

GNSS Remote Sensing:Overview and selected recent developments

Jens Wickert

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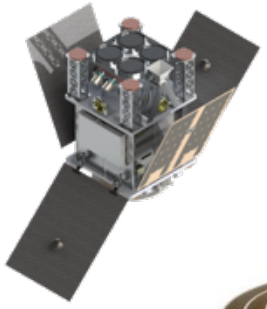
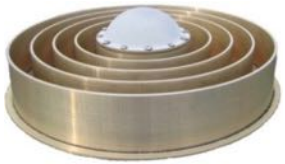
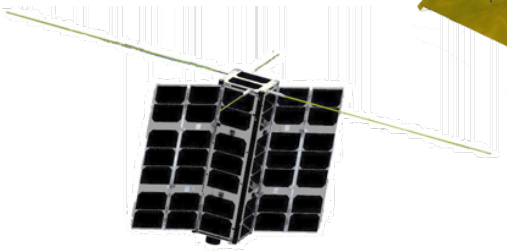
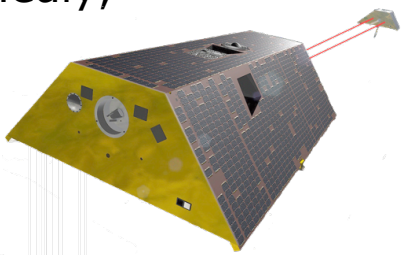
A. Kepkar, K. Lonitz, B. Männel, D. Masters,
T. Schmidt, M. Unwin, F. Zus

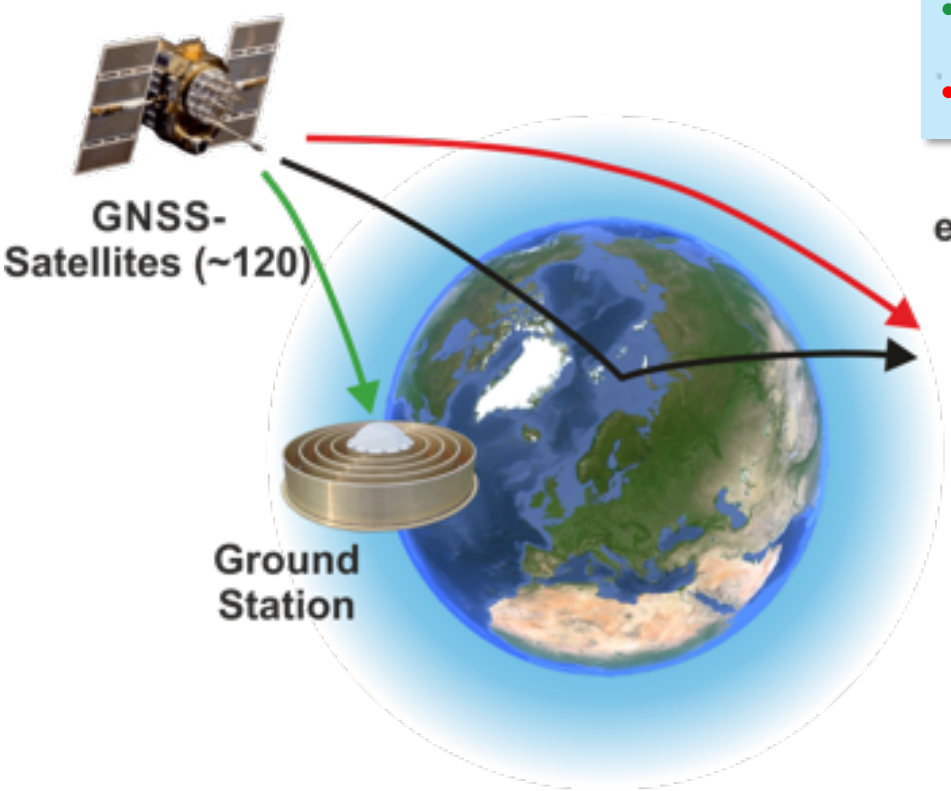



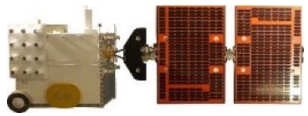
From Errors to Signals
GNSS Remote Sensing

