Assessing and improving the accuracy of GNSS tropospheric products for climate research

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A contribution to the IAG Joint Working Group C.8 (GNSS for climate)

Context and objectives

- **Requirements for climate applications:**
  - Accuracy : mean error PW < 0.5 kg/m^2 or 2% => mean error ZTD < 3 mm
  - Stability: trend error PW < 0.1 kg/m^2/decade => trend error ZTD < 0.6 mm/decade
  - Realistic uncertainty information associated to PW and ZTD estimates

- **Main limitations of current state-of-the-art GNSS ZTD data sets:**
  - Tropospheric parameters (ZTD, gradients) treated as side-products, no QC/QA applied => big outliers can be found
  - PW and ZTD biases are highly station-dependent, but no clear relation to the equipment type yet established
  - Only a fraction (~35%) of inhomogeneities (bias changes) is explained by equipment changes
  - ZTD formal errors are not representative of the true uncertainty wrt to SI-traceable reference

- **Objectives of this work:**
  - Better understand the causes of outliers, biases, and inhomogeneities in GNSS ZTD data
  - Improve the accuracy and stability of GNSS ZTD time series => optimal processing & post-proc.
  - Improve the uncertainty predictor of GNSS ZTD estimates => enhanced QC/QA & calibration procedures

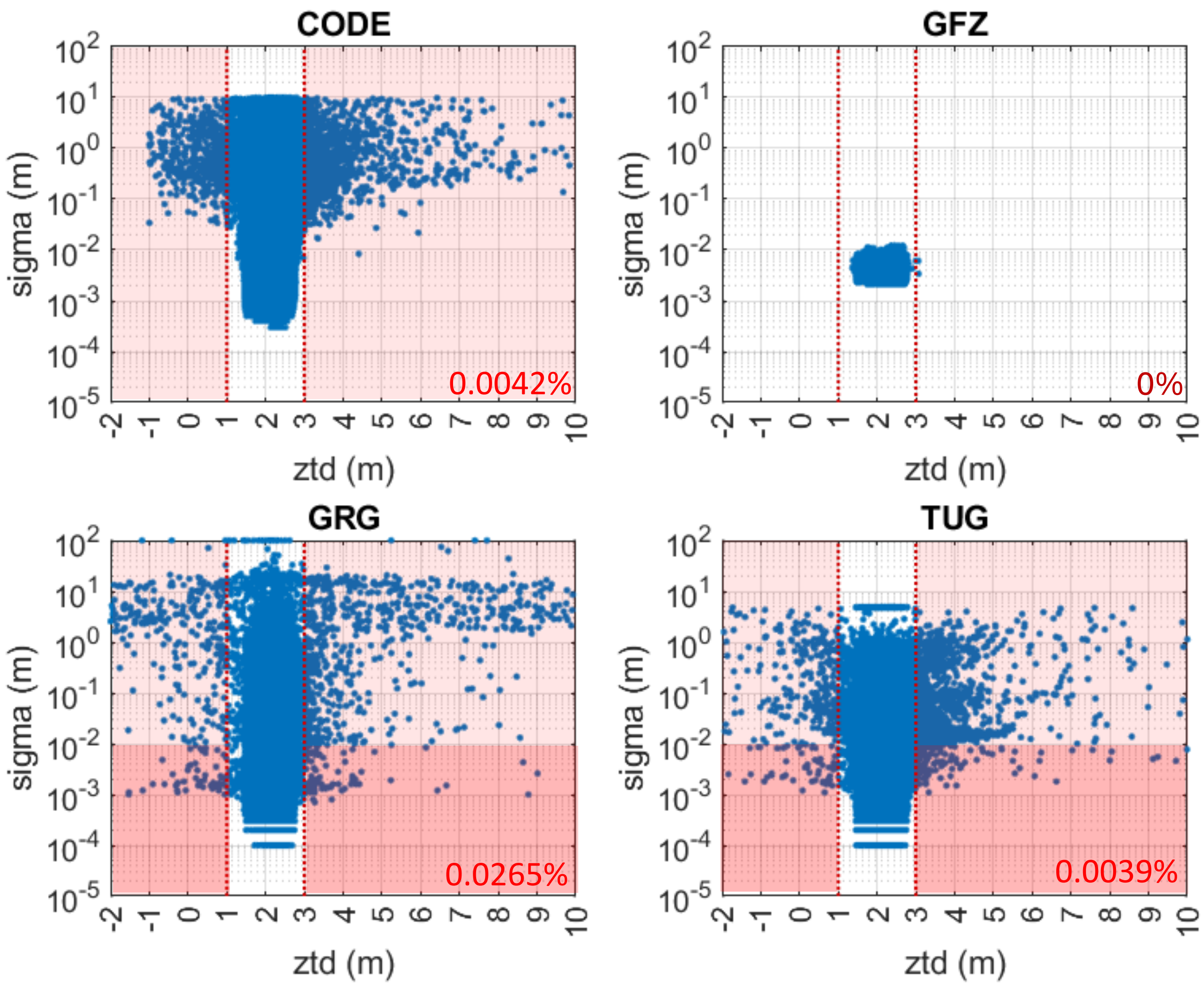
- **This presentation:**
  - Assess GNSS ZTD data sets produced with different software packages and processing procedures

