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# Tracking biases and inhomogeneities in GNSS PW time series


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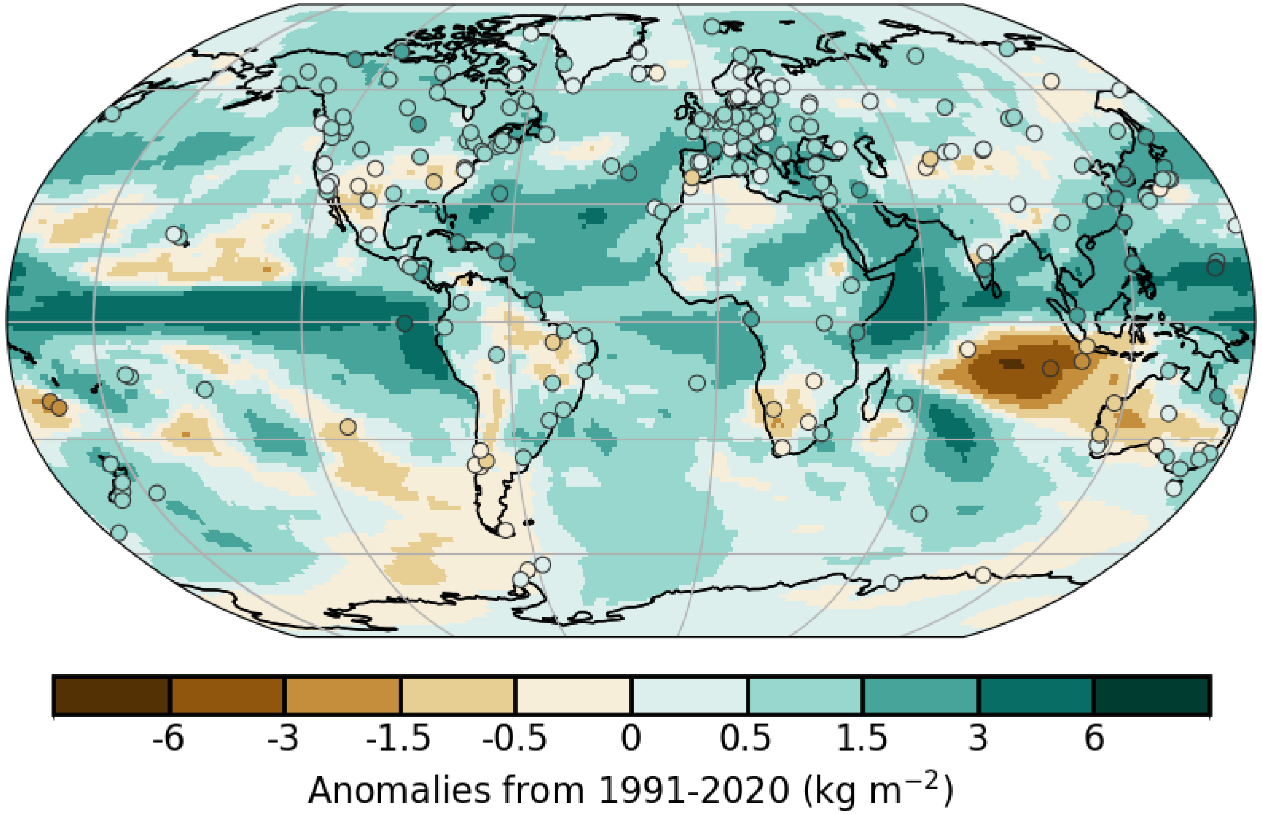
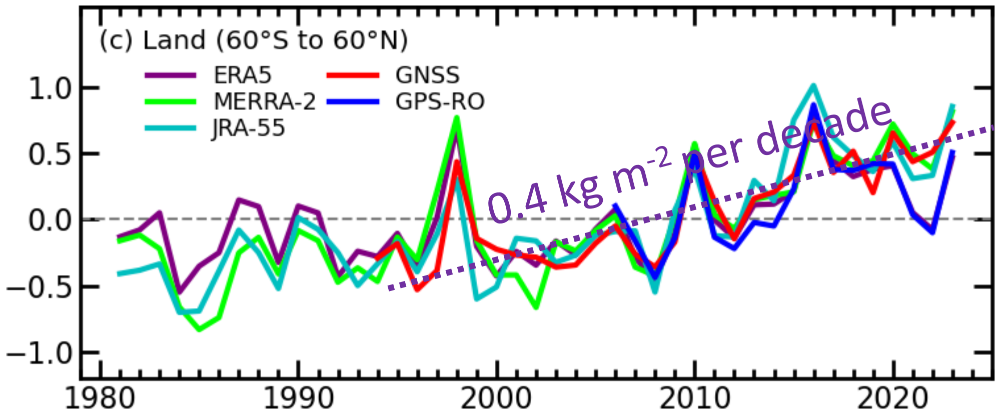
# Objectives

- Better understand and reduce
  - GNSS PW biases and inhomogeneities
- Produce long-term, high-quality GNSS PW data with:
  - small or known biases
  - high spatial and temporal homogeneity
  - realistic uncertainties
- Monitor:
  - climate variability and trends
- Calibrate/validate PW from
  - reanalyses, climate models
  - satellites, and other observations
- Goal:
  - absolute accuracy: 0.5 kg $m^{-2}$ (or 3%)
  - trends: 0.1 kg $m^{-2}$ (or 0.6%) per decade

