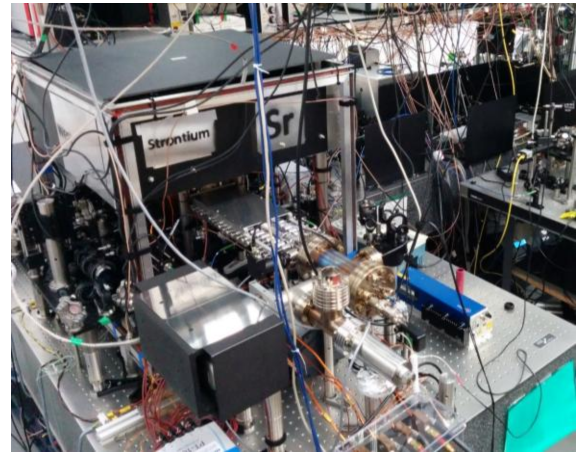
SES your satellite company

2) 4.-29. June 2015: Optical clock comparison



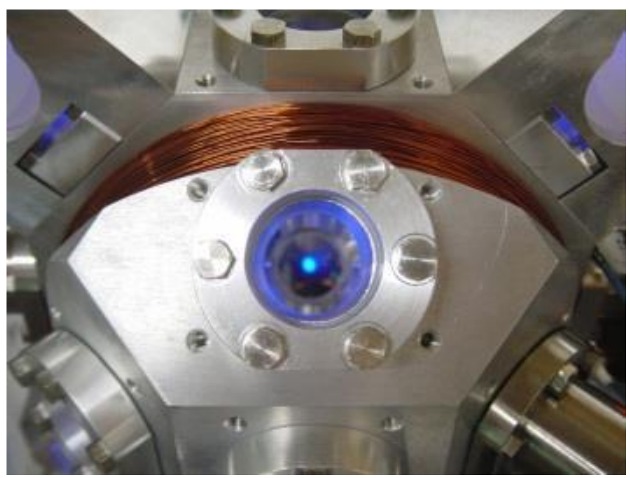
NPL





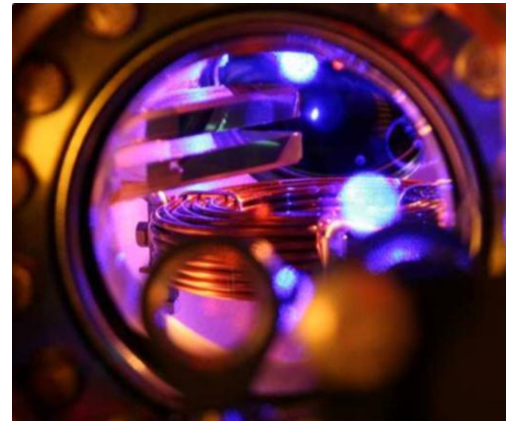
Yb$^+$ (E3), Sr lattice

LNE- SYRTE



Sr lattice + Cs fountain

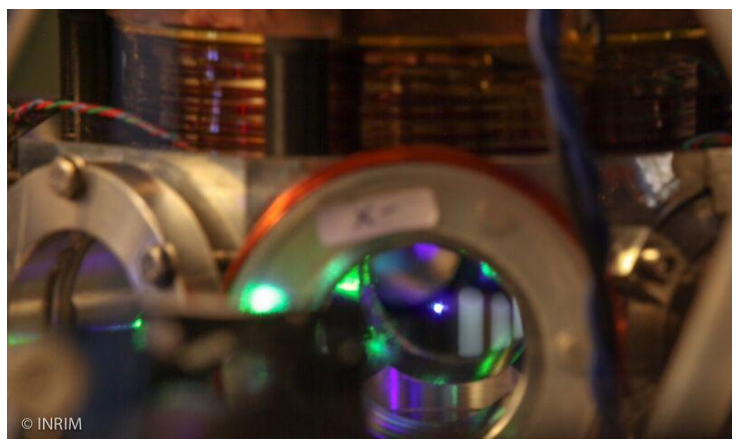
PTB



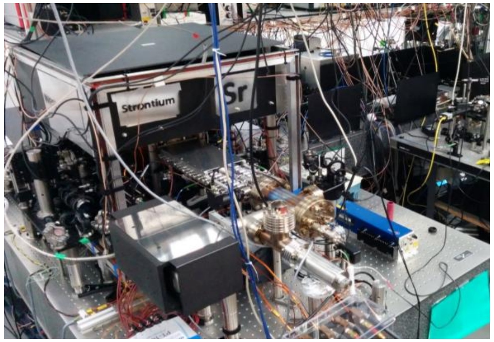
Yb^+ (E3), Sr lattice

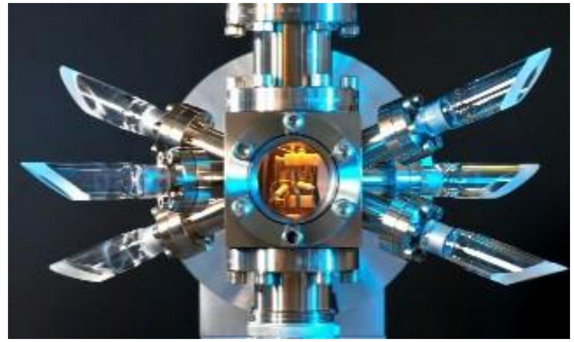
+ 2 Cs fountains

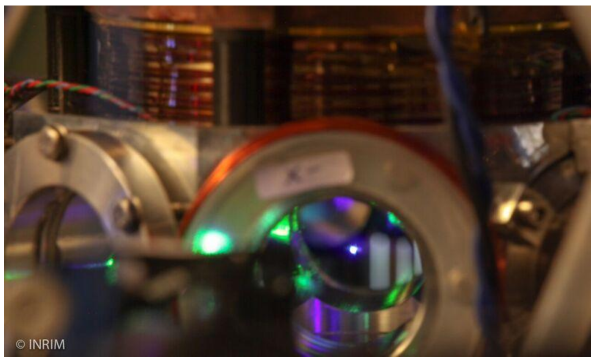
INRIM

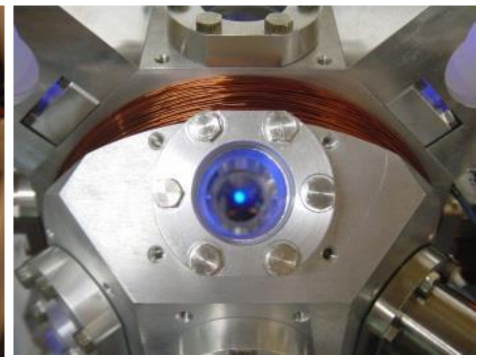
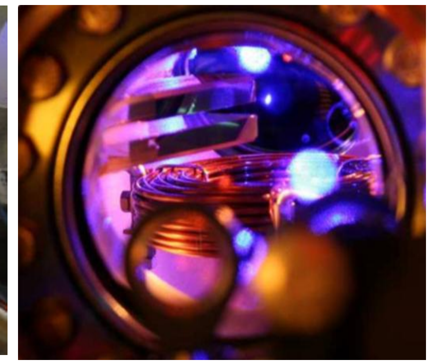


