GNSS-PW DATA FORMAT (A6) AND METROLOGICAL CLOSURE (B8)

Galina Dick, GNSS-PW Task Team,
Florian Zus, Jens Wickert, Benjamin Männel, Markus Bradke, Markus Ramatschi

GFZ German Research Centre for Geosciences, Potsdam, Germany

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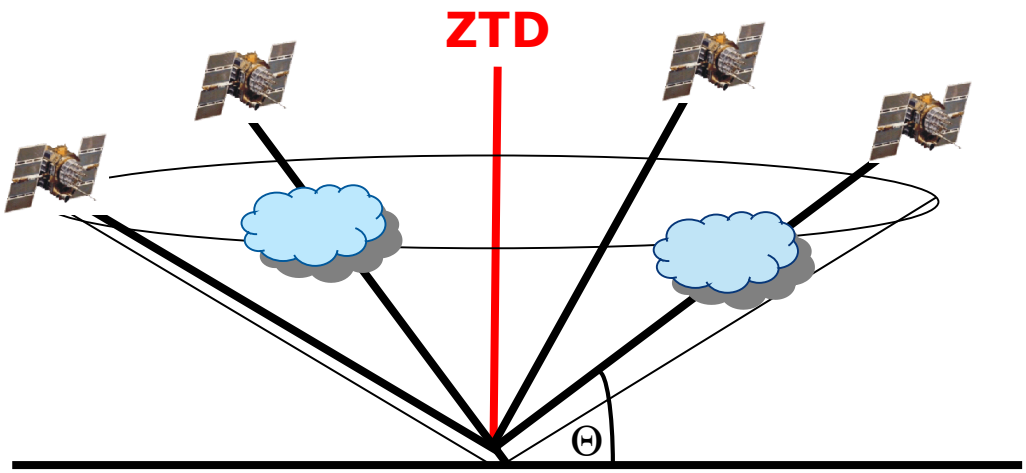
GFZ Helmholtz Centre Potsdam

HELMHOLTZ

GNSS-derived Precipitable Water Vapor



Isotropic water vapor distribution & known mapping function (~1/sin Θ)