Processing details of four IGS repro3 tropo solutions used in this work

Analysis Center	COD	GFZ	GRG	TUG
Software package	Bernese	EPOS	GINS	GROOPS
Processing mode	PPP-AR	ZD	ZD	ZD
Obs type	GRE	GRE	GRE	GRE
Cutoff	3°	7°	8°	5°
Obs variance	1/cos(Z)^2	0.5*sin(e), e<30° 1, e>=30°	1/(0.5+0.7*sin(e))	1/sin(e)^2
MFh, MFw	VMF1h, VMF1w	VMF1	GPT2	VMF3h, VMF3w
ZHD prior	Zh (VMF1)	GPT2	GPT2	Zh (VMF3)
ZWD estimation	PWL 1h	PWCst 1h	PWL 2h	PWL 2h
ZWD constraint	5m	Tikhonov	No	No
MF gradient	Chen-Herring	Bar-Sever	Chen-Herring	Chen-Herring
GE/GN prior	no	no	no	VMF3
GE/GN estimation	PWL 2/day	CST 1/day	CST 2/day	PWL 2/day
GE/GN constraint	5m	yes	No	No
Number of stations	493	331	236	1182
Time span	2000-2020	1994-2020	2000-2020	1994-2020

Statistics will be shown for 200 common stations - period 2000-2020

Comparison of ZTD estimates from IGS repro3 solutions: COD, GFZ, GRG, TUG



IGS repro3 results [1]

- COD, GRG and TUG have a fraction of unphysical values (red shade), vs. GFZ (0%)

  => unconstrained vs. constained estimation

- GRG and TUG have 5 and 12% of outliers with small formal errors (< 1 cm) vs. COD

  => network (ZD) processing vs. PPP

- Outliers are AC-specific

  => differences in pre-processing/data editing procedures in the different s/w packages

- Outliers are station-specific

  => periods of degraded observation quality

Other studies

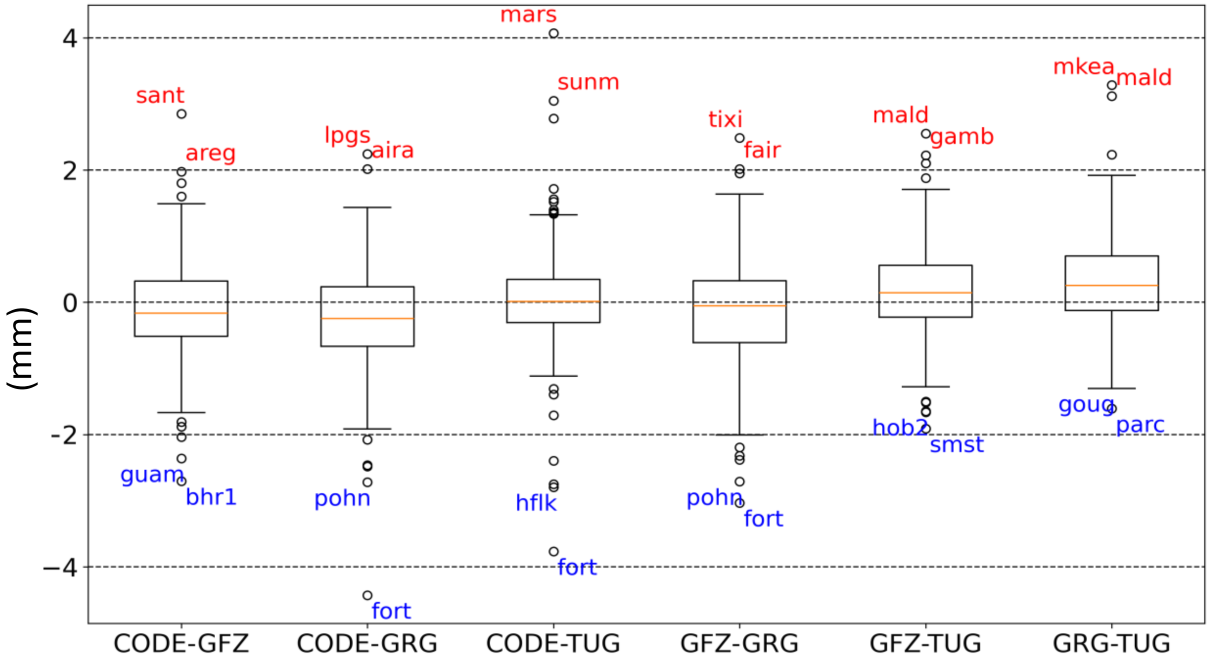
- PPP solutions have fewer outliers than network (DD) solutions and almost none with small formal errors [2, 3, 4].

