TR
Y
AT

OSZ LiSE MEITNER

TRACK YOUR ATMOSPHERE

TRYAT

TRYAT – Was uns GNSS-Satelliten über Wetter und Klima verraten können.

Eine strategische Partnerschaft im Rahmen von Erasmus+

Fadwa Alshawaf und Galina Dick, GFZ Potsdam

Swantje Wiebalck und Boris Reusch, Lise-Meitner-Schule Berlin

Open Educational Resources

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Co-funded by the Erasmus+ Programme of the European Union

ZUR GNSS-METEROLOGY

1. In der **Forschung**: Wissenschaftliche Grundlagen und state-of-the-art
2. In der **Schule**: Experimente mit Lernenden
3. Überblick zum **Projekt**, Kontakt und
4. Fragen

Open Educational Resources

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Co-funded by the Erasmus+ Programme of the European Union

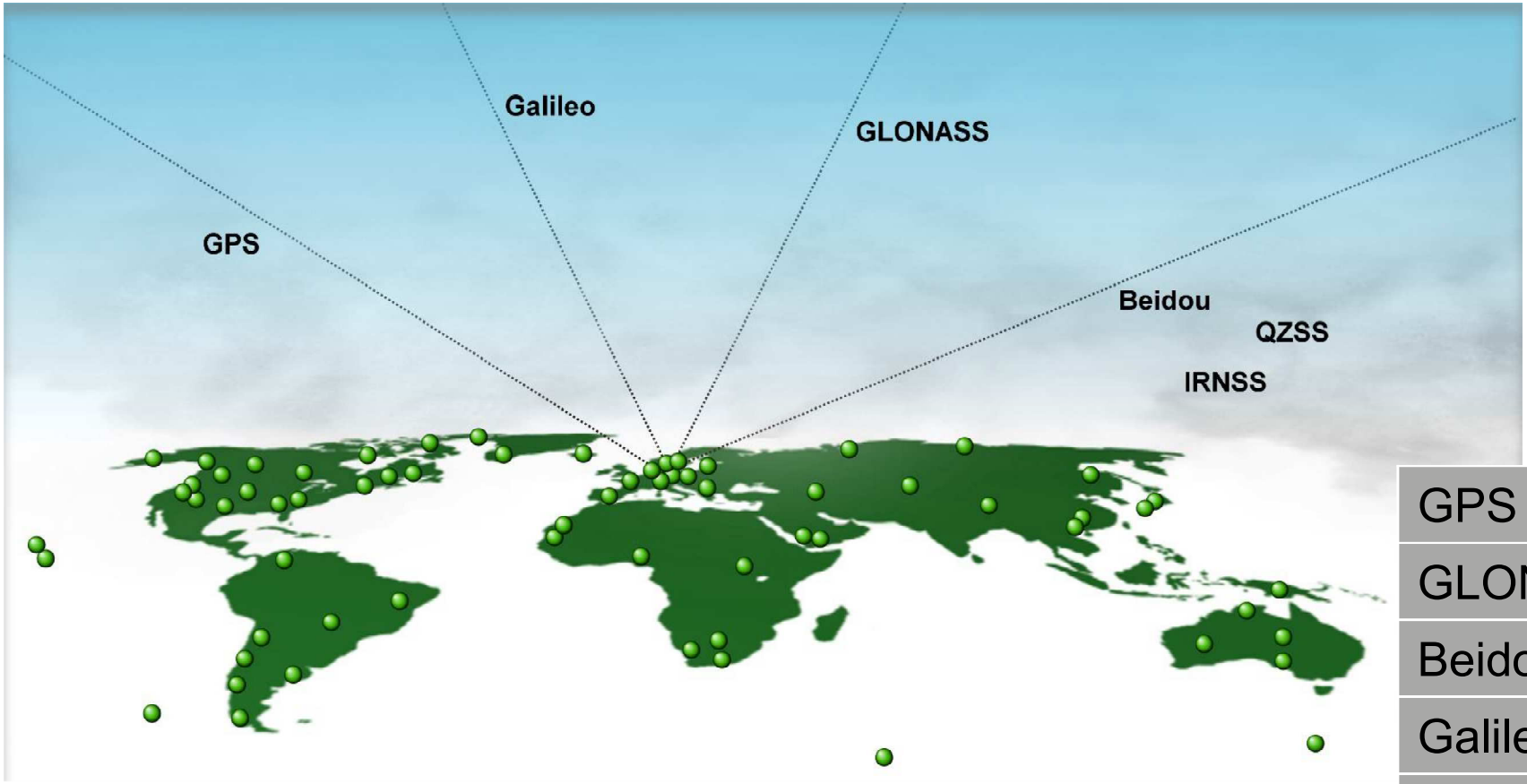
From Geodesy to Environment—
Atmospheric Water Vapor Mapping Using GNSS

Dr.Eng. Fadwa Alshawaf

fadwa.alshawaf@gfz-potsdam.de

Overview

G Global
N Navigation
S Satellite
S Systems



GPS	31
GLONASS	24
Beidou	33
Galileo	22
QZSS	4
IRNSS	7

GNSS can pretty much everything!

Any time
Any weather
Anywhere

Overview

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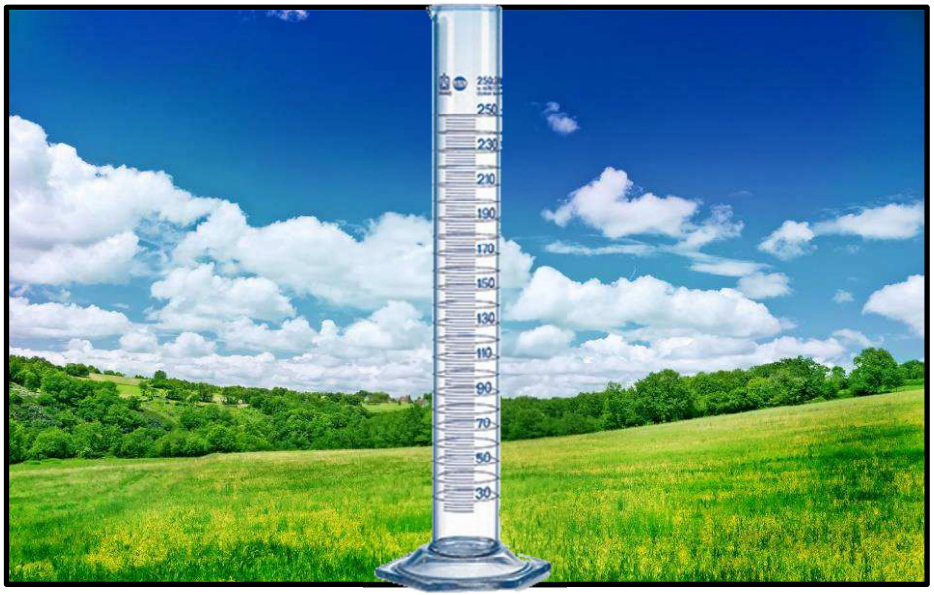
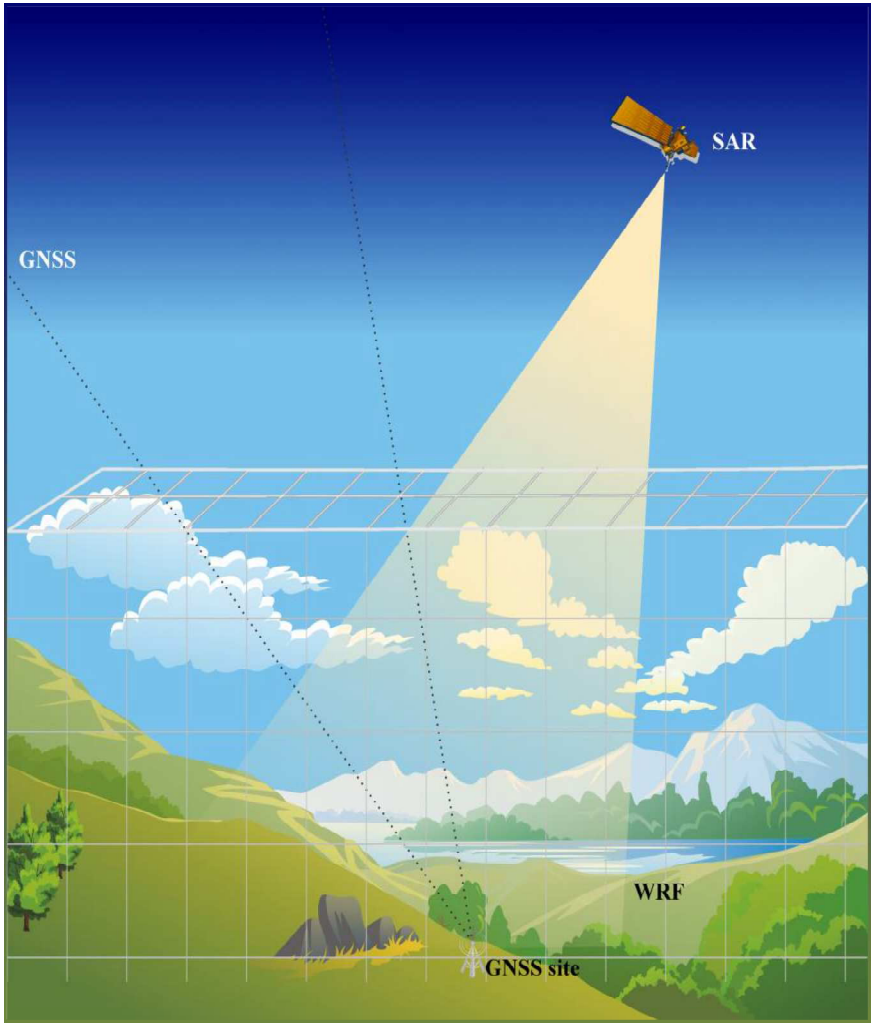


Overview

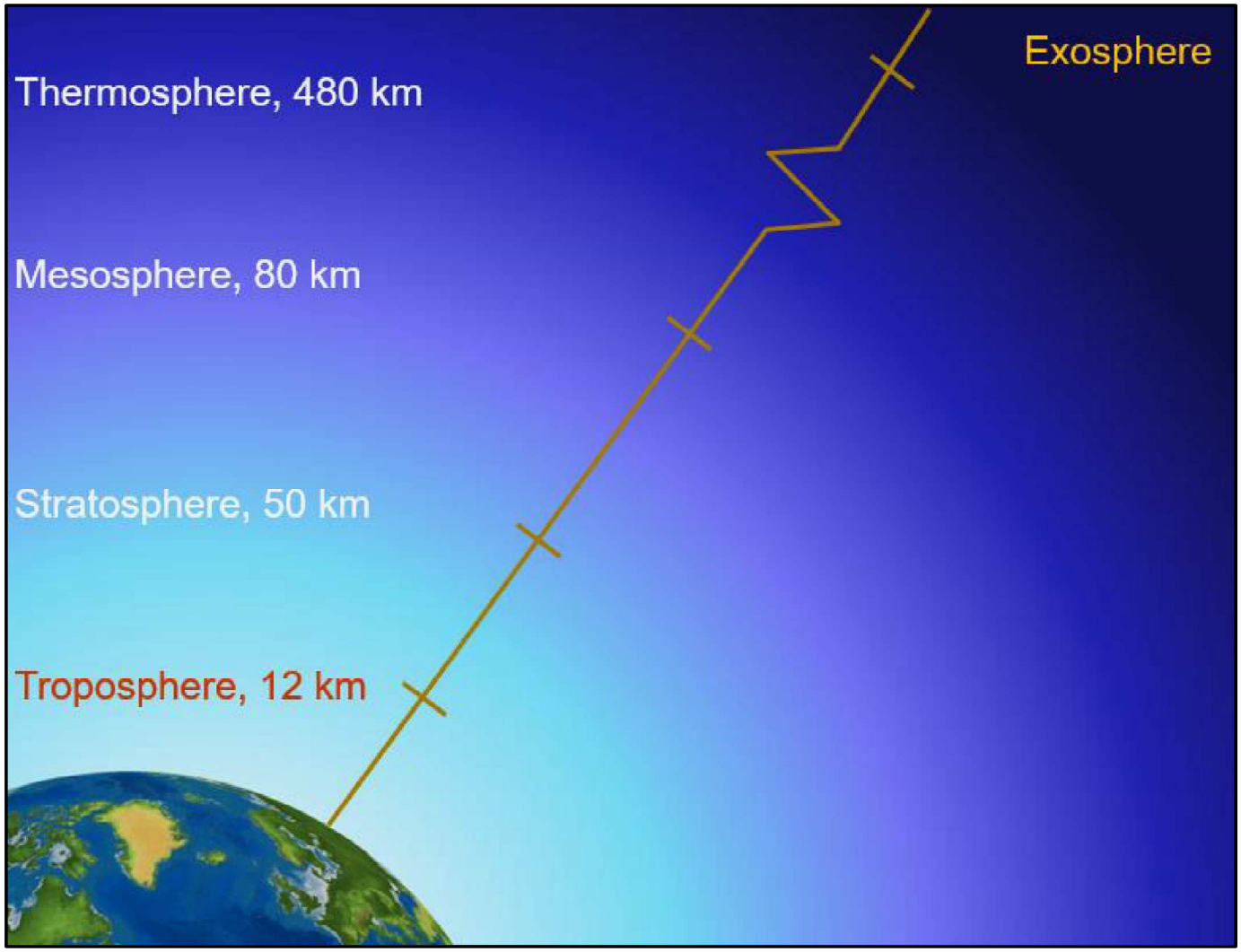
G Global
N Navigation
S Satellite
S Systems