Additional: pressure and temperature at the station for conversion of ZTD to PWV

Result of GNSS data analysis: Zenith Total Delay (ZTD) with mm-accuracy

dry, hydrostatic wet

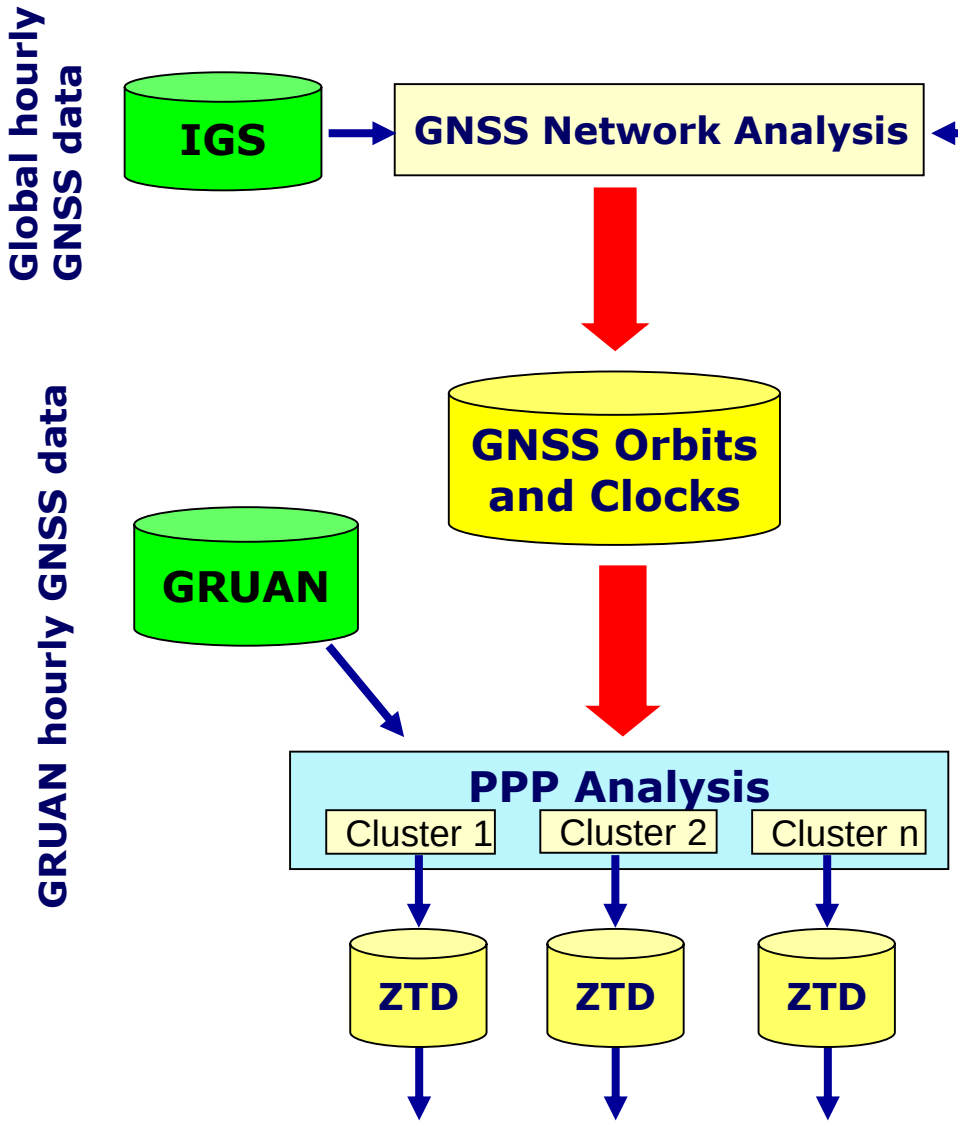
$$ZTD = ZHD + ZWD$$

$$ZHD = f(\text{pressure}) \; [\pm 1 \text{ mm accuracy}]$$

$$PWV = \Pi(T_m) \bullet ZWD$$

Converted Precipitable Water Vapor (PW) or Integrated Water Vapor (IWV)

GNSS Processing with GFZ EPOS.P8 Software



Part 1 - Orbit Improvement

- Adjustment of precise orbits & clocks using global GNSS network of IGS

Part 2 - PPP Analysis

- Estimation of ZTDs and other tropospheric parameters with high sampling rate (15 minutes for ZTD/PW)

Part 3 - Product Generation

- Conversion ZTDs to PW
- Estimation of PW uncertainty

Product generation:
conversion to PW, uncertainty estimation
Product distribution to GRUAN LC

GNSS-PW Uncertainty Estimate

dry, hydrostatic wet

ZTD = ZHD + ZWD

ZHD = f (pressure) [±1 mm accuracy]

PW = Π (T_m) • ZWD

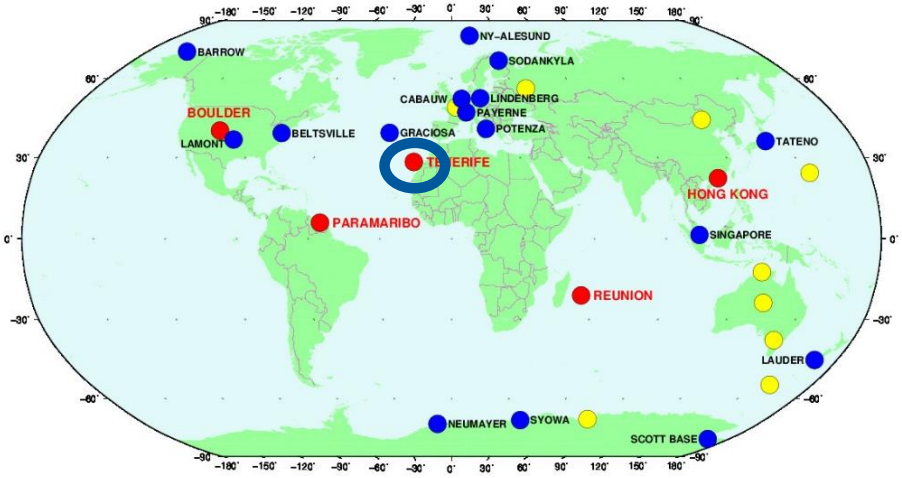
$$\sigma_{PW} = \sqrt{\left(\frac{\sigma_{ZTD}}{\Pi}\right)^2 + \left(\frac{2.2767\sigma_{P_0}}{f(\lambda,H)\Pi}\right)^2 + \left(\frac{P_0\sigma_c}{f(\lambda,H)\Pi}\right)^2 + \left(PW\frac{\sigma_\Pi}{\Pi}\right)^2}$$

Ning et al., 2016: The uncertainty of the atmospheric integrated water vapor estimated from GNSS observations, AMT

σ_{ZTD} (>75%); σ_c (10-20%); σ_{Tm} (2-4%)

GFZ Contribution to GRUAN: GNSS-PW

Network:
- 17 GNSS sites (blue dots + Tenerife)
- 4 new sites (red), 2023/2024



Operational Data Center:
- data handling and archiving
- monitoring of all changes

Processing Centre:
- operational PW estimation
- consistent re-processing
- quality control and uncertainty estimation

Product Validation:
- Good agreement GNSS vs RS, WVR, VLBI and ERA5
- high accuracy of GNSS-PW products

Certification of GFZ GNSS-PW products as GRUAN Data Product on-going

GNSS-PW GDP Formats at GFZ

- SINEX-TRO (IGS):
  - daily file per site
- COST 716 (COST Action 716):
  - hourly (NRT mode) or daily (repro) file per site
  - developed by European Weather Services for operational assimilation
- ASCII (GFZ):
  - one file per year and site, easy to read
- **NetCDF GFZ/DWD (M. Bender):**
  - finished