Note: 1 mm PW = 1 kg $m^{-2}$ TCWV or IWV

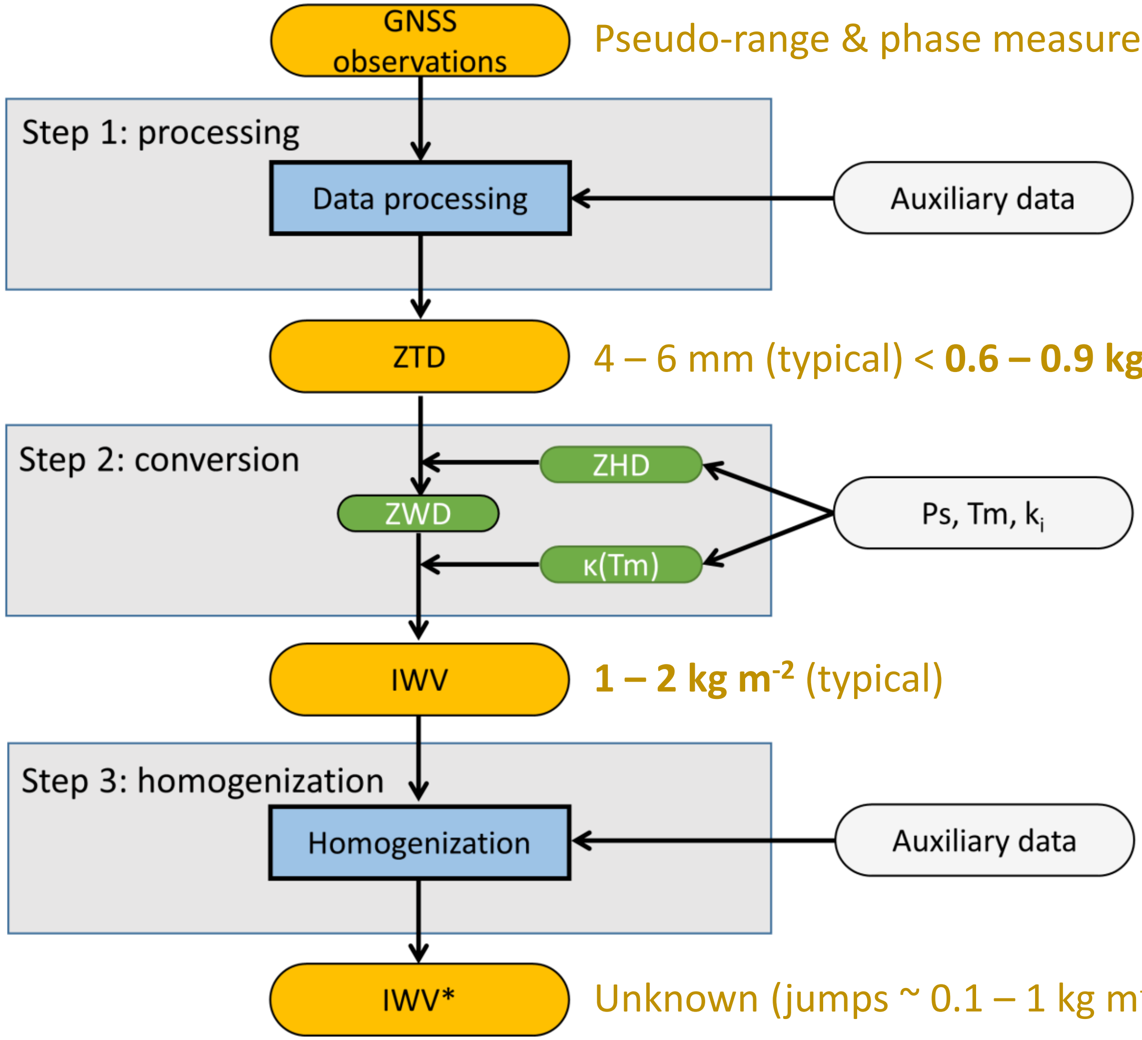
ERA5 & GNSS, TCWV anomaly, 2023




*Bock et al., BAMS, State of the Climate in 2023, in press.*

# Error sources in GNSS PW estimation




Pseudo-range & phase measurements ~ a few mm

Satellite products (orbits & clocks), EOPs
Models: mapping functions, antenna PCO/PCV…

4 – 6 mm (typical) < **0.6 – 0.9 kg m$^{-2}$**

Surface pressure ~ 1 hPa x 0.35 kg m$^{-2}$ hPa$^{-1}$ ~ **0.35 kg m$^{-2}$**
Weighted mean temp. ~ 3 K x 0.069 kg m$^{-2}$ K$^{-1}$ ~ **0.21 kg m$^{-2}$**
Refractivity constants: k1 ~ **0.23 kg m$^{-2}$**, k3 < **0.22 kg m$^{-2}$** (systematic)

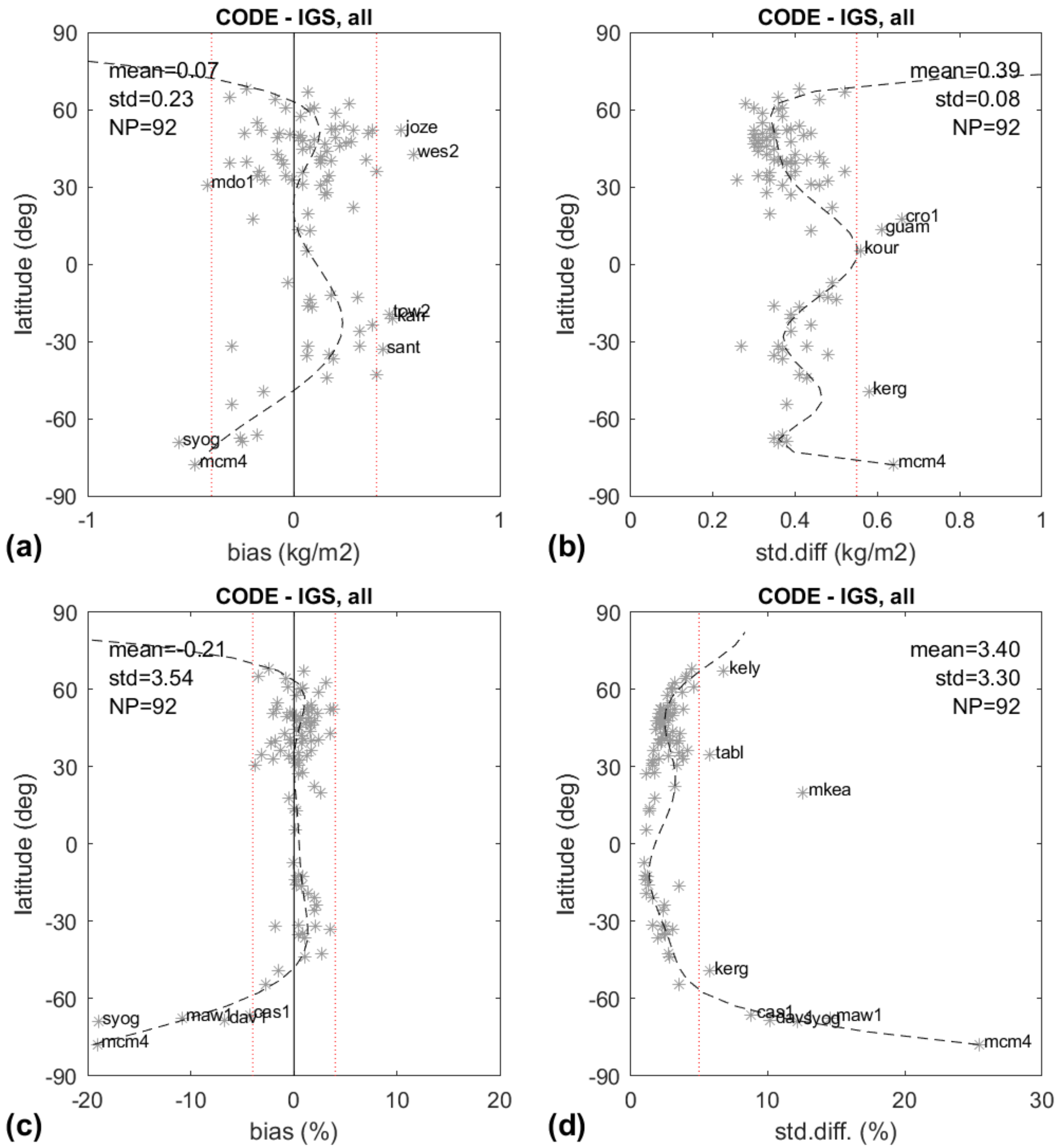
**1 – 2 kg m$^{-2}$** (typical)

IWV from nearby GNSS stations/reanalyses
Metadata (GNSS site-logs)

Unknown (jumps ~ 0.1 – 1 kg m$^{-2}$, typical)