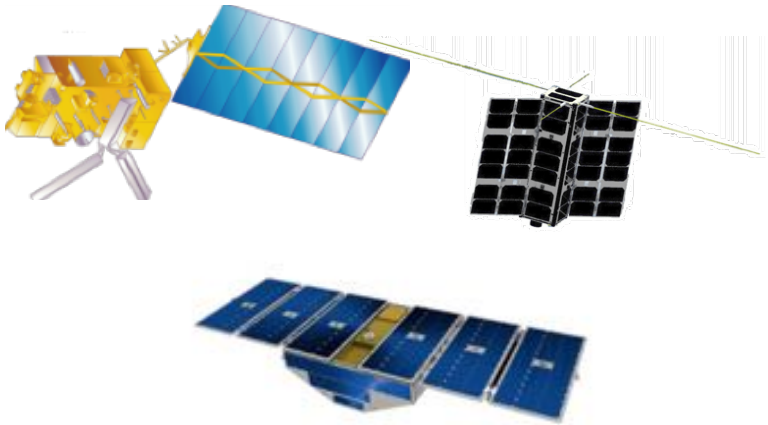
Derivation of

- 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

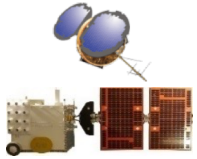

GLONASS


QZSS

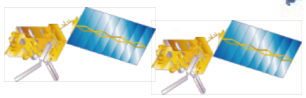

BeiDou

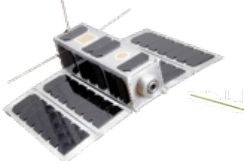

Galileo

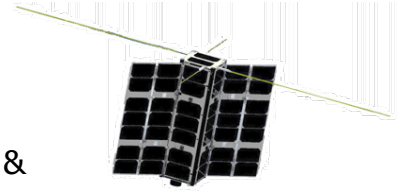

FY3-C/D


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

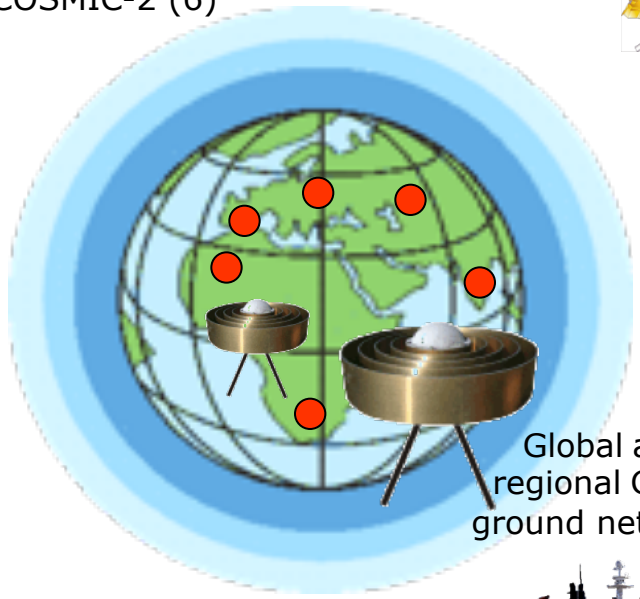

TerraSAR-X
TanDEM-X

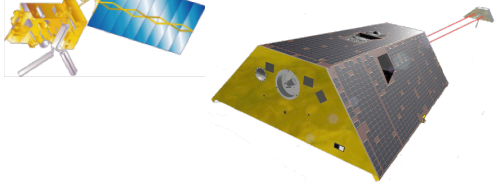

Metop A/B/C

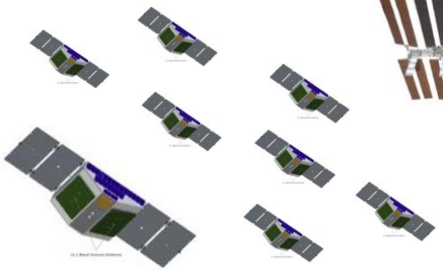



Mini satellites &
constellations

LEMUR (~100)




GRACE-FO


CYGNSS (8)


