# Processing of multi-GNSS constellations based on raw observations

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**EGU General Assembly 2019, Vienna, Austria**

2019-04-09

# Raw observation approach

# Raw observation approach

Key concept

- Use all available observations…
- … as they are observed by the receiver…
- … in a common least squares adjustment.

Undifferenced and uncombined multi-GNSS processing

More details:

- Strasser et al. (2018). *Processing of GNSS constellations and ground station networks using the raw observation approach*. Journal of Geodesy.

DOI: 10.1007/s00190-018-1223-2


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# System of normal equations

Exemplary single day processing (GPS + Galileo)

- 47 satellites
- 160 stations
- All available code and phase observables
- 30-second sampling

**GPS**

| Freq. | Code | Phase |
|---|---|---|
| L1 | C1C | L1C |
| L1 | C1W | L1W |
| L2 | C2W | L2W |
| L2 | C2X | L2X |
| L2 | C2S | L2S |
| L2 | C2L | L2L |
| L5 | C5X | L5X |
| L5 | C5Q | L5Q |

**Galileo**

| Freq. | Code | Phase |
|---|---|---|
| E1 | C1C | L1C |
| E1 | C1X | L1X |
| E5a | C5X | L5X |
| E5a | C5Q | L5Q |
| E5b | C7X | L7X |
| E5b | C7Q | L7Q |
| E5 | C8X | L8X |
| E5 | C8Q | L8Q |

# System of normal equations

Exemplary single day processing (GPS + Galileo)

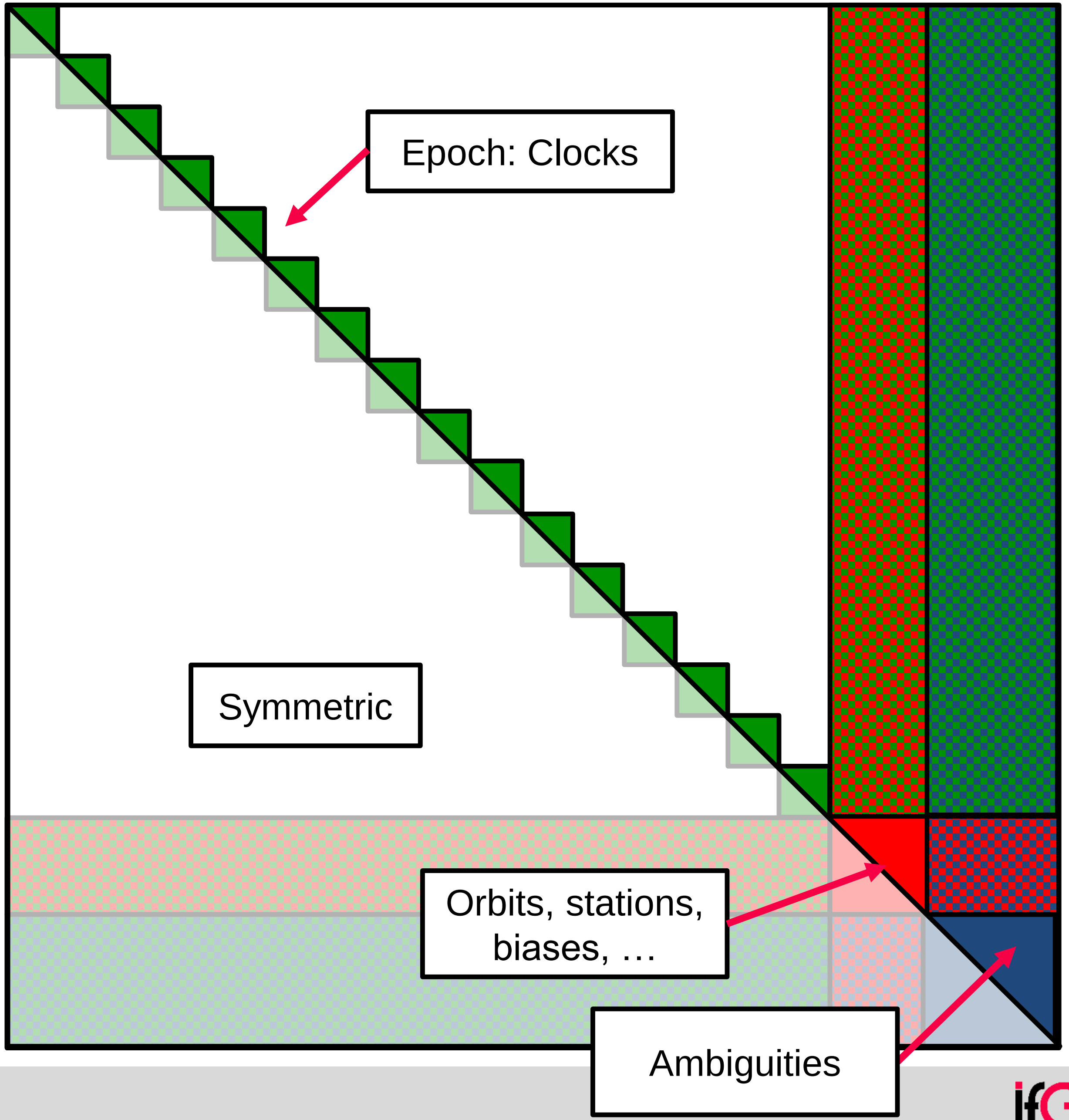
- Observation equations: 42 million

- Parameters
  - STEC (Ionosphere) (pre-eliminated)
  - Clocks 630 000
  - Orbits, stations, biases, … 6 600
  - Ambiguities 42 000