GNSS-PW NetCDF Example

ncdump-4.1.1 -h pots22275.nc

```
...
float iwv(station, time) ;
        iwv:units = "kg m-2" ;
        iwv:valid_range = 0., 150. ;
        iwv:_FillValue = 9.96921e+36f ;
        iwv:long_name = "Integrated water vapour" ;
        iwv:standard_name = "atmosphere_mass_content_of_water_vapor" ;
        iwv:comment = "Integrated or precipitable water vapour" ;
…
// global attributes:
        :title = "GNSS-PW GRUAN Data Product Version 1 (GNSS-PW-GDP.1)" ;
        :institution = "GFZ German Research Centre for Geosciences, Potsdam" ;
        :source = "GNSS" ;
        :history = "...date... Data conversion from TROPO SINEX to GRUAN netCDF" ;
        :references = "See the GRUAN documentation on GNSS-PW." ;
        :comment = "This is a RELEASE version of a data product file." ;
```

NetCDF: Open Questions (ICM14) -> Answers

- Separate file for each GRUAN site? -> **YES**
- Yearly/monthly/daily files? -> **FLEXIBLE**
- Only for re-processed products or also for NRT? -> **ALSO NRT**
- nc3 and/or nc4? – **nc4**
- Include also the gradients or ZTD/PW only? - **ALL**
- Header information – **FINISHED**

Metrological Closure of GNSS-PW

Statistics GNSS-PW minus ERA5 for 2021

SITE ID	BIAS (mean -0.3 kg/m2)	STDDEV (kg/m2)
Cabauw	- 0.5	+/- 1.4
Graciosa	0.3	+/- 1.9
Lindenberg	- 0.7 (LDB2)	+/- 1.1
Lindenberg	- 1.1 (LDB0)	+/- 1.1
Lauder	- 0.7	+/- 1.5
Ny Alesund	- 0.3	+/- 0.7
Payerne	- 0.3	+/- 1.3
Lamont	- 0.3	+/- 1.8
Singapore	- 0.1	+/- 2.2
Sodankylä	0.2 (SODA)	+/- 0.8
Sodankylä	0.9 (SODF)	+/- 0.9
Syowa	- 0.2	+/- 0.5
Tsukuba	- 0.6	+/- 1.6
Barrow	- 0.9	+/- 0.8

Polar region

Equator region

Polar region

Statistics GNSS-PW minus ERA5 for 2022

SITE ID	BIAS (mean -0.27 kg/m2)	STDDEV (kg/m2)
Cabauw	- 0.7	+/- 1.6
Graciosa	0.3	+/- 1.7
Lindenberg	- 0.8 (LDB2)	+/- 1.1
Lindenberg	- 1.2 (LIN0)	+/- 1.1
Lauder	- 0.7	+/- 1.5
Ny Alesund	- 0.3 **Polar region**	+/- 0.7
Payerne	- 0.4	+/- 1.7
Lamont	- 0.2	+/- 1.9
Singapore	0.9 **Equator region**	+/- 2.6
Sodankylä	0.0 (SODA)	+/- 0.9
Sodankylä	0.9 (SODF)	+/- 0.9
Syowa	0.0 **Polar region**	+/- 0.4
Tsukuba	- 0.6	+/- 1.2
Barrow	- 1.0	+/- 0.8

