Continuous and Multi-Constellation IPPP Link for UTC

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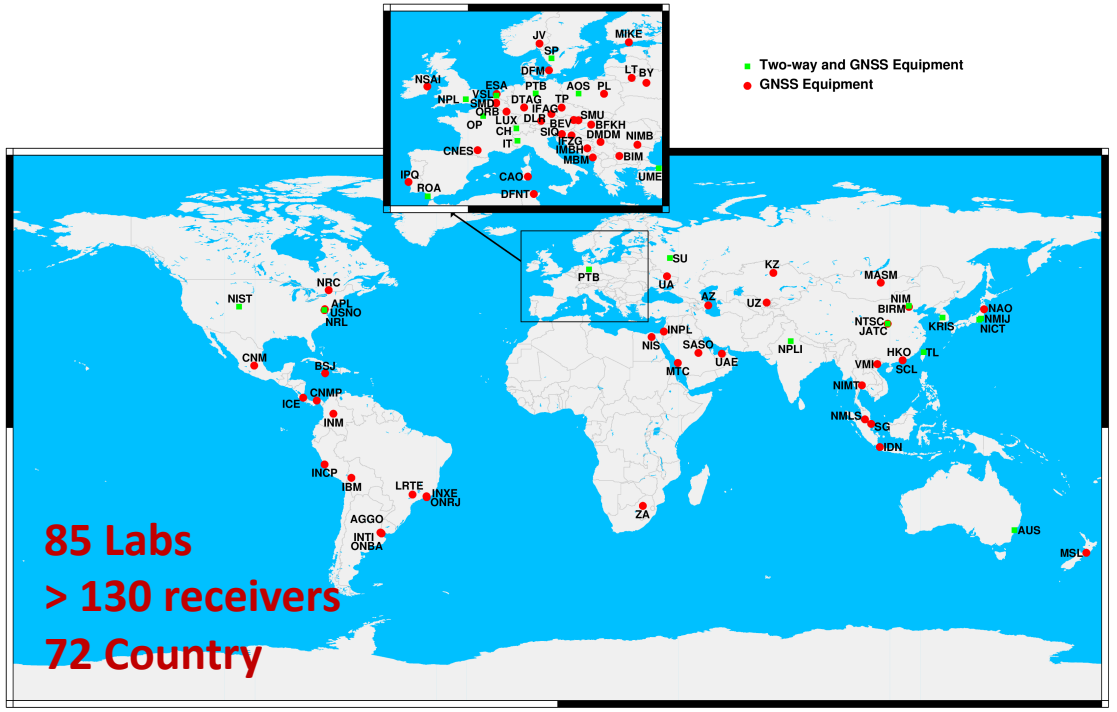
Motivation

- ❑ Coordinated Universal Time (UTC) is the international time standard.
- ❑ PPP is widely used for time and frequency transfer to compare clocks participating in UTC.
- ❑ Current BIPM operational PPP processing mainly relies on GPS only.
- ❑ PPP-AR (IPPP) has been evaluated at BIPM, but is not yet operationally used for UTC.
- ❑ BIPM is in the process of evaluating new tools for operational PPP/PPP-AR in UTC.

Coordinated Universal Time (UTC)

- UTC is the international reference time scale for global applications.
- UTC is computed each month in monthly batches by the Bureau International des Poids et Mesures (BIPM).
- UTC is generated from weighted average of highly stable atomic clocks operated by timing laboratories worldwide.

Geographical distribution of the laboratories that contribute to TAI and time transfer equipment (2025)

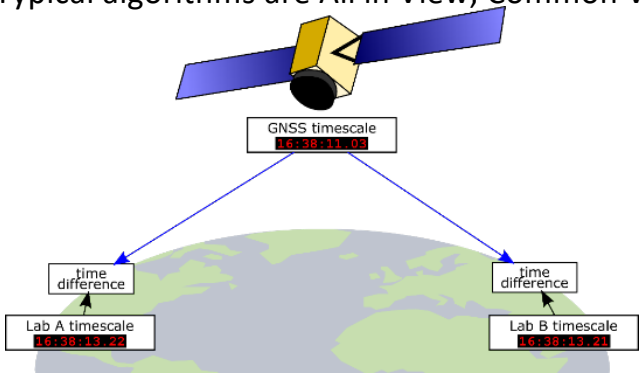


Time Transfer to Compare Clocks Participating in UTC

BIPM

Global Navigation Satellite Systems (GNSS)

GNSS are based on time broadcasting from satellites to ground receivers (one-way time transfer). Distant labs equipped with GNSS receivers periodically compare their clocks to the broadcasted time and send the result to the BIPM.
Typical algorithms are All in View, Common View, and Precise Point Positioning



Operational since ~ 1980
Number of links : all contributing laboratories
Typical freq. transfer accuracy @1d : a few 10^{-15}
Typical time transfer accuracy : a few ns