⇒ Sparse normal equations: 28 GB

- Computation time (Intel Xeon 32 cores @ 2.1 GHz)
  - Obs. eq. and accumulate normals 5:30 min
  - Solve 9:05 min
  - Compute residuals and STEC 0:35 min
  - Total 15:10 min

Without preprocessing, ambiguity resolution (AR), …





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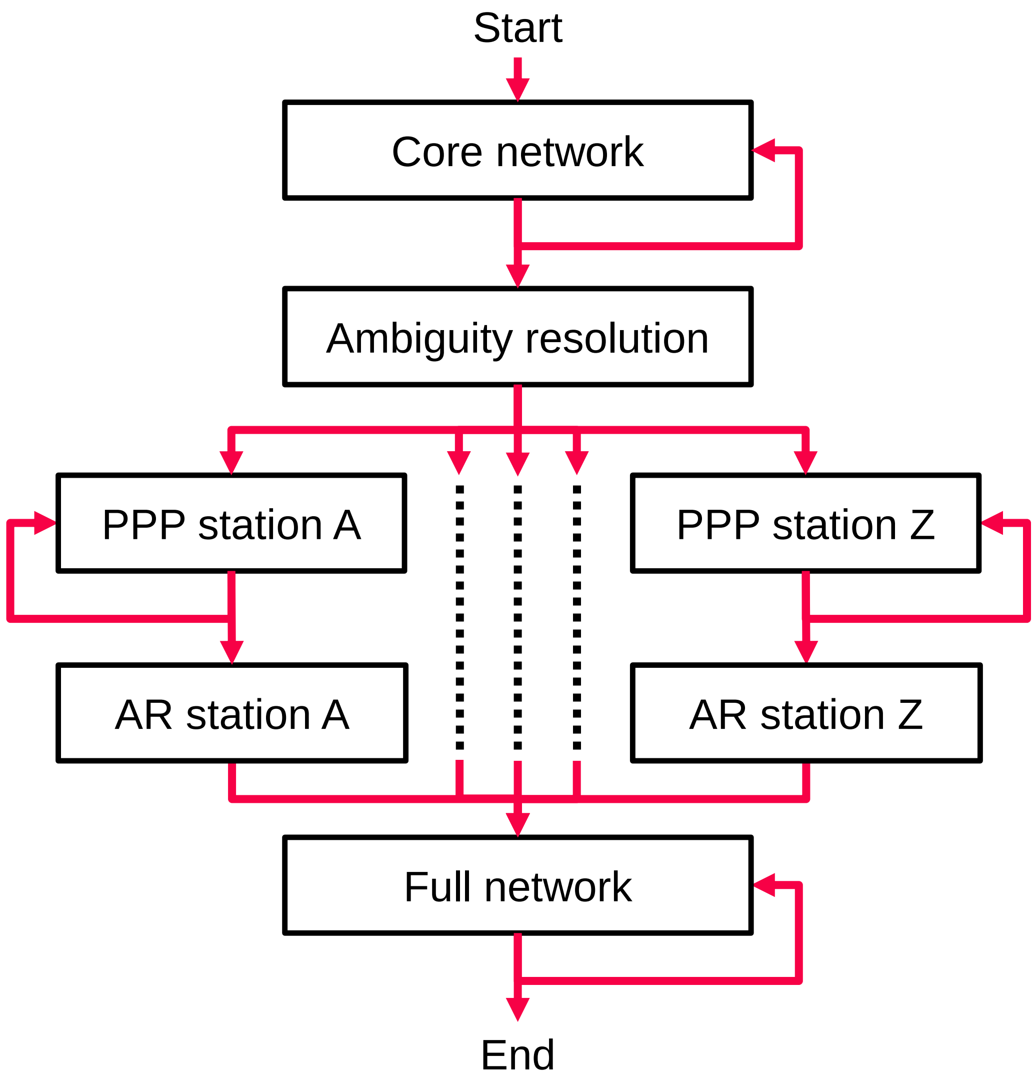
# System of normal equations

- To speed up computation and reduce memory consumption
  1) Solve system with a core station network (~60 stations) and resolve integer ambiguities
  2) Resolve integer ambiguities individually per station for all other stations with fixed constellation parameters
  3) Solve system with fixed integer ambiguities using full station network

- Computation time (Intel Xeon 32 cores @ 2.1 GHz)
  - [Full network iteration (w/ ambiguities) 15:10 min]
  - Core network iteration (w/ ambiguities) 2:25 min
  - Full network iteration (w/o ambiguities) 4:15 min

- Fast computation enables iterative solving
  - Downweighting of outliers
  - Relative weighting of observation groups via variance component estimation (VCE)





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# Multi-frequency and multi-GNSS processing


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# Multi-frequency and multi-GNSS processing

Signal biases in the raw observation approach

- Easy setup of signal bias for each signal type (code and phase)
- Composed signals: Bias as linear combination (e.g. GPS: C2D = C1C + C2W - C1W)
- No need for additional inter-frequency and inter-system parameters

⇒ Clear and straightforward definition

Additional constraints needed to remove rank deficiencies

- Clock errors and signal biases cannot be determined in absolute sense
- Definition of transmitter/receiver clocks? (e.g. GPS convention: ionosphere-free combination of C1W and C2W)