[1] Breton et al., proceedings of the IAG Scientific Assembly, Rimini, Italy, 2025.

[2] Stepniak et al., AMT, 2017; [3] Stepniak et al., J Geodesy, 2021; [4] Bock et al., EGU 2026.

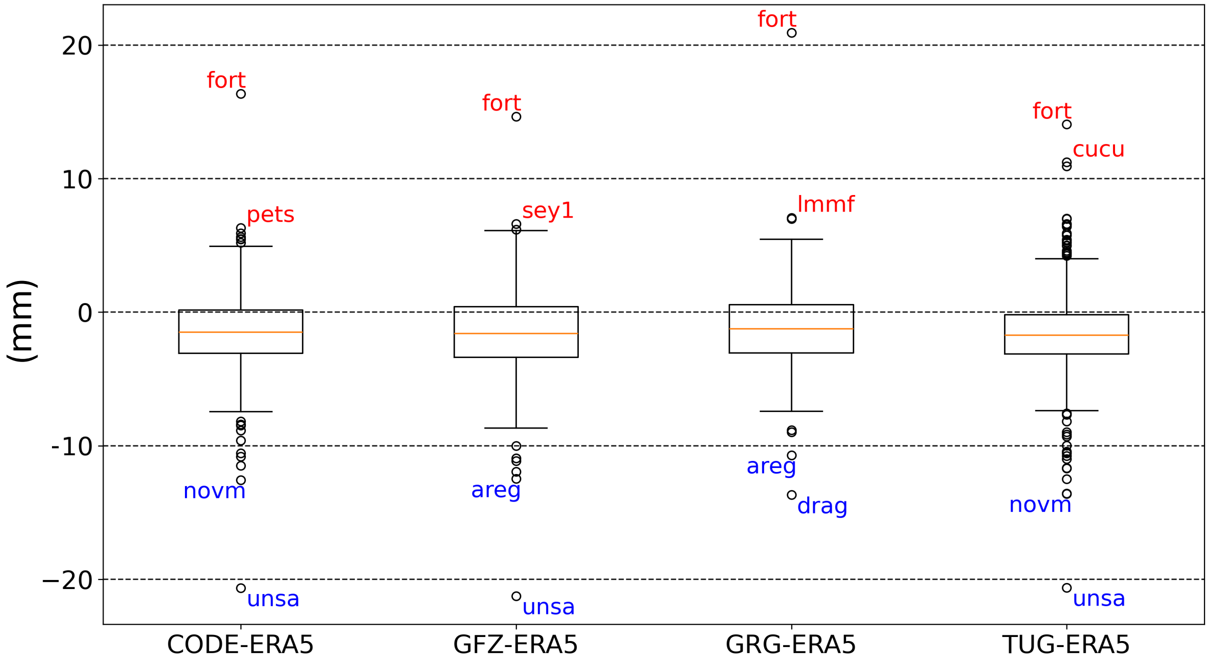
Comparison of ZTD estimates from IGS repro3 solutions: COD, GFZ, GRG, TUG

Median ZTD differences between ACs



- Average difference between ACs is ± 0.2 mm
- Some stations have differential bias up to ± 4 mm