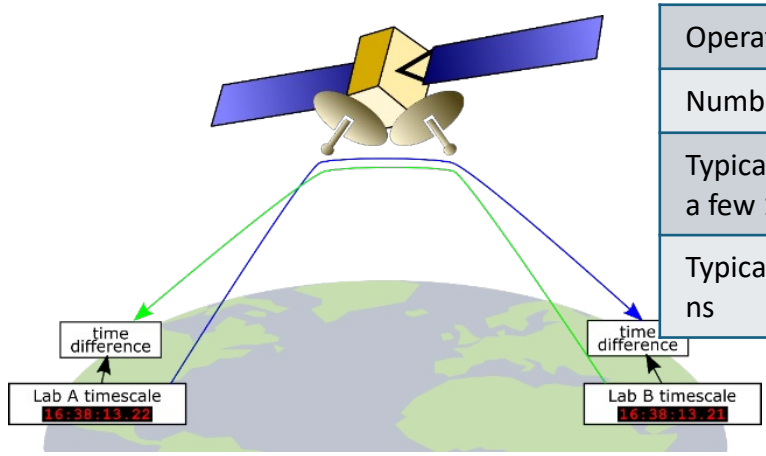
Progress in GNSS measures

GPS+ GLONASS + Beidou + Galileo

PPP-AR : Precise Point Positioning with integer ambiguity resolution

Two-Way Satellite Time & Freq. Transfer (TWSTFT)

dedicated ground terminals simultaneously receive and transmit time transfer signals (two-way time transfer) on geostationary telecom satellites.
Two-way method cancels out (at first order) the propagation time of the signal.



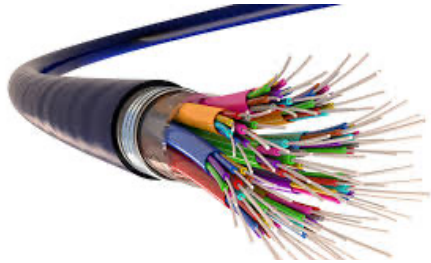
Operational since ~2000
Number of links : 18
Typical freq. transfer accuracy @1d : a few 10-15
Typical time transfer accuracy : ≳ 1 ns

Progress in TWSTFT

Software Designed Radio and TWSTFT Carrier Phase

We are very grateful to IGS and ACs for their efforts in maintaining GNSS service

A growing number of UTC laboratories are gaining access to fiber links dedicated to time and frequency. Although few of them are currently interconnected by operational, high-duty cycle links, this number is expected to grow quickly during the next decade.



PPP-AR for Timing: Lesson Learned

BIPM

- ❑ BIPM has several years of experience using PPP-AR for time transfer
  - based on CNES GINS software, final ephemerides and daily batch.
- ❑ This processing relies on CNES final orbits
  - latency of the product not compatible with UTC computation schedule and the process requires manual validation
- ❑ Multi-day batches are more robust and easier to handle than traditional daily batches but require dedicated software and compatible ephemerides.

PPP-AR Software Selection

BIPM

- ❑ PPP/PPP-AR solutions rely on existing GNSS precise processing software.
- ❑ Two software packages are currently evaluated at BIPM:
  - PRIDE PPP-AR: open-source (GPLv3), developed by Wuhan University
  - Atomium: legacy software from the timing community, developed by ORB