Yb lattice + Cs fountain

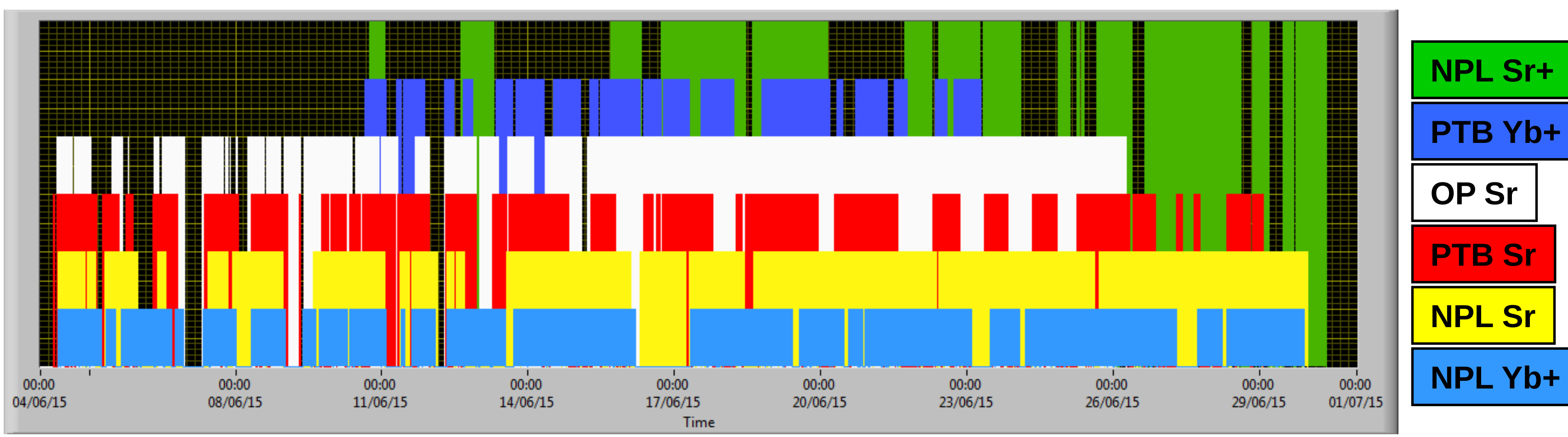






Overall uptime up to 90%

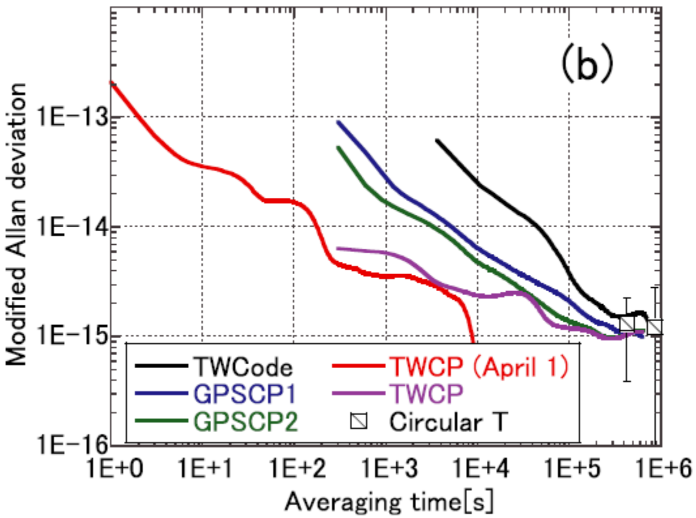


Yb lattice from INRIM not analysed yet

Physikalisch-Technische Bundesanstalt
Braunschweig und Berlin

EURAMET

In addition: TWCP measurement during first weeks, carried out by NICT:



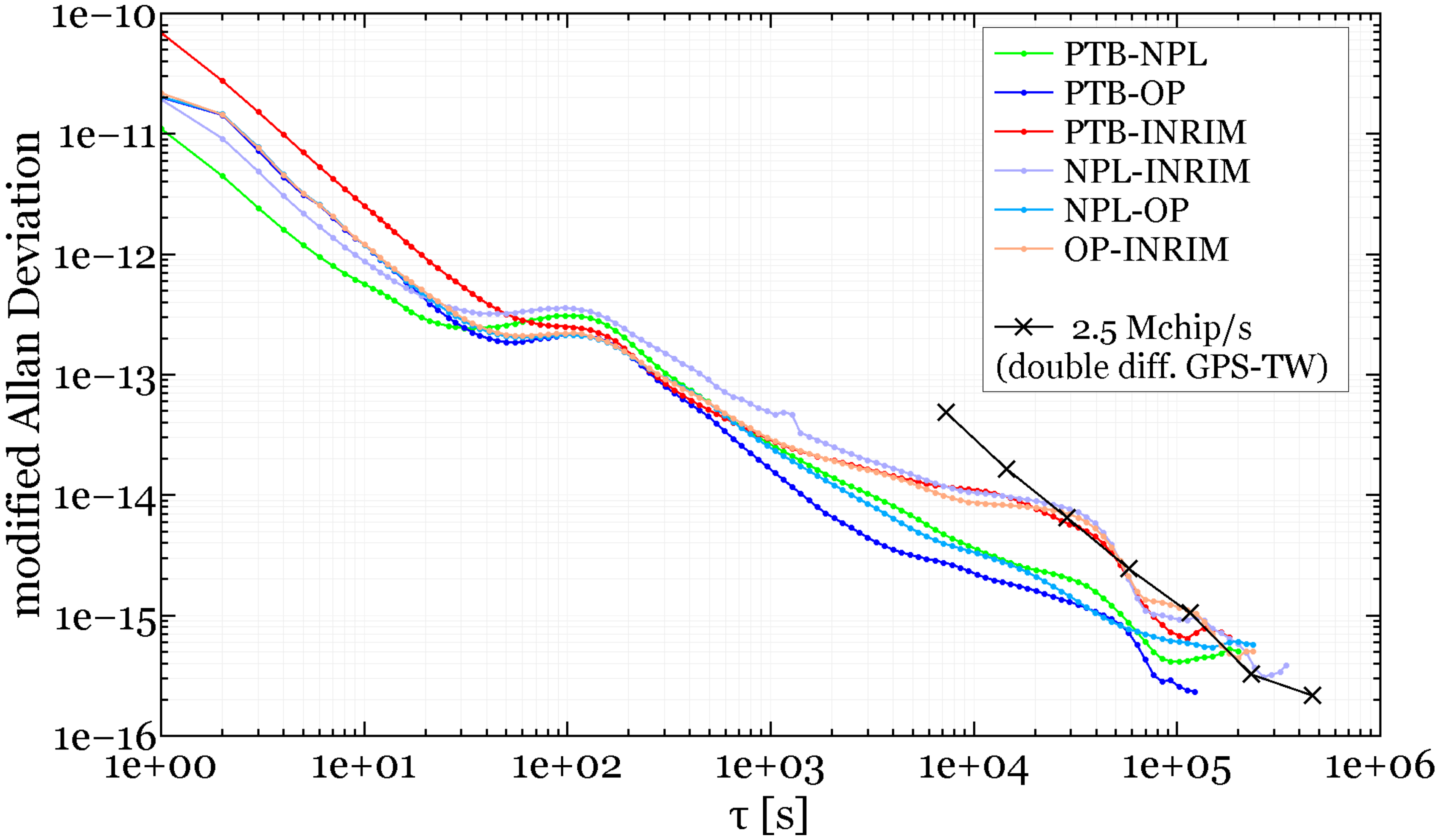
M. Fujieda et al., Metrologia **51** (2014) 1–10

