GFZ
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RESEARCH FOR GRAND CHALLENGES

GNSS-PW GDP FORMATS AND METROLOGICAL CLOSURE WITH RADIOSONDES

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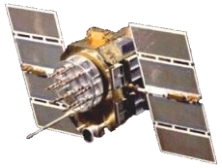
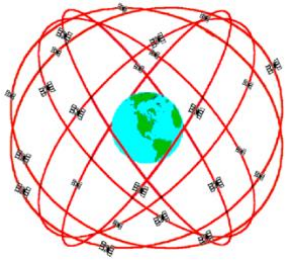
Sessions 10-3 and 10-4, GRUAN ICM-14, December 2, 2022, Reunion Island

GNSS: Global Navigation Satellite Systems

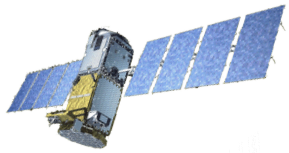
GPS (USA): 31 satellites



GLONASS (Russia): 24 satellites

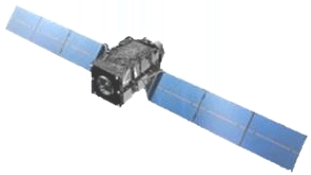


Galileo (EU): 28 satellites



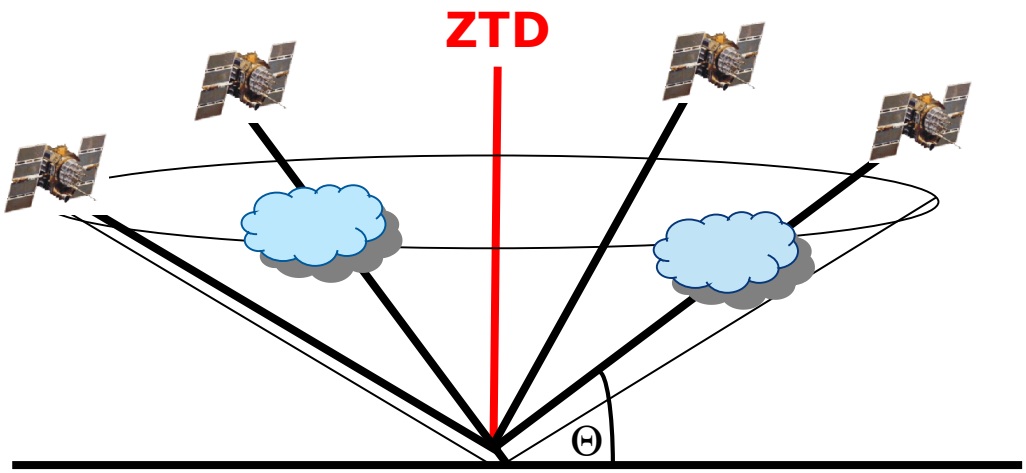
BeiDou (China): 35 satellites

QZSS (Japan, regional): 4 satellites



More than 120 satellites in the sky

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 PW

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

dry, hydrostatic wet

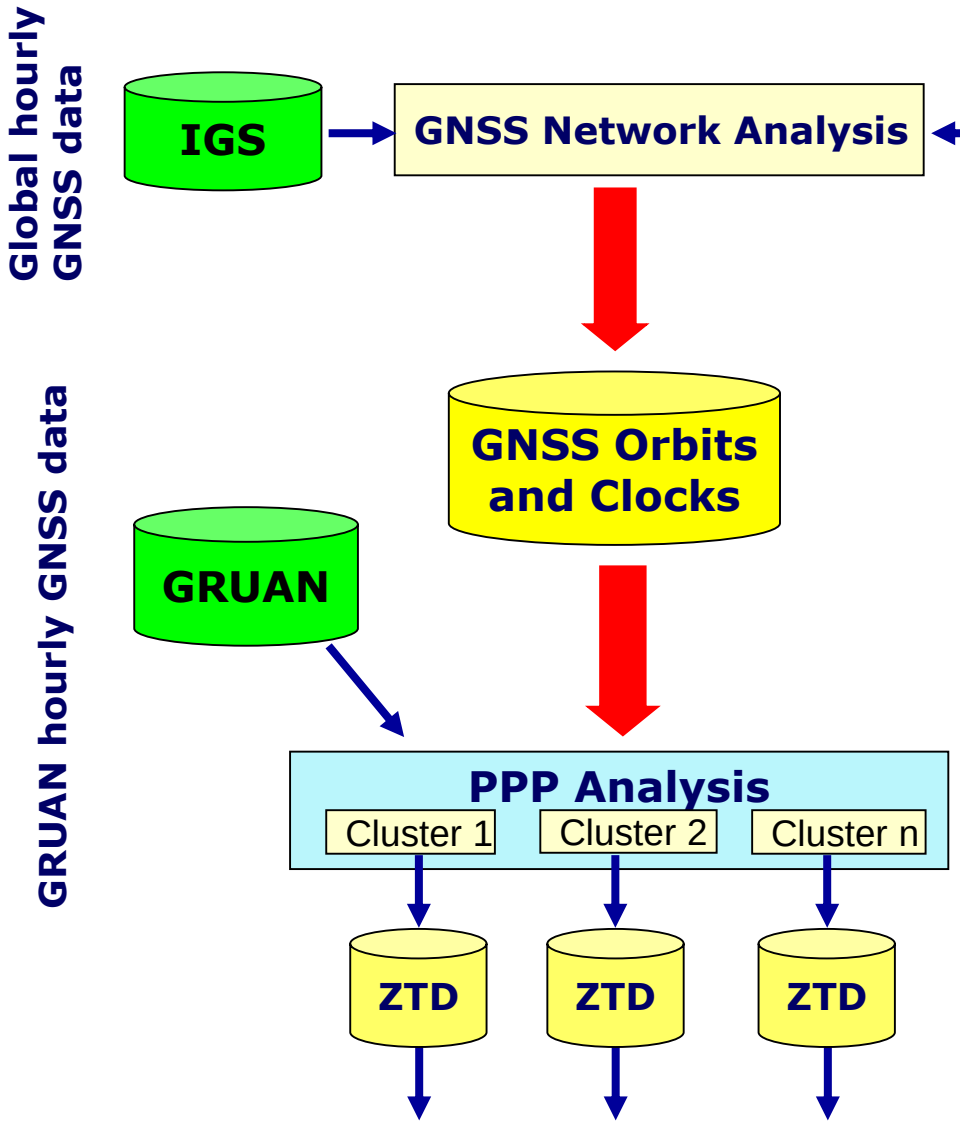
$$ZTD = ZHD + ZWD$$

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

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

Converted Precipitable Water Vapor (PW)

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

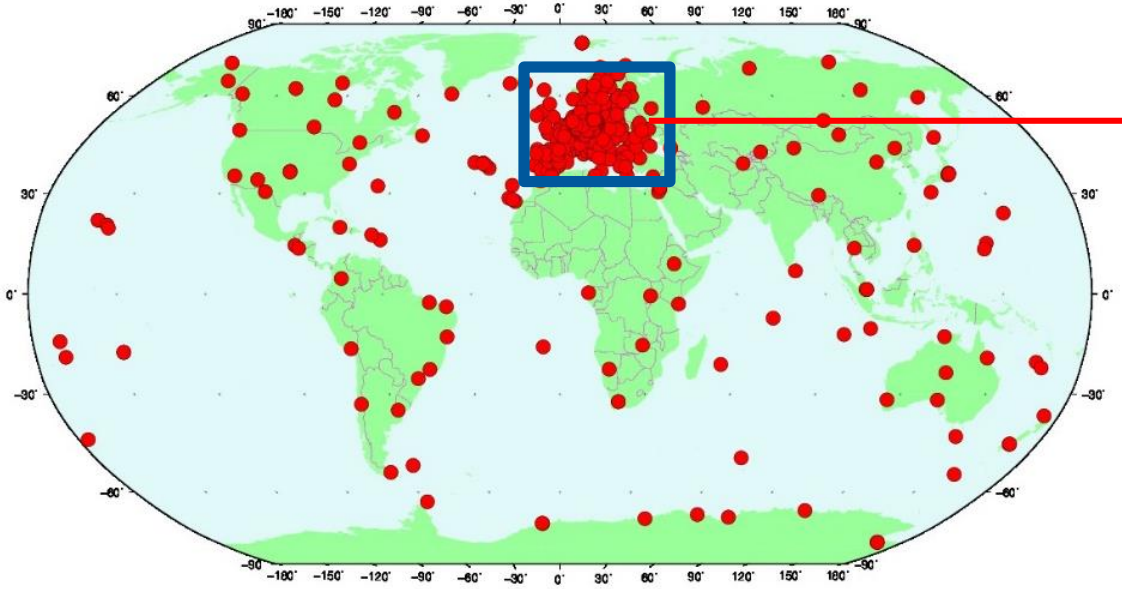
- Estimation of ZTDs and other tropospheric parameters with high sampling rate (15 minutes for ZTD/PW)

