Multi-frequency and multi-GNSS processing with the raw observation approach

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The raw observation approach

Raw observation approach

Key concept

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

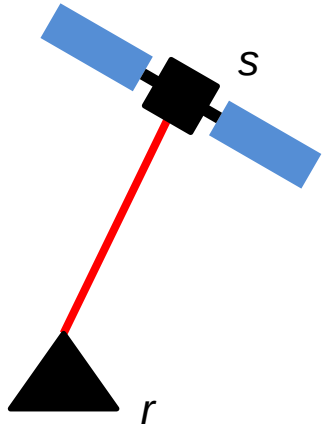
Geometrical distance | System time offset | Ionosphere | Phase biases | Ambiguity

Phase: $$\varphi_{r,sig}^{s,sys} - \Delta\varphi_{r,sig}^{s} = \rho_r^s + c(\delta_r - \delta^s + \tau^{sys}) + I_{r,sig}^s + T_r^s + \lambda_{sig}\left(b_{r,sig}^{sys} + b_{sig}^s + N_{sig}\right) + \varepsilon_{r,sig}^s$$

Range (Code): $$R_{r,sig}^{s,sys} - \Delta R_{r,sig}^{s} = \rho_r^s + c(\delta_r - \delta^s + \tau^{sys}) + I_{r,sig}^s + T_r^s + B_{r,sig}^{sys} + B_{sig}^s + \varepsilon_{r,sig}^s$$

Observation | Clock errors | Troposphere | Code biases

Known corrections
- Antenna center offsets/variations
- Phase wind-up
- Relativistic time correction
- …



System of normal equations

Exemplary single day processing (GPS + Galileo)

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

GPS		Galileo	
Code	Phase	Code	Phase
C1C	L1C	C1C	L1C
C1W	L1W	C1X	L1X
C2W	L2W	C5X	L5X
C2X	L2X	C5Q	L5Q
C2S	L2S	C7X	L7X
C2L	L2L	C7Q	L7Q
C5X	L5X	C8X	L8X
C5Q	L5Q	C8Q	L8Q

System of normal equations

Exemplary single day processing (GPS + Galileo)

