Worldwide 10^{-17} clock comparison with IPPP

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IAG JWG 2.1
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Motivation

- Standard techniques:
  'Classical' GNSS and two-way time & frequency transfer limited to few 10^{-16} after several days of averaging.
- Advanced techniques:
  Using phase measurements improves over standard code techniques, but requires phase continuity:
  - GPS IPPP provides 1×10^{-16} at 3 days, low 10^{-17} at 20 days.
  - TWCP should be even better but phase continuity may be more difficult to ensure.

Outline

- Continuous IPPP time links
- Link comparisons
  - optical time transfer links
  - two-way carrier-phase link
  - T2L2

Integer Precise Point Positioning (IPPP)

- Developed by CNES:
  - D. Laurichesse and F. Mercier, 20th ION GNSS, 2007
  - J. Delporte et al., IJNO, 2008
  - S. Loyer et al., J Geod 86, 2012
  - GINS software: J.-C. Marty, 2013
- CNES and CLS operate GRG IGS analysis center to generate integer SV clocks and WSB (www.igsac-cnes.cls.fr)
- BIPM post-processing to ensure continuity of the time links
  - G. Petit et al., Metrologia 52, 2015
- User-friendly post-processing software in development at BIPM.

Integer ambiguity fixing

receiver phase clock

integer ambiguity

noise

$$L_{IF}^{c} + c\delta t_{s}^{L_{IF}} = \rho + \boxed{c\delta t_{r}^{L_{IF}}} + T_{w} + \lambda_{IF} N_{IF} + \epsilon^{L_{IF}}$$

satellite phase clock

corrected iono-free phase equation

geometric distance

troposphere

$$\lambda_{IF} \approx 6\,\mathrm{mm}$$

Two-step procedure: Ambiguities of the two frequencies f_1, f_2 are determined as the widelane ambiguity $N_W=N_2-N_1$ and N_1.

1. Zero-difference widelane identification: N_W
2. Ambiguity fixing in the zero-difference iono-free phase equation: N_1

Integer ambiguity fixing

1. Zero-difference widelane identification: N_W

widelane receiver bias

widelane ambiguity

$$L_{MW} - \overline{b_r^{LWM}} + b_s^{LMW} = \boxed{\lambda_{WL} N_{WL}}$$

$$\lambda_{WL} \approx 86\,\mathrm{cm}$$

Melbourne-Wübbena
linear combination

widelane satellite bias

WSB: daily (from GRG products)
WRB: estimated epochwise

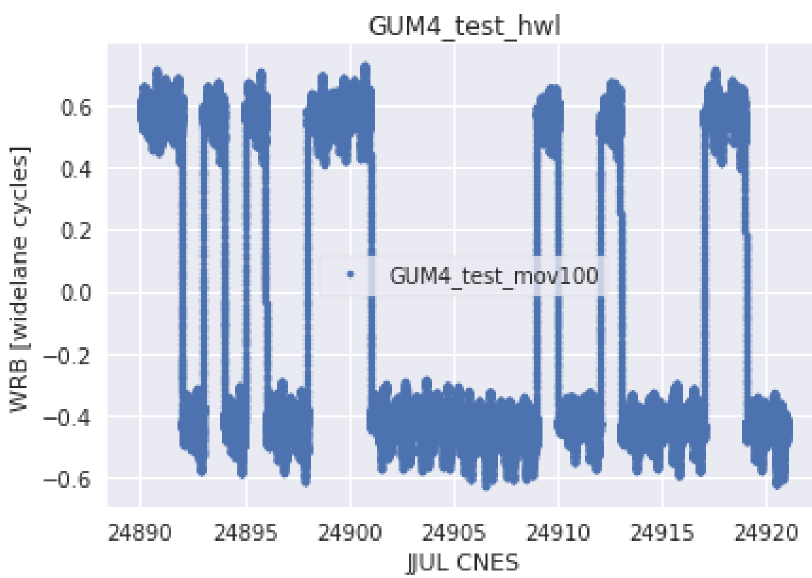
Integer ambiguity fixing

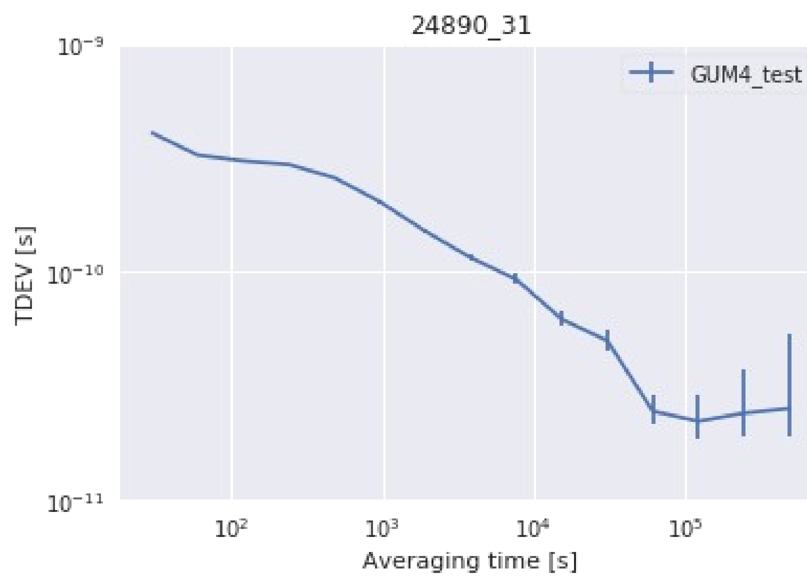
1. Zero-difference widelane identification: N_W