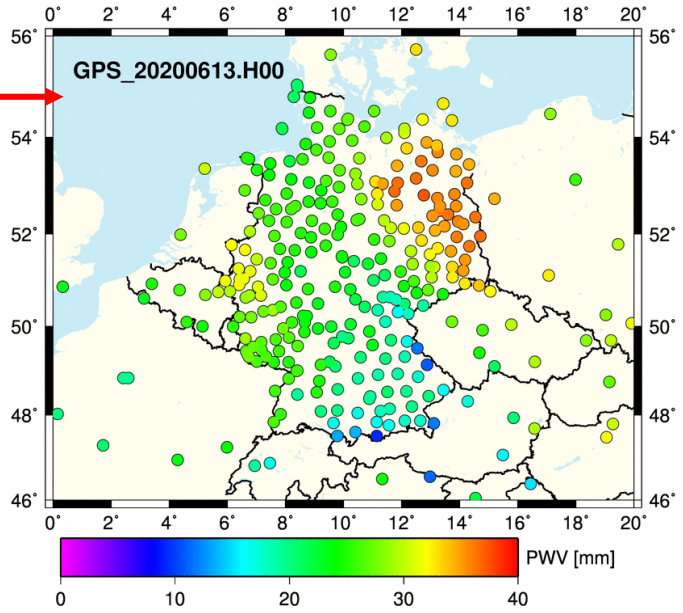
Part 3 - Product Generation

- Conversion ZTDs to PW
- Estimation of PW uncertainty

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

Operational GNSS-PW Monitoring at GFZ



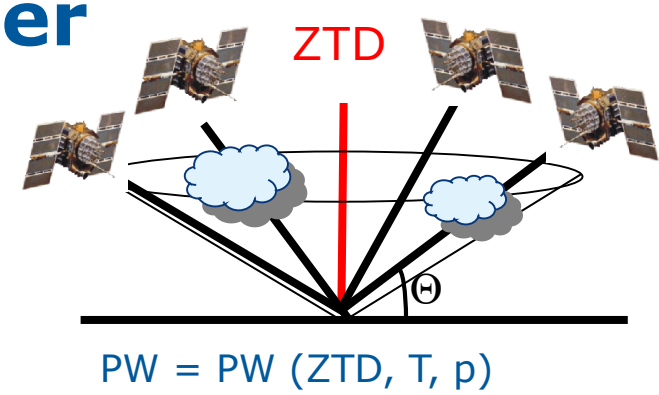


- ~600 GNSS stations globally
- Operational time delay < 15 minutes after the end of each hour (**near real-time, 24/7**)
- ZTD products of GFZ used by European Weather Services for weather forecast

GNSS-based Products:

Zenith Total Delay
Precipitable Water Vapor
Slant Total Delay
Gradients

GNSS-based Precipitable Water Vapor: Advantages

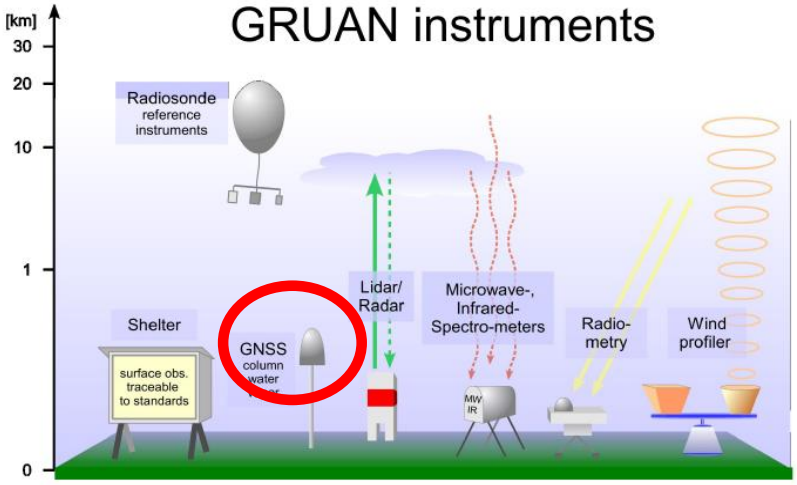


PW = PW (ZTD, T, p)

- High accuracy of about 1-2 mm PW
- All weather capability
- Low costs
- High resolution in space and time
- Long-term stability
- Continuous time series
- PW trends with mm accuracy

GRUAN:
Reference Network

GNSS is priority number one technique for water vapor monitoring



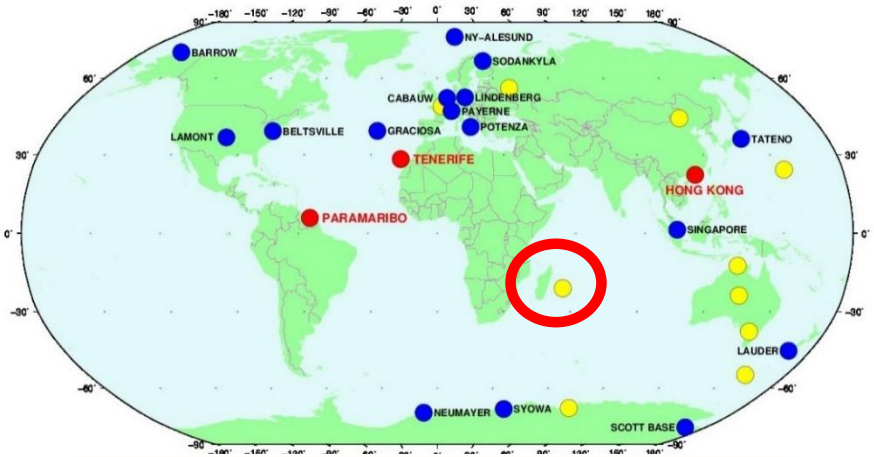
GFZ Contribution to GRUAN: GNSS-PW

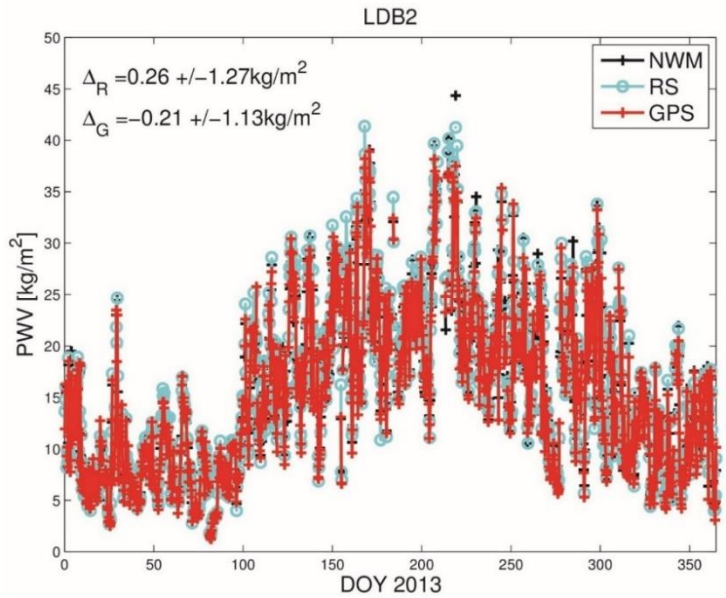
GNSS network:
Currently 16 GNSS sites (blue dots) in PWV processing, 4 planned sites (red)