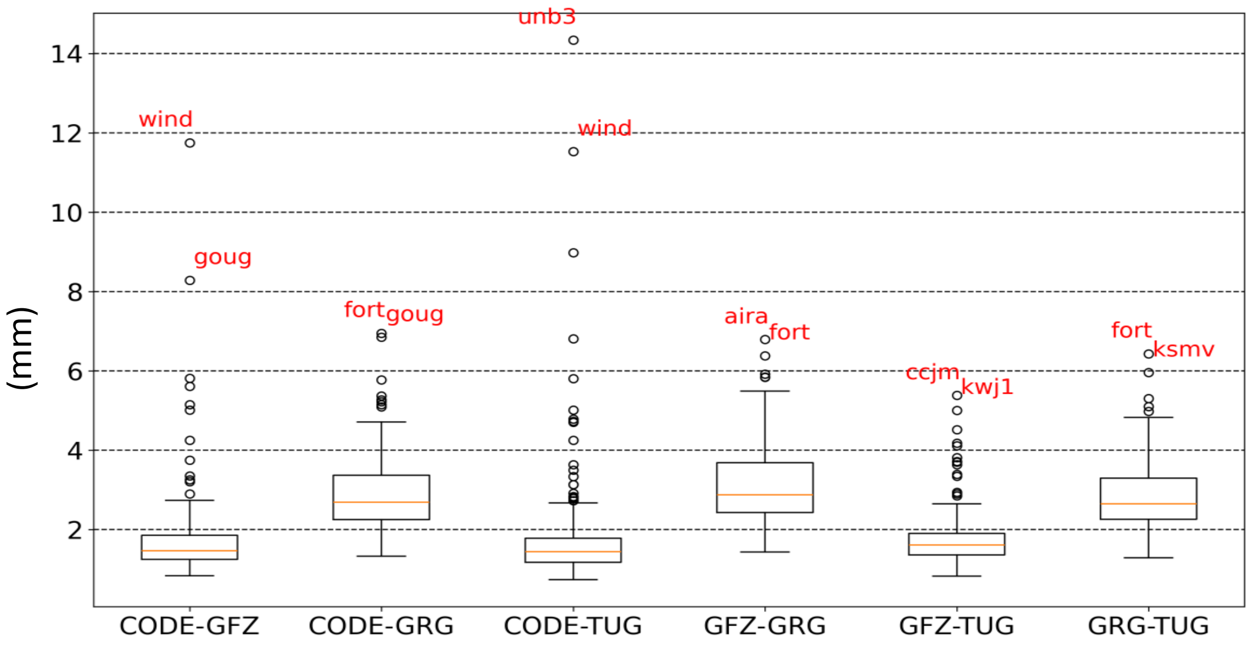
Median ZTD differences wrt ERA5



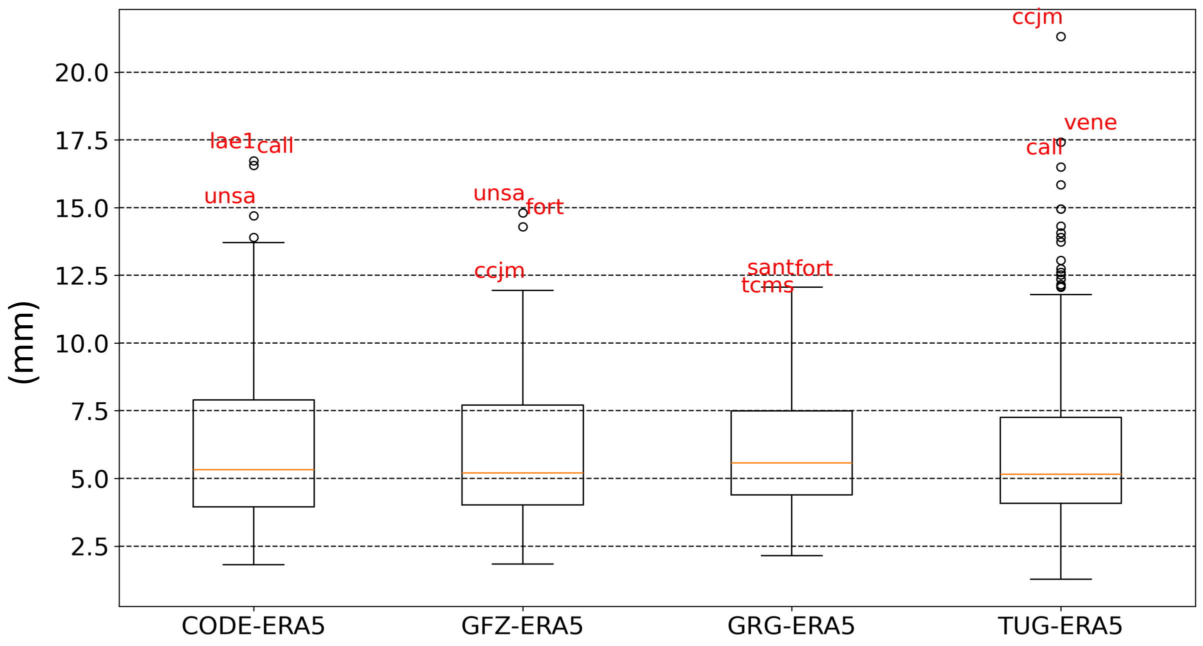
- Overall small bias GNSS vs. ERA5 of - 2 mm
- Some stations have absolute bias up to ± 20 mm

