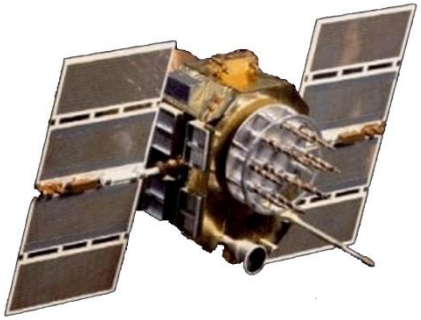
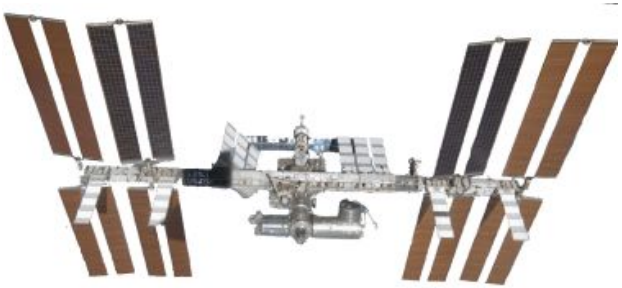
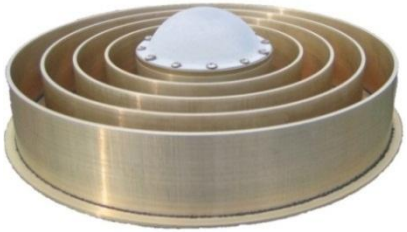




GNSS Remote Sensing at GFZ: Recent Results and Prospects

Jens Wickert

C. Arras, M. Asgarimehr, A. Brack, G. Dick, P. Jales, A. Kepkar, B. Männel, M. Ramatschi, T. Schmidt, H. Schuh, F. Zus



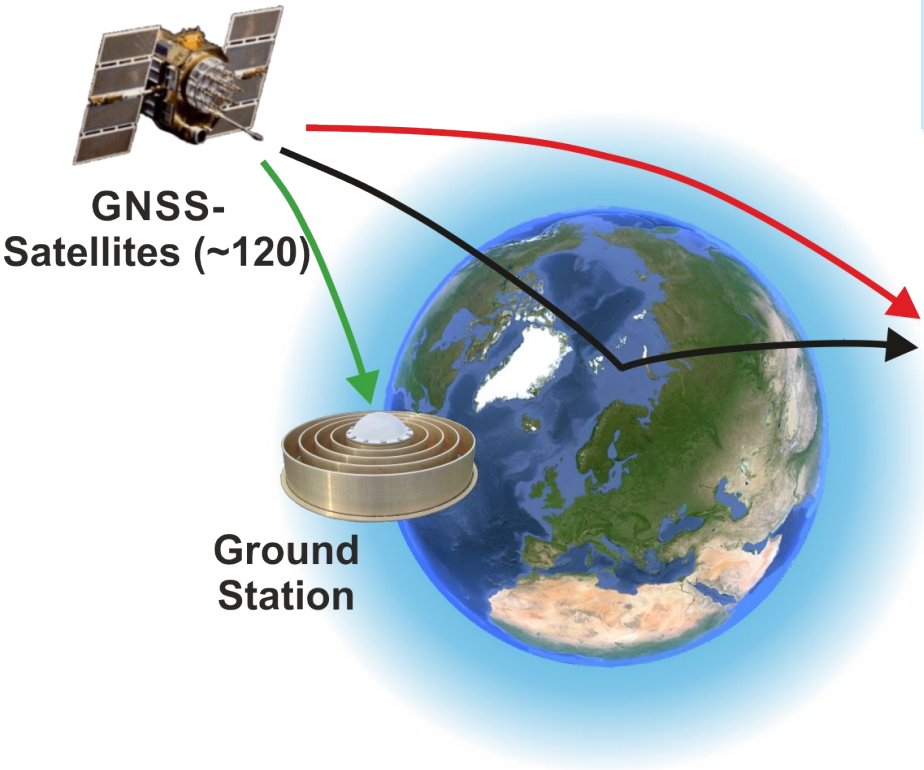


From Errors to Signals

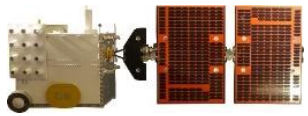
GNSS Remote Sensing

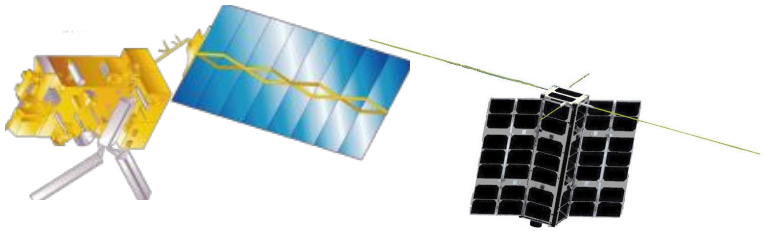
Derivation of

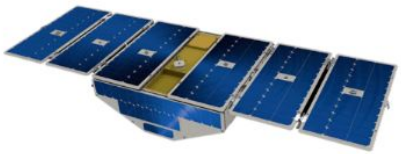
- Temperature and water vapor
- Water, ice and land surface properties
- Water vapor
- Electron density



e.g., Lemur, COSMIC-2,
Metop, CYGNSS







Unique properties (all-weather, long-term stable, high spatiotemporal resolution, cost effective)

GNSS Observation Infrastructure

(Observation on different scales in space and time feasible)

GPS

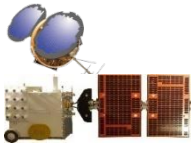
GLONASS

QZSS

BeiDou

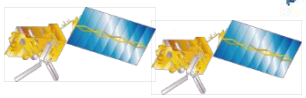
Galileo

FY3-C/D

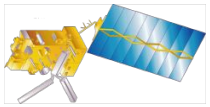


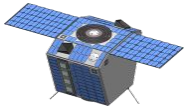
COSMIC-1 (6)
COSMIC-2 (6)

TerraSAR-X
TanDEM-X



Metop A/B/C

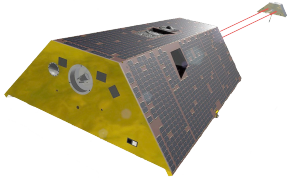




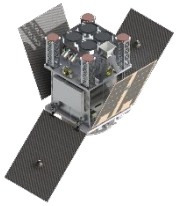
PRETTY

Mini satellites &
constellations

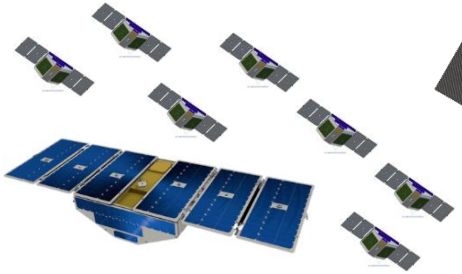
Lemur
(100+)



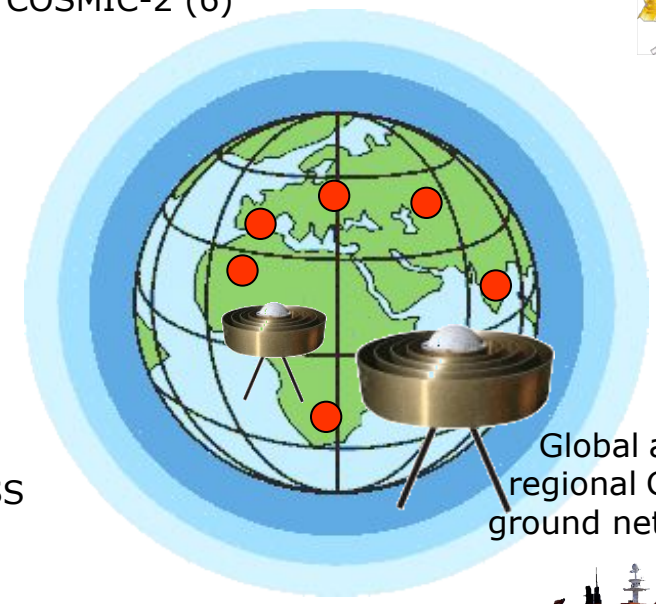
GRACE-FO



HydroGNSS



CYGNSS (8)



Global and
regional GNSS
ground networks

Airships,
Aircrafts
(HALO)