*Note: numbers from COST GNSS4SWEC final report (Chap. 5)*

# Impact of data processing scheme on PW




IGS repro1 vs. CODE “repro2”

| | IGS repro1 | CODE REPRO2015 |
|---|---|---|
| Software | GIPSY OASIS II | Bernese GNSS software v5.3 |
| Strategy | PPP solution | Double-difference solution of a global network |
| Orbits, clocks, ERPs | IGS repro1 (1995.0–2008.0) + IGS final (2008.0–2011.0) | CODE repro2 (1994.0–2015.0) + CODE final (2015.0–2019.0) |
| Reference frame | IGS05 | IGb08 |
| Antenna calibration | igs05.atx | igs08_1852.atx until 28 January 2017, igs14.atx from 29 January 2017 |
| Window length | 24 h | 72 h |
| Elevation cutoff angle | 7° | 3° |
| Observations | GPS | GPS (1994.0–2002.0), GPS+GLONASS (2002.0–2019.0) |
| Observation sampling | 5 min | 3 min |
| Observation weighting | uniform | $\sigma^2 = 36 \times 10^{-6}/\cos^2(Z)$ where Z = zenith angle |
| Tropospheric model | ZHD and ZWD a priori: ZHD = 1.013 × 2.27 × exp(−0.116*ht), ZWD = 0.1 m. GMF mapping functions (hydrostatic and wet). Random Walk model for ZWD and gradient parameters with constraints: 3 mm $h^{-1/2}$ (ZWD) and 0.3 mm $h^{-1/2}$ (gradients). ZWD and gradient sampling: 5 min | ZHD and ZWD a priori: 6-hourly ECMWF analysis (provided by TUV). VMF1 mapping functions (hydrostatic and wet). Piece-wise linear model for ZWD with constraints: 5 m absolute and 5 m relative. Sampling : 2 h (ZWD), 24 h (gradients). |
| Tropo files | ZTD and gradient estimates provided in SINEX files (0000, 0005,... 2345 UTC) | ZTD and gradient estimates provided in SINEX files (resampled to 01, 03,... 23 UTC) |
| Coordinate estimates | Estimated once per 24 h | Estimated once per 24 h |
| Ambiguity resolution | Float | Fixed |

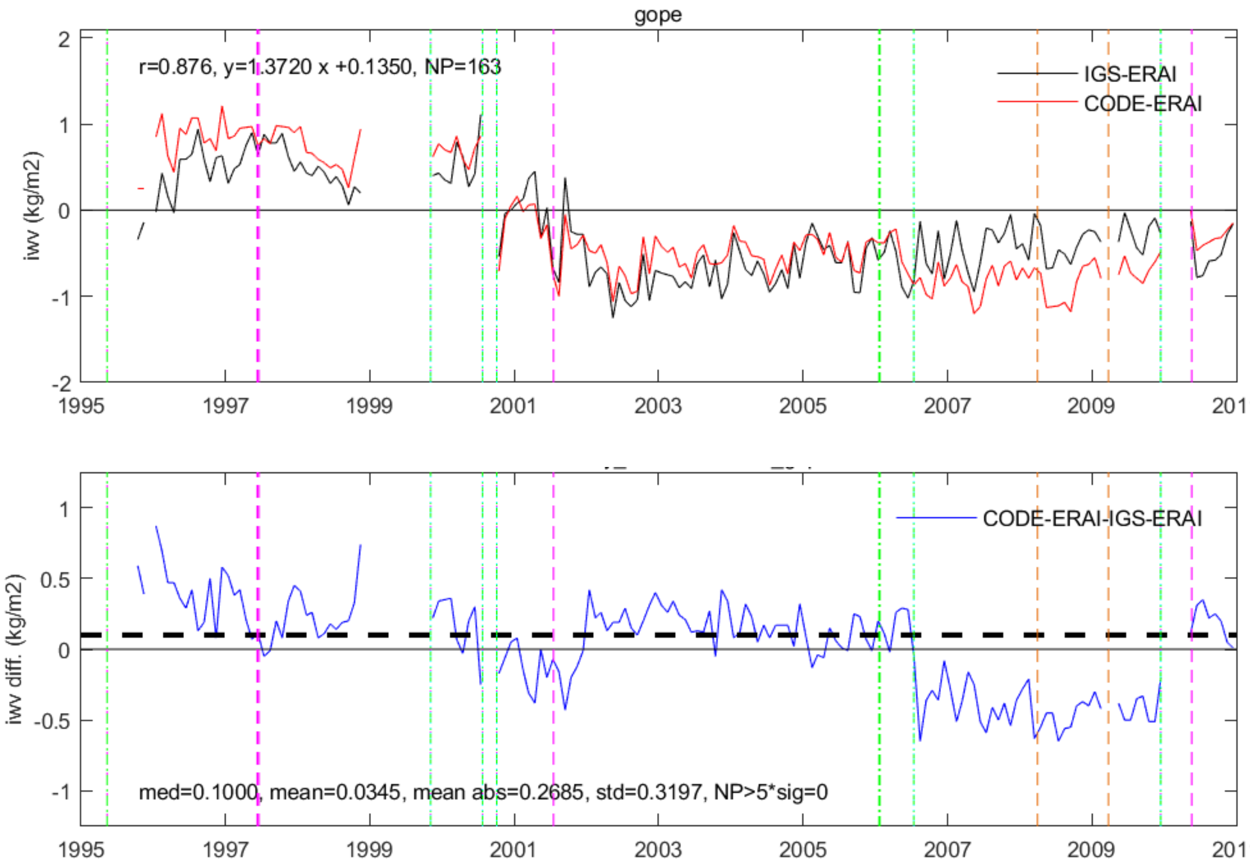
92 stations (1995..2010), daily data

*Nguyen et al., Atmosphere, 2021*

# Impact of equipment changes on PW

Eq. Changes:

- Receiver
- Antenna/radome




**IGS - ERAI**

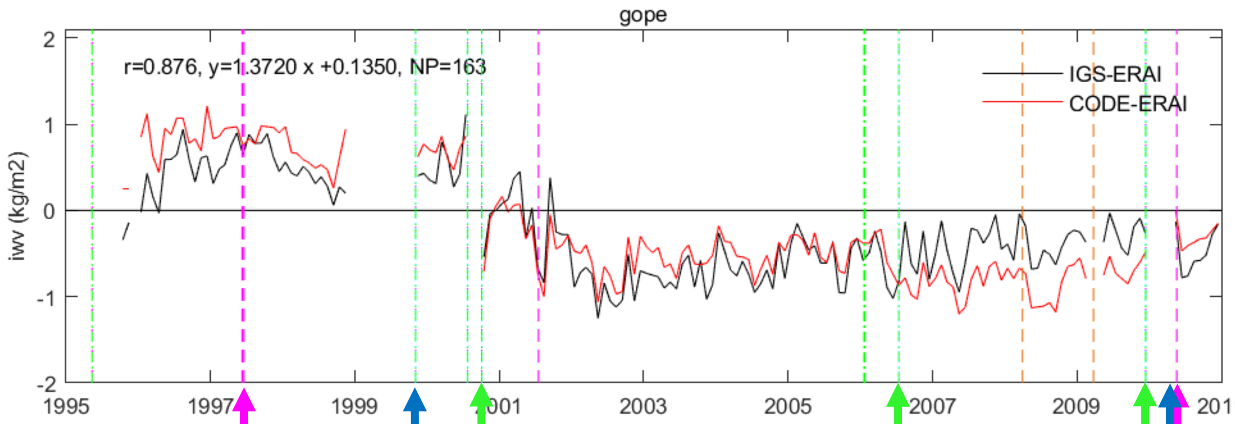
**CODE - ERAI**

**CODE - IGS**

=> Eq. changes impact, differently, the two GNSS solutions

*Nguyen et al., Atmosphere, 2021*

# Impact of cutoff and APCV model on PW




**IGS - ERAI**

**CODE - ERAI**

Eq. Changes:

Receiver: Trimble 4000SSE | ASHTECH_Z18 | TPS_NETG3

Cutoff: CO=15° | CO=5° | CO=0°

Antenna/radome: TRM14532.00/NONE | ASH701946.3/SNOW | TPSCR3_GGD/CONE | TPSCR.G3/TPSH

APCV models:

IGS: igs05.atx

CODE: igs08_1852.atx

TRM14532.00/NONE:
ROBOT, N=4, Jan 2003
ROBOT, N=22, Mar 2011

ASH701946.3/SNOW:
IGS: COPIED from AOAD/M_T, N=1, Jan 2003
CODE: COPIED from AOAD/M_T, N=2, Mar 2011