Long Story Short

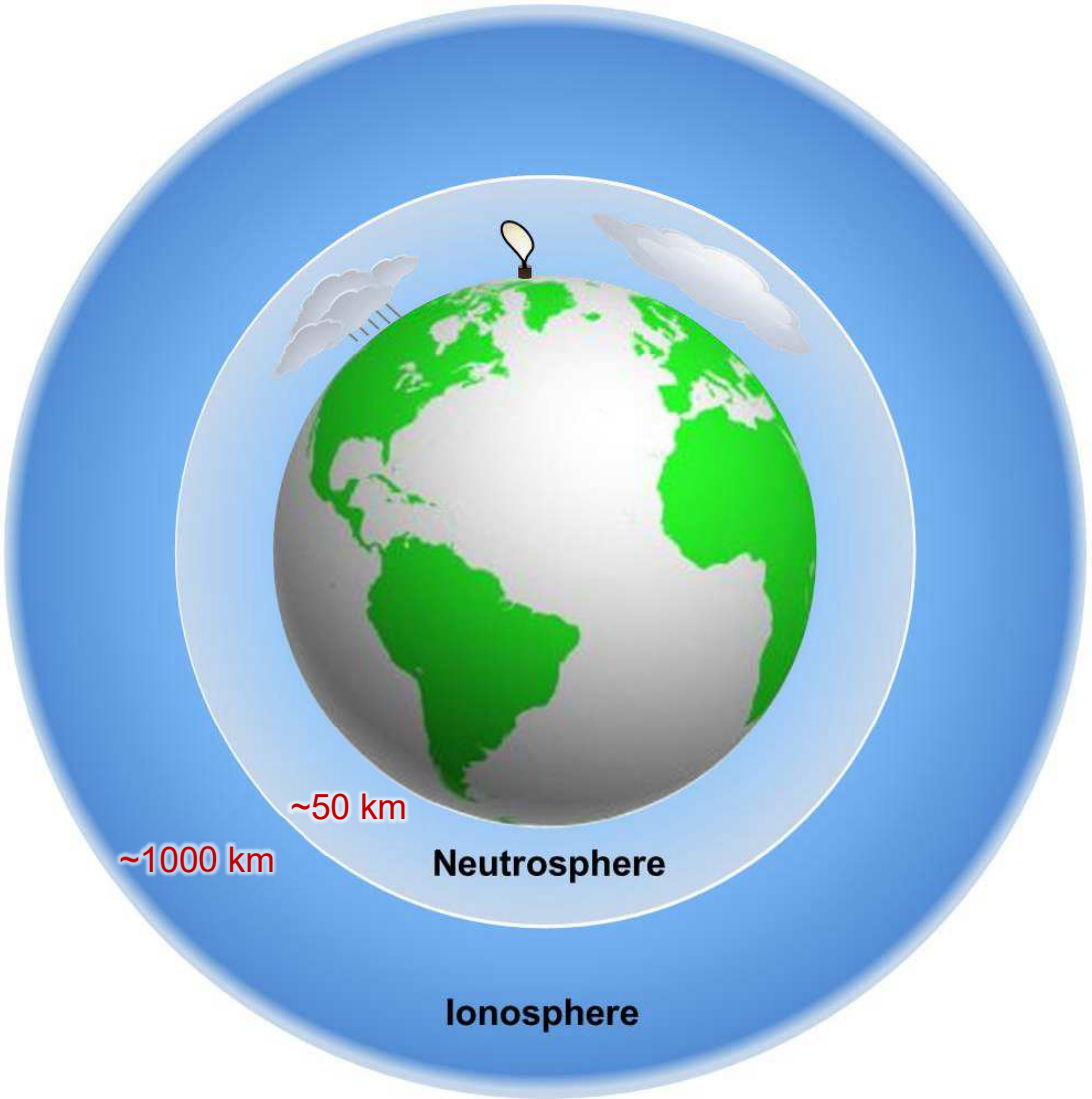
GNSS Meteorology



The Earth's atmosphere

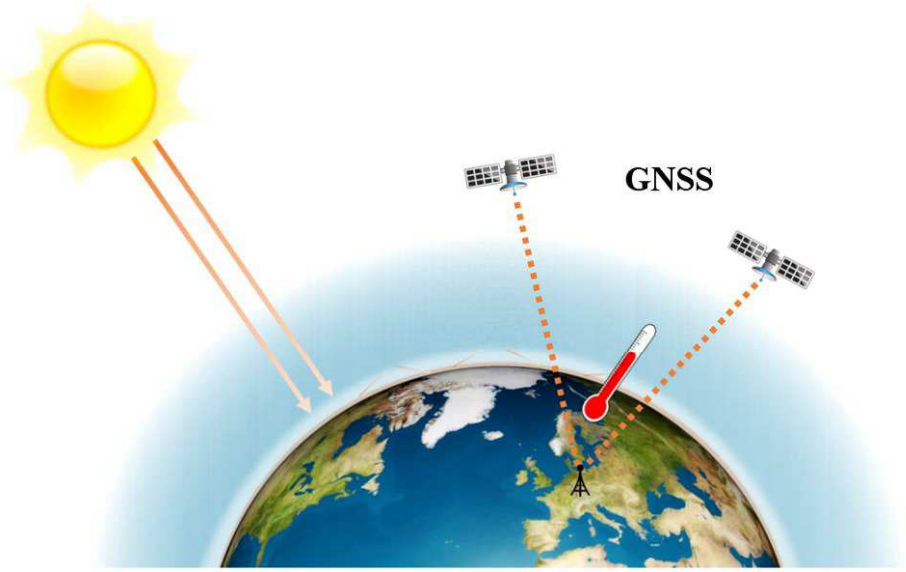


The Earth's atmosphere



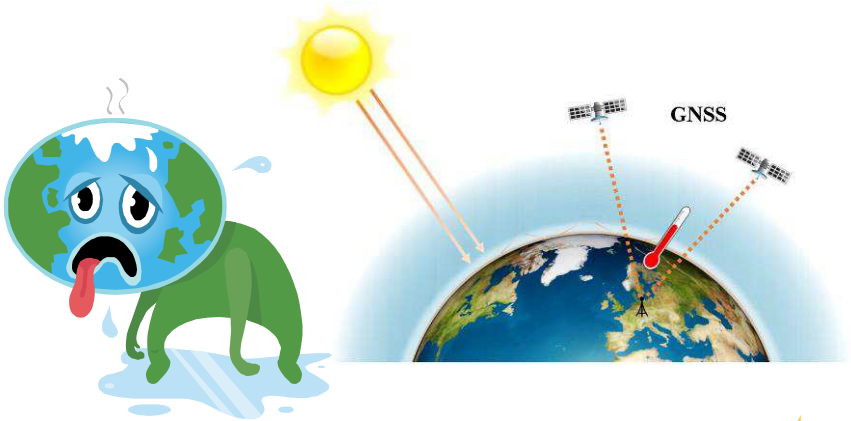
Atmospheric Water Vapor

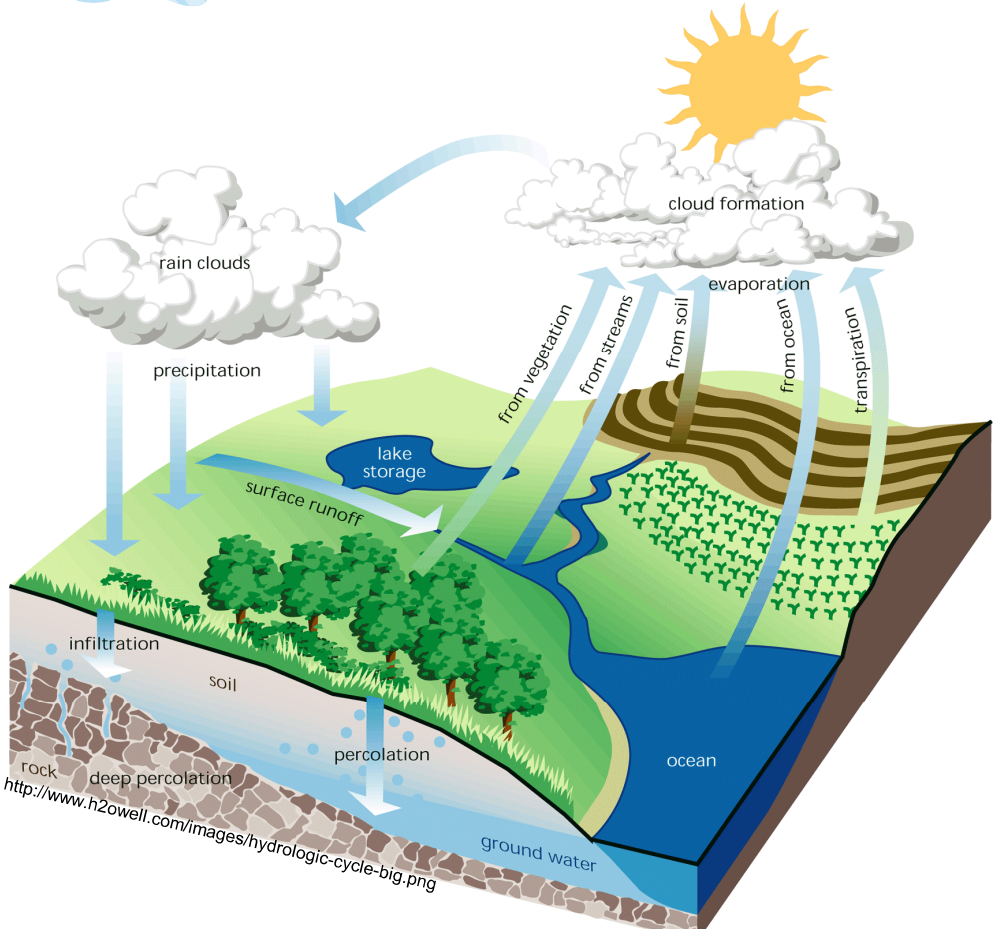
- Greenhouse gas
- Climate studies



Atmospheric Water Vapor

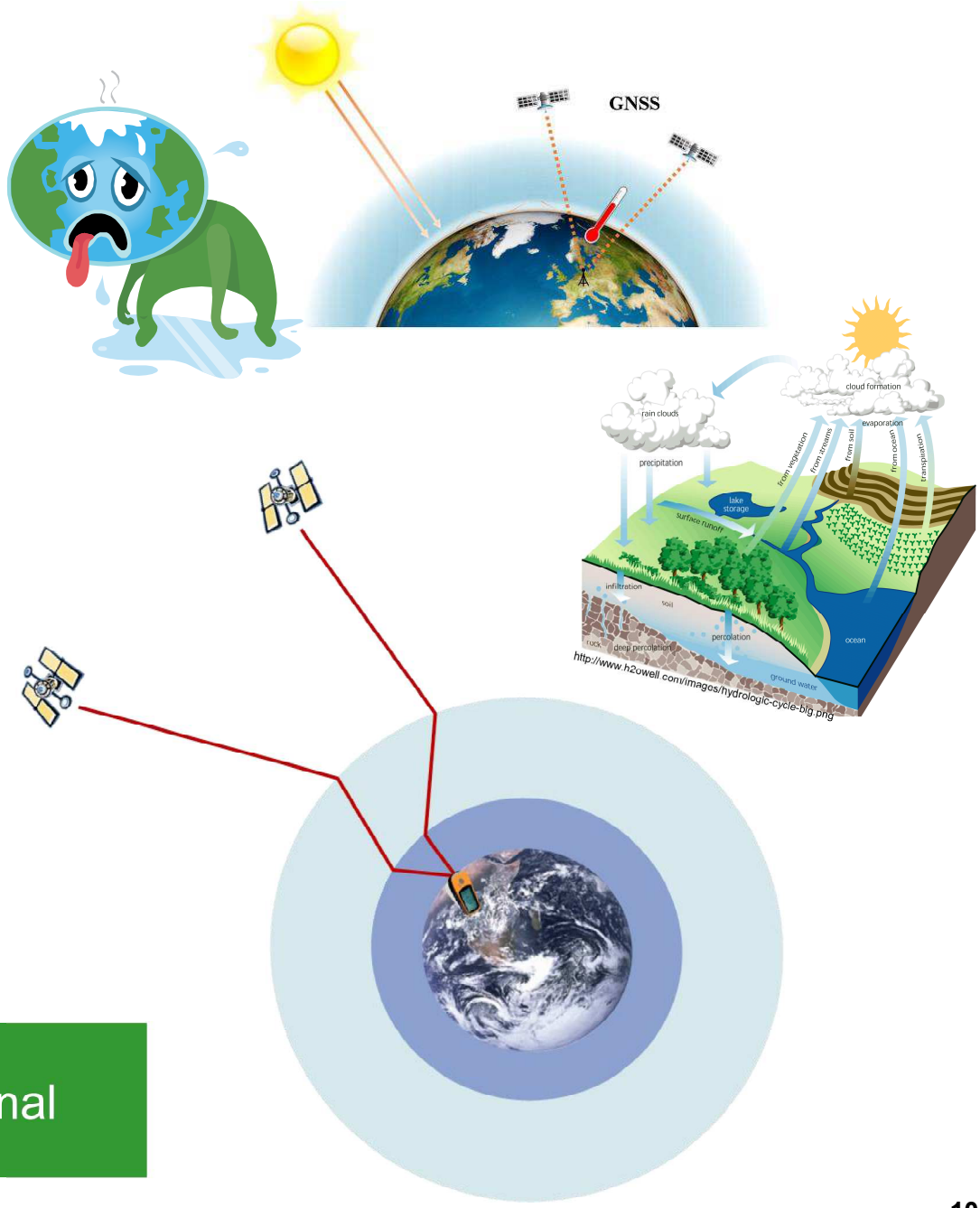
- Greenhouse gas
- Climate studies
- Weather forecasting
- High spatial and temporal variations





Atmospheric Water Vapor

- Greenhouse gas
- Climate studies
- Weather forecasting
- High spatial and temporal variations
- Delays microwave signals
  e.g., GNSS
- Absorption and scattering of optical signals



Error (Delay) >> Informative signal

Atmospheric Water Vapor

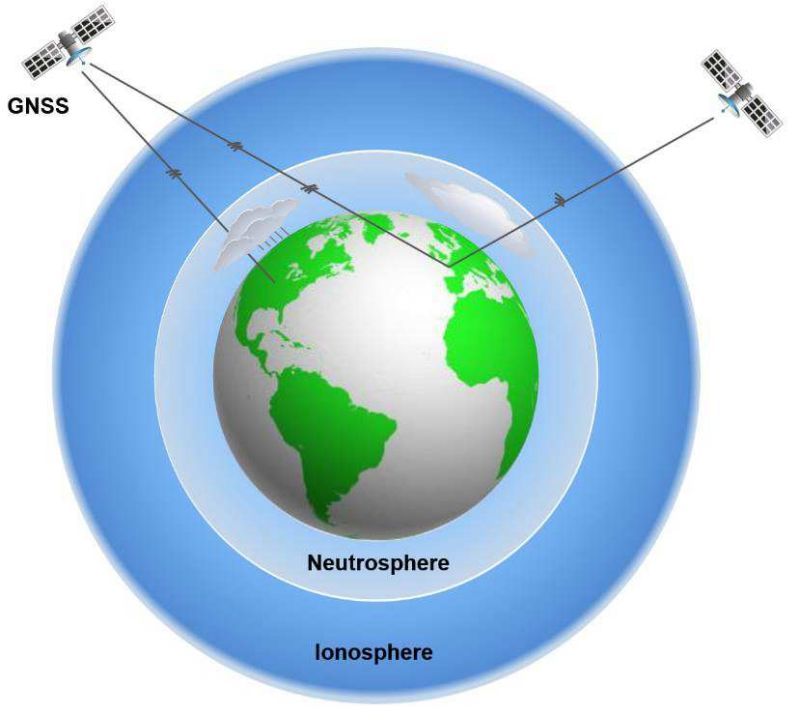
- Condensing column of the atmosphere, produces water content → Precipitable water vapor, PWV

Neutrospheric Delay

For Microwave signals (300 MHz – 30 GHz):

- Neutrospheric delay

✓ Neutrosphere → Neutral layer
Non-dispersive (f <30 GHz)
Delay → Estimation during data processing

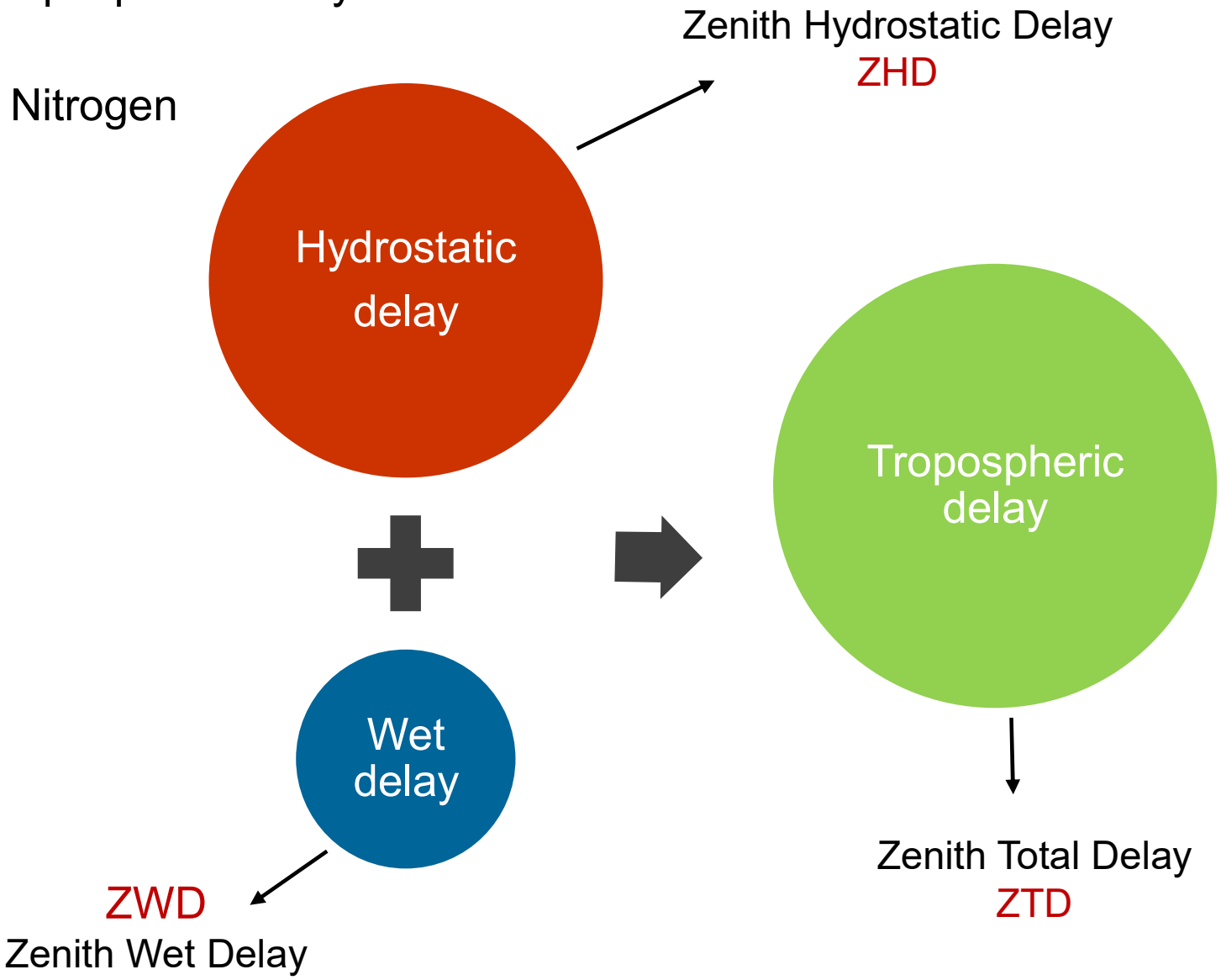


Neutrospheric Delay

Neutrospheric delay = Tropospheric delay

- Dry gases: Oxygen, Nitrogen
- 90%
- ~ 2.4 m
- Accurately modeled

- Water vapor
- 10%
- ≤ 0.4 m
- Has to be estimated

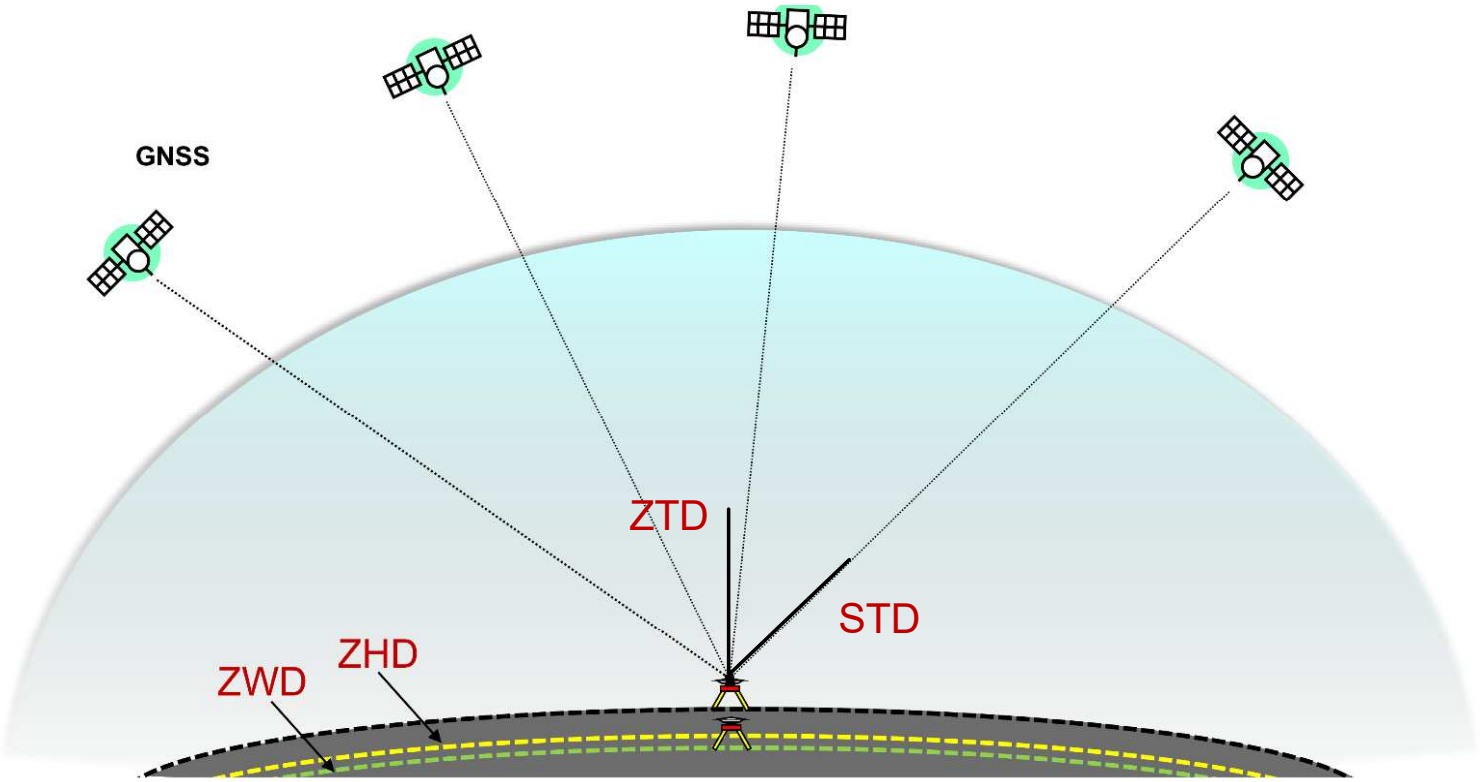


GNSS Data Processing

Linear combination of L1, L2 phase observations:

$$\psi_{L1,L2} = \frac{f}{c} \cdot \rho - f \cdot \delta T + f \cdot \delta t + \Delta^{NEU} - \Delta^{ION} + N + \epsilon$$

- φ carrier phase
- f signal frequency
- c speed of light
- ρ geometrical range
- δT receiver clock error
- δt satellite clock error
- Δ^{NEU} neutrospheric delay
- Δ^{ION} ionospheric delay
- N phase ambiguity
- ε noise



GNSS Data Processing

$$ZHD = \frac{0.002277\ p}{1 - 0.0026 \cdot \cos 2\phi - 0.00028 \cdot H}$$

H, ϕ: Station height, and latitude
p: Air pressure

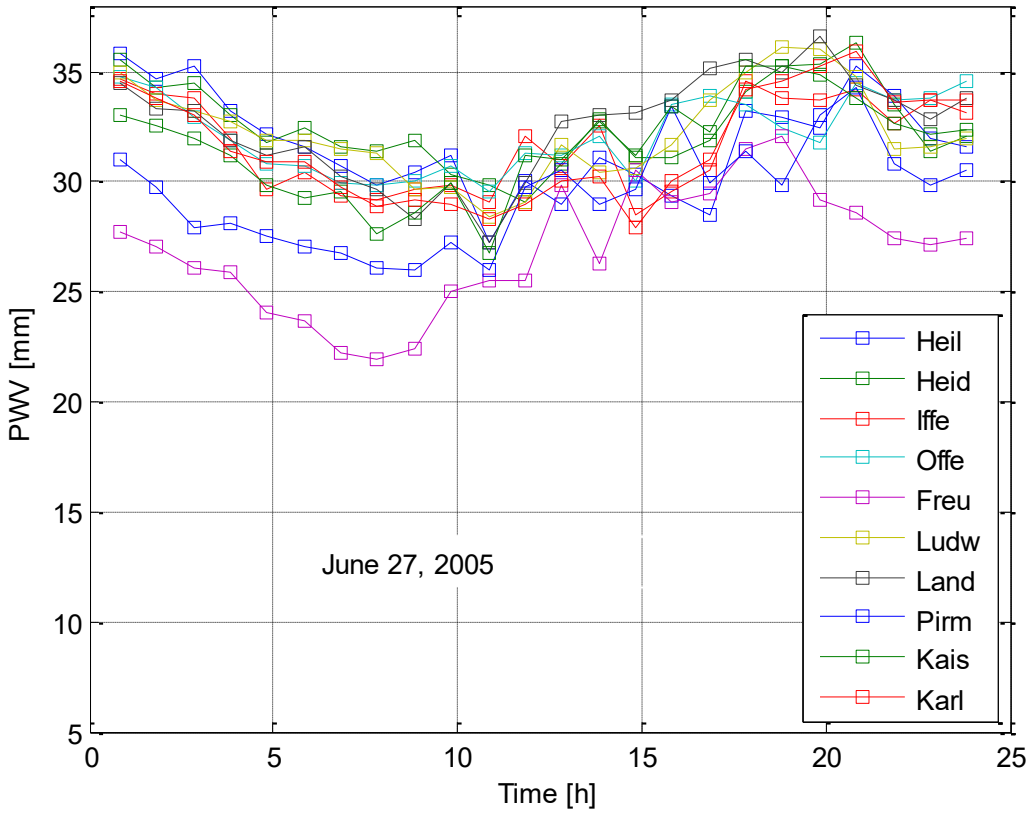
$$ZWD = ZTD - ZHD$$

Conversion to PWV: $PWV = \Pi \cdot ZWD,$ $\Pi \approx [0.15 - 0.17]$

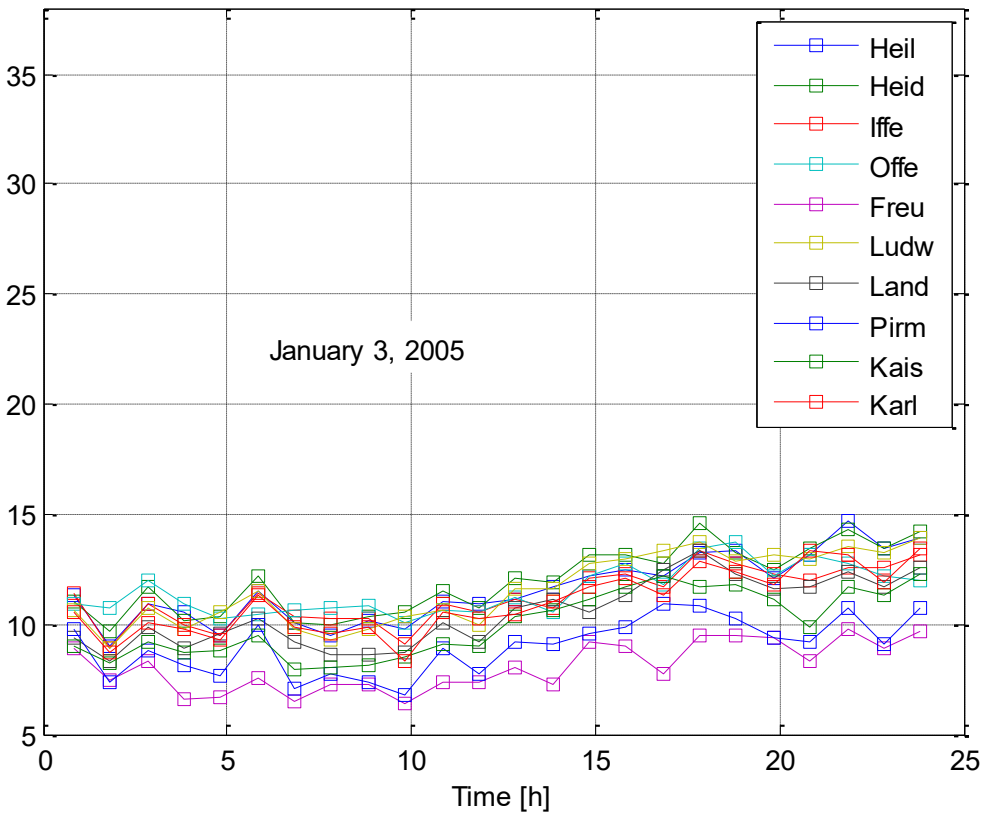
It is calculated based on the water-vapor-weighted mean temperature