GEROS-ISS

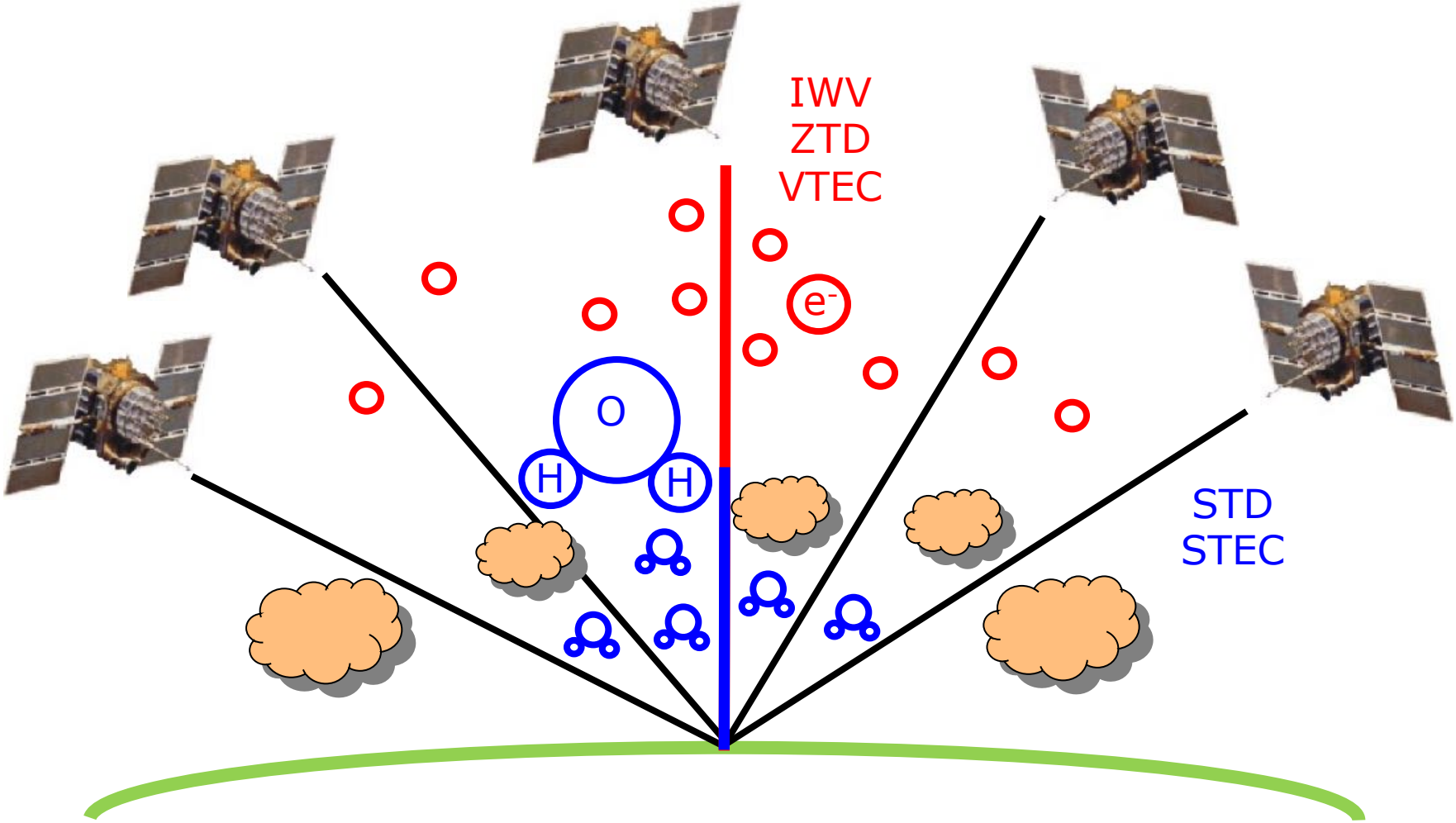
Global and
regional GNSS
ground networks


Airships,
Aircrafts
(HALO)