WRB:
•epochwise,
•fractional part of the floating ambiguity:

$$\lambda_{WL} a_{WL} = L_{MW} + b_s^{L_{MW}}$$

WRB between -0.5 and 0.5 WLC
WLC steps in the WRB
-> integer step in N_W





Integer ambiguity fixing

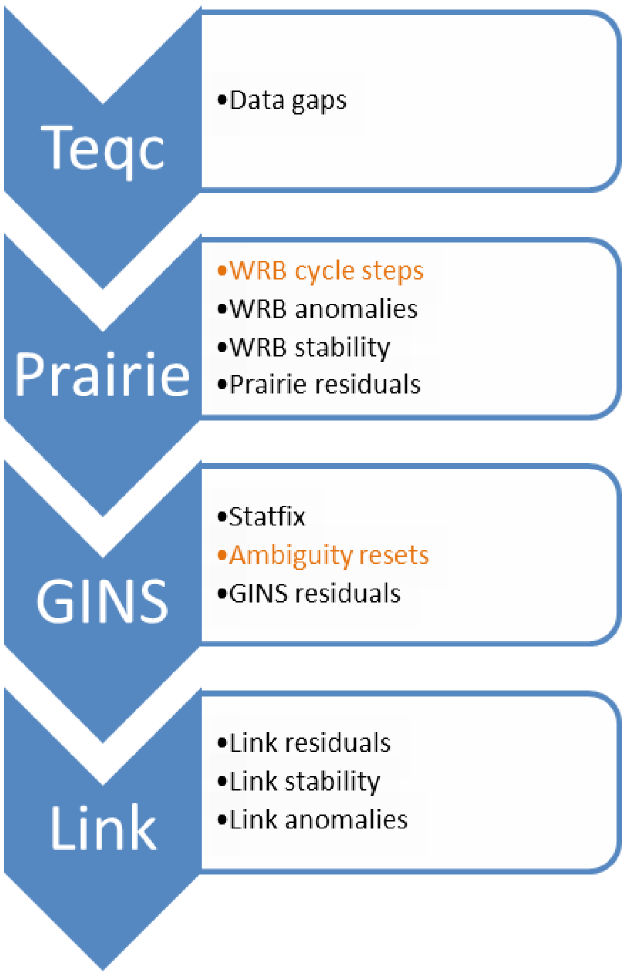
2. Ambiguity fixing in the zero-difference iono-free phase equation: N_1

With $N_{IF} = -17N_1 + 60N_{WL}$

$$L_{IF}^{c} + c\delta t_s^{L_{IF}} - 60\lambda_{IF}N_{WL} = \rho + \boxed{c\delta t_r^{L_{IF}}} + T - 17\lambda_{IF}N_1 + \epsilon^{L_{IF}}$$

$$17\lambda_{IF} \approx 10.7\,\mathrm{cm}$$

Continuous IPPP time links

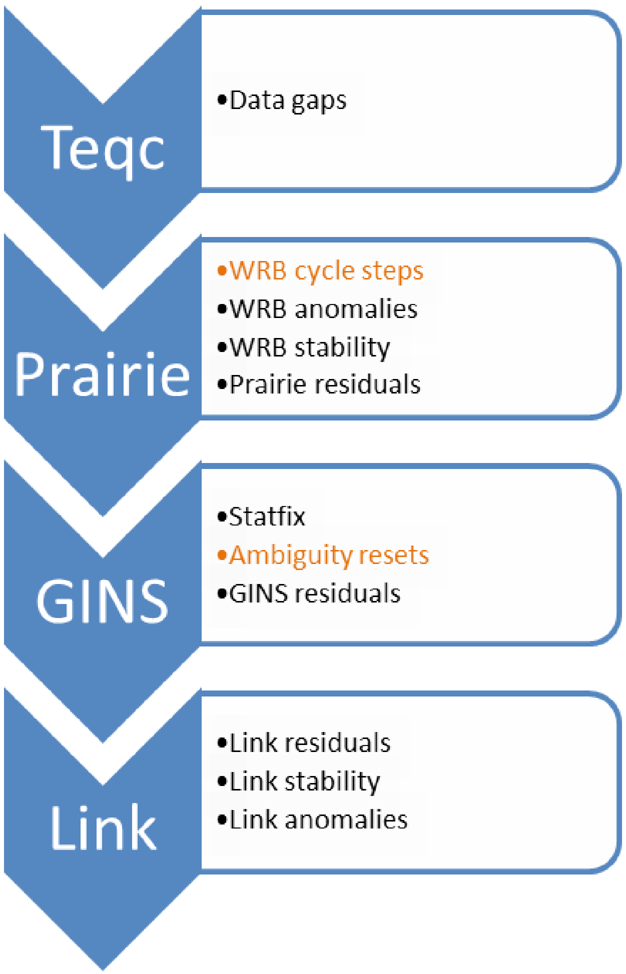


Integer jumps of the widelane ambiguity lead to cycle slips in the IPPP clock solution (3.5 NLC)

Ambiguity resets (intraday, day-boundaries) can result in cycle slips in the IPPP clock solution (integer NLC)

If integer cycle slips can be determined, slips can be corrected without introducing additional noise

Continuous IPPP time links



Challenges:

- Discontinuities of the reference timescale
- Link noise
- Clock noise

→ Fixing of integer cycle slips only in differential mode between two stations

→ Averaged link + clock noise must be significantly below 180 ps (half a NLC)