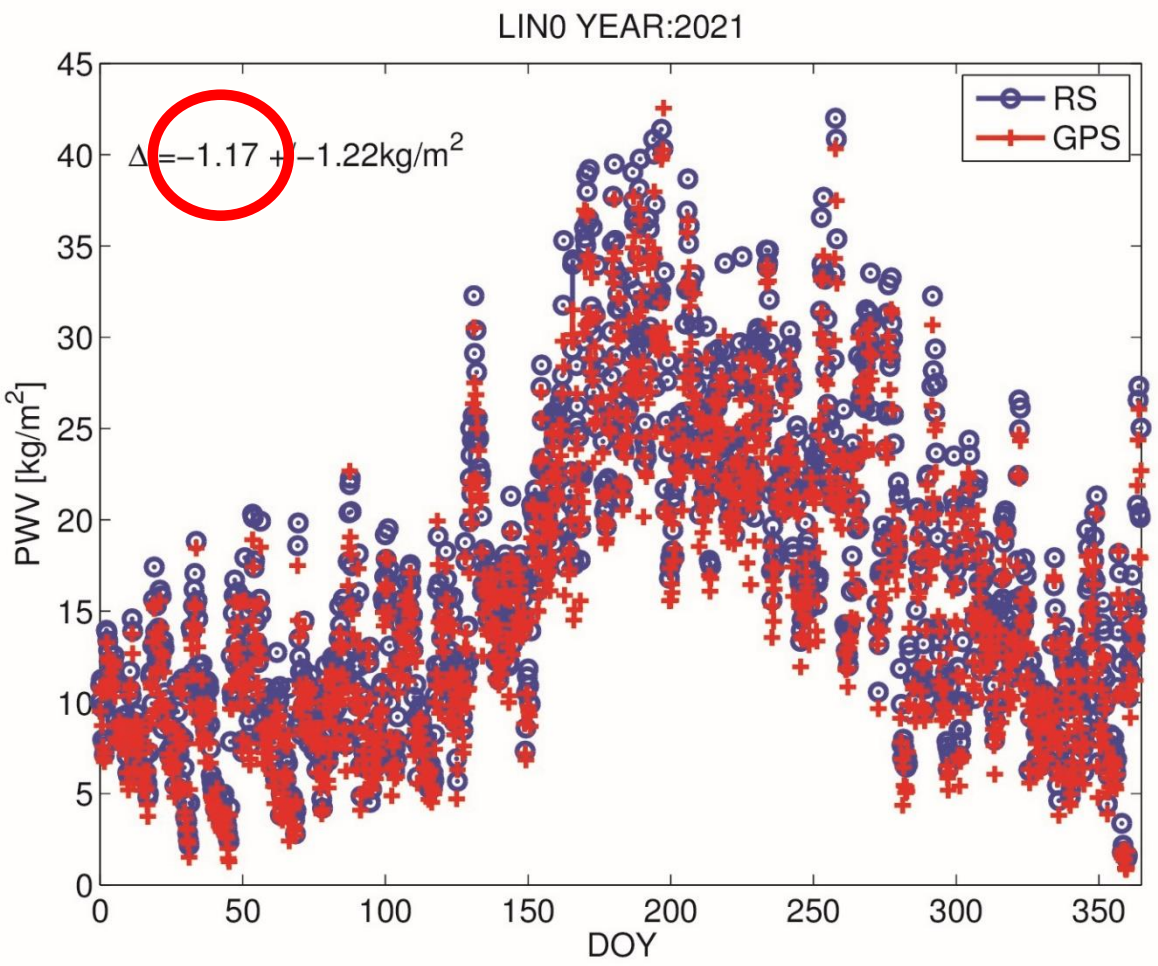
GNSS-PW minus ERA5 and RS41.v1 for 2021

SITE ID	BIAS (mean -0.34/-0.52 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	- 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

