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IGS INTERNATIONAL GNSS SERVICE

BAR

Modern Satellite Products:

From Application to Performance

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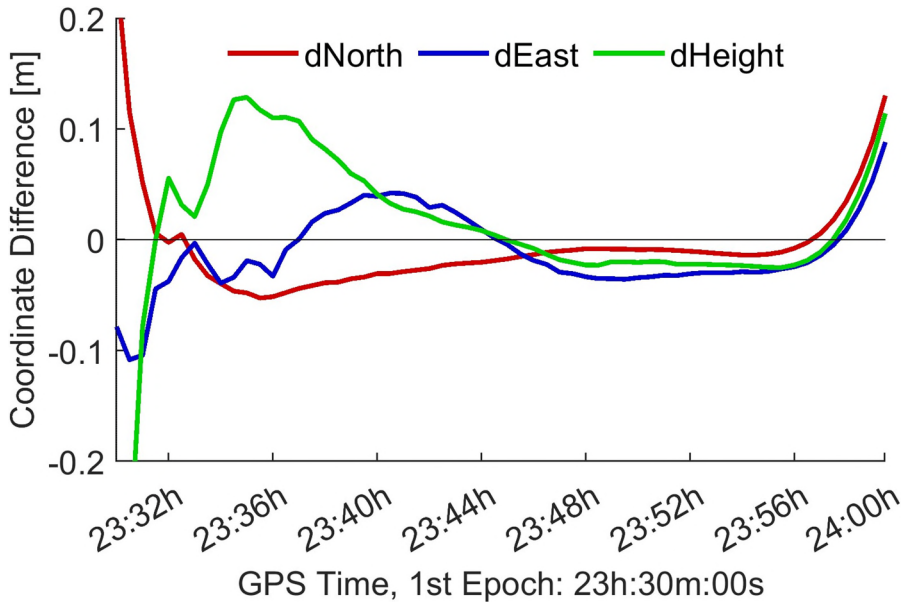
Content

- some topics and issues from the PPP user perspective
- short test of different satellite products and combined products
- summary & outlook

Application

Epoch 24:00

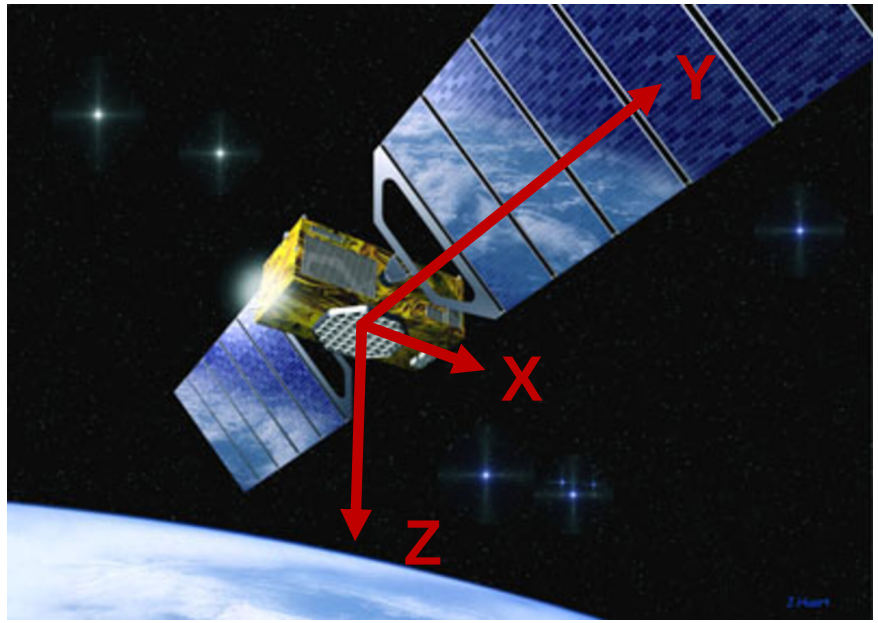
- PPP requires interpolation of satellite products (→ daily files)
- end-of-day issues may occur
- 24:00 epoch make things easier



more details

ORBEX Attitude

- easy to implement
- using attitude information leads to slight improvements in all regards
- particularly useful in eclipse seasons
- ~30 mb / day

