Sub 10^{-16} frequency transfer with IPPP

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What needs to be achieved to compare clocks at a distance?
In terms of frequency accuracy ≡ time stability

« Commercial » clocks

Cs tube, H-maser

$10^{-14} \approx$ 1 ns / 1 day

$10^{-15} \approx$ 0.1 ns / 1 day


« Best » present standards

Cs fountains (in ~ 10 labs)

$10^{-16} \approx$ 0.1 ns / 10 days

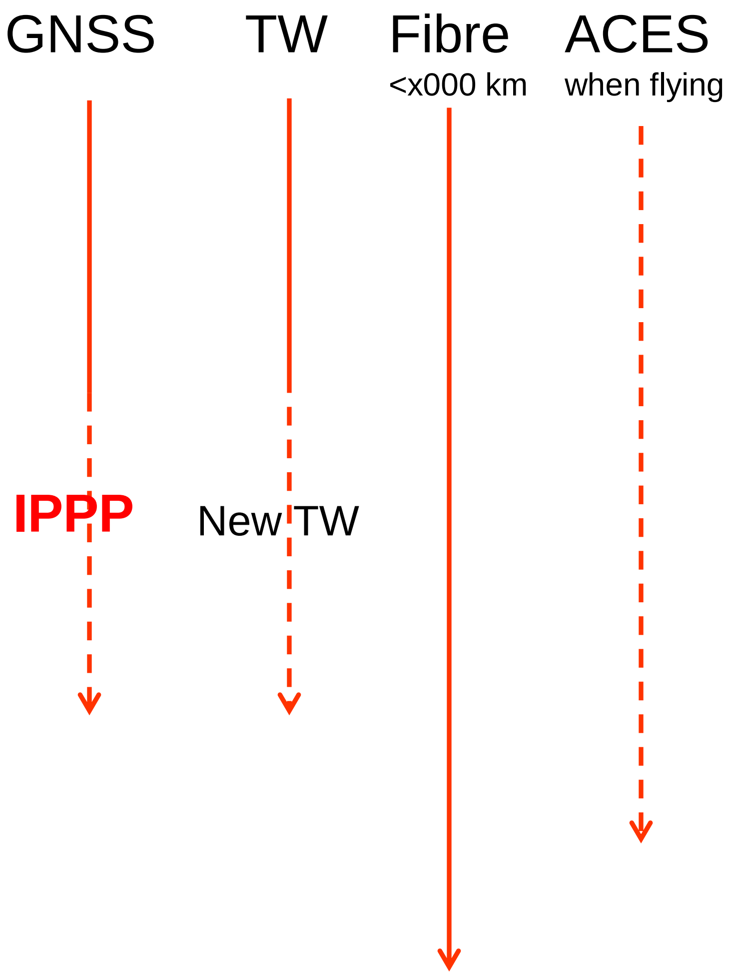
10 ps / 1 day


« Future » standards

Lattice (e.g. Sr), trapped ions

$10^{-17} \approx$ 1 ps / 1 day

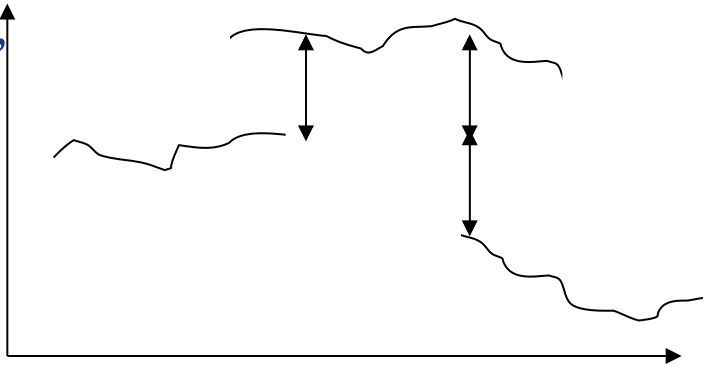
$10^{-18} \approx$ 1 ps / 10 days

- **PPP with integer ambiguity resolution (IPPP): reminder**
- Comparisons of IPPP with other links
- Conclusions and outlook

IPPP: PPP with integer ambiguity resolution

- Phase clocks are ambiguous and need to be aligned to ensure continuous PPP results.
- Taking into account the **integer nature of the ambiguities** allows, in principle, to rigorously solve the problem of boundary discontinuities.
  - For integer ambiguities solutions, such discontinuities should be integer numbers of the "Narrowlane wavelength" λ_c (357 ps) and can be exactly determined.



