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On the consistency between GNSS and radiosonde total column water vapor data

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1. Context and objectives

Assess metrological closure of GNSS and Radiosonde PW (precipitable water)

- **GRUAN TT5: Comparison of GNSS and radiosonde GDPs**
  - previous results presented by G. Dick (2020, 2021, 2022, 2024), T. Simeonov (2024)
  - new results from Aurélie shown hereafter
- **GRUAN TT6: Uncertainty of the GNSS GDP**
  - current methodology for "pw_uc" is based on T. Ning et al., AMT, 2016 (described in TD6 "GNSS PW")
  - methodology needs to be updated/enhanced and TD6 revised accordingly
- **Data products:**
  - Radiosonde GDP: Vaisala RS92 (TD4) & **RS41** (TD8), Meisei iMS-100 & RS-11G (TD5)
  - **GNSS PW from GFZ** for ~20 sites, NRT and repro products (described in TD6)
- **Metrological closure:**
  - Goal = measurements should agree within their uncertainties
- **ECVs requirements** (GCOS 245) for PW or IWV (integrated water vapour)
  - 2-sigma uncertainty: Goal = 0.1 kg/m2, Breakthrough = 0.5 kg/m2, Threshold = 1 kg/m2
  - stability: Goal = 0.1 kg/m2/decade, Breakthrough = 0.2 kg/m2/decade, Threshold = 0.5 kg/m2/decade
  - Goals reformulated in percent of PW: 0.1% and 0.1%/decade (poles) to 1% and 1%/decade (tropics)

2. Previous results (1/2)

GNSS-PW minus ERA5 and RS41.v1 for 2021 (by Florian)

SITE ID	BIAS (kg/m2)		STDDEV (kg/m2)	
Graciosa	+ 0.48	-0.94	+/- 1.83	1.50
Lindenberg	- 0.99	-1.17 LIN0	+/- 1.07	1.22
Lauder (186 km apart)	0.54	-0.12	+/- 1.52	3.52
Ny Alesund	- 0.27	-0.43	+/- 0.57	0.64
Payerne	- 0.36	-0.57	+/- 1.18	1.01
Lamont	- 0.21	-0.67	+/- 1.72	1.19
Singapore	- 0.65	-1.39	+/- 1.34	1.56
Sodankylä	+ 0.27	+0.18 SODA	+/- 0.70	0.73
Barrow	- 0.81	-0.93	+/- 0.70	0.69

range -1.39 to + 0.18 kg/m2
mean -0.52 kg/m2

range 0.64 to 1.56 kg/m2
mean 1.06 kg/m2

GRUAN ICM-15 (Mar 2024), G. Dick et al.