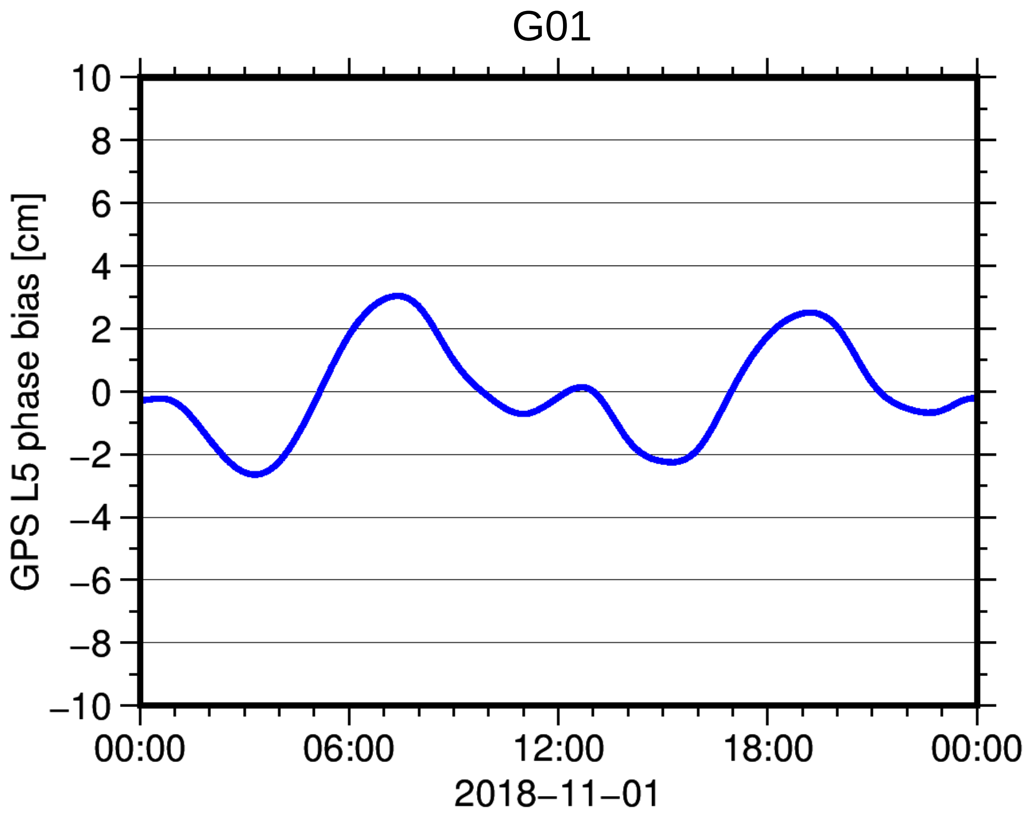
⇒ Definition of constraints not straightforward (work in progress)

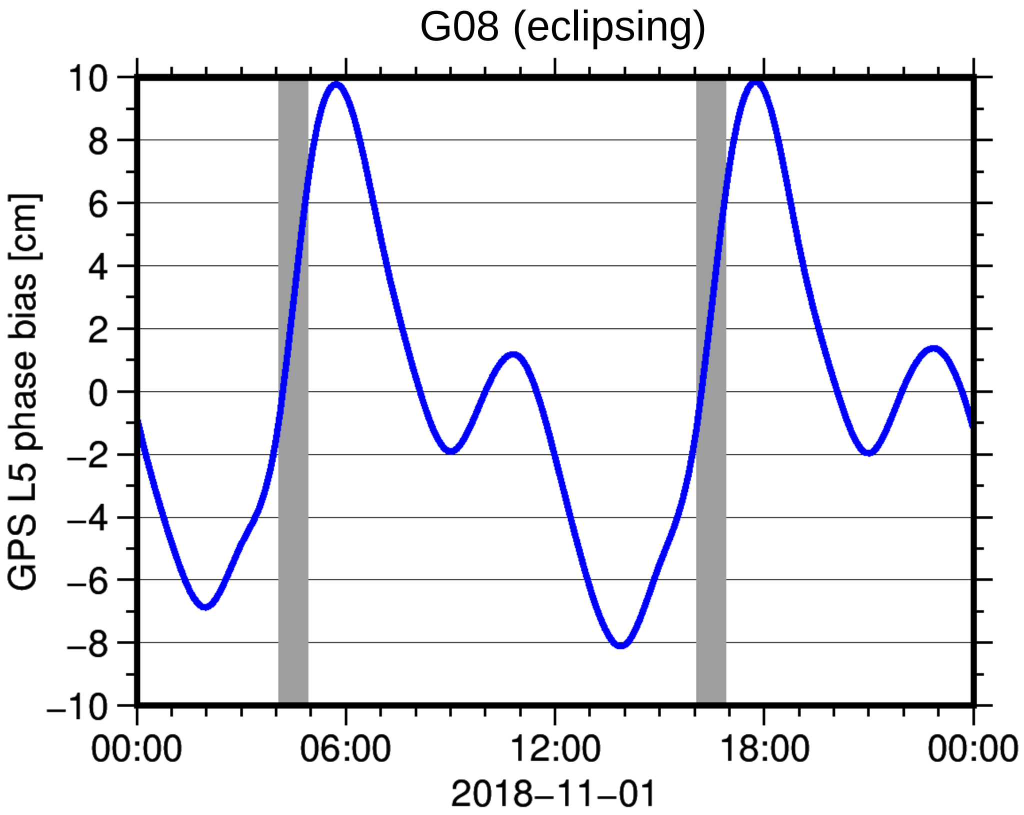
⇒ Flexible choices are possible via zero-mean constraints

Additional problem: time-variable biases (e.g. GPS L5)