→ Possibility: aligned products, longer continuous batches

Continuous IPPP time links

Teqc
- Data gaps

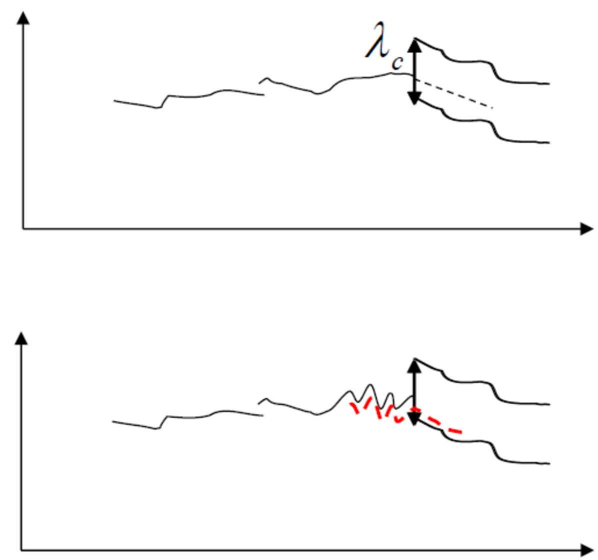
Prairie
- WRB cycle steps
- WRB anomalies
- WRB stability
- Prairie residuals

GINS
- Statfix
- Ambiguity resets
- GINS residuals

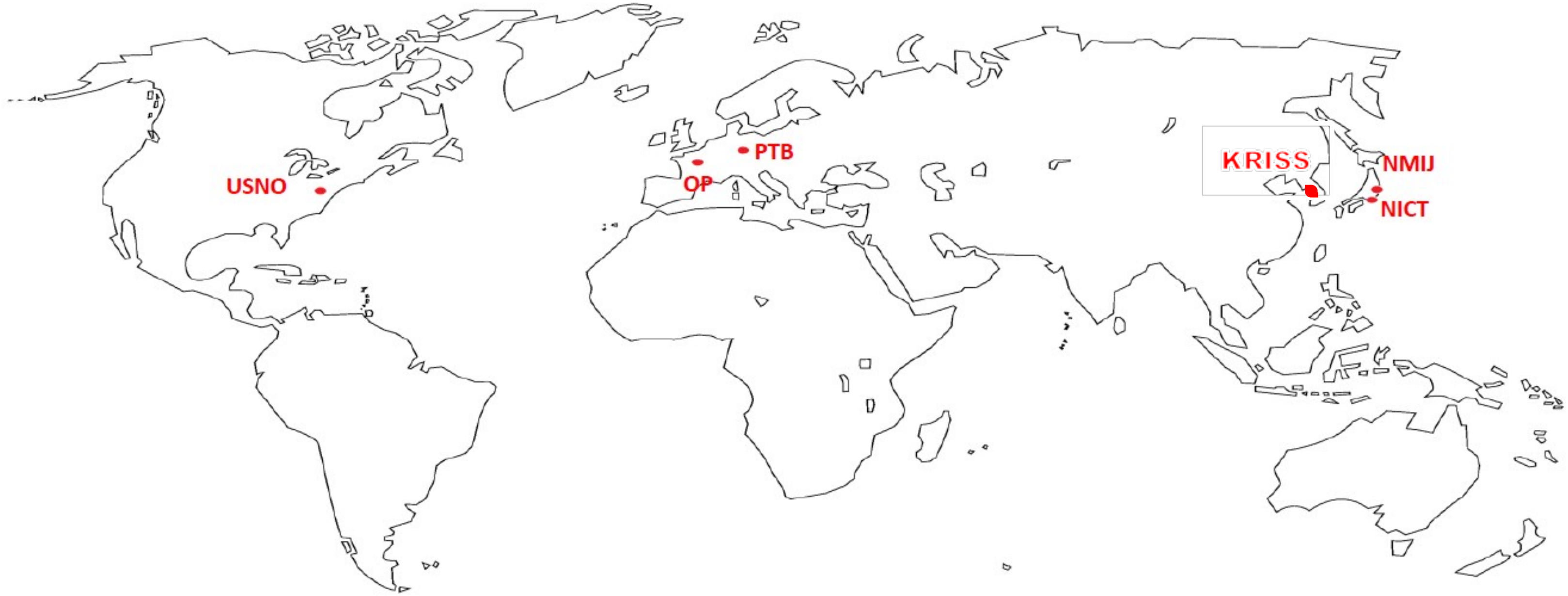
Link
- Link residuals
- Link stability
- Link anomalies

Cycle slip fixing depending on clock noise:

- sufficiently stable clock (AHM): simple linear fit
- less stable clock (Cs): “bridge method”
  - remove clock noise using continuous PPP solution
  - works at batch-boundaries
  - does not work with real receiver ambiguity resets