Operational Data Center:
GNSS data handling, archiving, monitoring of all changes

GNSS Processing Centre:
Operational PW estimation, consistent re-processing, quality control and uncertainty estimation

Product Validation:
Very good agreement between GNSS and RS, WVR, VLBI and NWM ERA5, indicating a high accuracy of GNSS-PW data product of GFZ





Start of **certification** of GFZ GNSS-PW products as GDP in 2021

Operational Data Centre (ODC) at GFZ

- Operational since 2018
- Ability to process all GNSS related data
- Data passes quality check before GNSS data analysis
- Monitoring of station behaviour
  - operational comparison of measured temperature and pressure at GNSS site with ERA5 for monitoring of meteo sensor (**new after ICM-13**)
  - feedback for station operators
- Short data processing latency (< 1 minute per station)

Courtesy: M.Bradke

GNSS-PW GDP Formats

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

NEW after ICM-13:

- ASCII (GFZ):
  - one file per year and site, easy to read
- **NetCDF (GFZ/DWD (M. Bender):**
  - nc3 and nc4

GNSS-PW GFZ ASCII Example

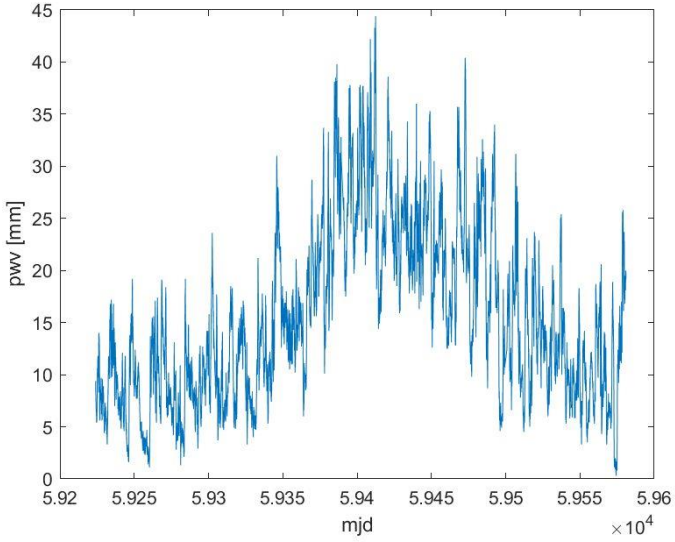
ASCII file **LIN0PWV_2021.txt**

Time [sec]	ZTD [mm]	PWV [mm]	p [hPa]	T [k]
LIN0_A21:001:00450	2316.4	9.5	990.7	275.6
LIN0_A21:001:01350	2317.1	9.6	990.7	275.6
LIN0_A21:001:02250	2316.3	9.5	990.7	275.6
LIN0_A21:001:03150	2315.0	9.3	990.7	275.6
LIN0_A21:001:04050	2314.5	9.3	990.6	275.7
LIN0_A21:001:04950	2315.1	9.4	990.6	275.7
LIN0_A21:001:05850	2316.2	9.5	990.6	275.7
LIN0_A21:001:06750	2316.9	9.6	990.6	275.7
LIN0_A21:001:07650	2316.0	9.5	990.7	275.8
LIN0_A21:001:08550	2316.4	9.5	990.7	275.8
LIN0_A21:001:09450	2316.9	9.6	990.7	275.8
…				

GNSS-PW NetCDF Example

```
netCDFFile='GruanTest-2021-LIN0-nc3.nc';
disp(['GRUAN NC FILE' ': ' netCDFFile])
...
ZTD  = ncread(netCDFFile , 'TROTOT');%m
PWV = ncread(netCDFFile , 'TROPWV');%mm
MJD  = ncread(netCDFFile , 'TRO_MJD');%mjd
Pres  = ncread(netCDFFile , 'MetPres');%p hpa
Temp = ncread(netCDFFile , 'MetTemp');%T C


...
figure(1)
plot(MJD,PWV)
xlabel('mjd')
ylabel('pwv [mm]')
```

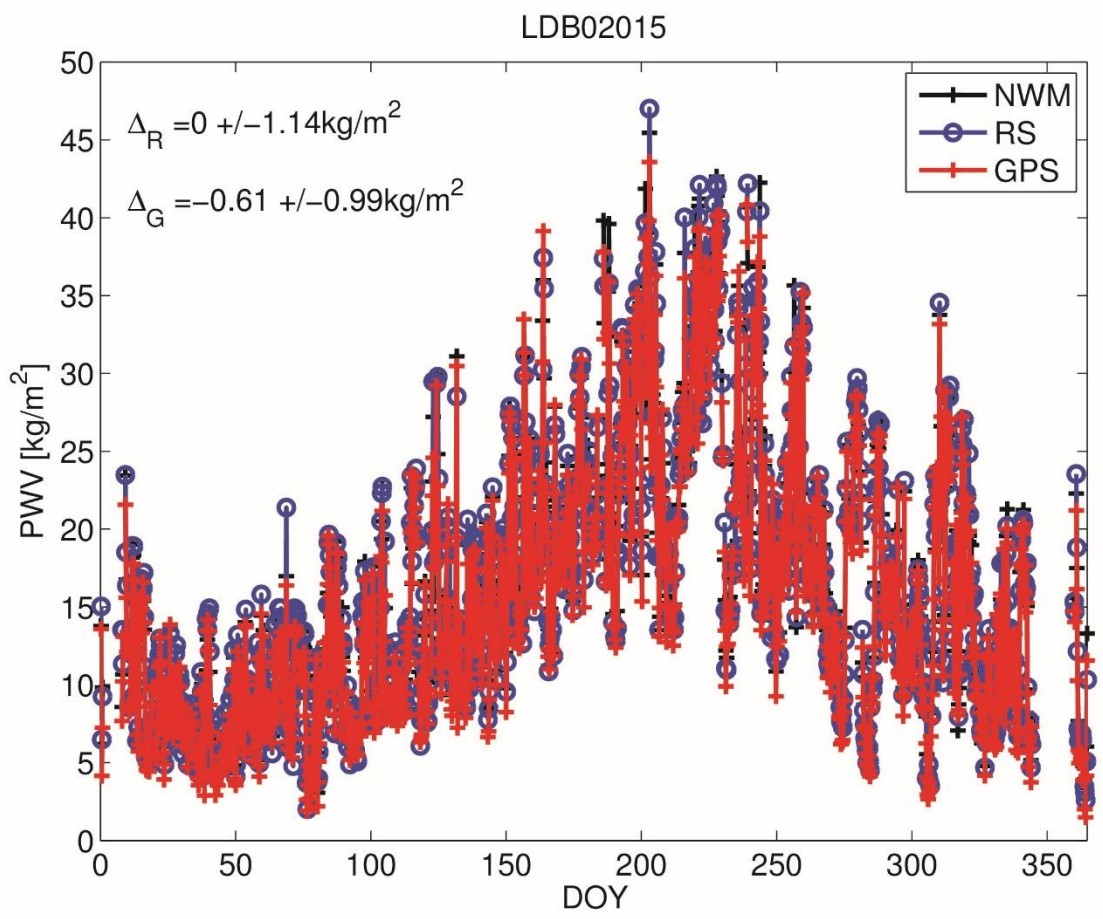


NetCDF: Open Questions

- Separate file for each GRUAN site?
- Yearly/monthly/daily files?
- Only for re-processed products or also for NRT?
- nc3 and/or nc4?
- Include also the gradients or ZTD/PW only?
- Header information
- …

