Long-Term TCWV Climate Data Record Using Ground-Based GNSS

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GNSS (Global Navigation Satellite Systems)

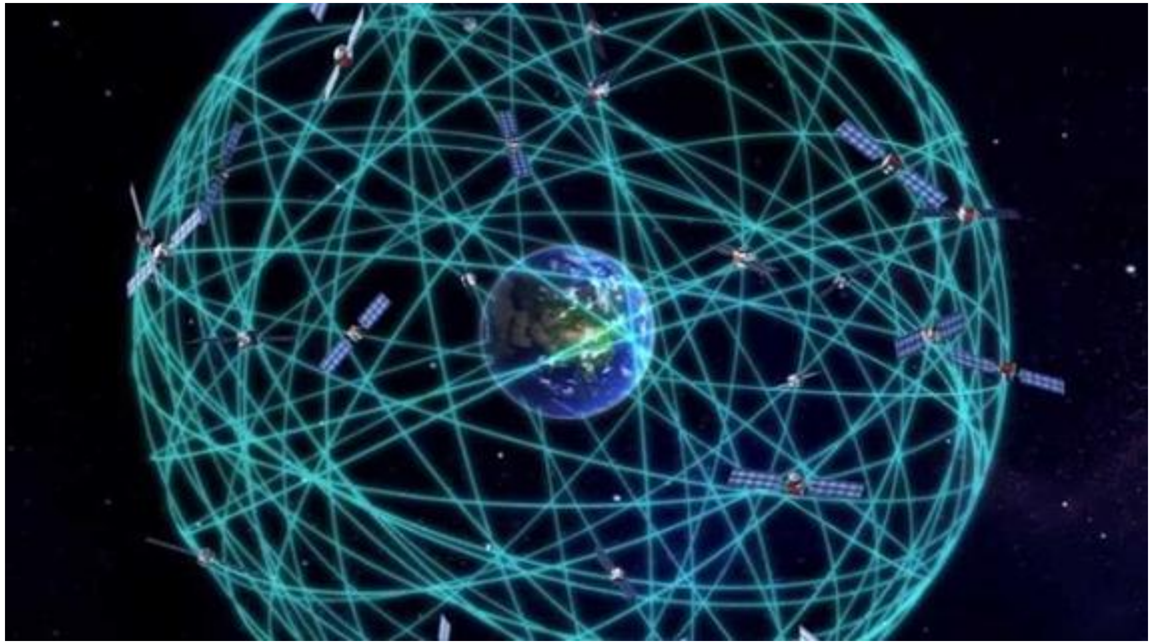
satellite constellations that provide global positioning, navigation, and timing (PNT) signals.

Space segment:

- GPS (USA)
  31 MEO satellites at 20,200 km, since 1994
- GLONASS (Russia)
  24 MEO satellites at 19,130 km, since 2011
- Galileo (Europe)
  31 MEO satellites at 23,222 km, since 2018
- BeiDou (China)
  44 LEO/MEO/GEO satellites at 21,500 km, since 2020

Signals:

- Satellites transmit three or more L-band MW signals (1.1 – 1.6 GHz)

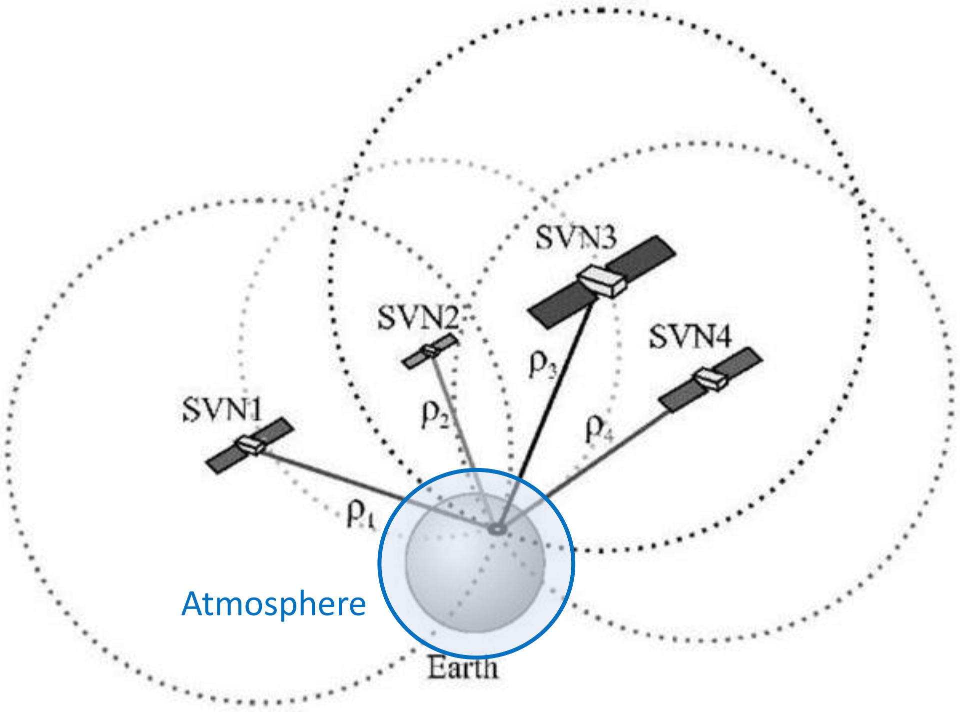


https://www.geospatialworld.net

Atmospheric remote sensing with GNSS

Signals transmitted by the GNSS satellites are measured by:

- ground-based geodetic receivers
  - Zenith Tropospheric Delay (ZTD) -> NWP
  - Integrated Water Vapor (IWV) -> climate research
- LEO satellites (Radio-Occultation)
  - Refractivity & bending angles -> NWP
  - Temp, humidity, density profiles -> climate research



https://mobacommunity.com/

Geodetic data processing (positioning)

Simultaneous estimation of:

- Receiver position (1 per 24h)
- ZTD parameters (typ. 1 per hour) and gradients
- Receiver clock offsets, ambiguities, iono delays…

Observable (carrier phase):

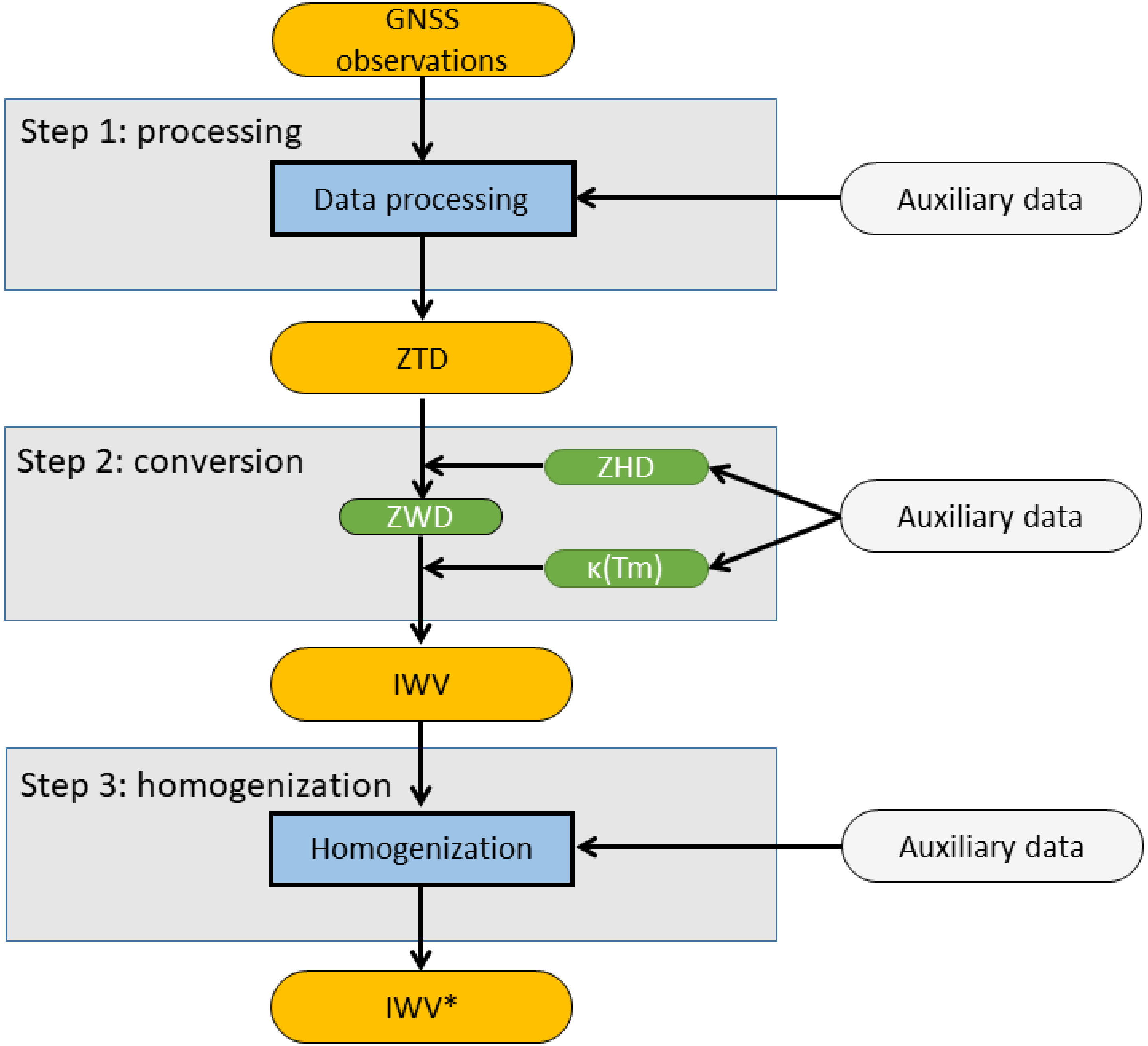
$$L_r^s = \rho_r^s + c \cdot (\delta t_r - \delta t^s) + \lambda \cdot n_r^s - d_{iono} + d_{tropo} + d_{ant}$$