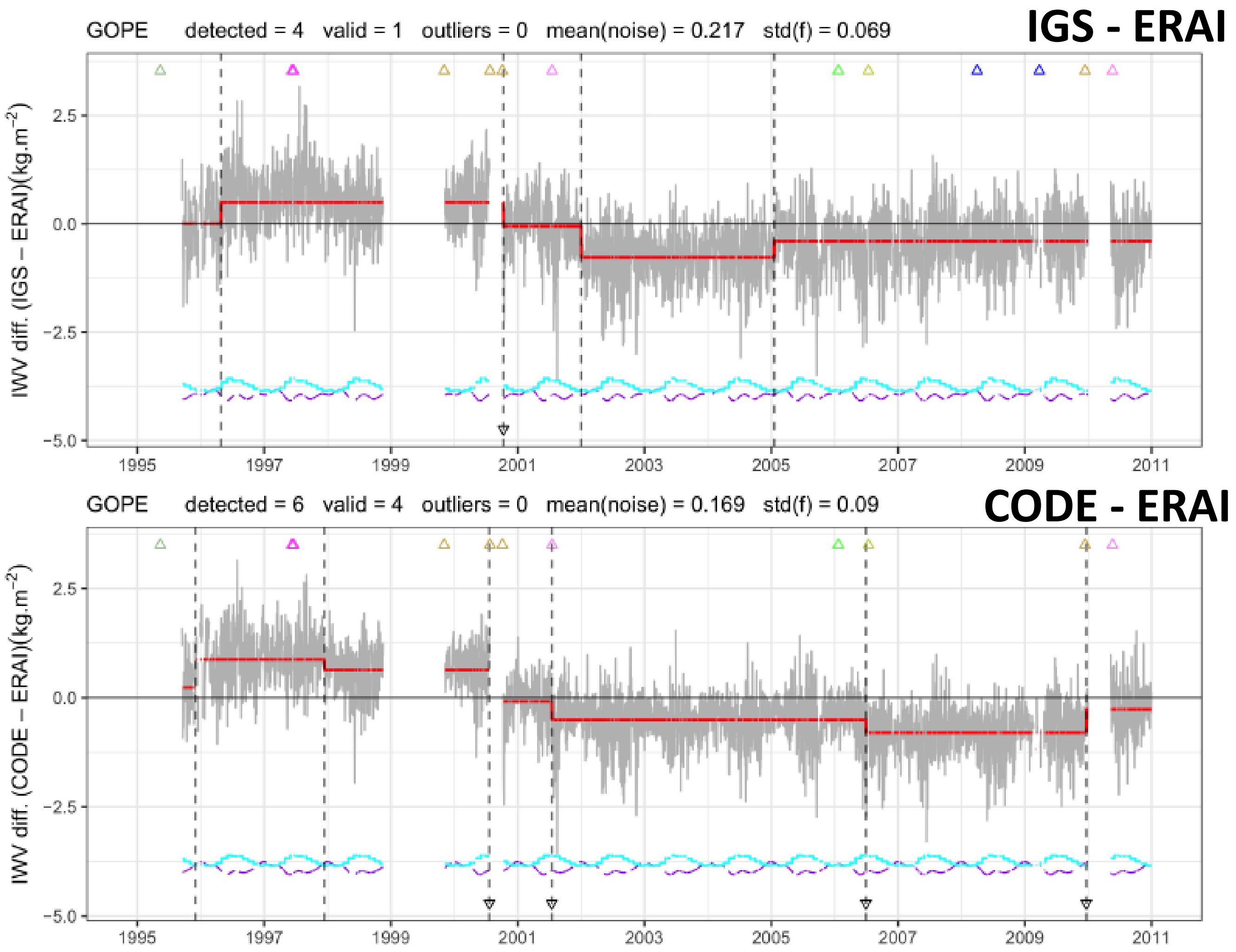
TPSCR3_GGD/CONE:
FIELD, N=3, Apr 2005
ROBOT, N=159, Apr 2013

TPSCR.G3/TPSH:
ROBOT, N=51, Mar 2008
ROBOT, N=60, Mar 2011



*Nguyen et al., Atmosphere, 2021*

# Segmentation (change-point detection)




**GNSSseg** R package (Quarello, 2022)

Model:

- change in mean at unknown times
- periodic bias
- noise with monthly varyring variance

Method:

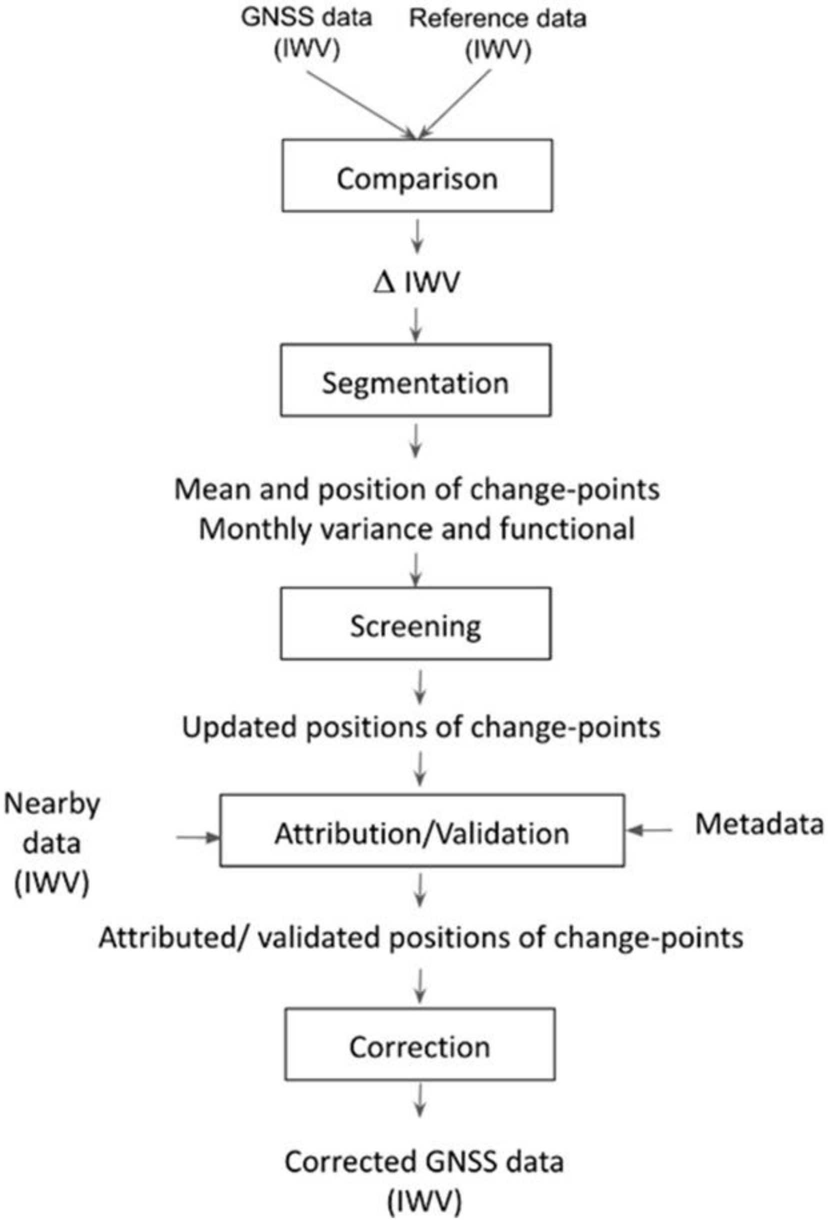
- Penalized Maximum Likelihood
  - *4 criteria implemented*
- Relative segmentation method
  - GNSS – reanalysis daily IWV diff.

Results:

- One of the best methods tested on a simulated benchmark dataset (Van Malderen et al., 2020)
- Applied to several GNSS reprocessed data sets.