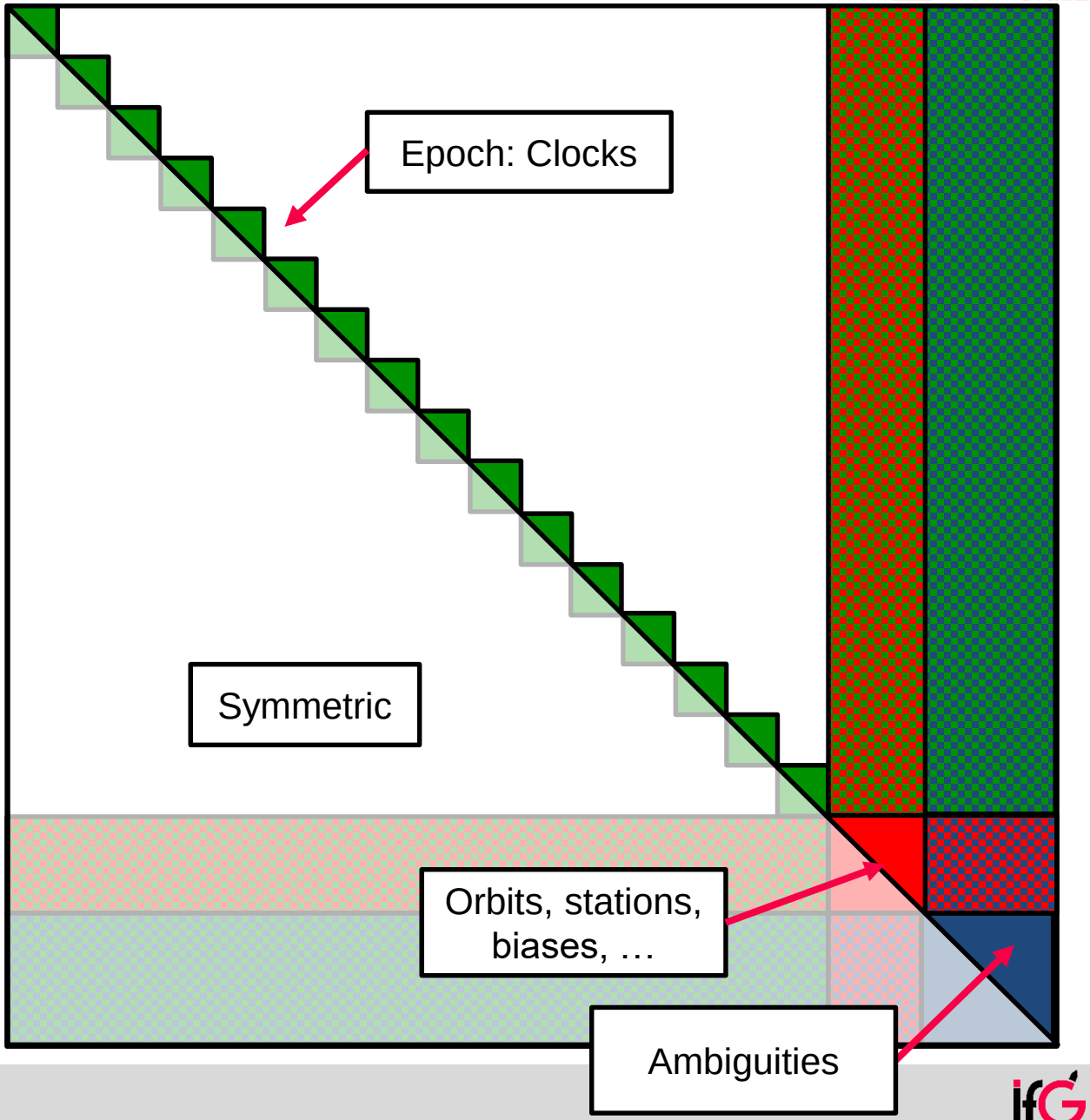
- Observation equations: 42 million

- 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, …

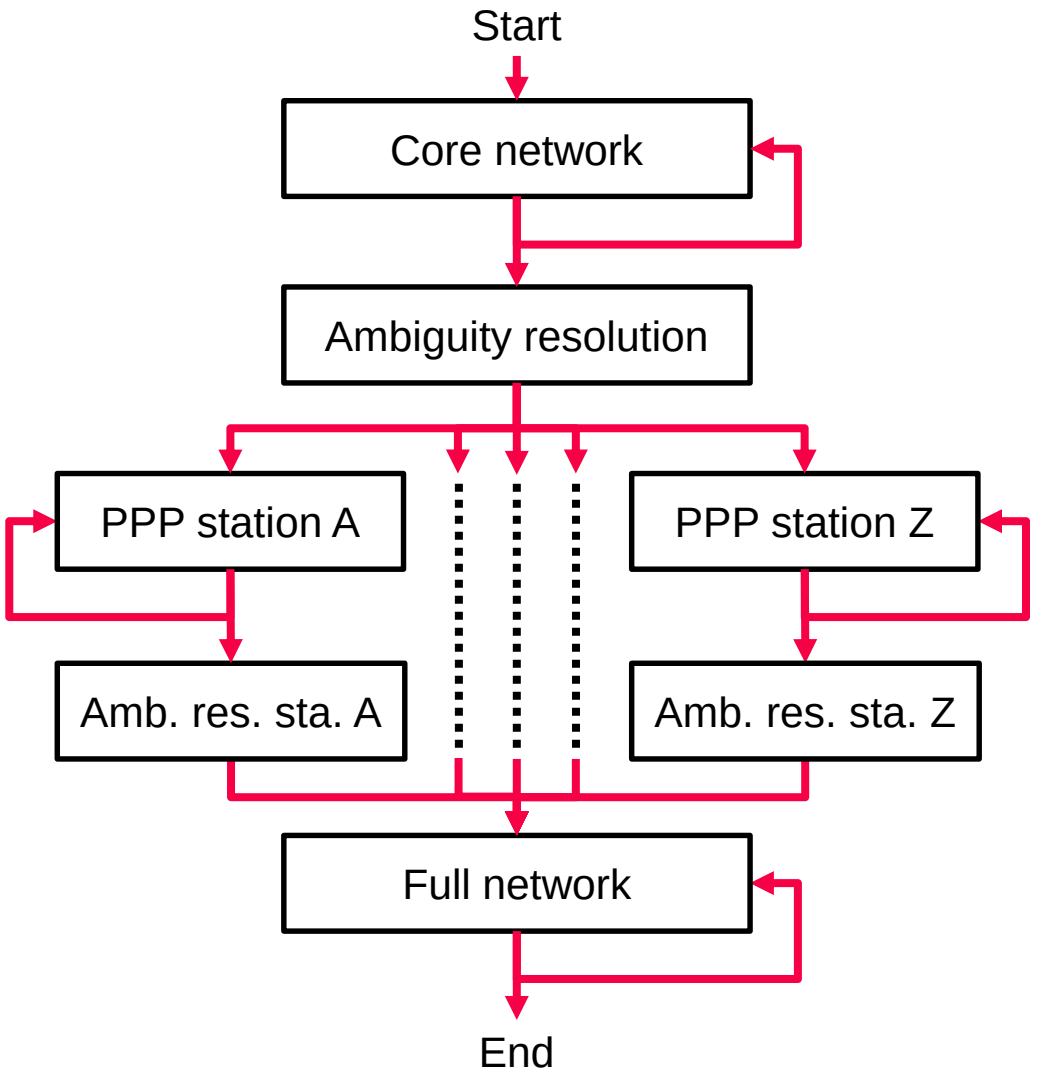


System of normal equations

- 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