Comparison of ZTD estimates from IGS repro3 solutions: COD, GFZ, GRG, TUG

Stdev ZTD differences between ACs



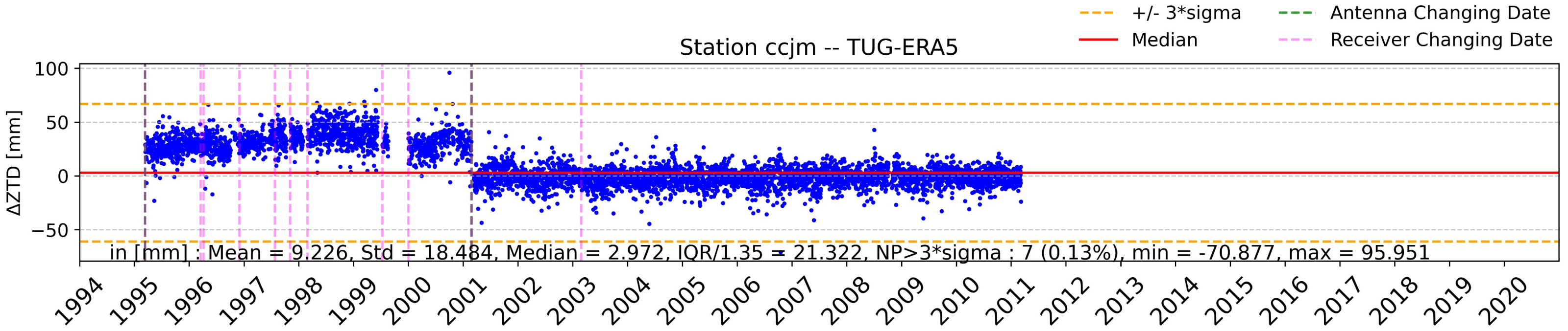
Stdev ZTD differences wrt ERA5



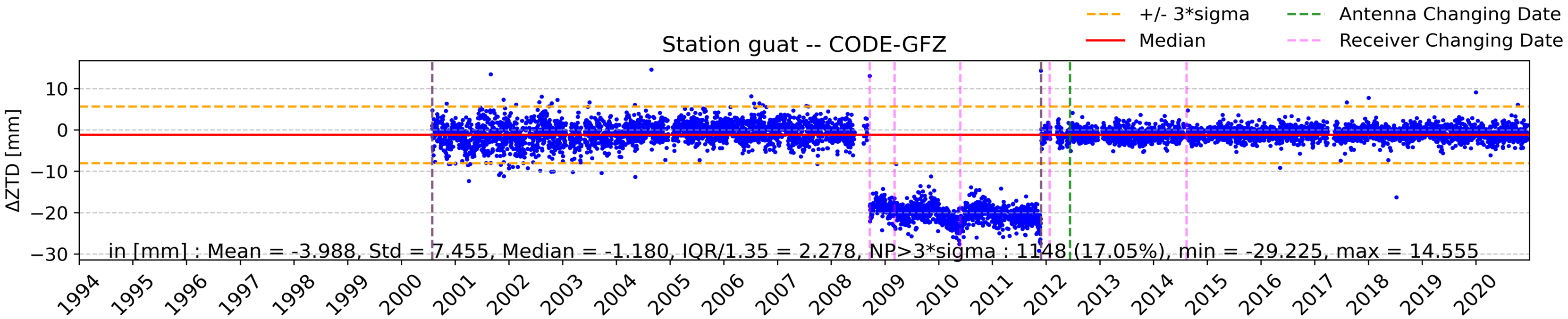
- Average Stdev < 2 mm (COD, GFZ, TUG) > 2 mm (GRG)
- Average Stdev GNSS wrt ERA5 ~ 5 mm (includes representativeness difference)

- Extreme Stdev's are not due to noise or outliers but to inhomogeneities (bias changes)

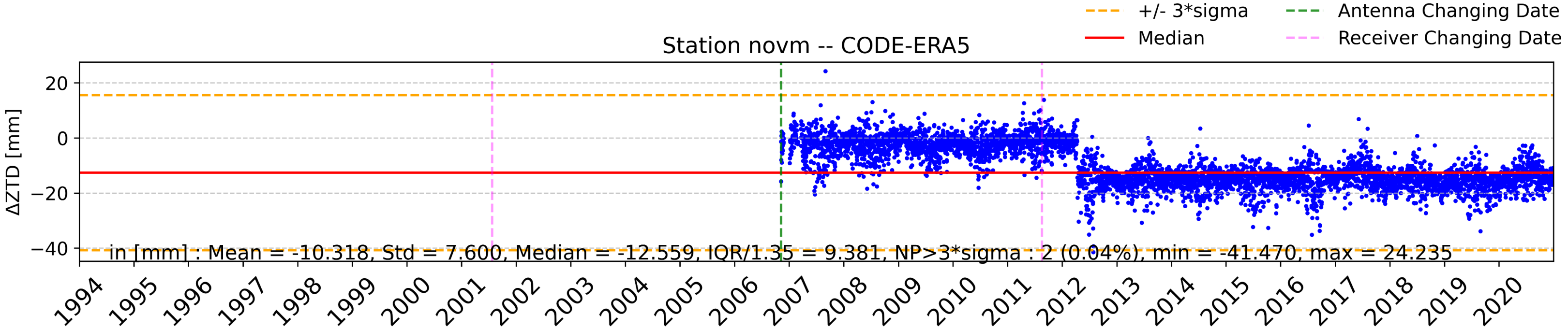
Inhomogeneities in IGS repro3 ZTD difference time series: bias changes