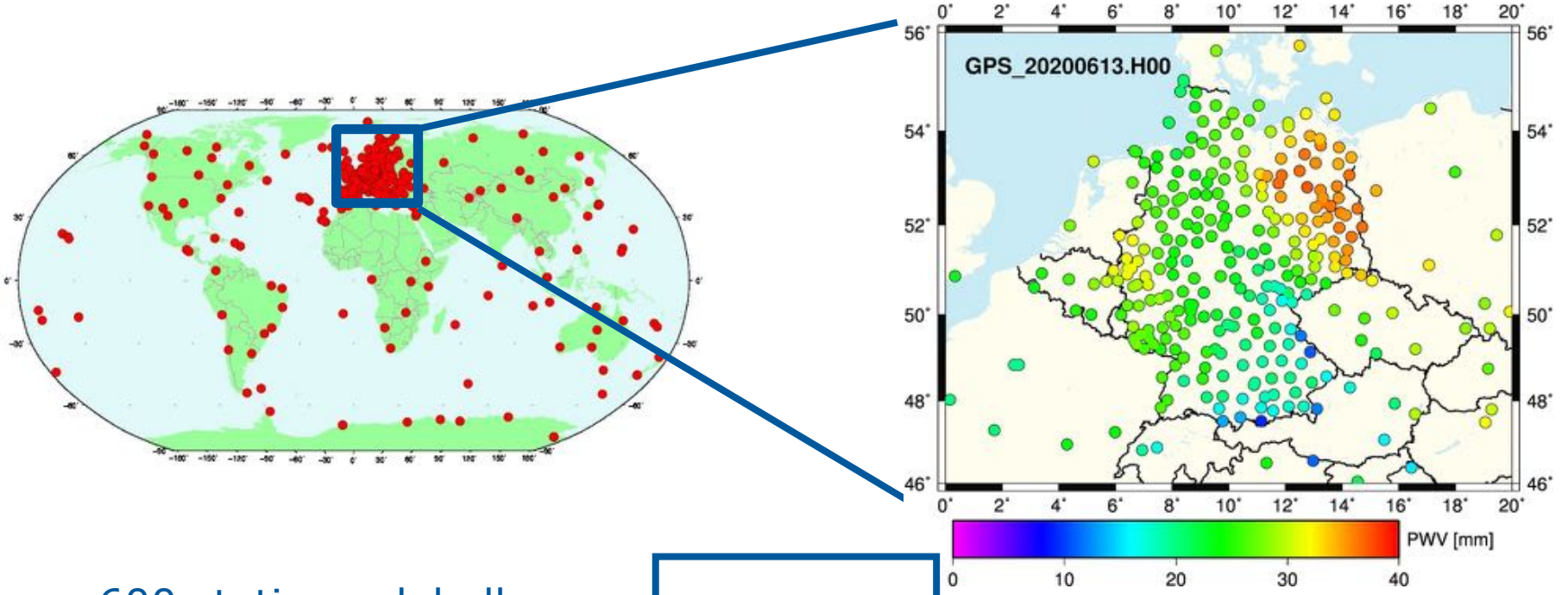

Ships (e.g. Mozaic)