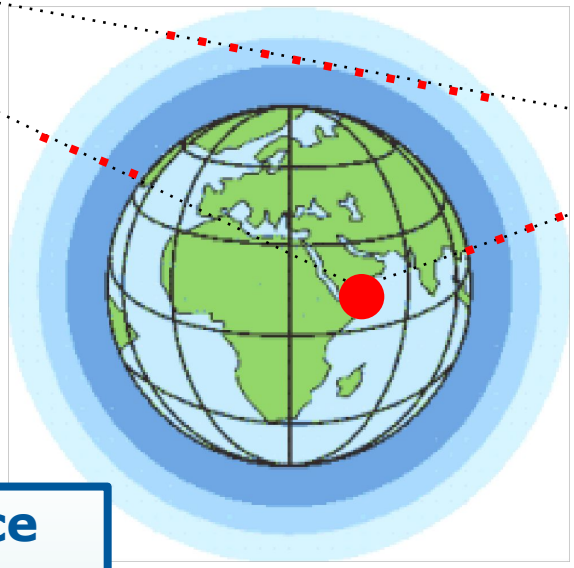
Ships

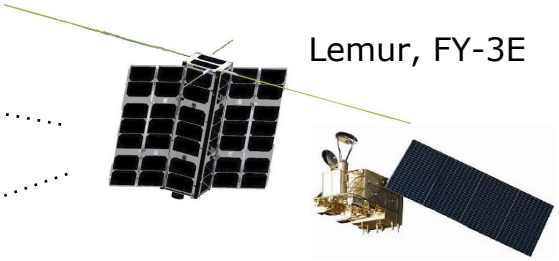
GNSS Remote Sensing: Versatile Earth Observation

GPS

Weather
Temperature, wind, humidity, precipitation, …

Ionosphere/ Space Weather
Electron density





Lemur, FY-3E

Climate
Temperature, water vapor, sea level, ice shelf, sea ice, salinity, …

Disasters
Tsunamis, flooding, severe weather, e.g., hurricanes, ...

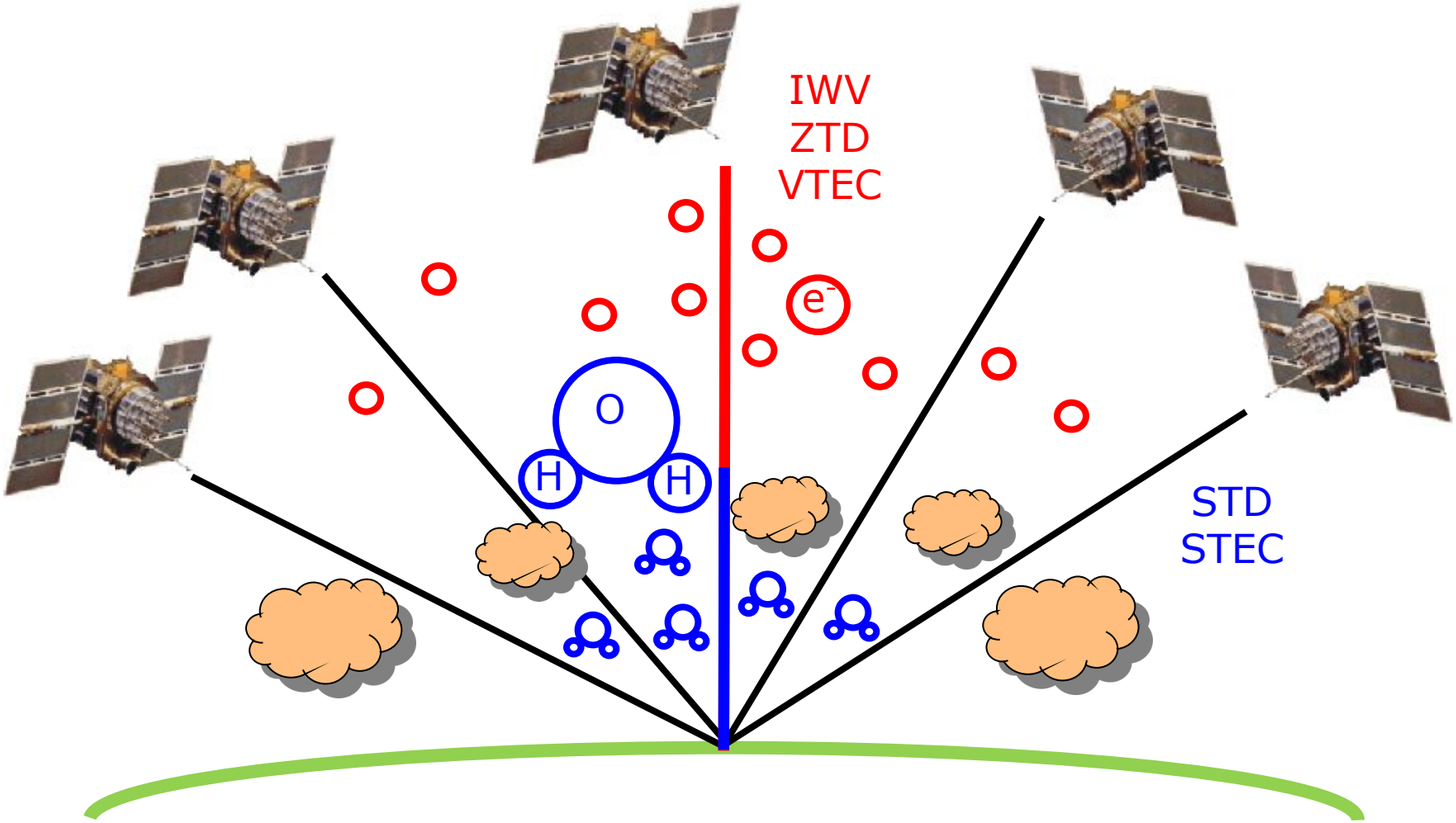
Land surface
Soil moisture, biomass, snow cover/depth, snow water equivalent ...

Infrastructure
Ship monitoring

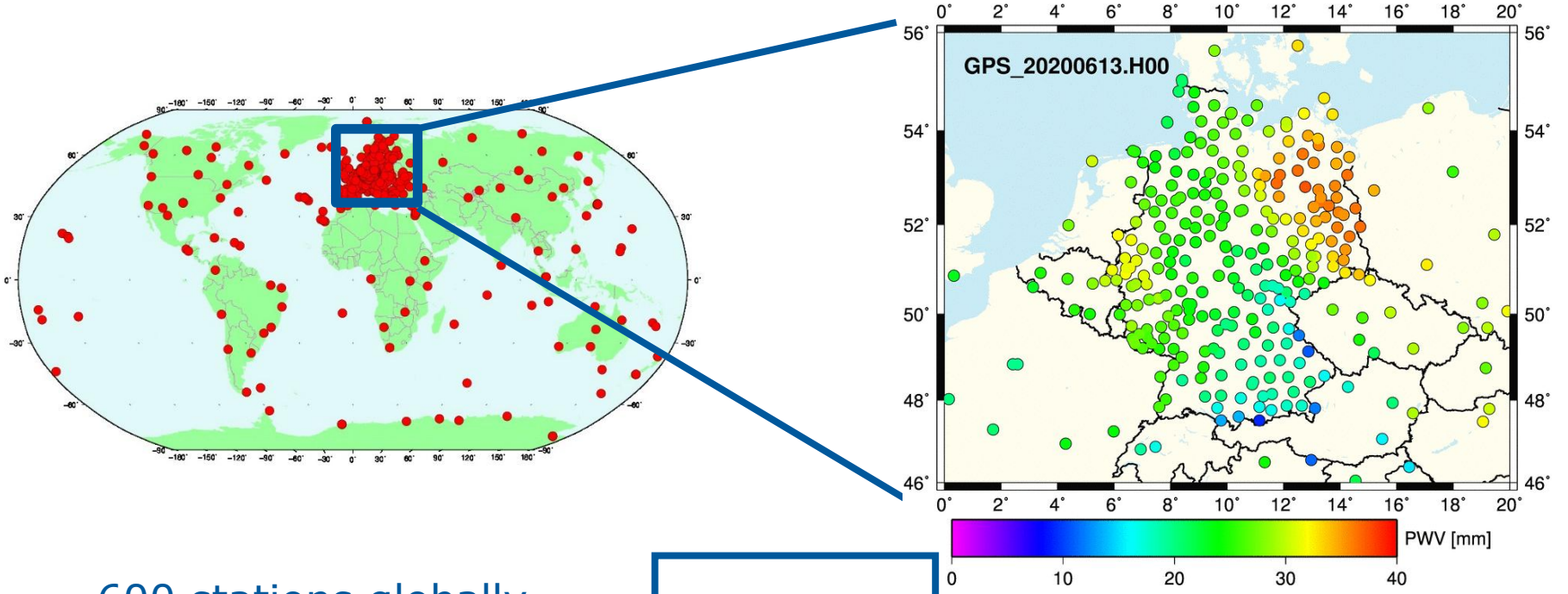
Wickert et al., EU report GfG², 2012

Ground-based
GNSS Atmosphere Sounding

Zenith/Slant Total Delay (ZTD, STD)
Integrated Water Vapor (IWV)
Total Electron Content (VTEC/STEC)