Red: GRUAN radiosonde product RS41.v1

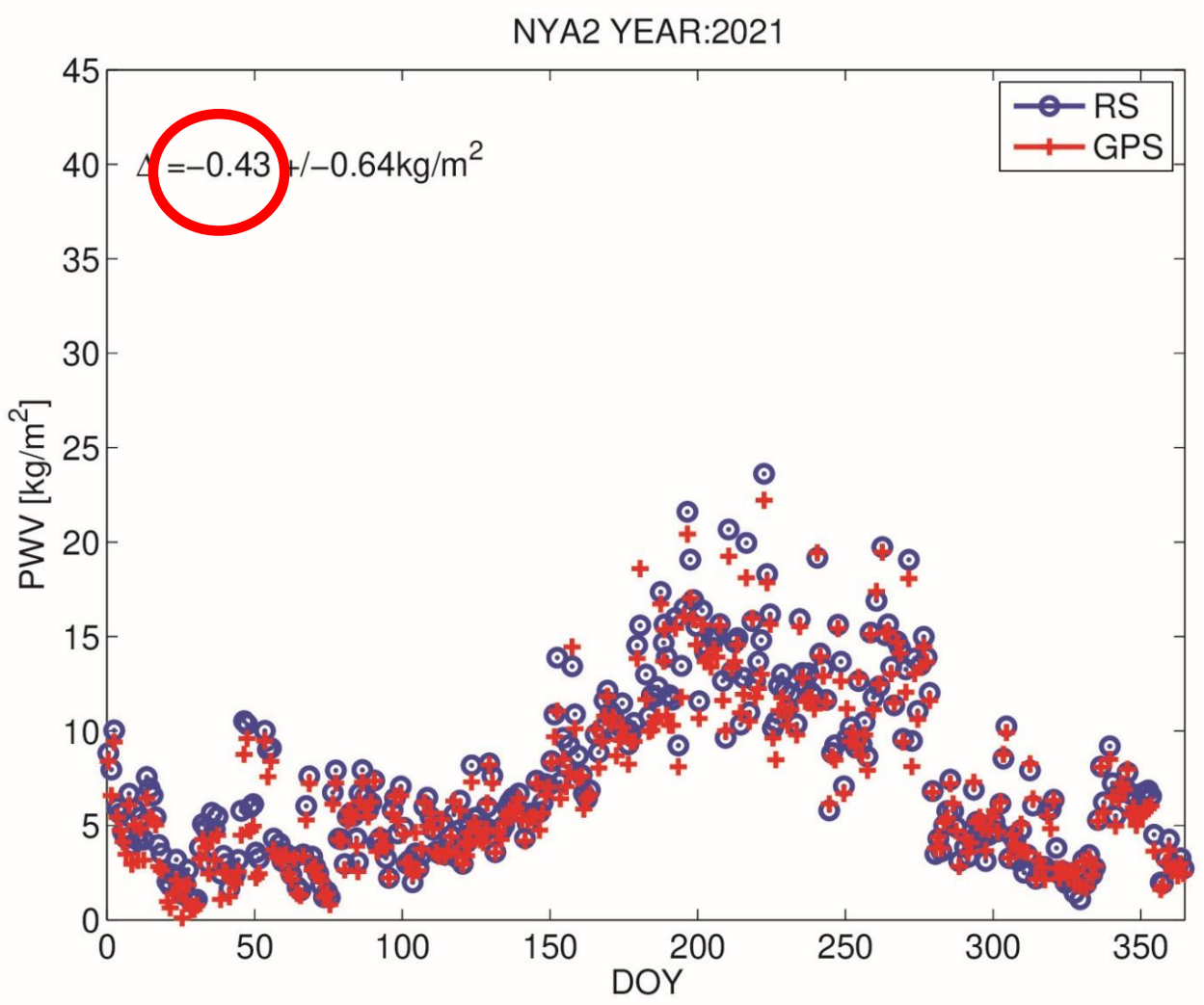
Large STDDEV for RS in Lauder

GNSS vs RS for Lindenberg for 2021



Blue: GRUAN Radiosonde product (RS41.v1 GDP) for 2021
Red: GNSS-PW solution of GFZ

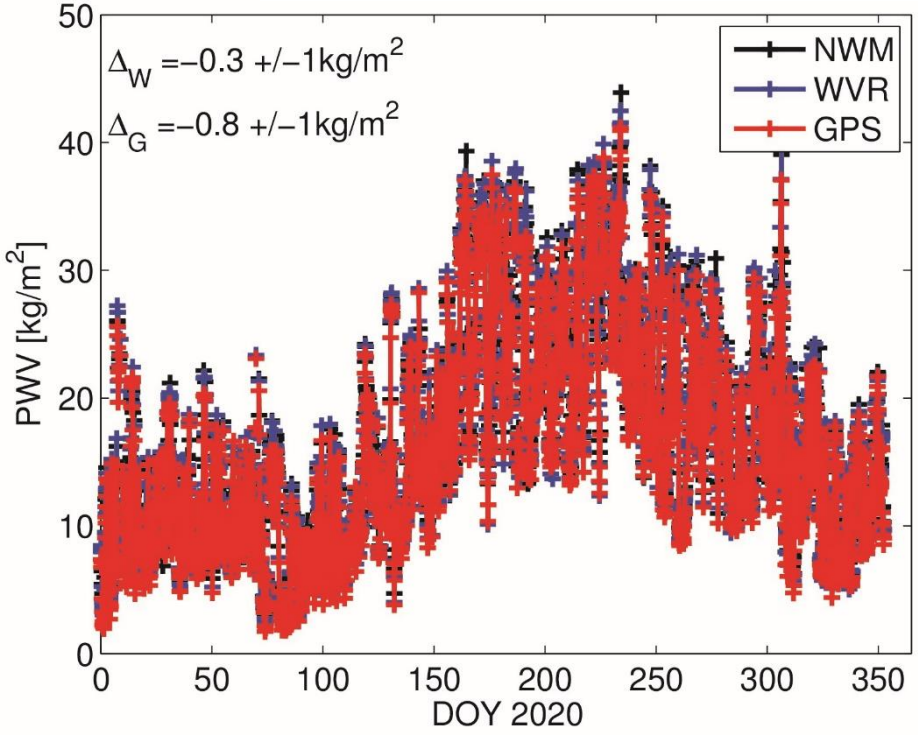
GNSS vs RS for Ny-Ålesund for 2021

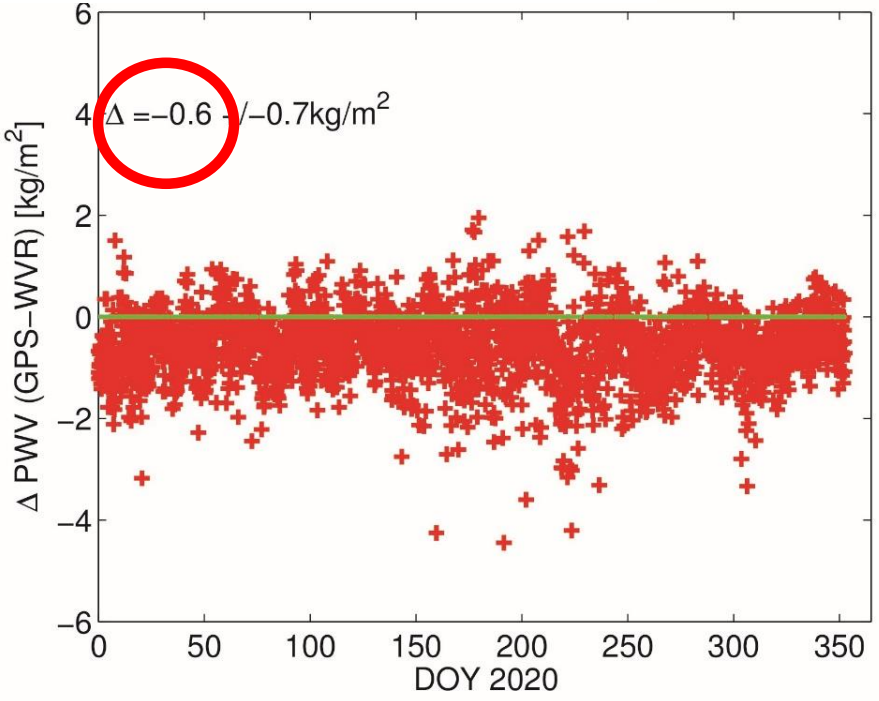


Blue: GRUAN Radiosonde product (RS41.v1 GDP) for 2021
Red: GNSS-PW solution of GFZ