Broadband TWSTFT

TWCP

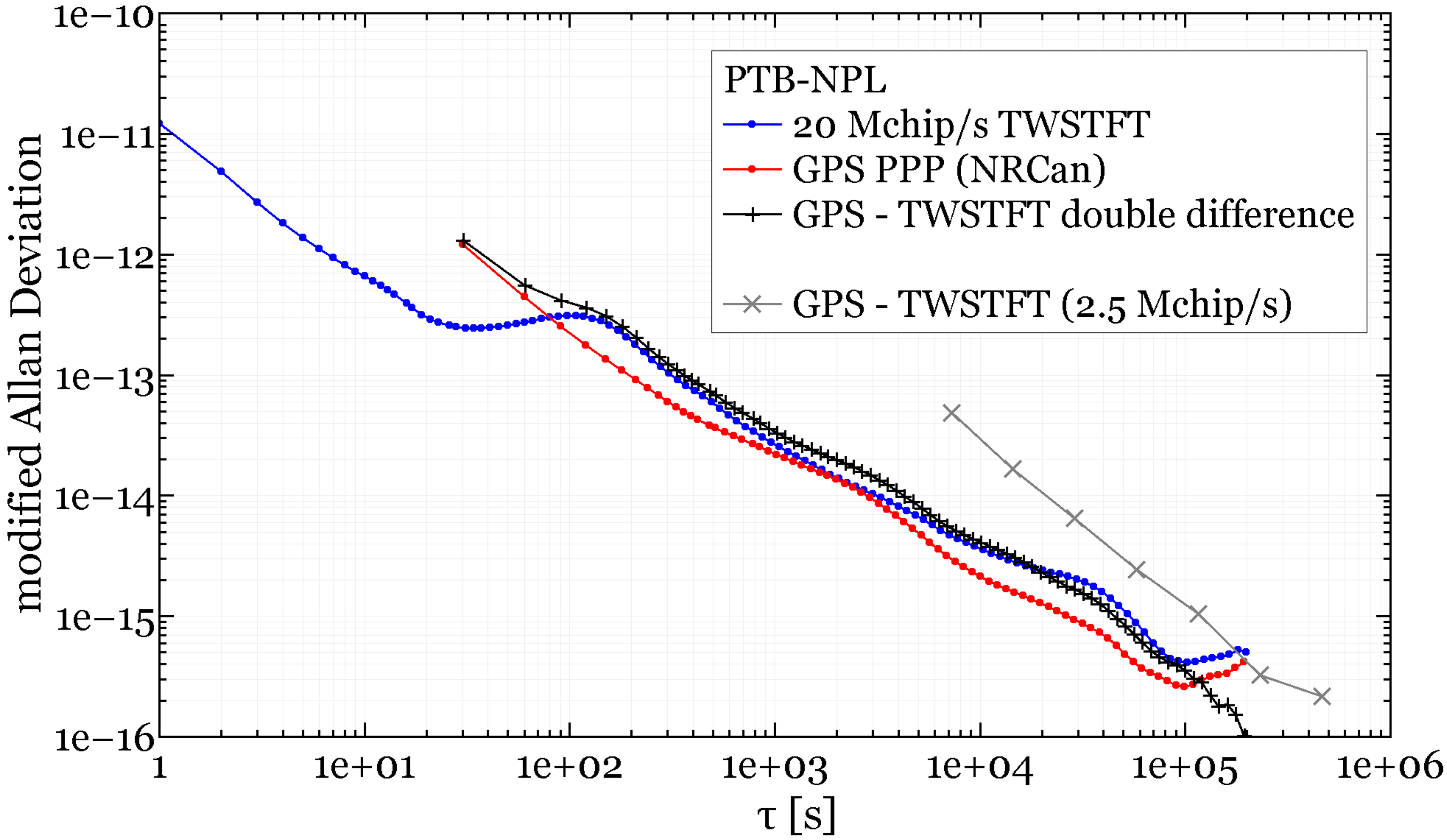
Clock comparison campaign: link performance