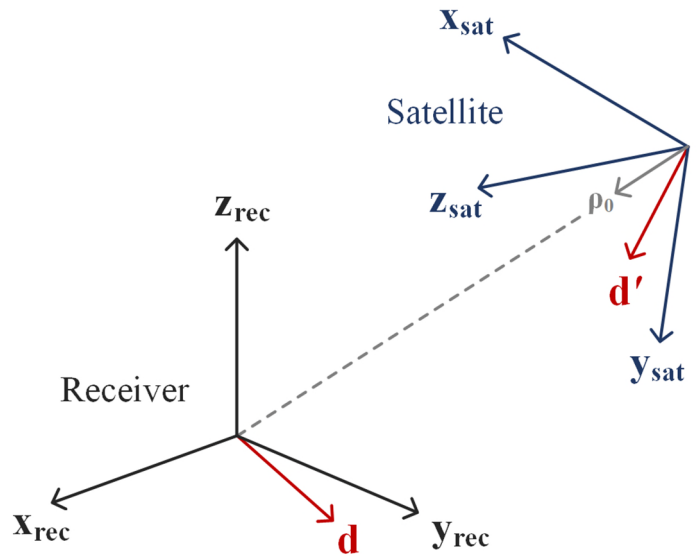


Phase Wind-Up

- sign(…): which side **los$_0$** points with respect to the plane ε defined by **d** and **d'**
- sign(…) near zero → coplanarity → critical
- numerical issues?

$$\Delta\varphi = \operatorname{sign}\left(\boldsymbol{los}_0 \cdot \left(\boldsymbol{d}' \times \boldsymbol{d}\right)\right) \arccos\left(\frac{\boldsymbol{d}' \cdot \boldsymbol{d}}{\|\boldsymbol{d}'\| \, \|\boldsymbol{d}\|}\right)$$

$$\Delta\Phi_i = 2N\pi + \Delta\varphi$$



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Antenna Calibrations

- PPP user must consistently apply the ANTEX file
- essential for:
  - PPP-AR
  - uncombined processing
  - 3+ frequencies
- how to replace missing antenna calibrations?

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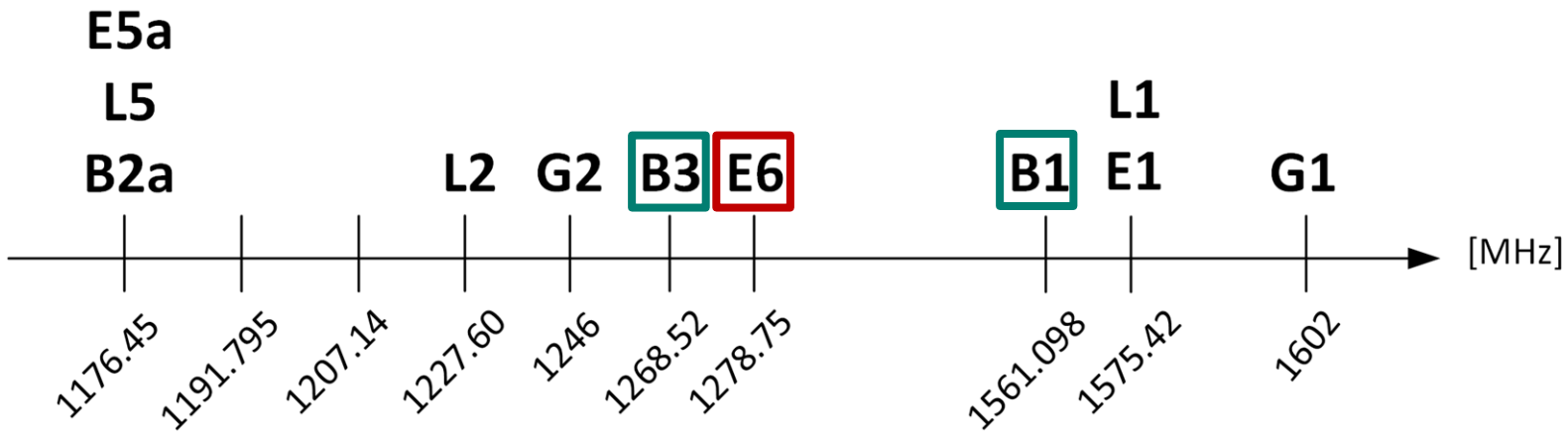
missing antenna calibrations:

→ PCV: take nearest available

→ PCO: linear interpolation

ANTEX Corrections



… processed frequencies

more details

ANTEX Change

- PCO/PCVs of some satellites changed in week 2345
- backward compatibility is lost, for example:
  - satellite products were generated with old values
  - PPP user applies latest igs20.atx file

```
Changes:                                                    COMMENT
  week 2356 Added C234 (C47), C235 (C49)                    COMMENT
            Added JAVRINGANT_3L   NONE                      COMMENT
                  JAVRINGANT_3L   JAVD                      COMMENT
                  STX3050         NONE                      COMMENT
  week 2354 Updated PCO and PV for E225, E226, E227, E232   COMMENT
            Updated PCO for G079                            COMMENT
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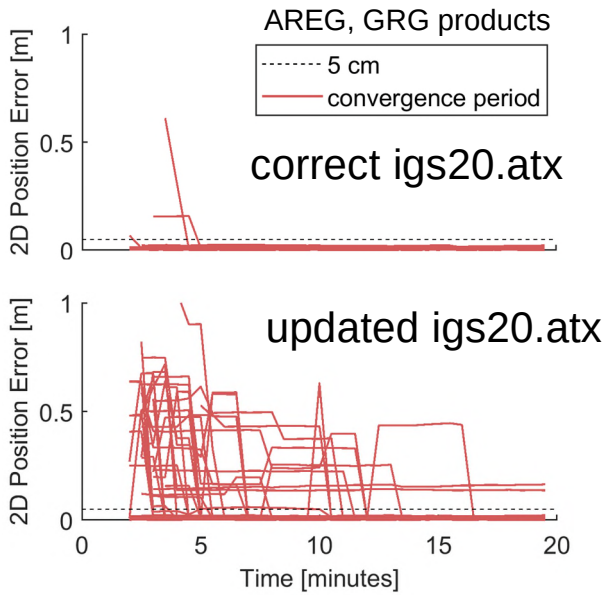
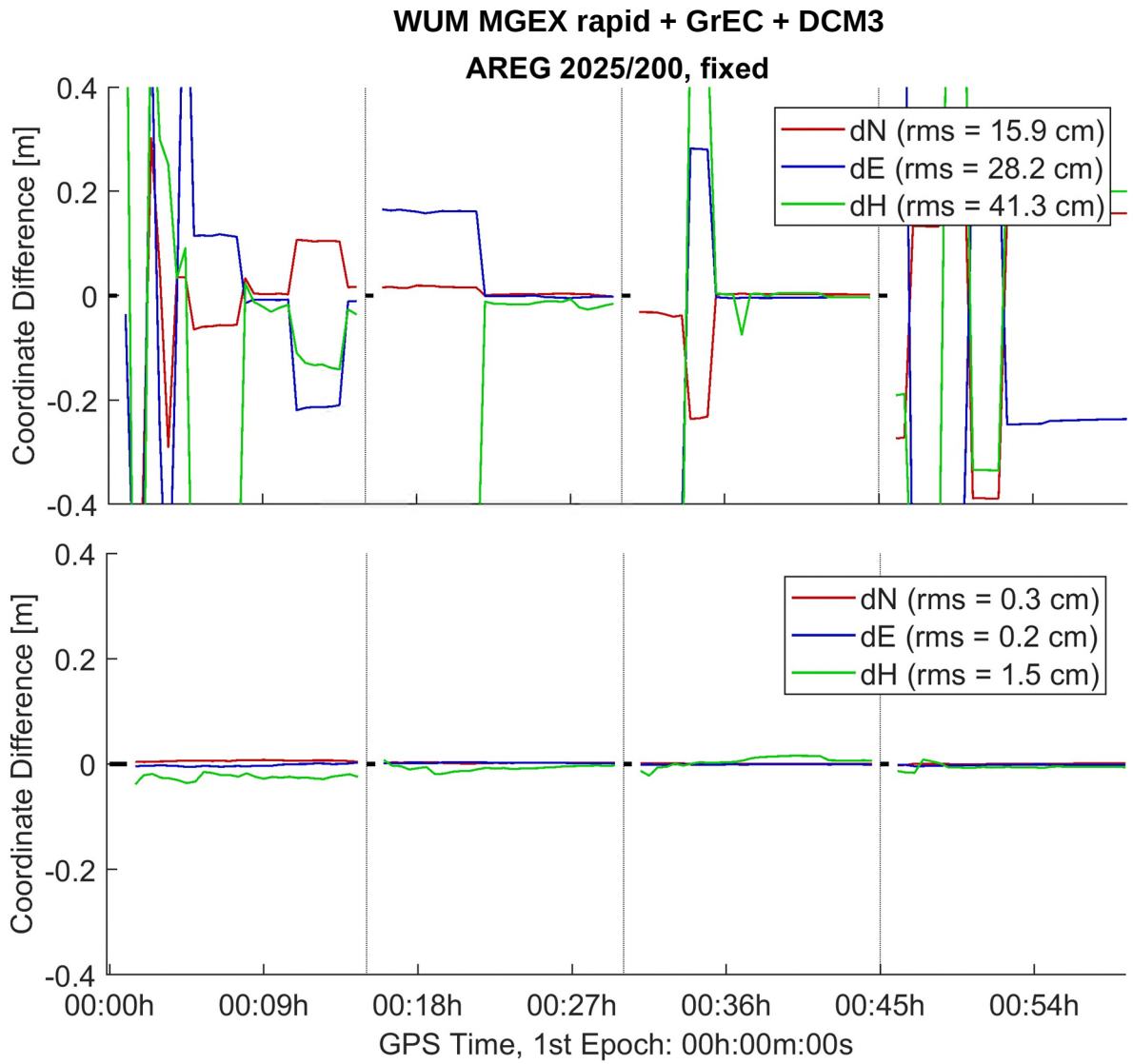
igs20_2356.atx, https://files.igs.org/pub/station/general/





→ BeiDou PRN reassignment?