GNSS vs WVR for Lindenberg for 2020

Lindenberg (LDB2), Germany



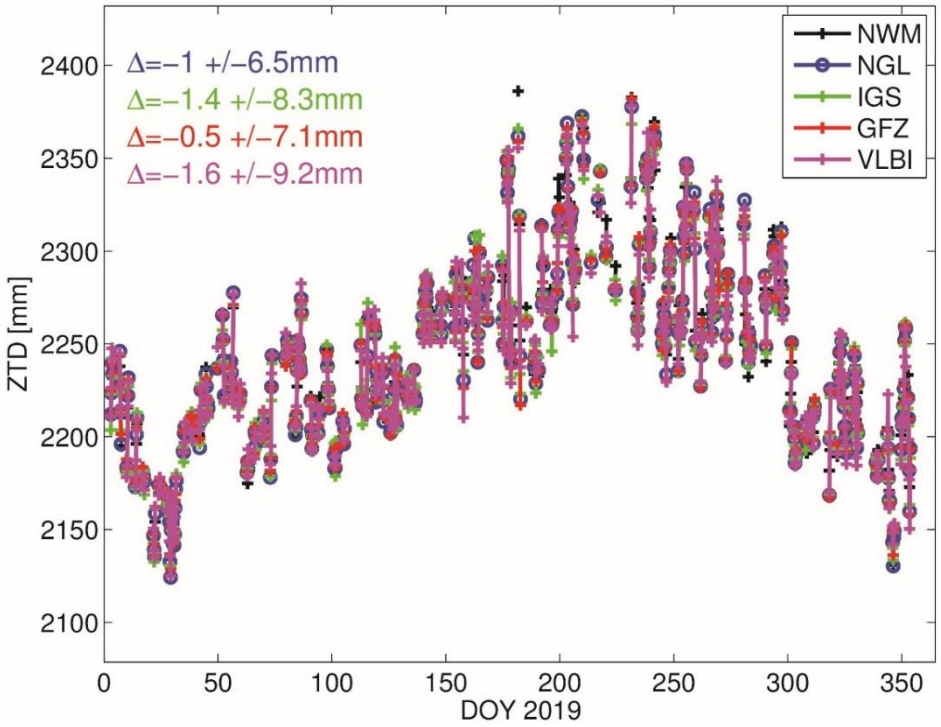


Differences between GNSS-PW and WVR-PW for 2020

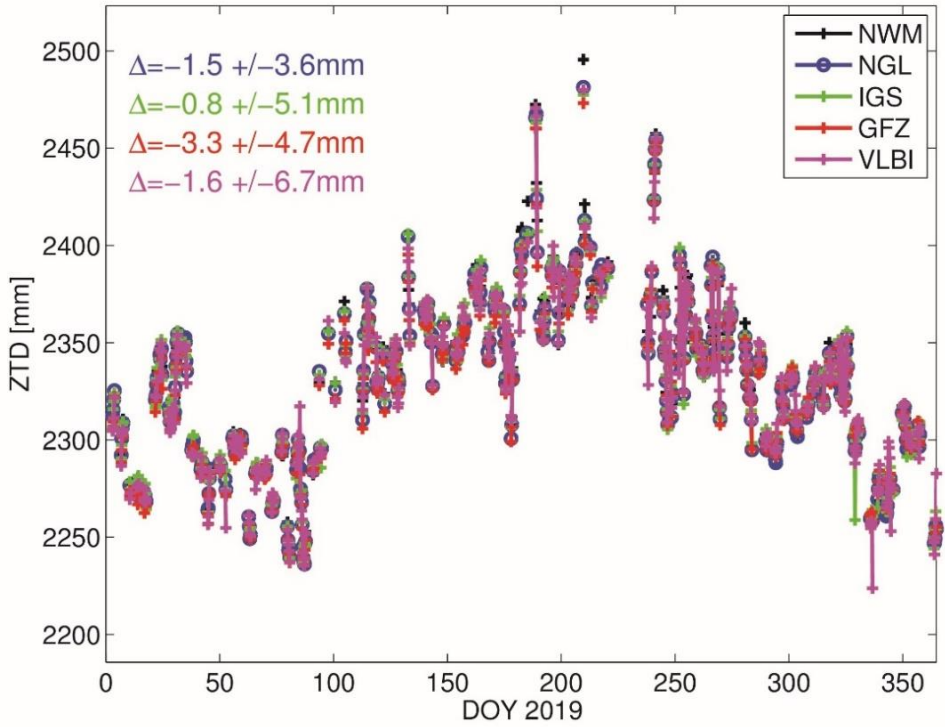
Black: ERA5 atmospheric reanalysis of ECMWF
Blue: Water Vapour Radiometer (WVR)
Red: GNSS solution of GFZ