$d_{tropo} \approx 10^{-6} \int N(s)ds$: includes dry air + water vapour

≈ 2.50 m at zenith

≈ 20 m at elevation $e = 5°$

GNSS IWV Climate Data Record development workflow



International Assoc of Geodesy (IAG)'s products:

- Precise GNSS satellite orbits & clocks
- Earth Orientation Parameters
- Antenna calibration models
- Solid Earth deformation conventions and models
- Tropospheric mapping (air-mass) functions (NWP model)

- Refractivity constants (empirical)
- Surface air pressure (barometer / NWP model)
- Column-mean air temperature (NWP model)

- Change-point detection and correction (statistical methods)
- Equipment-change records (if available)
- Independent validation data (if available)

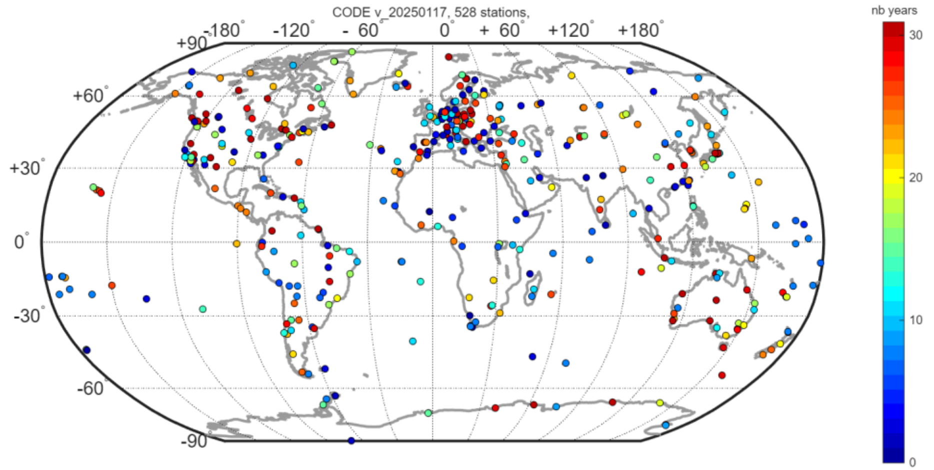
Status and initiatives for establishing GNSS IWV CDRs

There is currently no formal international authority that delivers an endorsed, global, long-term ZTD or IWV data set for climate research.

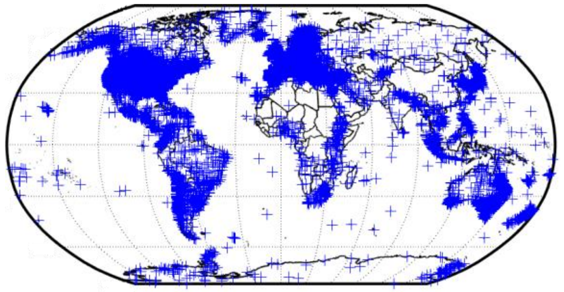
What exists and what is done:

- **IGS (International GNSS Service) / IAG:**
  - provides GNSS infrastructure products (orbits, clocks, antenna models) necessary to most scientific applications (positioning, NWP…),
  - computes ZTD as analysis-center (AC) dependent side-product.
- **E-GVAP / EUMETNET:**
  - Near-real time ZTDs for NWP (bias-corrected by the assimilation system)
- **GCOS / WMO:**
  - GNSS recognized as important contributor to baseline/reference networks
  - GRUAN certified its GNSS IWV ^{2}data product in 2025
- **Various individual research initiatives and projects.** Two examples:
  - **NGL** (Nevada Geodetic Lab, Univ. Nevada, Reno): process 20 K stations in PPP with GipsyX (NASA/JPL software) using JPL (IGS AC) satellite products
  - **SPOTGINS** (French research consortium): process 6K stations in PPP with CNES's GINS software using GRG (IGS AC) satellite products.

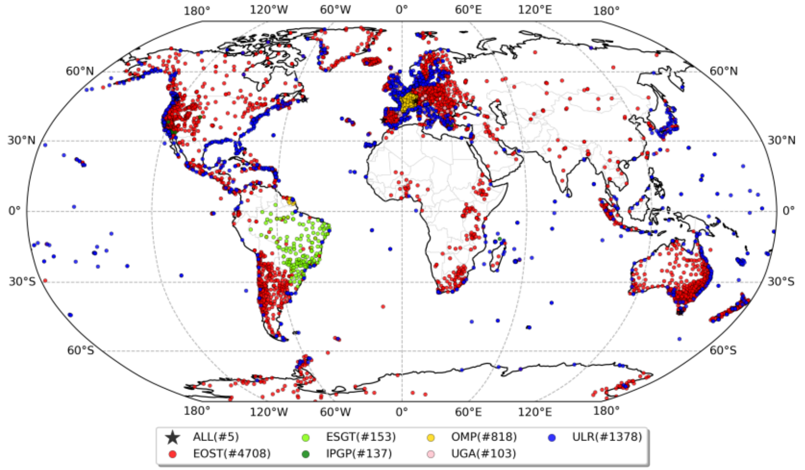
IGS : 30 yrs



NGL : 20K sta



SPOTGINS : 6K sta



Accuracy and stability of GNSS IWV CDRs

(multi-year mean values, for single sites)

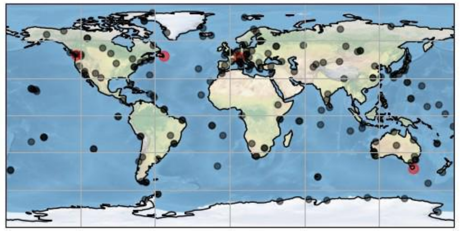
- **Software/AC consistency**:
  - Typically better than ± 2 mm (ZTD) or ± 0.3 kg m^{-2} (IWV)
  - Occasionally up to ± 20 mm (ZTD) or ± 3 kg m^{-2} (IWV) e.g. due to station metadata mis-handling

- **Site-to-site consistency**:
  - Typically better than ± 0.5 kg m^{-2} (< 2%)
  - Occasionally up to ± 3 kg m^{-2} due to system malfunctioning