Continuous IPPP time links – link quality



Continuous IPPP time links – link quality

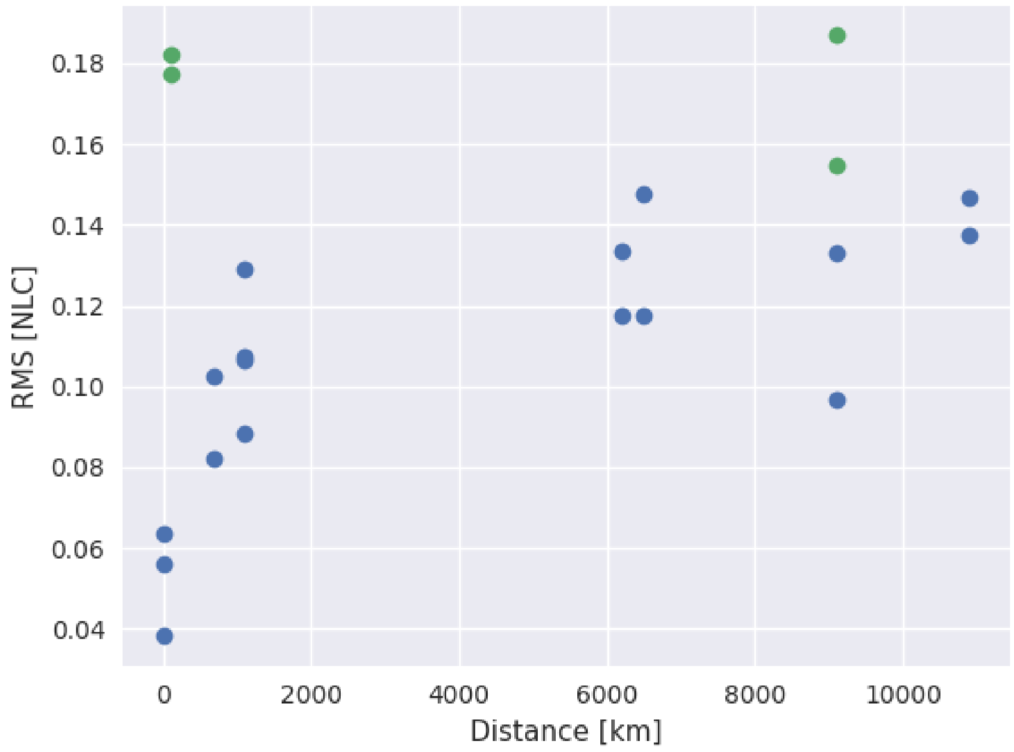
Residuals of the IPPP link cycle slip fixing depending on the baseline length

Link	Length [km]	*Mean [NLC]*	*RMS [NLC]*	
PTBB / PTBG	0	0.00	0.04	short baseline
NC01 / NM0D	100	-0.03	0.18	continental baselines
PTBB / OPMT	690	0.00	0.08	
KRIS / NC01	1100	-0.01	0.09	
OPMT / USN7	6200	0.05	0.12	intercontinental baselines
PTBB / USN7	6500	0.03	0.12	
PTBB / NC01	9100	-0.03	0.13	
USN7 / NC01	10900	0.01	0.15	

All stations are connected to AHMs

Continuous IPPP time links – link quality

Residuals of the IPPP link cycle slip fixing depending on the baseline length



Link comparisons

IOP Publishing Metrologia
Metrologia 50 (2013) 133–145 doi:10.1088/0026-1394/50/2/133

Dissemination of time and RF frequency via a stabilized fibre optic link over a distance of 420 km

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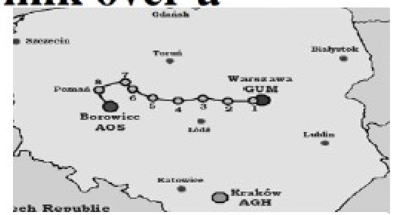
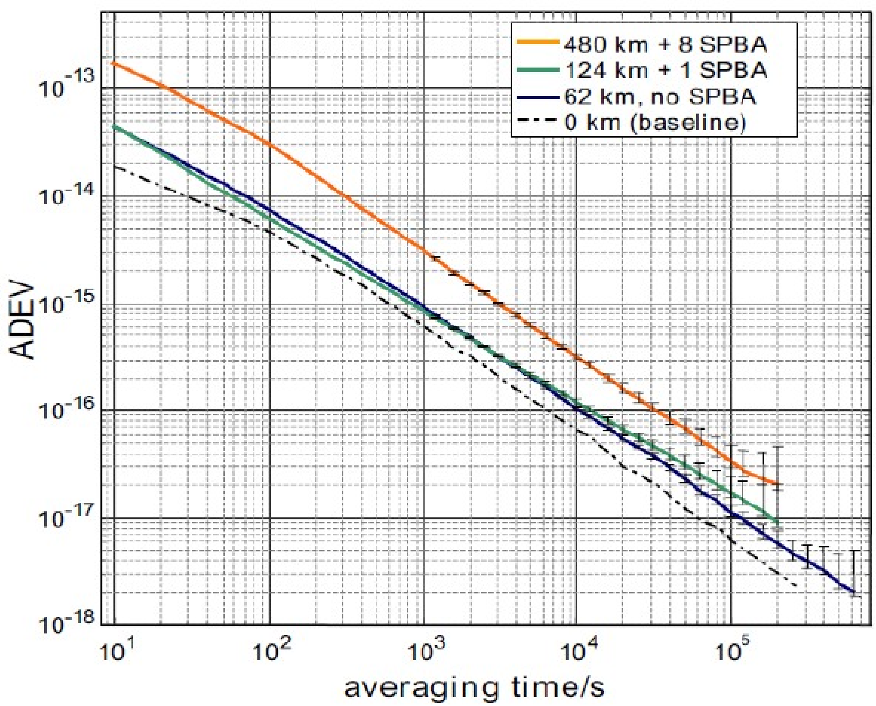