Broadband TWSTFT links, selected intervals

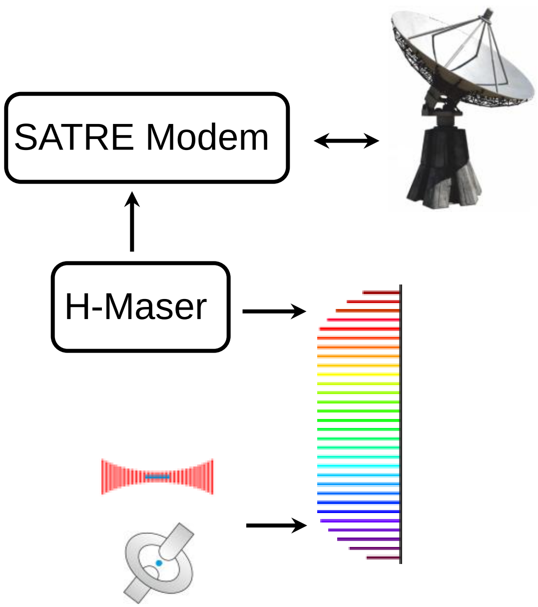


Clock comparison campaign: link performance

PTB-NPL link, broadband TWSTFT, GPS PPP and (GPS-bbTW) double difference

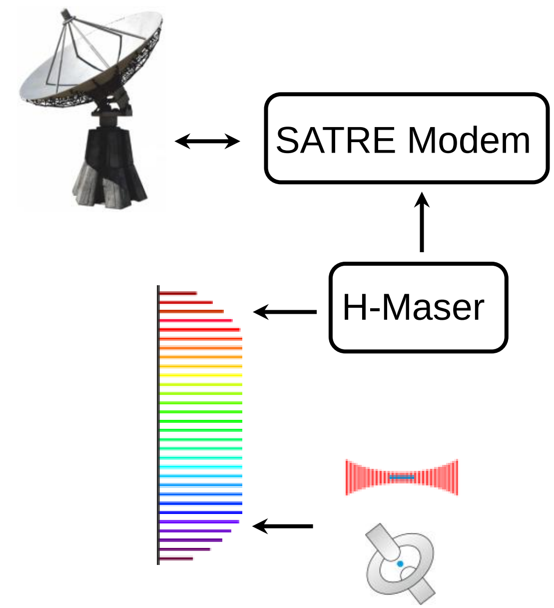


Clock comparison: data analysis



Link data:
Dominated by white phase noise
& technical disturbances

$$x_{link}(t) = x_{Maser1}(t) - x_{Maser2}(t)$$



Maser vs. Clock #1:
Dominated by white frequency noise

$$y_1(t) = y_{clock1}(t) - y_{Maser1}(t)$$

Maser vs. Clock #2:
Dominated by white frequency noise

$$y_2(t) = y_{clock2}(t) - y_{Maser2}(t)$$