# Time-variable biases – GPS L5 satellite phase bias

- GPS L5 phase biases on block IIF satellites are time variable (most likely due to temperature changes)
- Co-estimated as cubic splines with hourly nodes
- Resulting biases clearly show behavior described by Montenbruck et al. (2012)





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# First results of combined GPS + GLONASS + Galileo processing


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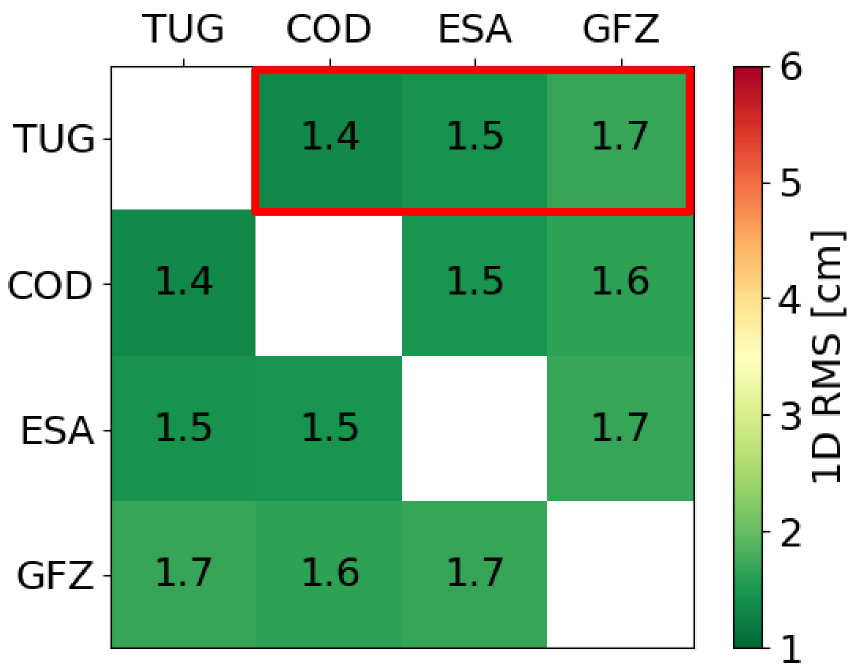
# Comparison to other multi-GNSS products – GPS

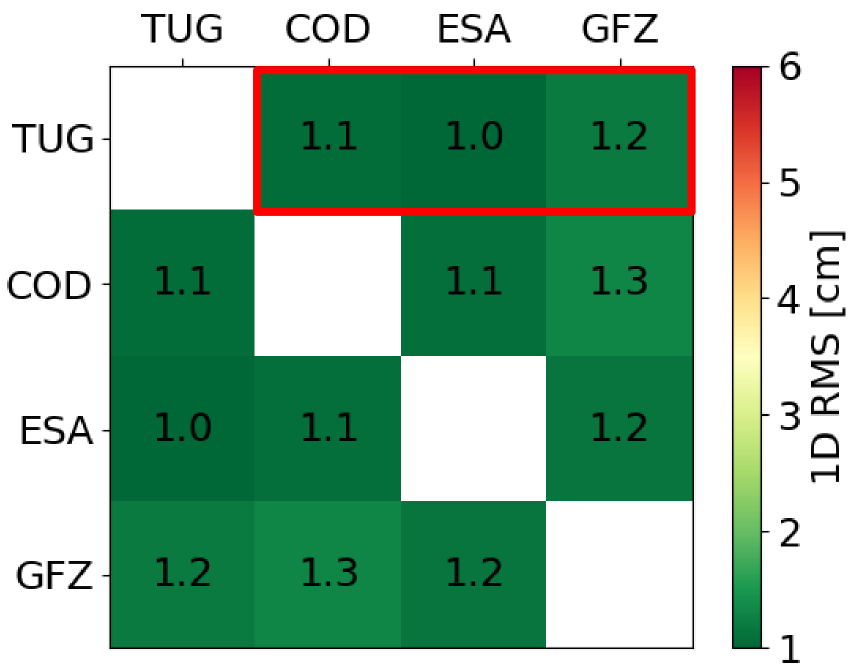
- Orbit and clock difference RMS for November 2018

GPS orbits




Reference frame differences corrected (Helmert)

GPS clocks




Clocks corrected for radial orbit difference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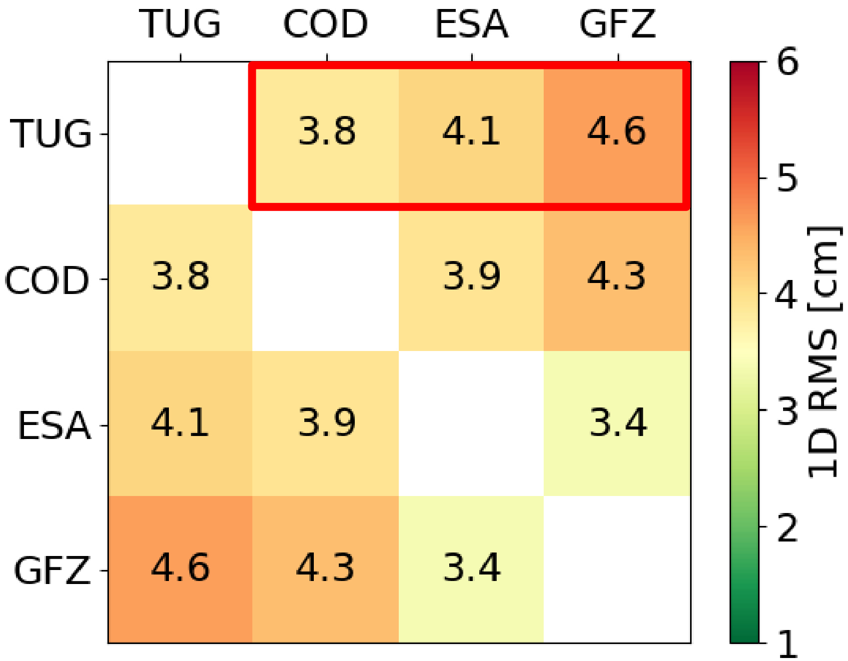
# Comparison to other multi-GNSS products – GLONASS