- Products of the GRG analysis center of the IGS, see : www.igsac-cnes.cls.fr):
  - wide-lane satellite biases : WSB, file grgxxxxx.wsb
  - phase clocks : clocks, file grgxxxxx.clk
- User then take these GRG products to determine integer ambiguities in the PPP solution (IPPP), e.g. with the GINS software developed by CNES.

- IPPP: Two-step procedure, where the ambiguities at the two frequencies N_1/N_2 are determined as the Widelane $N_w = N_2 - N_1$ and e.g. N_1
  1. Zero-difference widelane identification => N_w
  2. Ambiguity fixing in the Zero-difference iono-free phase equation => N_1

Zero-difference widelane identification

Step 1 = Determine N_w (Widelane wavelength λ_w = 86.19 cm)

integer widelane ambiguity

$$N_w = f\left(P_1, P_2, L_1, L_2\right) + \mu_i - \mu^j$$

4 observable Melbourne-Wübenna linear combination

Receiver bias (variations below 0.1 N_w for geodetic receivers)

Transmitter bias (contained in GRG products)

For details : see Delporte et al. IJNO, 2008 and Loyer et al. J. Geod, 2012.

$$N_w = N_2 - N_1$$

Frequency 2 ambiguity

Frequency 1 ambiguity

Ambiguity fixing method in zero-difference iono-free phase equation

Step 2 = iono-free phase solution with integer N_1 (Narrowlane wavelength λ_c = 10.69 cm)

wind-up effect

frequency 1
integer ambiguity (each pass)

$$\frac{\gamma\lambda_1 L_1 - \lambda_2 L_2}{\gamma - 1} = D_c + \lambda_c W - \lambda_c N_1 + \frac{\lambda_2}{\gamma - 1} N_w + \Delta h$$

ionosphere free
phase combination

propagation distance
(model, including troposphere)

widelane integer
ambiguity

receiver/emitter clock
difference (each epoch)

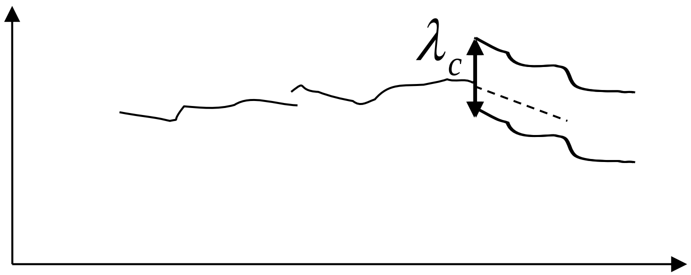
L_1, L_2 : phase measurements on the two frequencies (cycles)

λ_1, λ_2 : wavelength on the two frequencies, γ is the squared frequency ratio

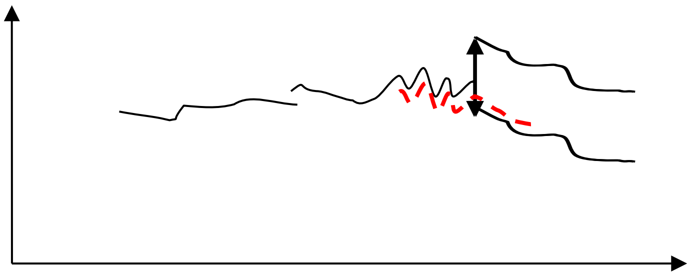
$\lambda_c = \frac{\gamma\lambda_1 - \lambda_2}{\gamma - 1}$: equivalent wavelength for the ionosphere-free problem ~ 10.69 cm or 357 ps

Step 3: Remove discontinuities between batches for a link

- When forming a link, problems with the GRG reference vanish and receiver clock differences are defined up to an overall unknown number of cycles of λ_c. Discontinuities between batches should be integer multiples of λ_c.
- Two techniques to connect non-overlapping batches;
  - Extrapolation, assuming the stability of the compared clocks is sufficient



  - Bridging, assuming another time link solution exists to bridge the discontinuity.