2. Previous results (2/2)

GNSS-PW (NRT) minus RS41.GDP1 for 2018-2024 by Tzvetan

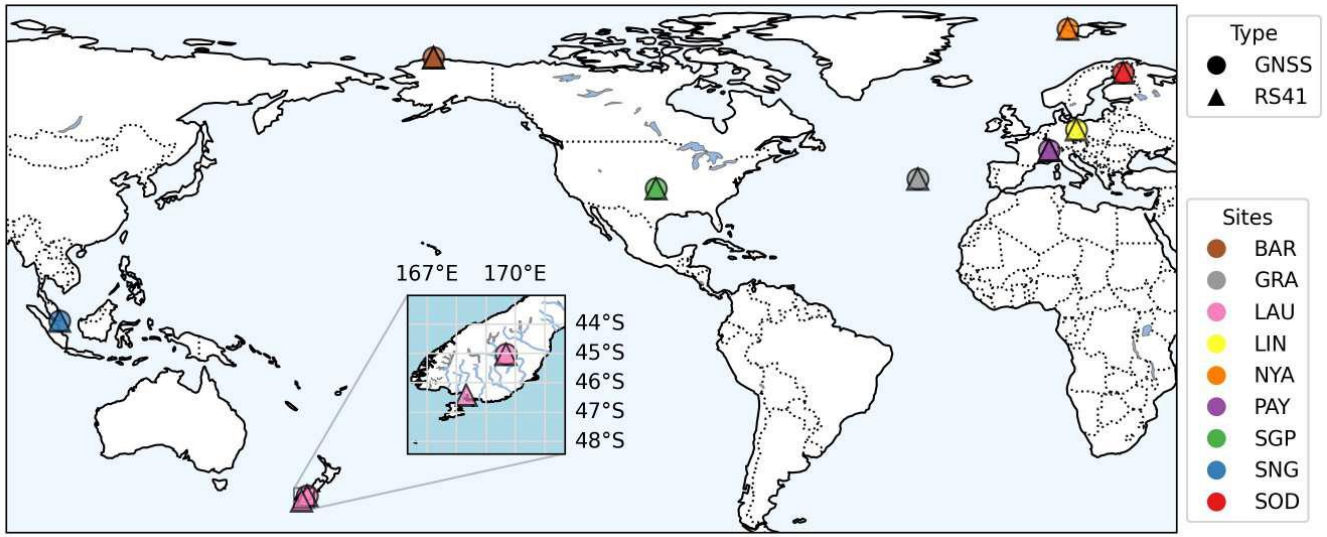
Station	Period	Num obs	Δ IWV mean	σ (Δ IWV)	u(Δ IWV) mean	IWV Consistent	Δ ZTD	Verdict
Barrow	2018 – 2024	2353	-1.1 kg m^{-2} **+ trend**	0.73	0.42 kg m^{-2}	17 / 19 %	**2 mm no trend**	Inconsistent Sig. Different
Beltsville	2018 – 2024	**70**	-0.3 kg m^{-2}	1.03	0.77 kg m^{-2}	66 / 24 %	-4 mm	**Consistent** (small sample)
Graciosa	2019 – 2024	417	-1.2 kg m^{-2}	0.97	0.77 kg m^{-2}	30 / 40 %	**15 mm**	In Agreement
Lauder	2018 – 2024	2685	-0.6 kg m^{-2}	**3.78**	0.55 kg m^{-2}	49 / 10 %	9 mm	Sig. Different
Lamont	2019 – 2024	4113	-0.9 kg m^{-2}	0.99	**0.84** kg m^{-2}	39 / 41 %	-4 mm	In Agreement
Lindenberg	2019 – 2024	4066	-1.3 kg m^{-2}	0.74	0.51 kg m^{-2}	**9** / 20 %	**3 mm**	Sig. Different
NyAlesund	2018 – 2024	2485	-0.7 kg m^{-2}	0.61	0.39 kg m^{-2}	35 / 29 %	11 mm	In Agreement
Payerne	2019 – 2024	2204	-0.6 kg m^{-2}	0.72	0.57 kg m^{-2}	41 / 36 %	7 mm	In Agreement
Ross Island	2019 – 2024	1012	0.1 kg m^{-2}	0.46	0.35 kg m^{-2}	**83** / 12 %	5 mm	**Consistent**