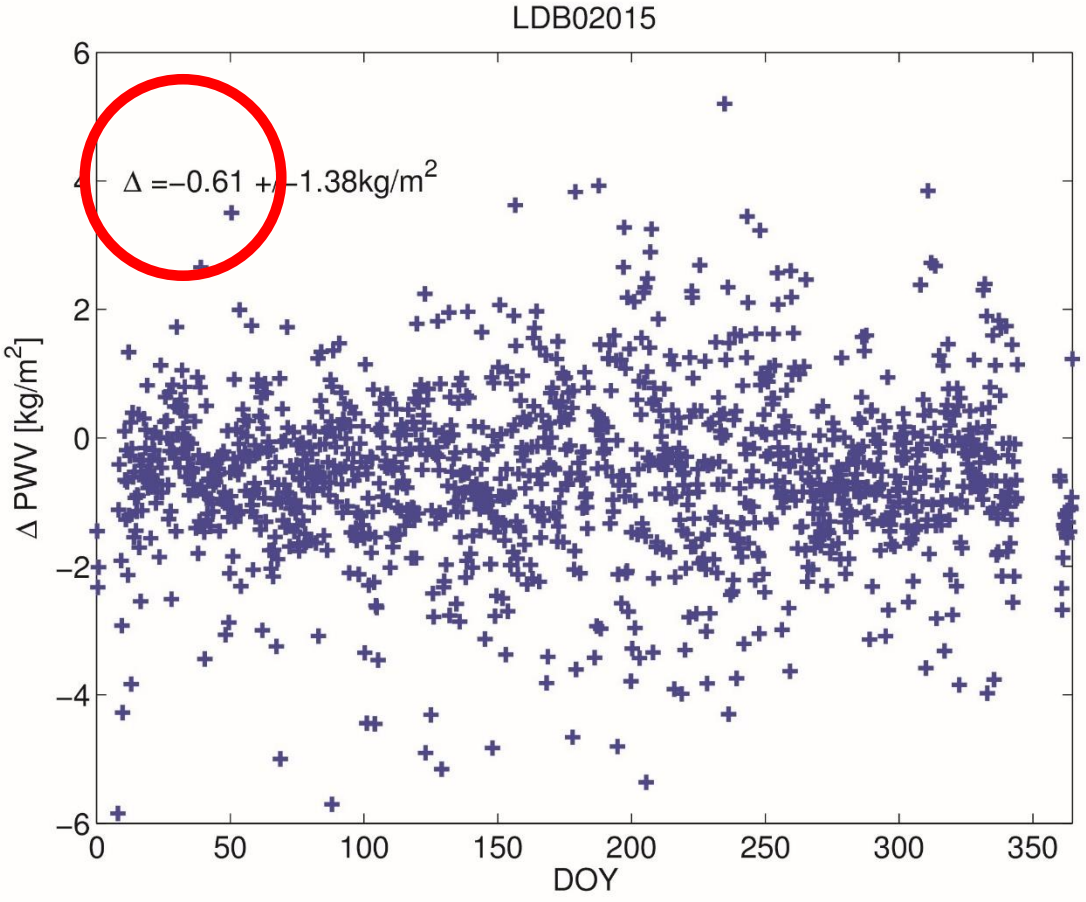
Metrological Closure of GNSS-PW GDP and RS

Validation of GNSS-PW with RS for Lindenberg (LDB0) for 2015



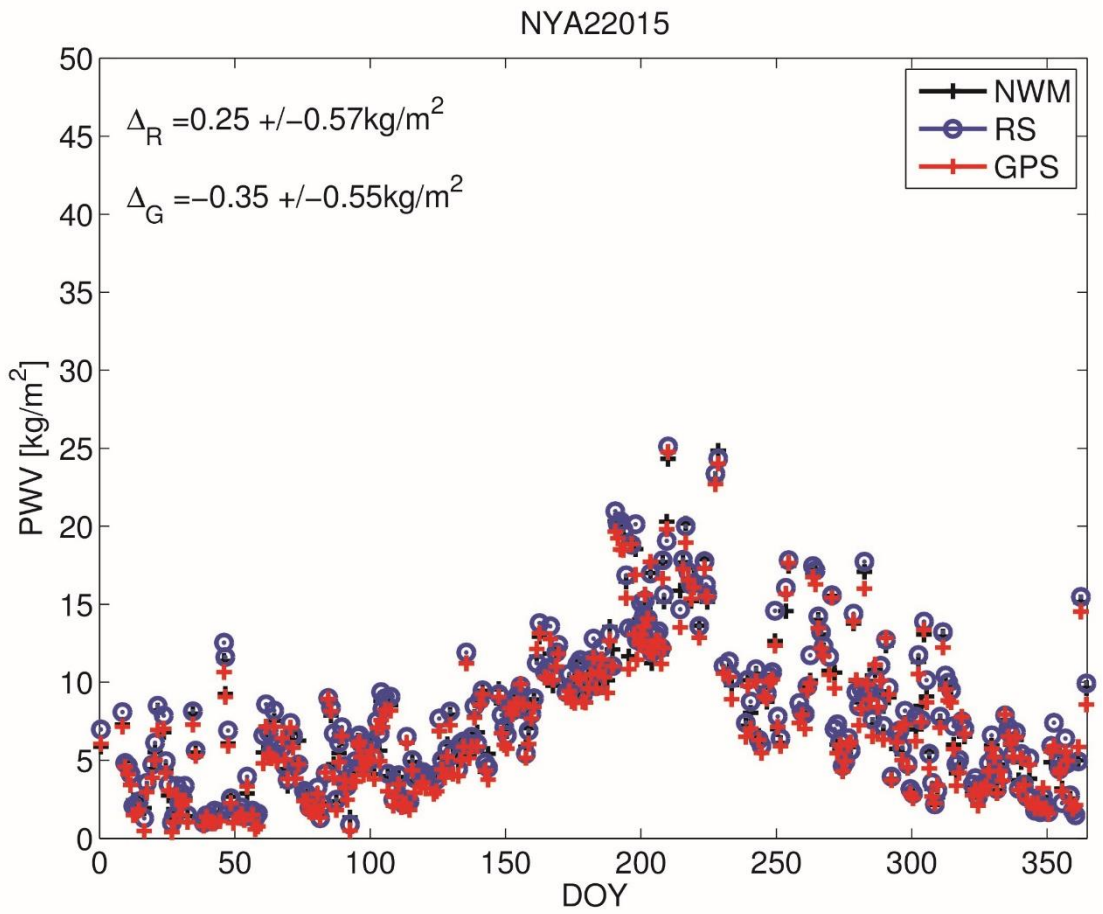
Black: **ERA5 atmospheric reanalysis of ECMWF**
Blue: **GRUAN RS product (RS92 GDP)**
Red: **GNSS solution of GFZ**