Operational ZTD/IWV/STD Monitoring at GFZ

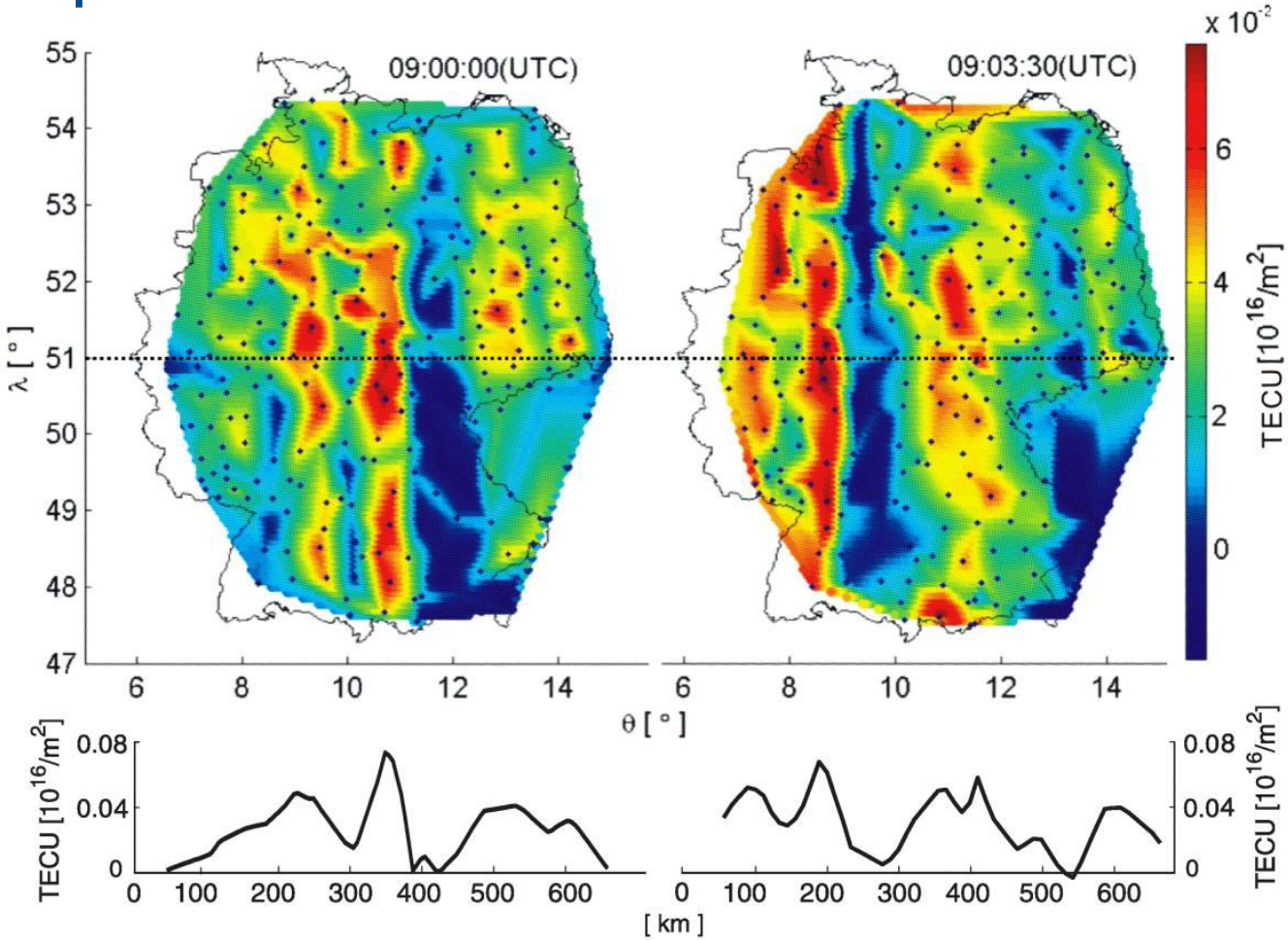


- ~600 stations globally
- ~300 in Germany
- Operational delay <1h
- Used by European Weather Services (DWD, MetOffice, MeteoFrance ..)

ZTD
IWV
STD
Near-Real Time
24/7

Severe weather in Brandenburg
June 13, 2020

Ionospheric Perturbation above Germany



Medium**S**cale**T**ravelling**I**onospheric**D**isturbance event

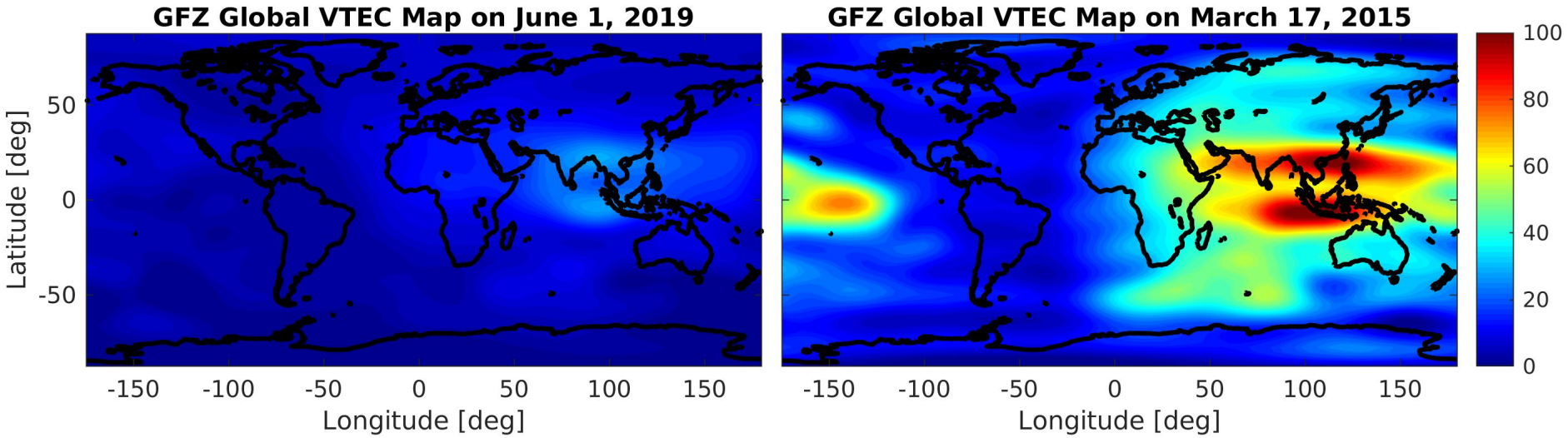
September 27, 2009 (~300 stations)