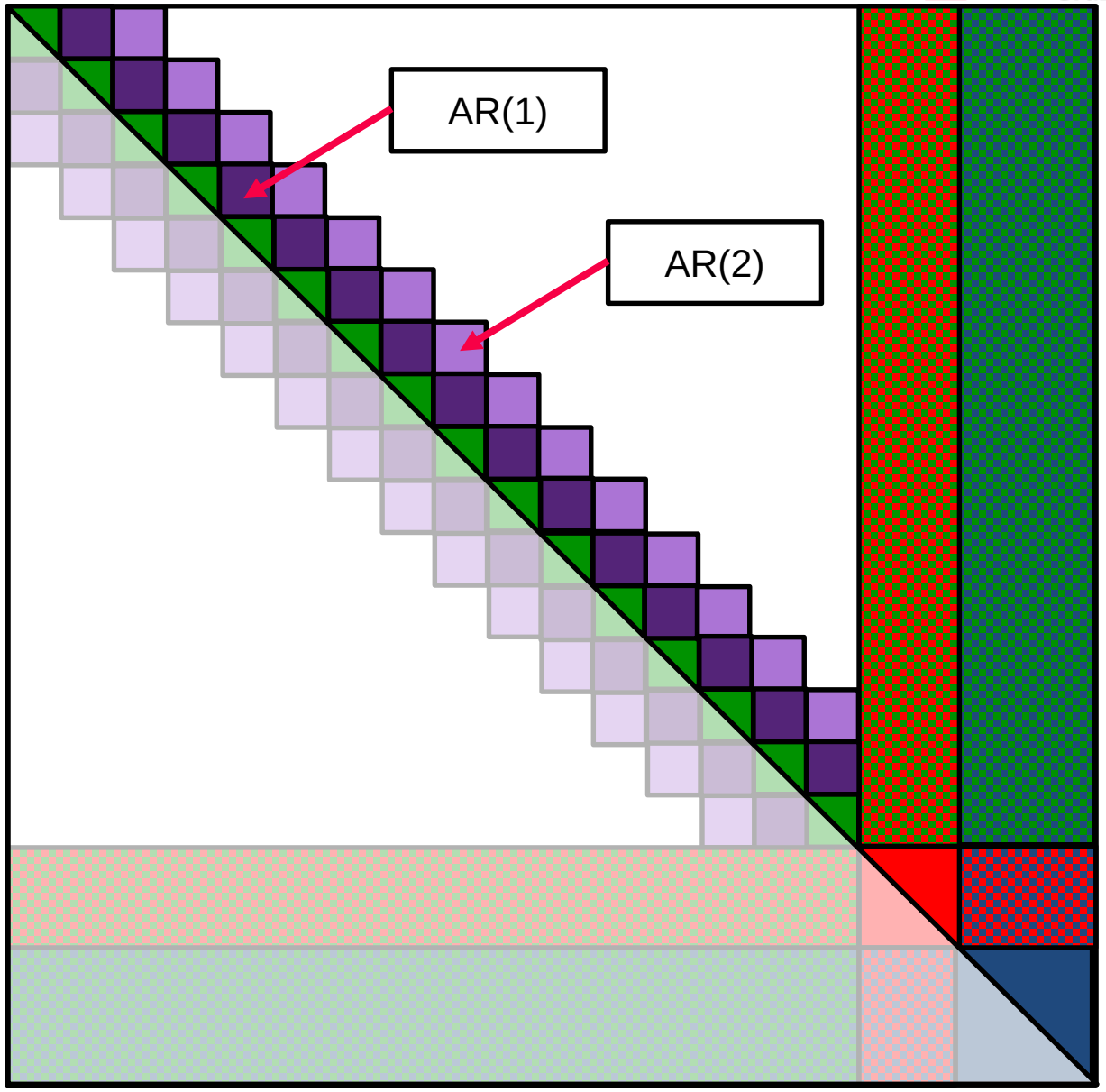
- Computation time (Intel Xeon 32 cores @ 2.1 GHz)
  - [Full network iteration (w/ ambiguities) 15:10 min]
  - Core network iteration (w/ ambiguities) 2:25 min
  - Full network iteration (w/o ambiguities) 4:15 min