- Advantage: Step 3 takes care of all discontinuities: between daily batches but also due of other interruptions (not breaking the phase continuity), if they are recognized!

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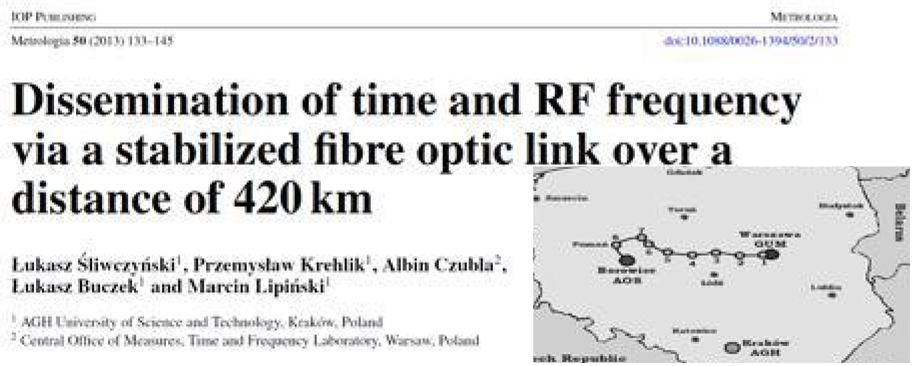
Test of IPPP vs. 420-km fibre link

- Fibre link technology developed at AGH Univ. Stable ~10^{-17} region @ τ =1 day
- UTC(AOS)-UTC(GUM) fibre link and Rinex files reported to the BIPM.
- Basis of first successful test of IPPP