ŁŚliwczyński *et al*



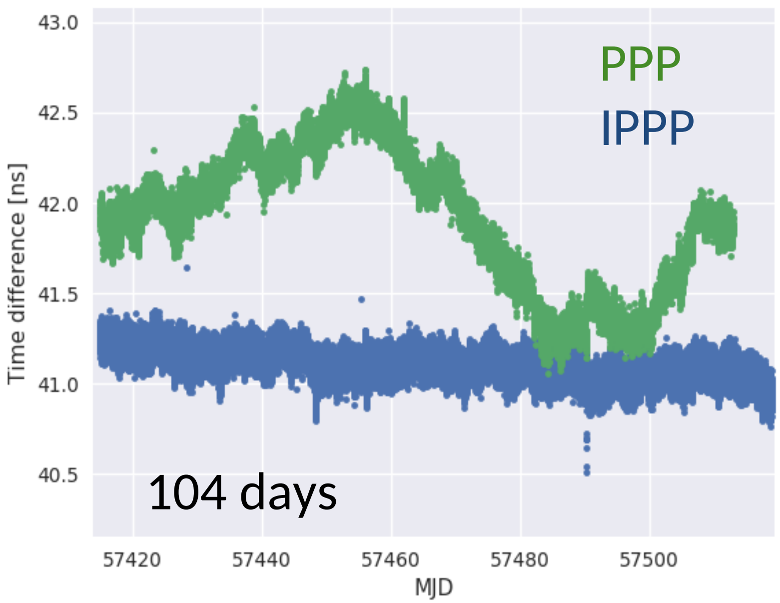
Fibre link technology developed at AGH University

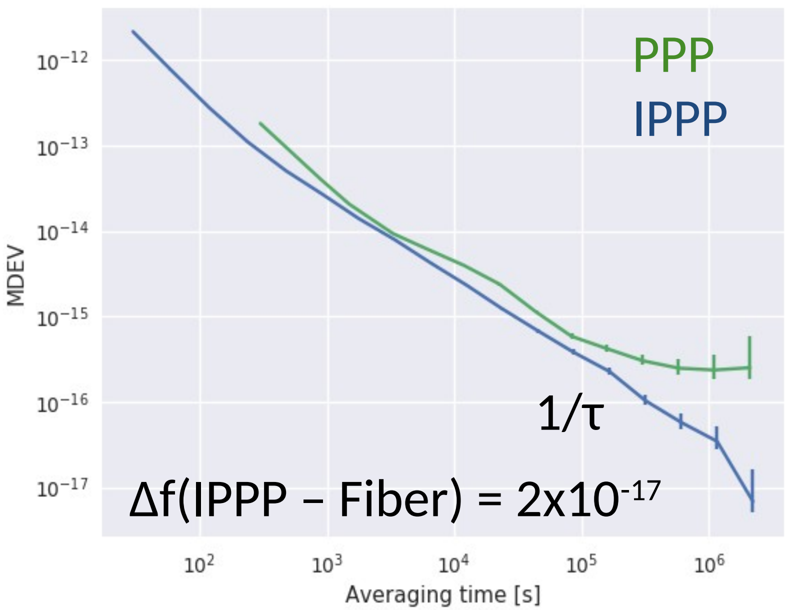
Instability 10^{-17} region @ 1 day

UTC(AOS)-UTC(GUM) fibre link
Reported to BIPM since 04/2013

Link comparisons: Optical time transfer link

AOS / GUM, optical time transfer link, 400 km



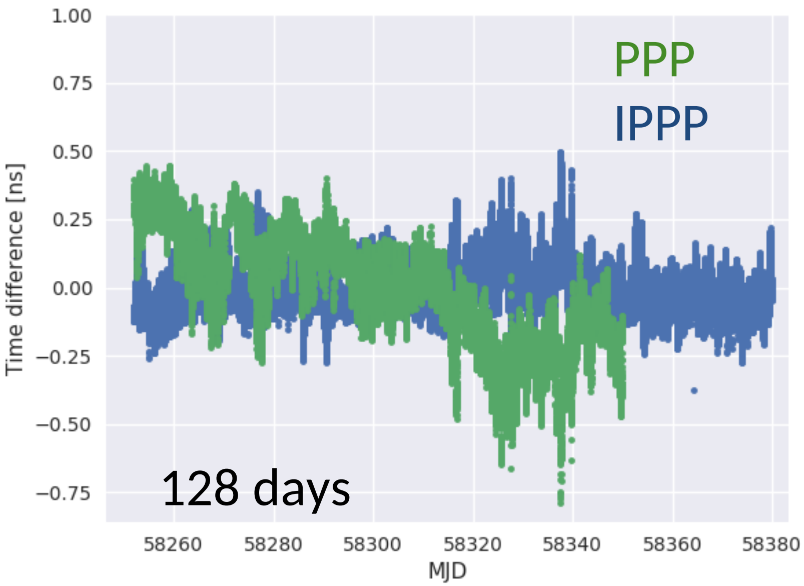


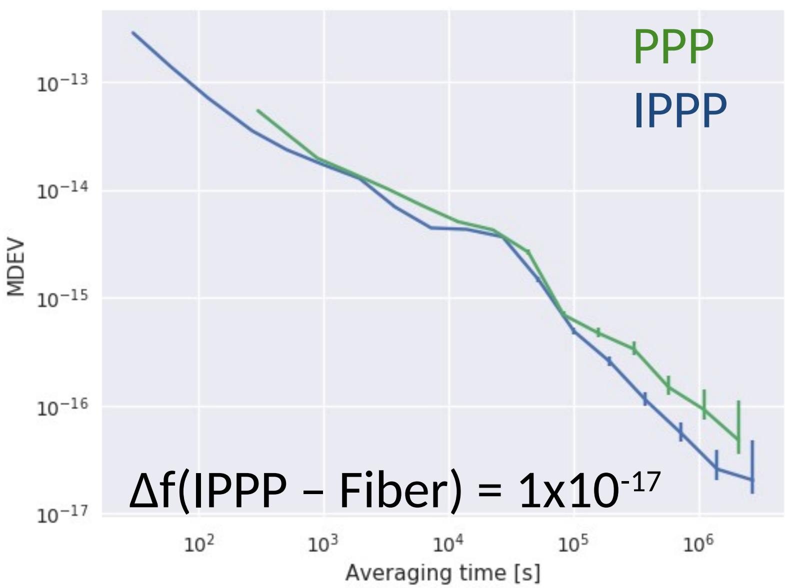
Fiber link: Ł. Śliwczyński et al., *Metrologia, 2013*

