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Repro3 PPP-AR Products

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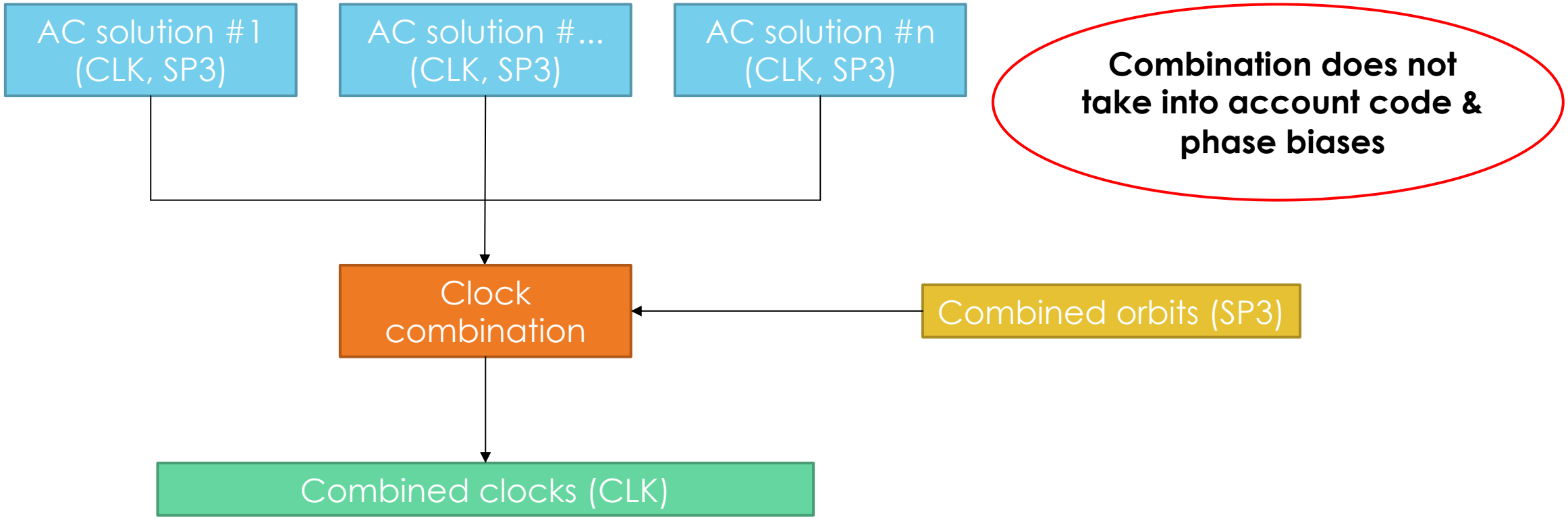
Context