VLBI vs GNSS for Wettzell/Ny-Ålesund 2019

Wettzell (WTZR), Germany



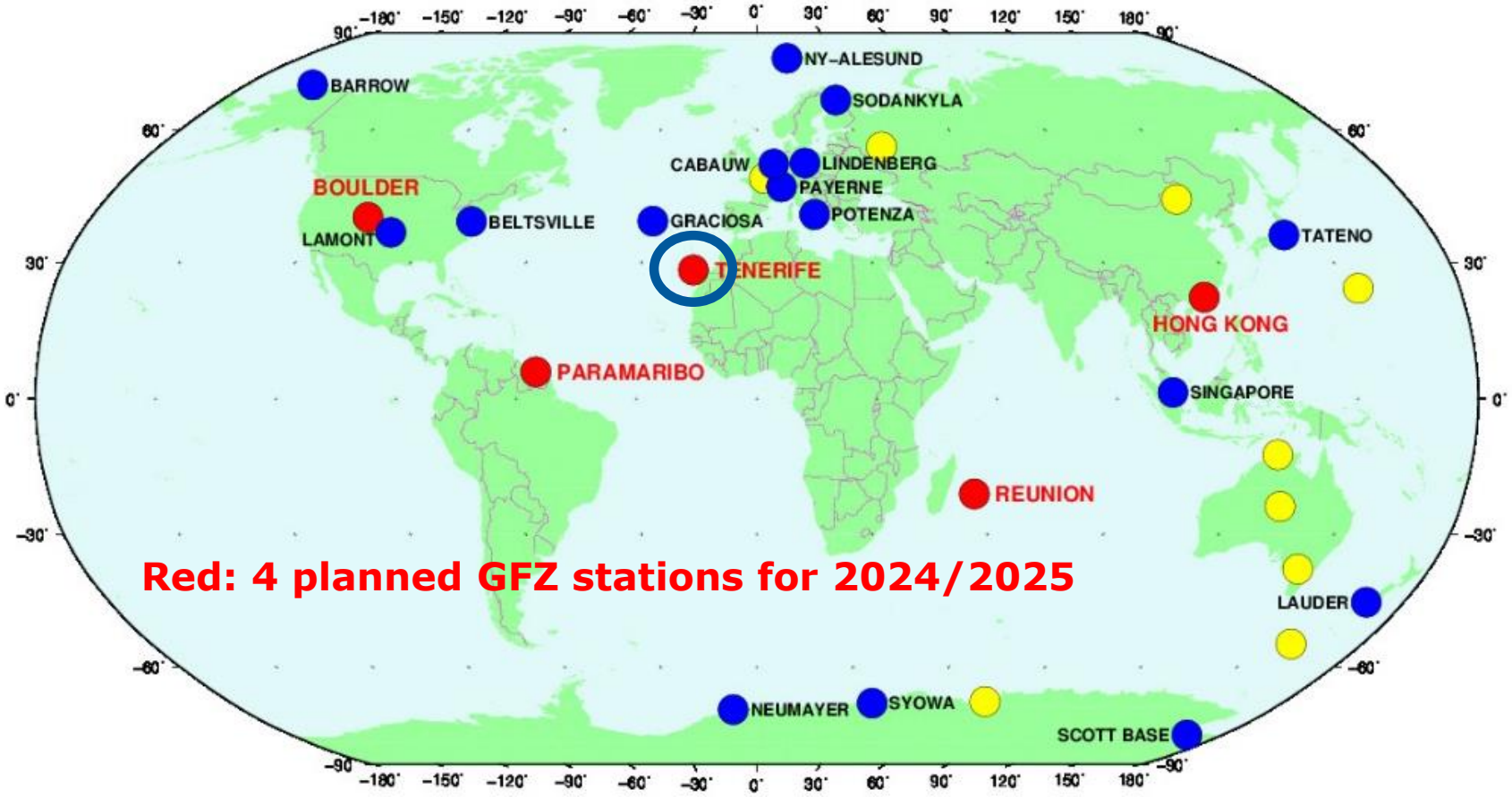
Ny-Ålesund (NYA2), Norway



Black: ERA5 atmospheric reanalysis of ECMWF
Blue: GNSS solution of Nevada Geodetic Laboratory (NGL)
Green: GNSS solution of IGS
Red: GNSS solution of GFZ
Purple: VLBI solution of GFZ

Status of GNSS Sites

GRUAN GNSS Network



Blue: in GNSS-PW processing
2023: 16 sites
2024: 17 sites (new Tenerife)