Results

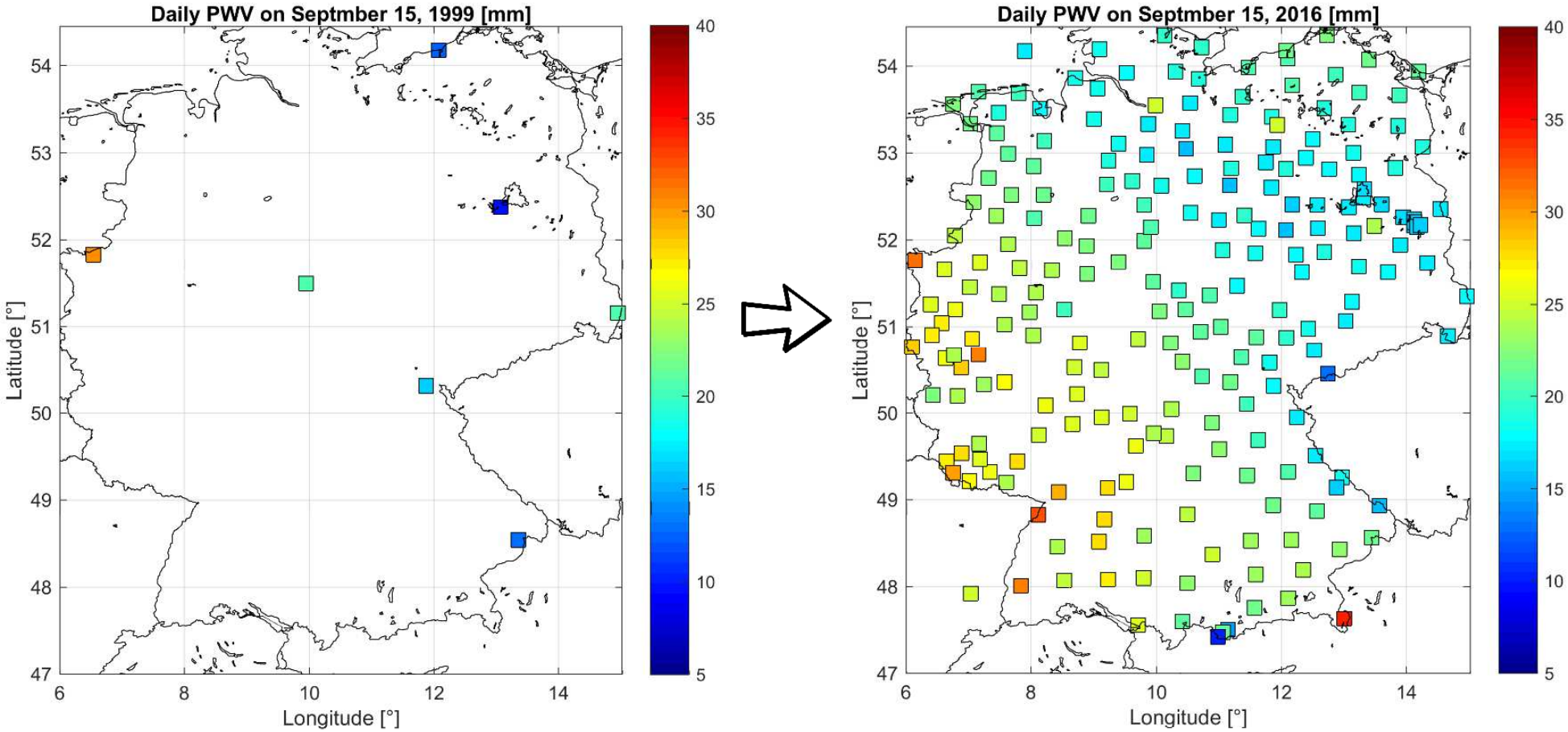
Summer



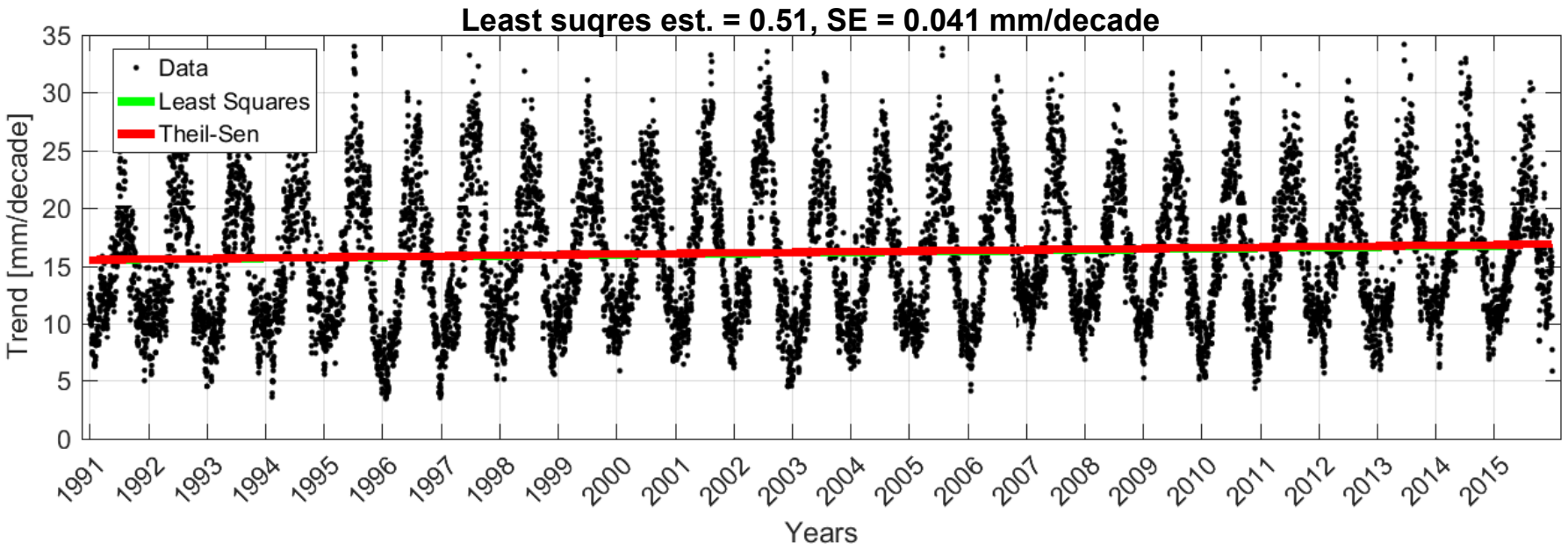
Winter



Results


Daily PWV on Septmber 15, 1999 [mm]
Daily PWV on Septmber 15, 2016 [mm]
Latitude [°]
Longitude [°]
54
53
52
51
50
49
48
47
6
8
10
12
14
40
35
30
25
20
15
10
5

Results


Least suqres est. = 0.51, SE = 0.041 mm/decade
Data
Least Squares
Theil-Sen
Trend [mm/decade]
Years
0
5
10
15
20
25
30
35
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015

Summary

Water vapor from GNSS data

☺ Accurate
☺ Total content of water vapor
☺ High temporal resolution
😐 Spatial averaging
☹ Pointwise measurements

Summary

Water vapor from GNSS data

☺ Accurate
☺ Total content of water vapor
☺ High temporal resolution
😐 Spatial averaging
☹ Pointwise measurements

Thank you very much!

Now, Dr. Galina Dick presents the framework of atmospheric monitoring at GFZ

GFZ
Helmholtz Centre
POTSDAM

HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

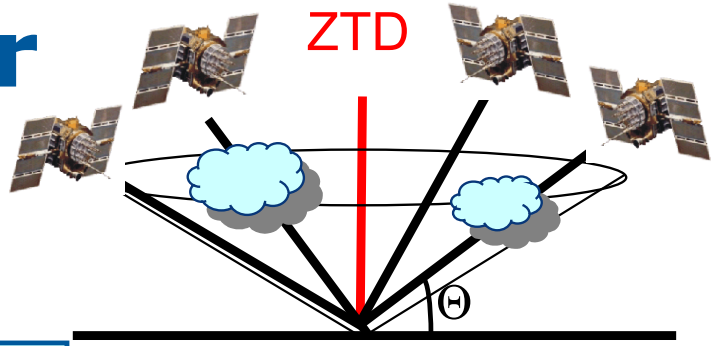
GNSS FÜR ATMOSPHÄRENMONITORING AM GFZ

Galina Dick
Fadwa Alshawaf, Benjamin Männel, Florian Zus, Markus Ramatschi,
Markus Bradke, Jens Wickert

Deutsches GeoForschungsZentrum GFZ, Potsdam
Department 1 „Geodäsie"
Sektion 1.1 „Geodätische Weltraumverfahren"

MNU-Tagung, Berlin, 20.08.2019

Warum GNSS-abgeleiteter Wasserdampf?



PWV = PWV (ZTD, T, p)

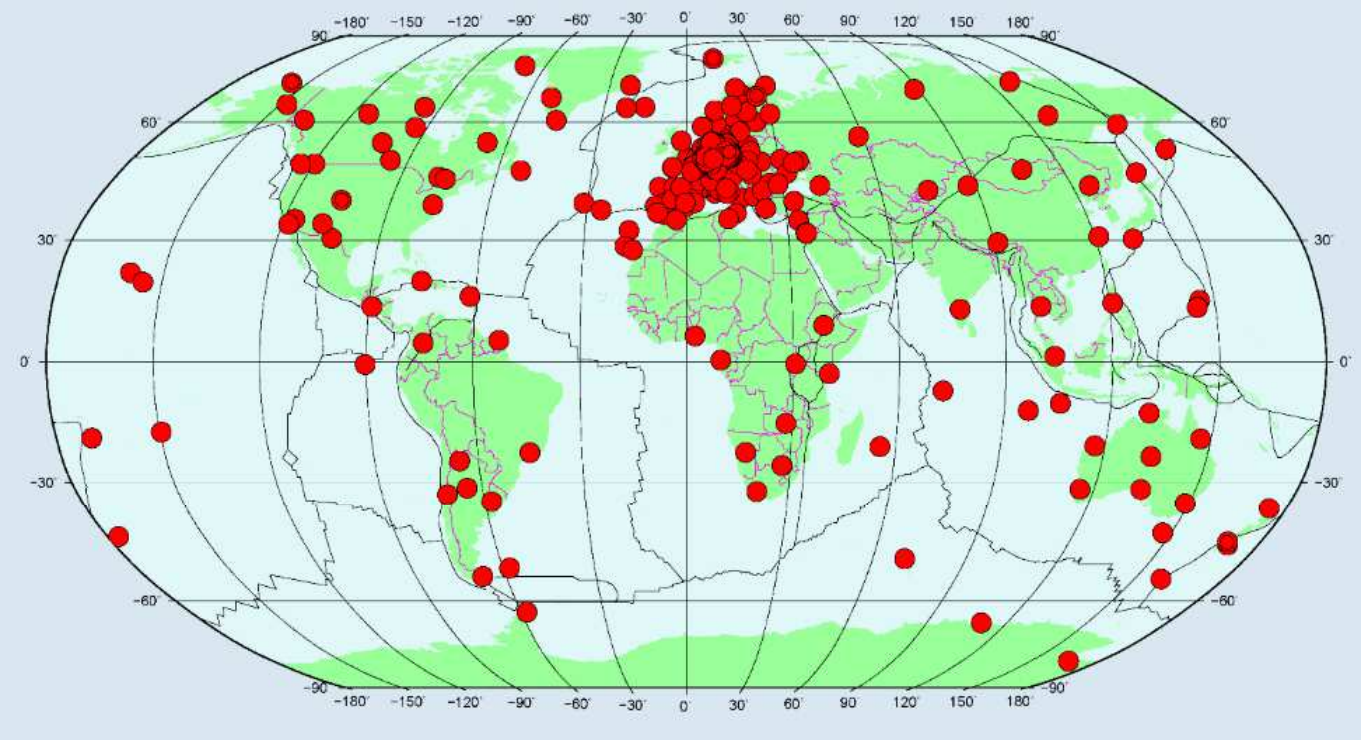
Hohe zeitliche und räumliche Auflösung, Wetterunabhängigkeit, Zuverlässigkeit, geringe Zeitverzögerung, niedrige Kosten

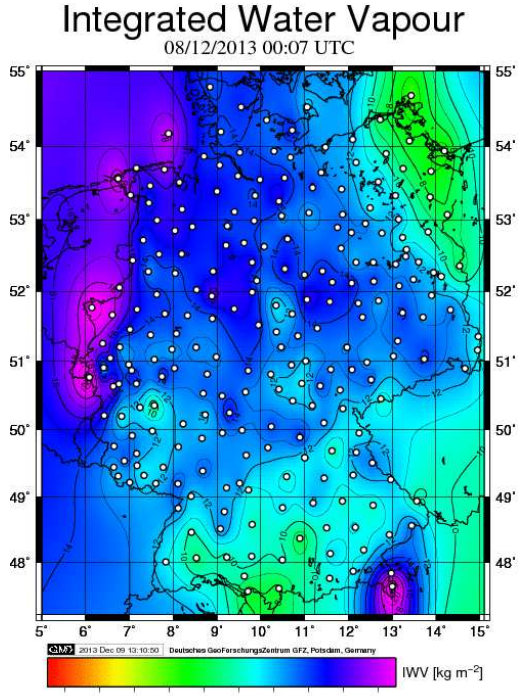
Hohe Genauigkeit (1-2 mm Wasserdampf), vergleichbar mit Messungen meteorologischer Instrumente wie Radiosonden, Wasserdampf-Radiometer, Lidar-Systeme

Klimaforschung:
Kontinuierliche Zeitreihen, Langzeitstabilität

GNSS-basiertes Atmosphärenmonitoring am GFZ

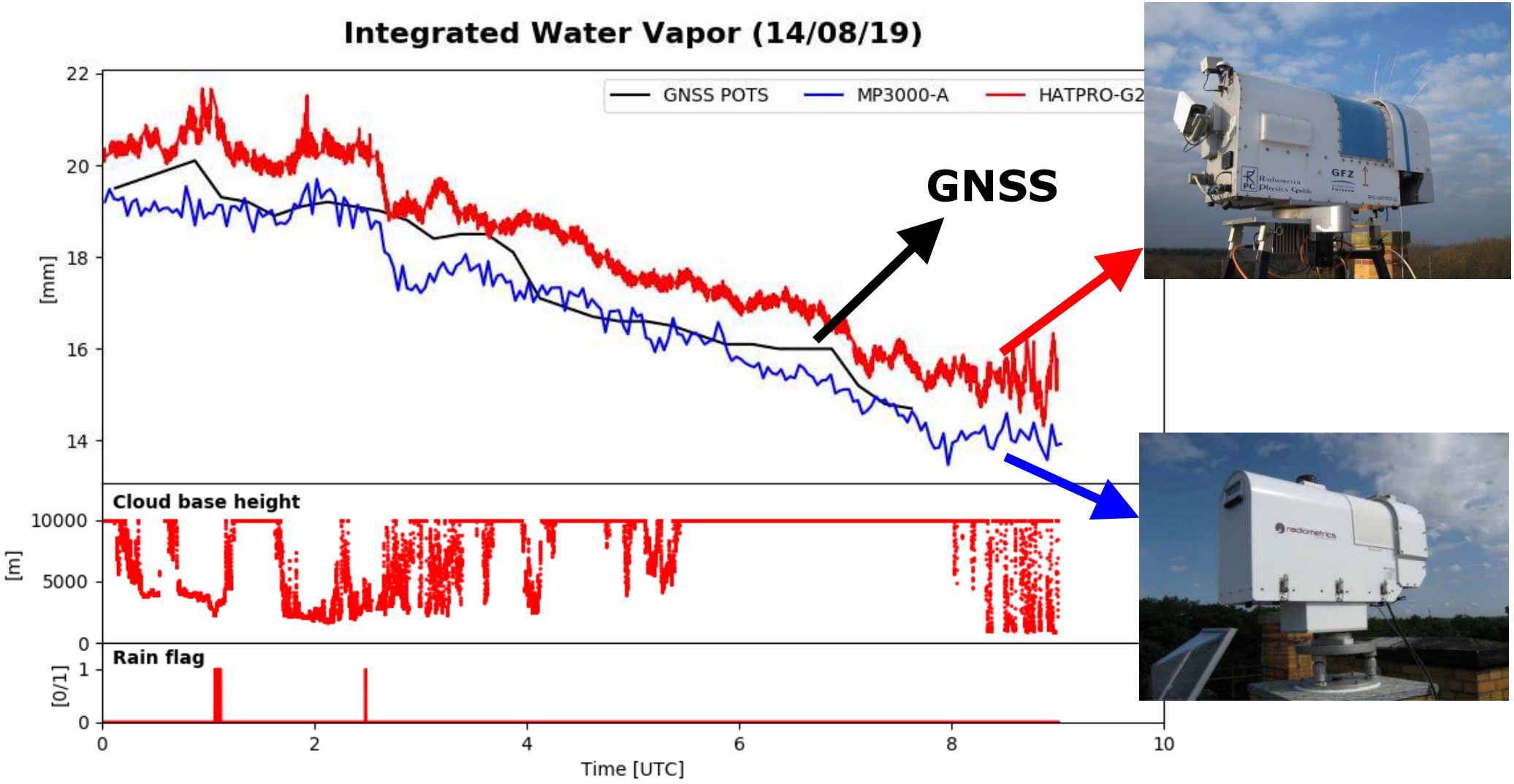
- Seit 2000 operationell, GFZ EPOS Software
- Stündliche Analyse von **~600 GNSS-Stationen** (300 in Deutschland)
- **Produkte**: ZTDs/WD/Gradienten (15 Min. Zeitauflösung),
  „Slant Total Delays" (2,5 Min.)
- Verzögerung: < 30 Min nach letzter Datenepoche ("nahe Echtzeit")
- Genauigkeit: ~1-2 mm Wasserdampf





Orkan Xaver 8.12.2013

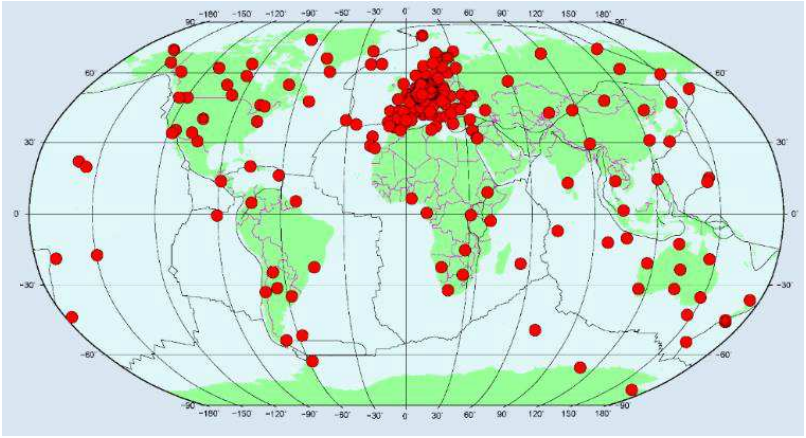
GNSS-abgeleiteter Wasserdampf



GNSS-abgeleiteter Wasserdampf für Station Potsdam: Vergleich mit Wasserdampf-Radiometern des GFZ