- Orbit and clock difference RMS for November 2018

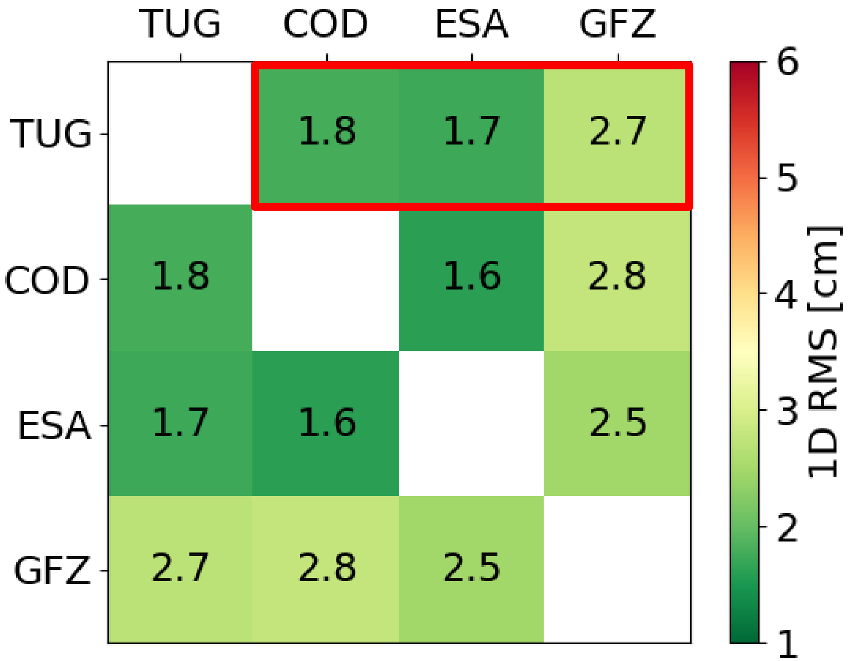
TUG is currently a float solution for GLONASS

GLONASS orbits




Reference frame differences corrected (Helmert)