Petit et al., *Proc. EFTF, 2017*

Link comparisons: Optical time transfer link

PTB / DTAG, optical time transfer link, 150km



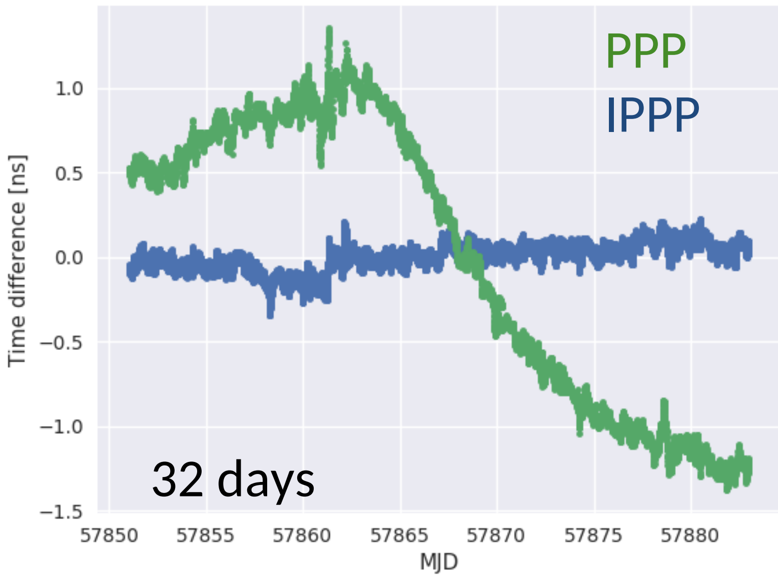


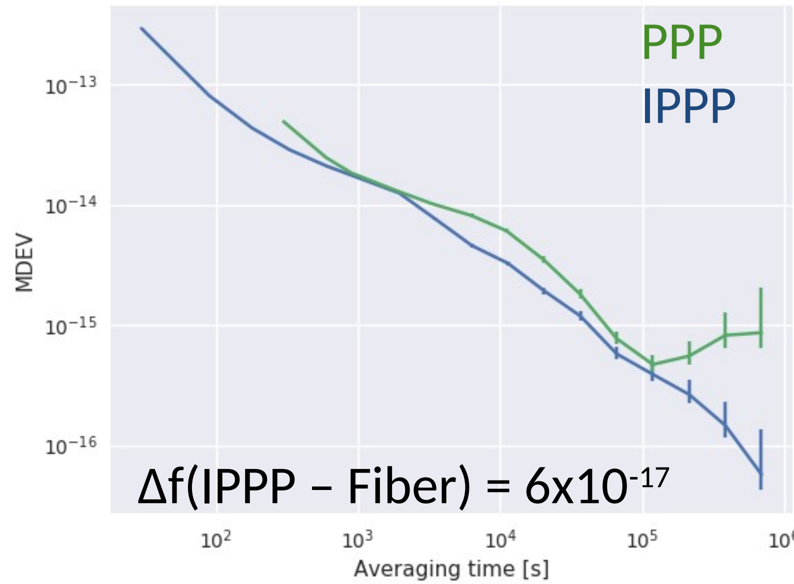
Fiber link: Ł. Śliwczyński et al., *Proc. EFTF, 2018*

Data from Deutsche Telekom Technik

Link comparisons: Two-way carrier-phase link

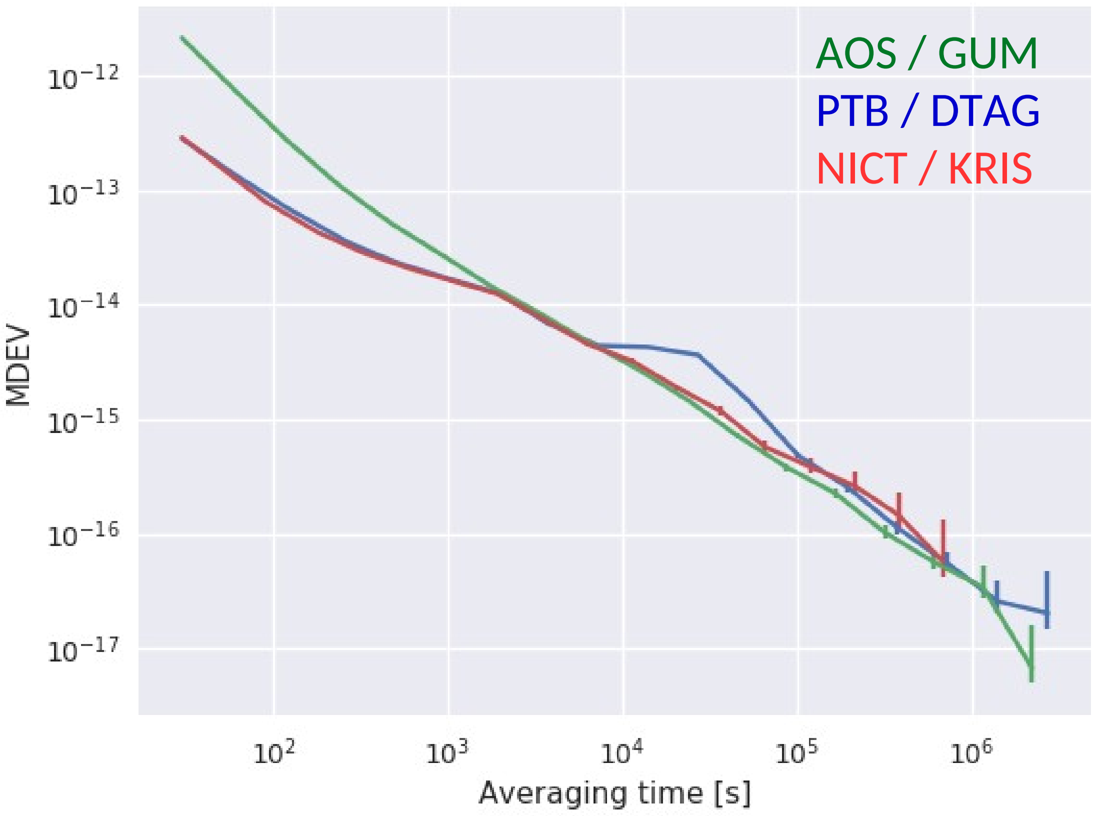
NICT / KRIS, two-way carrier-phase, 1100 km