PRIDE Lab
Positioning
Racers to Image
& Decipher the Earth

ROYAL OBSERVATORY
OF BELGIUM
Communication and Information

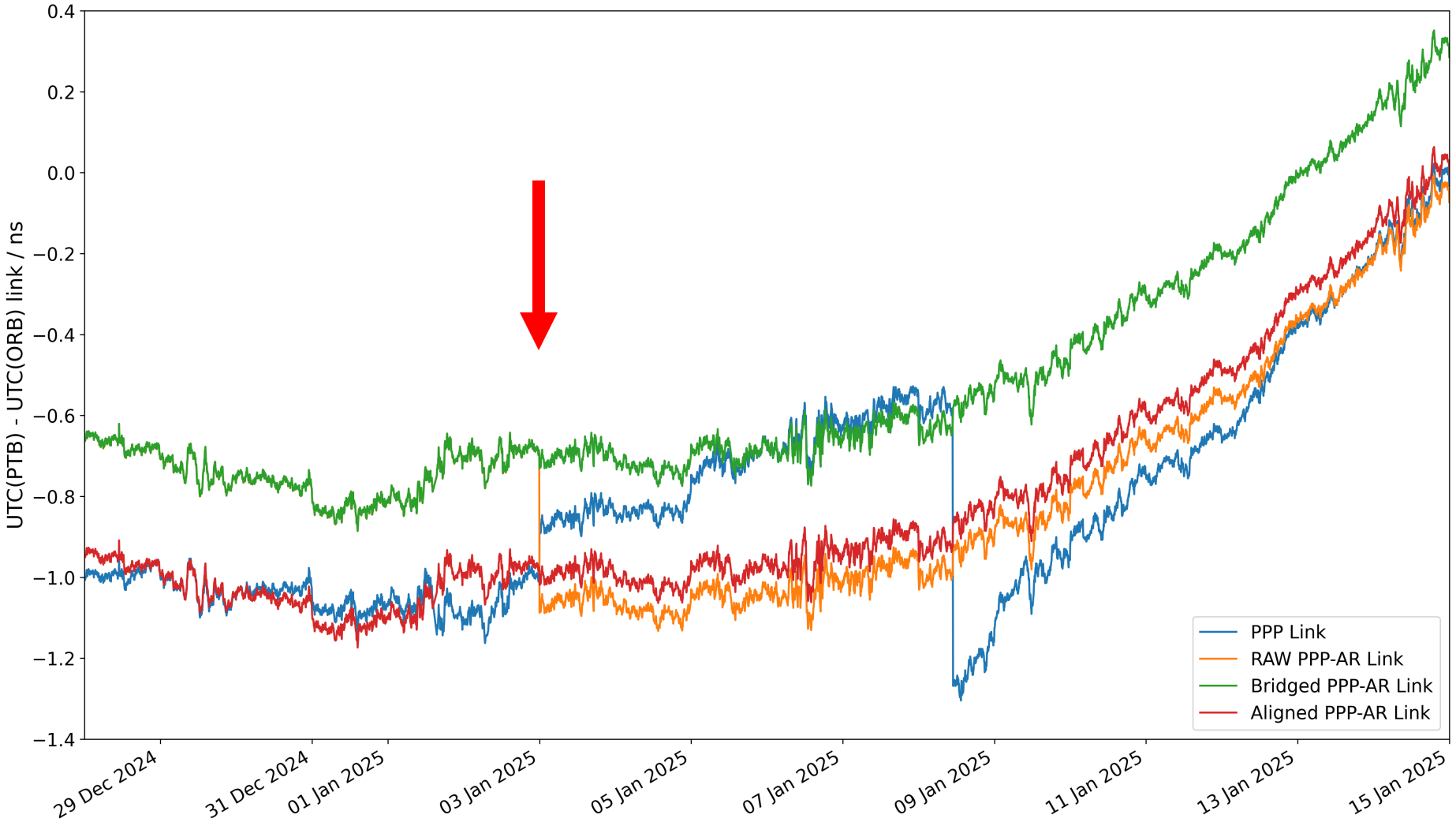
Precise Ephemerids

❑ Several precise ephemerids are available for PPP/PPP-AR, in this study we tested:

Products	PPP	PPP-AR	Continuity at day boundaries	Constellation
IGS rapid	√	×	√	GPS
Wuhan rapid	√	√	√	GPS/Galileo/BDS
CODE rapid (aligned by BIPM)	√	√	×(√)	GPS/Galileo

- IGS rapid products: support PPP only; currently used in UTC
- CODE rapid products: enable PPP-AR; continuity ensured via extra alignment at day boundaries

Outline of the PPP-AR Computation in BIPM



1) PPP and PPP-AR solution

(with 35-day batch)

2) Form time links with PTBB

3) Bridge Narrow Lane integer step where possible

4) Align bridged PPP-AR to PPP

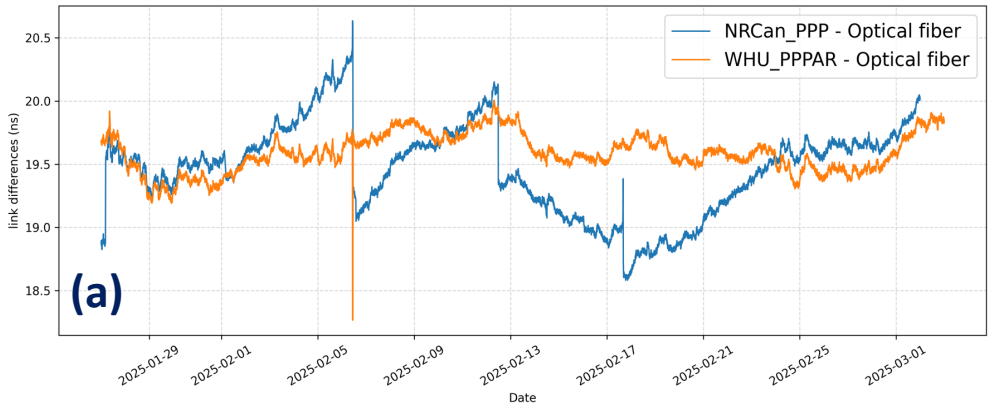
Results

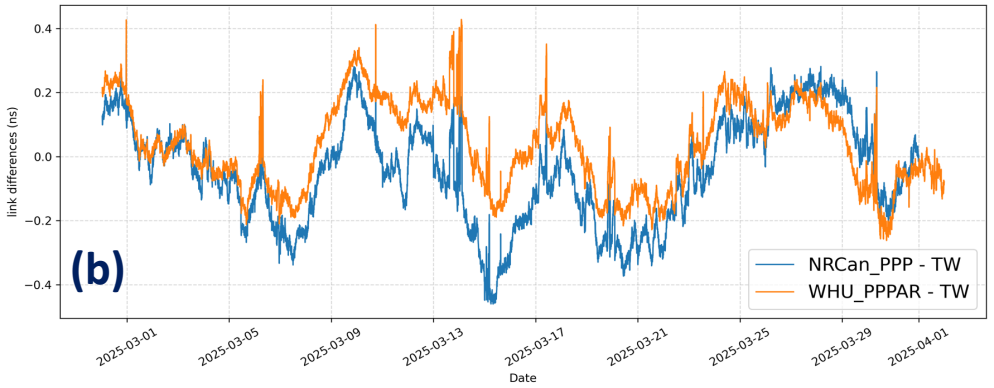
- PPP-AR solutions based on PRIDE PPP AR software for 12 months in 2025 on ~90 stations.