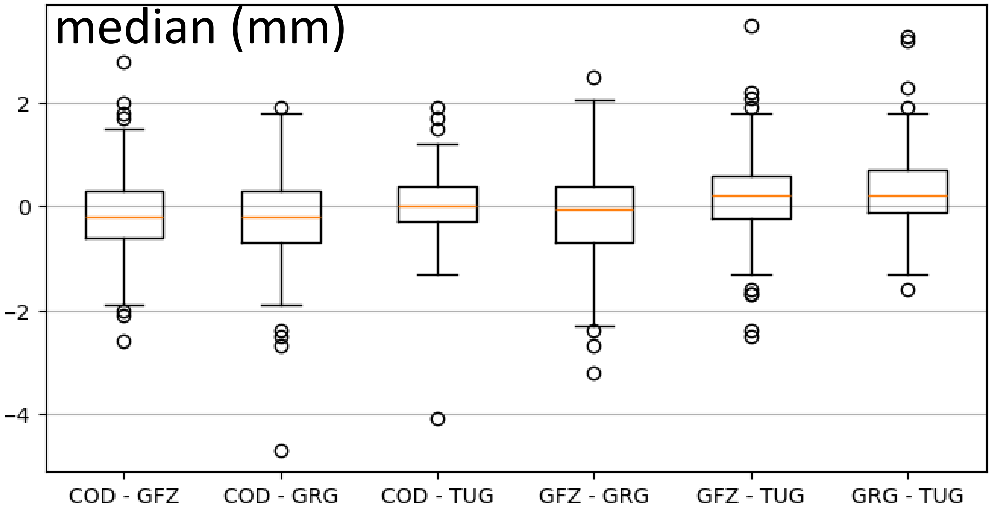
- **Uncertainty in absolute accuracy**:
  - GNSS vs. radiosondes & MW radiometers: bias < ± 0.5 to ± 1 kg m^{-2} (< 2%)
  - Impact of uncertainty in refractivity formulation: ~ 0.1% (2.5 mm or 0.3 kg m^{-2})

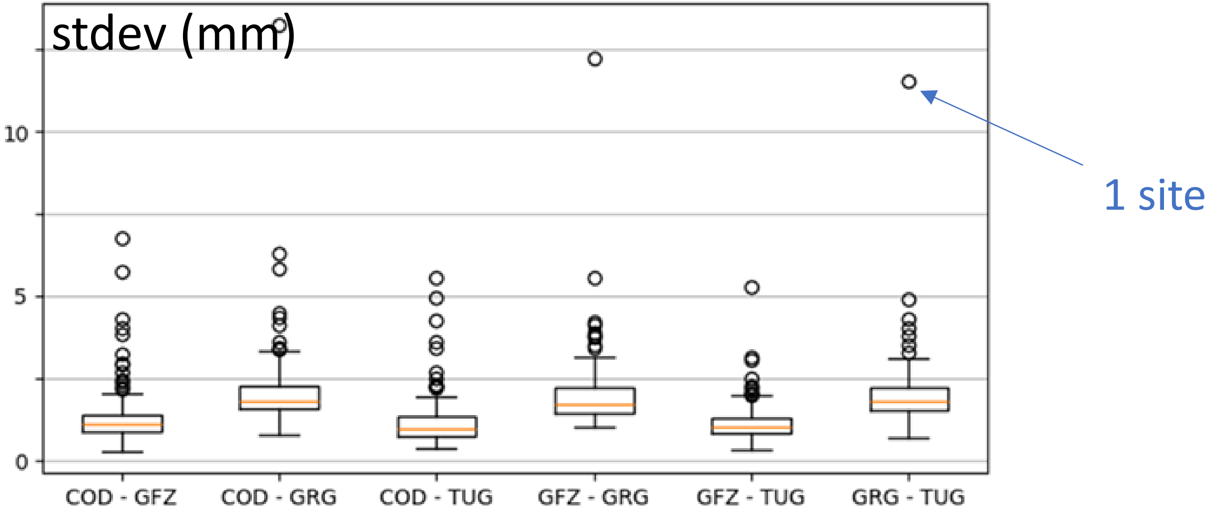
- **Stability / homogeneity:**
  - Primary cause of instability is impact of equipment changes (receiver, antenna, radome) assuming fixed processing procedure
  - Can cause linear trend estimate error at a single site up to 1 kg m^{-2} $decade^{-1}$ (but negligible on global average)

Software and processing consistency



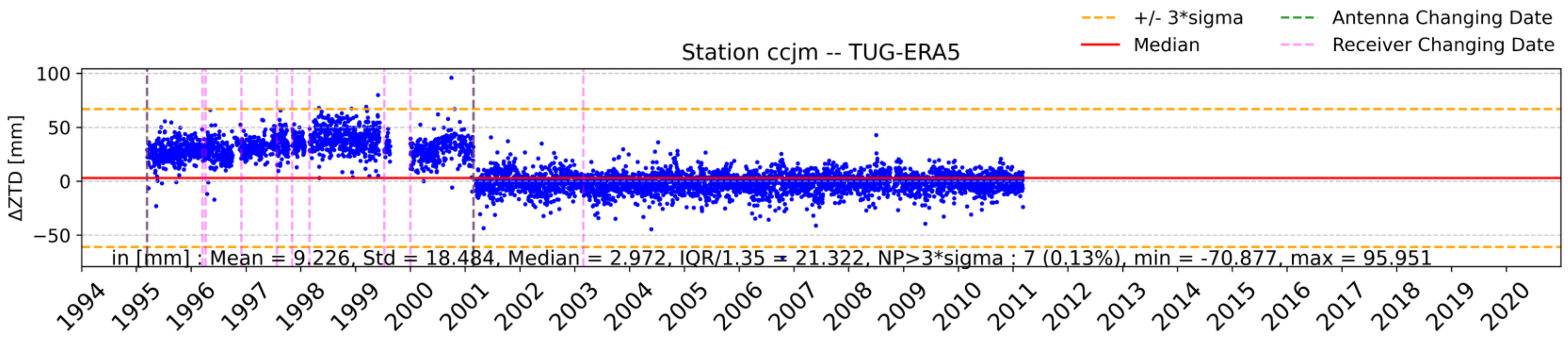
Comparison of daily mean ZTD estimates from 4 IGS Analysis Centres (200 global sites, 20 years)



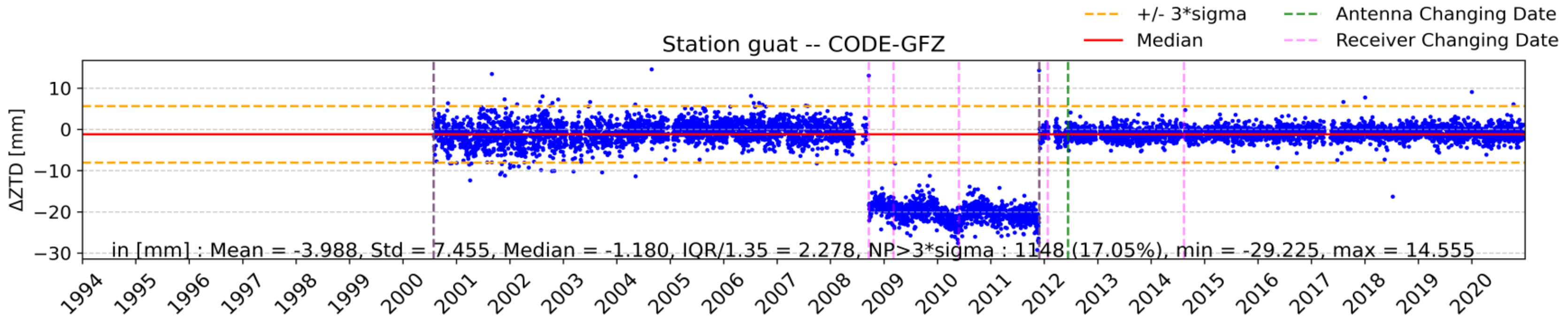


- Consistency between ACs is good, despite differences in software and processing schemes.
- Dispersion in results due to a variety of station equipments and environments.
- Extreme values in stdev due to station metadata mis-handling (this could be avoided at processing level).