- Fast computation enables iterative solving
  - Downweighting of outliers
  - Relative weighting of observation groups via Variance Component Estimation (VCE)



System of normal equations

- Stochastic modeling can be easily incorporated as autoregressive (AR) process
  - AR(1)
  - AR(2)
  - …
- Possible AR parametrization
  - Clocks
  - Time-variable signal biases (e.g. GPS L5)
  - …



Results of GPS-only reprocessing

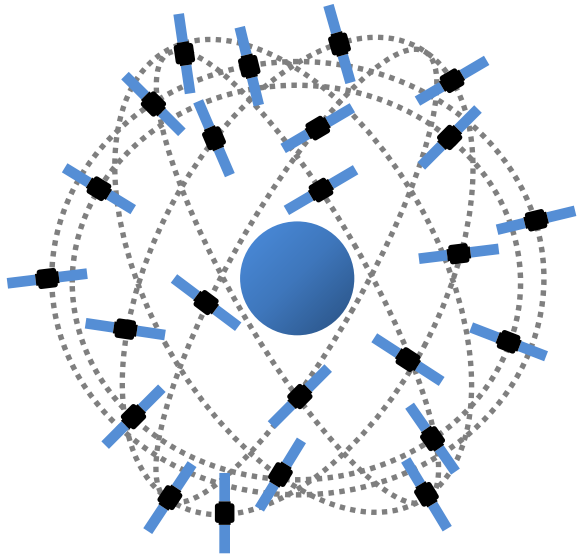
GPS-only reprocessing

Processing overview

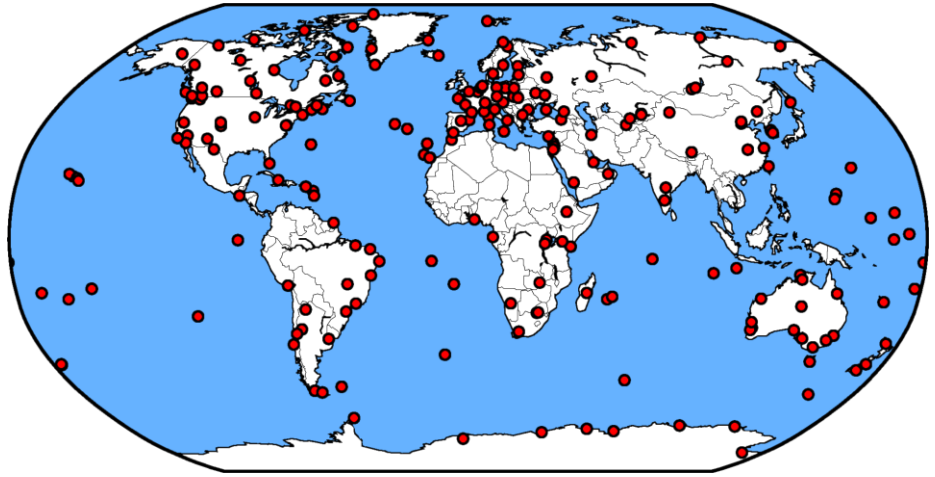
- 15 years (2003-2017)
- GPS constellation
- IGS14 station network
- IGS14 antenna calibrations
- State-of-the-art background models

Resulting products

- Satellite orbits
- Station positions
- Clocks
- Signal biases
- Earth orientation parameters