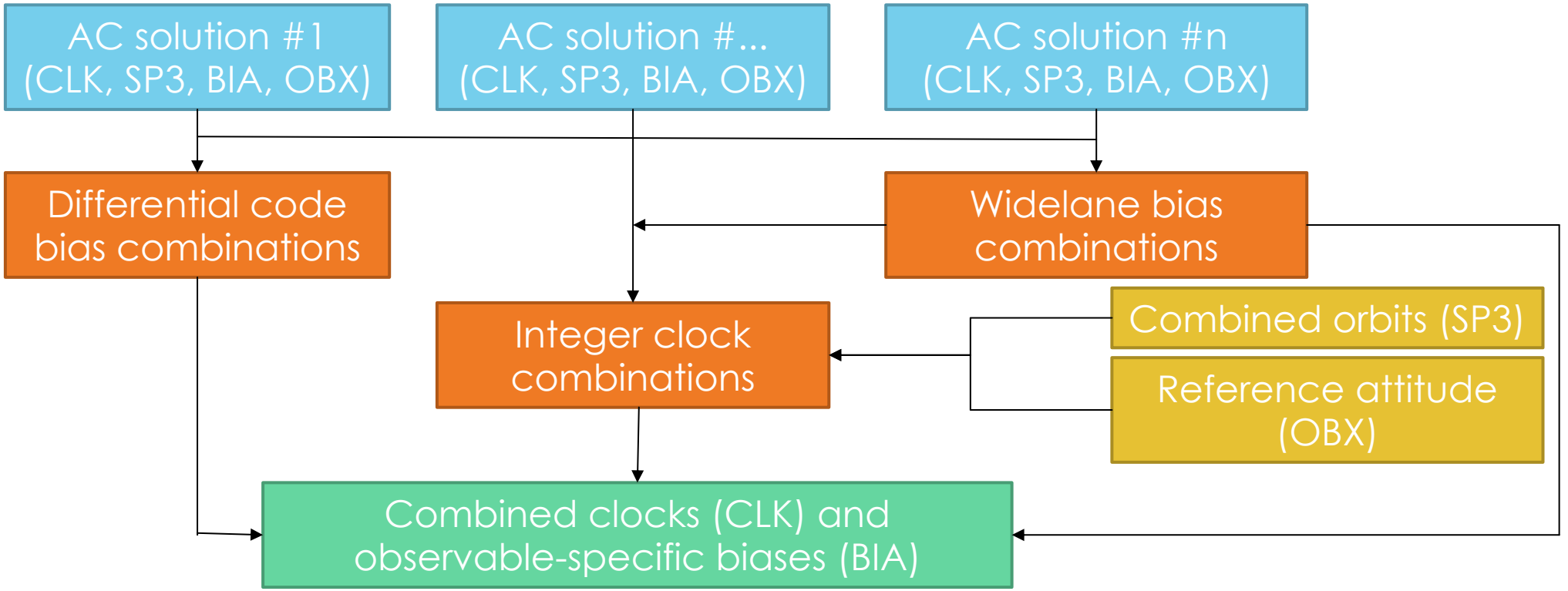
- Several analysis centers (ACs) now provide code and phase biases allowing for precise point positioning with ambiguity resolution (PPP-AR)
- The PPP-AR working group was created to test the inter-operability of PPP-AR products from ACs and generate combined products
- Repro3 is the perfect framework to test the combination over an extended period of time

Satellite clock combination (current)



Satellite clock combination (proposed)

- The consistency of clocks and biases needs to be preserved to achieve PPP-AR at the user end



See: Banville et al. (2020) On the interoperability of IGS products for precise point positioning with ambiguity resolution. Journal of Geodesy

Bias SINEX format

- Biases are (should) be provided in the Bias SINEX format (.BIA)

  See: Schaer S (2016) Bias-SINEX format and implications for IGS bias products. In: IGS Workshop, 8–12 February, Sydney, Australia

```
*BIAS SVN_  PRN STATION__  OBS1 OBS2 BIAS_START____ BIAS_END_____ UNIT  __ESTIMATED_VALUE____ _STD_DEV___ __ESTIMATED_SLOPE____ _STD_DEV__
 OSB        G01            C1W       2020:001:00000 2020:002:00000 ns                  11.8070
 OSB        G01            C2W       2020:001:00000 2020:002:00000 ns                  19.4455
 OSB        G01            C1C       2020:001:00000 2020:002:00000 ns                  10.5799
 OSB        G01            L1W       2020:001:00000 2020:002:00000 ns                  -0.1678
 OSB        G01            L2W       2020:001:00000 2020:002:00000 ns                   0.0401
 OSB        G02            C1W       2020:001:00000 2020:002:00000 ns                 -11.7467
 OSB        G02            C2W       2020:001:00000 2020:002:00000 ns                 -19.3462
 OSB        G02            C1C       2020:001:00000 2020:002:00000 ns                 -10.1931
 OSB        G02            L1W       2020:001:00000 2020:002:00000 ns                   0.2190
 OSB        G02            L2W       2020:001:00000 2020:002:00000 ns                   0.0578
```

- Users apply these biases directly to the observations
- These biases remain valid for linear combinations of observations

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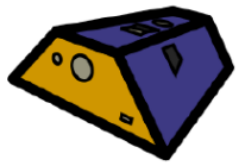
Satellite attitude

- Satellite attitude in the form of quaternions in the ORBEX format (.OBX)