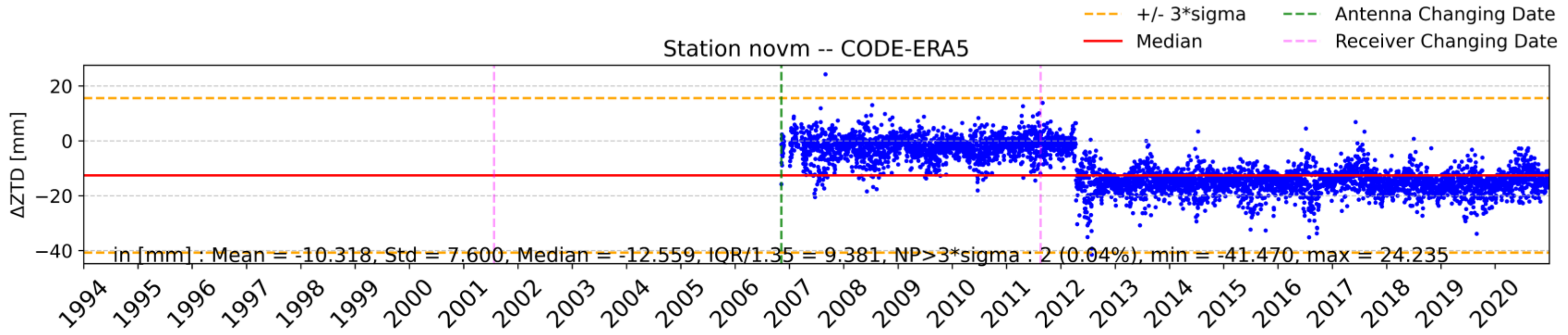
Examples of station metadata mis-handling



- Antenna + radome not calibrated before 2001 => 20 mm bias ~ 3 kg m^{-2}

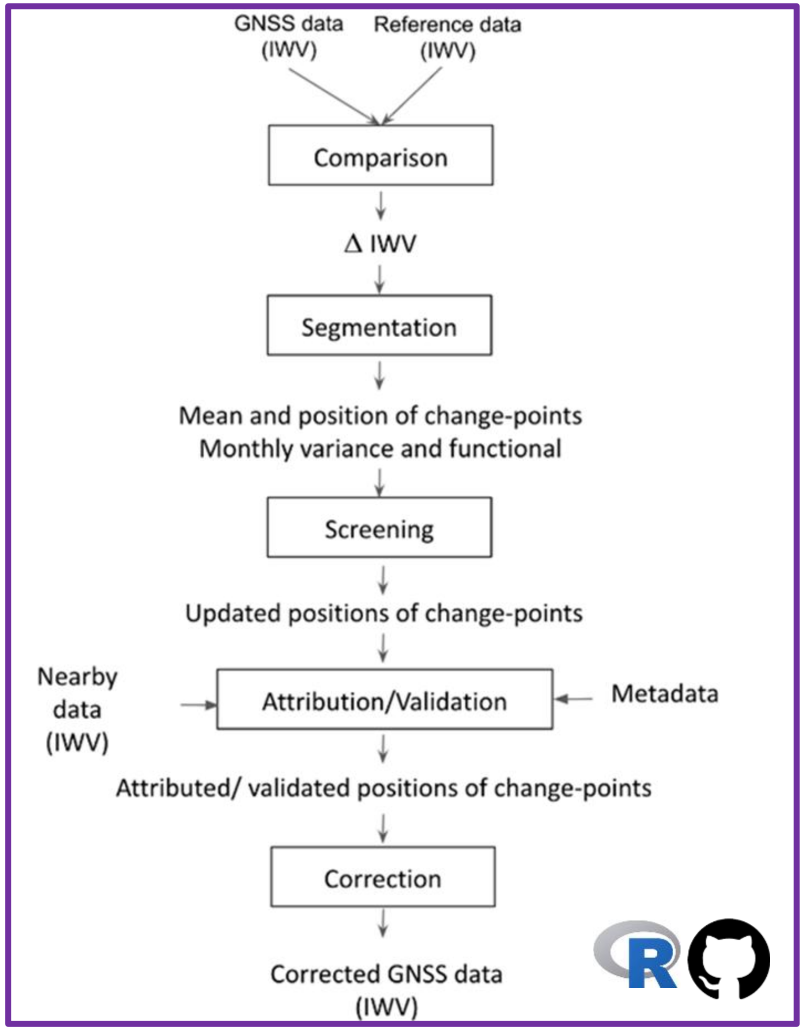


- AC applied antenna change at wrong date => 20 mm bias ~ 3 kg m^{-2}



- Possibly wrong equipment change in sitelog => 12 mm bias (~ 2 kg m^{-2})

Homogenization of GNSS ZTD or IWV time series



Quarello et al., 2022, https://doi.org/10.3390/rs14143379
Nguyen et al., 2024, https://doi.org/10.1002/joc.8441

Segmentation:

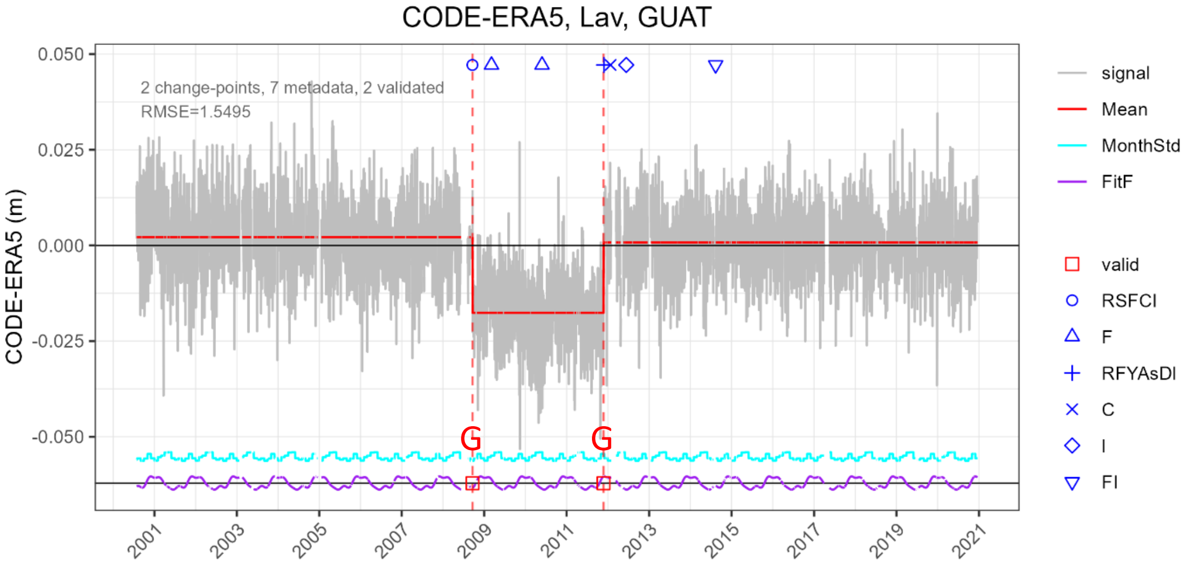
- Differential approach: GNSS – ERA5 daily IWV-difference series
- PMLseg (Penalized Maximum Likelihood segmentation) R package
- *https://github.com/khanhninhnguyen/PMLSeg*

=> detect number and position of change-points

Attribution:

- Multiple-pairwise comparison with nearby stations
- Generalized LS test & Random Forest classifier trained on 40K cases (NGL)

=> predict if change-point in IWV-difference series is due to GNSS or ERA5



Homogenization of GNSS ZTD or IWV time series

<u>Segmentation results</u>:

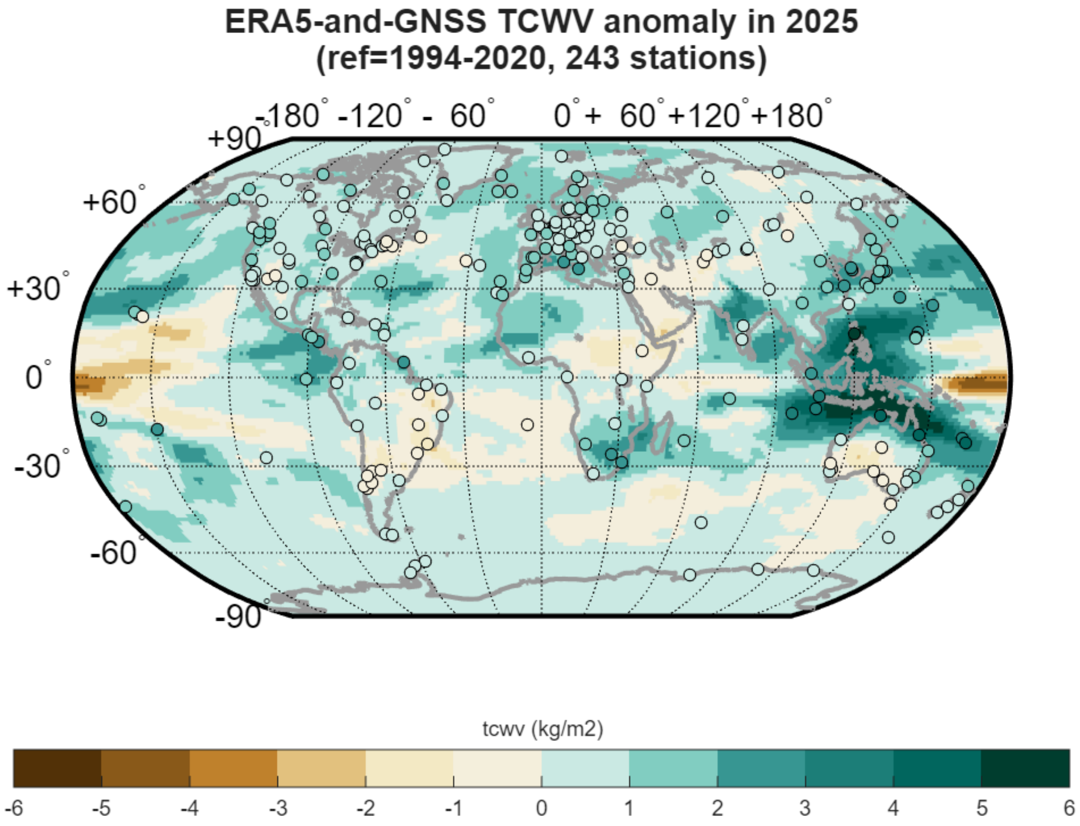
- Method applied to global GNSS data sets:
  - IGS repro3 from 4 ACs (200 sites, 1994 – 2020)
  - NGL repro3 (6048 sites, 1994 – 2022)
  - CODE/IGS AC (416 sites, 1994 – 2025)