East to West, λ~ 302 km, period ~7 min, v~700 m/s

Deng et al., 2013

IGS Product: Global Ionospheric Maps from GNSS

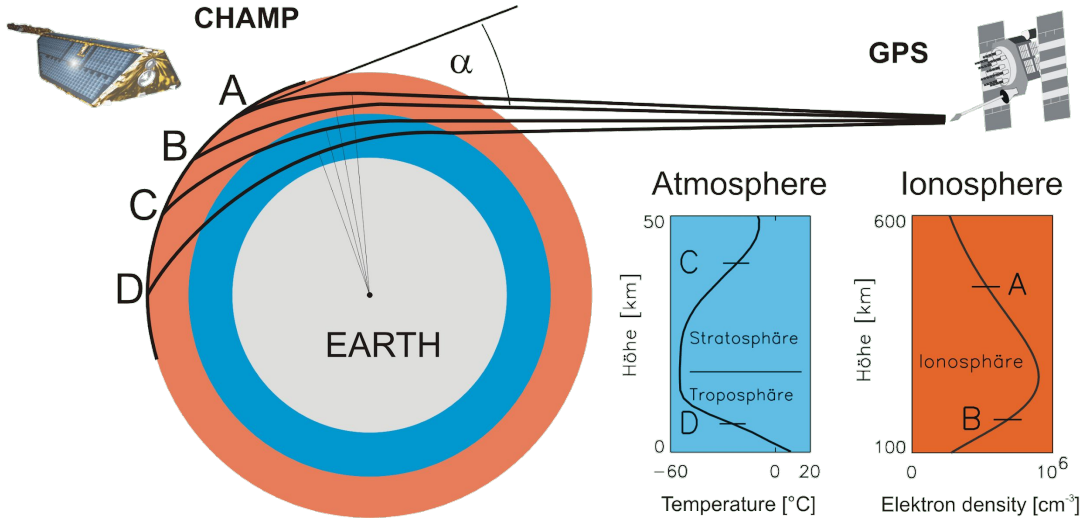
- Data from ~250 stations
- Multi-GNSS supported (GPS, GLONASS, Galileo, BeiDou, QZSS)



- Pre-operational maps (08:00 UTC) since 2021, 2000-2022
- Day with moderate ionospheric activity (left)
- During the St. Patrick's day geomagnetic storm (right)

Brack et al., 2021

Satellite-based GNSS Atmosphere Sounding: Radio Occultation



Operational use of GPS-RO for weather forecast

- 2006: Initial operational CHAMP/GRACE and COSMIC data use by MetOffice and ECMWF

- Currently used by all leading weather centers

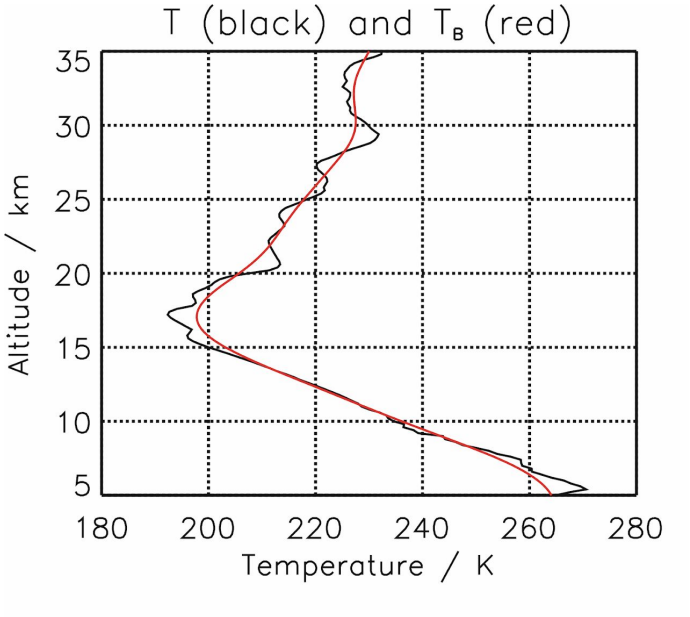
- Relatively small number of observations has big impact: Why?

*Superior vertical resolution compared to other satellite sounders

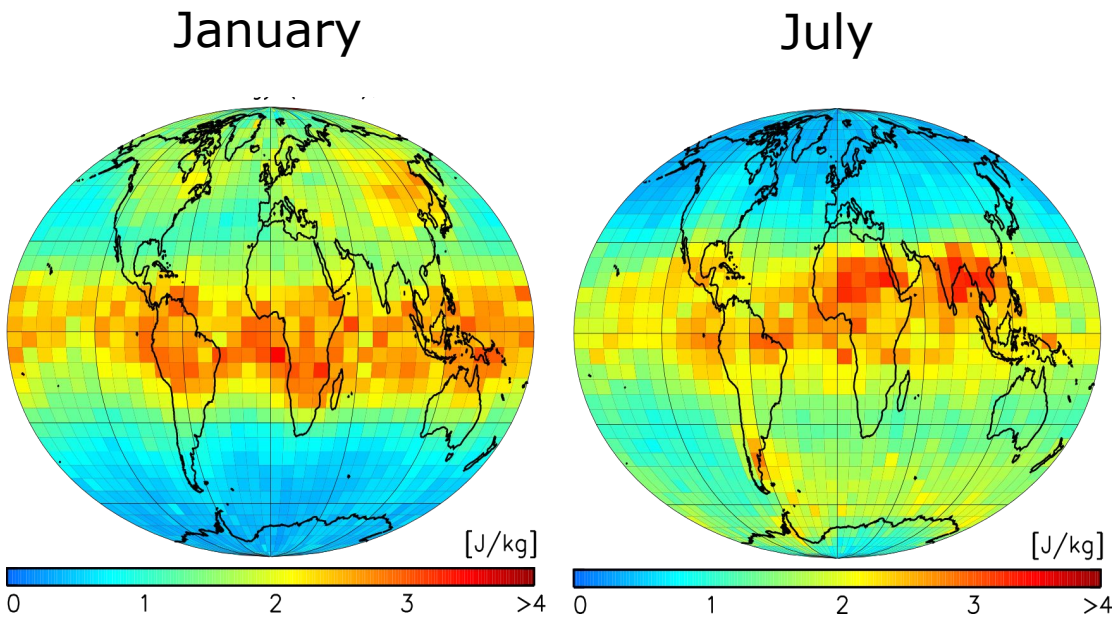
*Assimiliation without bias correction

Atmospheric Waves

Mean potential energy 2005-2012 (CHAMP, GRACE, COSMIC-1)