GLONASS clocks

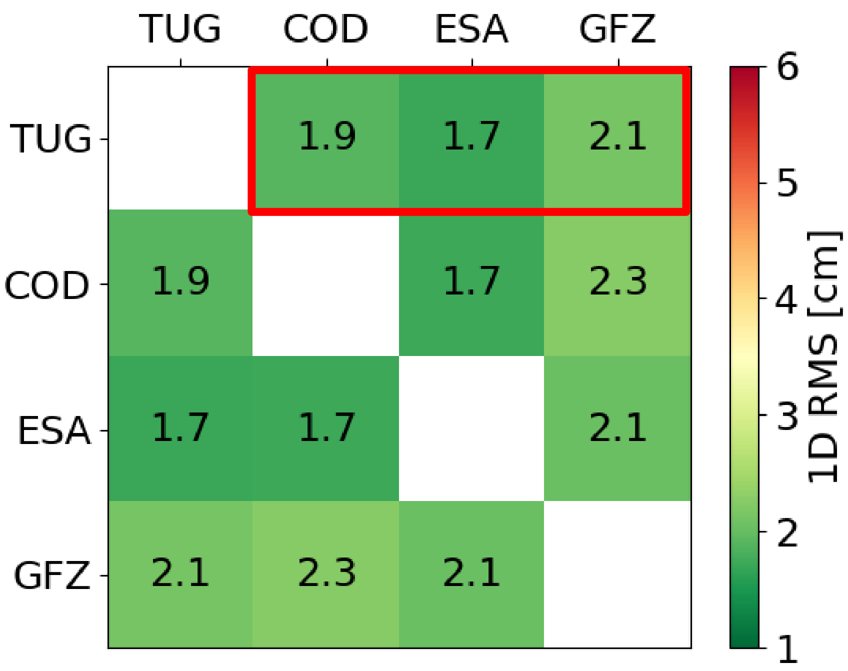



Clocks corrected for radial orbit difference

# Comparison to other multi-GNSS products – Galileo

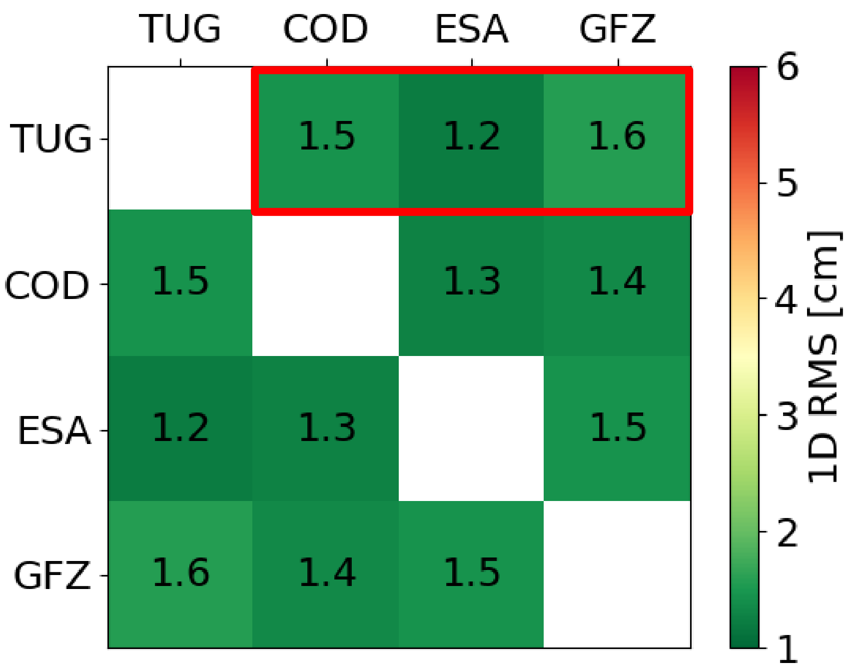
- Orbit and clock difference RMS for November 2018

Galileo orbits




Reference frame differences corrected (Helmert)

Galileo clocks




Clocks corrected for radial orbit difference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# Kinematic PPP comparisons using various signals


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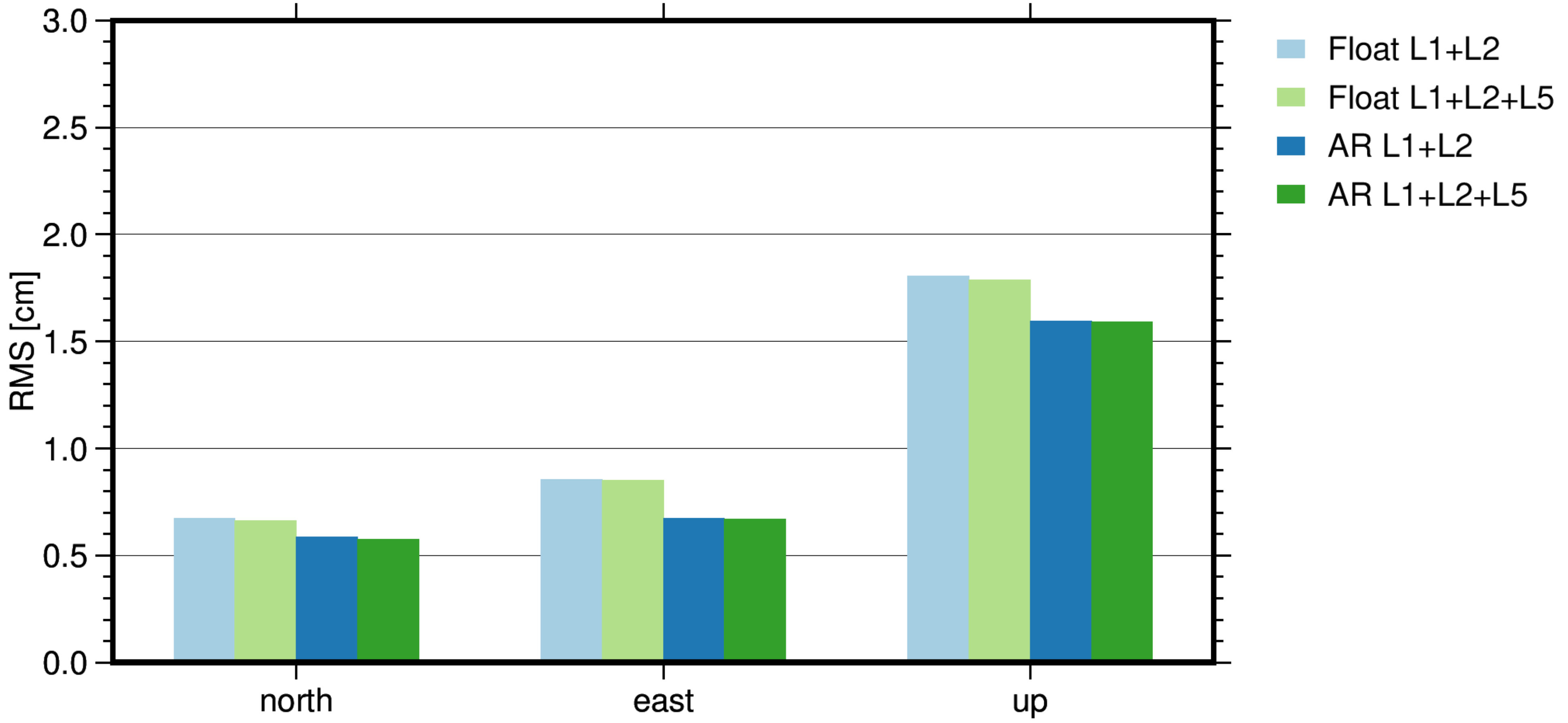
# PPP kinematic station position RMS – GPS only (31 satellites)