*Quarello, A., PhD thesis 2020.*
*Quarello et al., Remote Sensing, 2022: GNSSseg a new segmentation package in R*

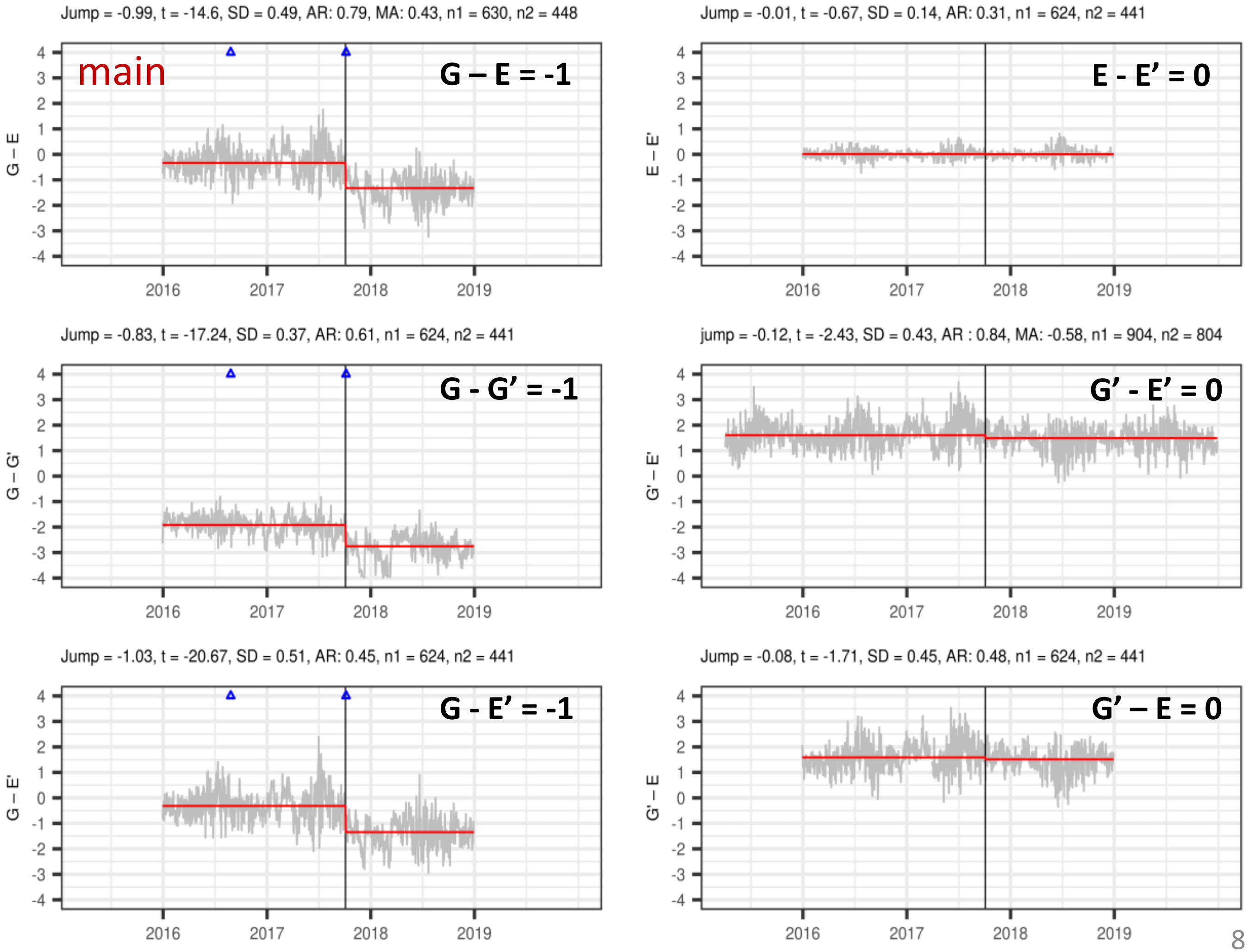
# Homogenization




*Nguyen, N.K., PhD thesis 2023; Nguyen et al., Int. J Climatol, 2024.*

**<u>Attribution method</u>**, for each break-point:

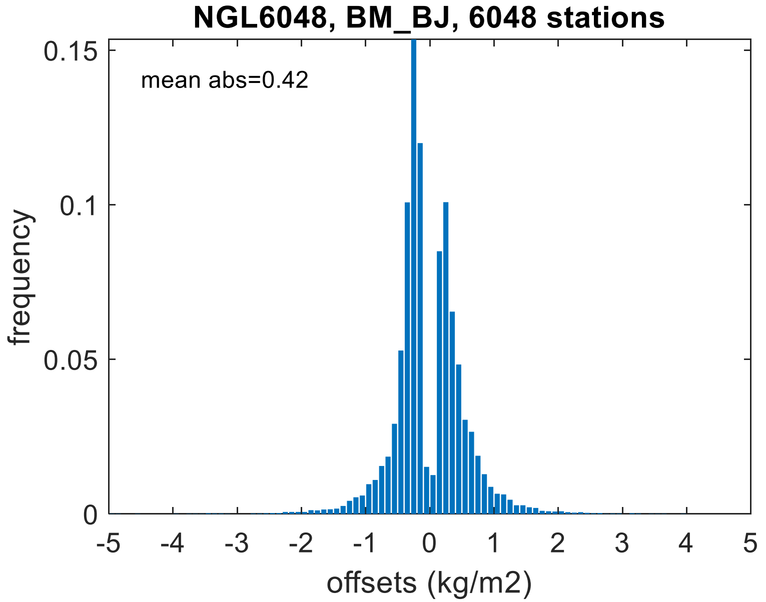
- associate main (G, E) & nearby (G', E') => 6 series of differences
- do statistical test for change in mean in each of the 6 series
- attribute (predict) origin of jump in each of the 4 base series (G, E, G', E'), method is based on a machine learning algorithm
  - *current algorithm was trained on 494 triplets (main-break-nearby)*

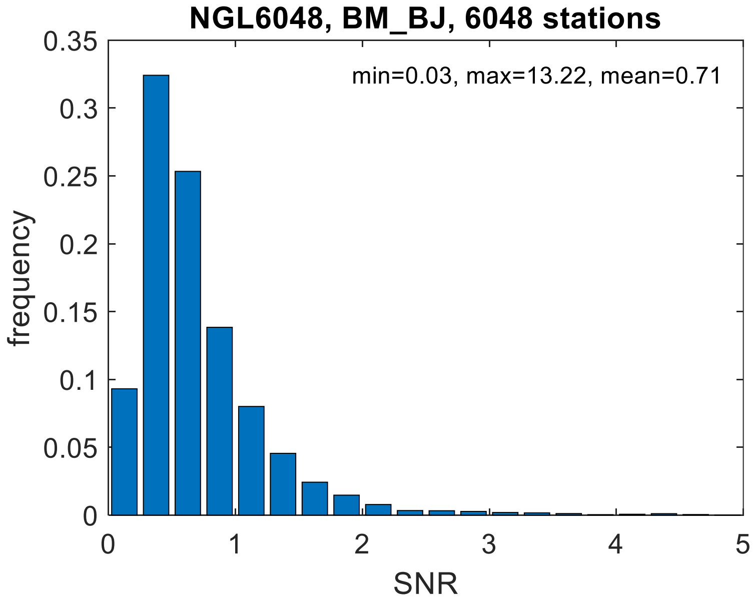


# Temporal homogeneity of various GNSS datasets

## Segmentation/validation/attribution results

- Quarello, 2020: IGS repro1, 120 sta/16 yrs => 1.5 bk/sta/10yrs (32% validated wrt GNSS metadata)
  - *Quarello, 2022: semi-automatic validation based on 3 penalty criteria + metadata => 1.0 bk/sta/10yrs (59% validated)*
- Nguyen, 2021: CODE repro2, 81 sta/25 yrs => 1.7 bk/sta/10yrs (36% validated wrt GNSS metadata)
  - *Nguyen, 2024: automatic attribution of 114 bk in 49 main with 704 nearby from NGL => **62% due to G and 19% to E***
- Work in progress: NGL repro3, 6048 sta/29 yrs => 1.7 bk/sta/10yrs (GNSS metadata lacking)
  - *10% stations have homogeneous series (no bk detected)*
  - *Attribution algorithm is currently trained with 44,474 triplets (632 main & 3960 nearby) => R package in prep.*