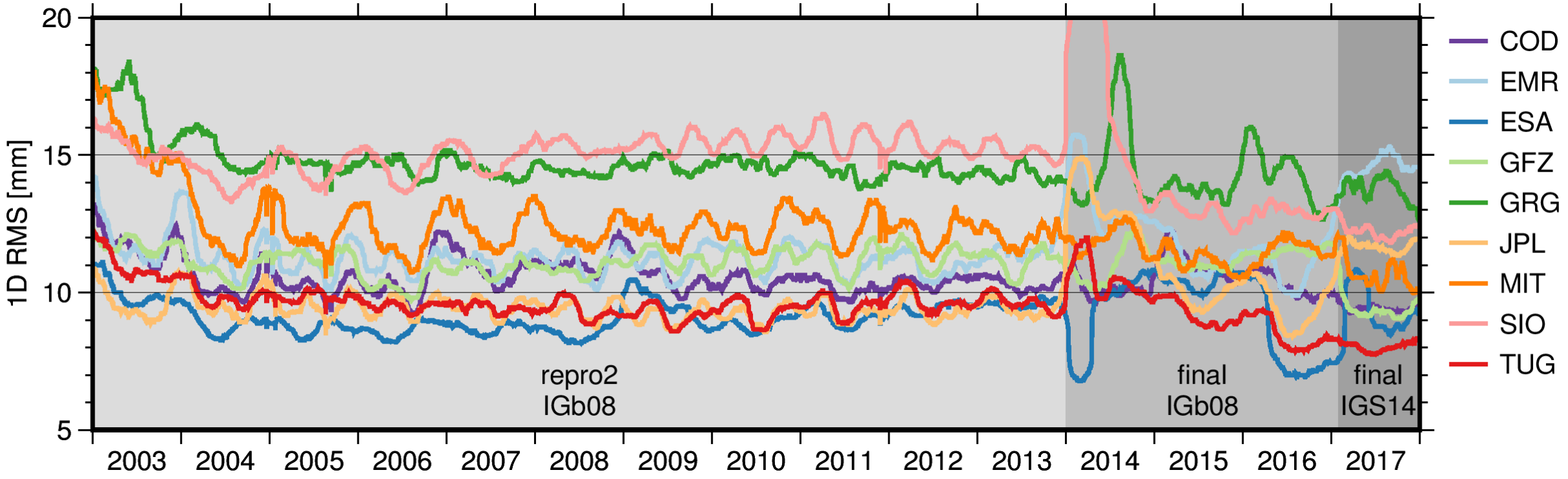
GPS constellation



IGS14 station network

Evaluation by comparison to products of the IGS analysis centers.

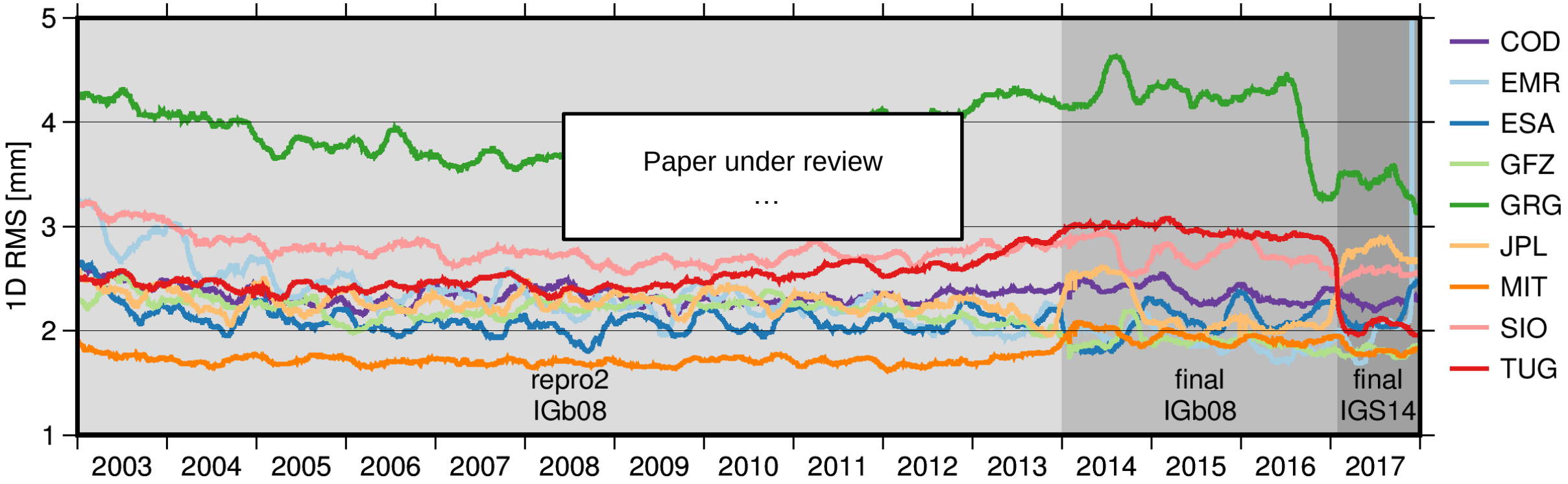
Daily GPS orbit RMS relative to IGS combination



Orbits synchronized between all institutions
(reference frame differences corrected, outage periods removed)

91-day median-filtered for clarity

Daily station position RMS relative to IGS combination



All IGS14 stations processed by individual institution used
(reference frame differences corrected, outlier removal based on robust 3σ-level)

91-day median-filtered for clarity

Multi-frequency and multi-GNSS processing

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

$\Rightarrow$ 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)