- antenna+radome in use before 2001 does not have a model in igs.atx
  => 30 mm bias (~ 4.5 kg m^{-2})



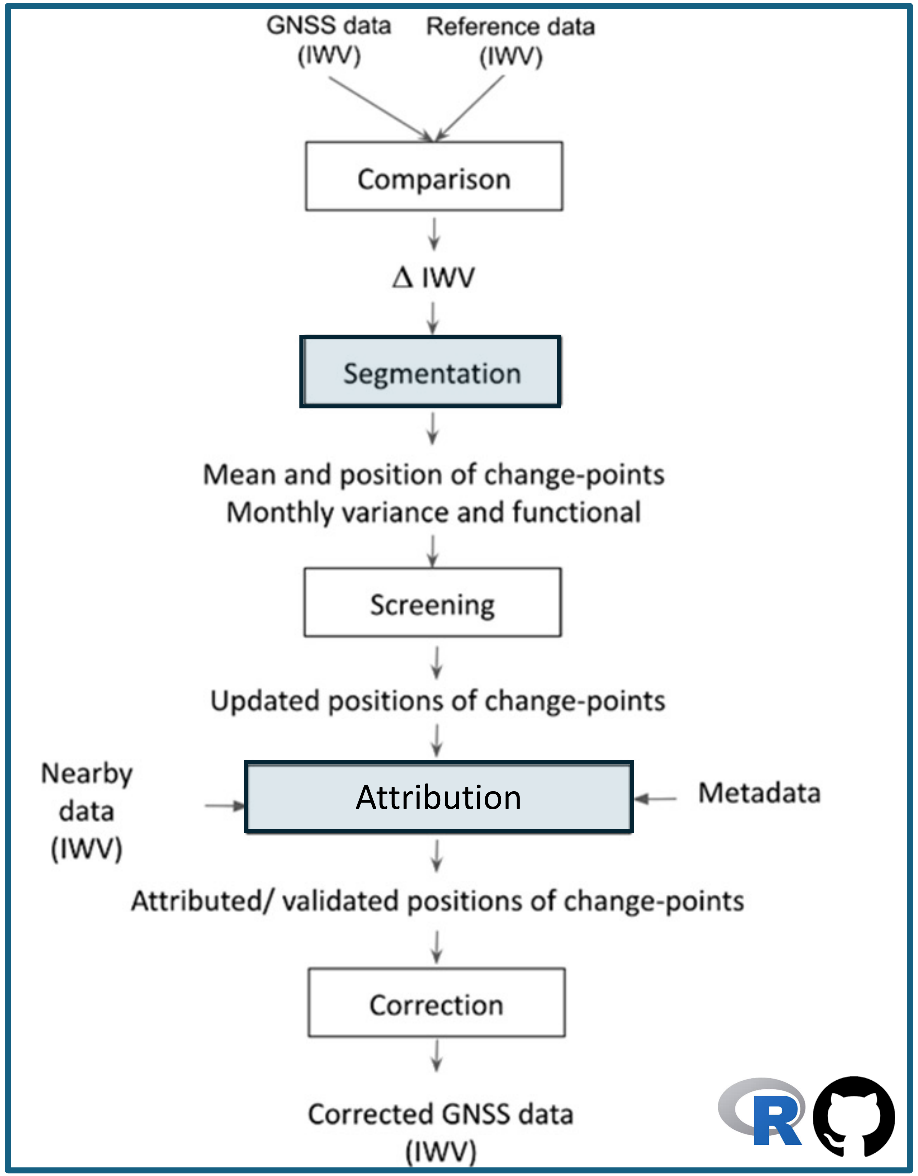
- antenna change applied at wrong date => 20 mm bias (~ 3 kg m^{-2})



- metadata info possibly wrong
  => 12 mm bias (~ 2 kg m^{-2})