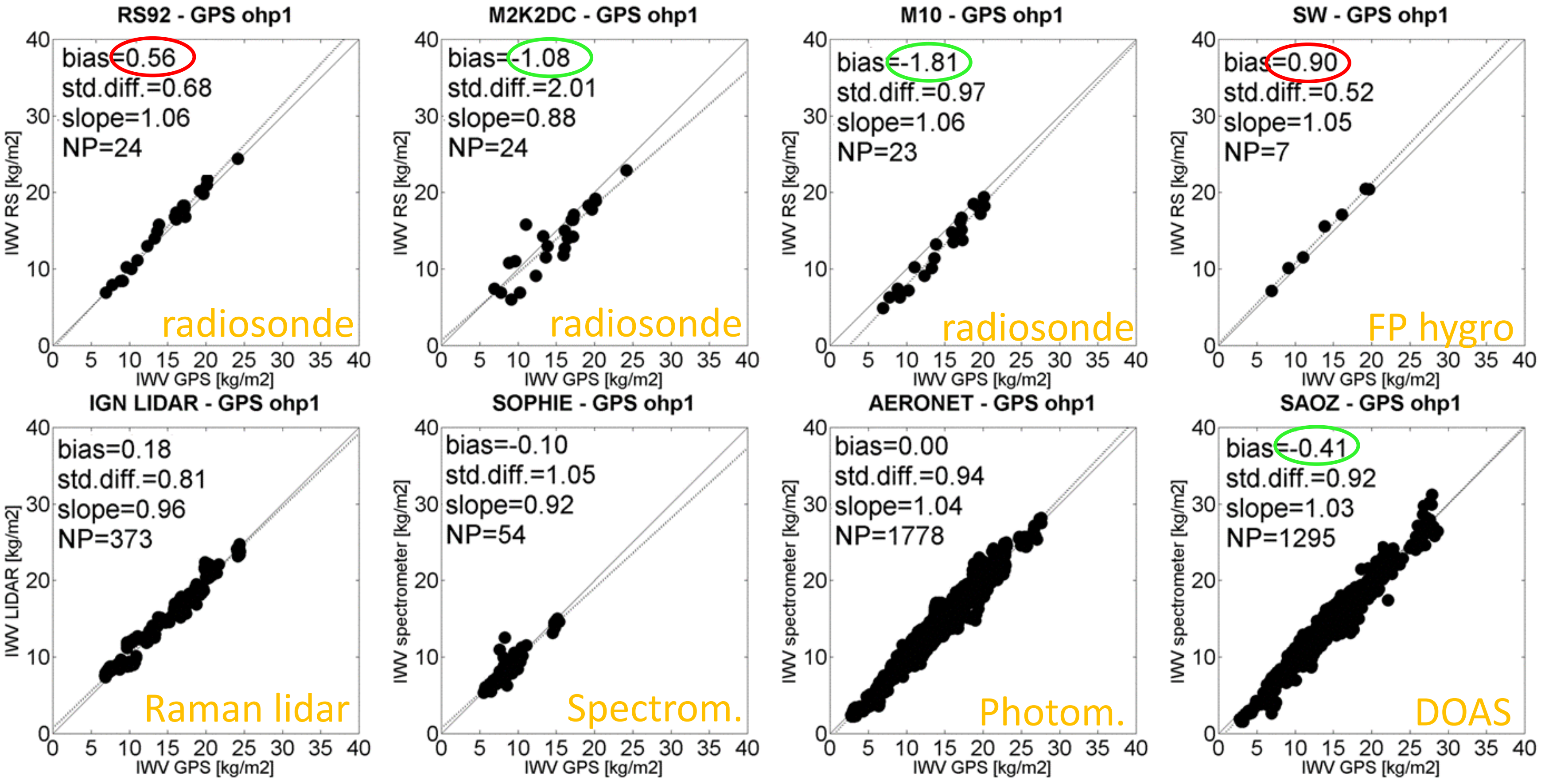


# Absolute accuracy of GNSS PW

## GNSS compared to other techniques

### DEMEVAP campaign, Obs. Haute Provence, Sept-Oct. 2011

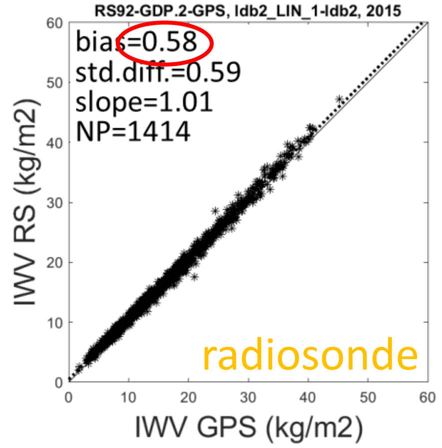


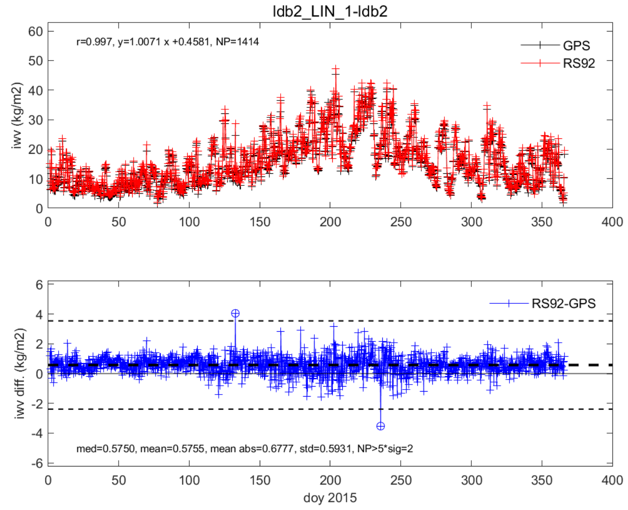

GNSS dry? GNSS wet?