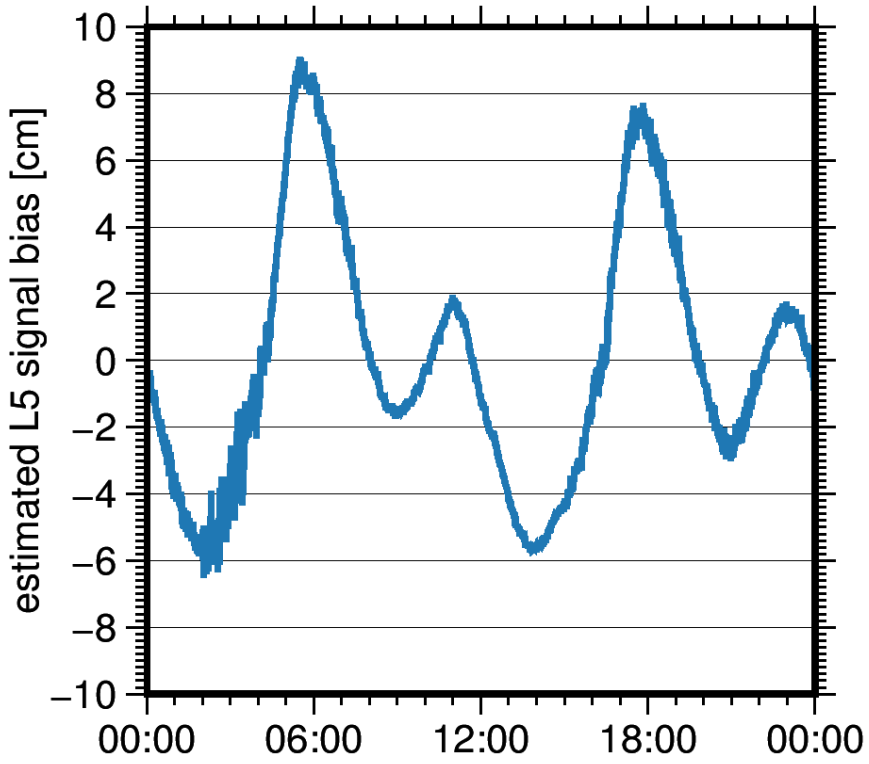
$\Rightarrow$ Definition of constraints not straightforward (work in progress)

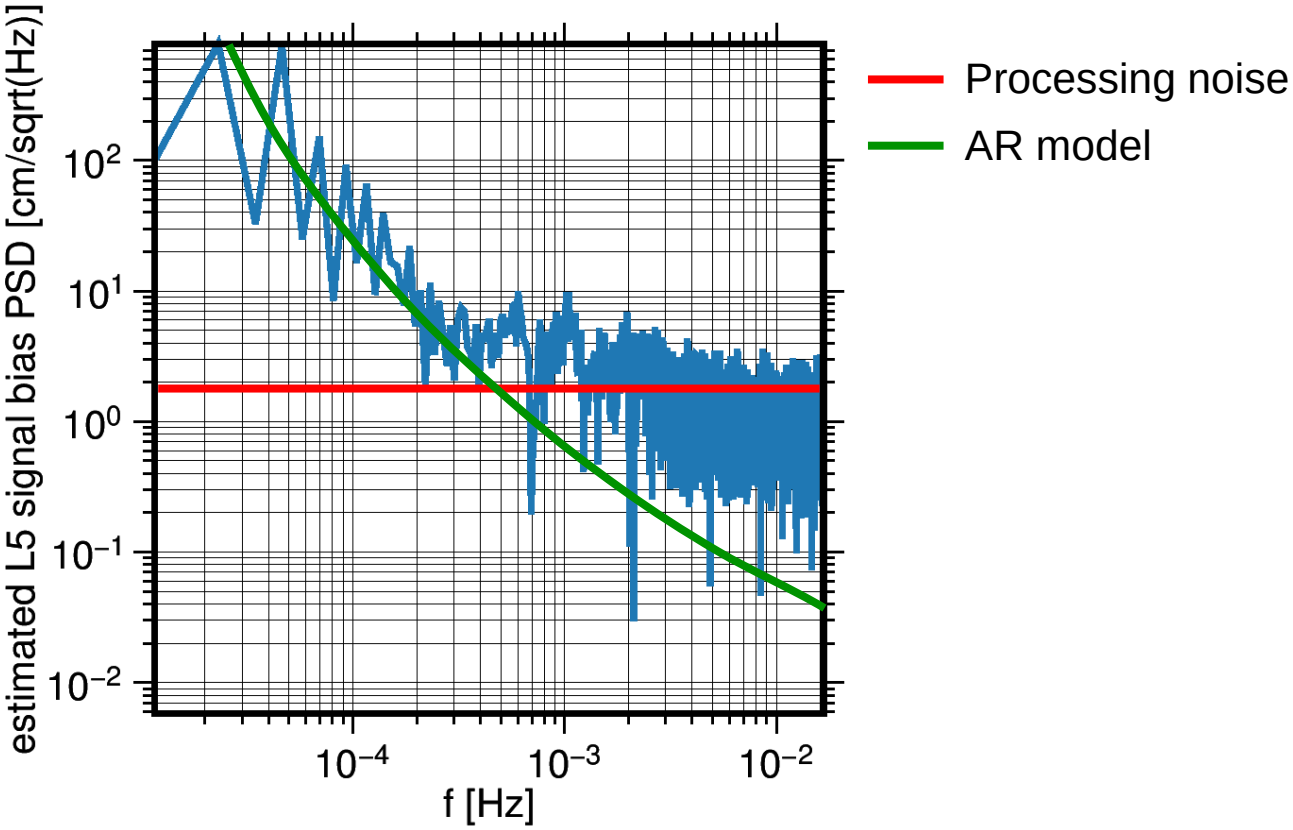
$\Rightarrow$ Flexible choices are possible via no-net shifts