Calculation of $\bar{y}_{clock1/clock2} \approx \bar{y}_{clock1} - \bar{y}_{clock2}$ with respective uncertainty

Clock comparison: data analysis

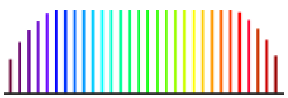
Maser vs. Clock #1:
Dominated by
white frequency noise

Link data:
Dominated by white phase noise
& technical disturbances

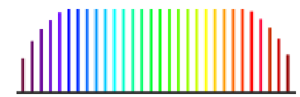
Maser vs. Clock #2:
Dominated by
white frequency noise

$$x_{link}(t) = x_{Maser1}(t) - x_{Maser2}(t)$$

$$y_1(t) = y_{clock1}(t) - y_{Maser1}(t)$$



$$y_2(t) = y_{clock2}(t) - y_{Maser2}(t)$$



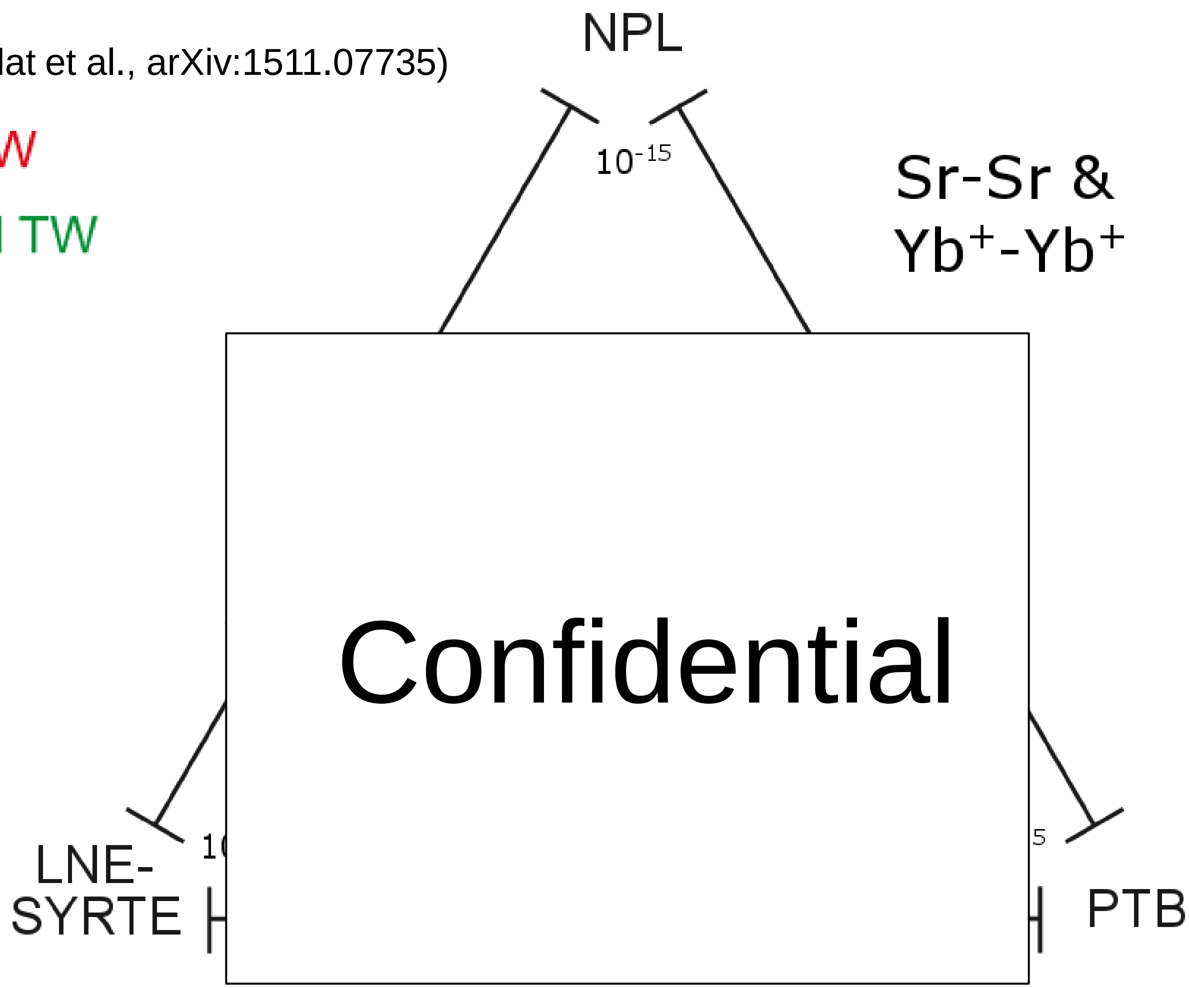
Calculation of $\bar{y}_{clock1/clock2} \approx \bar{y}_{clock1} - \bar{y}_{clock2}$ with respective uncertainty:

- Pre-average over 1-day-intervals to minimize white noise and suppress diurnals
- Use different weighting functions to eliminate white phase and frequency noise, respectively
- Choose intervals with negligible gaps
- Use local Yb/Sr measurement to fill gaps in clock data
- Take serial correlations into account for the determination of the statistical uncertainties

Clock comparison results

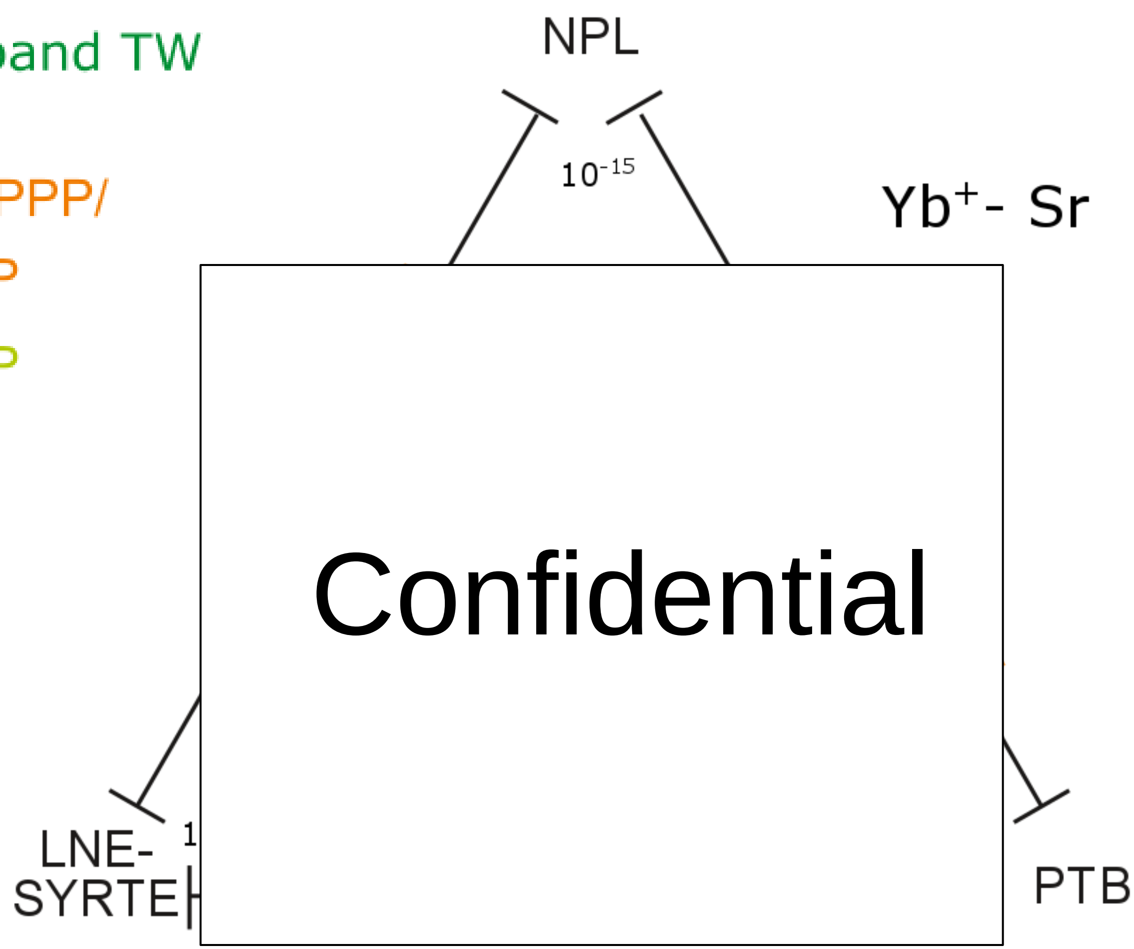
- Sr - Sr fiberlink (Lisdat et al., arXiv:1511.07735)
- Sr - Sr broadband TW
- Yb^+ - Yb^+ broadband TW