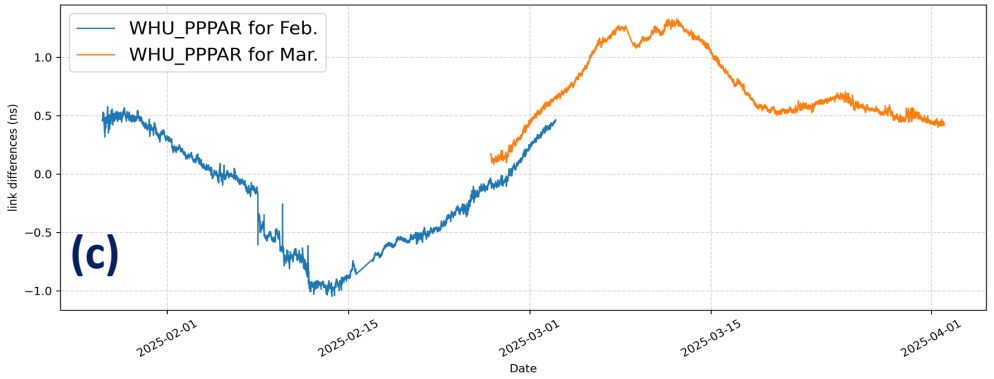
Solutions	Products	Constellation
IGS_G_PPP	IGS rapid	GPS
WHU_GEC_PPP	Wuhan rapid	GPS+Galileo+BDS
WHU_GEC_PPPAR	Wuhan rapid	GPS+Galileo+BDS
COD_GE_PPP	CODE_align rapid	GPS+Galileo
COD_GE_PPPAR	CODE_align rapid	GPS+Galileo
NRCan_G_PPP	IGS rapid	GPS