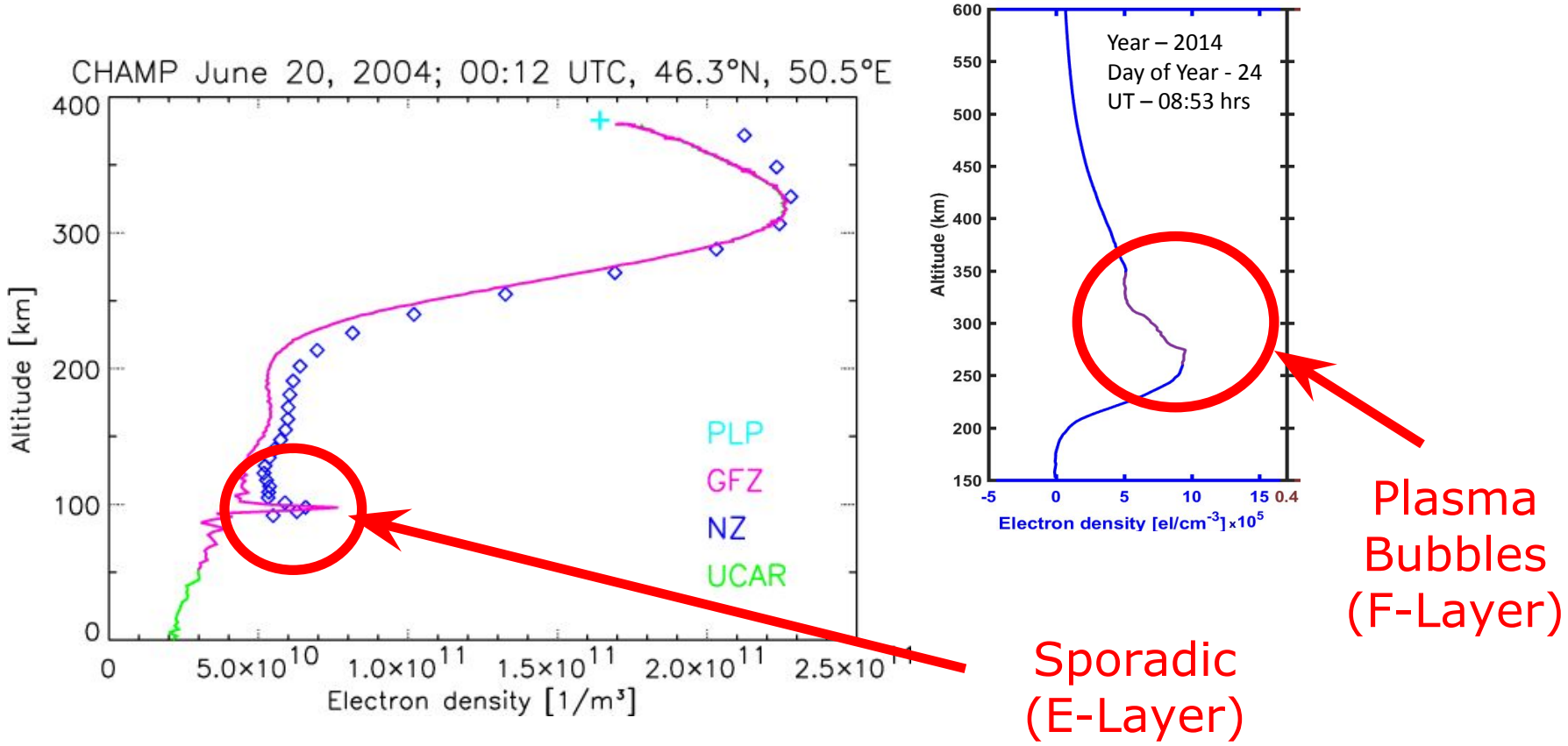
25 km, λ<10 km, 5°x10°



Waves are visible in vertical temperature profiles

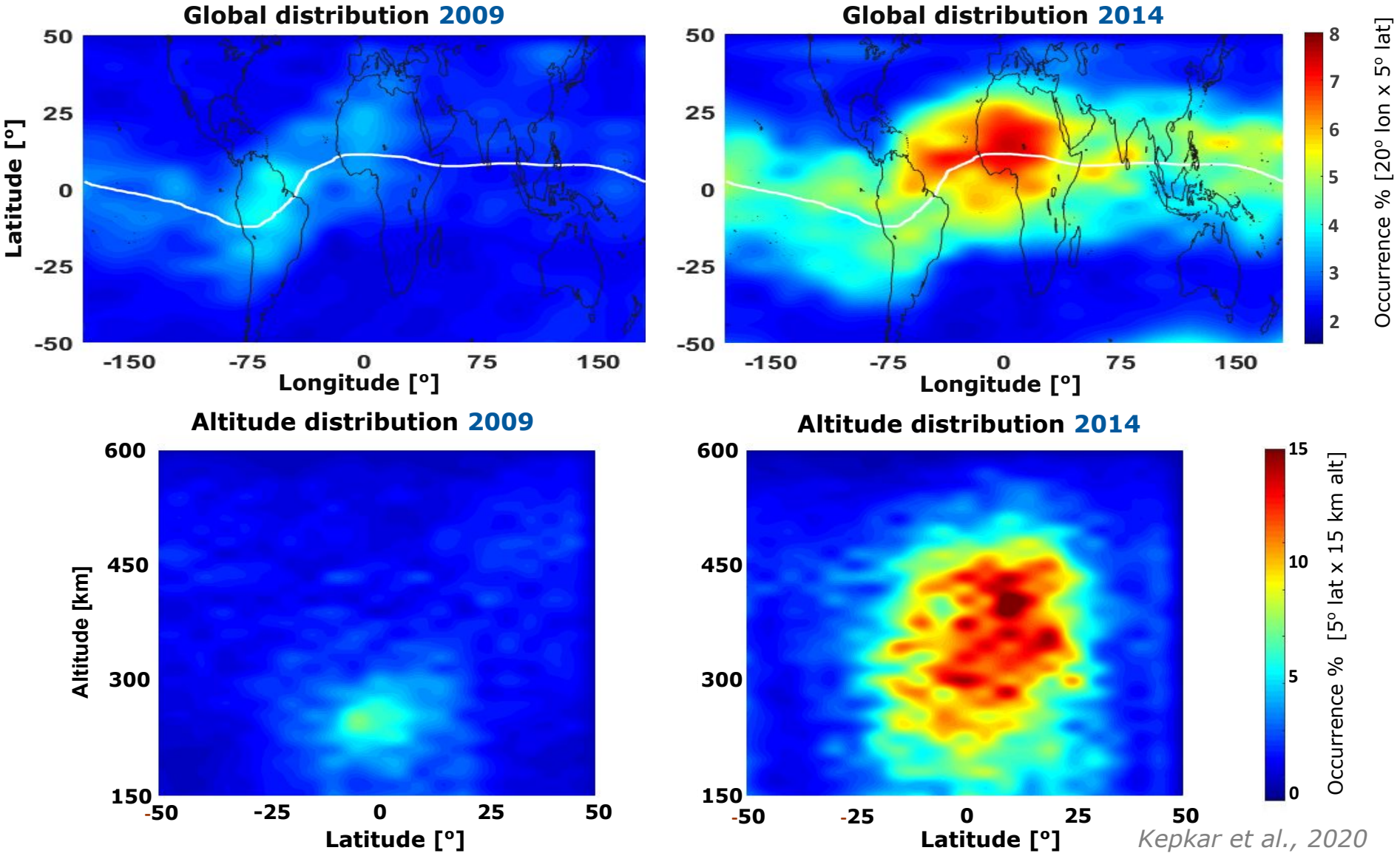
- Sources can be identified
- Convection, orography

Ionosphere: Vertical Electron Density Profiles and Detection of Disturbances



- Relevant for navigation and communication
- Studies of atmospheric coupling processes

Equatorial Plasma Bubbles

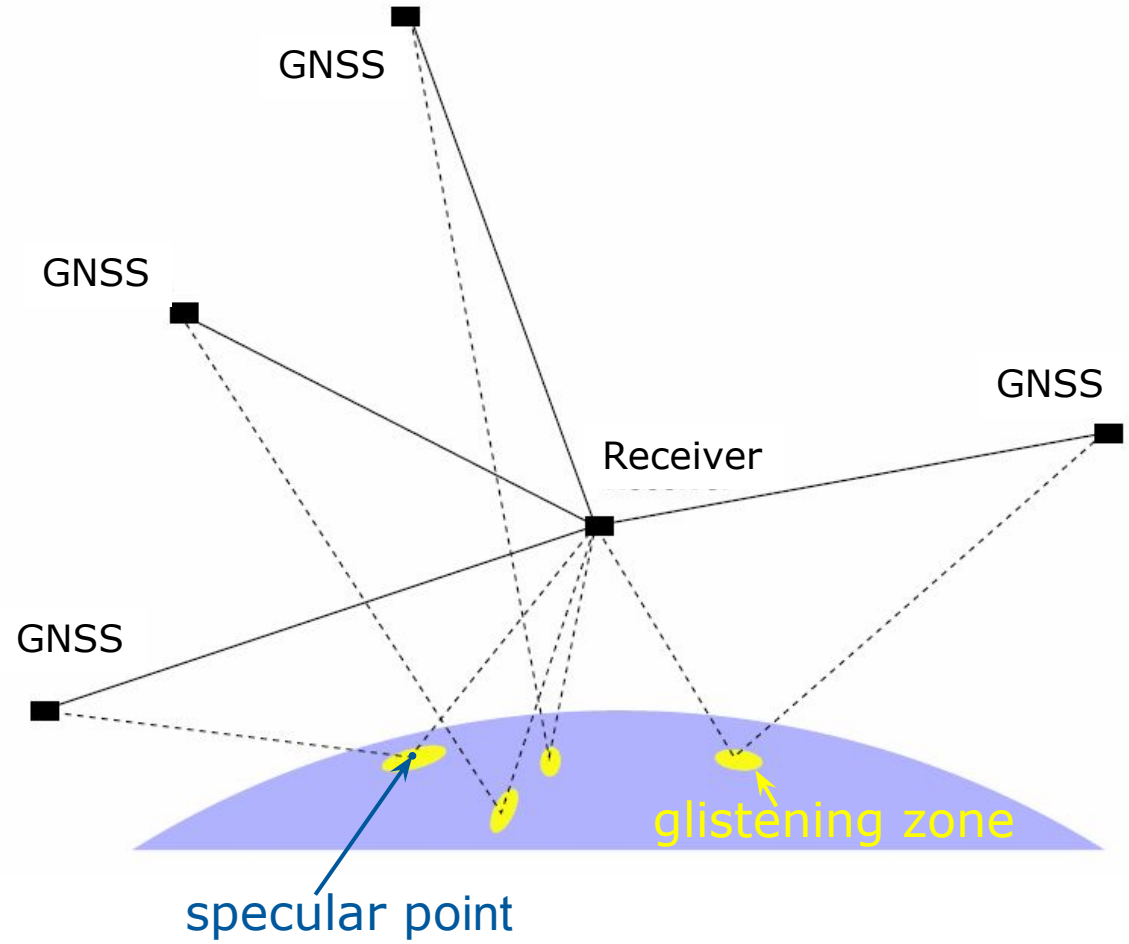


Kepkar et al., 2020

GNSS Reflectometry:

New Observation Technique

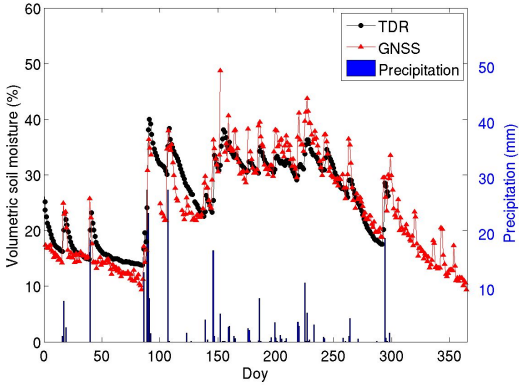
GNSS Reflectometry



- Multistatic radar
- Transmitters ~120, signals „free of charge“
- High rain transmissivity
- Reflections over oceans, land, ice, snow

Soil Moisture

Sutherland, South Africa

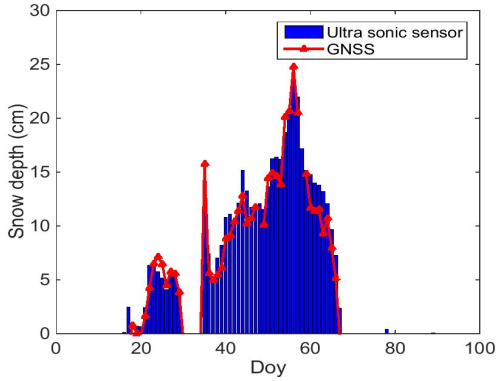


Precipitation events and evapotranspiration well visible

Vey et al., 2016

Snow Height

Wettzell, Germany



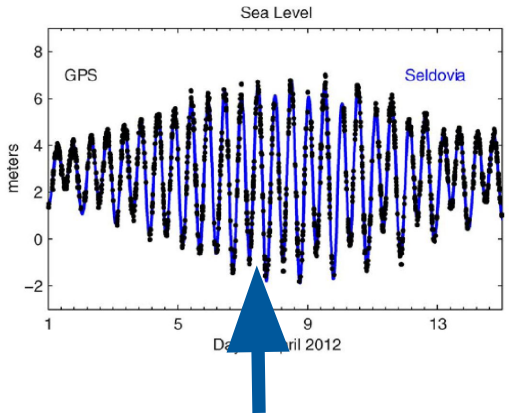
GNSS vs. ultra sonic sensor

RMSE 1.7 cm

Vey et al., 2016

Sea Level

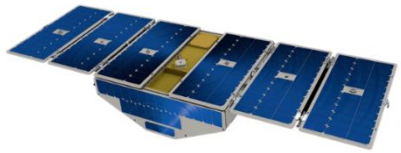
Kachemark Bay, Alaska



Nine meters tide amplitude

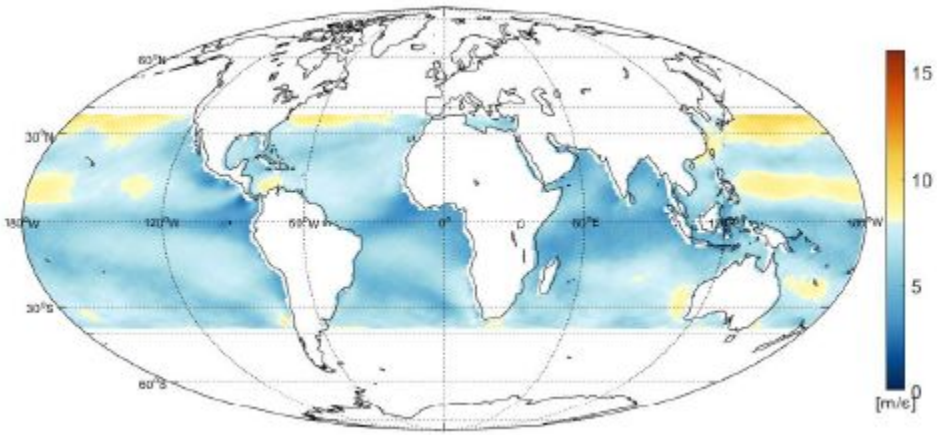
Thanks K. Larson

CYGNSS: Data Processing at GFZ

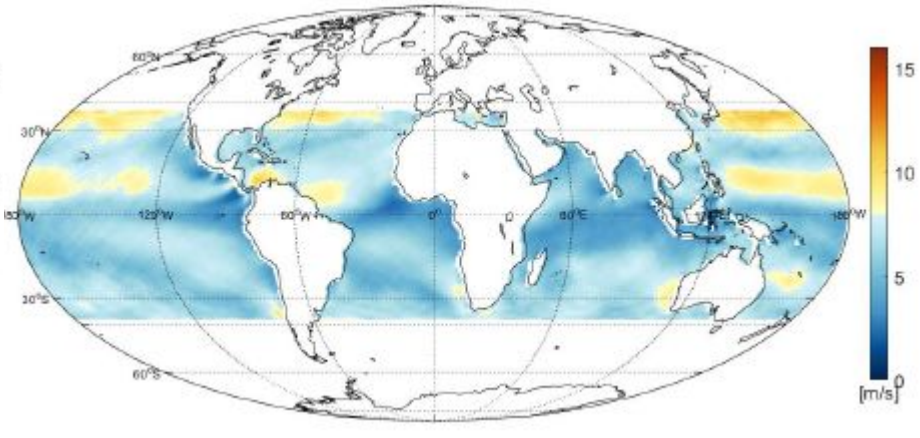