Validation of GNSS-PW with RS for Lindenberg (LDB0) for 2015



Differences between GNSS-PW and RS

Validation of GNSS-PW with RS for Ny-Ålesund (NYA2) for 2015



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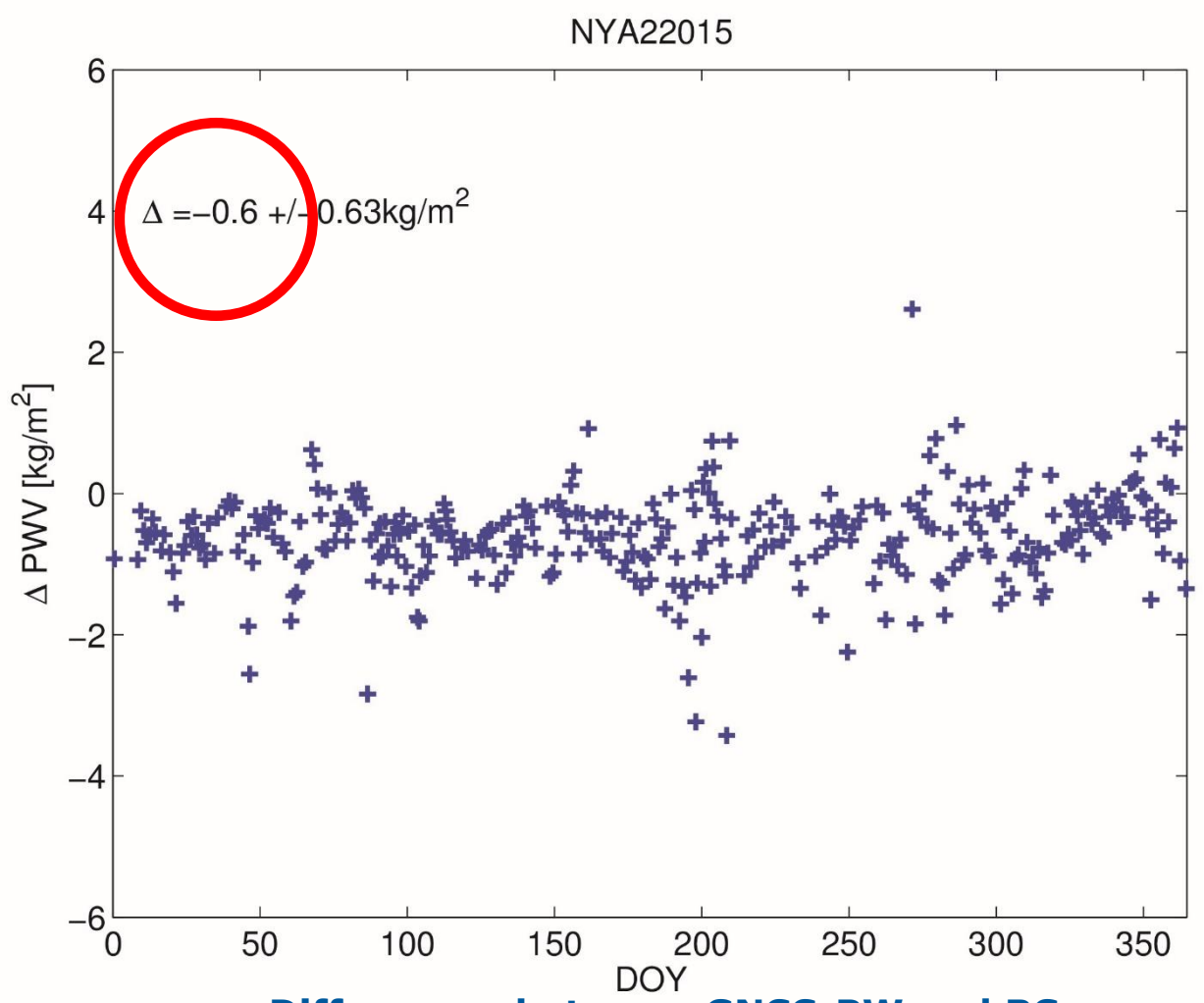
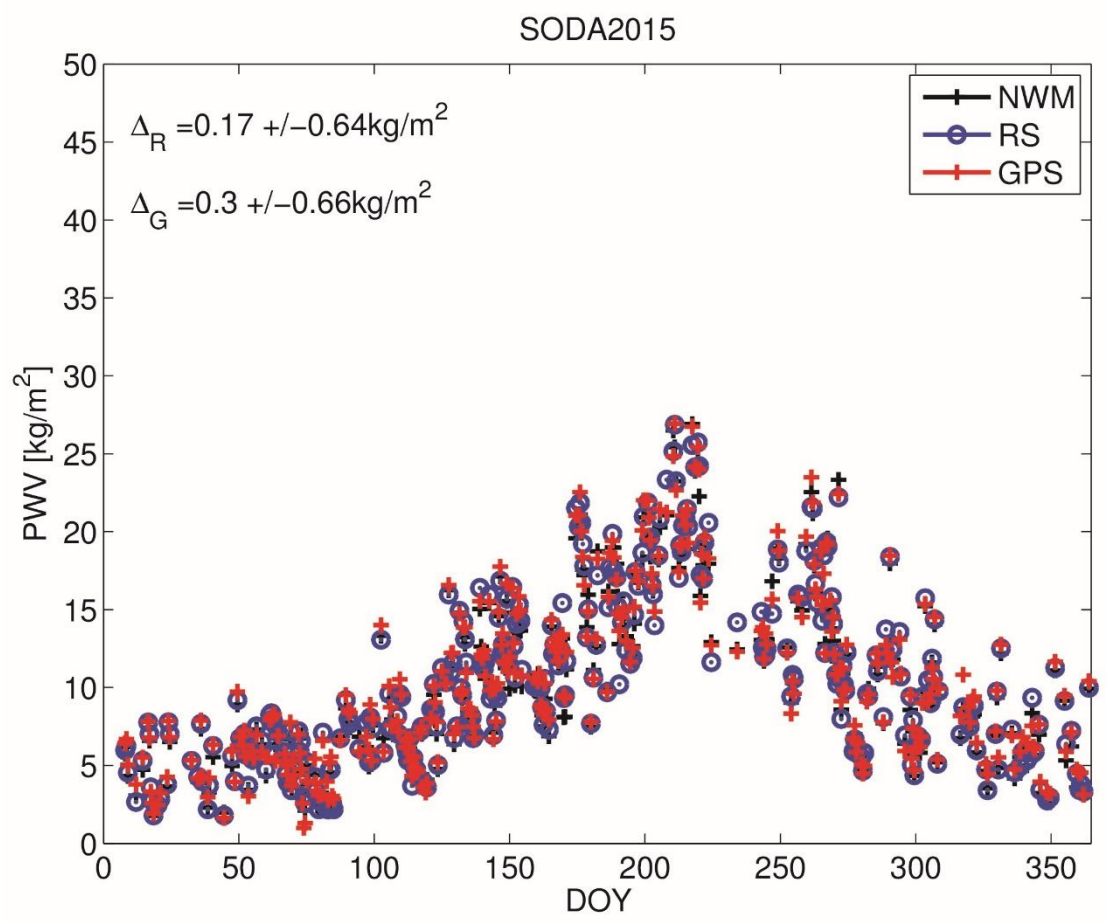
Validation of GNSS-PW with RS for Ny-Ålesund (NYA2) for 2015