See Metrologia 2015, 52, 301-309


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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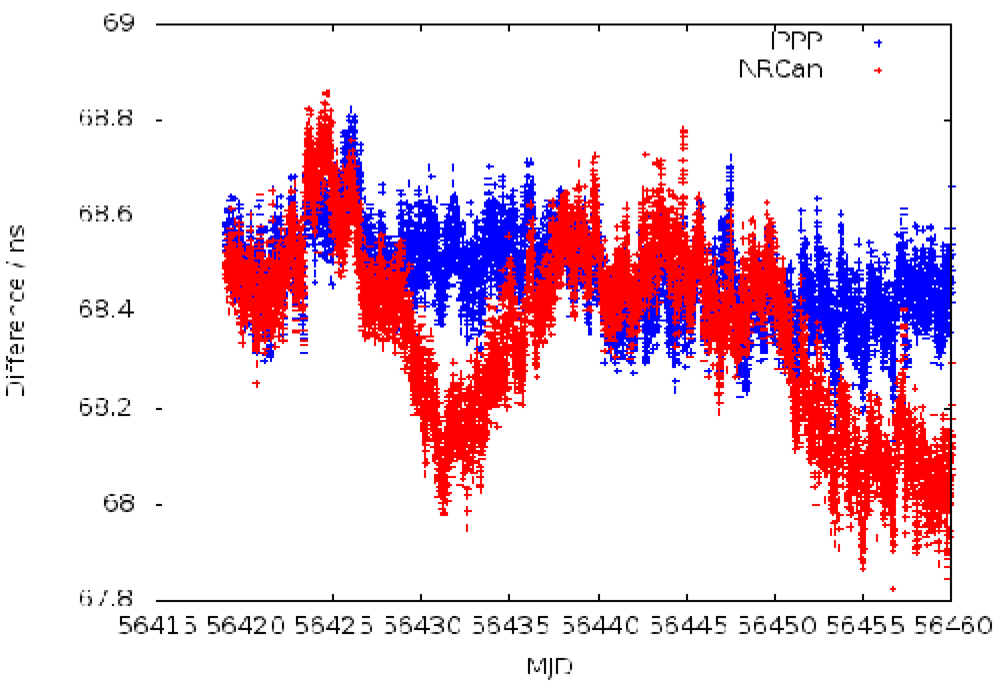
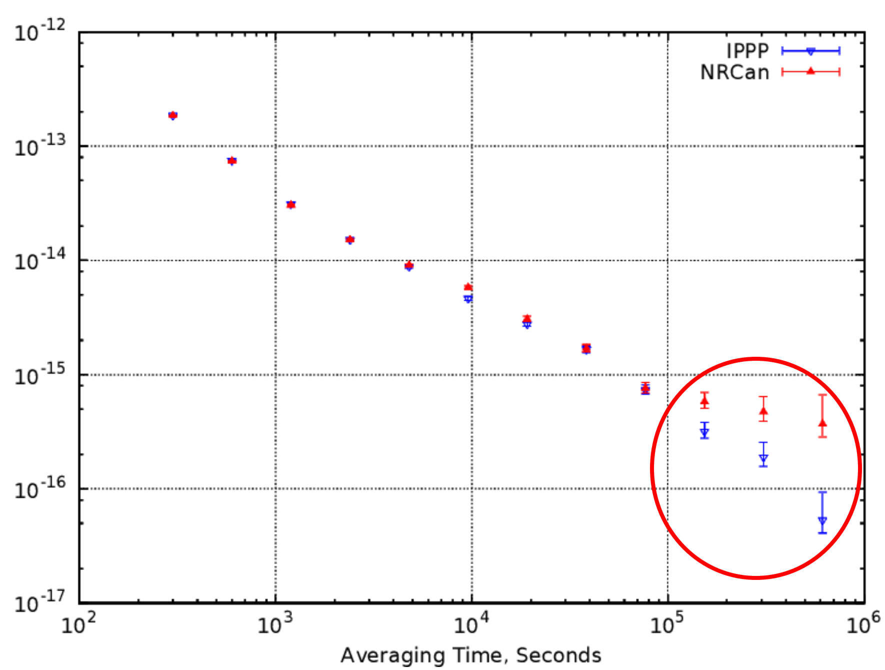
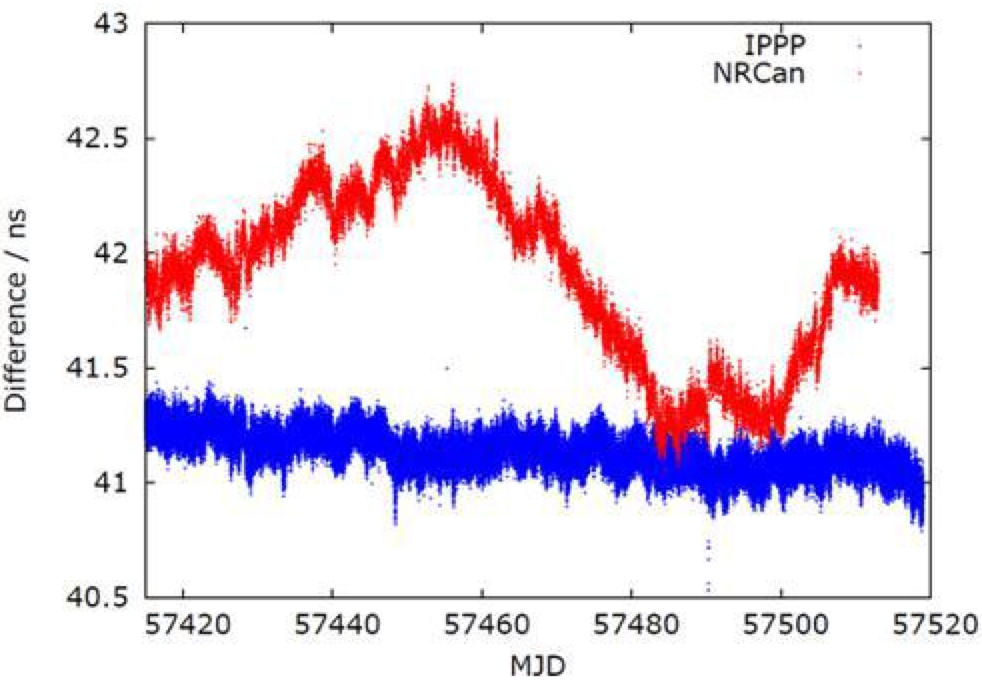