Equipment changes

Homogenization of GNSS ZTD time series



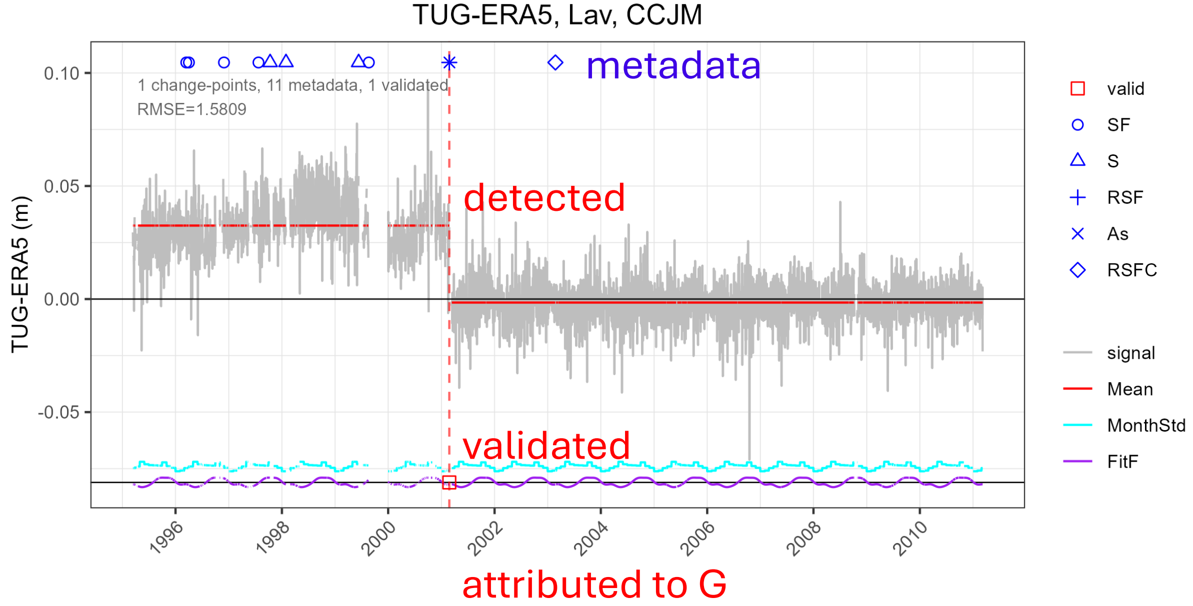
https://github.com/khanhninhnguyen/PMLSeg

Segmentation:

- Detect the number and position of change-points in a time series
- Penalized Maximum Likelihood segmentation (**PMLseg**) R package
- Time series of PW or ZTD difference, GNSS – ERA5 (G – E)

Attribution:

- Predict if change-points are due to G or E
- Random Forest (ML classifier) trained on 40K cases (NGL)
- Multiple pair-wise comparisons with nearby stations (< 50 km)



Segmentation results for various global GNSS data sets: daily ZTD differences (GNSS – ERA5)

- IGS repro1
  - JPL: 120 stations, 1995-2010 (Gipsy-Oasis, PPP)
- IGS repro2
  - CODE REPRO2015: 81 stations, 1994-2018 (Bernese, DD)

  - 6% stations are homogeneous
  - Detected 1 CP / station / 5.6 yrs
  - Validated 34% with metadata

- IGS repro3
  - COD: 493 stations, 2000-2020 (Bernese, PPP-AR)
  - GFZ: 331 stations, 1994-2020 (EPOS, ZD)
  - GRG: 236 stations, 2000-2020 (GINS, ZD)
  - TUG: 1182 stations, 1994-2020 (Groops, ZD)

  200 common stations (2000-2020)
  - 7-11% stations are homogeneous
  - Detected 1 CP / station / 4.5-7.1 yrs
  - Validated 31-35% with metadata