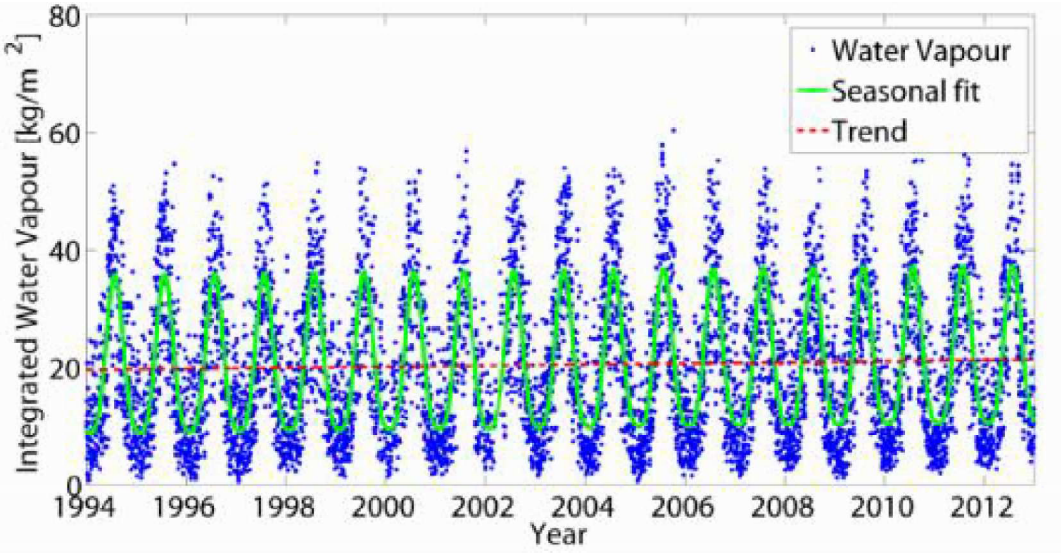
GNSS-WD: Anwendungen

Globale/Regionale Netzwerke



Repro

Beispiel: Greenbelt (USA), +0.94 mm/Dekade

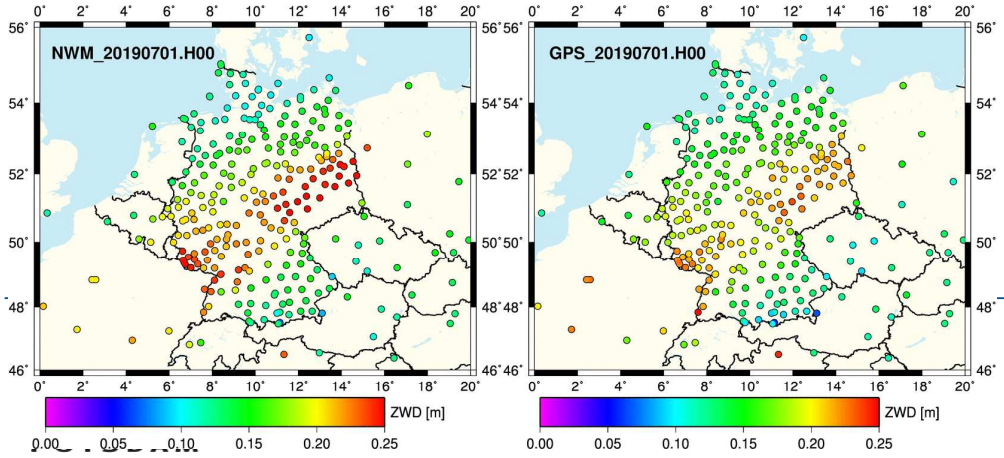


"nahe Echtzeit"

GNSS-Meteorologie:
Nutzung von GNSS-Daten durch Wetterdienste für die operationelle Wettervorhersage

Klimaforschung:
Langzeit-WD-Datenreihen, Trendanalyse

Modell GFS **GNSS**

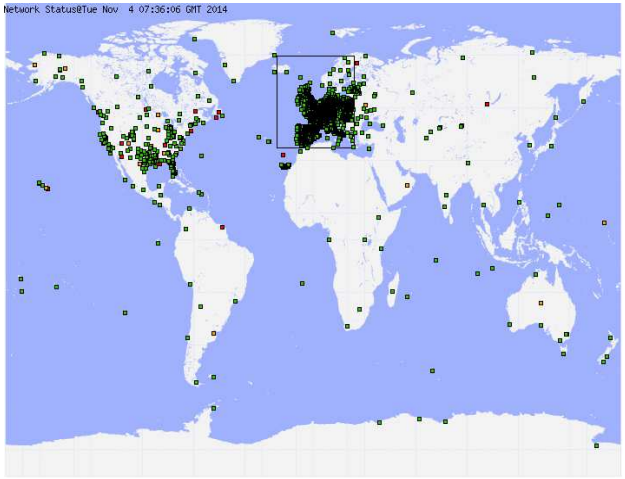


GRUAN:
Referenznetzwerk für Klima

HELMHOLTZ

Europäisches Meteo-Projekt E-GVAP

E-GVAP GNSS-Netzwerk



EUMETNET GNSS Water Vapour Programme

E-GVAP I,II,III: 2006 - 2018

E-GVAP IV: 2019-2023

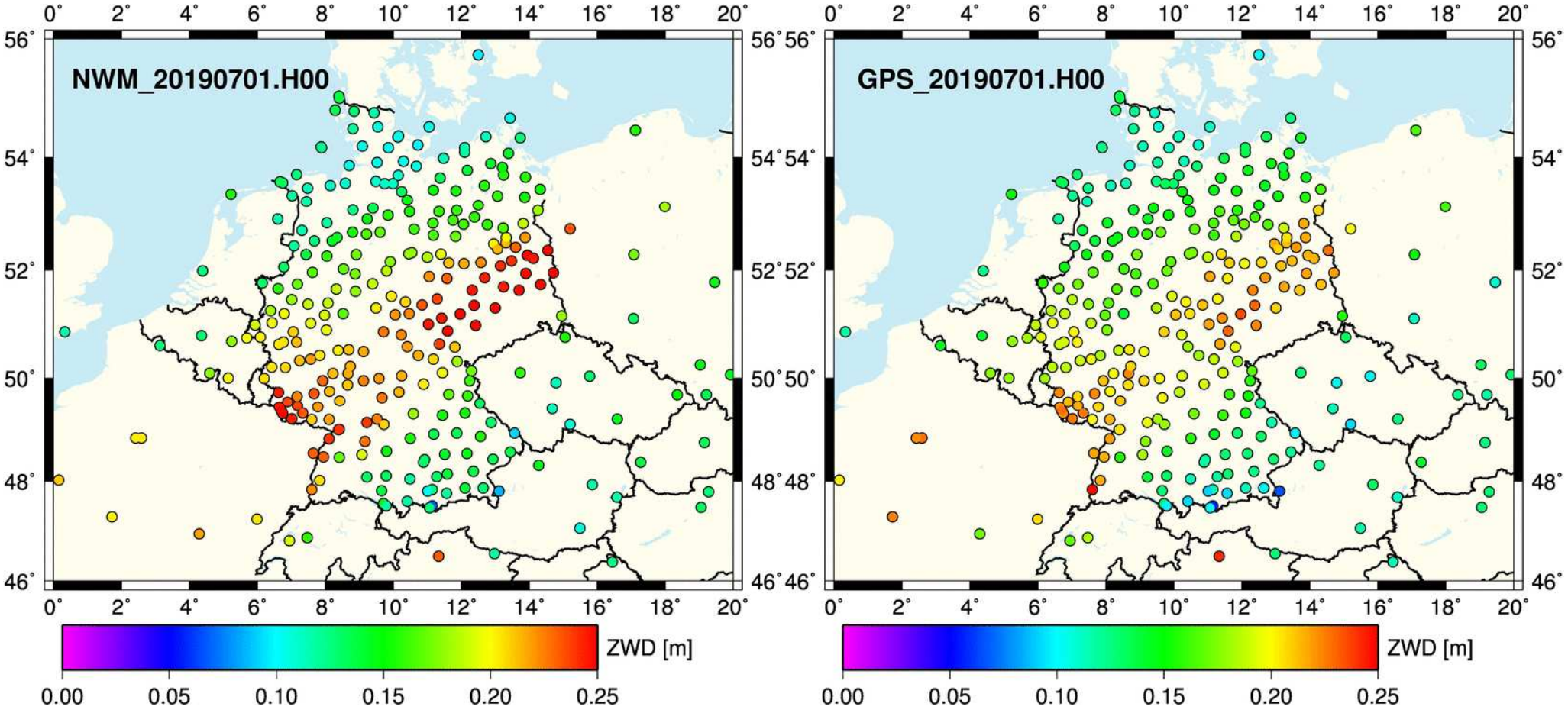
20 Analysezentren in Europa
(10 operationell)
~4000 GNSS Stationen

Operationelle Assimilation GFZ GNSS-ZTDs durch einige Meteo-Dienste (MeteoFrance, UK MetOffice)

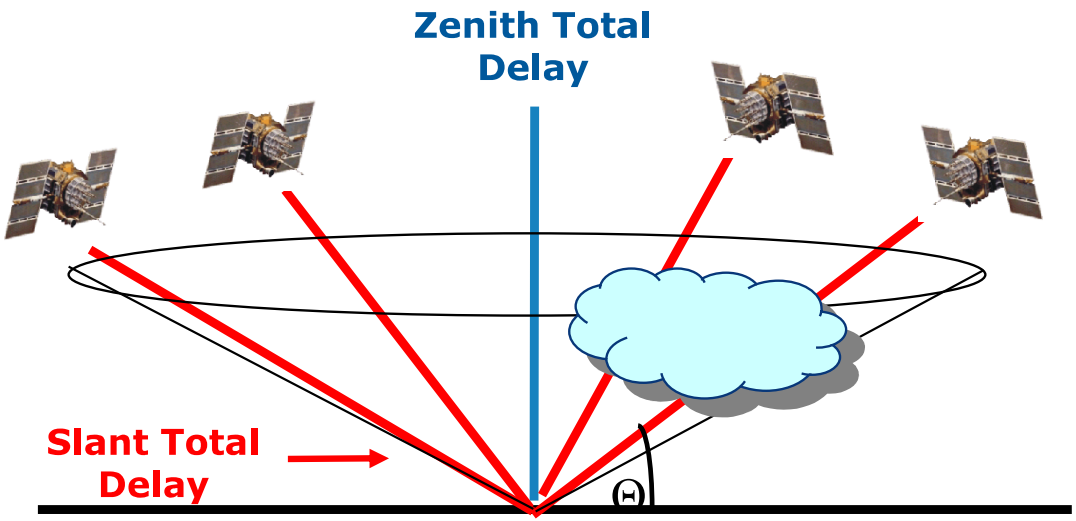
GNSS-basiertes Wasserdampfmonitoring: Vergleich mit Wettermodell GFS

Modell GFS

GNSS



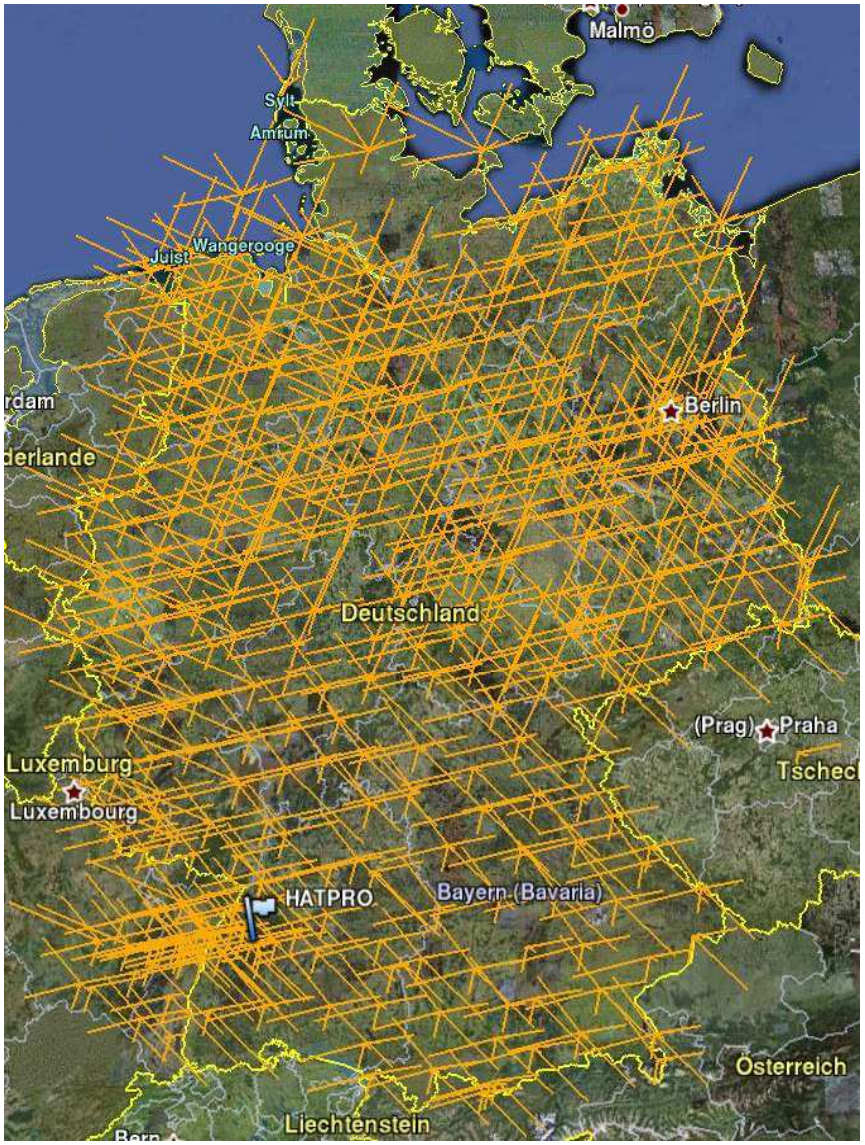
“Slant Total Delays”-Prozessierung



Automatische Prozessierung von ~100000 „Slants“ pro Stunde in nahe Echtzeit

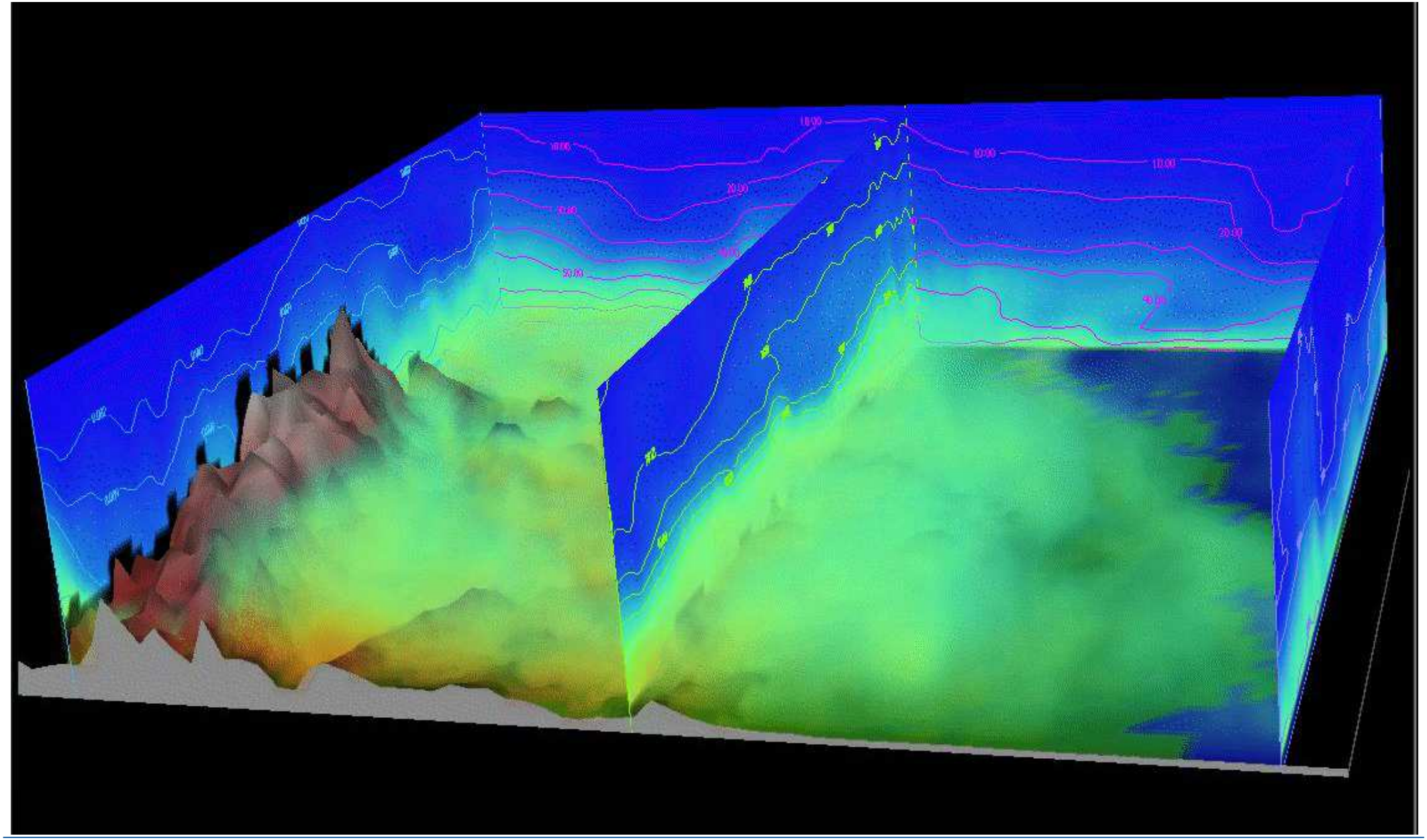
3D-Wasserdampf-Rekonstruktion (Tomografie) für Deutschland, basierend auf „Slant Delay“-Information

Assimilation von „Slants“ in die Wettermodelle des DWD



‚Slant Delays‘, abgeleitet von SAPOS-Stationen in Deutschland

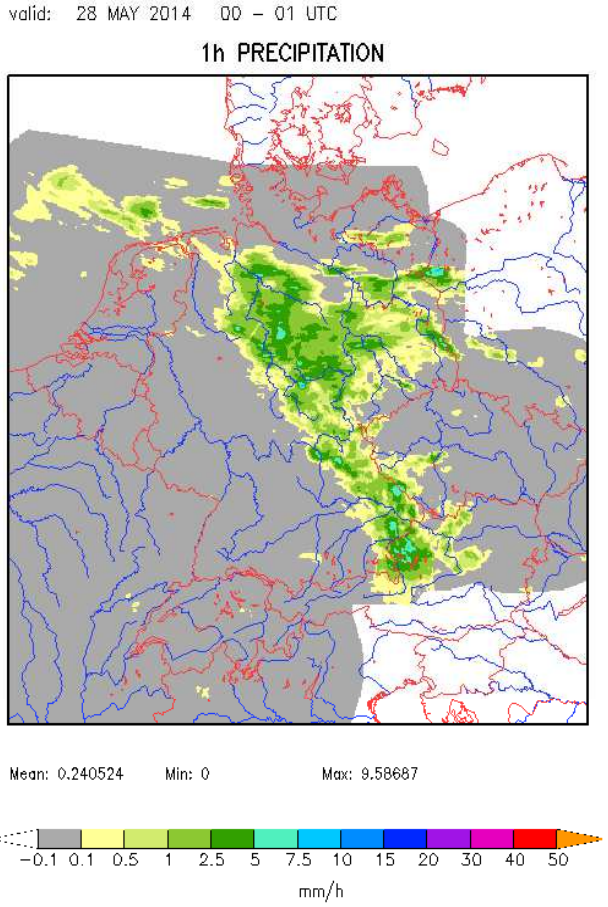
GNSS-Wasserdampf-Tomographie



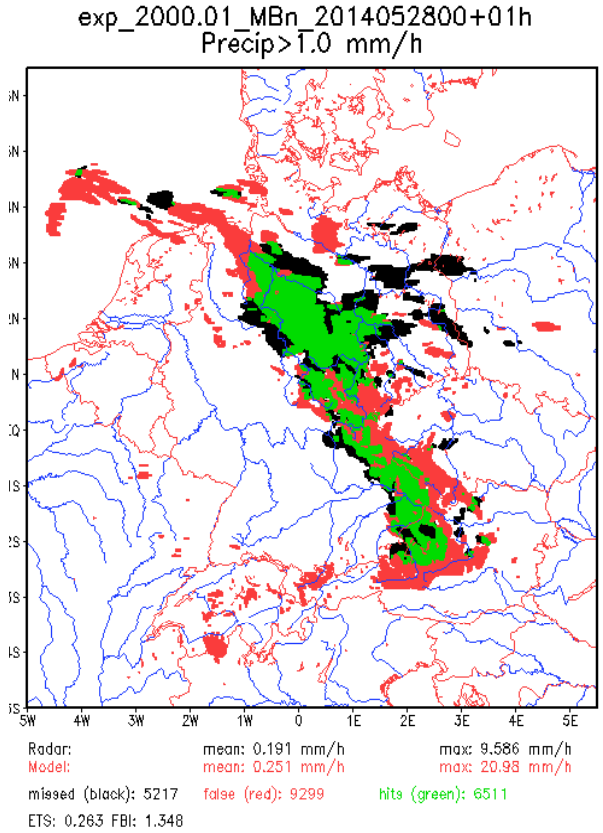
Niederschlagsvorhersage (DWD)