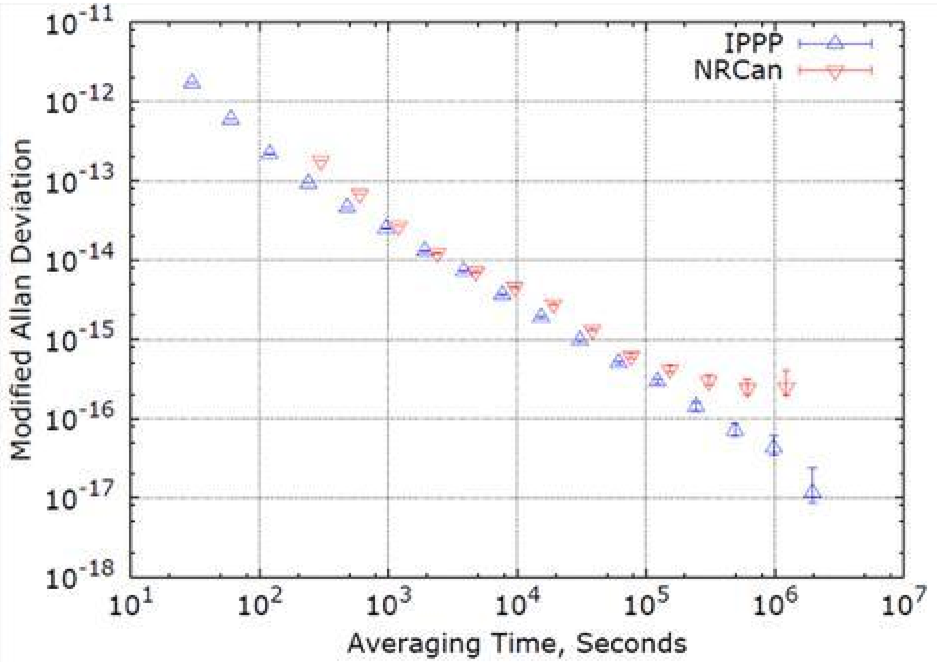


IPPP and PPP vs. 420-km fibre link: best result

- Computation passed to “operational mode” in December 2015
- Longest continuous solution: 104 days
- (IPPP – Fibre) crosses $1x10^{-16}$ at about 4 day averaging, **low 10^{-17} at > 10 days**
- (IPPP – Fibre) frequency difference **– $2.1x10^{-17}$** .
- Classical PPP limited ~ $2\text{-}3x10^{-16}$