-1.3 to + 0.1 kg/m2
mean -0.75 kg/m2

0.46 to 1.03 kg/m2
mean 0.78 kg/m2

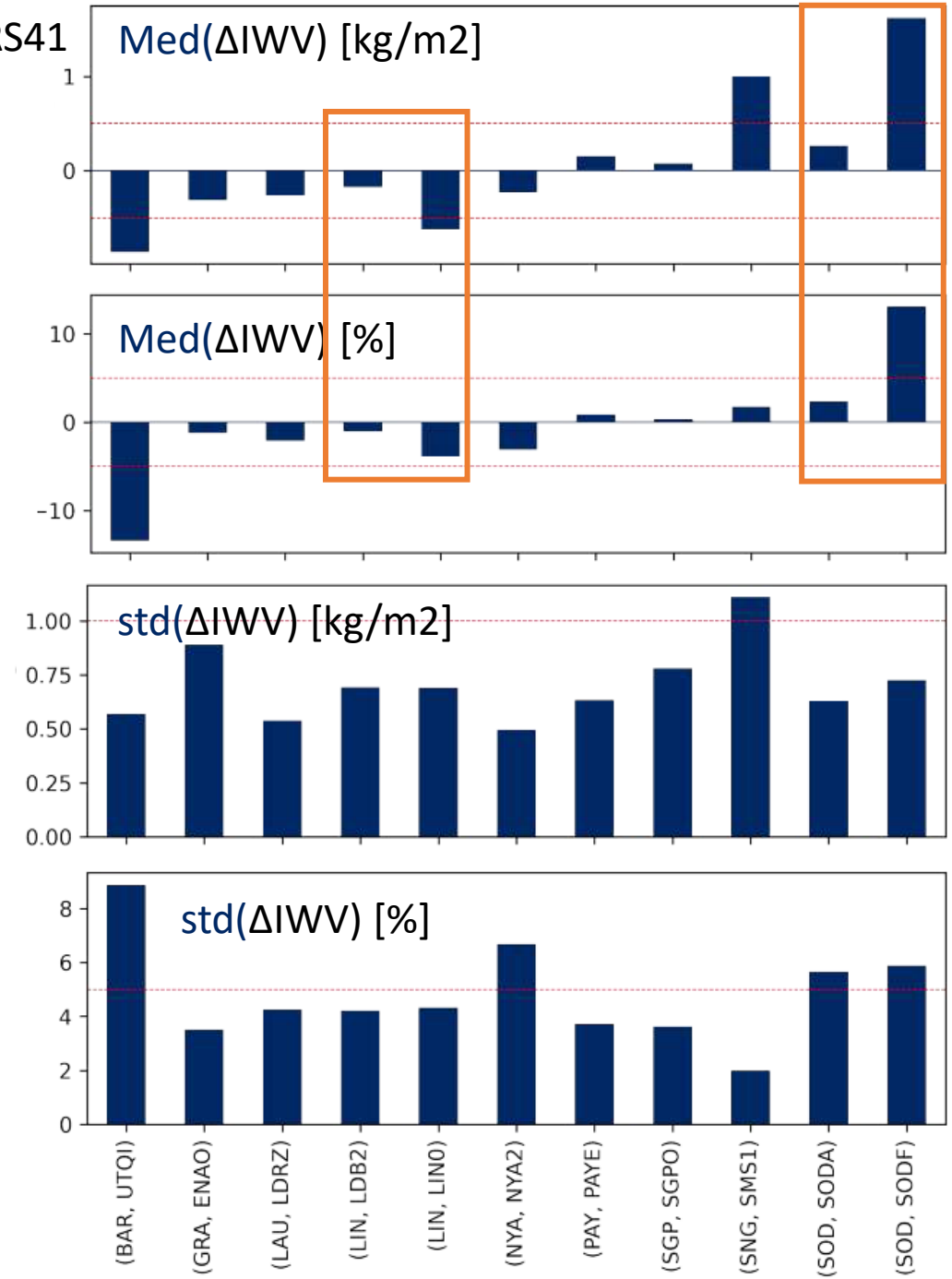
GRUAN ICM-15 (Mar 2024), T. Simeonov

3. New results



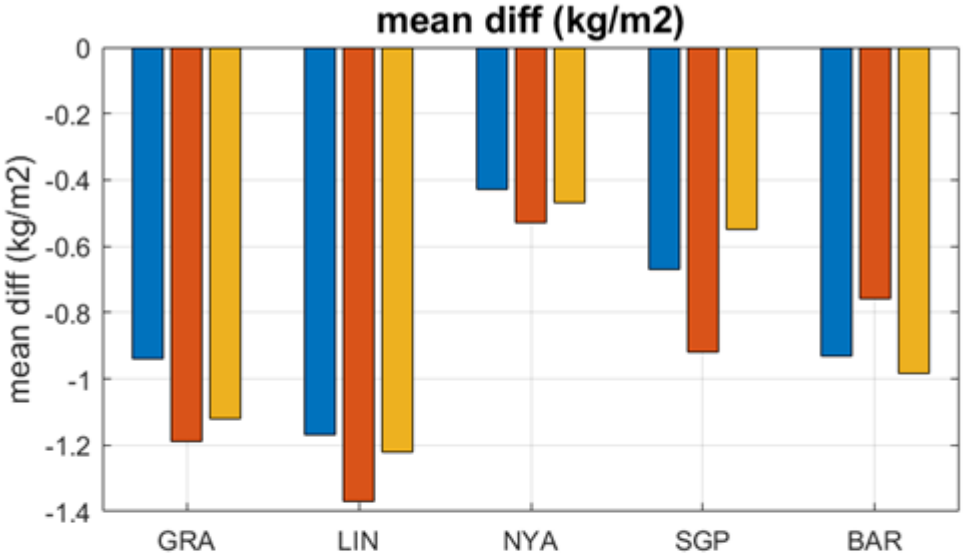
- 9 GRUAN sites / 11 GNSS stations
- data=RS41.GDP.1, GNSS GFZ PW (pp)
- Period 2021-2023
- Collocated GNSS sites have different biases
- Positive bias discovered in the computation of GNSS PW (~ 0.26 kg/m2 or 2.6%), corrected in next slide