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

Time-variable biases

- To analyze the behavior: unconstrained epoch-wise parametrization
- Determine AR(p) model in the spectral domain
- Determine daily weights via VCE during routine adjustment





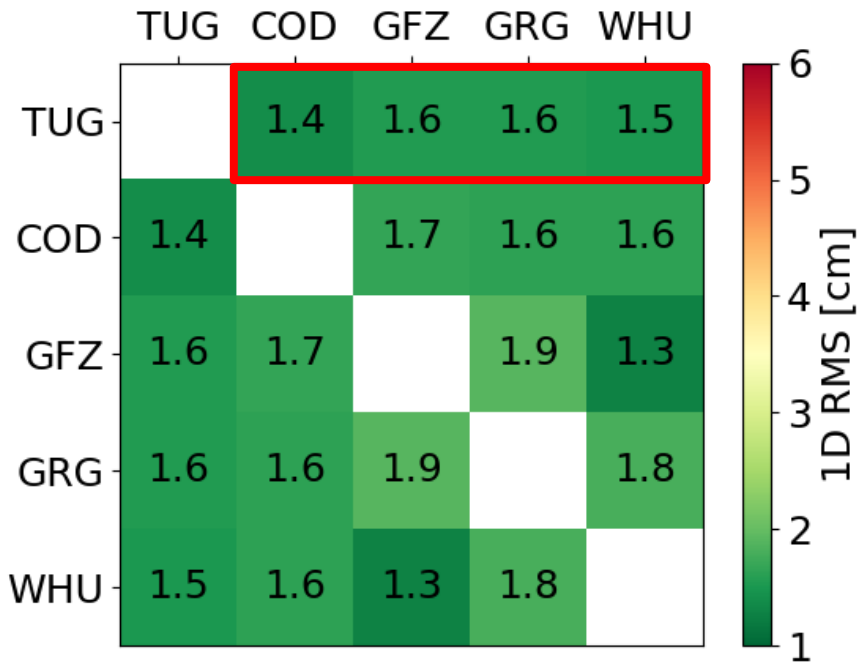
- Same approach can be used to model clock errors of stable clocks

First results of combined GPS + Galileo processing

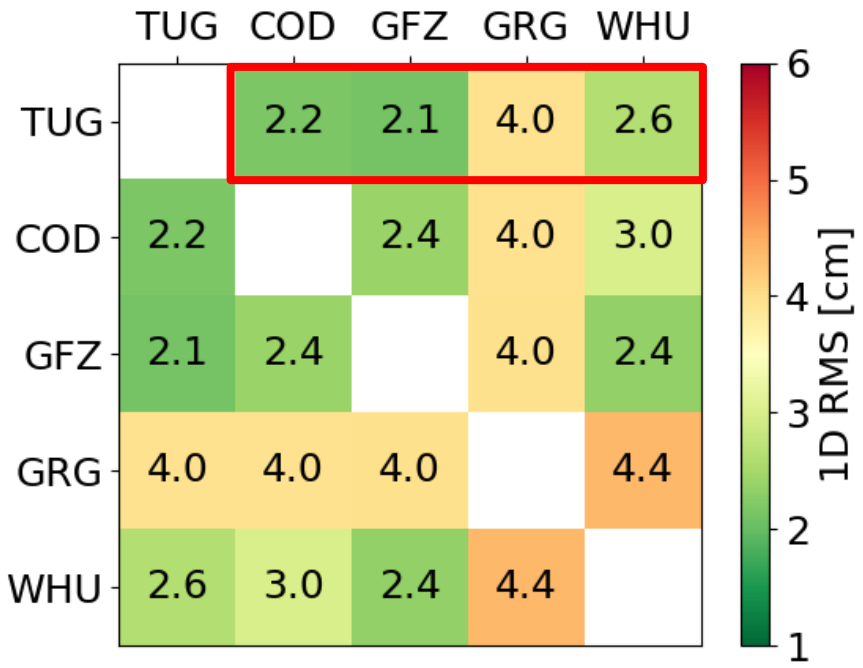
Comparison to MGEX products – Satellite orbits