=> Found an average of 1.5 change-points per station every 10 years

- 60% change-points attributed to GNSS (of which 50% documented)
- 20 to 30% to ERA5 (TBC)
- 10 to 20% other causes.

=> GNSS IWV anomalies and decadal trends more spatially homogeneous and consistent with other data (ERA5, satellites).

=> Contribution to the *BAMS State of the Climate* annual report.



Global mean TCWV anomaly in 2025
+0.68 kg/m2 (+2.79%)

(Mears & Bock, TCWV, State of the Climate in 2025, BAMS, under review)

Uncertainty in absolute accuracy

Traditional refractivity formulation:

$$N = k_1 \frac{P_d}{T} Z_d^{-1} + k_2 \frac{P_v}{T} Z_v^{-1} + k_3 \frac{P_v}{T^2} Z_v^{-1}$$

Errors introduced during IWV conversion:

$$IWV = \kappa(T_m) \times (ZTD - ZHD)$$

hydrostatic delay

$$ZHD = \frac{10^{-6} k_1 R_d}{g_m} \times P_s$$

conversion factor (m -> kg/m2)

$$\kappa(T_m) = \frac{10^6}{R_v\left(k_2' + \frac{k_3}{T_m}\right)}$$

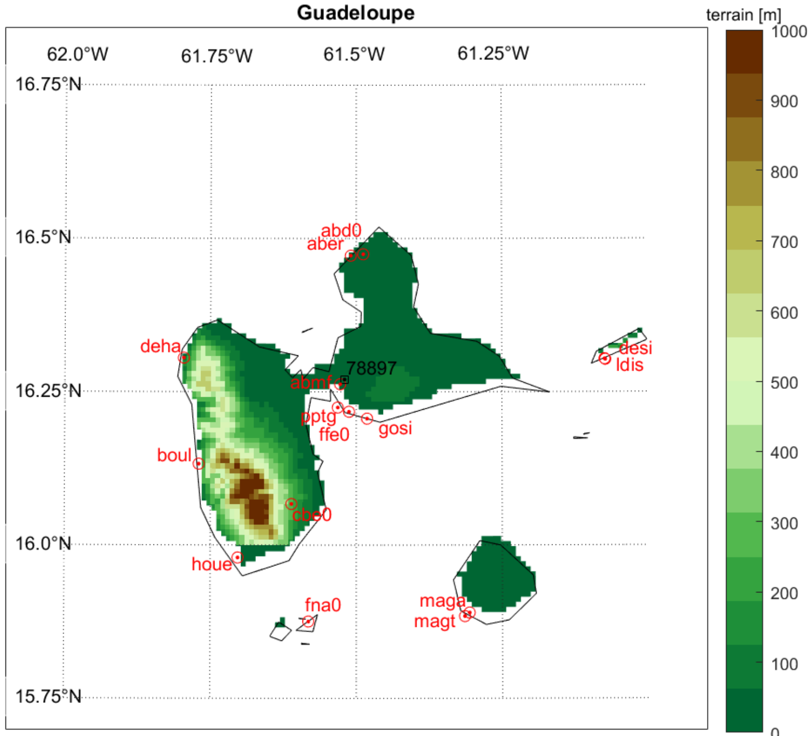
weighted mean temperature

$$T_m = \frac{\int \rho_v(z)dz}{\int \frac{\rho_v(z)}{T(z)}dz} \approx a + bT_s$$

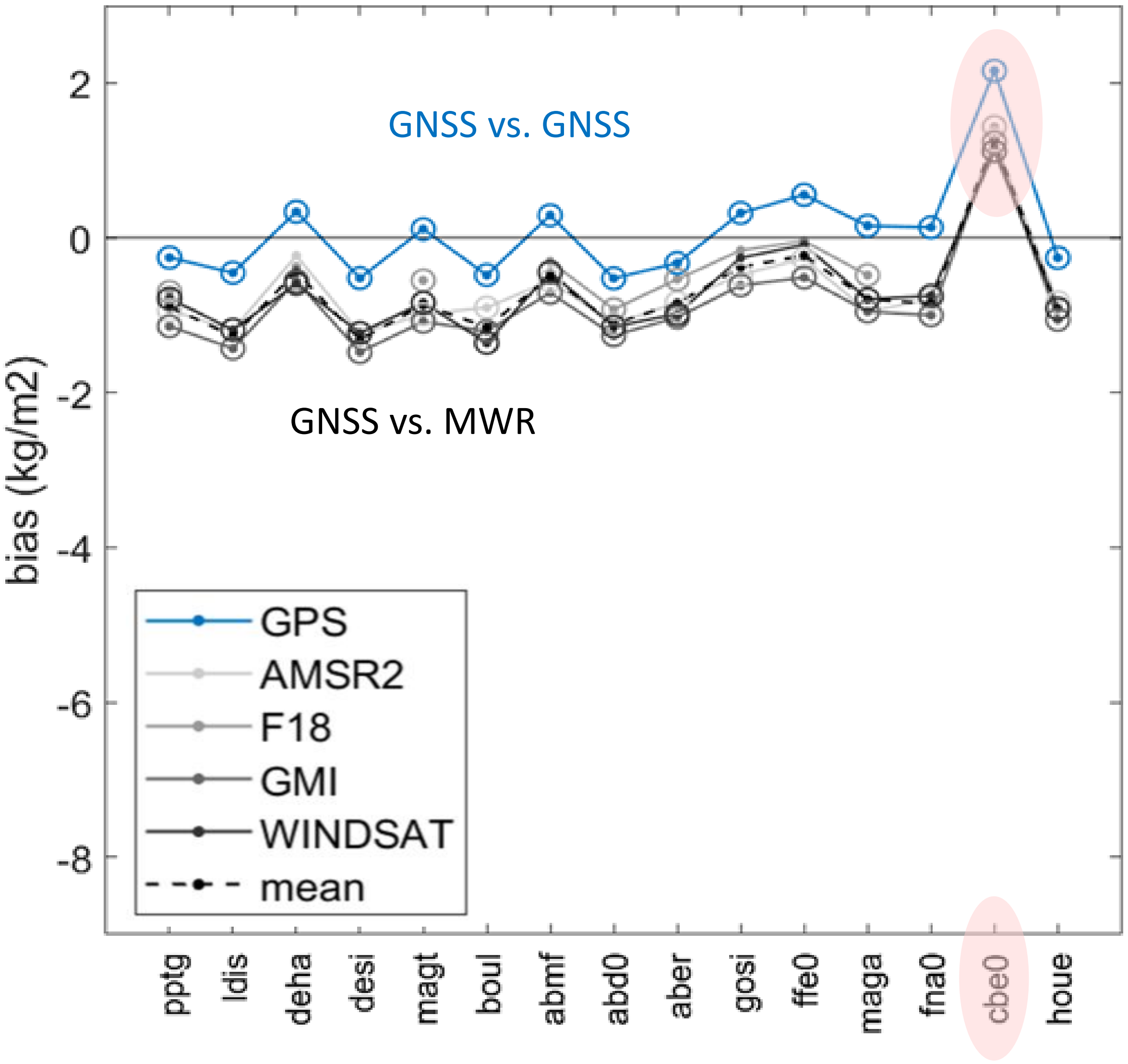
Sensitivity analysis:	Standard errors:		δIWV
$\left(\frac{\partial IWV}{\partial ZTD}\right) \approx 0.15$ kg m^{-2}.mm^{-1}	δZTD = 5 mm	=>	0.75 kg m^{-2}
$\left(\frac{\partial IWV}{\partial Ps}\right) \approx -0.35$ kg m^{-2}.hPa^{-1}	δPs = 1 hPa	=>	0.35 kg m^{-2}
$\left(\frac{\partial \ln(IWV)}{\partial Tm}\right) \approx 0.37$%.K^{-1}	δT_m = 3 K	=>	0.20 kg m^{-2} (*)
$\left(\frac{\partial IWV}{\partial k_1}\right) \approx -4.5$ kg m^{-2} per K.hPa^{-1}	δk_1 = 0.04 K.hPa^{-1}	=>	0.18 kg m^{-2}
$\left(\frac{\partial \ln(IWV)}{\partial k_2}\right) \approx$ - 0.07 % per K.hPa^{-1}	δk_2 = 1 K.hPa^{-1}	=>	0.013 kg m^{-2} (*)
$\left(\frac{\partial \ln(IWV)}{\partial k_3}\right) \approx$ - 2.6 10^{-4} % per K^2.hPa^{-1}	δk_3 = 10^3 K^2.hPa^{-1}	=>	0.048 kg m^{-2} (*)