See: Loyer et al. (2019a) GNSS Attitude quaternions exchange using ORBEX, version 30/04/2019. Available online: http://acc.igs.org/misc/proposal_orbex_april2019.pdf

```
+EPHEMERIS/DATA
*REC ID_              N ___q0_(scalar)_____ ____q1__x_________ ____q2__y_________ ____q3__z_________
## 2020  1  1  0  0  0.000000000000  31
 ATT G01              4  0.0527183285603730  0.2354348638796859 -0.4049814903282852 -0.8819190411796513
 ATT G02              4  0.5095354860666030  0.1753306274361990 -0.6131697981550162  0.5776292566622957
 ATT G03              4  0.1286686244066377  0.0130622269512094 -0.3287540152701171 -0.9355183380159656
 ATT G05              4  0.3955116258638559  0.0075529415144335 -0.9103275344548667  0.1217262785693066
 ATT G06              4  0.1587035961776324  0.4297700120219956 -0.1290208857212101  0.8794683145938887
 ATT G07              4  0.1622095453857573  0.0677779940634163 -0.9497403402990026 -0.2590125342820696
 ATT G08              4  0.0274901071929424 -0.2276582920960294  0.8458083421237554  0.4816889498839512
 ATT G09              4  0.2249761199695971  0.0726848200148178 -0.7680223252617401 -0.5951843162268213
```

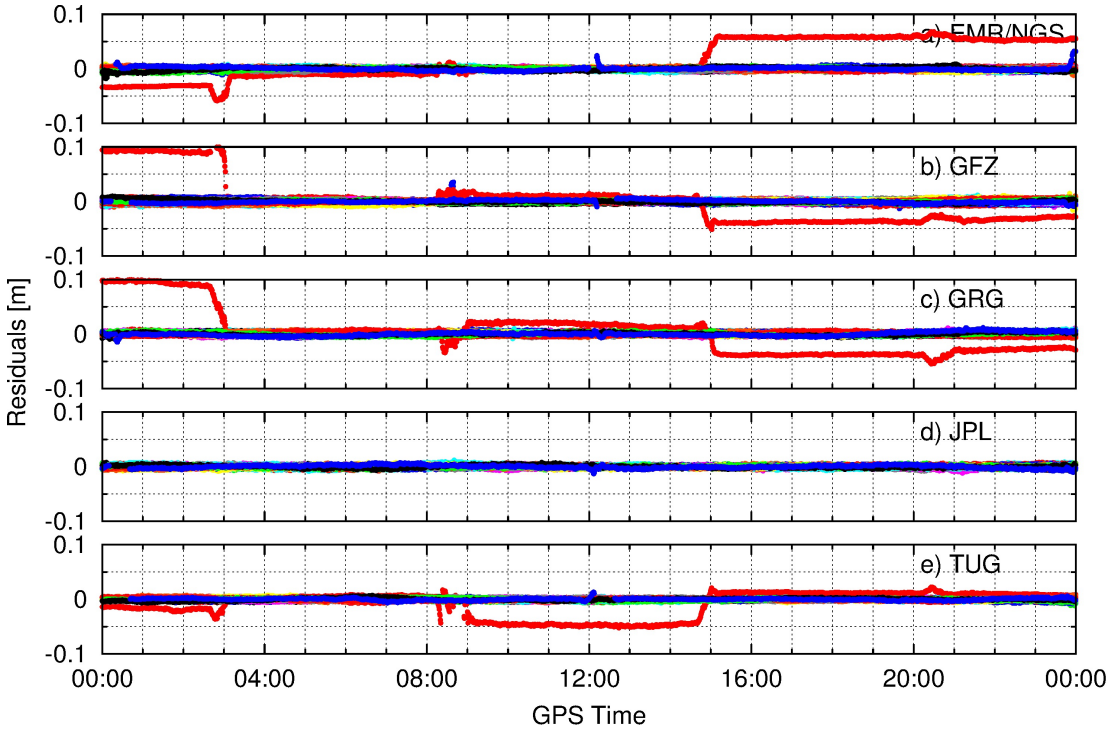
- Reference attitude provided by GROOPS
  - All attitude models have been implemented in TUG's open-source software GROOPS. The C++ source code, documentation, and an overview of model parameters are available on GitHub (https://github.com/groops-devs/groops). A dataset containing test output for all models is also available. See: Strasser et al. (2021) Comparison and generalization of GNSS satellite attitude models. EGU 2021