Global ocean wind speed based on Artificial Intelligence techniques

Average wind speed
January – March 2019



ERA5



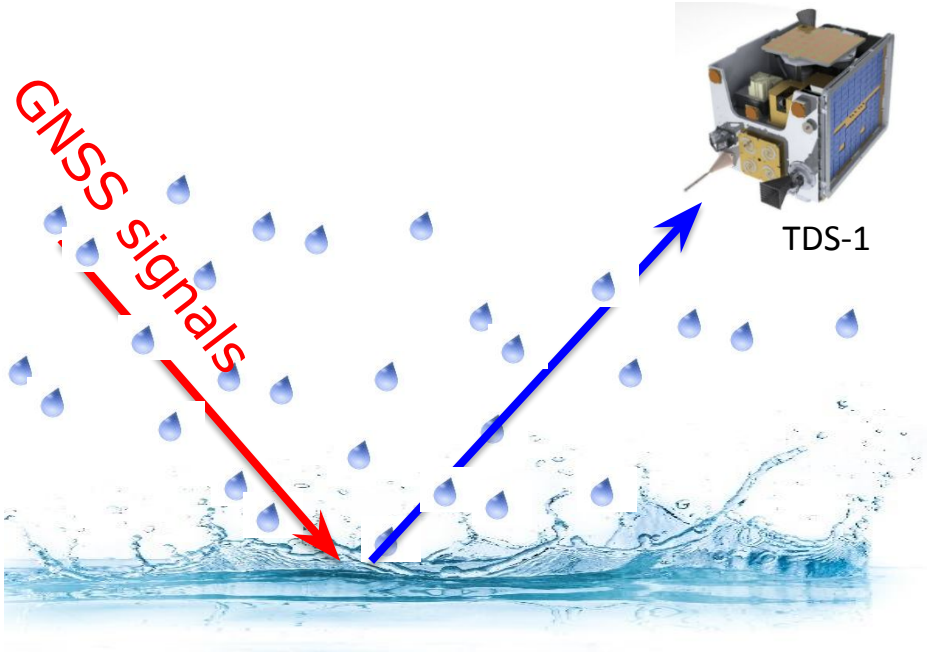
CYGNSS - processed at GFZ

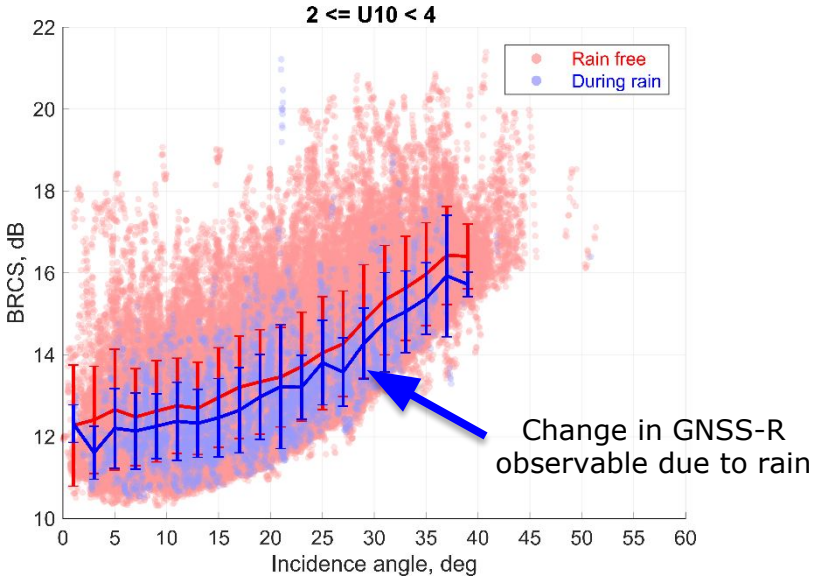
The best quality of global wind products so far:
RMSE of 1.2 m/s using deep learning over a test dataset

Asgarimehr et al., 2019/2020

First ever Rain detection with GNSS-R from TDS-1

Feasibility of detecting rain over oceans with high spatial coverage and unprecedented sampling rate





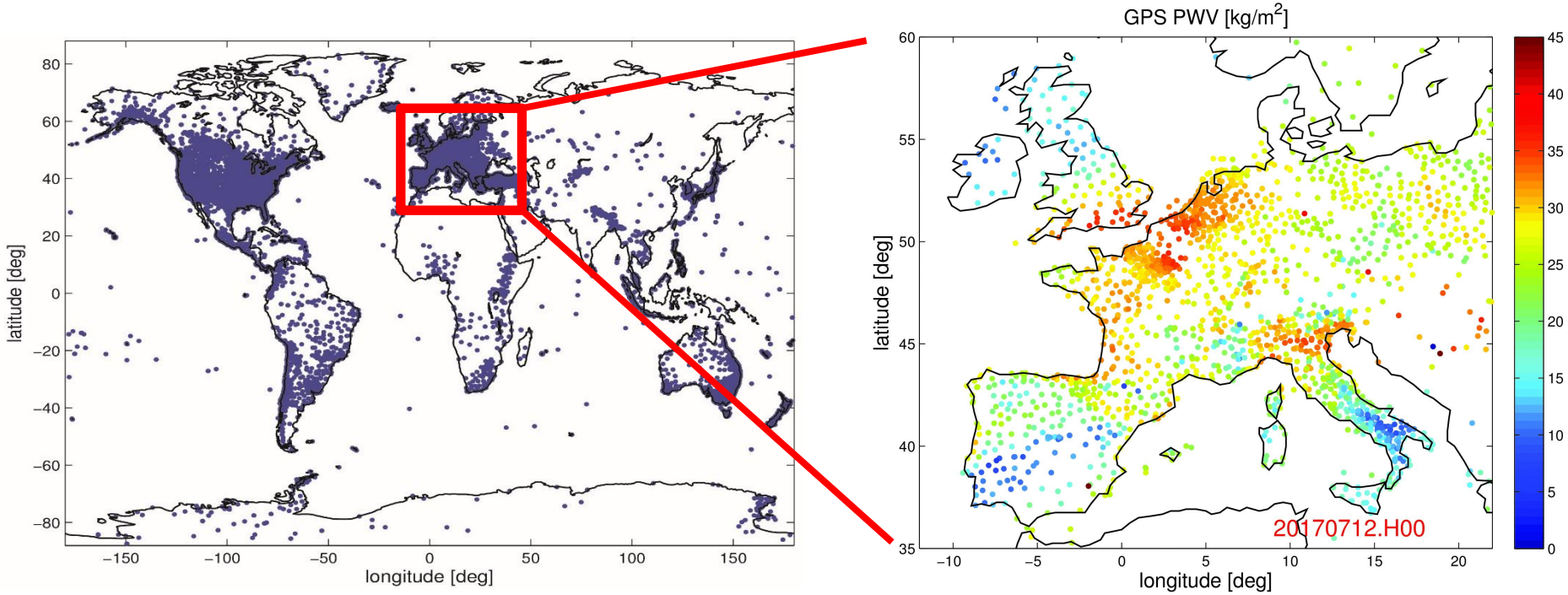
GNSS-R observable Bistatic Radar Cross Section decreases due to rainsplash effect

Asgarimehr et al., 2018 (GRL)

Future Developments

More than 18,000 GNSS Stations Globally

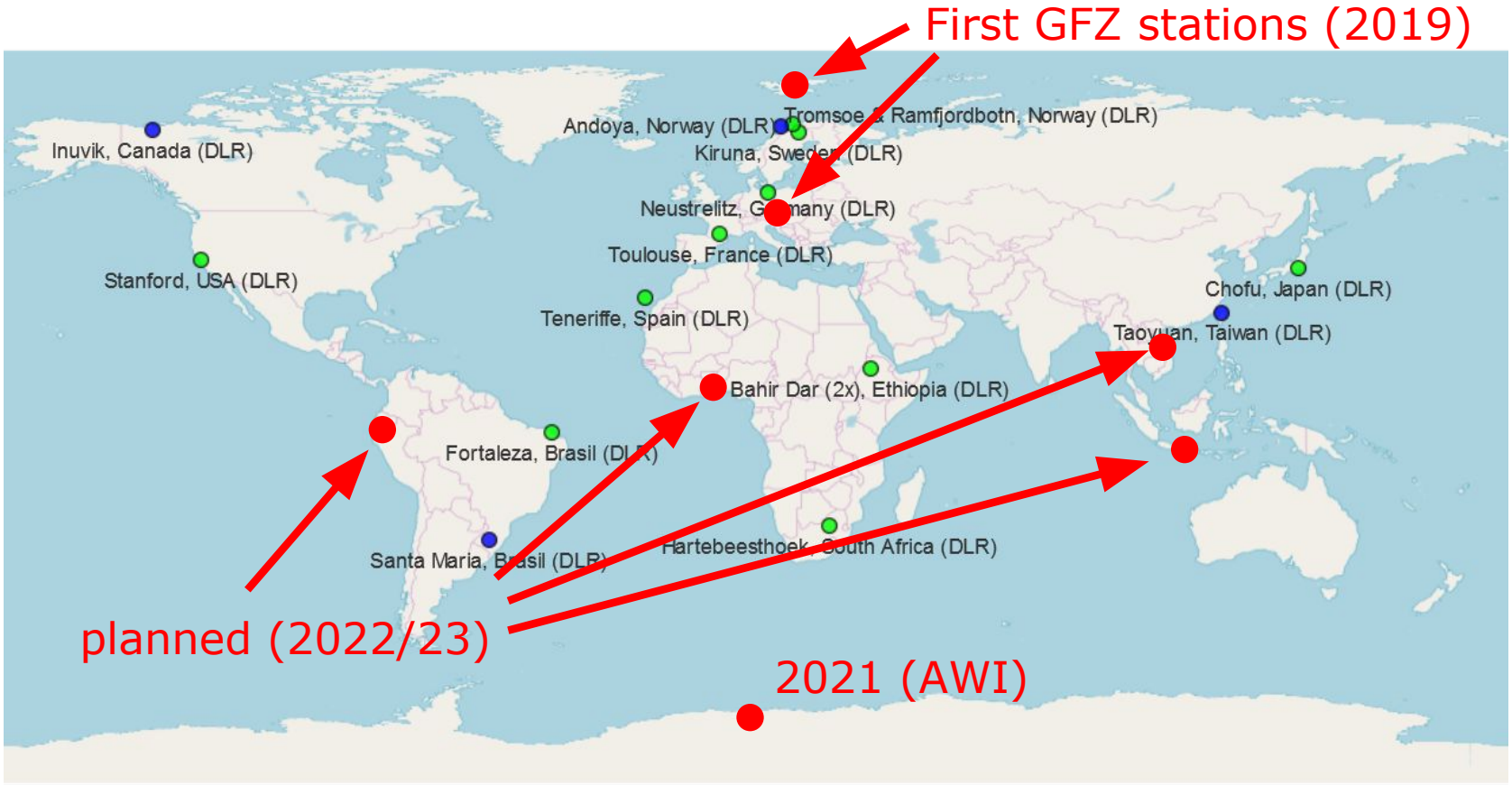
(as of 12.01.2021)