- Legacy NRCan GPS PPP are displayed for comparison

Link Performance Assessment





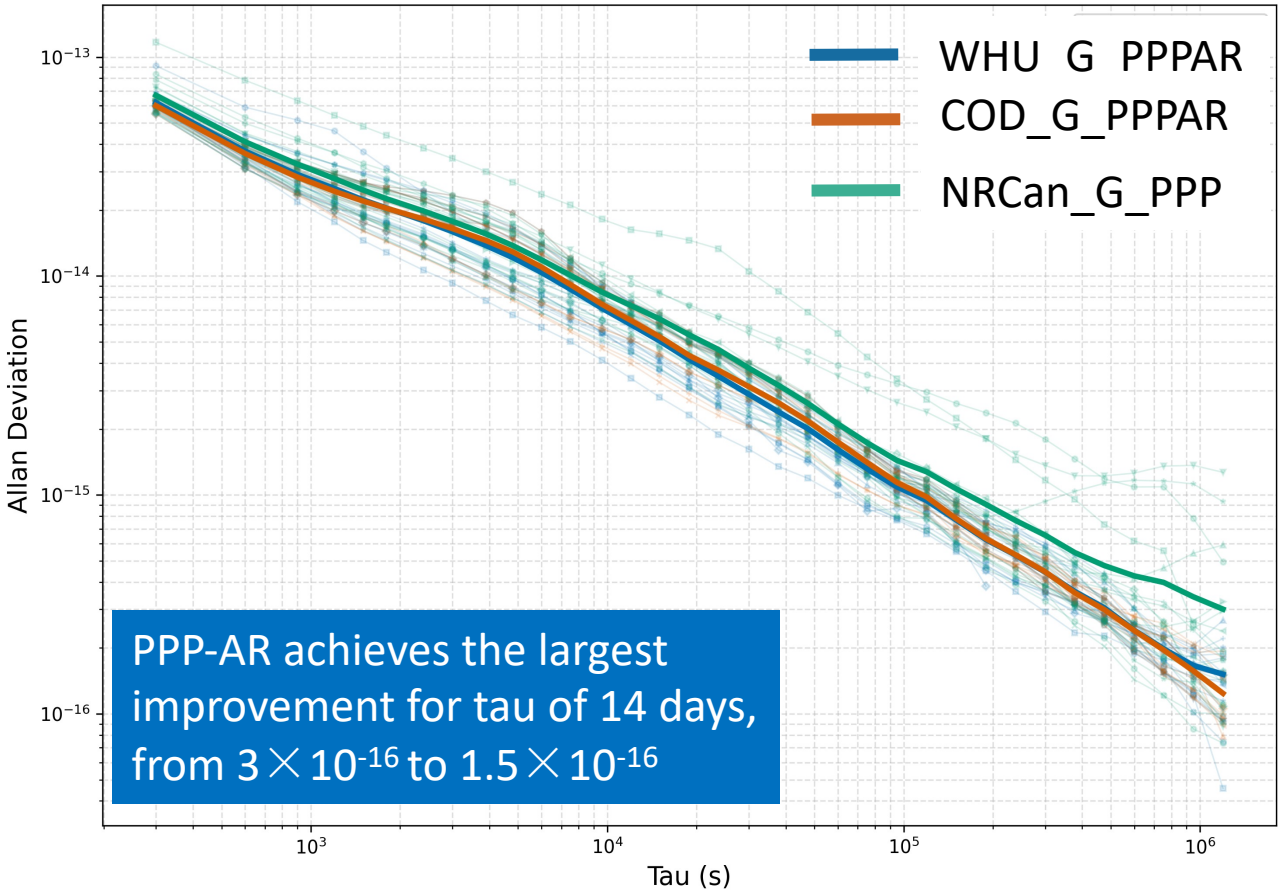


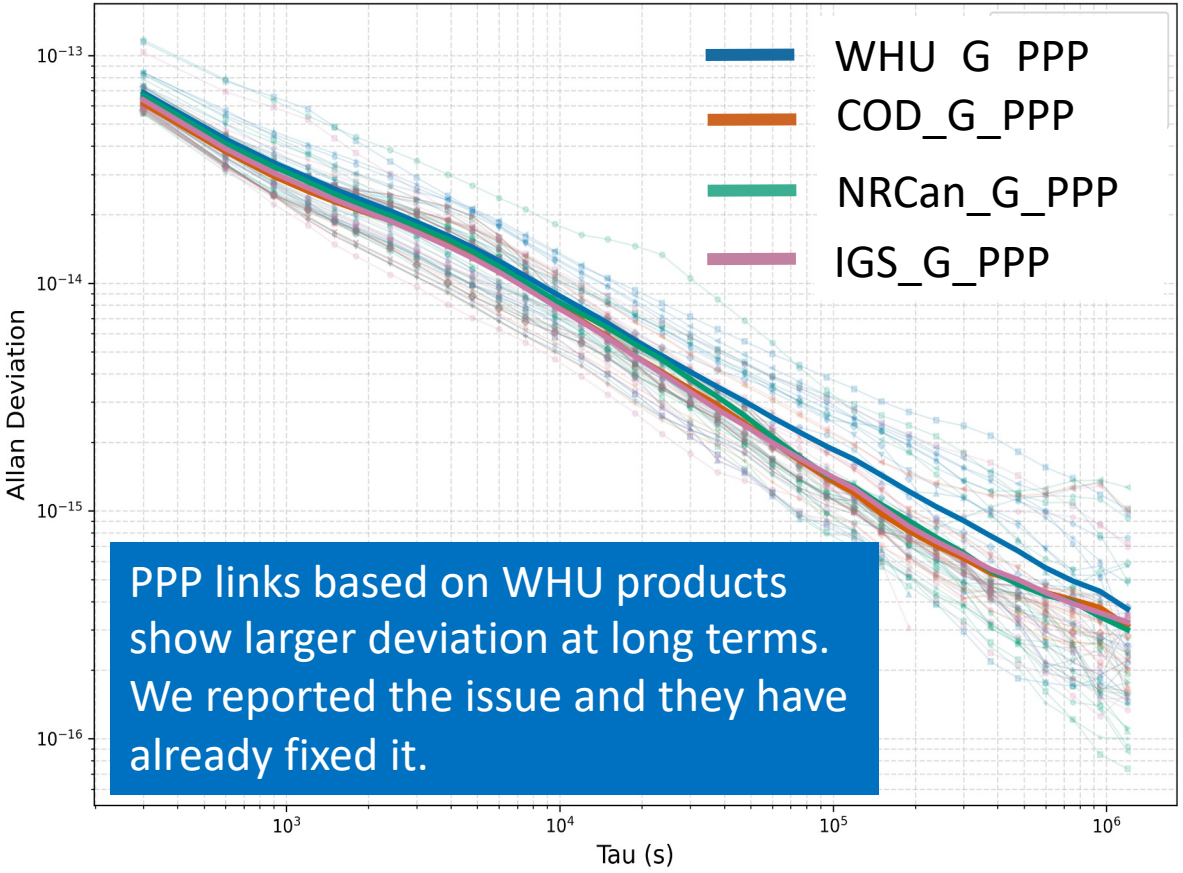
- ❑ **PPP/PPPAR Link Differences to Optical Fiber**
  - **One Optical fiber AOS-PL in Poland**
  - **Allan deviation**
- ❑ **PPP/PPPAR Link Differences to Two-way time transfer link**
  - **20 TW links between labs and PTB**
  - **Allan deviation**
- ❑ **Overlap biases between adjacent batches of PPP/PPPAR links**