Differences between GNSS-PW and RS

Validation of GNSS-PW with RS for Sodankylä (SODA) for 2015



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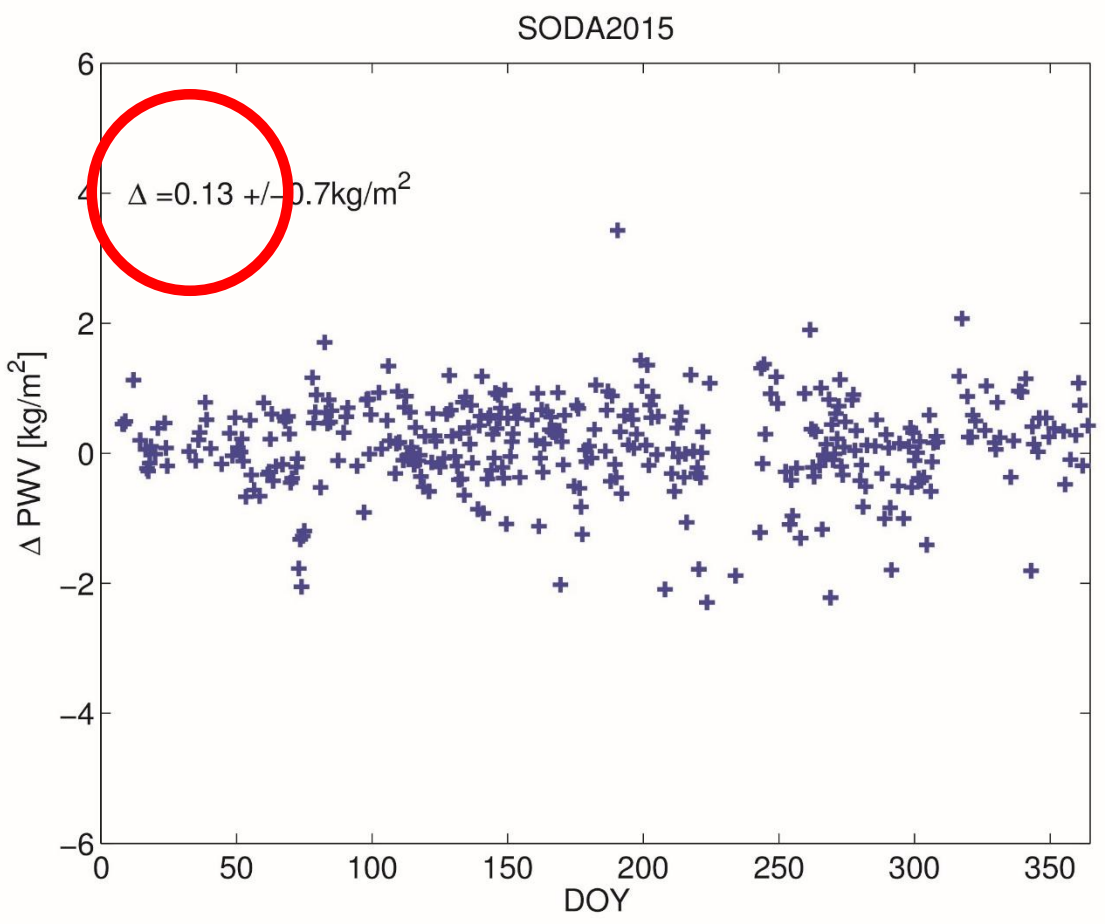
Validation of GNSS-PW with RS for Sodankylä (SODA) for 2015

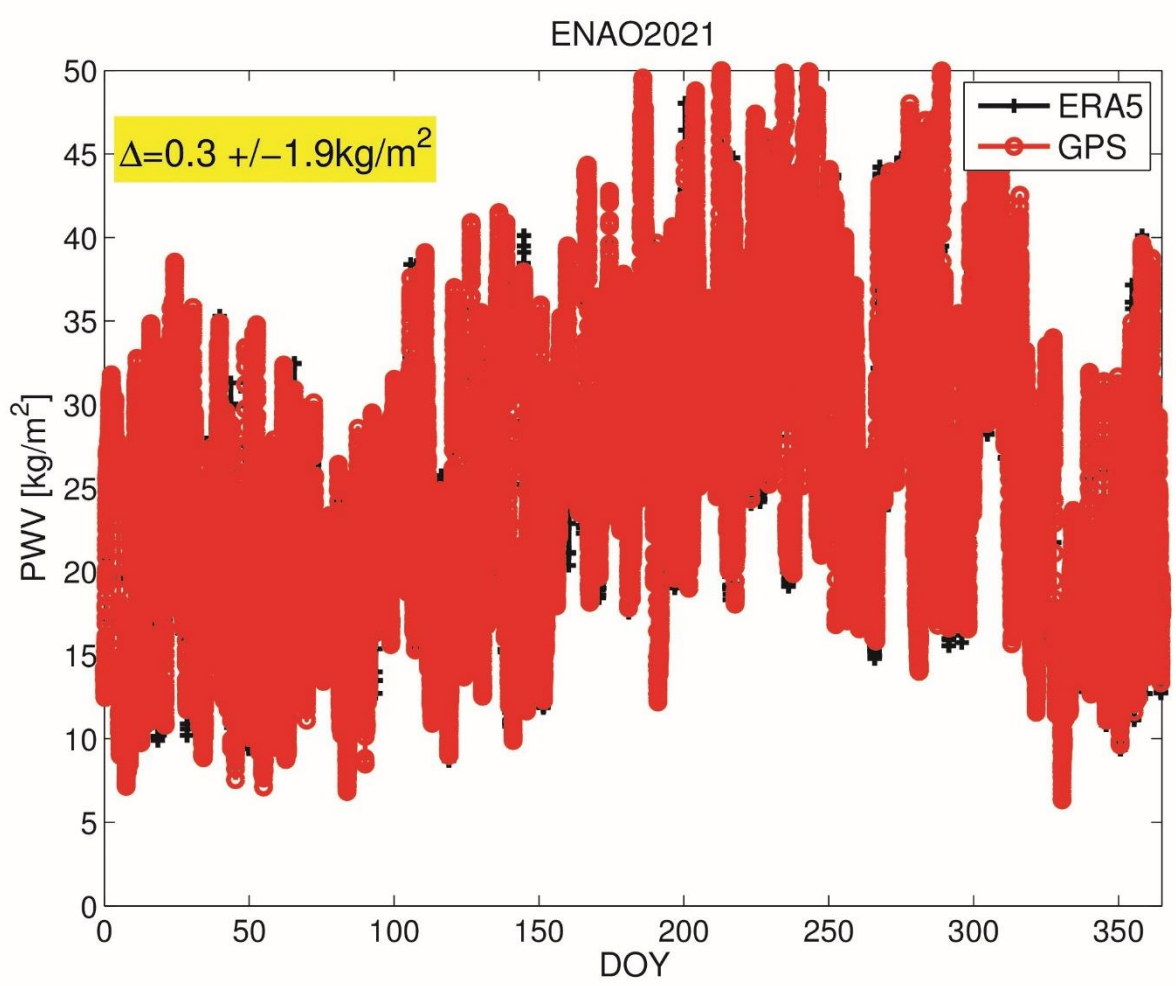


Differences between GNSS-PW and RS

GNSS-PW Validation with ERA5 of ECMWF

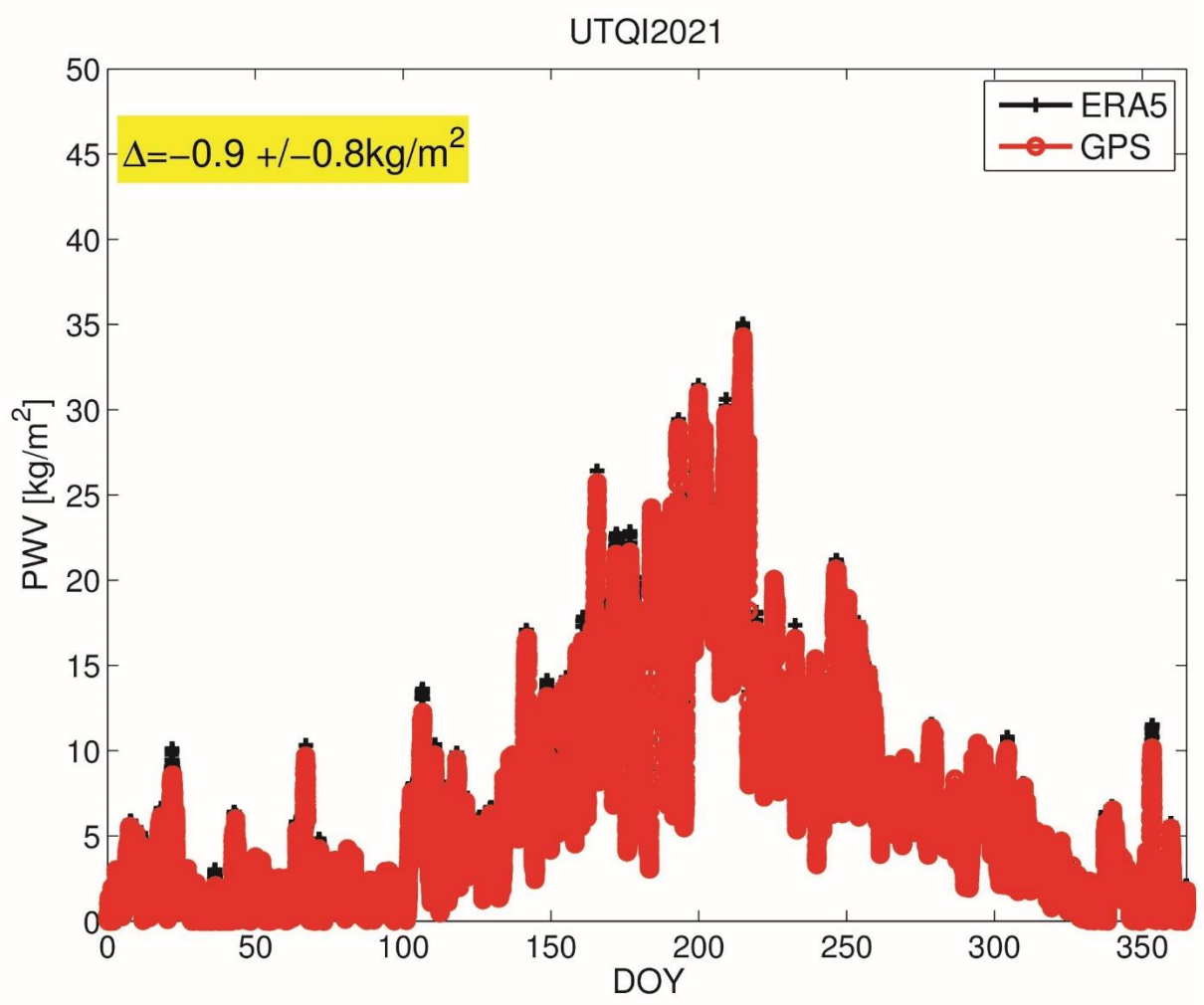
Daily updated validation plots are available at
ftp://ftp.gfz-potsdam.de/GNSS/products/nrttrop/MONITORING_IFS/