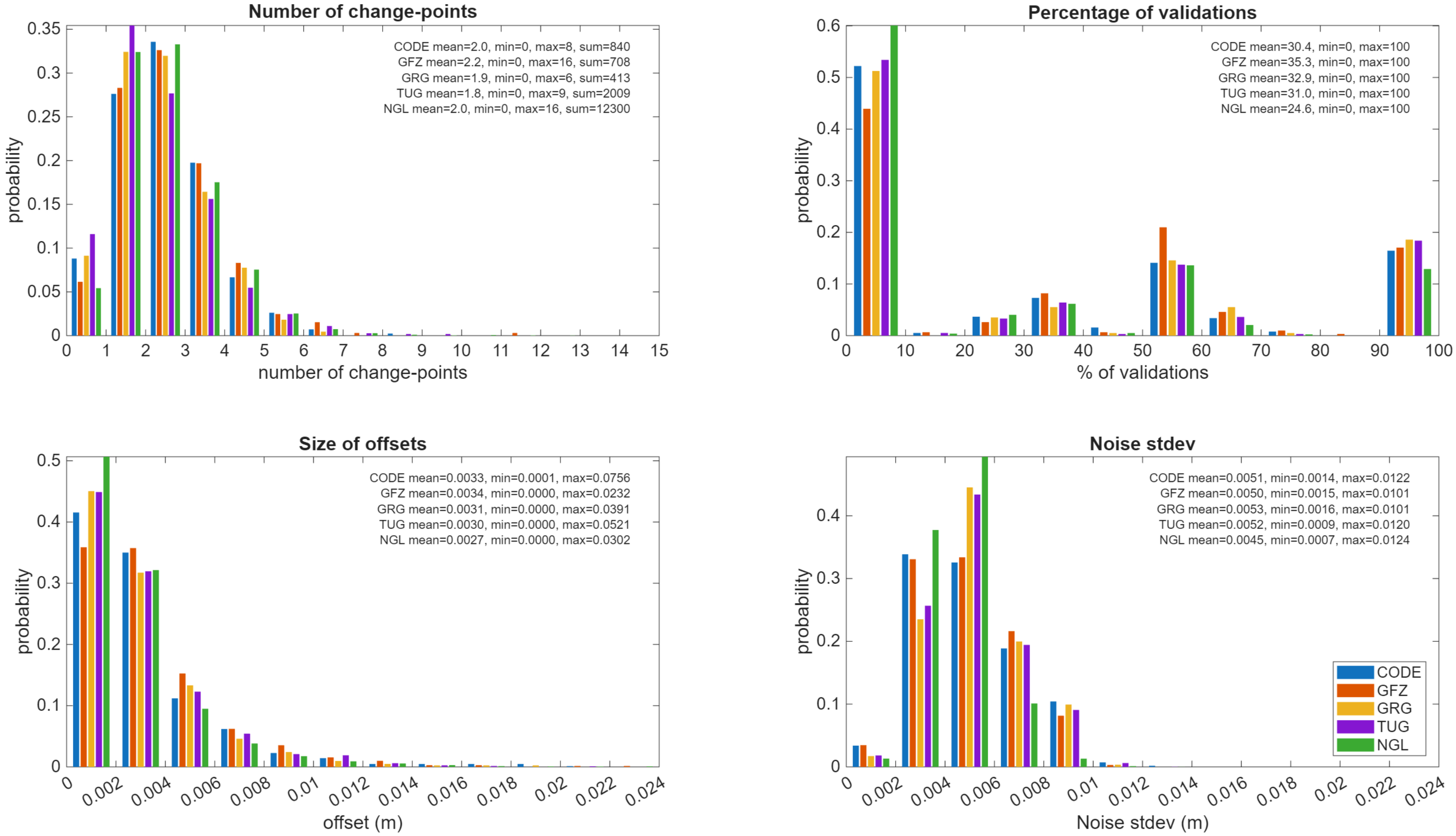
- NGL repro3
  - 6048 stations, 1994-2022 (Gipsy-Oasis, PPP-AR)

  - 5.5% stations are homogeneous
  - Detected 1 CP / station / 6.7 yrs
  - Validated only 22% with metadata
    (33% on IGS stations)

- SPOTGINS
  - 5735 stations, 1994-2025 (GINS, PPP-AR)

Bock et al., manuscript in preparation.

Segmentation results for various ZTD data sets: IGS repro3 (COD, GFZ, GRG, TUG) and NGL



=> Homogeneity of time series depends on software & processing details

Conclusions and recommendations: GNSS for climate applications

- Outliers, biases, noise and inhomogeneities in ZTD estimates vary across Analysis Centers
  - Processing mode (PPP vs network), obs. editing strategy, constraining of parameters => impact outliers (up to ± 100 m)
  - Use of **wrong or incomplete antenna + radome calibration** model => impact biases and offsets (up to ± 30 mm)
  - Tropo model (mapping function, a priori...) and elev cutoff angle => impact biases and random error (up to ± 5 mm)

- Recommendations on GNSS station metadata handling
  - There is a general need to **improve the FAIRness and quality assurance** of GNSS station metadata

- Recommendations on GNSS data processing
  - Check the **validity of metadata** information prior to processing
  - Produce ZTD data records with a **fixed (re-)processing strategy**
  - **Prefer PPP** to DD and ZD processing
  - **Prefer NWP-based mapping functions** to empirical
  - When applying **constraints** to tropo parameters, **efficient data editing** is required during (pre-)processing

- Recommended post-processing steps prior to ZTD time series interpretation
  - **Screening**: detect and remove outliers ideally by comparison with a reference (e.g. reanalysis)
  - **Segmentation:** check the homogeneity of time series (station position, ZTD, gradients...), possibly blacklist the station
  - **Homogenization:** if possible, attribute the change-points and correct the offsets
  - **QC/QA**: if possible, compare to other GNSS data sets (e.g. other Analysis Centers) or a SI-traceable reference (e.g. radiosonde)

- On-going research and activities within the IAG JWG C.8
  - We encourage the intercomparison with other ACs, testing of various processing strategies, and the development of enhanced screening, segmentation, homogenization, and QC/QA procedures.

  => join here: https://iccc.iag-aig.org/joint-work-groups/ICCC-JWGC8