*Bock et al., AMT, 2013: DEMEVAP campaign*

### Lindenberg, 2015

GRUAN RS92-GDP.2

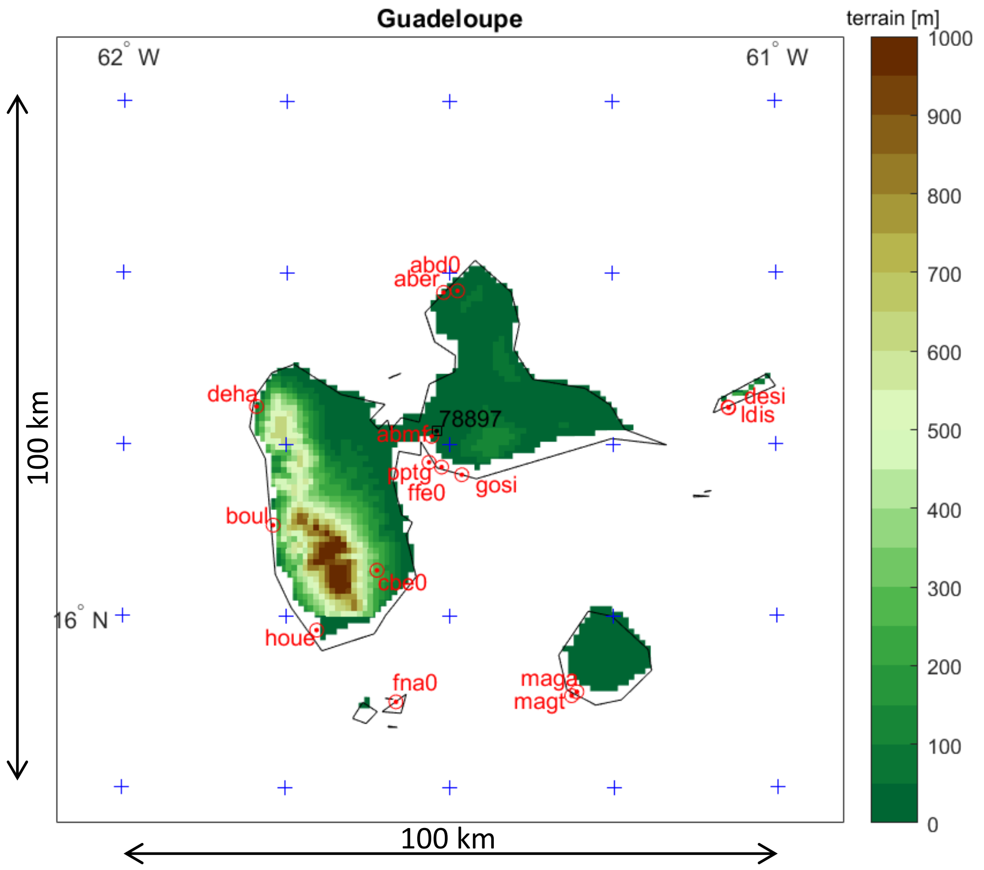


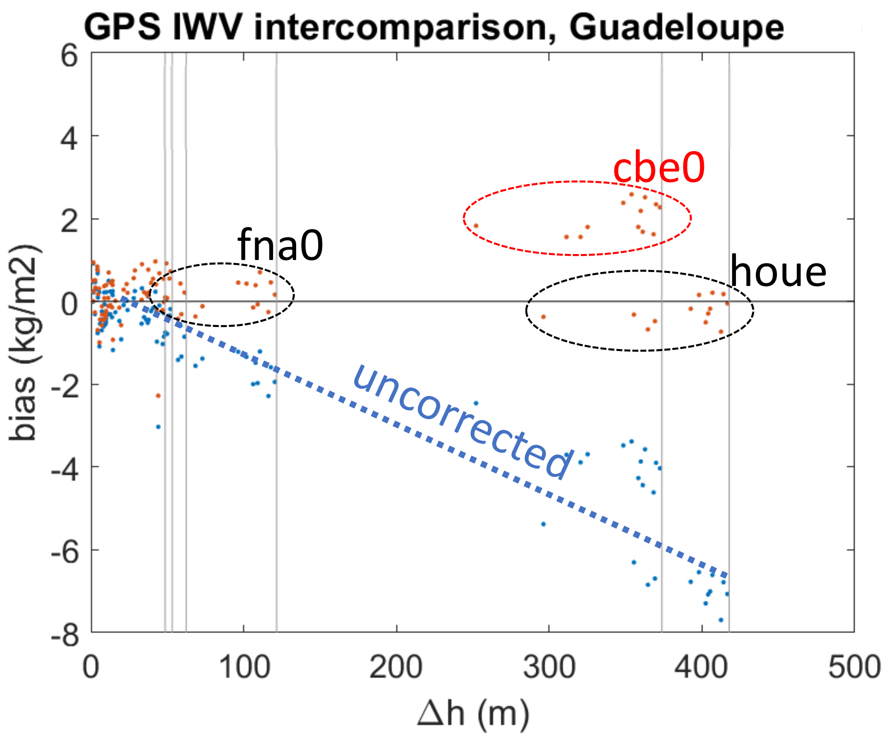
# Spatial homogeneity vs. station-specific biases

## GNSS vs. GNSS intercomparison

- Case study: 15 GPS stations in Guadeloupe, 2020




| station | height (m) |
|---|---|
| pptg | 1 |
| ldis | 4 |
| deha | 5 |
| desi | 11 |
| magt | 13 |
| boul | 14 |
| abmf | 15 |
| abd0 | 20 |
| aber | 25 |
| gosi | 49 |
| ffe0 | 53 |
| maga | 62 |
| fna0 | 122 |
| cbe0 | 374 |
| houe | 418 |

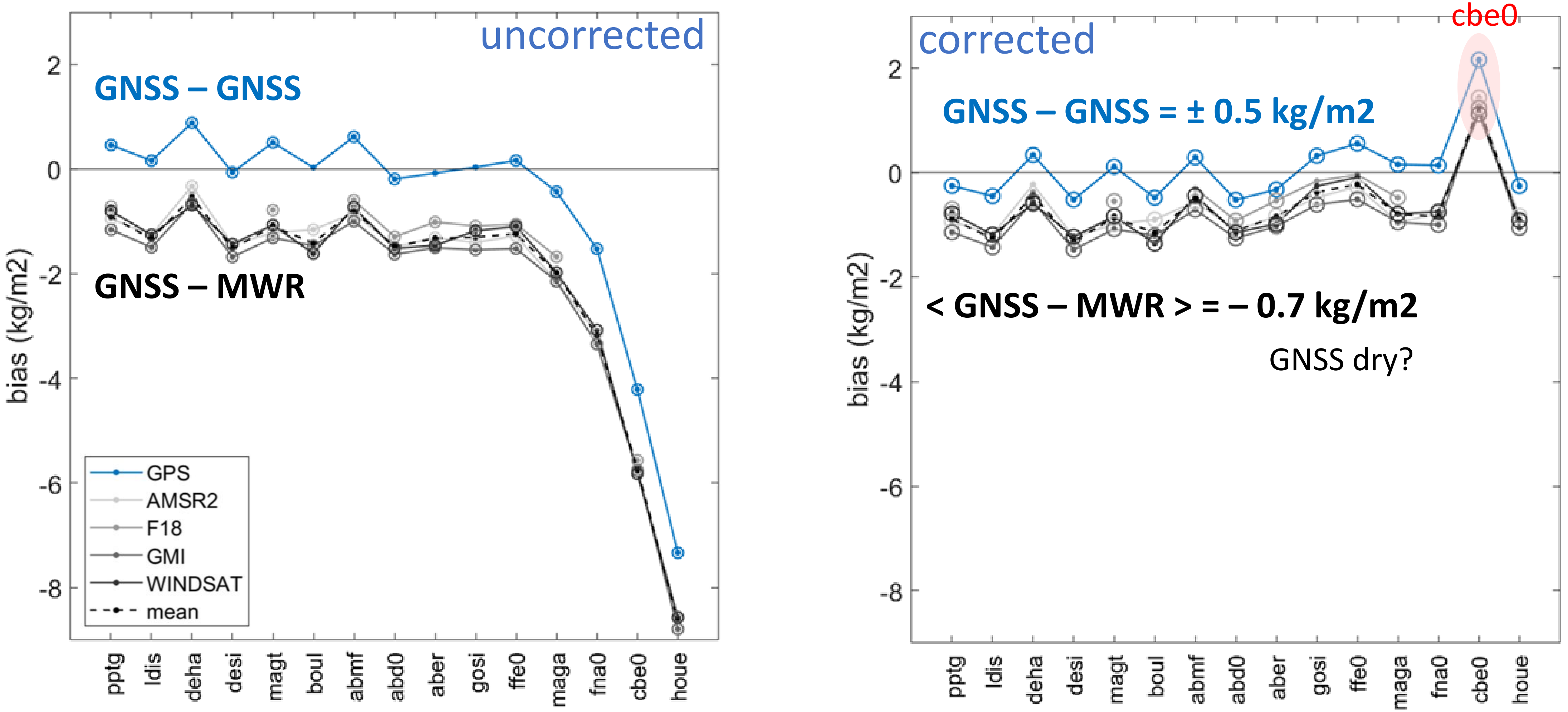



*Bock et al., AMT, 2022: a new* ***vertical correction method*** *for the inter-comparison of IWV data*