current igs20.atx

igs20_2375.atx

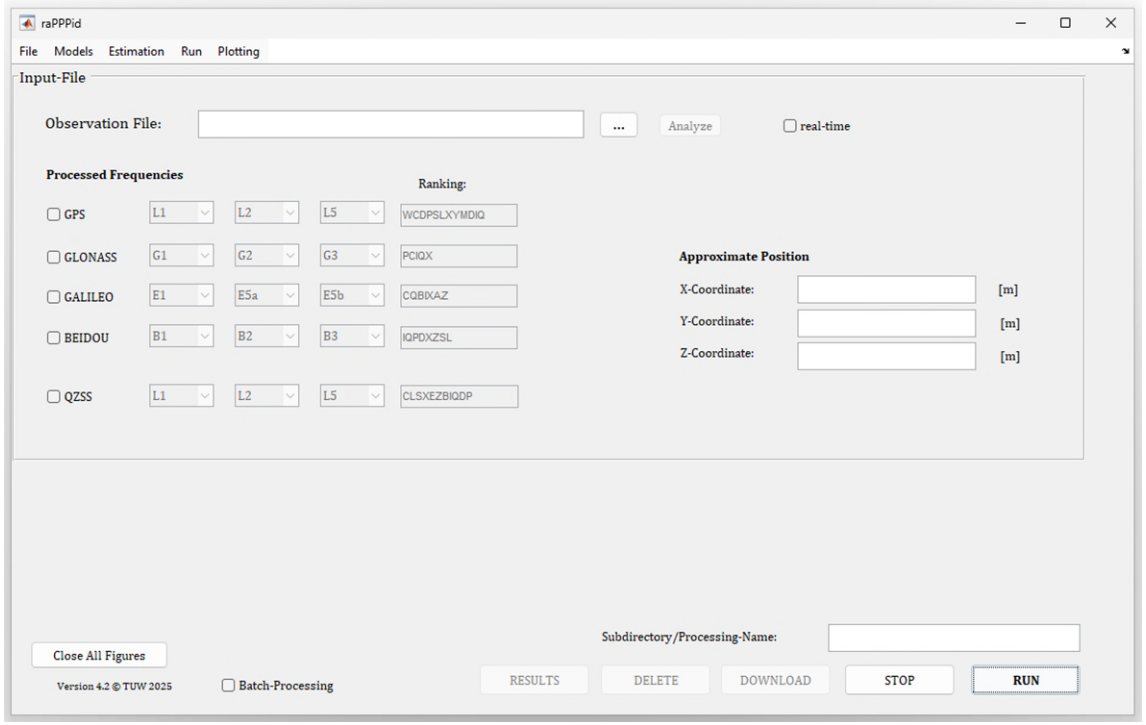
Performance

VieVS
Vienna VLBI and Satellite Software

raPPPid

- open-source PPP software
- GitHub:
  https://github.com/TUW-VieVS/raPPPid
- documentation:

  https://vievswiki.geo.tuwien.ac.at/en/raPPPid



Overview

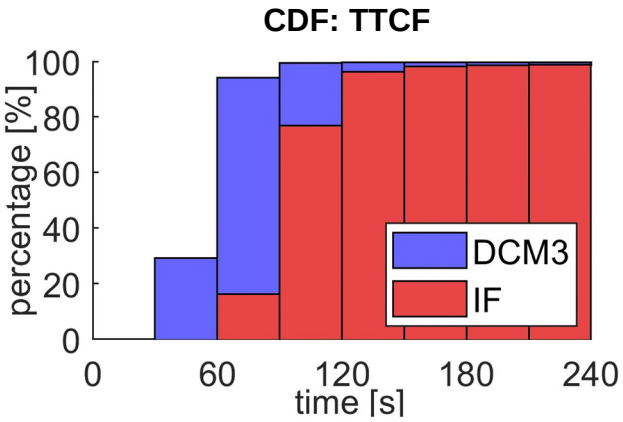
operational (MGEX) products with phase biases

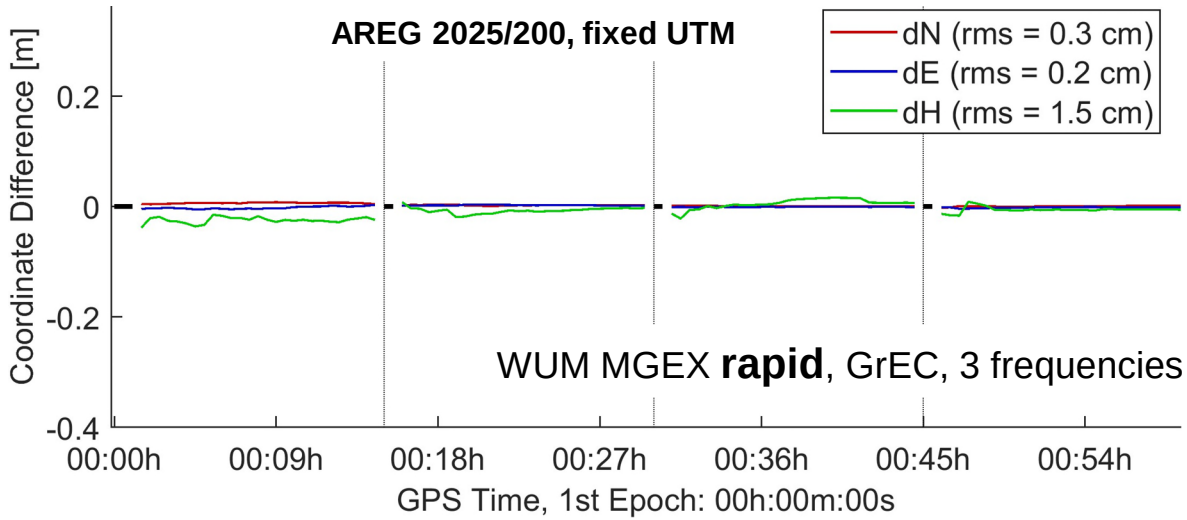
Analysis Center		Source
COD	Center of Orbit Determination Europe	ftp.aiub.unibe.ch/CODE_MGEX/CODE
GFZ	GeoForschungsZentrum Potsdam	ftp.gfz-potsdam.de/pub/GNSS/products/mgex/
GRG	Centre National d'Études Spatiales	https://cddis.nasa.gov/archive/gnss/products/
HUS	Huazhong University of Science and Technology	ftp://ggda.ac.cn/pub/mgex/products/
WUM	Wuhan University	ftps://bdspride.com/wum/ https://cddis.nasa.gov/archive/gnss/products/
WCC	Wuhan Combination Center	ftps://bdspride.com/wcc/ ftp://igs.gnsswhu.cn/pub/whu/phasebias/
IGS	IGS demonstration combination	https://cddis.nasa.gov/archive/gnss/products/