- Station positions, velocities, IWV
- TEC feasible (not yet provided)

Thanks J. Blewitt, geodesy.unr.edu

Scintillation receivers (Javad): Cooperation of GFZ with DLR



DLR: 11 installed, 4 planned

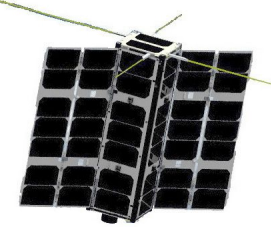
GFZ: 2 installed (2019), 1 AWI, 3 planned (2021/22)

Thanks: J. Berdermann (DLR)

Scintillation receivers: Planned Installation at Piura (Peru)

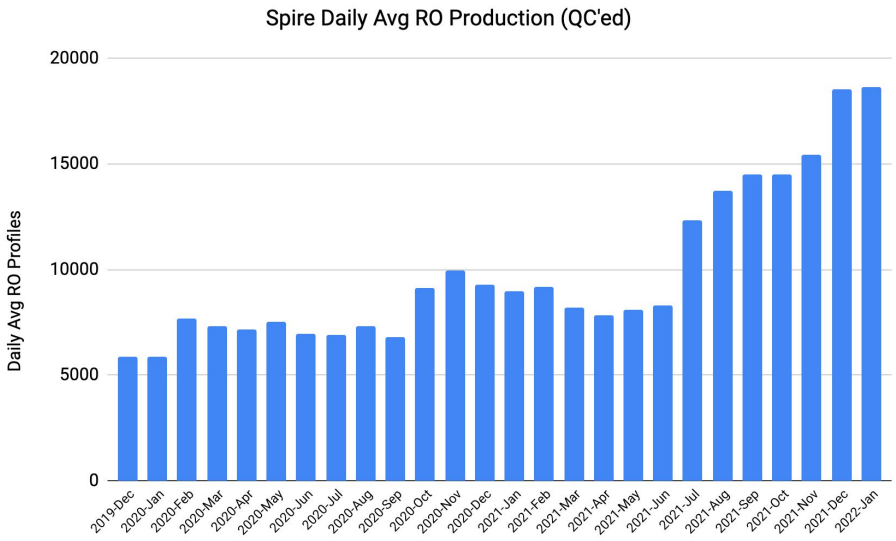
spire GNSS Radio Occultations (many many)

- Spire constellation is currently producing **18000+ quality-controlled profiles per day** and within reach of IROWG/CGMS long-term goal of 20000 per day



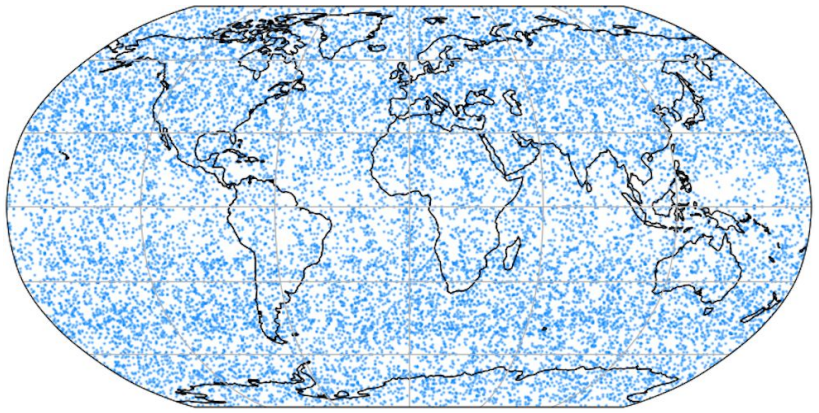
Lemur (120+)

Long-term RO production increase



12/2019

World's largest producer of RO profiles

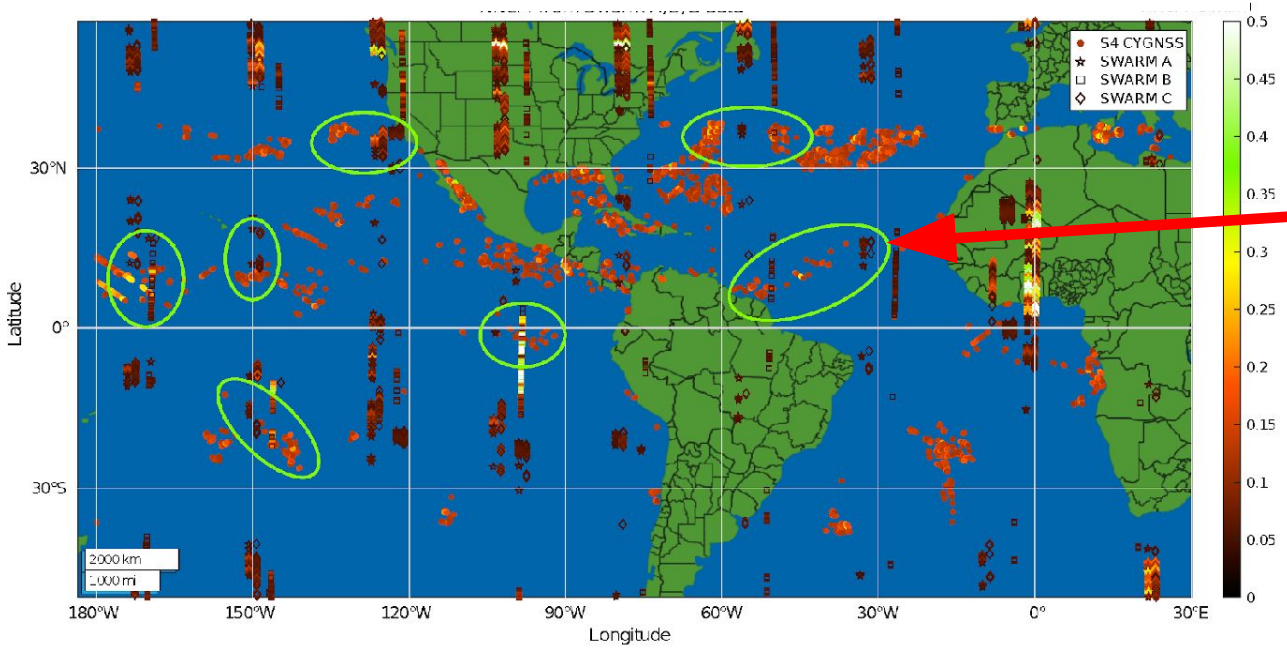


01/2022

Ionosphere monitoring using GNSS-R

Initial idea already in 1996
(Katzberg/Garrison)

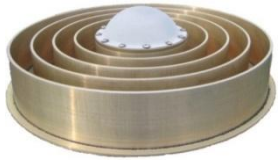
August 24, 2017, 00:00-24:00 UTC



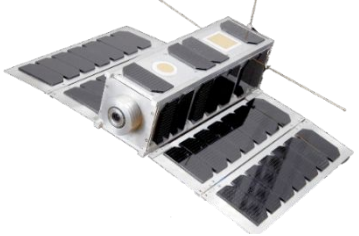
S4 index from CYGNSS with corresponding SWARM plasma density observations (NNeFI)
much more data from CYGNSS

Recent pioneering study for ionosphere monitoring over oceans
Plasma Bubbles on the signal path after reflection over calm sea

Molina/Camps, 2020



Conclusions and Outlook



- Overview and selected highlights of GNSS remote sensing at GFZ were given
- Ground based water vapor sounding is operationally applied for weather forecast and part of the Global Climate Observing system, extension to TEC observation demonstrated
- GNSS radio occultation provides unique data for weather prediction and climate research, additional use for space weather applications
- GNSS reflectometry is a novel and versatile Earth Observation technique with promising ionosphere sounding capability
- Several new missions combine several GNSS remote sensing techniques to be applied aboard small satellites

Thank you !