- Sr - Sr GPS PPP
- Yb^+ - Yb^+ GPS PPP



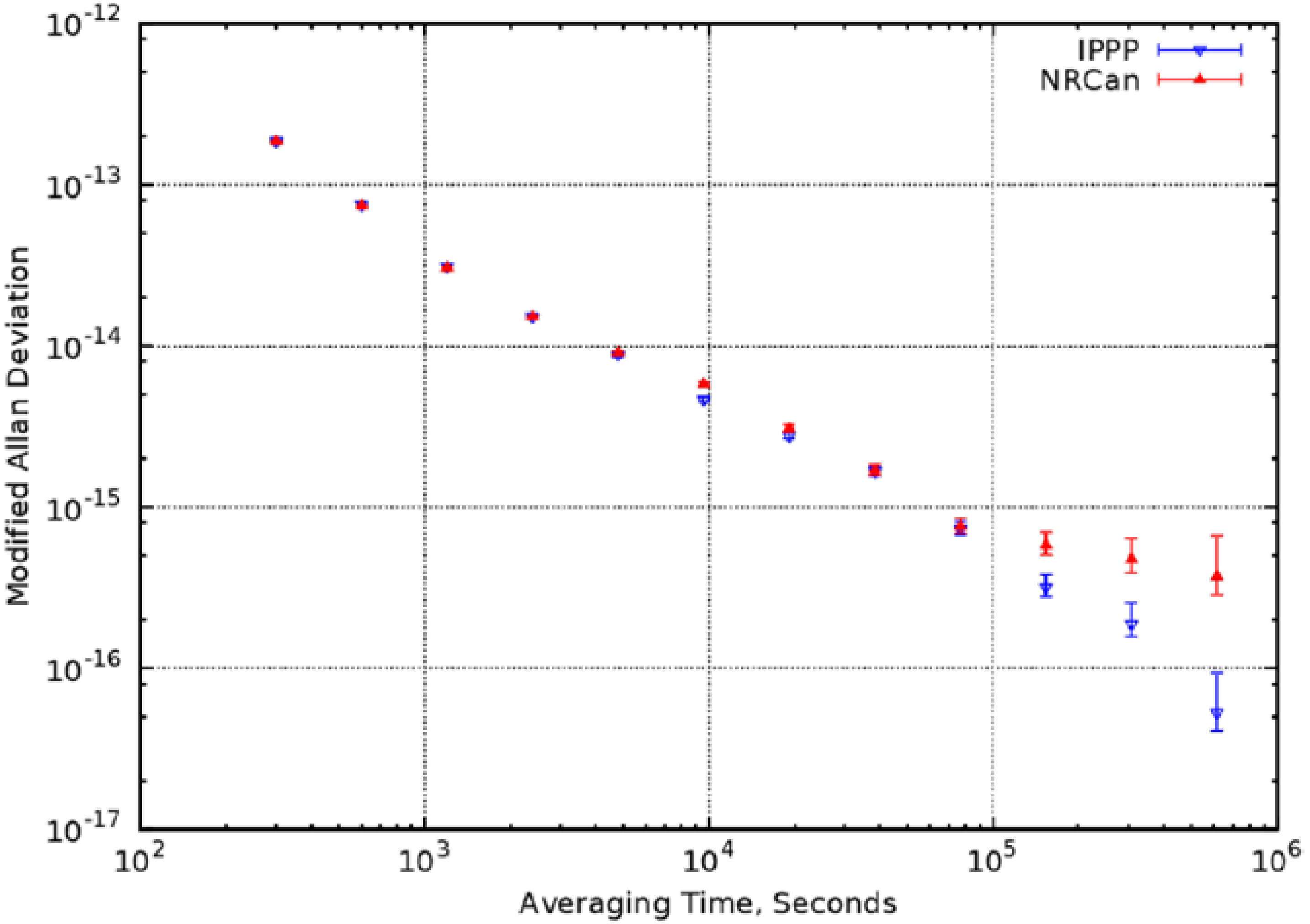
Clock comparison results

- Yb^+_{PTB} - $Sr_{NPL/LNE}$ broadband TW/
  Yb^+_{NPL} - Sr_{LNE} broadband TW
- Yb^+_{NPL} - Sr_{PTB} broadband TW
- Yb^+_{PTB} - $Sr_{NPL/LNE}$ GPS PPP/
  Yb^+_{NPL} - Sr_{LNE} GPS PPP
- Yb^+_{NPL} - Sr_{PTB} GPS PPP