- RMS over ~210 IGS stations for November 2018





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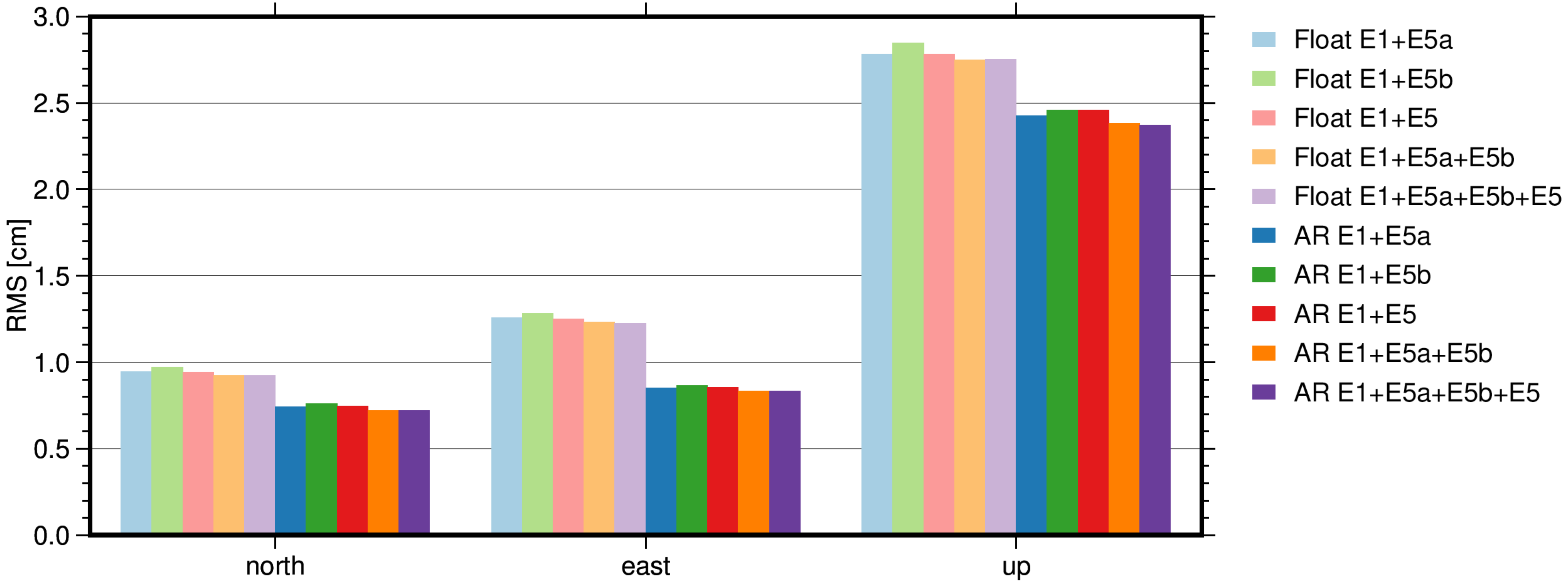
# PPP kinematic station position RMS – Galileo only (20 satellites)

- RMS over ~100 IGS stations for November 2018





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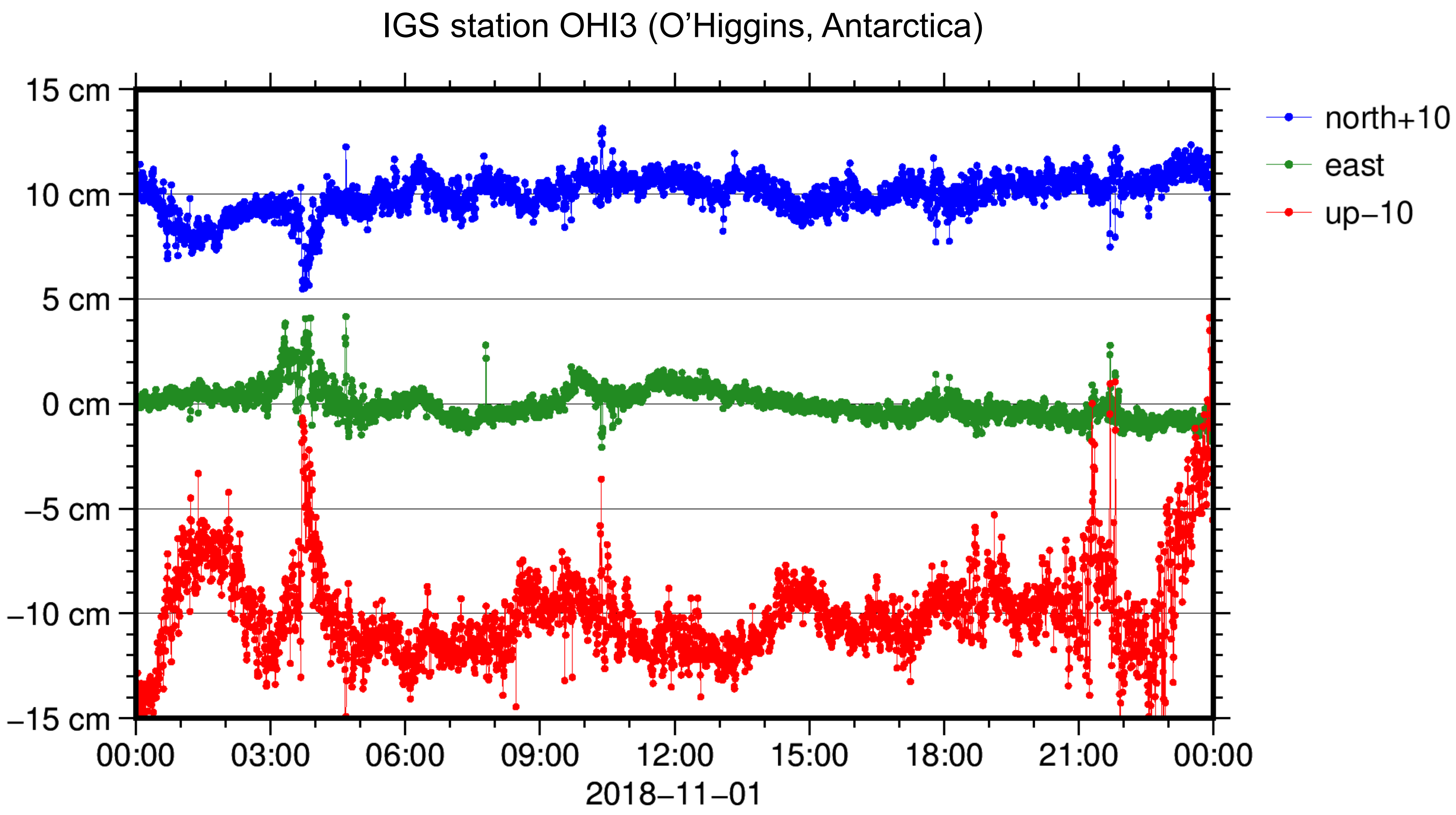
# PPP-AR kinematic station position – Galileo E1+E5a