3+ Frequencies

- all mentioned products enable PPP-AR with IF LC
- WUM enables all-frequency PPP-AR:
  - 3+ frequencies
  - other PPP models

→ e.g. Decoupled Clock Model





more details on DCM

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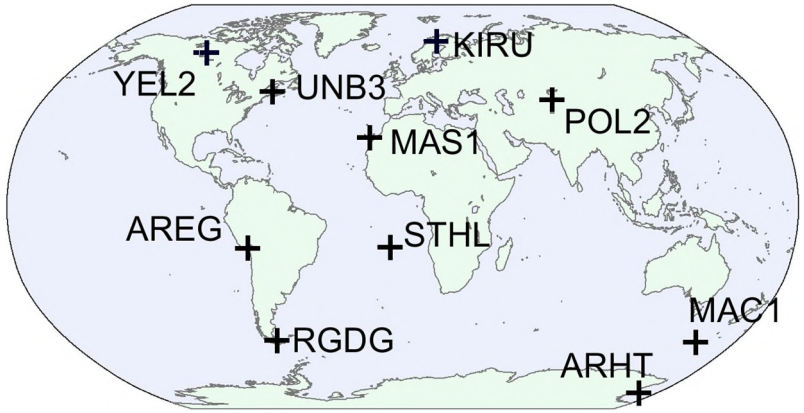
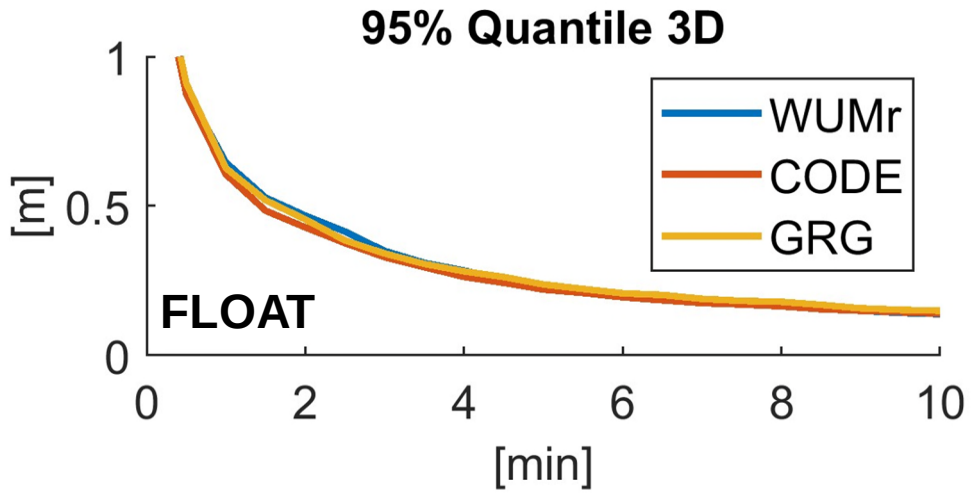
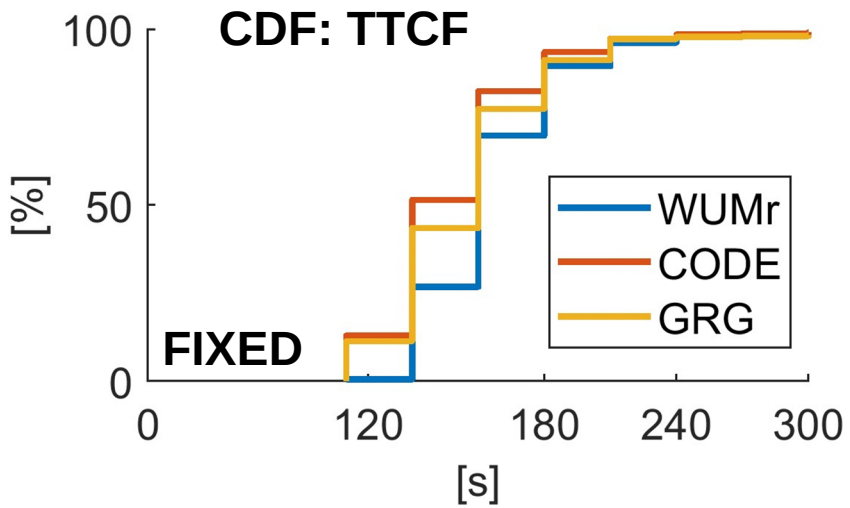
Test case

Software	raPPPid (https://github.com/TUW-VieVS/raPPPid)
Data	10 IGS MGEX stations, March 1, 2026
Observations	GPS: L1+L2, GLONASS: G1+G2, Galileo: E1+E5a 30 sec interval, reset of solution: every 15 min
Satellite products	COD **or** GRG **or** WUM **or** WCC **or** IGS



COD / GRG / WUM

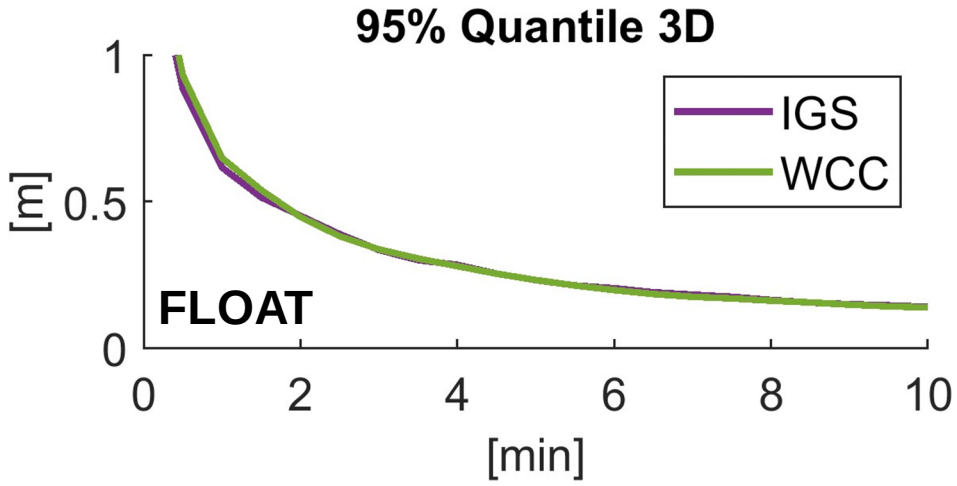


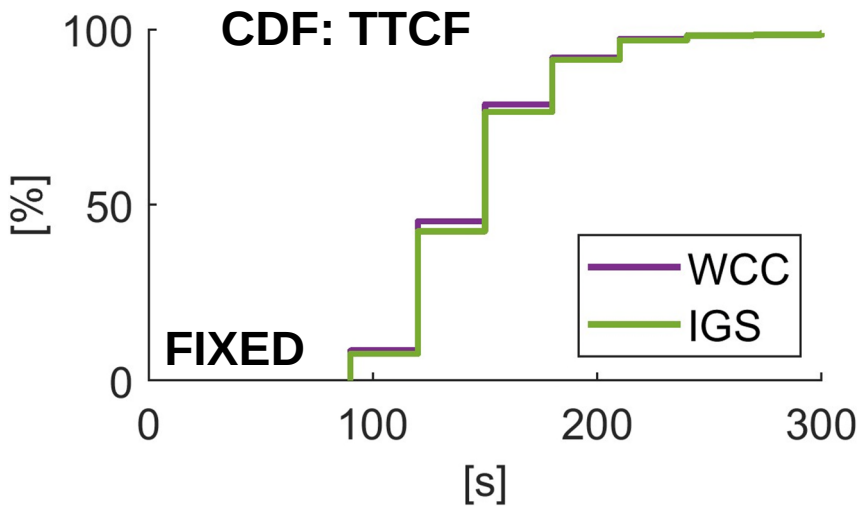


FIXED	COD	GRG	WUMr	
Ø TTCF[1] (2D < 5 cm)	2.36	2.47	2.66	min
no correct fix	0.10	0.10	0.10	%
median 2D error	0.55	0.58	0.51	cm
median 3D error	1.41	1.48	1.36	cm
2D < 5 cm	84.41	83.67	82.48	%
3D < 5 cm	81.84	81.83	80.07	%
Ø ZTD error	0.59	0.62	0.62	cm