Blue = IPPP – Fibre link
Red = NRCan – Fibre link

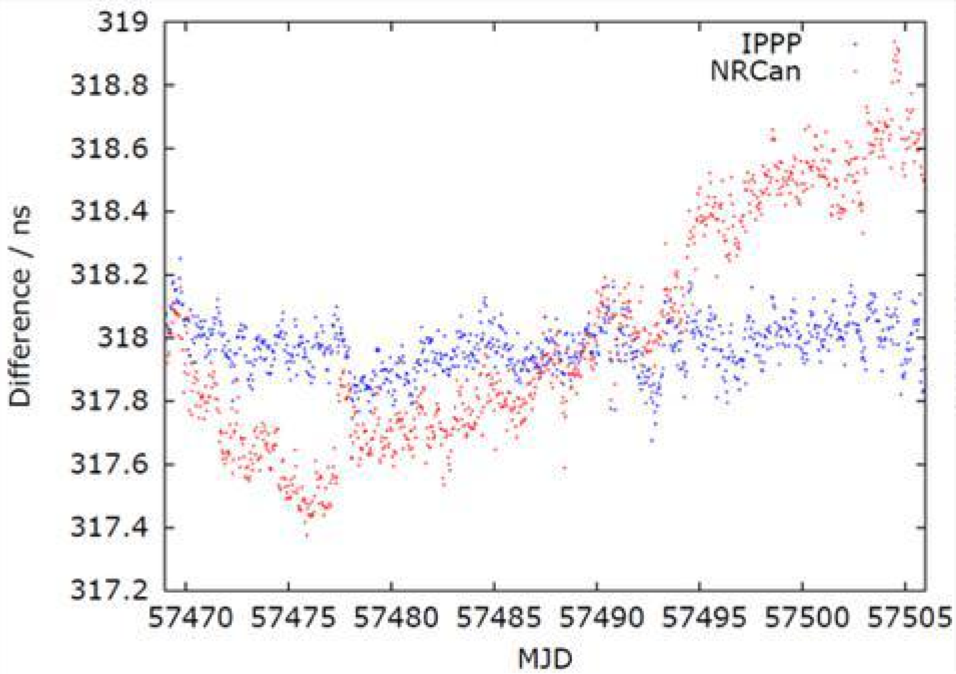


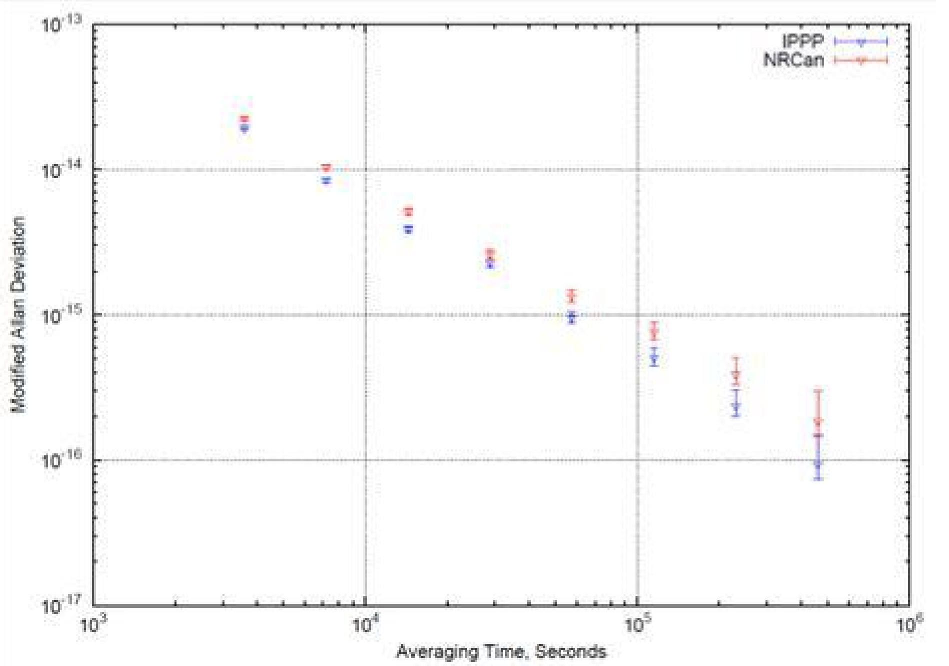


IPPP vs TW Software Defined Receiver

- TW SDR more stable than classical TW
- Example with TL-KRISS a ~ 1400 -km baseline
- Difference 1x10^{-16} at about 5 day averaging (limited by TW noise at short term)

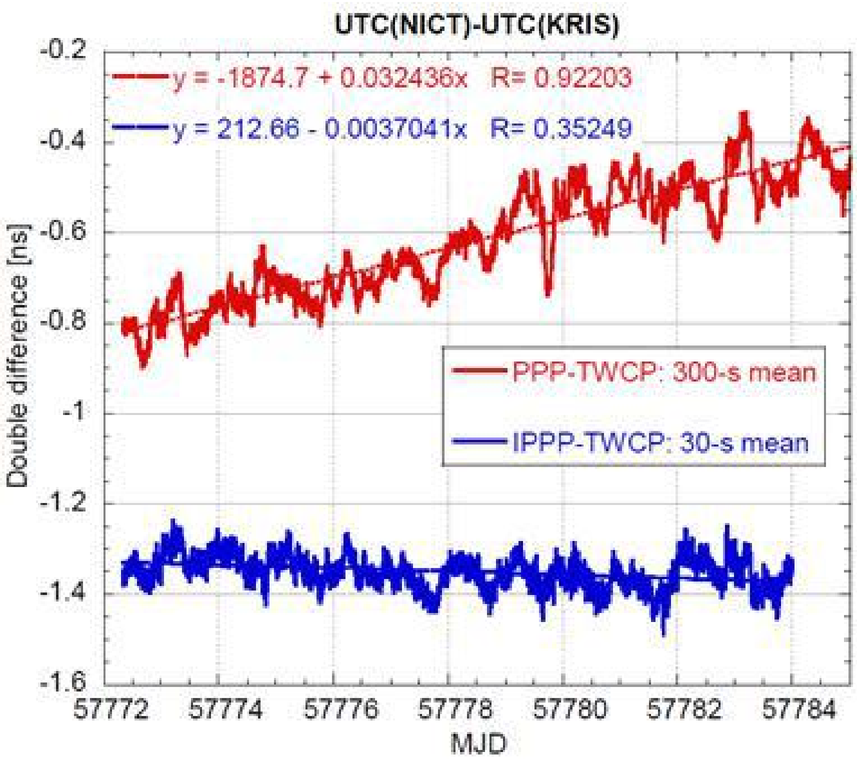
Blue = IPPP – TW SDR
Red = NRCan – TW SDR