28.5.2014, 1:00 UTC, 0:00 UTC Vorhersage

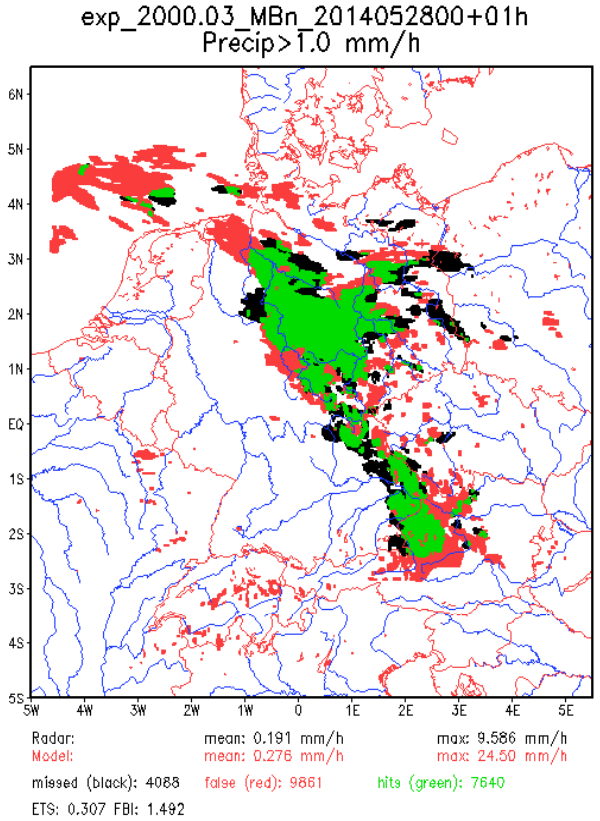
Radar observations



Control experiment



Slant assimilation



~20% Verbesserung der Niederschlagsvorhersage
durch Assimilierung der GNSS-"Slant"-Daten

Courtesy: C. Schraff/M. Bender (DWD)

Klimauntersuchungen mit GNSS

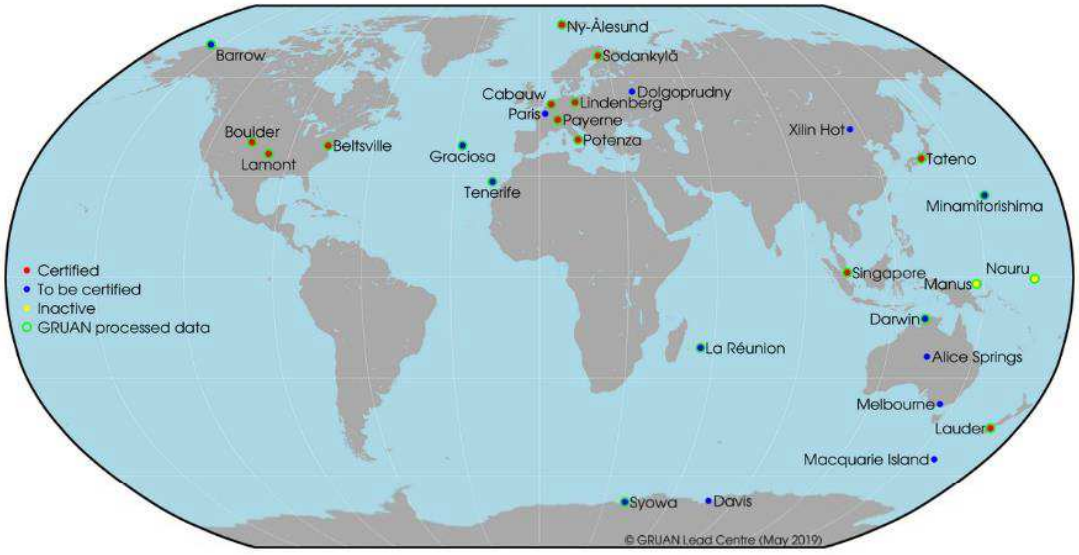
Was ist GRUAN?

Global **C**limate **O**bserving **S**ystem (GCOS) **R**eference **U**pper-**A**ir **N**etwork

Netzwerk für bodengestützte Referenzbeobachtungen der Atmosphäre für **Klimaforschung** im Rahmen von GCOS (WMO)

GCOS
GLOBAL CLIMATE OBSERVING SYSTEM

GRUAN **www.gruan.org**



- Seit 2007
- GRUAN-Zentrale: MO Lindenberg (DWD)
- 27 Stationen weltweit

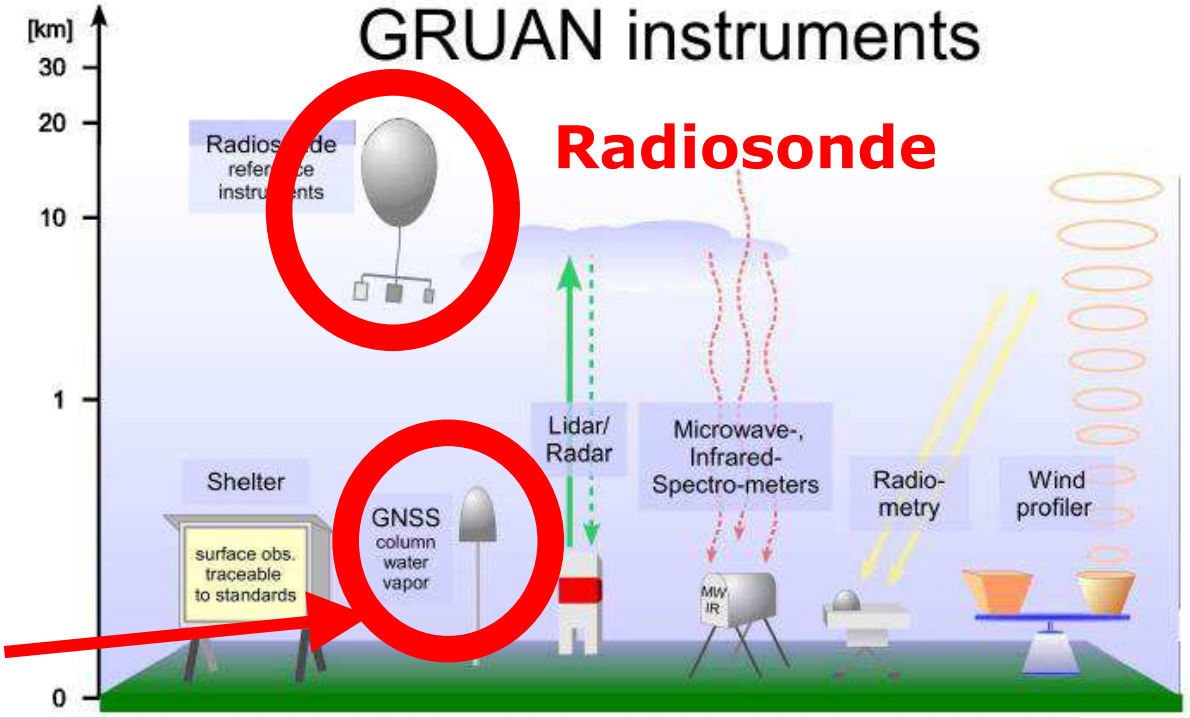
GRUAN-Beobachtungen

Priorität Nr. 1: Temperatur, Druck, Wasserdampf

Priorität Nr. 2: Ozone, Methane, …

Anforderungen:

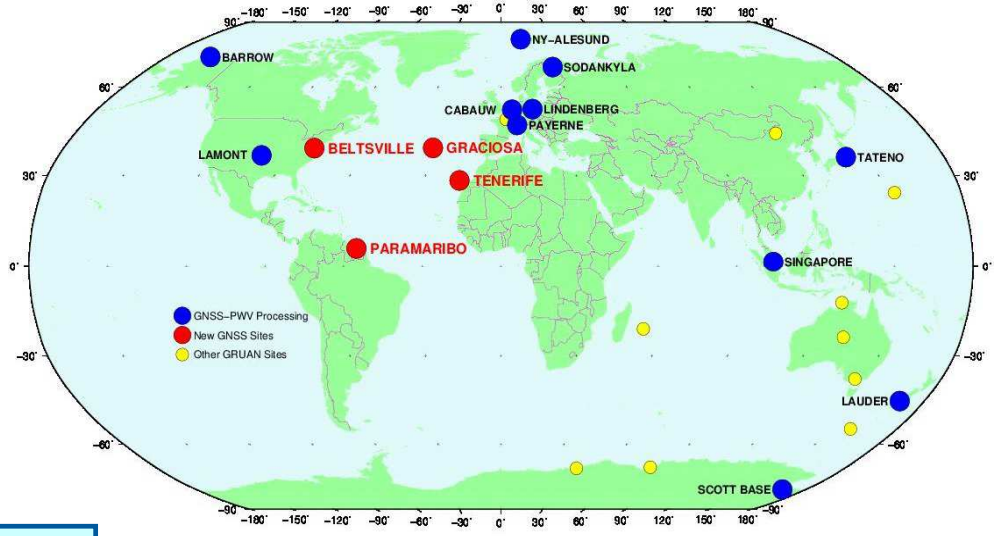
- Höchste Genauigkeit
- Langzeitstabilität

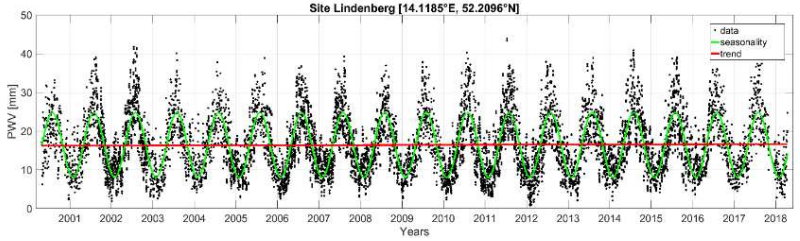


GNSS wurde als "Priorität Nr. 1"-Technik für die Wasserdampf-Bestimmung anerkannt

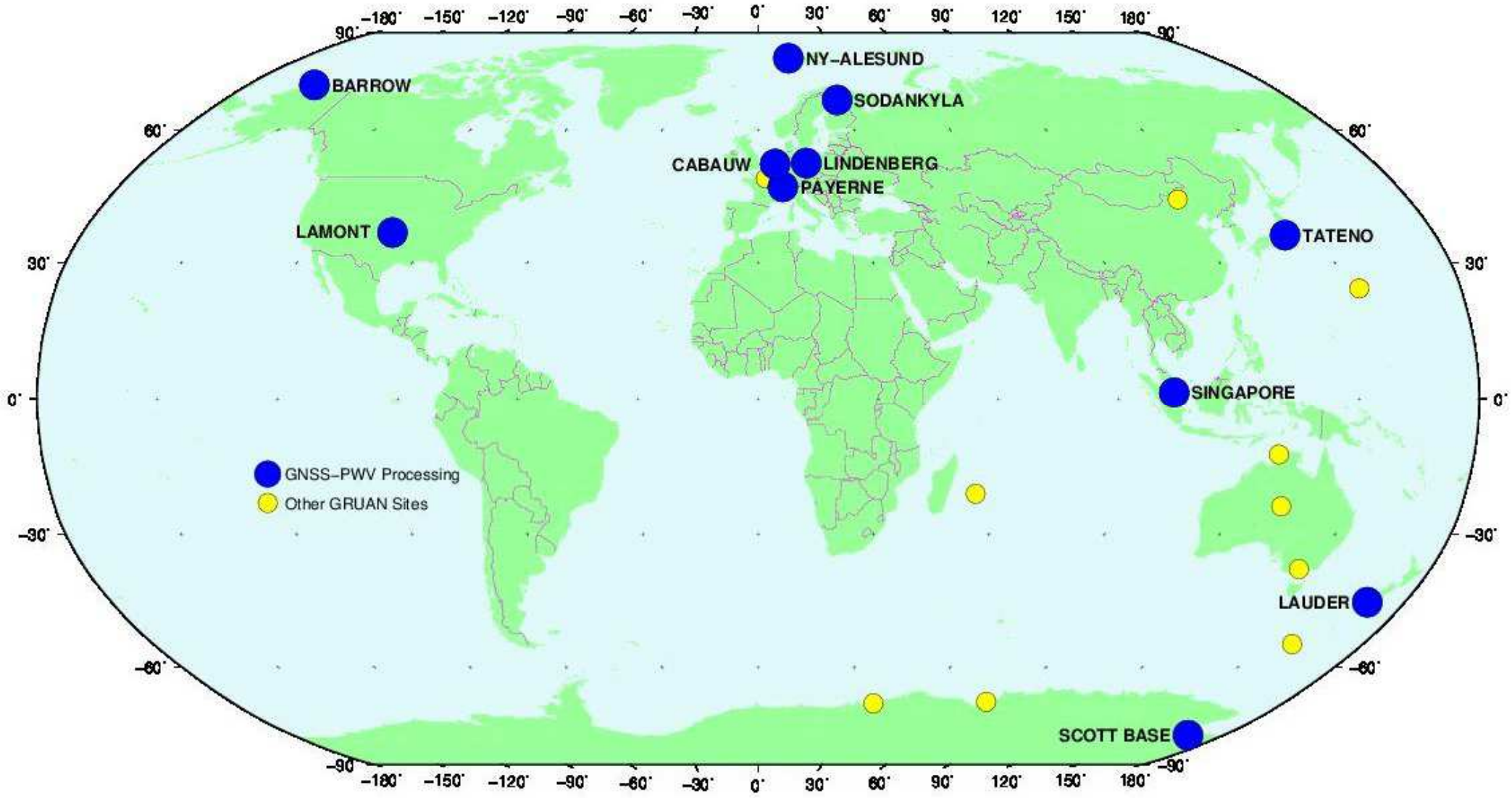
GFZ-Beitrag zu GRUAN

- **GNSS Task Team**
- **GNSS network**
- **GNSS-PWV Processing Centre**
- **Validations with RS, WVR, NWM**
- **GNSS-PWV trend analysis**



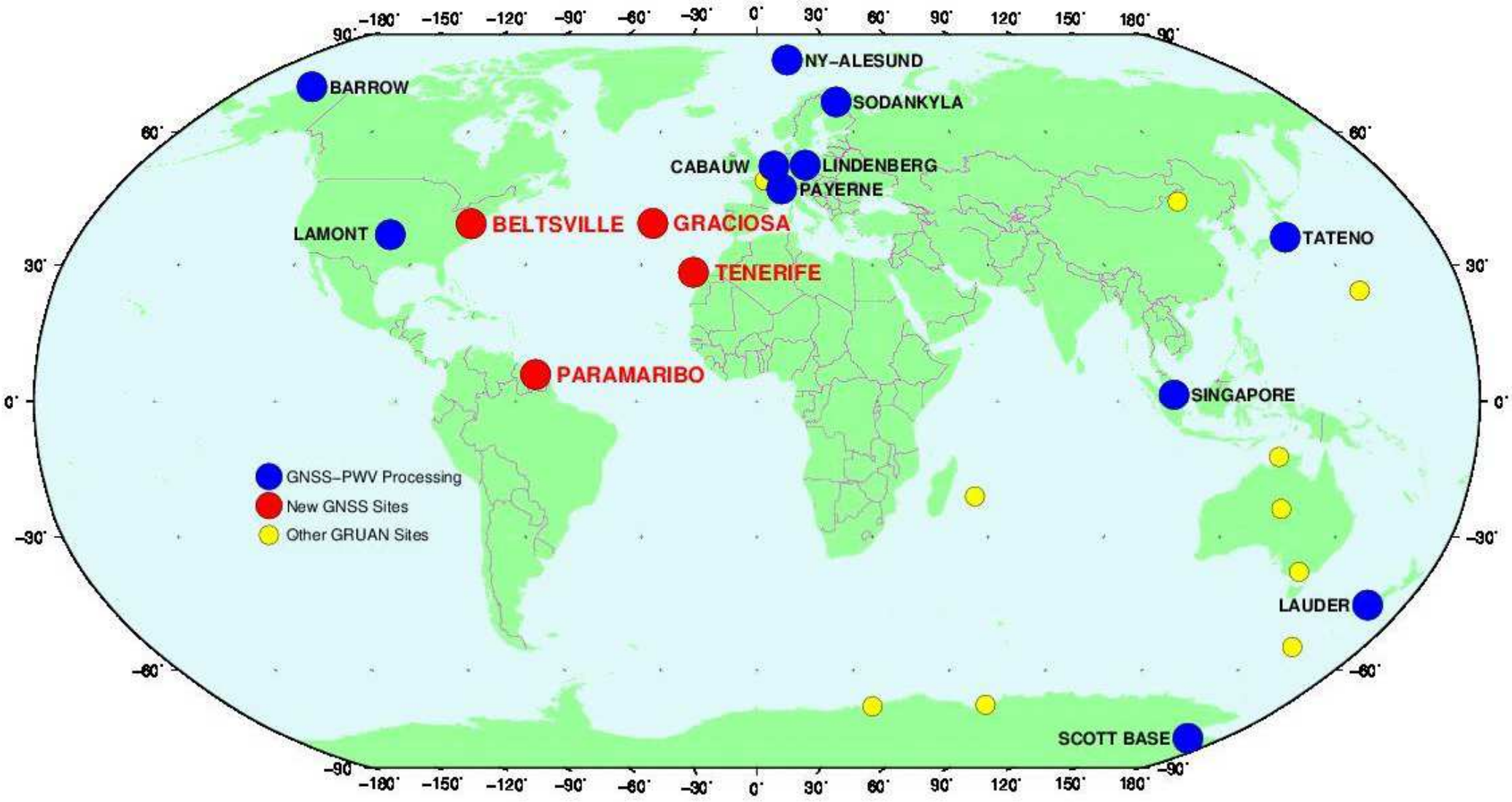


GRUAN-GNSS-Netzwerk im GFZ-Betrieb



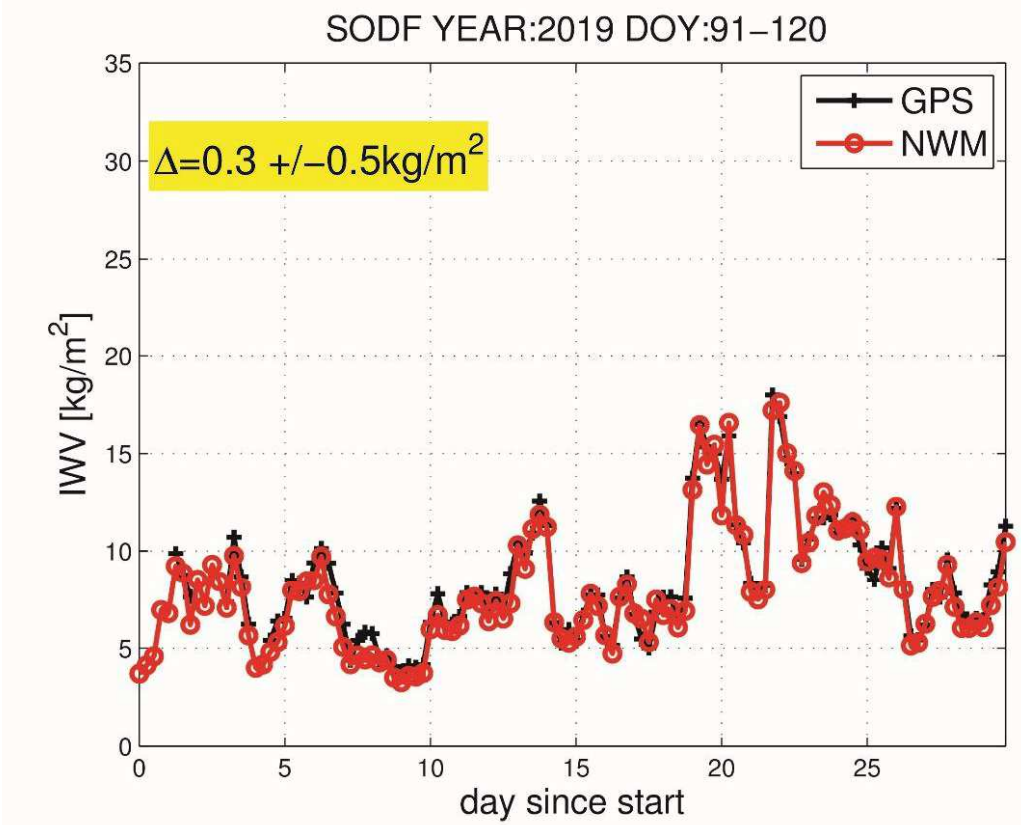
11 GRUAN Stationen in GNSS-WD-Prozessierung