[1] … time to correct fix, achieved when 2D < 5 cm for the complete remaining period

Combined Products





FIXED	IGS	WCC	
Ø TTCF[1] (2D < 5 cm)	2.47	2.45	min
no correct fix	0.21	0.10	%
median 2D error	0.47	0.50	cm
median 3D error	1.37	1.36	cm
2D < 5 cm	83.56	83.78	%
3D < 5 cm	81.89	82.16	%
Ø ZTD error	0.58	0.58	cm

[1] … time to correct fix, achieved when 2D < 5 cm for the complete remaining period

Statistics

FIXED	COD	GRG	WUMr	IGS	WCC	
Ø TTCF[1] (2D < 5 cm)	2.36	2.47	2.66	2.47	2.45	min
no correct fix	0.10	0.10	0.10	0.21	0.10	%
median 2D error	0.55	0.58	0.51	0.47	0.50	cm
median 3D error	1.41	1.48	1.36	1.37	1.36	cm
2D < 5 cm	84.41	83.67	82.48	83.56	83.78	%
3D < 5 cm	81.84	81.83	80.07	81.89	82.16	%
Ø ZTD error	0.59	0.62	0.62	0.58	0.58	cm

[1] … time to correct fix, achieved when 2D < 5 cm for the complete remaining period

Summary

- several high-quality satellite products enabling PPP-AR
- combined products are promising
- rapid products lead to similar PPP performance as final products

Outlook

- more satellite products enabling PPP-AR