Comparison PPP-AR versus Optical Fiber Links

BIPM

- Allan deviation of (PPP-AR – fiber) and (PPP – fiber) clock measures

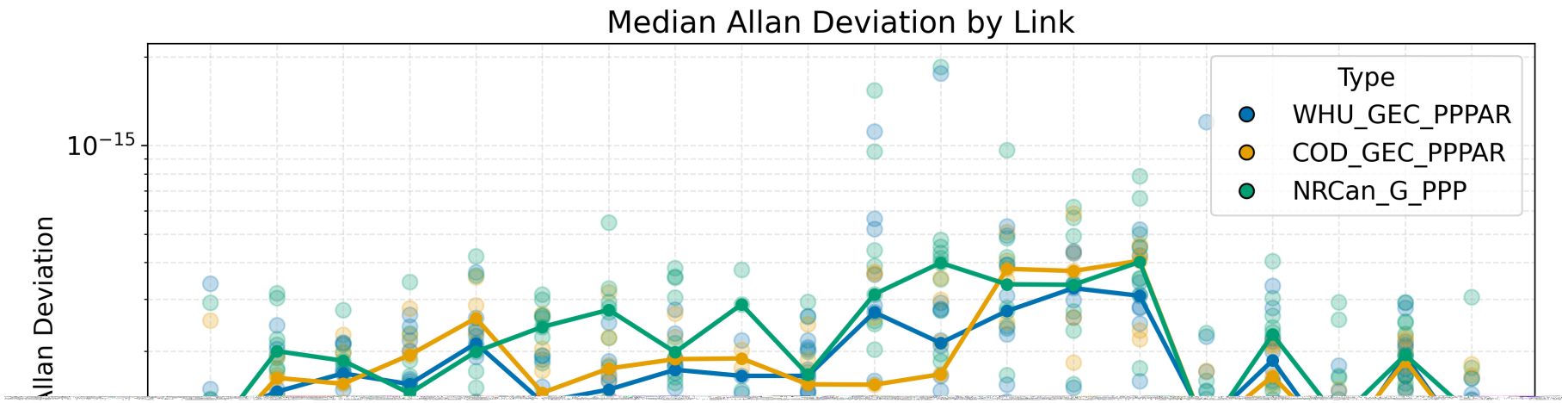




Comparison PPP-AR versus TWSTFT Links

BIPM

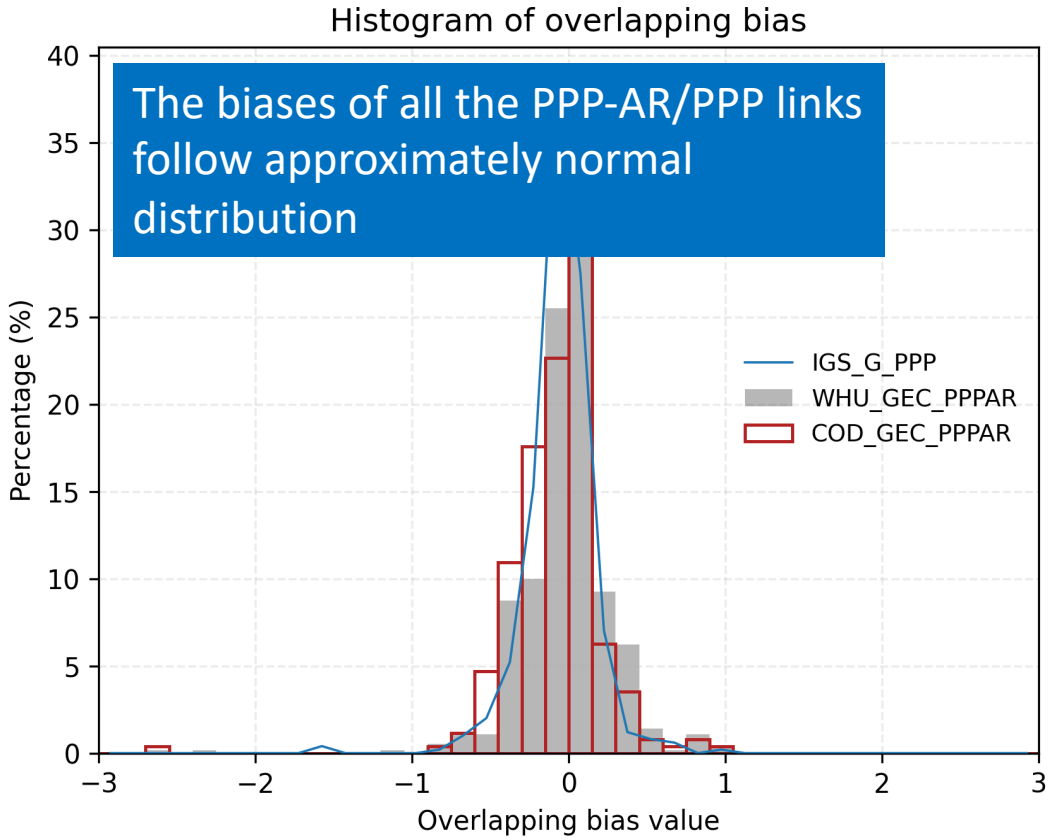
❑Allan deviation of (PPP-AR – TWSTFT) clock measures by link (τ = 14 days)