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



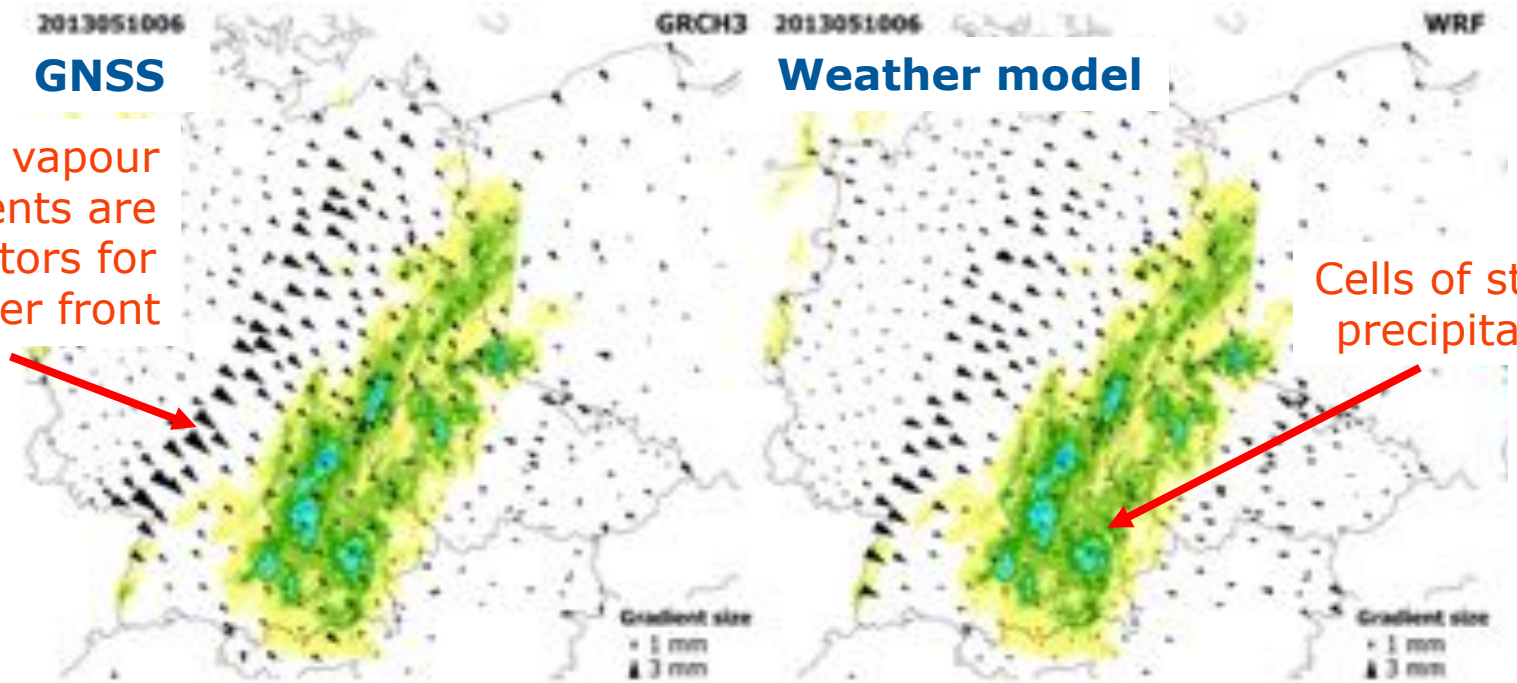
- ~600 stations globally
- ~300 in Germany
- Operational delay <1h
- Used by European Weather Services (DWD, MetOffice, MeteoFrance ..)

ZTD
IWV
STD
Near-Real Time 24/7

Severe weather in Brandenburg
June 13, 2020

Next Generation Data Products

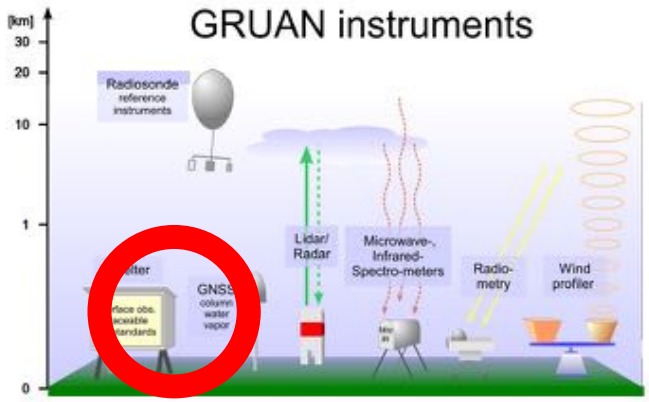
- DFG Project (started 01/2020): "Advanced MUlti-GNSS Array for Monitoring Severe Weather Events (AMUSE)"



- DFG Project (start in 2021): "Exploitation of GNSS Tropospheric Gradients for Severe Weather Monitoring And Prediction (EGMAP)"