GROOPS

Satellite attitude

- Issues when combining satellite clocks of eclipsing satellites

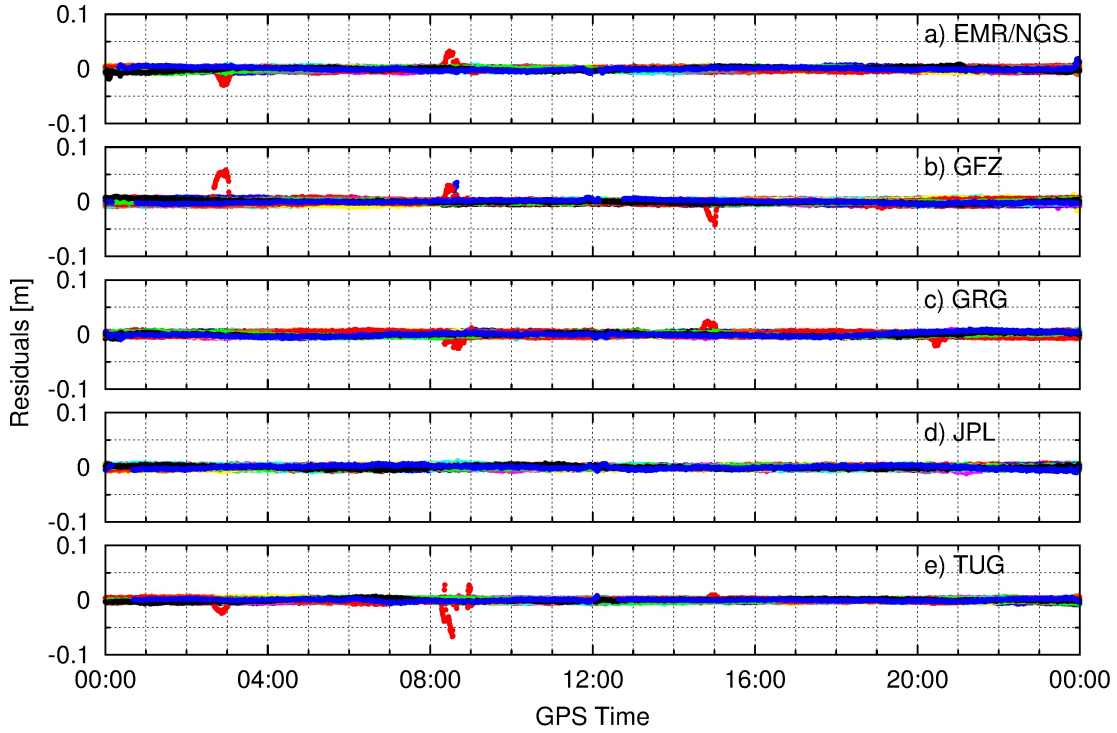


- Satellite G25 (in red) in a GPS IIF satellite observed at a beta angle ~0 degree
- IIF satellites are know to make unpredictable turns in this context
- Analysis centers model these turns differently which, due to the carrier wind-up effect, cause discrepancies in the satellite clock estimates

From: Loyer et al. (2021) Exchanging satellite attitude quaternions for improved GNSS data processing consistency. Advances in Space Research

Satellite attitude

- Issues when combining satellite clocks of eclipsing satellites



- Exchanging satellite attitude among analysis centers allows mitigating the inconsistencies previously observed
- Remaining effects are due to satellite phase center offsets propagating into clock estimates when the satellite is not oriented correctly

From: Loyer et al. (2021) Exchanging satellite attitude quaternions for improved GNSS data processing consistency. Advances in Space Research

Repro3 clock/attitude availability

AC product code	Constellations	Clock interval (sec)	Attitude interval (sec)
COD	GRE	30	900
EMR/NGS	G	30	30
ESA	GRE	30	None
GFZ	GRE	300	300
GRG	GRE	30	30
JPL	G	30	30
MIT	GE	300	None
TUG	GRE	30	30
WHU	GR	300	300

Repro3 phase-bias availability

AC product code	GPS			GLONASS		Galileo				
	L1	L2	L5	L1	L2	L1	L5	L6	L7	L8
COD	2000-124					2014-001				
EMR/NGS	2000-001									
ESA										
GFZ										
GRG	2000-124					2017-001				
JPL										
MIT										
TUG	1994-001		2010-240	2009-001		2013-001			2013-001	
WHU										