(*) IWV = 18 kg m^{-2}

Internal consistency and validation of GNSS vs. MWR



15 GNSS stations in Guadeloupe



Agreement between GNSS stations:

- BIAS = 0 ± 0.5 kg m^{-2} (± 1.1%), except cbe0

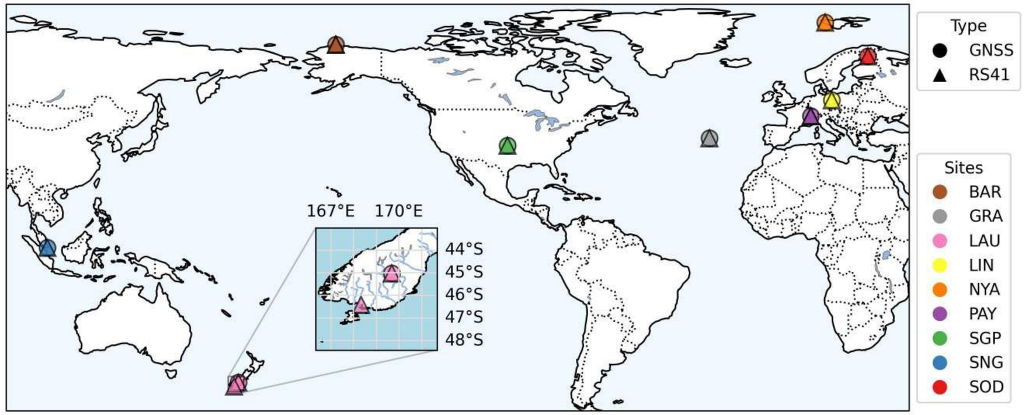
Agreement between GNSS and MWR:

- BIAS = - 0.7 ± 0.5 kg/m2 (- 1.5% ± 1.1%)

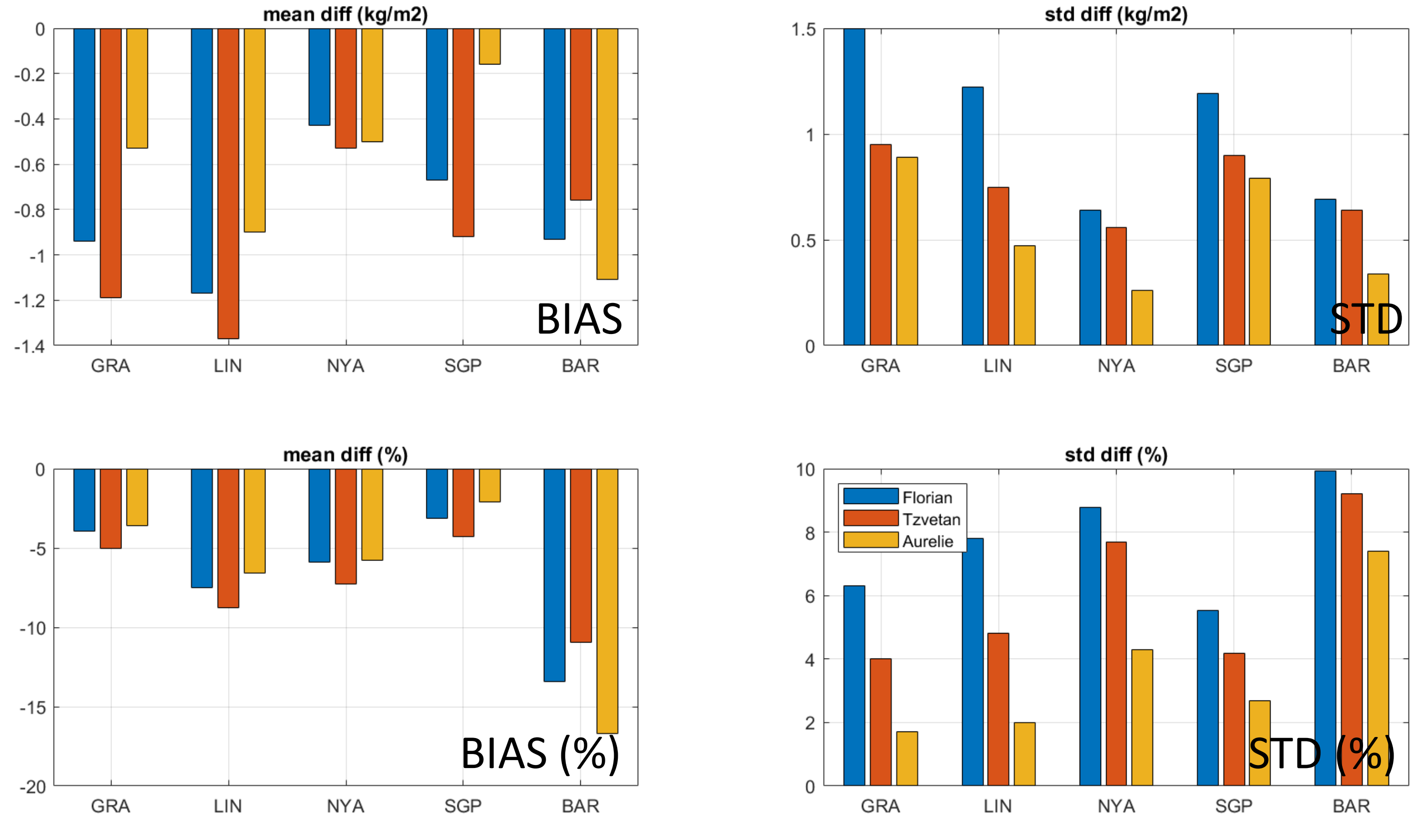
(Bock et al., 2022, https://doi.org/10.5194/amt-15-5643-2022)

Validation of GNSS vs. radiosonde

GCOS Reference Upper-Air Network (GRUAN)



GNSS – RS41.GDP comparisons (2021-2023)



Agreement between GNSS and RS (over 9 sites):

- Mean diff. -0.2 to -1.0 kg m^{-2} (-2 to -15%)
- Std. diff. 0.2 to 0.8 kg m^{-2} (2 to 7%)

Meta-analysis from 3 independent studies reveals:

- Frequent dry bias in GNSS vs RS41
- Site-to-site variability in bias
- Inconsistencies in data handling between studies

GRUAN ICM-16

A. Panetier, F. Zus, G. Dick, O. Bock, J. Wickert
EGU 2025 & GRUAN workshop 2025.

Conclusions and on-going research

- **Intrinsic accuracy of GNSS refractivity formulation, and thus ZTD and IWV retrieval, is ~0.1% (Aparicio, 2025)**

- **Observed accuracy in comparison to radiosonde and MWR measurements is at best 1-2 %**

- **Performance is site-dependent (equipment, environment) and to a lesser extent data processing-dependent.**