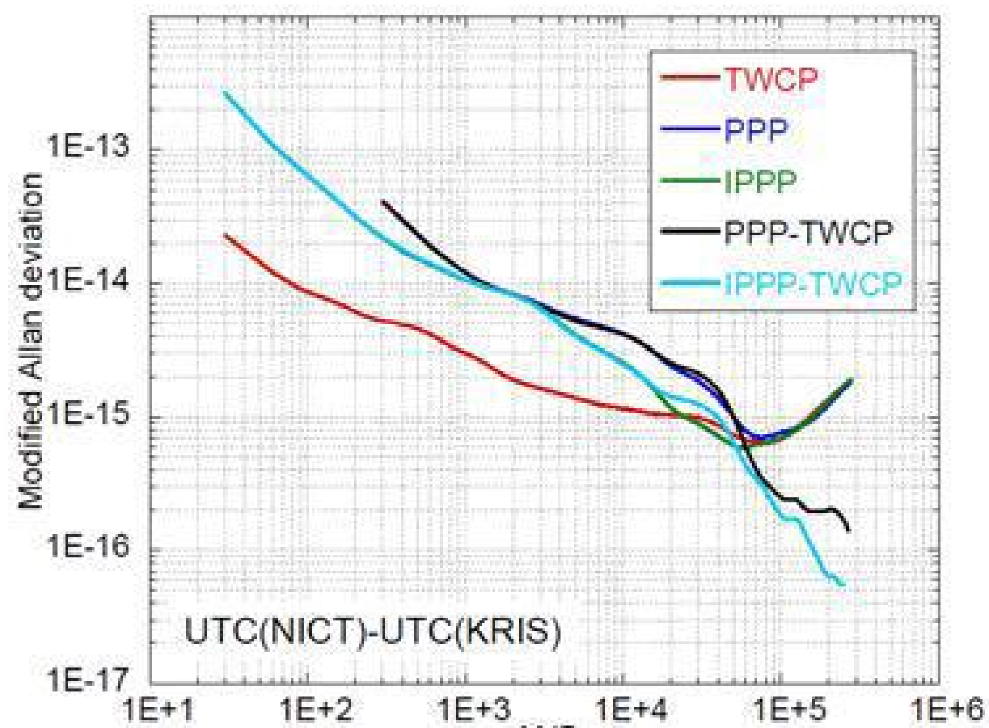




IPPP vs TW Carrier Phase

- Link KRISS (Daejeon, Korea) to NICT(Tokyo, Japan) ~ 1100 km
- TW Carrier phase: Data and analysis by Miho Fujieda, NICT (2017)
- IPPP and PPP by BIPM computation
- (IPPP – TWCP) frequency difference = – 4.3×10^{-17} .
- Classical PPP limited ~ 2×10^{-16} ; (PPP – TWCP) = 3.8×10^{-16}





Conclusions and outlook

- IPPP is a significant option for frequency transfer
  - Ubiquitous hardware; satellite products available from IGS ACs.
  - Main constraint is the need for continuous measurements; only « weak continuity » needed i.e. some gaps allowed.
  - Seems to provide **$1x10^{-16}$ @ ~3 days, low 10^{-17} @ 10-20 days**
  - Some room for improvement at short term (at least from troposphere modeling).

- May be limited at the 10^{-17} level on the long term ?
- Also limited by « usual GNSS error sources » at short term ?
- Not clear what multi-GNSS solutions could bring

THANK YOU

Acknowledgements:

- AOS and GUM for providing fibre link data to the BIPM
- NICT, KRISS, TL for TW data
- NRCan for continuous support on PPP

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