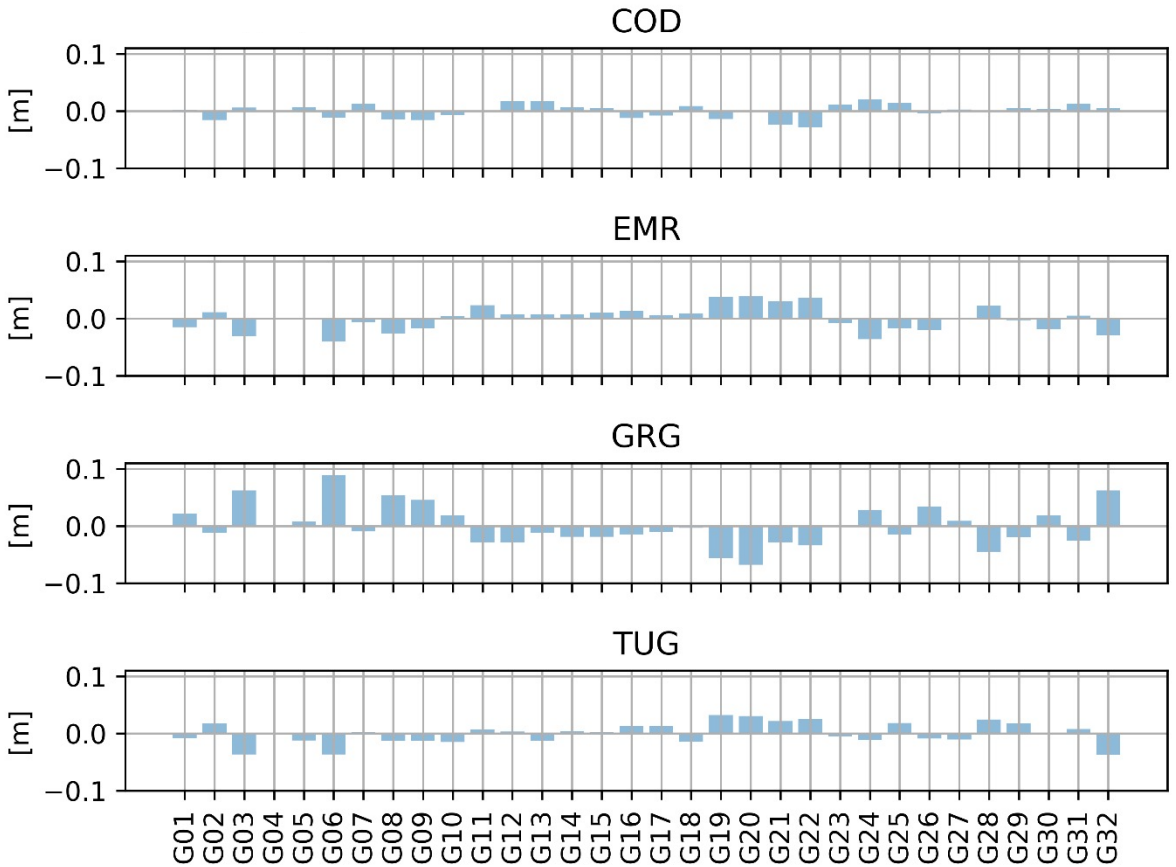
Date at which at least 3 analysis centers are contributing