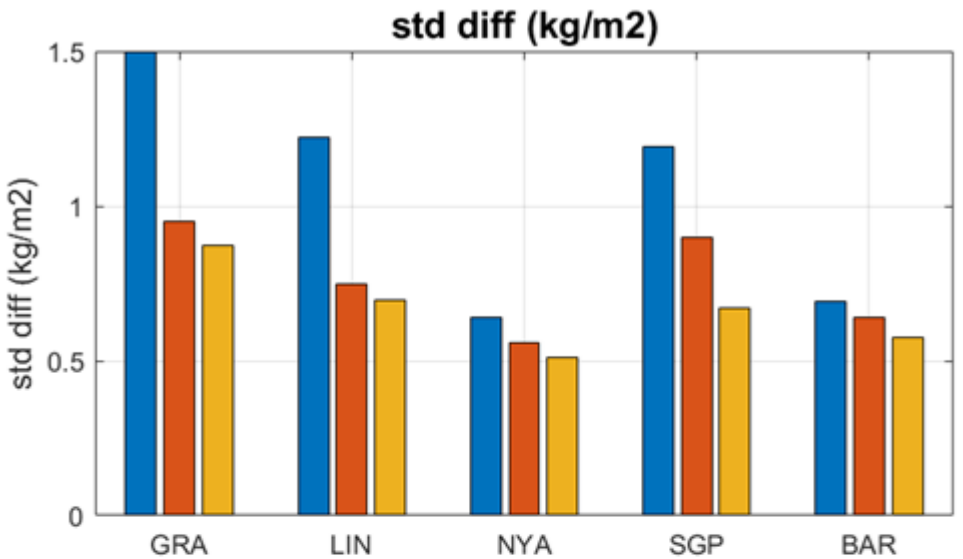
GNSS – RS41

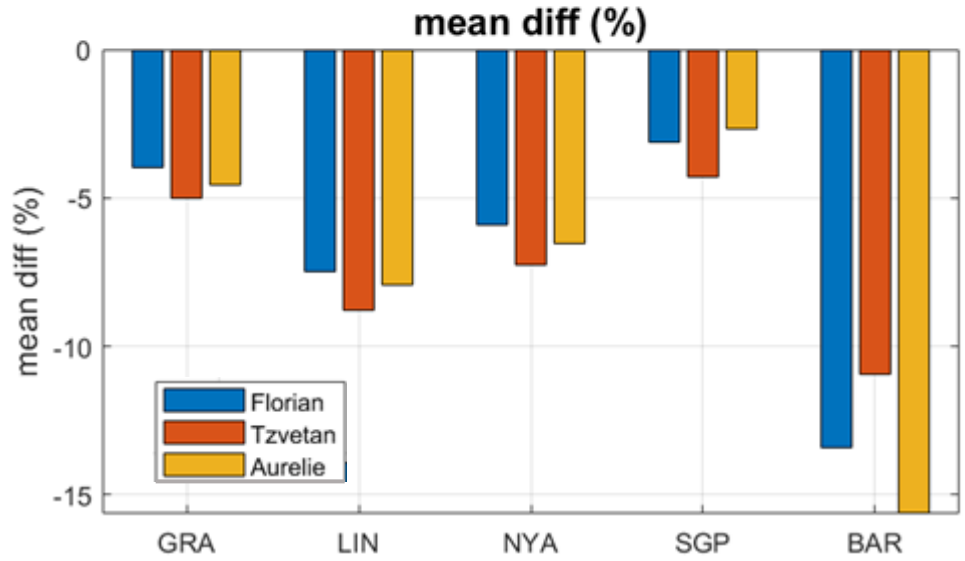


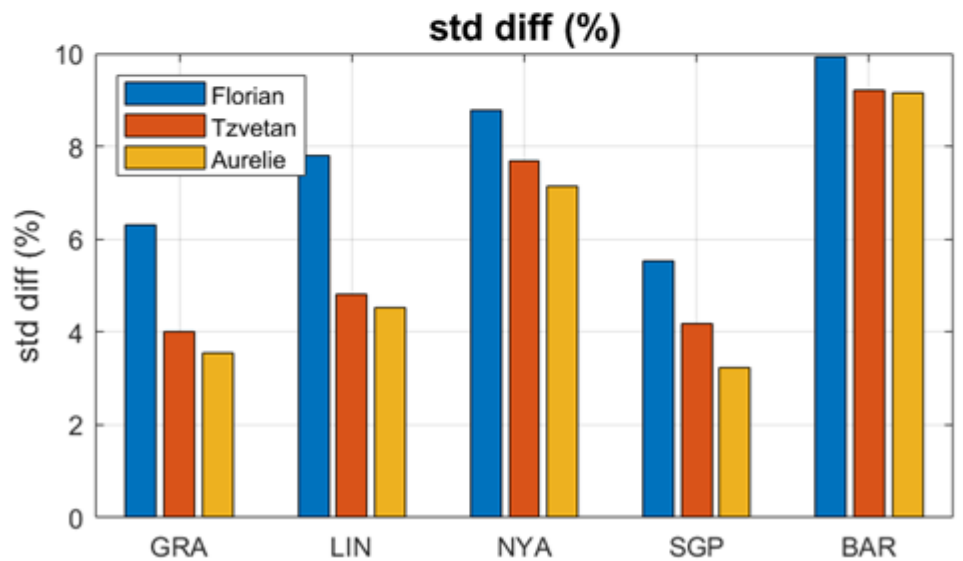
A. Panetier, F. Zus, G. Dick, O. Bock, J. Wickert, ICCC