PW for Graciosa Island



Validation with ERA5 for Graciosa Island (ENAO) for 2021

PW for Barrow

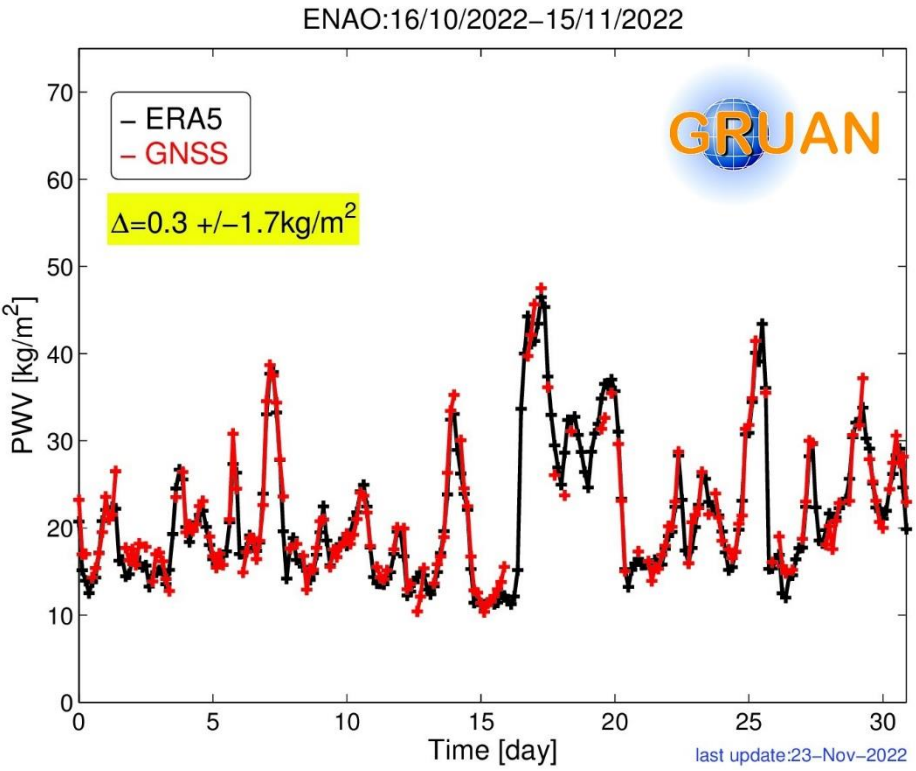


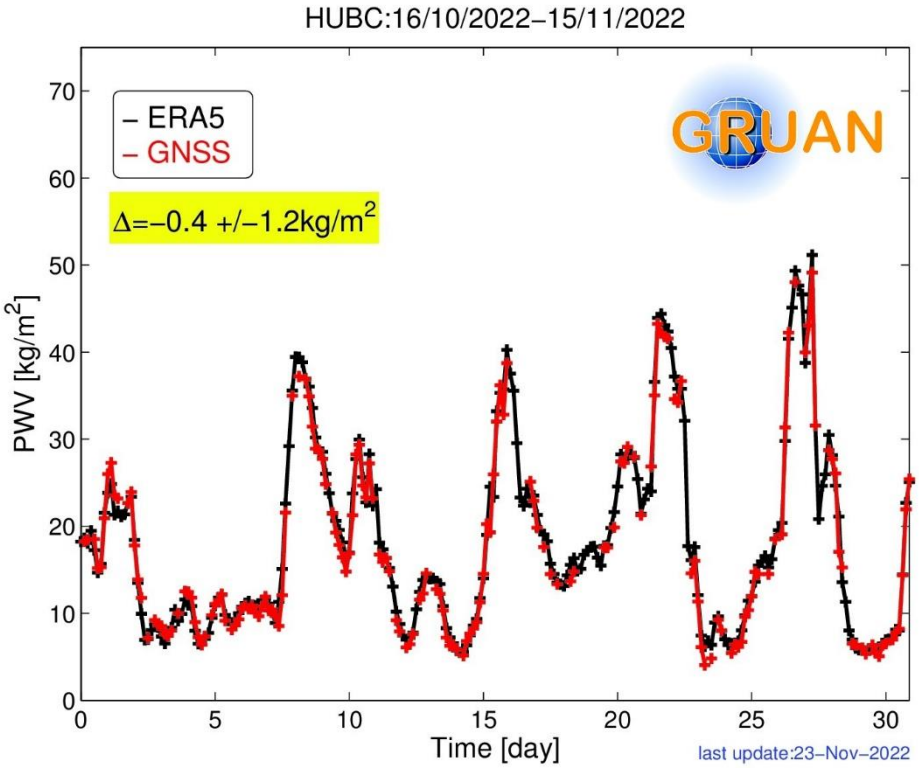
Validation with ERA5 for Barrow (UTQI) for 2021

Statistics GNSS-PW minus ERA5 2021

SITE ID	BIAS (mean -0.3 kg/m2)	STDDEV (kg/m2)
CBW1	- 0.5	+/- 1.4
ENAO	0.3	+/- 1.9
LDB2	- 0.7	+/- 1.1
LIN0	- 1.1	+/- 1.1
LDZR	- 0.7	+/- 1.5
NYA2	- 0.3	+/- 0.7
PAYE	- 0.3	+/- 1.3
SGPO	- 0.3	+/- 1.8
SMS1	- 0.1	+/- 2.2
SODA	0.2	+/- 0.8
SODF	0.9	+/- 0.9
SYOG	- 0.2	+/- 0.5
TSK2	- 0.6	+/- 1.6
UTQI	- 0.9	+/- 0.8

PW for Graciosa (ENAO) and Beltsville (HUBC)