# Spatial homogeneity vs. station-specific biases

## GNSS vs. satellite MWR intercomparison

- Case study: 15 GPS stations in Guadeloupe, 2020

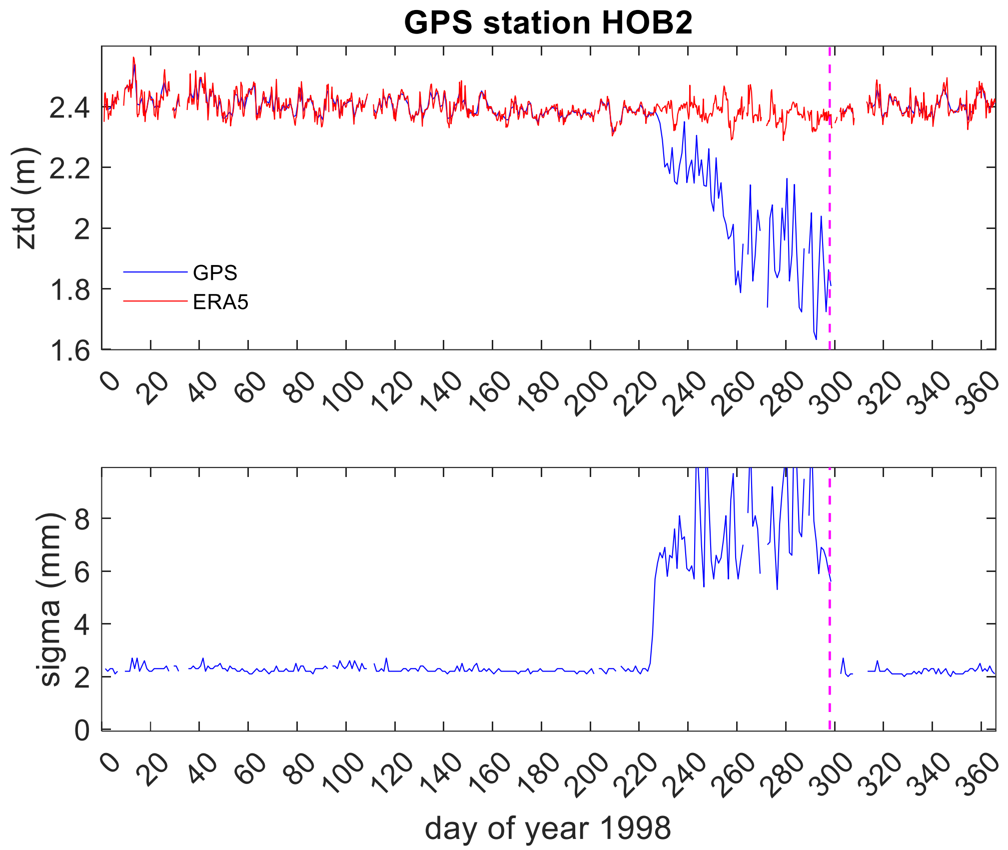


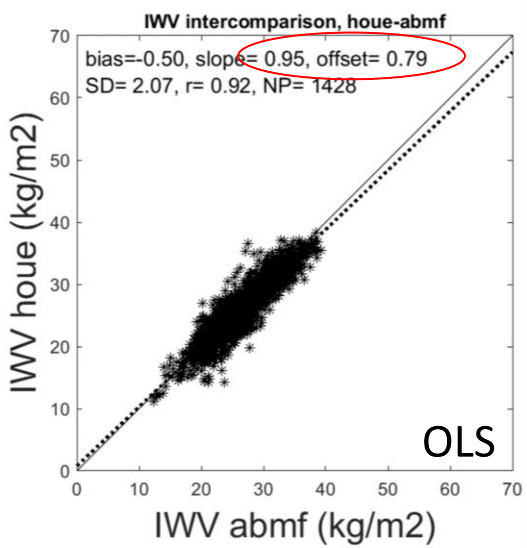

*Bock et al., AMT, 2022: a new **vertical correction method** for the inter-comparison of IWV data*

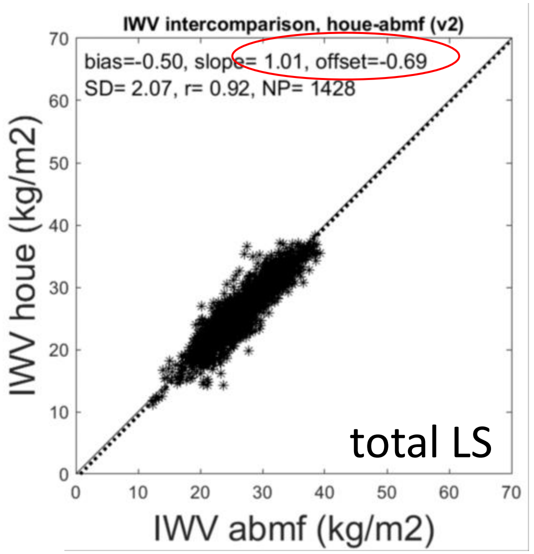
# Estimation of GNSS PW uncertainty

- Is GNSS ZTD formal error estimate valuable?
  - Can help detect instrumental issues
  - Median value ~2 mm (0.3 kg m$^{-2}$) seems too small
- Three-way error analysis (Guadeloupe)
  - u_GNSS = 1.06 kg m$^{-2}$
  - u_MWR = 0.67 kg m$^{-2}$ (AMSR2)
  - u_ERA5 = 1.82 kg m$^{-2}$

  => Suggests to rescale GNSS formal error by x 3
- Realistic uncertainty is important for slope and offset regression (also for trend estimation)



# Summary and discussion

## GNSS PW errors (random & systematic)

- are site/station-specific
  - instrumentation, environment/multipath, geographic/climatic region
- depend on processing settings and models
  - mapping functions, antenna PCV, cutoff angle, weighting function…
- change with time (cause inhomogeneities)

## Pathways, tools, methods to mitigate errors:

- optimize site/station-specific processing settings and models
  - tune CO, WF, MF, APCV
  - minimize biases, inhomogeneities, and random errors wrt reference measurements (e.g. GDP)
- detect and correct remaining inhomogeneities with post-processing methods
  - segmentation tool to characterize (in-)homogeneity of time series
  - attribution tool + jump correction => provide homogenous time series
- assess site/station-specific biases
  - exploit measurement redundancy (multiple GNSS, RS, MWR) with improved vertical correction method
  - repeat at global scale (GRUAN & IGS networks) => assess statistical significance
- global GNSS technique (dry) bias?
  - bias in APCV models? mapping functions? (both are cutoff-dependent)
  - refractivity coefficients ($k_i$) may have extra bias of 0.2 - 0.4 kg $m^{-2}$ (*Healy*, JGR, 2011, issue for GNSS-RO)
    - use revised coefficients (see *Bock et al.*, ESSD, 2021, adapted from *Rueger*, 2004); push for new $k_i$ measurements?
- collaborative effort
  - GRUAN GNSS-TT in liaison with IAG/ICCC WGs and larger GCOS community