Workshop 2025.

4. Comparison of results (1/2)









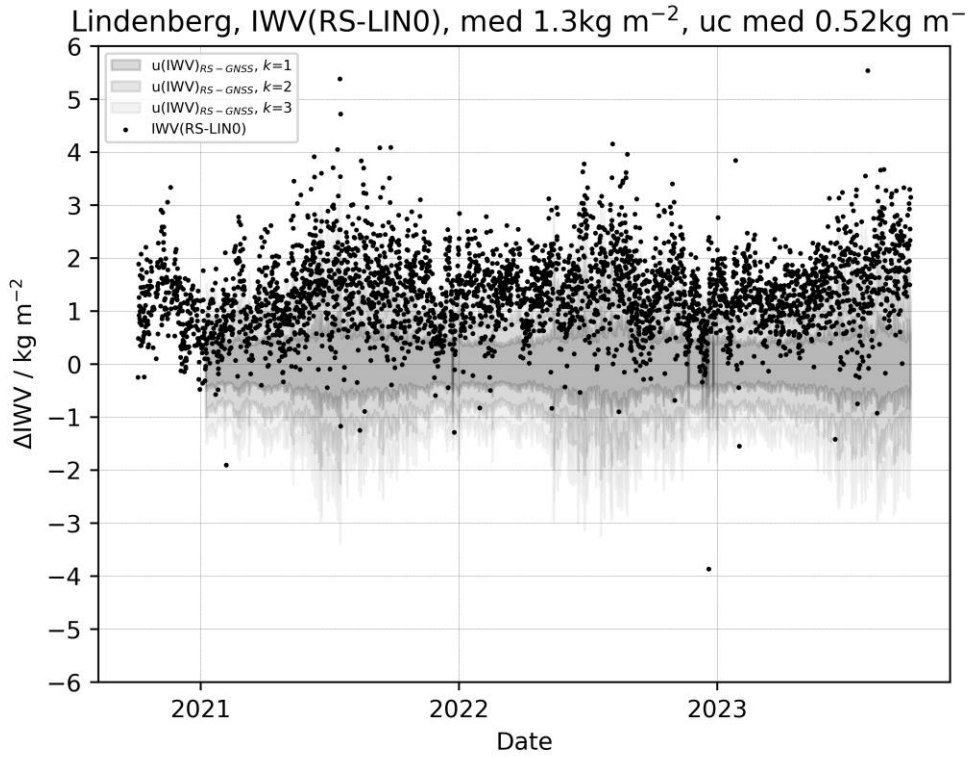
GNSS – RS41.GDP comparisons (various periods)