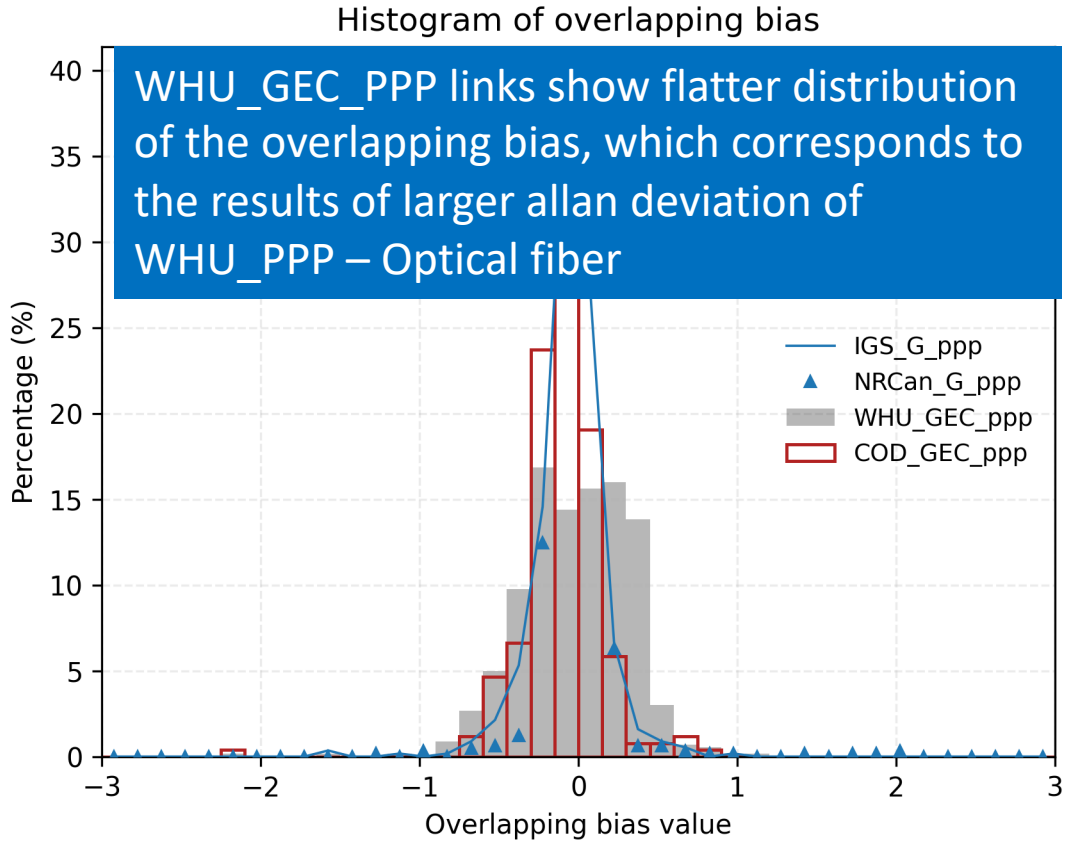


- Mostly limited by TWSTFT observation noise
- PPP-AR solutions (blue, yellow) on all links are equal or better than current PPP processing (green).

Bias with Previous Month

❑ Distribution of mean biases for overlapping links between adjacent months (ns)





Conclusions

- ❑ PPP-AR/PPP solutions based on PRIDE PPP-AR have been extensively tested.
- ❑ Multi-constellation PPP-AR outperforms current PPP solutions in terms of stability under operational–like conditions.

Outlook

- ❑continue the test of PPP-AR solutions for the operational use in UTC
- ❑ Encourage more IGS ACs to provide continuous products
- ❑ Integrate Atomium into the BIPM PPP-AR operational–like workflow
- ❑Collaborations are welcome!!