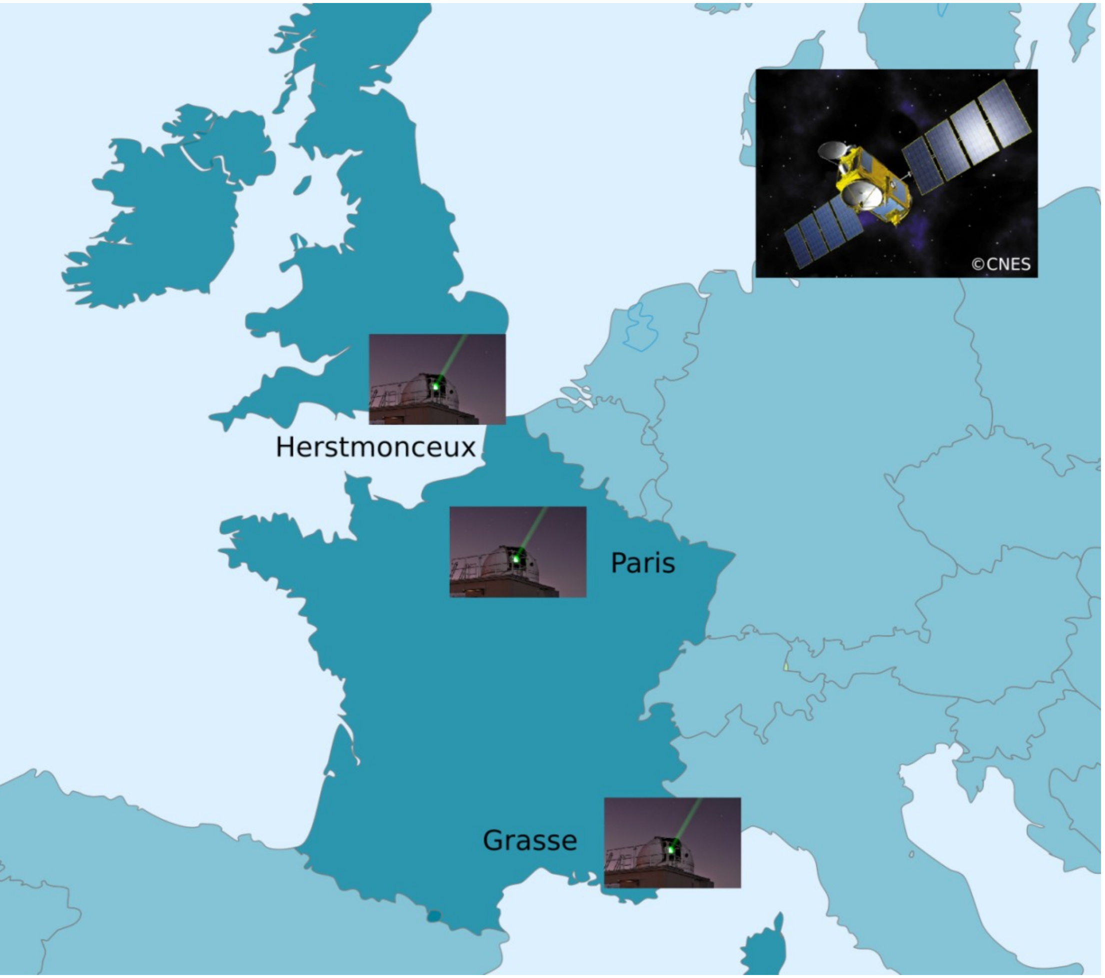


Fujieda et al., *Proc. EFTF, 2018*

Link comparisons



Link comparisons: T2L2



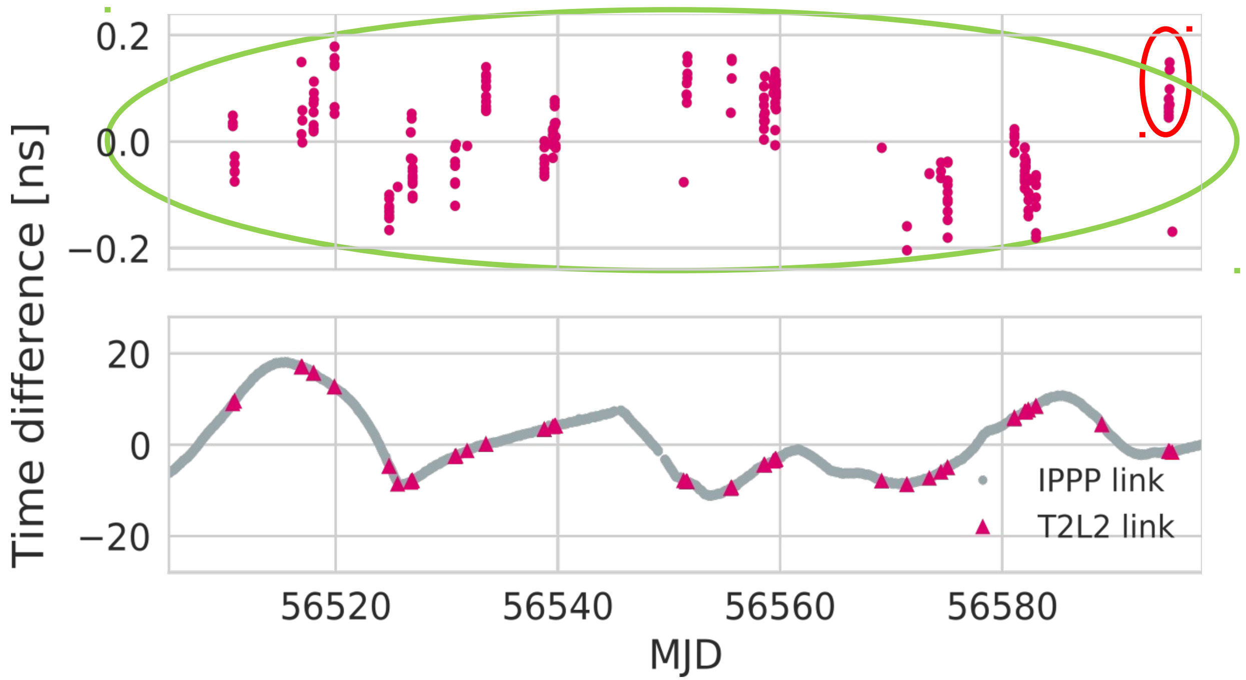
T2L2 developed by OCA and CNES

T2L2 CV uncertainty: 140 ps

Measurement campaign:
August – October 2013

E. Samain et al., Metrologia 52, 2015
P. Exertier et al., Metrologia 53, 2016
J. Leute et al., EFTF 2018

Link comparisons: T2L2



Link	*# passes*	*# points*	*STD / pass [ps]*	*STD [ps]*
SGF / OCA	43	220	27	90
OP / OCA	11	58	17	53
OP / SGF	6	22	15	36

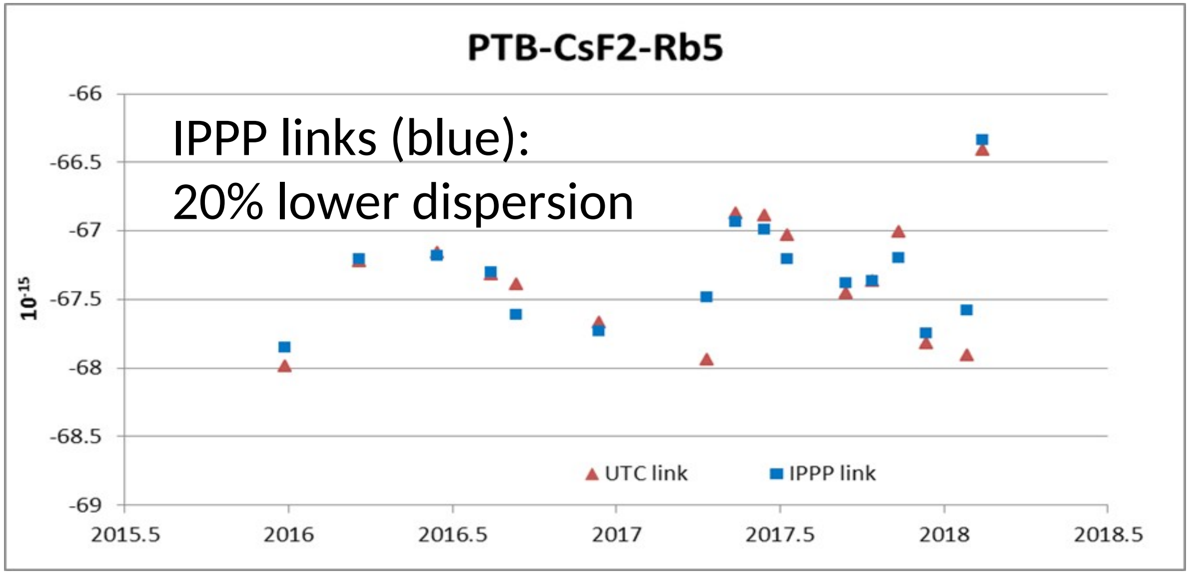
Leute et al., EFTF 2018

Conclusion

- IPPP enables time & frequency transfer based on the GNSS carrier-phase on intercontinental baselines
- Validation on the 10^{-17} level on continental baselines
- High accuracy continuous time transfer in combination with accurate calibration techniques like T2L2

Improved frequency comparisons of PSFS

Study of frequency differences between SYRTE-FO2(Cs and Rb), PTB-CsF2 and USNO Rb5



Fountain clocks	# periods	σ with UTC link	σ with IPPP
FO2(Rb)-Rb5	27	6.0×10^{-16}	5.1×10^{-16}
FO2(Cs)-Rb5	37	6.1×10^{-16}	5.3×10^{-16}
CsF2-Rb5	42	5.1×10^{-16}	5.0×10^{-16}
CsF2-Rb5 recent	16	4.5×10^{-16}	3.7×10^{-16}

Continuous IPPP time links – example with AHMs