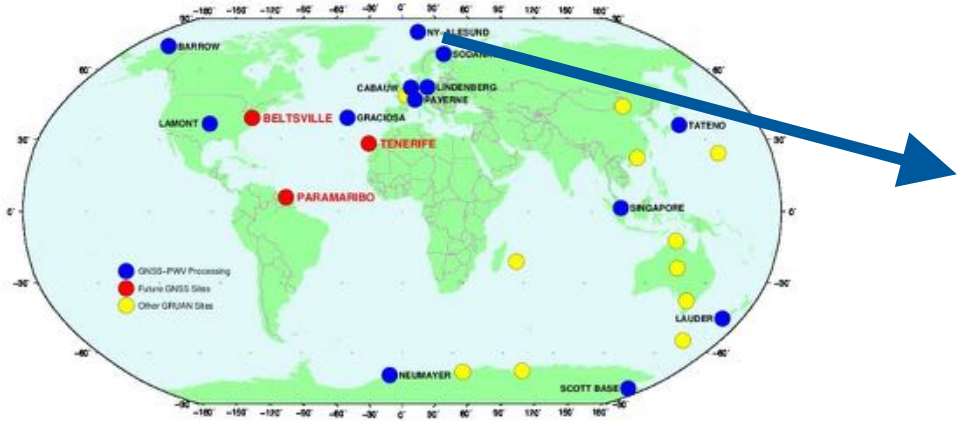
Wickert 2019/2020, DFG proposals

Reference Upper Air Network



- Lead centre: DWD, Germany
- GFZ is central GNSS processing centre and hardware provider since 2014

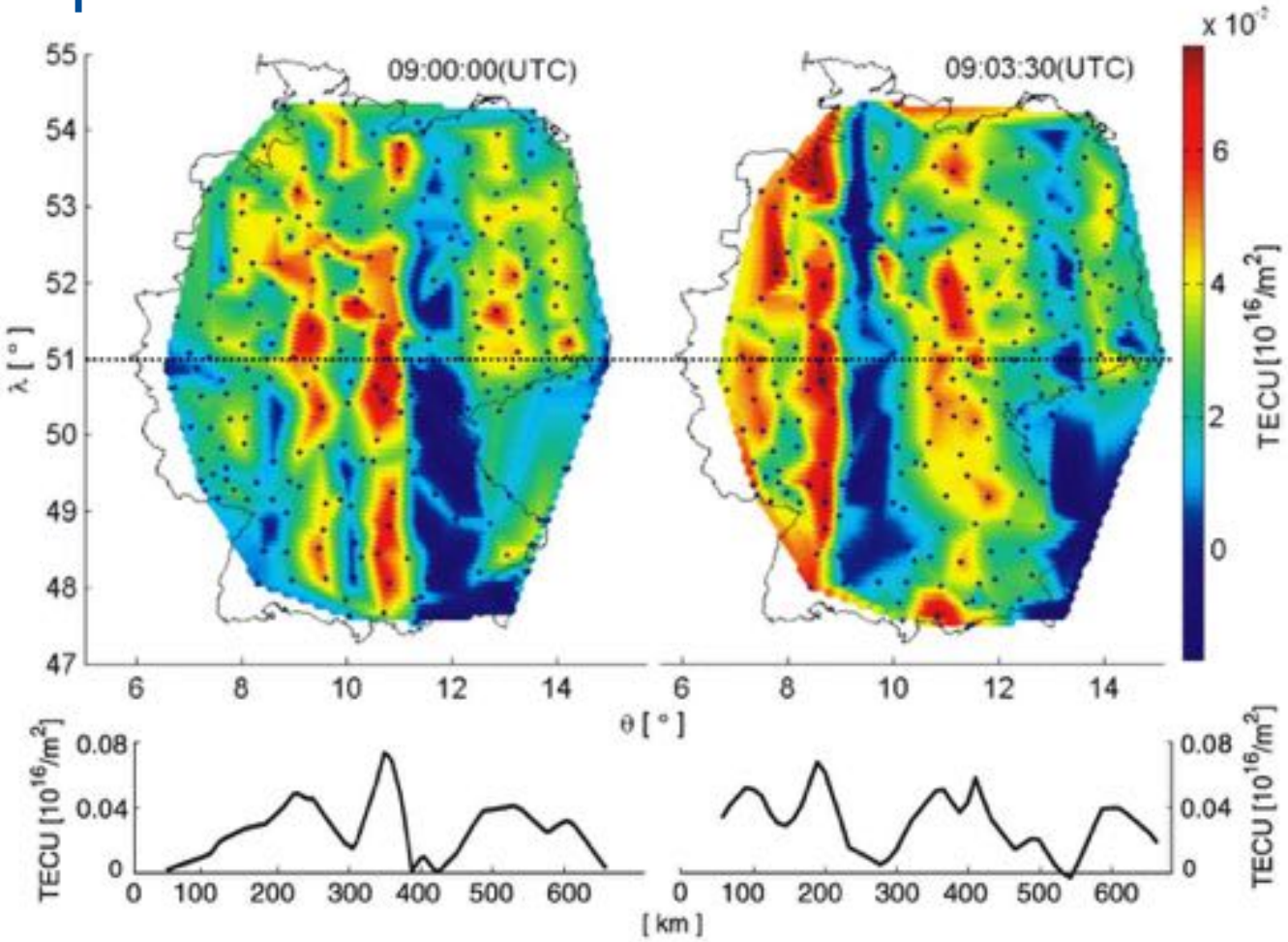
GNSS is priority one instrument



Currently 30 stations (**12/3** with GNSS)