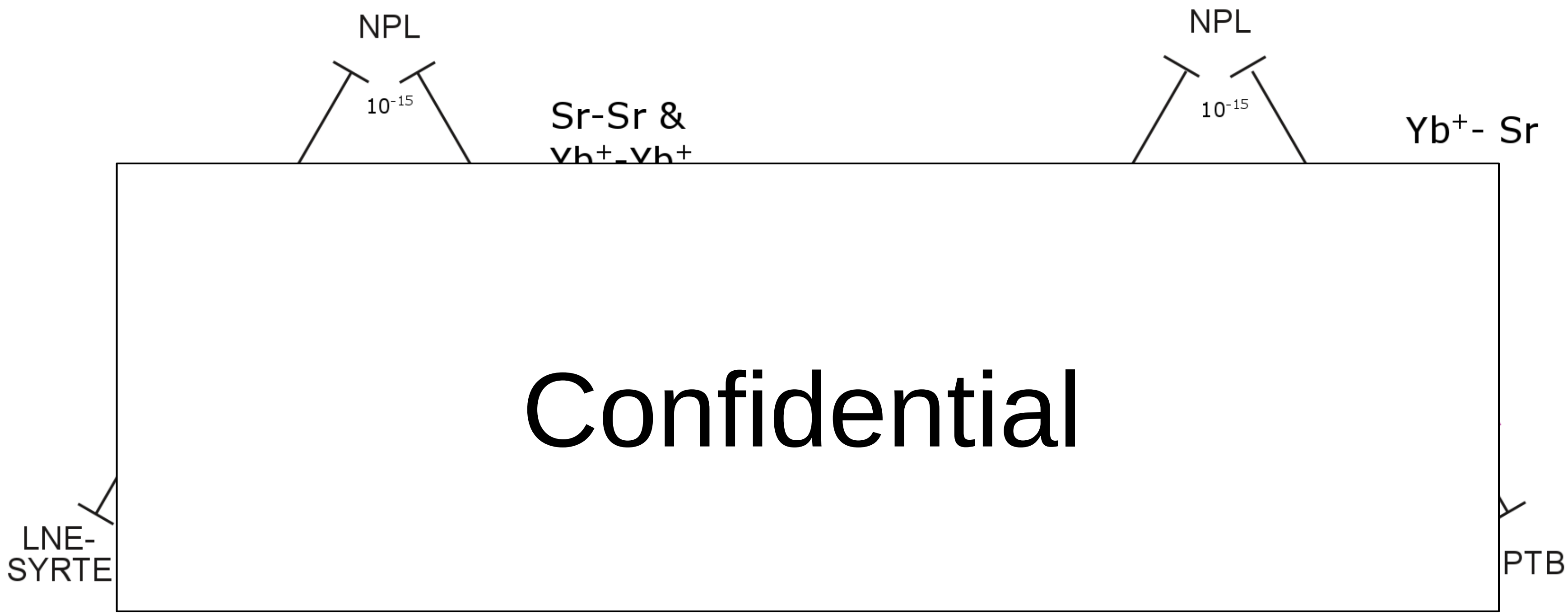
Integer PPP

Comparison between GPS PPP and IPPP:
instability of double difference with fiber link between AOS/GUM



Petit et al., Metrologia **52** (2015) 301–309

Clock compare results via IPPP



- Sr - Sr GPS IPPP
- Yb^+ - Yb^+ GPS IPPP

- Yb^+_{PTB} - $Sr_{NPL/LNE}$ GPS IPPP/
  Yb^+_{NPL} - Sr_{LNE} GPS IPPP
- Yb^+_{NPL} - Sr_{PTB} GPS IPPP

Summary

- Comparison of several optical clocks of NPL, LNE-SYRTE, INRIM and PTB over 26 days long period via broadband TWSTFT and GPS
- Instability of satellite links in low 10^{-16} range
- Statistical uncertainties for broadband TW and GPS PPP in low 10^{-16}, for GPS IPPP < 1×10^{-16}

Outlook

- Increasing the modulation bandwidth of TWSTFT yields a respective improvement of TW performance
- However, technique more suited for dedicated campaigns than for operational use
- GPS IPPP as a promising alternative, TWCP still to be compared with other link techniques

E. Benkler, F. Riedel, A. Al-Masoudi, S. Dörscher, C. Grebing, V. Gerginov, S. Häfner, N. Huntemann, J. Leute, B. Lipphardt, C. Lisdat, D. Piester, E. Peik, C. Sanner, S. Weyers, Chr. Tamm

G. P. Barwood, F. Baynes, C. F. A. Baynham, W. Bowden, S. Donnellan, P. Gill, R. M. Godun, I. R. Hill, R. Hobson, G. Huang, J. M. Jones, S. A. King, H. A. Klein, A. Lamb, H. S. Margolis, M. Menchetti, P. B. R. Nisbet-Jones, F. Ozimek, A. Rolland, F. Rust, S. Shemar, K. Szymaniec, P. B. Whibberley

M. Abgrall, J. Achkar, S. Bilicki, S. Bize, E. Bookjans, P. Delva, J. Guéna, R. Le Targat, J. Lodewyck, D. Rovera

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