Status GNSS-PW Processing

- **17 GNSS sites** in GNSS-PW processing chain:
  - Lindenberg (LDB2, LIN0)
  - Ny-Ålesund (NYA2, NYAL, NYA1)
  - Sodankylä (SODF, SODA)
  - Lauder (LDRZ)
  - Barrow (UTQI)
  - Graciosa (ENAO)
  - Lamont (SGPO)
  - Beltsville (HUBC)
  - Singapore (SMM1, SMS1)
  - Payerne (PAYE)
  - Cabauw (CBW1)
  - Ross Island (SCTB)
  - Tateno/Tsukuba (TATN, TSK2)
  - Syowa (SYOW)
  - **Tenerife (TFEG) NEW: Thanks to colleagues from Spain!**
  - Neumayer (NMSH) no PW-GDP, work in progress
  - Potenza (TITO) no PW-GDP, work in progress
- **Re-processing** with PW uncertainty estimation:
  - ongoing

Status Selected GNSS Sites

Tsukuba (TSK2):

- site close to Tateno, new IGS site replaced TSK2

Potenza (TITO):

- some technical issues still have to be solved

Sodankylä (SODA, SODF), Cabauw (CAB1):

- no meteo data, work in progress

Lindenberg (LIN0, LDB2):

- replacement of GFZ hardware for LIN0 planned for 2024

Neumayer (NMSH):

- GRUAN site in Antarctica, operated by AWI/GFZ
- data flow to GFZ, not in operational PW processing yet due to some technical problems

Planned GNSS Stations after ICM15

Planned to be installed in 2024:

- **Hong Kong (China):** intend to install own GNSS receiver
- **Paramaribo (Suriname):** GFZ will install GNSS receiver

Planned to be included to PW GDP:

- **Reunion:** GNSS data will be included to PW processing at GFZ (work in progress)

No contact: Trappes/Palaiseau, Xilin Hot, Dakar, Dolgoprudnyj

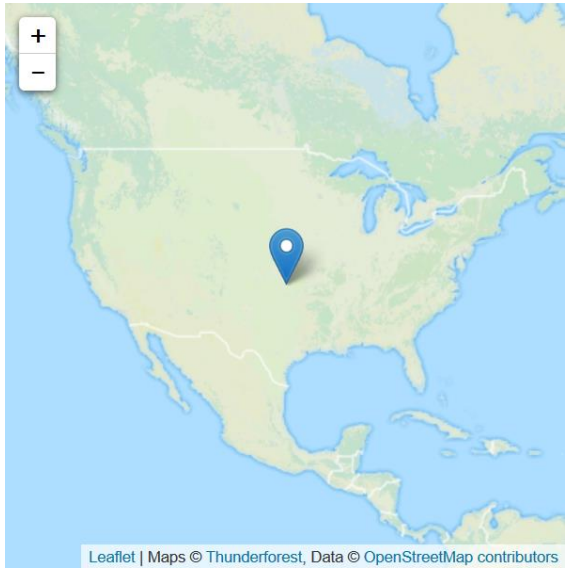
No data: Australia

Paramaribo (PMO, Suriname)

- GNSS hardware is transported by KLMI to Paramaribo by ship
- GFZ will install GNSS as soon as hardware will arrive to Paramaribo

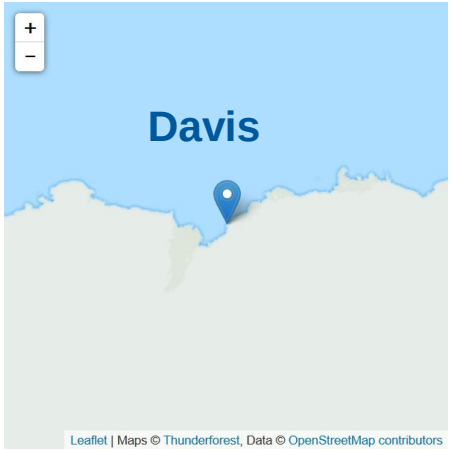
Marshall, Boulder (BOU, USA)

- TMS3 (close to Boulder) closed in October 2018
- New GNSS site should be installed on GRUAN site BOU (Marshall Field Test Site)
- MoU between NCAR and GFZ signed
- GNSS hardware planned to be installed by GFZ (negotiations with NCAR)



Australia: pending

Negotiations with Geoscience Australia, no progress



GNSS for GRUAN

GFZ offers to install and operate GNSS receivers on GRUAN sites

- **Requirements:**
  - power supply
  - internet connection
  - adequate antenna installation site

Future Work

- Re-processing with PW uncertainty estimation for the whole time period 2011-2023 (ongoing)
- Further validations with RS, WVR, VLBI and NWM
- Including of new GNSS sites to GNSS-PW GDP
- Finalization and operational use of NetCDF
- Providing of GNSS-PW GDP in all formats
- Investigations of Lindenberg (LIN0) and Barrow (UTQI)
- Finalization of certification of GNSS-PW GDP

GNSS-PW Products on GFZ FTP

Available in SINEX-TRO and COST 716 Formats

GRUAN NRT:

ftp://ftp.gfz-potsdam.de/GNSS/products/nrttrop/

sinex_trop_GRUAN_EPOS8/w****
product_GRUAN_COST_EPOS8/y****/m**

REPRO:

ftp://ftp.gfz-potsdam.de/GNSS/products/nrttrop/REPRO/

sinex_trop_EPOS8/w****
product_COST_EPOS8/y****/m**

Many thanks for your attention!