www.gruan.org

Ionospheric Perturbation above Germany



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

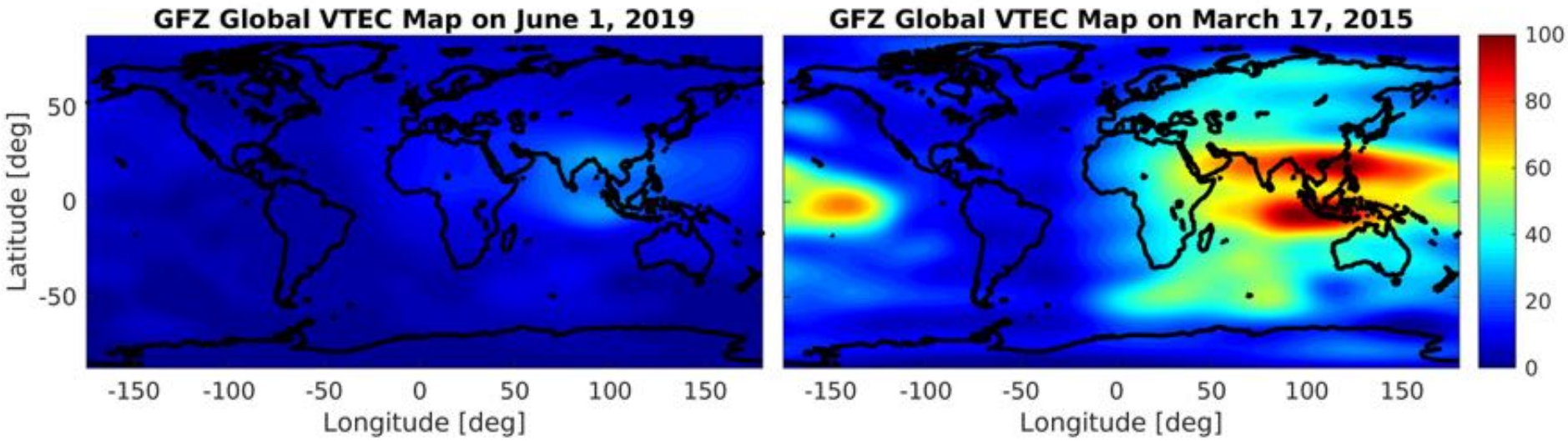
September 27, 2009 (~300 stations)

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)