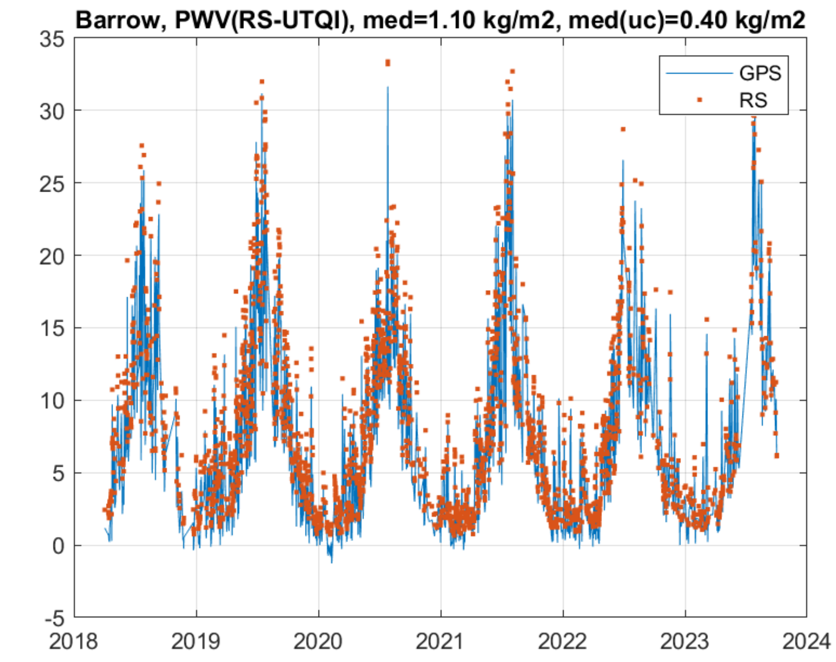
- **Dominant error source of IWV retrieval is with ZTD estimation.**

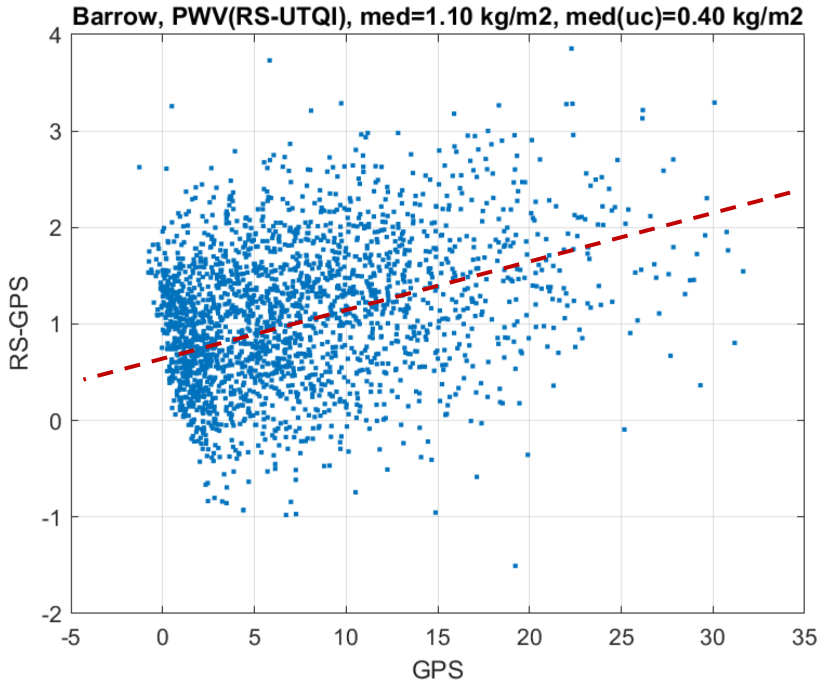
- **ZTD errors result from inconsistencies between observed and computed phases, including:**
  - measurement errors (e.g. multipath and EM interferences near the receiving antenna)
  - modelling errors (e.g. imperfect antenna PCV correction, over-simplistic mapping functions)

- **Establishing future GNSS IWV CDRs requires to pay attention to:**
  - the quality of ground-station's equipment and environment
  - use proper metadata information and physical models during data processing (ZTD estimation)
  - revise the refractivity formula (variability in air composition, departure from ideal gas)
  - quantify more accurately the uncertainty due to the different error sources
  - more generally improve the FAIRness of the GNSS IWV data production chain

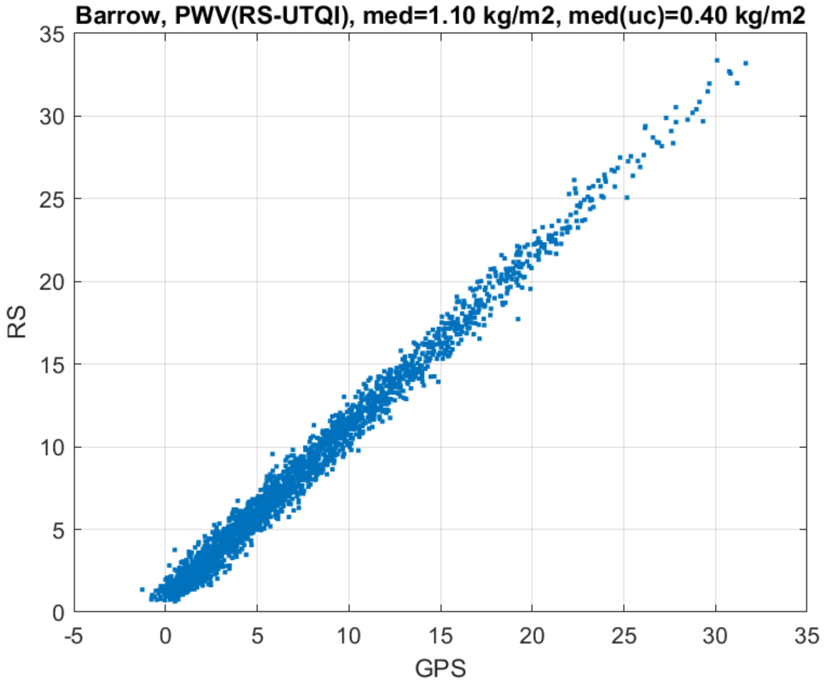
- **Collaborative international research:**
  - COST Action CRIM, GRUAN GNSS task team, IAG & ICCC JWG C.8

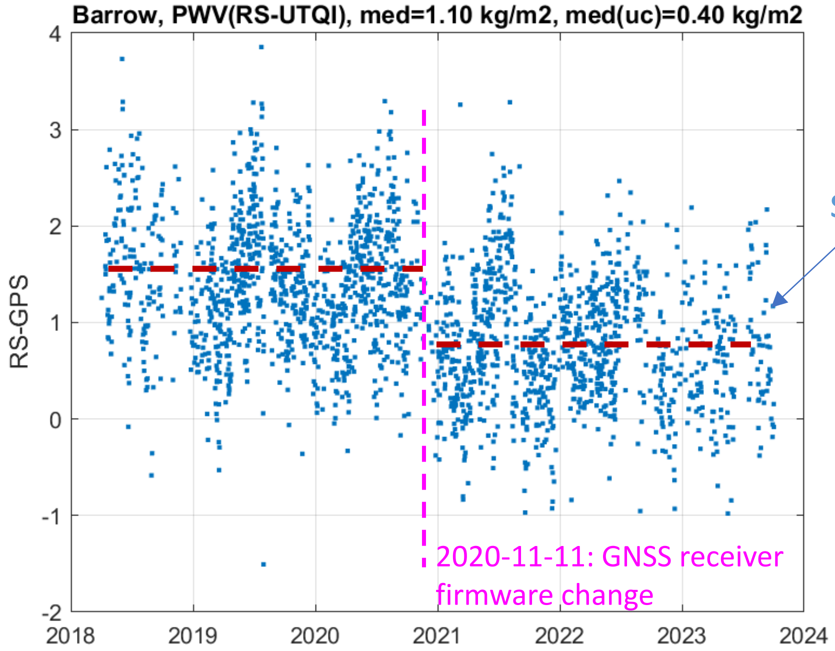
Thank you!