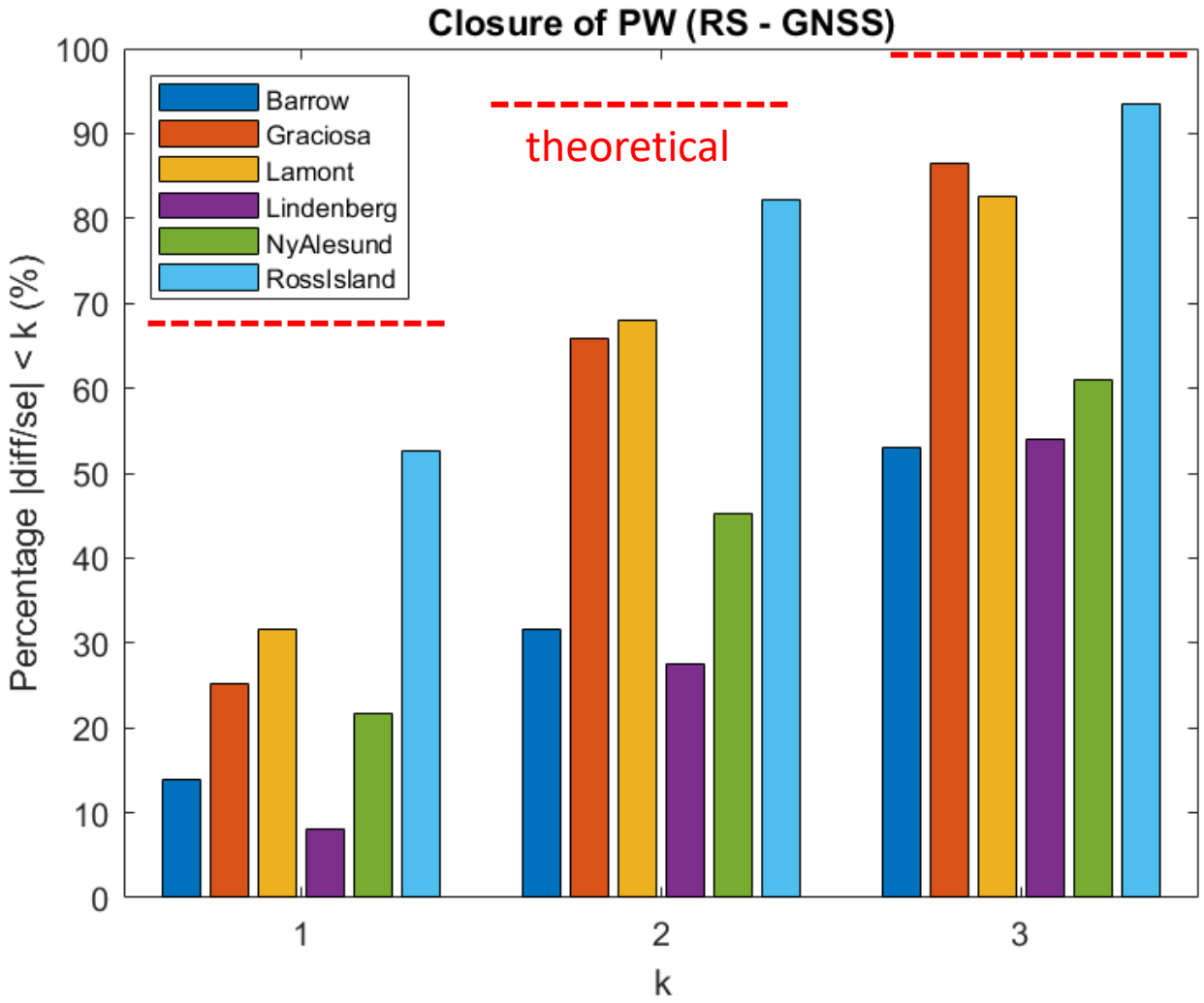
4. Comparison of results (2/2)