Example: satellite clock/bias combination

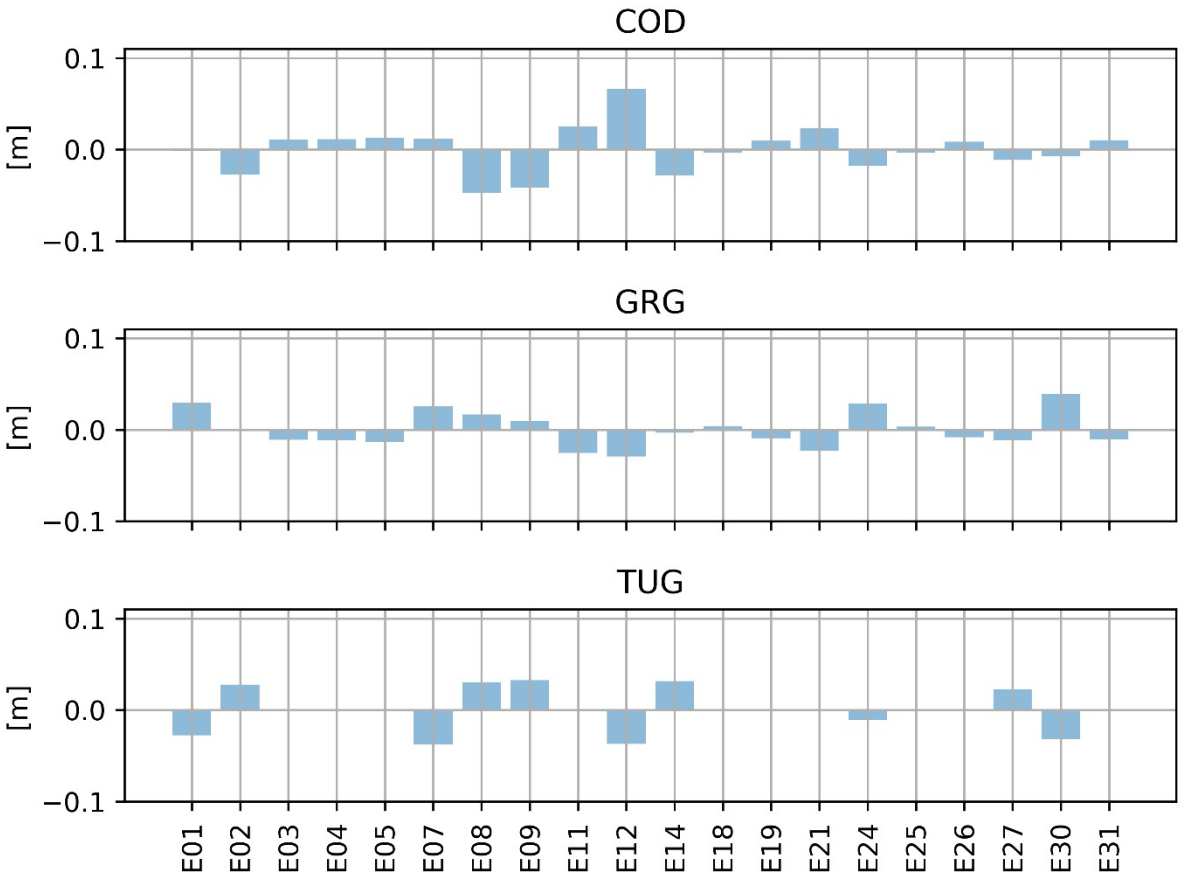
- GPS week 2010 (2018-196 to 2018-202)
- Constellations: GPS, GLONASS, Galileo
- Analysis centers: COD, EMR/NGS, ESA, GRG, JPL, TUG
- Combined orbits: solution IGS1
- Reference attitude: GROOPS
- PPP solutions from 100 globally distributed stations using the NRCan PPP software
- Reference station positions from SINEX combined solution