diff. is proportional to IWV

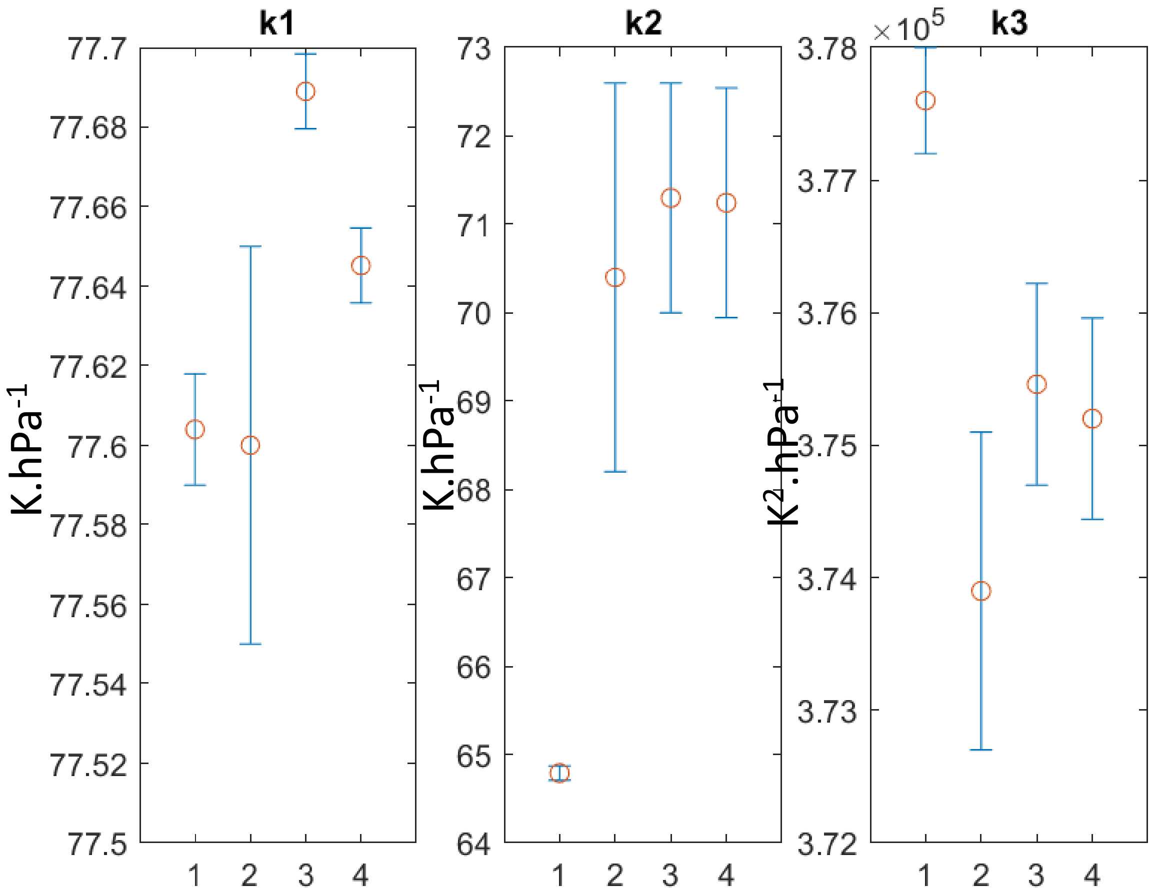




strong seasonal variation in the diff.

GNSS PW error propagation analysis

Impact of refractivity constants on IWV estimates



1: Thayer (1974), 2: Bevis et al. (1994), 3: Rueger (2002), 4: Bock (2021)
Other: Healy (2011), Aparicio (2011).

$$\delta IWV = \left(\frac{\partial IWV}{\partial k_1}\right)\delta k_1 + \left(\frac{\partial IWV}{\partial k_2}\right)\delta k_2 + \left(\frac{\partial IWV}{\partial k_3}\right)\delta k_3$$

$\left(\frac{\partial IWV}{\partial k_1}\right) \approx$ – 4.5 kg m^{-2} per K.hPa^{-1} of k1

$\left(\frac{\partial \ln(IWV)}{\partial k_2}\right) \approx$ - 0.07 % per K.hPa^{-1} of k2

$\left(\frac{\partial \ln(IWV)}{\partial k_3}\right) \approx$ - 2.6 10^{-4} % per K^2.hPa^{-1} of k3

δk_1 = + 0.04 K.hPa^{-1} => - 0.18 kg m^{-2}
δk_2 = + 1 K.hPa^{-1} => - 0.07 % ≈ - 0.013 kg m^{-2} (*)
δk_3 = + 10^3 K^2.hPa^{-1} => - 0.26 % ≈ - 0.048 kg m^{-2} (*)

(*) iwv = 18 kg m^{-2}

Bock et al., *Earth Syst. Sci. Data*, https://doi.org/10.5194/essd-13-2407-2021 .

Computation of “pw_uc” proposed by T. Ning et al., AMT, 2016 (described in TD6 “GNSS PW”, but not fully implemented)

$$\sigma_V = \sqrt{\left(\frac{\sigma_{\mathrm{ZTD}}}{Q}\right)^2 + \left(\frac{2.2767\sigma_{P_0}}{f(\lambda,H)Q}\right)^2 + \left(\frac{P_0\sigma_{\mathrm{c}}}{f(\lambda,H)Q}\right)^2 + \left(V\frac{\sigma_Q}{Q}\right)^2}$$

systematic error

random + systematic error

σ_{ZTD} combines the formal error issued by GNSS data processing software and a simulated ZTD error due to satellite orbit error propagated to ZTD (not implemented currently)

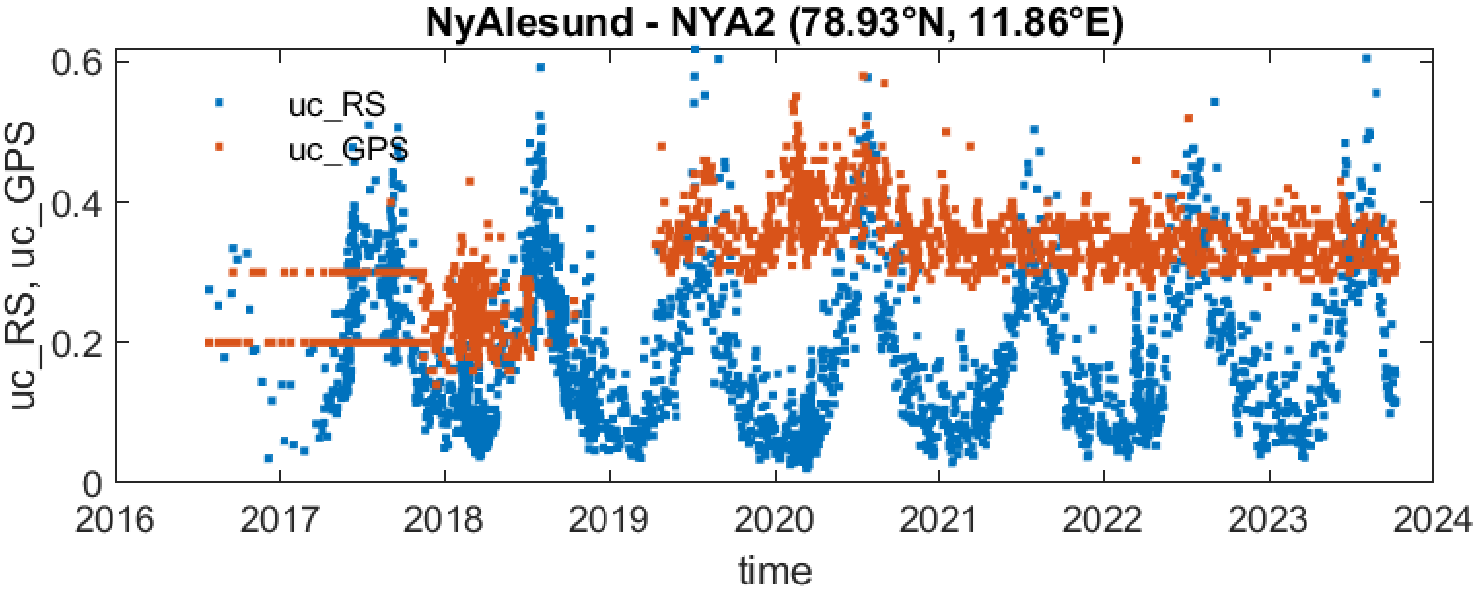
$$\sigma_Q = 10^{-6}\rho_{\mathrm{w}}R_{\mathrm{w}}\sqrt{\left(\frac{\sigma_{k_3}}{T_{\mathrm{m}}}\right)^2 + \sigma_{k_2'}^2 + \left(k_3\frac{\sigma_{T_{\mathrm{m}}}}{T_{\mathrm{m}}^2}\right)^2}$$

$$Q = 10^{-6}\rho_{\mathrm{w}}\,R_{\mathrm{w}}\left(k_2' + \frac{k_3}{T_{\mathrm{m}}}\right)$$

$$f(\lambda,H) = \left(1 - 2.66\times10^{-3}\cos(2) - 2.8\times10^{-7}H\right)$$

PW uncertainties estimates

- uc_RS
- uc_GPS



Ratio

- uc_RS / uc_GPS