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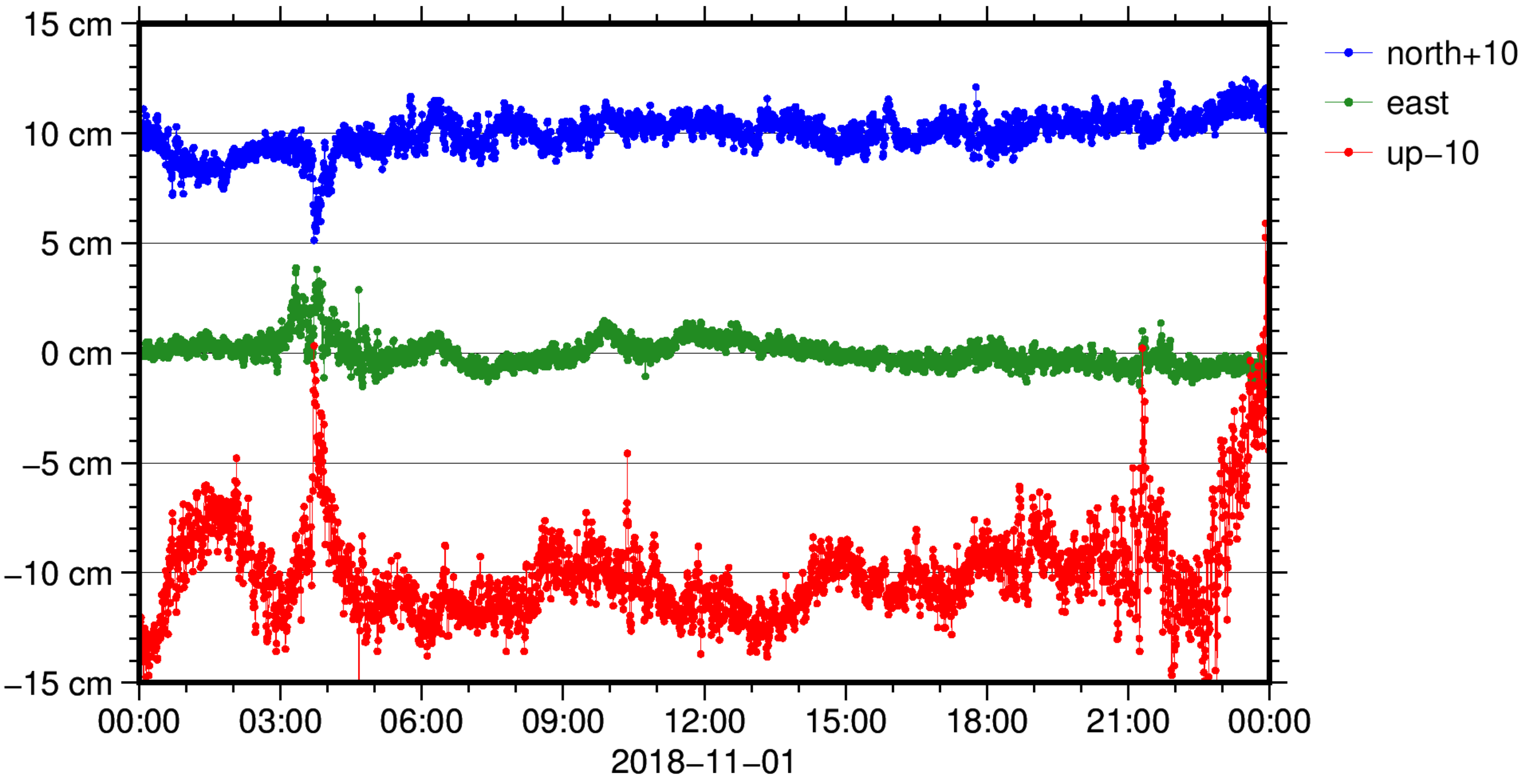
# PPP-AR kinematic station position – Galileo E1+E5a+E5b+E5

IGS station OHI3 (O'Higgins, Antarctica)





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# Summary and Outlook

Raw observation approach

- Well suited for multi-GNSS processing due to straightforward parametrization
- Access to all parameters enables…
  - Flexible definition of clocks and biases
  - Modeling of clocks, biases, …
- Resulting products are competitive

There is still a lot of work to do…

- BeiDou support (attitude, maneuvers, …)
- Regional systems (QZSS, NAVIC)
- Antenna center offsets/variations for new signal types

# Thank you!

Questions?