Orbit difference RMS for January 2018

GPS orbits



Galileo orbits

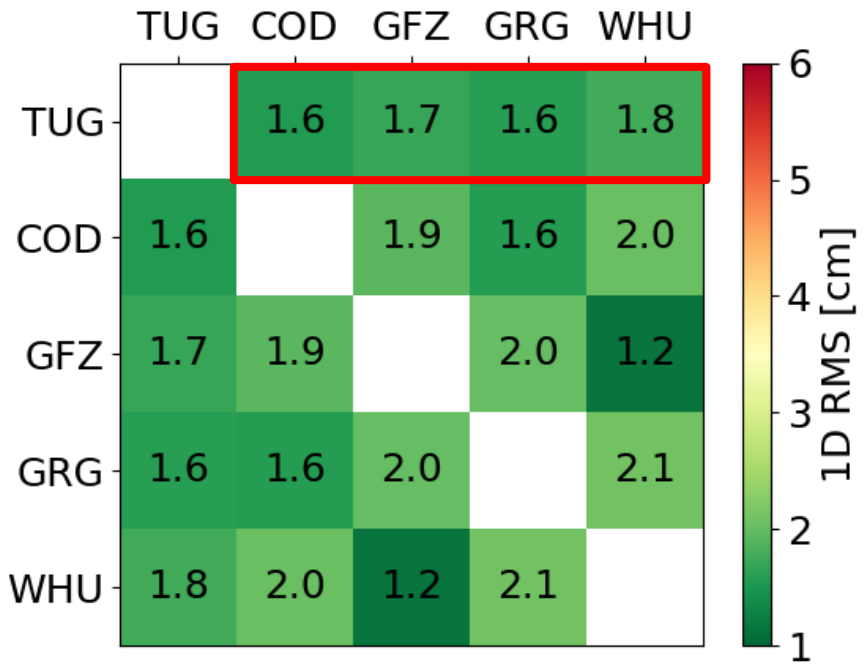


Reference frame differences corrected (Helmert)

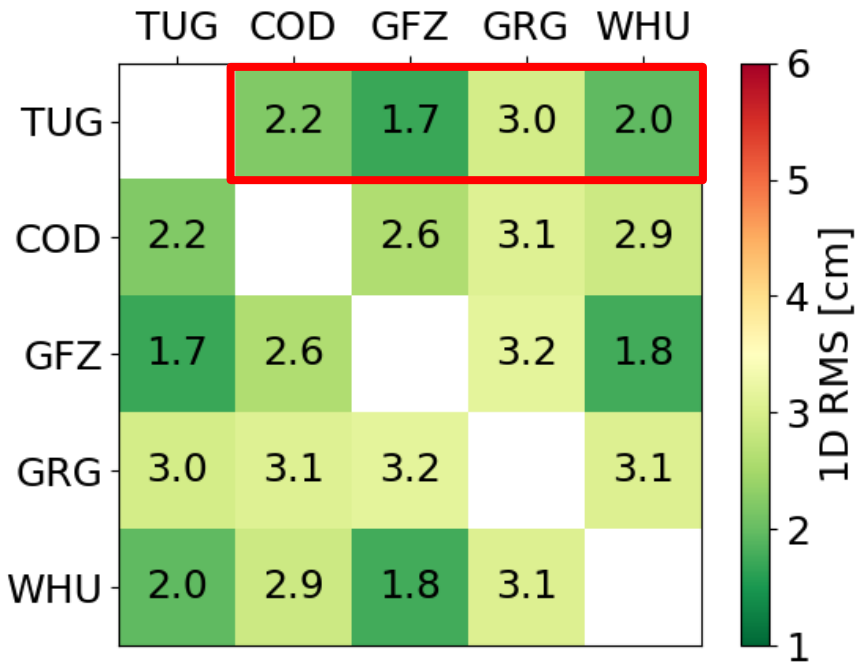
Comparison to MGEX products – Satellite clocks

Clock difference RMS for January 2018

GPS clocks



Galileo clocks



System-wide time shifts corrected

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…

- Attitude models for other GNSS
- Orbit maneuvers
- Antenna center offsets/variations for new signal types
- Estimation of optimal clock/bias stochastic models
- Adaptation of preprocessing
  - Outlier detection
  - Cycle slip detection

Thank you!

We would like to contribute to the IGS.

Course of action?

Question to the MGEX/Bias working groups

- Convention for definition of clocks/biases in a multi-frequency and multi-GNSS environment?