GRUAN-GNSS-Netzwerk im GFZ-Betrieb

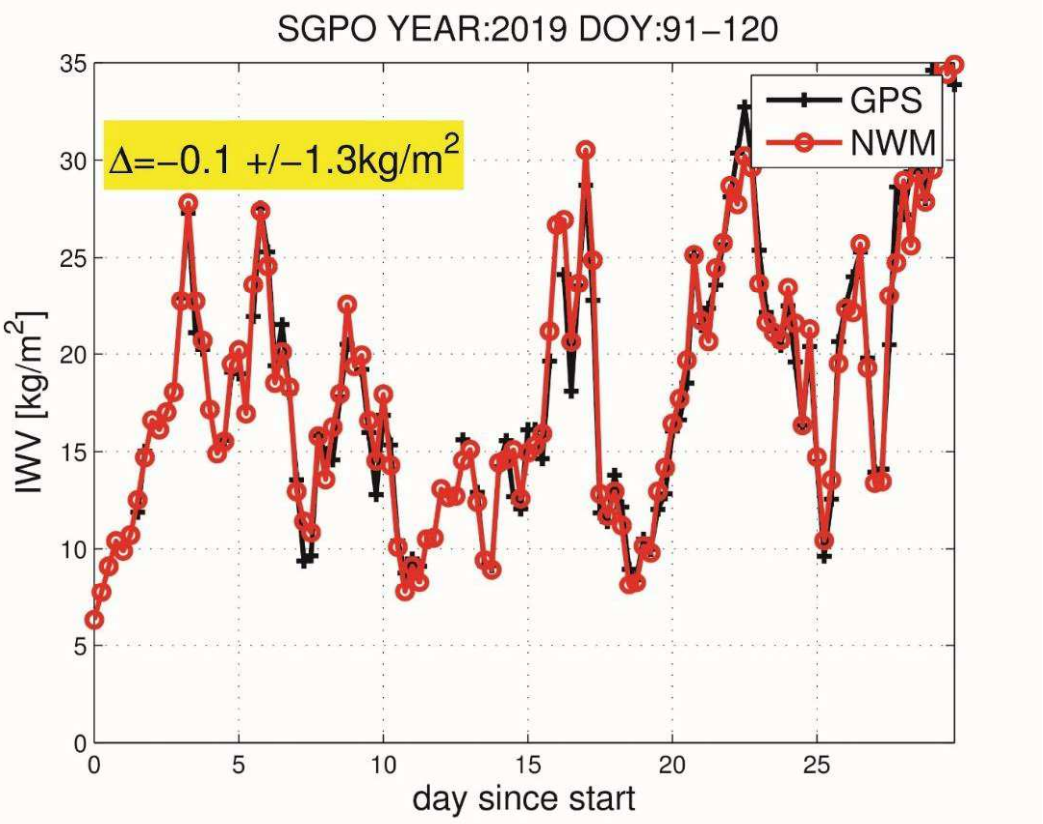


Plan 2019/2020: 4 neue GNSS-Stationen

GNSS-WD: Vergleich mit Wettermodell



Sodankylä (Finnland)



Lamont (USA)

Beispiele des Vergleichs mit dem Wettermodell des European Centre for Medium-Range Weather Forecasts (ECMWF, rot) für GRUAN-Stationen Sodankylä (Finnland) und Lamont (USA), April 2019

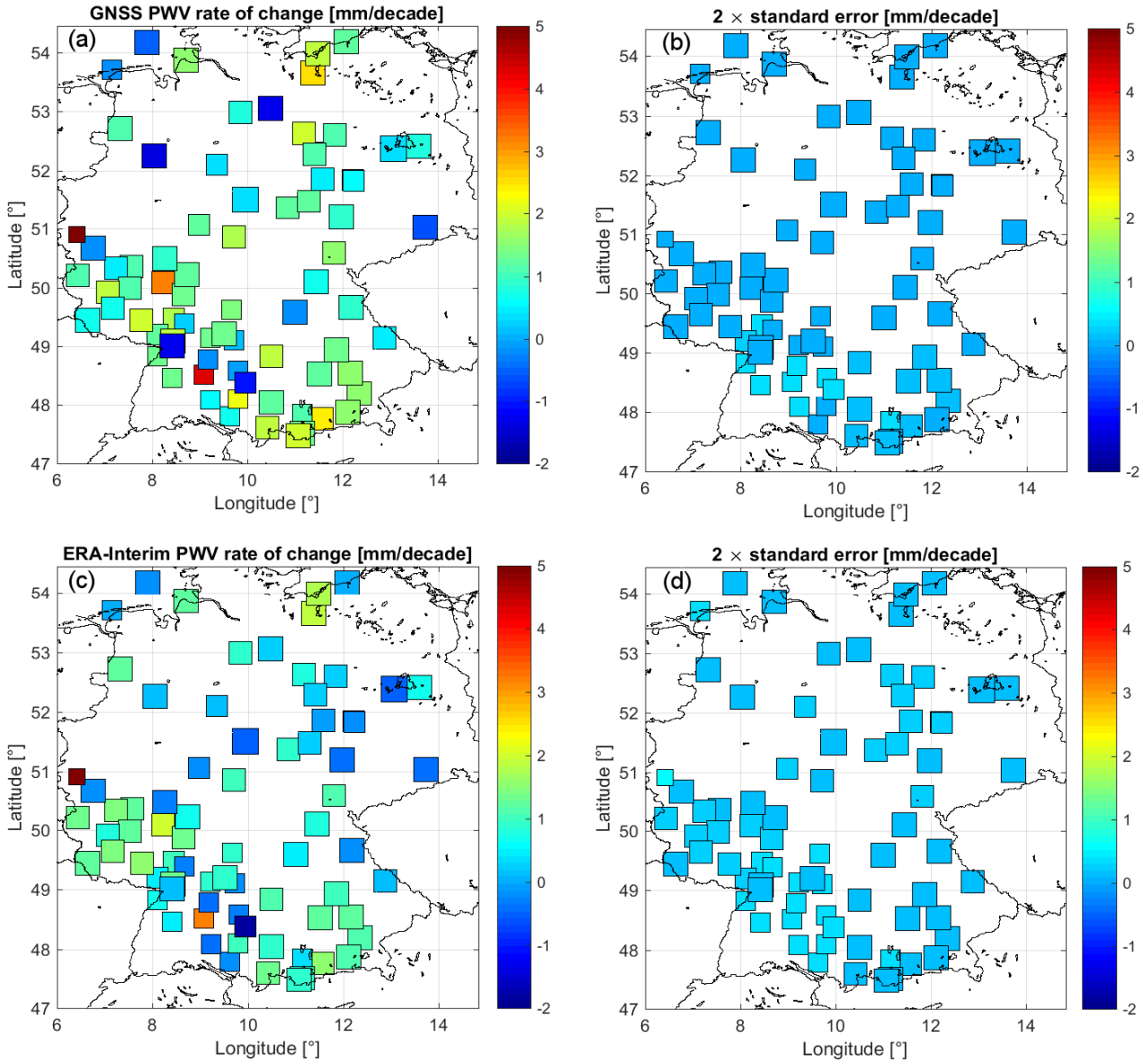
Wasserdampf-Trends für Deutschland aus GNSS-Daten

GNSS

Datensatzlänge:
10-19 Jahre

119 GNSS-Stationen

Modell ERA-Interim



Alshawaf et al., AMT, 2017

Perspektiven/Zukunftsarbeiten

- **Steigerung von Genauigkeit und Zuverlässigkeit**
  - höhere Anzahl von Satelliten:
    GPS/Galileo/GLONASS/BeiDou/QZSS ~ 100 Satelliten
  - höhere Genauigkeiten mit neuen Signalen

- **GNSS-Meteorologie:**
  - operationelle Assimilation von GNSS-"Slant"-Daten beim DWD
- **Klimaforschung:**
  - Expedition **„MOSAiC"**

Expedition „MOSAiC“: Multidisciplinary drifting Observatory for the Study of Arctic Climate

- Größte Arktisexpedition aller Zeiten
- AWI (Alfred-Wegener-Institut für Polar- und Meeresforschung) und Wissenschaftler aus 19 Nationen
- Start: Herbst 2019
- Der deutsche Forschungseisbrecher **Polarstern** wird ein Jahr lang durch das Nordpolarmeer eingefroren driften
- GFZ installierte GNSS-Empfänger für die Bestimmung des Wasserdampfs

GFZ-Kooperationspartner

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

DWD

Met Office

METEO FRANCE
Toujours un temps d'avance

FINNISH METEOROLOGICAL INSTITUTE

ARM
CLIMATE RESEARCH FACILITY

AWI

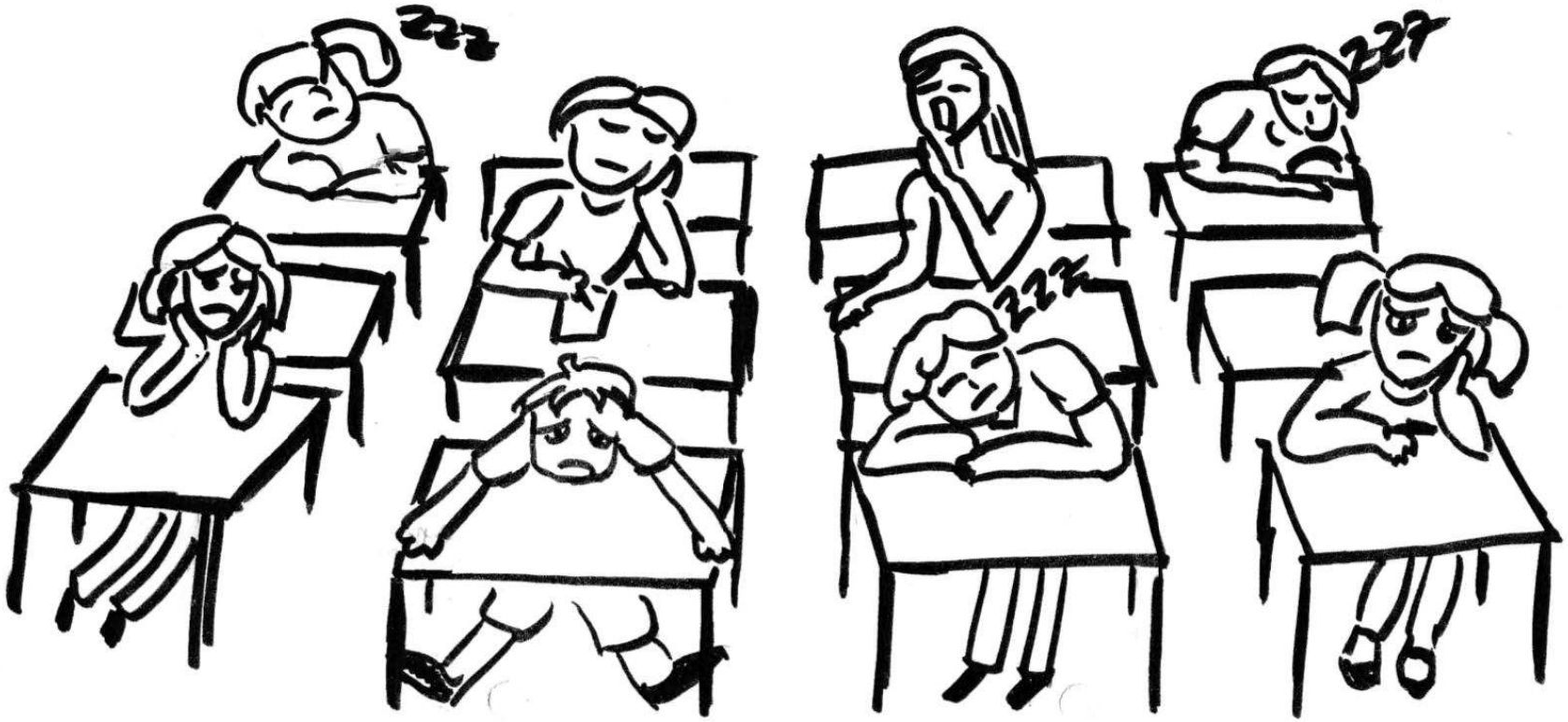
METEOROLOGICAL SERVICE SINGAPORE

MeteoSwiss

Koninklijk Nederlands Meteorologisch Instituut
Ministerie van Infrastructuur en Milieu

NIWA
Taihoro Nukurangi

Vielen Dank!



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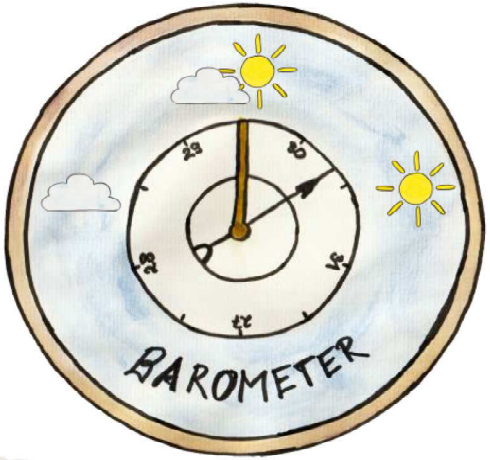

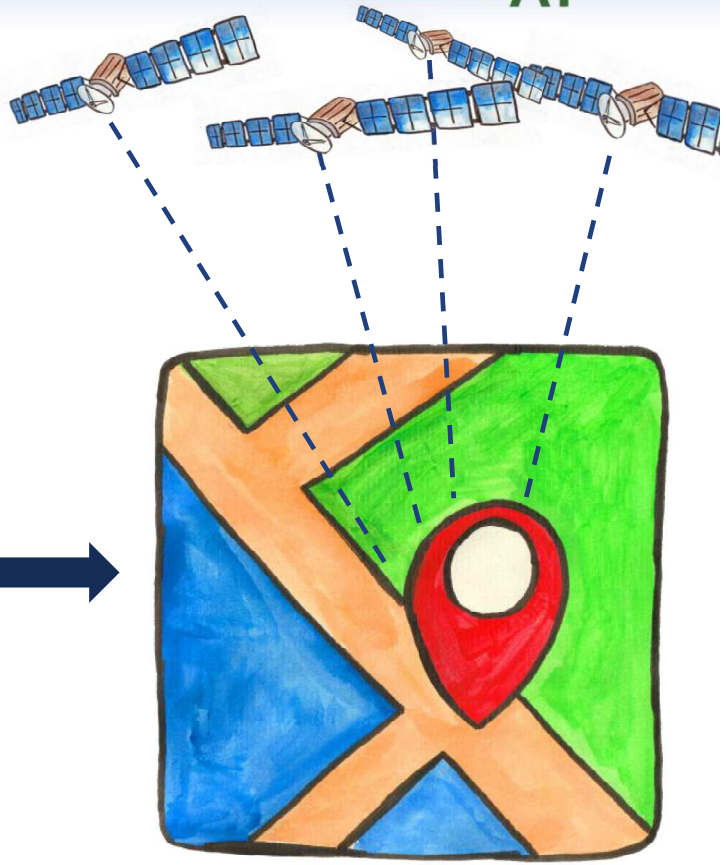

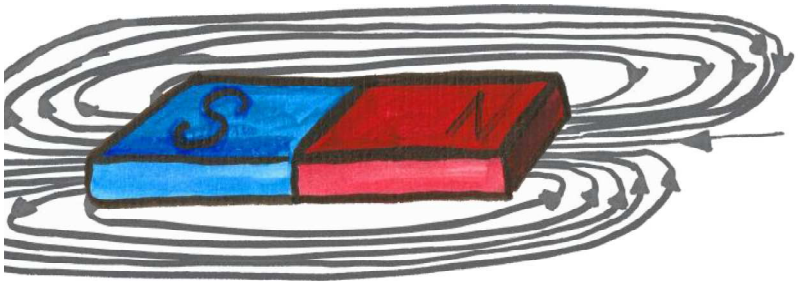

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GPSTest

- *Open source*
- Testet GNSS-Fähigkeit eines Geräts
- Anzeige des Messfehlers
- Echtzeitdaten zu Satelliten

GPS status

- *Nicht werbefrei*
- Kompass
- Position
- Signalstärke
- Geschwindigkeit
- Höhe
- …

phyphox

- *RWTH Aachen*
- Physikalische Experimente mit dem Smartphone
- Nutzung zahlreicher Sensoren
- Datenexport möglich

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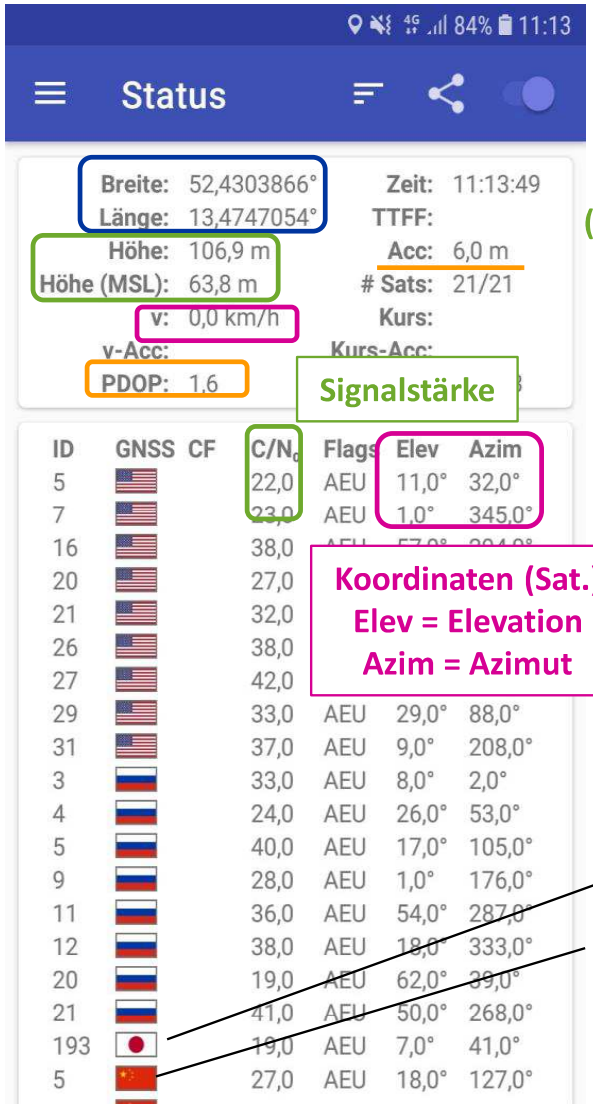
GPSTest



Eigene Koordinaten
(Maps: XX.XXX, YY.YYY)

Höhe
(MSL = Main Sea Level; „normal Null“)

Geschwindigkeit

Genauigkeitsparameter
(Position Dilution of Precision;
<4.0 = gut; >7.0 schwach)

Koordinaten (Sat.)
Elev = Elevation
Azim = Azimut

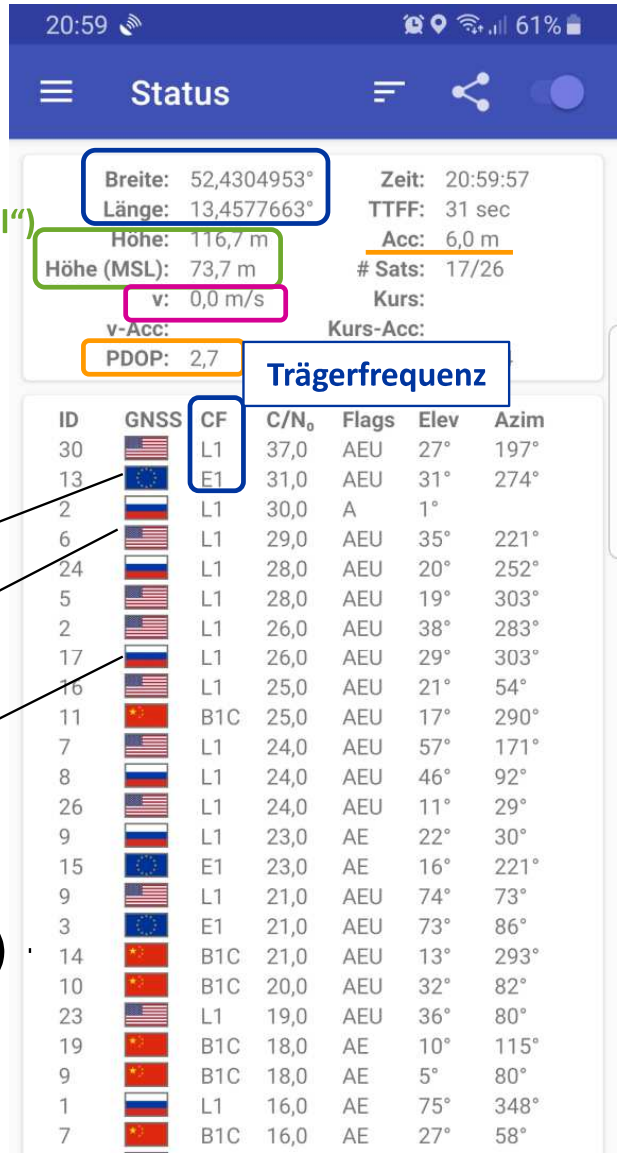
Galileo(EU)

GPS (USA)

GLONASS (Russ.)