- All three studies found:
  - an overall dry bias in GNSS PW vs RS41.GPD PW of – 0.5 kg/m2 or –5 % (and also vs RS92.GDP and MWR)
  - site-to-site variability in bias ± 0.5 kg/m2 (GNSS site/equipt-dependent errors)
- But results don't fully agree:
  - dispersion between studies, in bias and stdev, due to differences in:
    - GNSS ZTD data products (≈ ± 5 mm ≈ ± 0.75 kg/m2 random),
    - GNSS ZTD to PW conversion (≈ ± 0.2 to 0.5 kg/m2 bias + random),
    - correction for height difference btw sonde and GNSS (10m ≈ 0.1 kg/m2),
    - other methodological details (outliers removal, check for missing layers in sonde data...)
- Metrological closure cannot be satisfied
  - biases and outliers in data sets
  - std(Δ) ≈ 1.2 to 1.7 x mean(uc(Δ))
  - GNSS PW uc is probably under-estimated (what about RS PW uc ?)

5. Metrological closure test

$$|m_1 - m_2| < k \cdot \sqrt{\sigma_1^2 + \sigma_2^2}$$





GRUAN ICM-15 (Mar 2024), T. Simeonov et al.

6. Discussion

Need to enhance the methodology of closure assessment

- GNSS and RS PW must be representative of the same physical quantity
  - Remove soundings with missing layers (PW = integral of WV)
  - Correct PW for height difference (10 m ≈ 0.1 kg/m2)
  - Synchronize GNSS and RS times in comparisons (~ launch + 45 min)
  - Compare only measurements from collocated sites (max distance 20 km, vertical 100 m)
- Improve QC/QA of all input data and better understand the error sources in GNSS PW
  - Detect GNSS site-specific problems (e.g. equipment changes, issues during GNSS data processing, 1 mm ZTD error ≈ 0.15 kg/m2)
  - Use accurate P_s and T_m data for ZTD to IWV conversion (1 hPa ≈ 0.35 kg/m2, 1 K ≈ 0.37%)
  - Not all GRUAN sites currently provide their surface meteorological observations for GNSS conversion !
- Revise the PW uncertainty estimation methods
  - GNSS: enhance the theoretical model + cross-validate with statistical approach (GNSS – RS – MWR – satellite)
  - RS: computation of pw_uc should consider vertically correlated errors (TT2 ?)
- Use consistent thermodynamical constants and models to compute GNSS & RS PW (goal < 0.1%)
  - Refractivity coefficients of dry air and WV are not well known, uc ≈ 0.15% k1 ≈ 0.53 kg/m2, 0.3% k3 < 0.24 kg/m2 (Healy, 2011; Aparicio, 2011)
  - Compressibility factor of moist air (0.04% ≈ 0.12 kg/m2), CIPM formula uc ≈ 10^{-5}
  - Enhancement factor in ppwv (0.3 to 0.4% ≈ 0.3 kg/m2), CIPM formula uc ≈ 10^{-5}
  - Earth gravity model as a function of lat, lon, height, TD8 formula uc ≈ 10^{-4}
- Share definitions, models, metadata, etc. on a ‘’GRUAN’’ github repositoty

Thank you!