- 3+ frequencies and all-frequency phase biases
- transition from IF LC to uncombined

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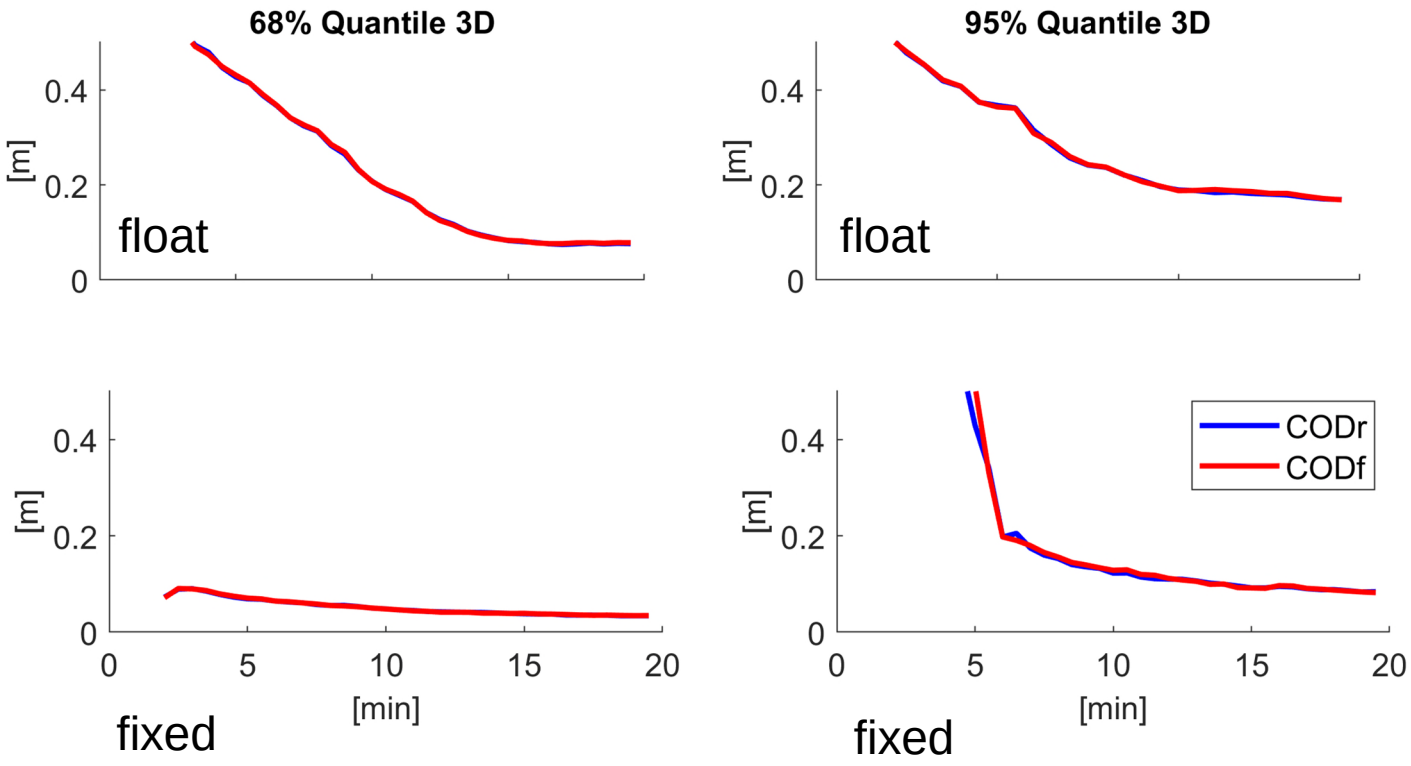
Supplementary

Software	raPPPid (VieVS PPP) (Glaner & Weber, 2023)
Data	10 globally distributed IGS MGEX stations (March 1, 2026)
Observations	GPS: L1+L2, GLONASS: G1+G2, Galileo: E1+E5a
Observation ranking	GPS: WC, GLONASS: PC, Galileo: CQX
Observation interval	30 sec, reset of solution: every 15 min
Processing mode	post-processing, static, ionosphere-free linear combination
Raw observation noise	code 30 cm, phase 2 mm
Observation weighting	elevation weighted, $\sin^2(\text{elev})$, cutoff angle 5°
Correction models	Phase Wind-Up, solid Earth tides, relativistic effects, PCO + PCV, ocean loading
Troposphere model	VMF3 + GRAD, residual zenith wet delay is estimated, process noise 5mm /$\sqrt{h}$
Float ambiguities	constant, zero-difference, cycle-slip detection: dLi-dLj
PPP-AR	fixing cutoff 10°, reference satellite = highest satellite
Fixing	LAMBDA 4.0 (Massarweh et al., 2024)
Orbits, Clocks, Biases, Attitude	WUM MGEX rapid (Geng et al., 2022)

CODE: rapid vs. final



GrE, other test case

fixed results	rapid	final
Ø TTCF [min]	3.52	3.56
median 2D error [cm]	0.89	0.90
Ø 3D error after 20 min [cm]	3.30	3.28

TTCF … time to correct fix

TTCF is achieved when 2D < 5 cm for the complete remaining period

References

- Geng, J., Wen, Q., Zhang, Q., Li, G., & Zhang, K. (2022). GNSS observable-specific phase biases for all-frequency PPP ambiguity resolution. Journal of Geodesy, 96(2), 11. https://doi.org/10.1007/s00190-022-01602-3
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- Massarweh, L., Verhagen, S., & Teunissen, P. J. G. (2024). New LAMBDA toolbox for mixed-integer models: Estimation and evaluation. GPS Solutions, 29(1), 14. https://doi.org/10.1007/s10291-024-01738-z
- Wareyka-Glaner, M. F. (under review). Instantaneous PPP convergence with a decoupled clock model, triple-frequency multi-GNSS observations, and integer ambiguity fixing. GPS Solutions