QZSS (Japan)

BeiDou/COMPASS (China)



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GPS status

Geschw. und Höhe

Eigene Koordinaten
(Maps: XX XX.X, YY YY.Y)

Druck

Himmelskugel mit Kompass

GPS (USA) (1-32) ■

GLONASS (Russ.) (r1-25) ■

BeiDou/COMPASS (China) (c1-c33) x

Galileo(EU) (e1-e35)+

Vergleich mit Daten von der professionellen Antenne:

https://www.tryat.eu/

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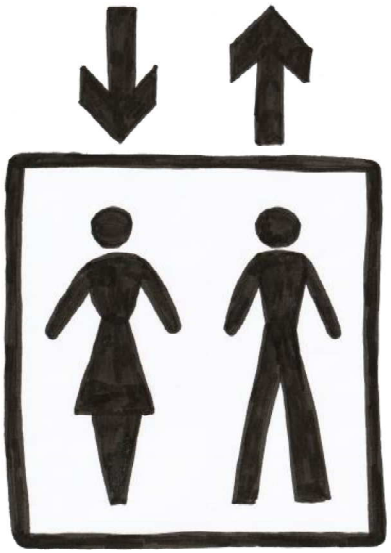
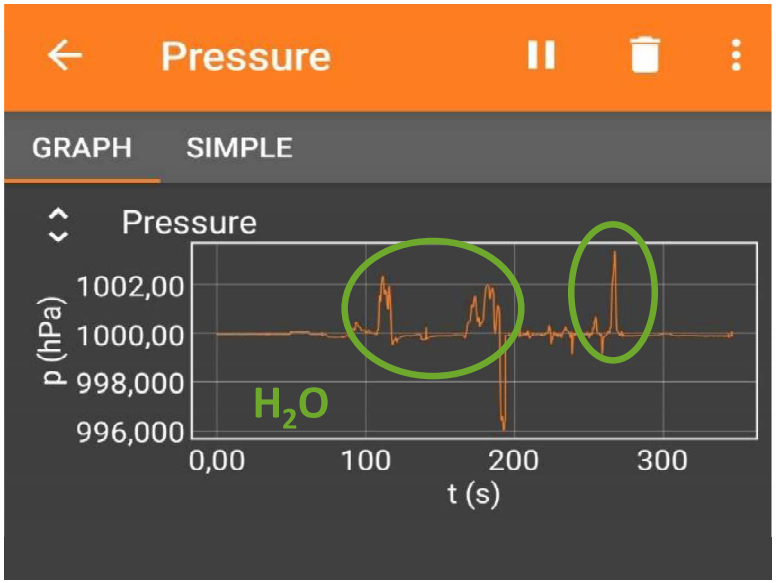
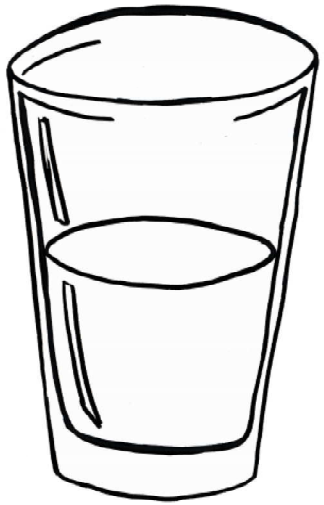
phyphox







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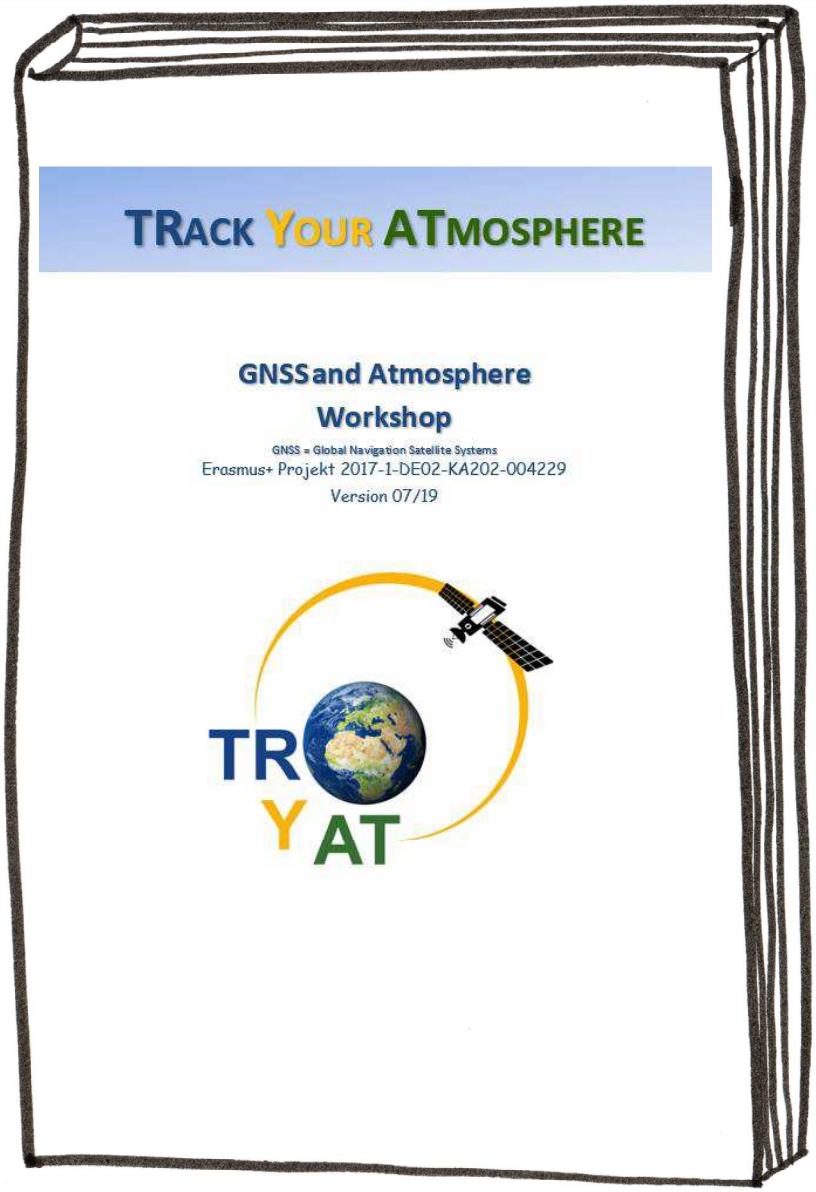
Ein komplettes Unterrichtsmodul zum Thema GNSS und Wasserdampf



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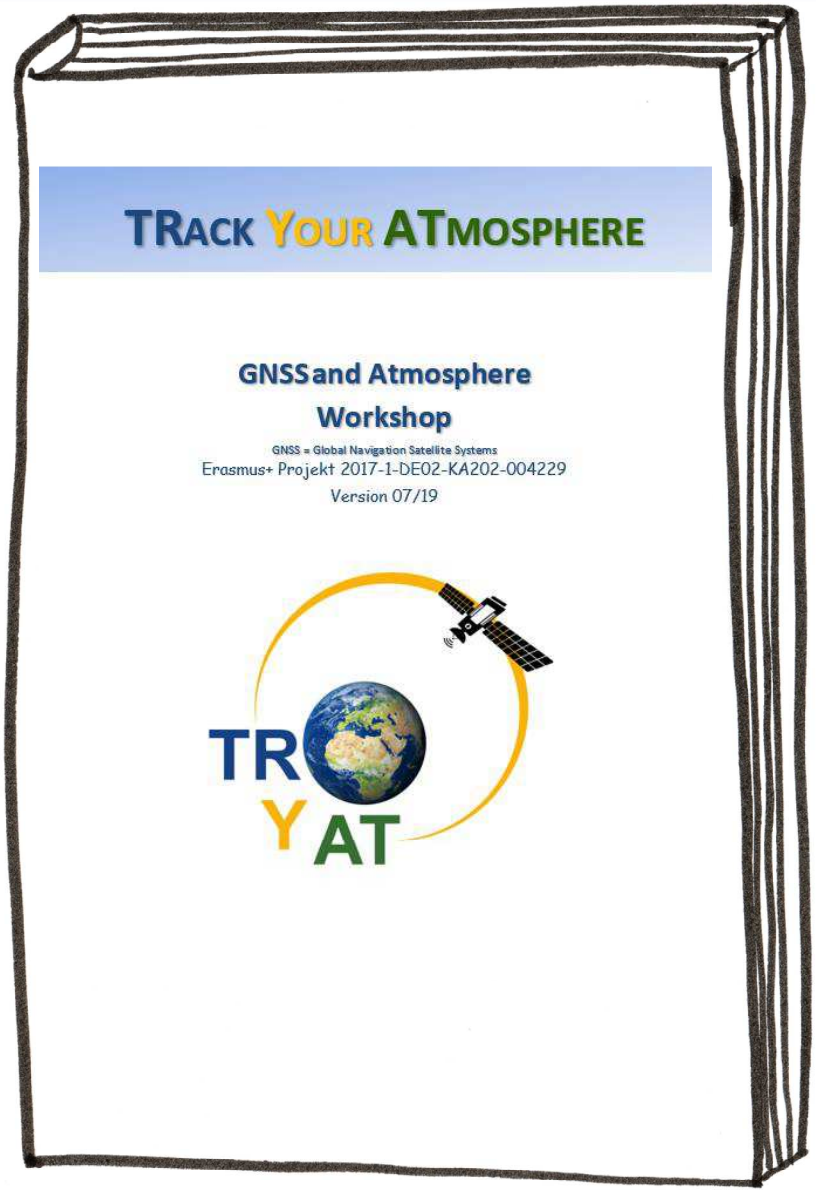
Ein komplettes Unterrichtsmodul zum Thema GNSS und Wasserdampf

- Schwingungen
- Mechanische und optische Wellen
- Mikrowellen
- Physik und Chemie der Atmosphäre
- Satellitenbahnen und Himmelsmechanik
- **Wasserdampfberechnung**



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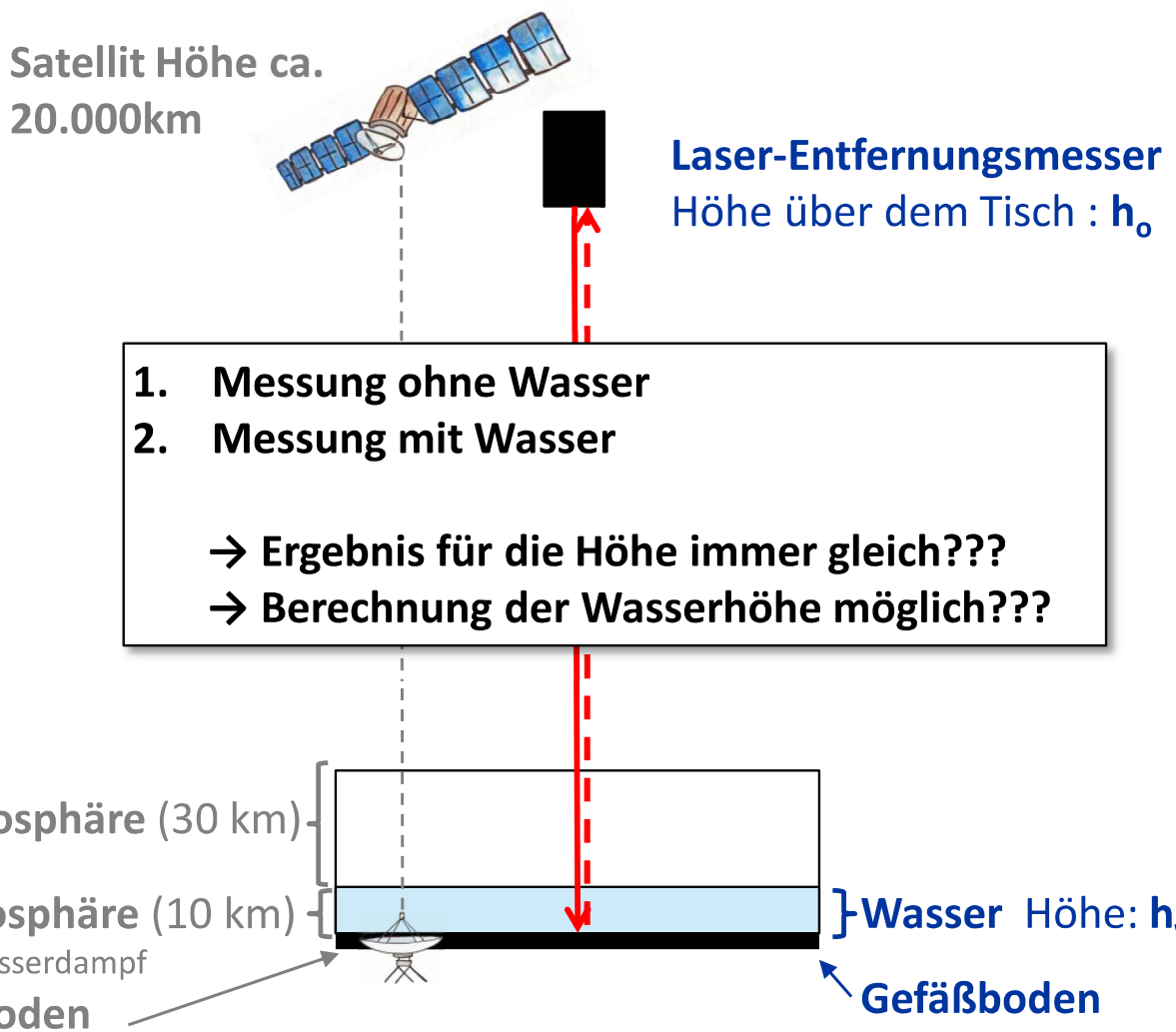
Modellversuch mit dem Laser-Entfernungsmesser

Von Widar23 - Eigenes Werk, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=52067807



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Berechnung der Wasserhöhe:

Wasser + Luft ⟶ **„optische Weglänge L“**

$$\boldsymbol{L} = n \cdot h$$

$$\boldsymbol{L = n_L \cdot (h_o - h_W) + n_W \cdot h_W}$$ ($n_L \approx 1$, Brechungsindex von Luft)

$\boldsymbol{h_W}$: Höhe der Wassersäule,
$\boldsymbol{n_W = 1,333}$ (Brechungsindex von Wasser)
$\boldsymbol{h_o}$: Abstand Entfernungsmessers - Tisch
(Messung mit dem Lineal oder ohne Wassersäule)

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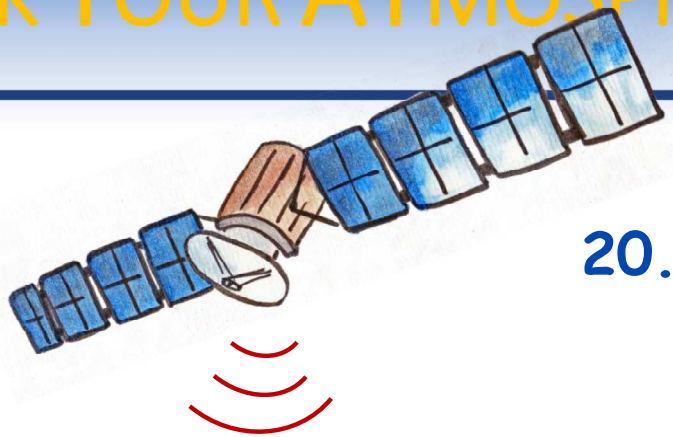
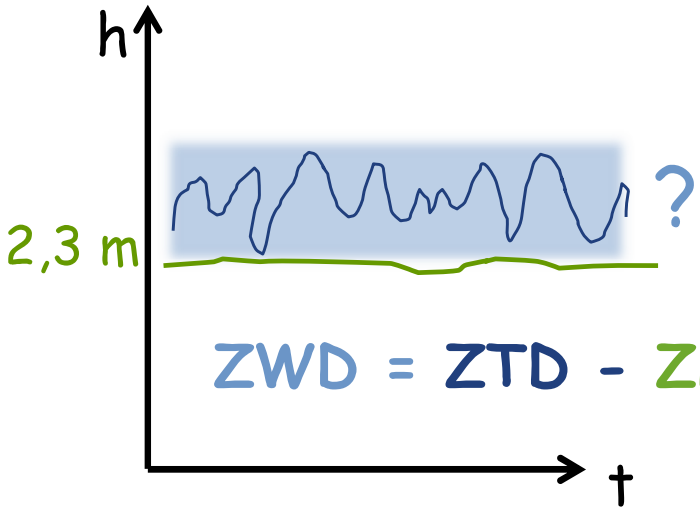
TR YAT



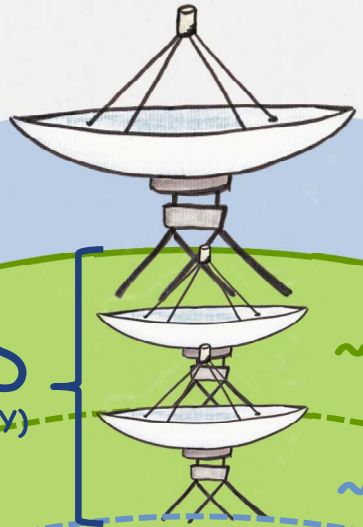
20.000 km



ZWD = ZTD - ZHD

c_{vac} = 300.000 km/s

78% N_2
21% O_2



~ 0,07 s (10 ms = 1/100 s)

ZTD
ZENITH HYDROSTATIC DELAY)

~ 2,3 m ZHD ZENITH HYDROSTATIC DELAY

~1-40 cm ZWD - ZENITH WET DELAY)

Berechnung der Wasserdampfmenge durch die Laufzeitverlängerung

- Tryat Datenbank: ***ZTD*** (Zenith Total Delay)
- Tryat Datenbank: **Luftdruck p_0**
- Mit p_0: ***ZHD*** berechnen
- ***ZWD*** = *ZTD – ZHD*

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Slants nach Stationen

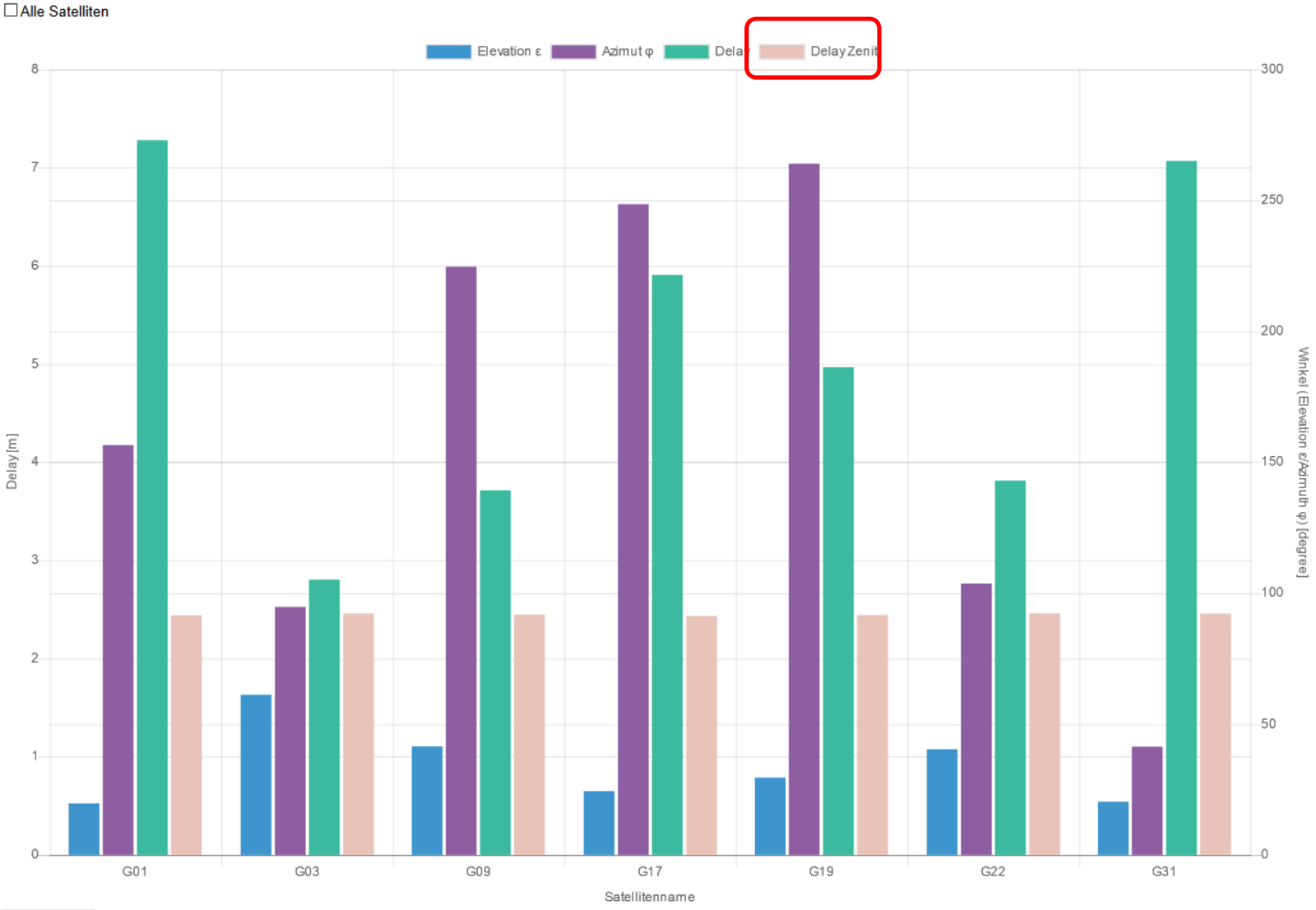
Liesmich

☐ Alle Stationen

Station POTS x=3800690 y=882078 z=5028790; l=13.0661 b=52.3793 h=144.583

Zeitpunkt Zurück 2019-07-31 18:00:19 Vor

☐ Alle Satelliten



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Tryat - Plots von Christian Hoffmann ist lizenziert unter einer Creative Commons Namensnennung 4.0 International Lizenz.