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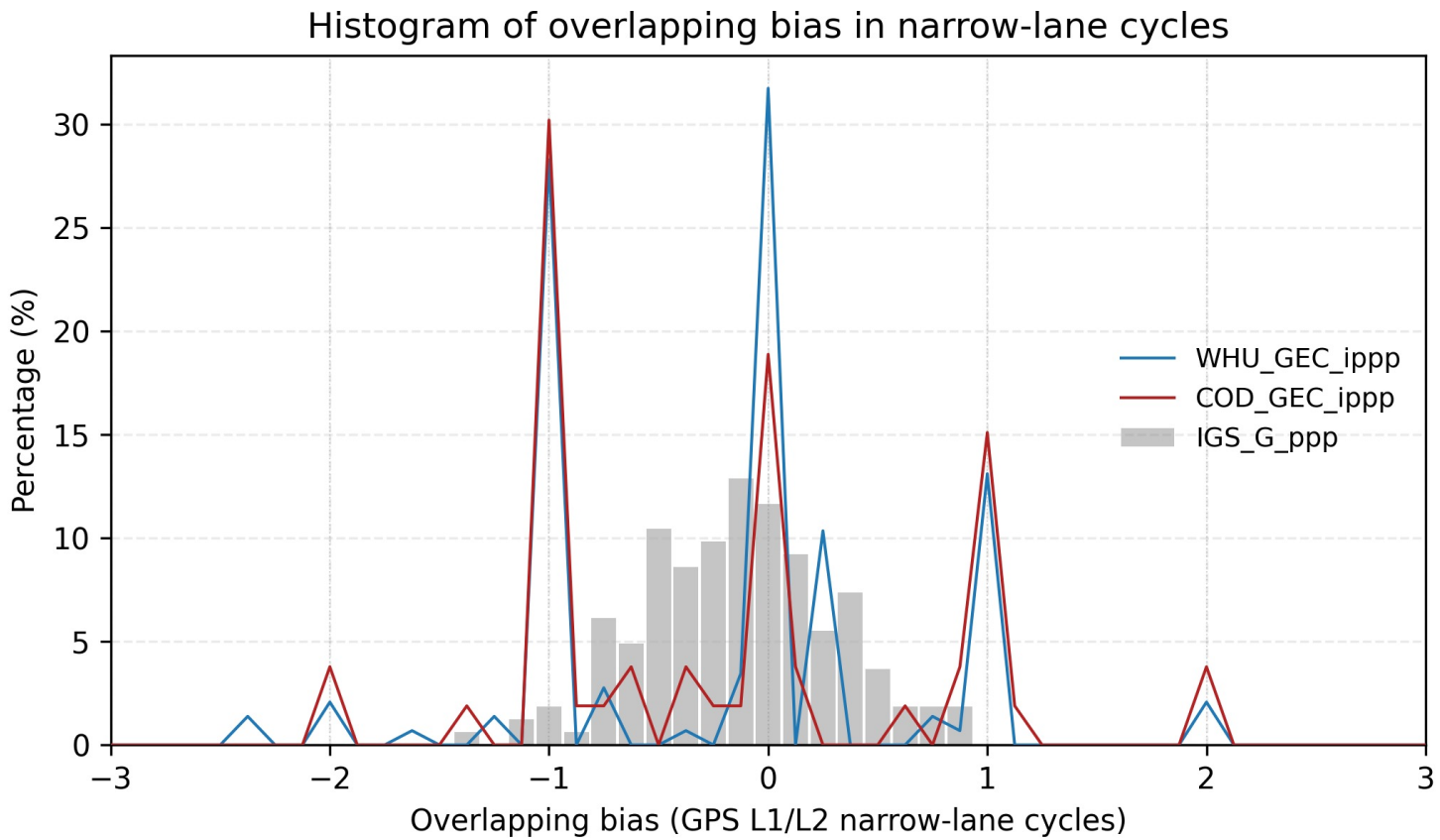
Bias with previous month

❑ Mean overlap biases of unaligned PPP-AR links (NL cycles)

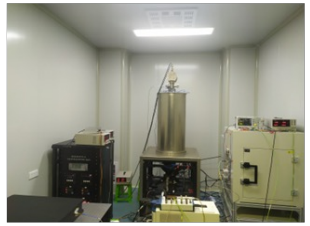


Links with unbridged discontinuities are excluded from the analysis

Inter-batch discontinuities of PPP-AR links exhibit integer-cycle characteristics, enabling continuity calibration.

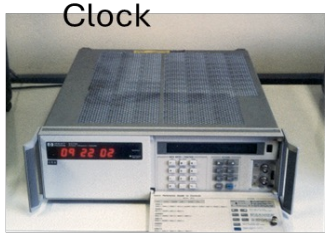
UTC: Calculations

NTSC Rubidium Fountain



Credit: NTSC

Caesium Clock



Hydrogen Masers

BIPM

Cesium Fountains: ~1e-16 frequency accuracy

Optical Frequency Standard up to 1e-18 frequency stability

≈ 420 atomic clocks in 85 laboratories

Weighted average

EAL

weight and prediction algorithms

≈ 26 PFS/SFS

steering

TAI

steering algorithm

Measurement of Earth's rotation

leap seconds

UTC(k)]

Circular T

UTC

≈ 26PFS/SFS

TT(BIPM)

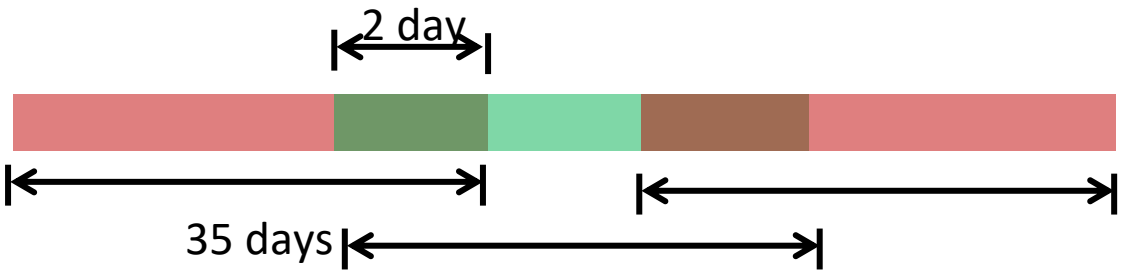
≈ 270 atomic clocks in 62 laboratories

weighted average

UTCr

Outline of the PPP-AR computation in BIPM

Perform PPP-AR processing for all stations (??) using PRIDE PPP-AR using batches of 35 days.



❑ **Post processing**

ADD Animation

1. Discontinuit

- Ambiguity rese
- Clock jumps

ging

tion

3. Alignment

- Align IPPP link to PPP reference (mean bias removal)