Example: widelane biases

GPS: L1/L2/C1W/C2W

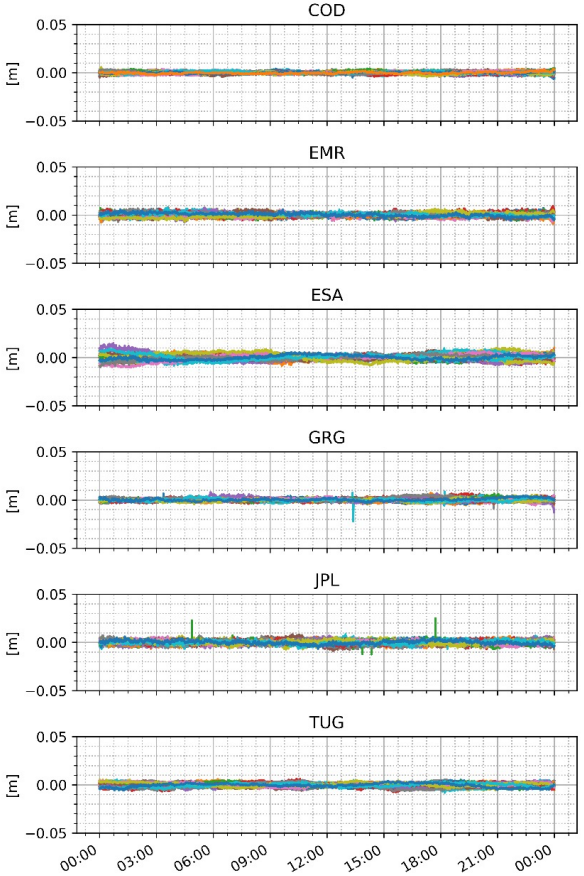


Galileo: L1/L5/C1C/C5Q

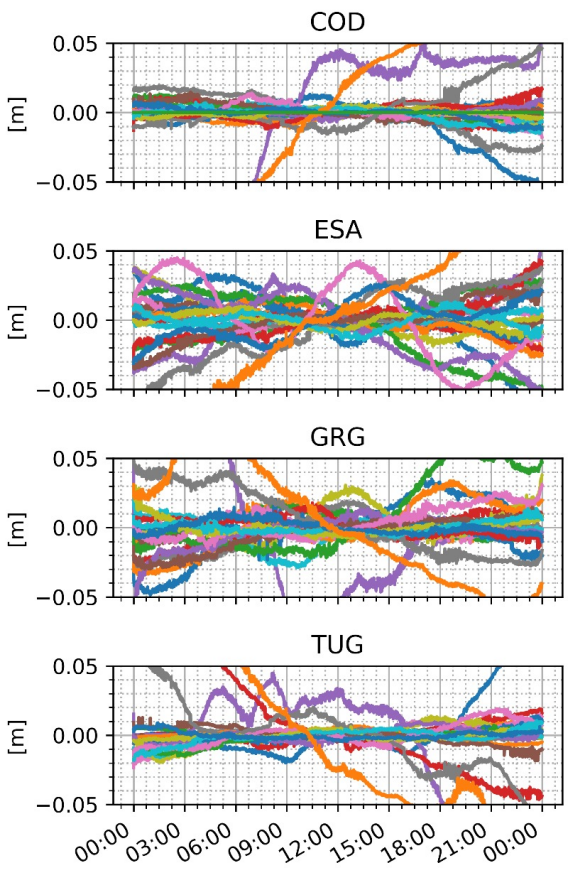


Example: clock combination residuals

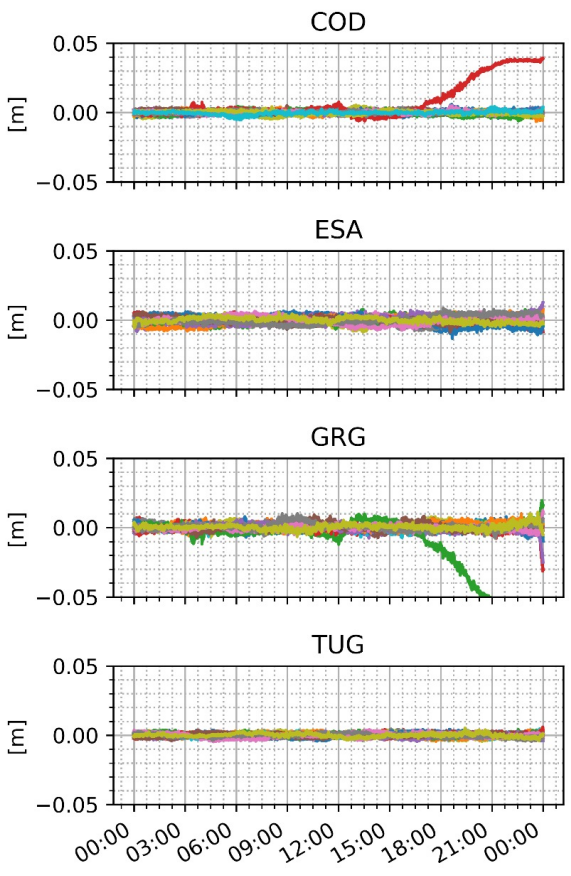
GPS



GLONASS

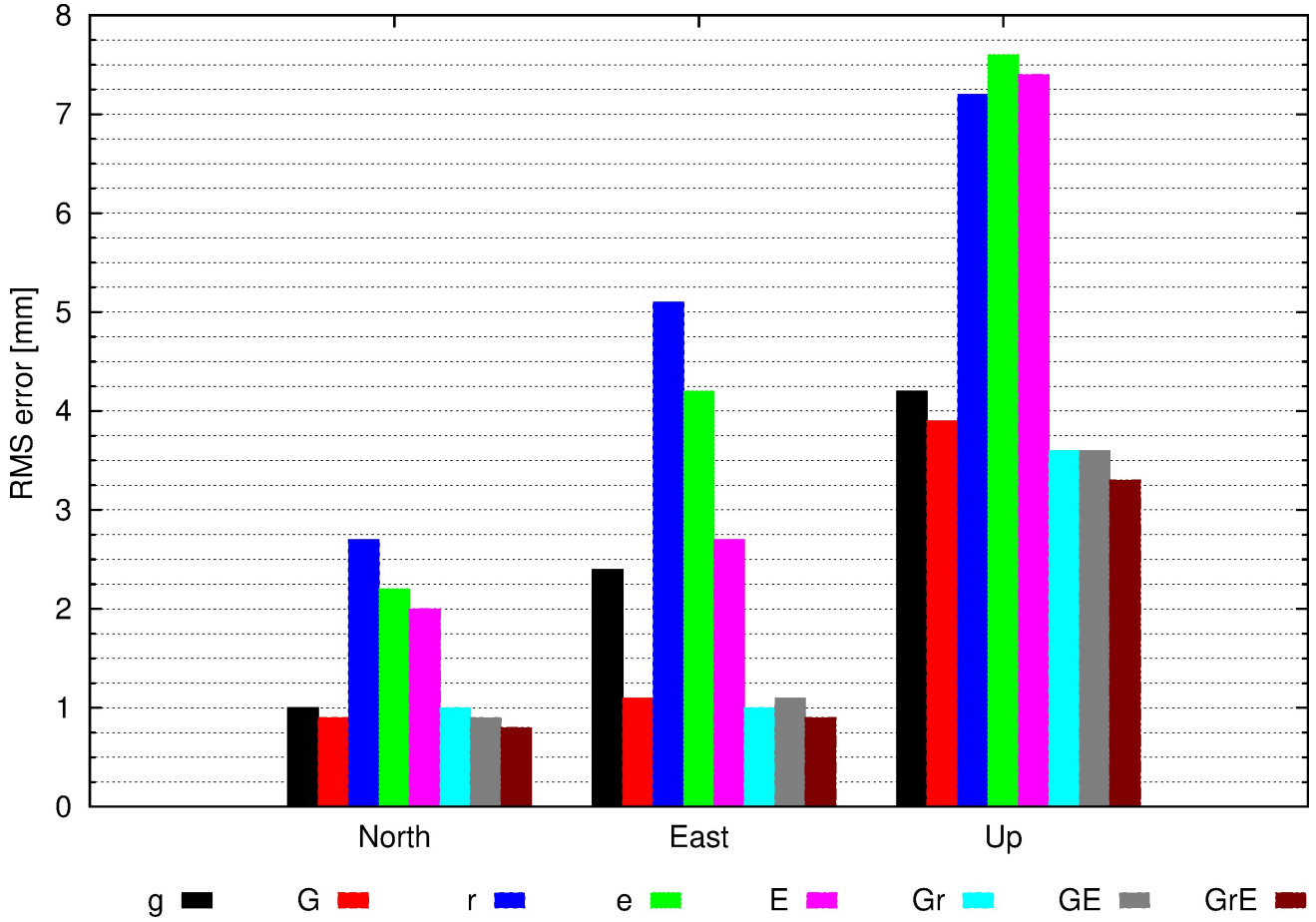


Galileo



- All analysis centers contribute to the clock combination, even if they don't provide phase biases
- The integer properties of the combined clock comes from analysis centers with phase biases

Example: PPP results, 24-h static



- Based on 700 PPP solutions (7 days / 100 stations)

- G: GPS
- R: GLONASS
- E: Galileo

- Lowercase: float ambiguities
- Uppercase: fixed ambiguities (PPP-AR)

- Not full Galileo constellation (~20 satellites)

- Lowest RMS error is the multi-GNSS solution with ambiguity resolution (!)

Summary

- Phase biases enabling PPP-AR could be generated:
  - GPS: starting 2000-124 (selective availability deactivated)
  - Galileo: starting 2017-001
- Proof of concept: integer clocks for GPS and Galileo allow for PPP-AR and improved accuracy
- More work needed to determine how to incorporate GLONASS satellite clocks into the combined products

Call for participation

- Anyone willing to contribute time/expertise/CPU to help the IGS PPP-AR WG can contact me
  - Investigate GLONASS clock combination strategies and measure their impact on PPP
  - Running GROOPS to generate reference attitude from 1994-2020
  - Running PPP-AR tests to verify the validity of the combined orbits/clocks
  - Etc.

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Thank You

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