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Kondensierte Wassermenge

- PWV = Precipitable Water Vapor
- **PWV** = 0,152 · ZWD = **25mm**
  Umrechnungsfaktor
- Das ist die Wassermenge, die aus dem Dampf stammt und die als Niederschlag auf die Erde fallen könnte

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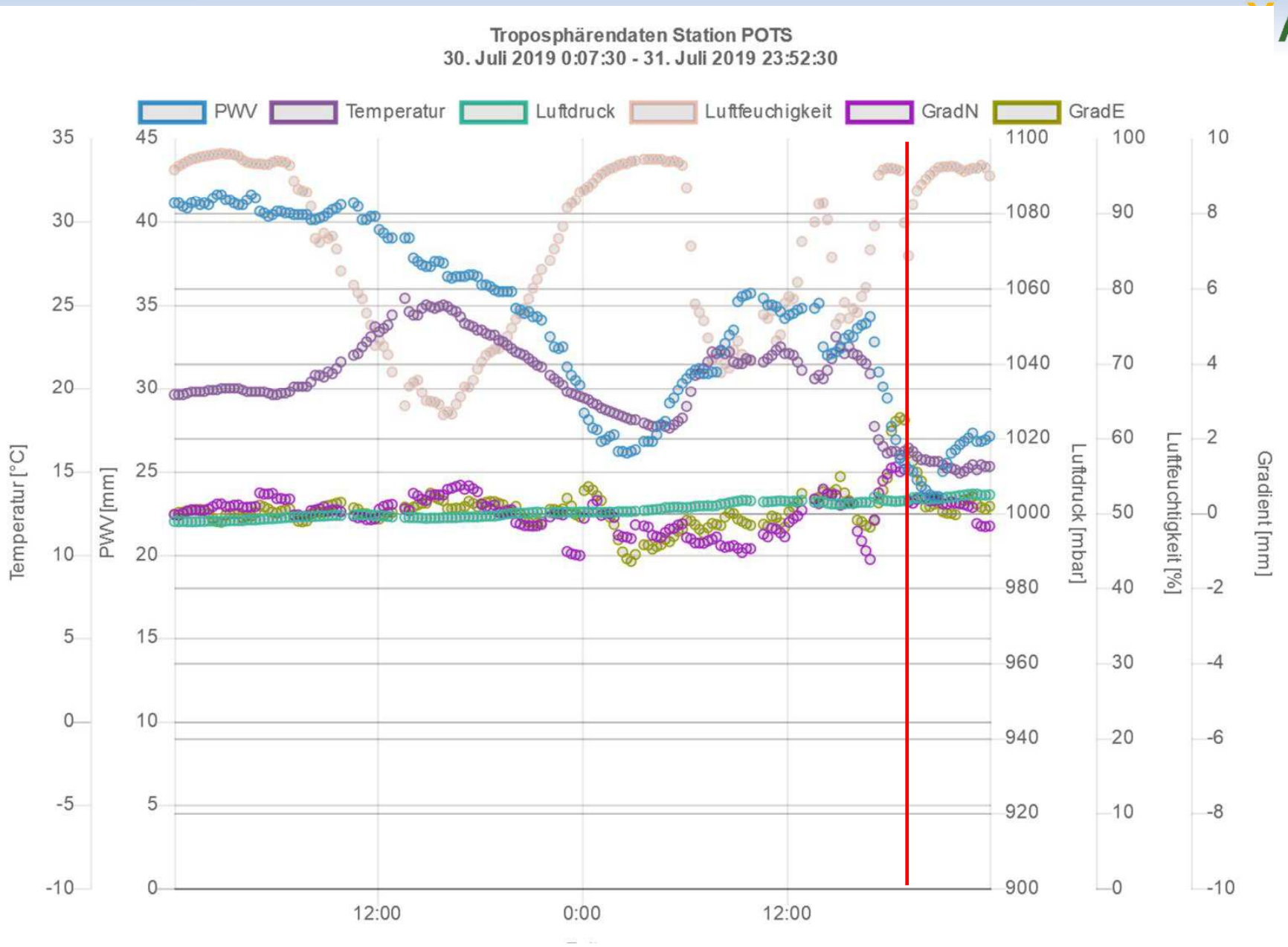

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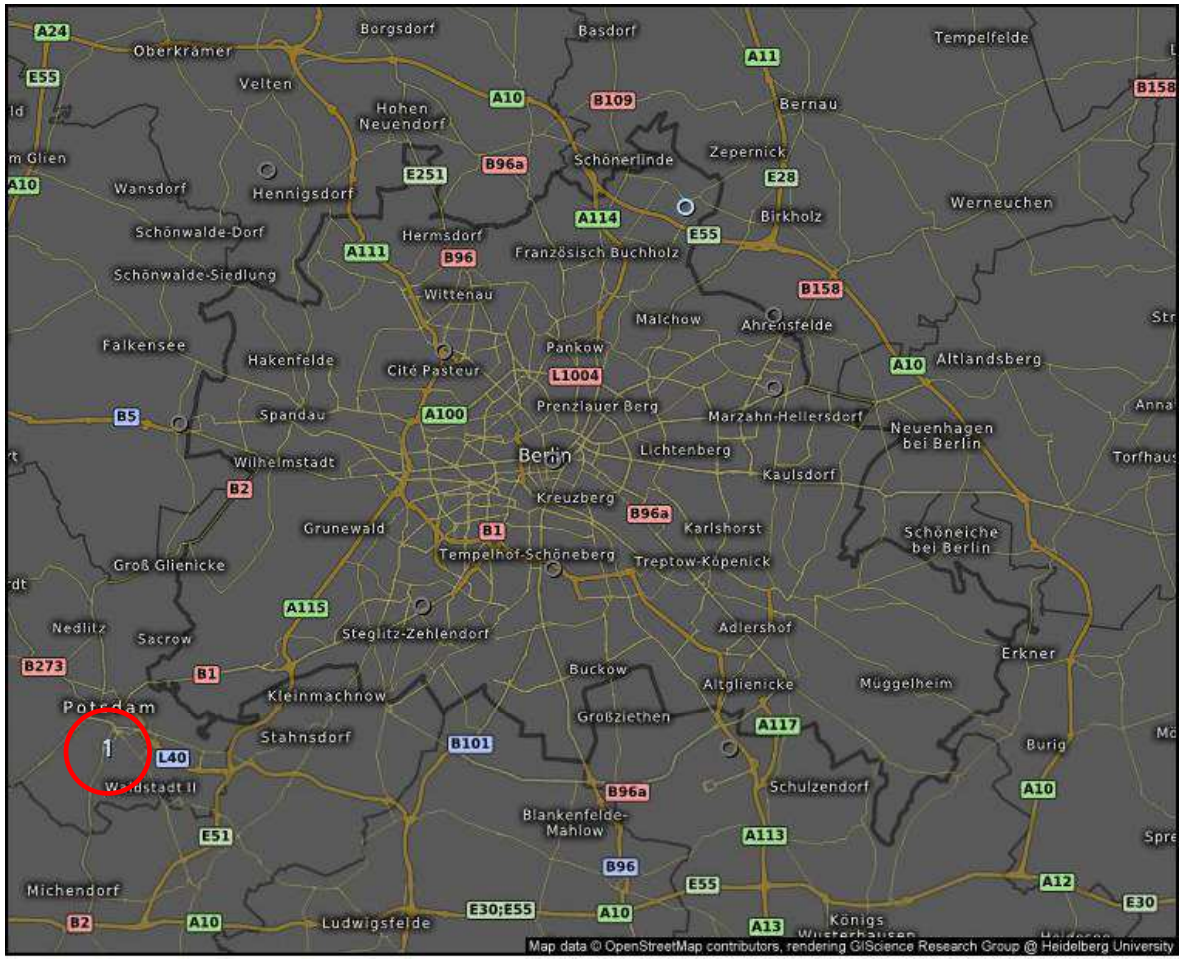

Niederschlagssumme, 1std (mm)

31.07.2019, 19:00 Uhr MESZ

0 3 5 10 15 30 50 75 100

kachelmannwetter.com WETTER HD

(C) Kachelmann GmbH, DWD

Berlin, 11 Stationen im Kartenausschnitt

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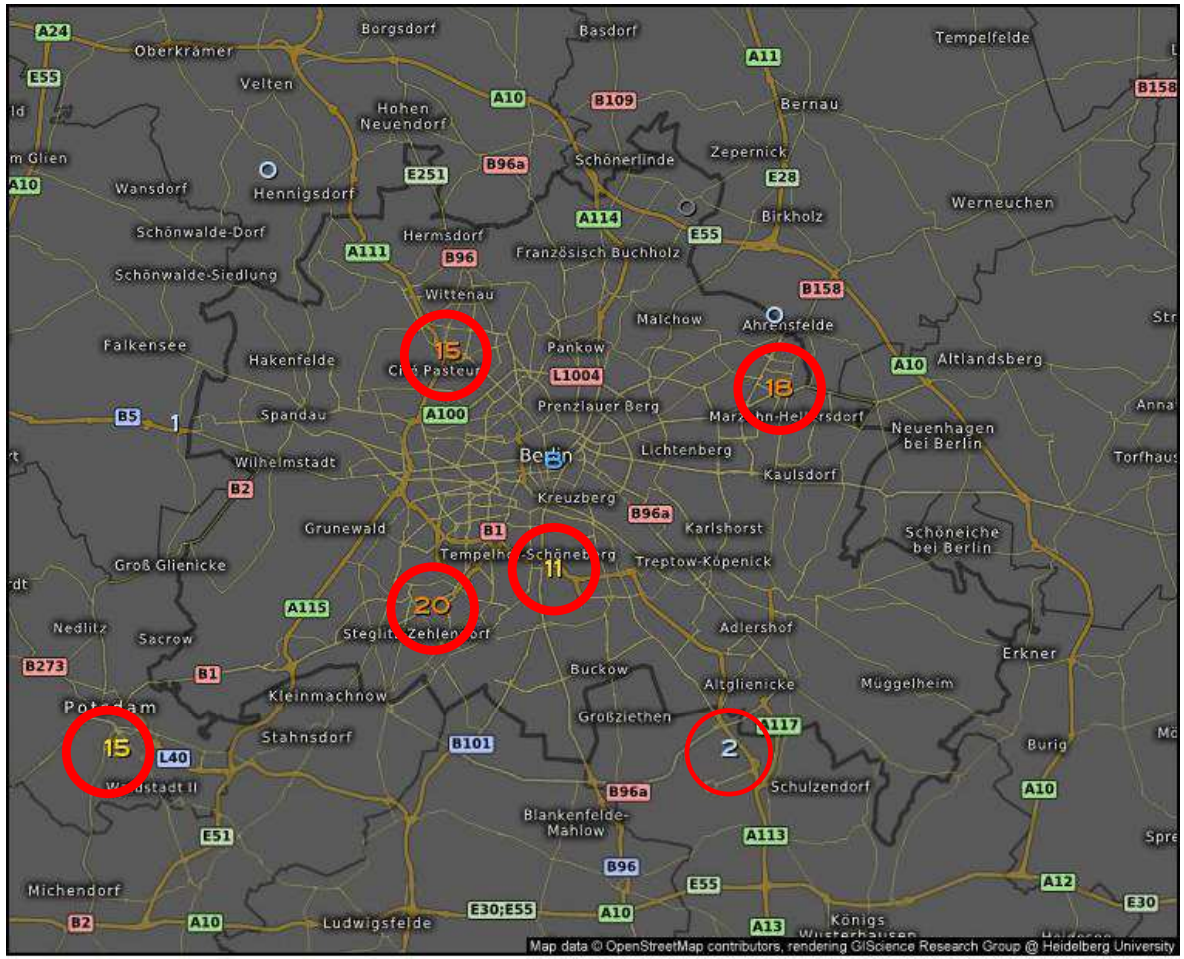

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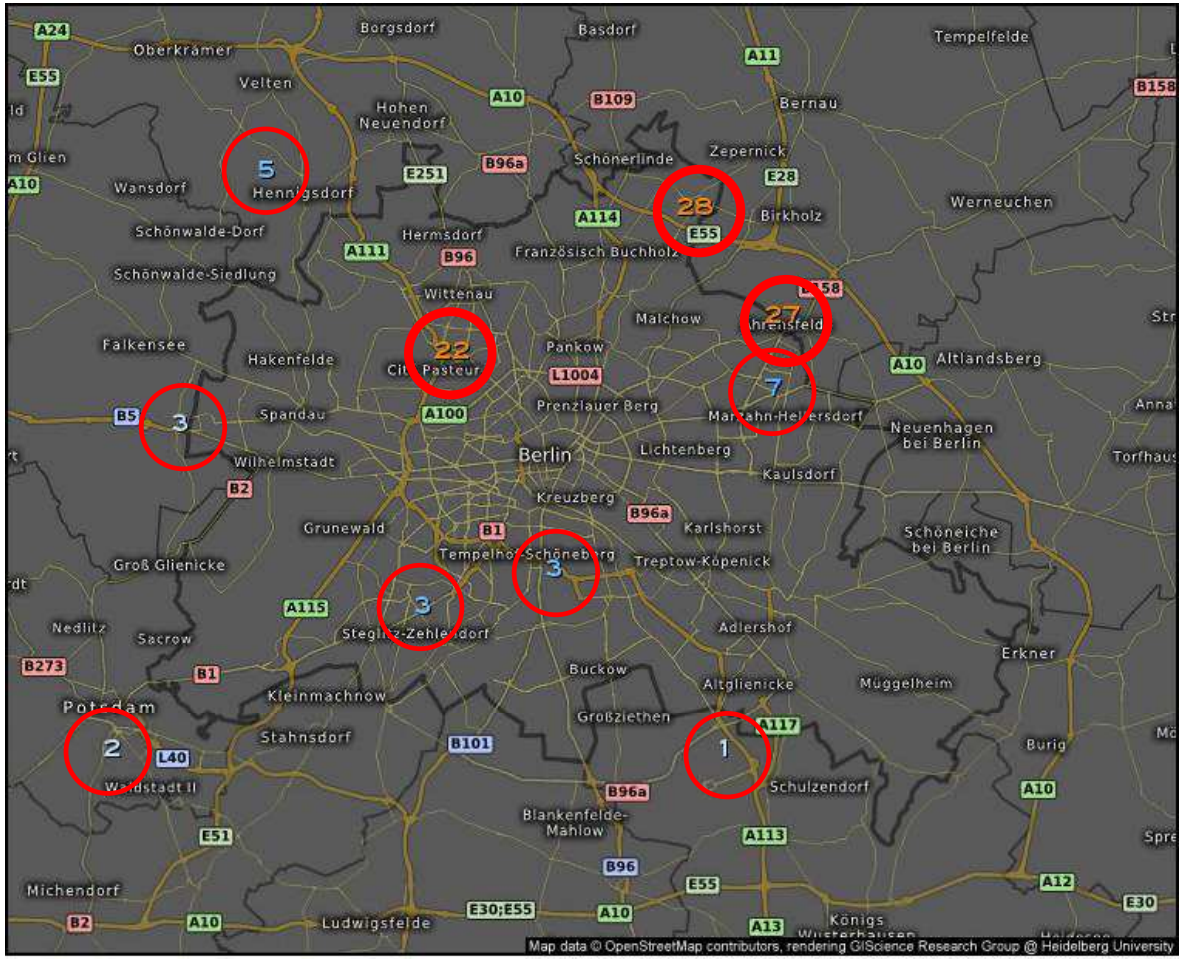

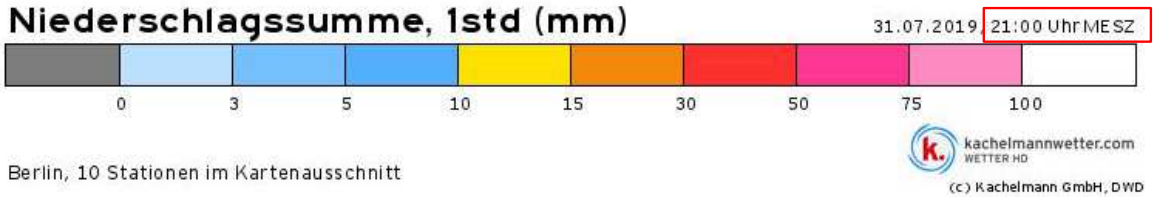

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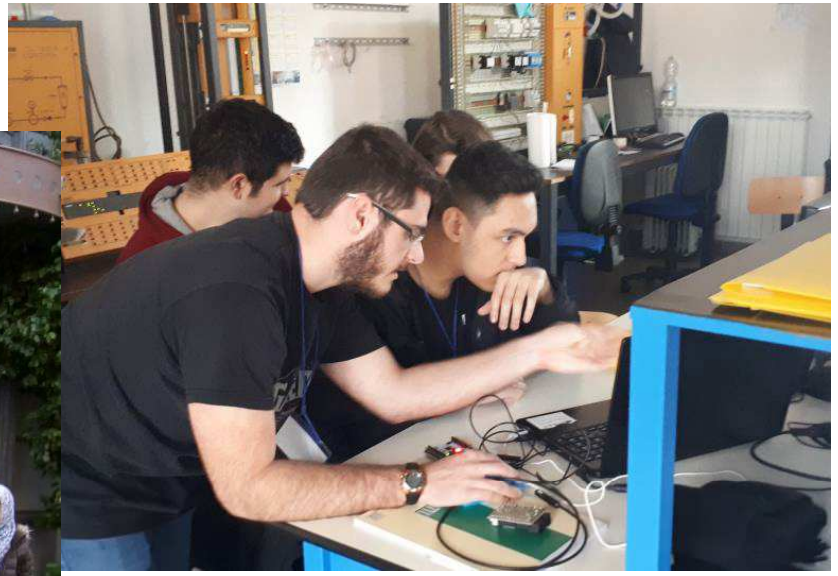

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TRACK YOUR ATMOSPHERE

Projektpartner

- IT Istituto Tecnico Industriale Statale Leonardo Da Vinci Napoli: **Pasquale Longo, Amelio Incollingo, Pasquale Ammirati**
- IT Istituto Nazionale di Geofisica e Vulcanologia, Osservatorio Vesuviano, Napoli: **Umberto Tammaro, Claudio De Martino**
- IT Università di Napoli Federico II: **Umberto Riccardi**
- FR Lycée Saint-Cricq, Pau: **Laurent Verdier, Dominique Joly, William Metref**
- DE GFZ Potsdam: **Fadwa Alshawaf, Markus Ramatschi, Galina Dick**
- DE Lise-Meitner-Schule Berlin (Projekt Koordination): **Britt Hennig, Boris Reusch, Ulrich Sander, Christian Hoffmann, Swantje Wiebalck**

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TRACK YOUR ATMOSPHERE

TRO YAT

Projektdaten

Projektlaufzeit: Oktober 2017 – September 2020

- Projektmittel: 377.212 EUR
- Webplattform
  GPS-Antennen mit Installationsguides
- Unterrichtseinheiten
- Erklärvideos
- Vier Sprachen: DE, EN, FR, IT

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Intellectual Outputs/Produkte

- **IO1** Learning Web Platform
- **IO2** Starter kit and installation guide for GPS antennae
- **IO3** Physical and technical foundations (Educational material)
- **IO4** Sensors and Data server for microcontrollers and embedded systems
- **IO5** Educational videos

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https://www.tryat.eu/