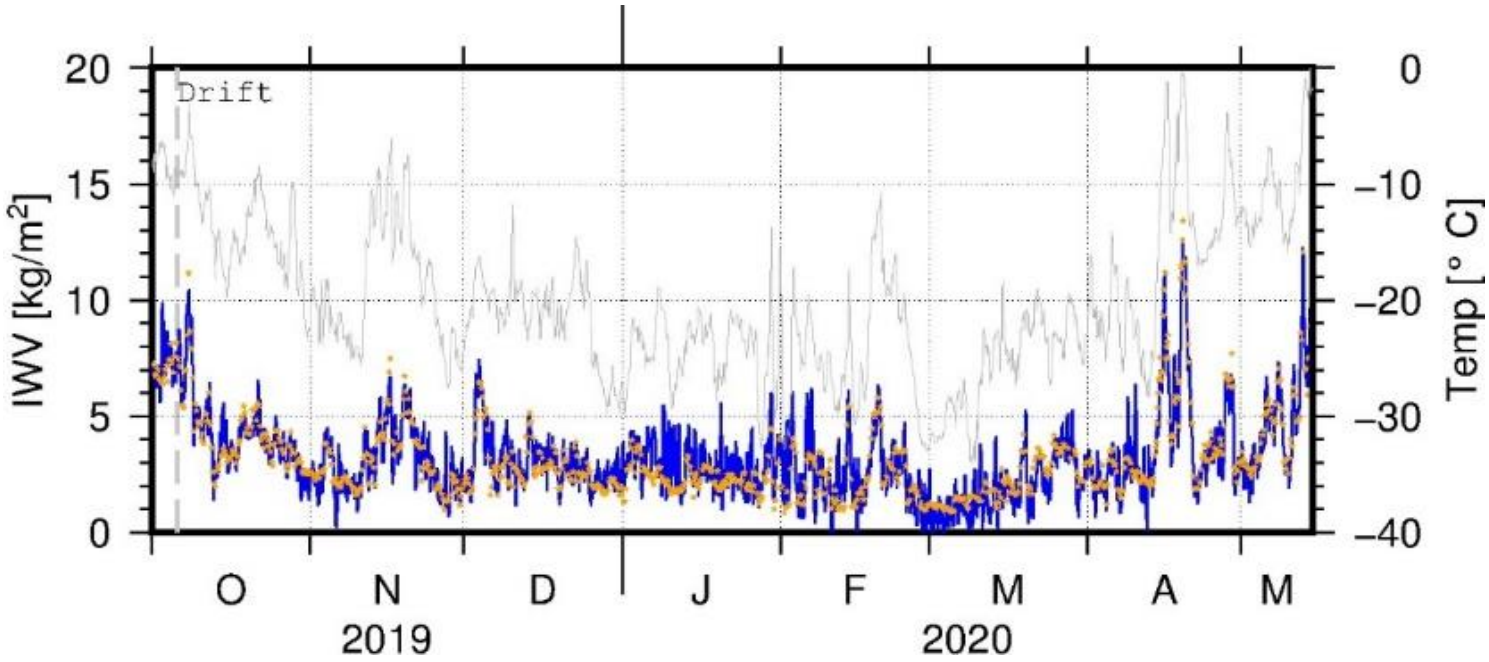




ENAO **HUBC**

Operational validation with ERA5 for ENAO and HUBC, Nov 2022

„MOSAiC“: Water Vapor Results



GNSS-based PW, radiosonde-based PW (AWI), temperature (ERA5)

- GNSS tracking was done fully autonomous using the GFZ developed tiny/PC3 and GORS receivers
- GNSS-based water vapor was compared to ERA-5, GNSS and VLBI coastal stations and frequent radiosonde measurements

Männel et al., 2021; ATM

Status of GNSS Sites

GRUAN GNSS Network

Blue: in GNSS-PW processing
11 sites (2019)
16 sites (2022)

Status GNSS-PW Processing

- **16 from 31 stations** in GNSS-PW processing chain:
  - Lindenberg (LDB0, 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)
  - **Neumayer (NMSH) no PW-GDP, work in progress**
  - **Potenza (TITO) no PW-GDP, work in progress**
- **Re-processing** with new PW uncertainty estimation:
  - done for 2019
  - ongoing for 2018, 2020, 2021

Status Selected GNSS Sites (1)

Tsukuba (TSK2):

- site close to Tateno
- operational hourly processing since 2021

Potenza (TITO):

- some technical issues have to be solved
- not in processing

Sodankylä (SODA, SODF):

- no meteo data, work in progress

Cabauw (CAB1):

- no meteo data, work in progress

Syowa (SYOW):

- only in re-processing mode

Status Selected GNSS Sites (2)

Singapore (MSS1, SMS1):

- renamed from MSS1 to SMS1 in 2022

Lindenberg (LIN0):

- replacement of GFZ site LDB0 with LIN0 (2020)
- LDB2 the second GNSS station in Lindenberg

Neumayer (NMSH):

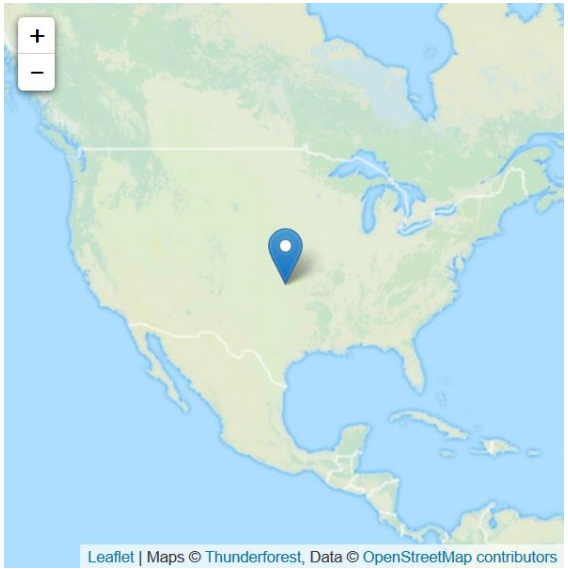
- GRUAN site in Antarctica, operated by AWI/GFZ
- data flow to GFZ, not in operational PW processing yet
- some problems with processing should be solved

Boulder:

- moving GNSS to Marshall Field still pending

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 was planned to be installed by GFZ in summer 2019, still pending



Planned GNSS Stations after ICM-14

Planned to be installed in 2023:

- **Tenerife (Spain):** intend to install own GNSS receiver
- **Paramaribo (Suriname):** GFZ visited Paramaribo Jan 2022

Planned to be included to PW GDP:

- **Reunion:**
  - GNSS data will be included to PW processing at GFZ
  - negotiated during visiting Maido observatory (thanks to Joel van Baelen and his team)
- Other GRUAN sites will be contacted by GFZ and PW TT: Paris, Xilinhot, Dakar, Hong Kong

Paramaribo (PMO, Suriname)

- GFZ Department Director Prof. Schuh visited Meteorological Service of Suriname in January 2022
- GFZ ordered GNSS receiver
- Installation planned for 2023

Planned GNSS Stations

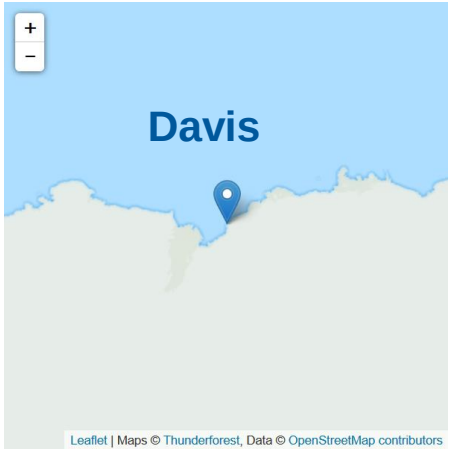
GFZ offers to install and operate GNSS receivers on GRUAN sites

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

Could be interesting for Dakar?

Australia: pending

Negotiations with Geoscience Australia



GNSS-PW GDP Summary

- Automatic hourly GNSS raw data flow and PW analysis including new uncertainty estimation established at GFZ (24/7)
- Data flow to LC
- Continuous re-processing and validation with RS, WVR and NWM
- Monitoring of product quality
- Development of NetCDF (first version available)
- Start of certification of GNSS-PW as GDP in 2021

Future Work

- Re-processing with new PW uncertainty estimation for the whole time period 2011-2022
- Ongoing validation with RS, WVR and NWM
- Including of new GNSS sites to GNSS-PW GDP
- Finalization of NetCDF
- Providing of GNSS-PW GDP in all formats
- Finalization of certification of GNSS-PW GDP

GFZ Products on 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**

Acknowledgements/Cooperation Partners

Many thanks for your attention!