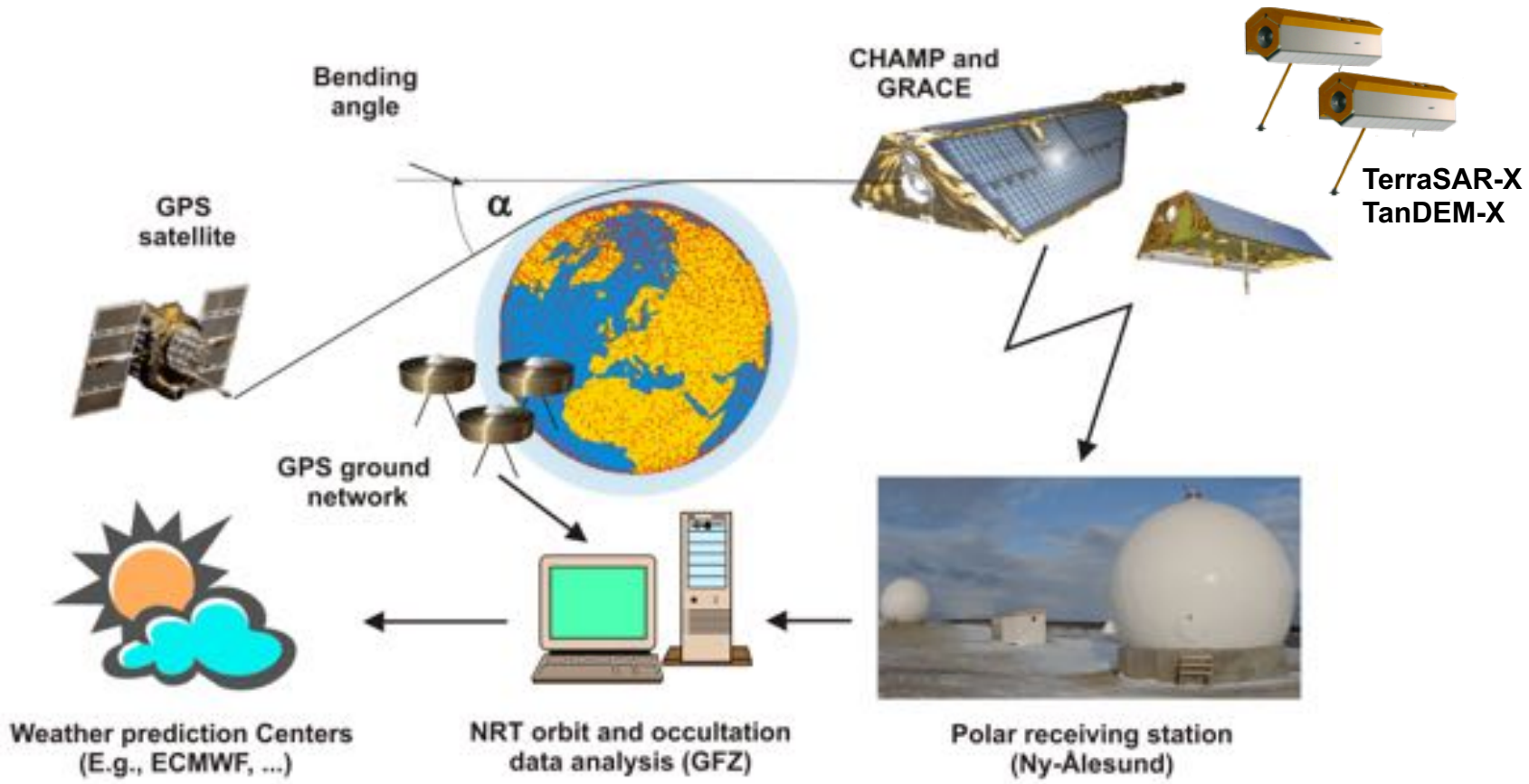


- Pre-operational maps (08:00 UTC)
- Day with moderate ionospheric activity (left)
- During the St. Patrick's day geomagnetic storm (right)

Wickert et al., 2020

Satellite-based GNSS Atmosphere Sounding: Radio Occultation

Operational GNSS-RO Data from GFZ to Improve Global Weather Forecasts

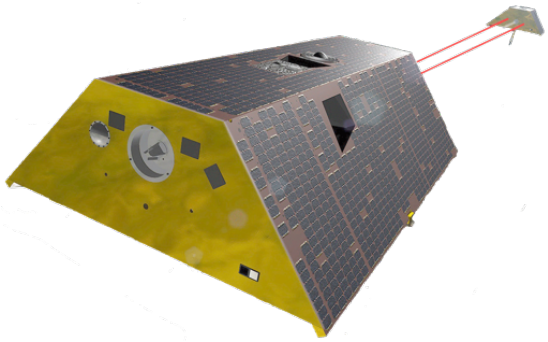


Precondition: Development and operation of complex Infrastructure inclusive of dedicated scientific analysis software

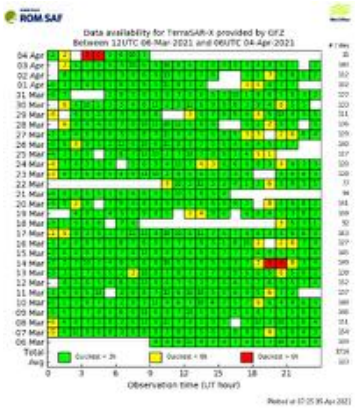
Operational GNSS-RO from GFZ (best effort)

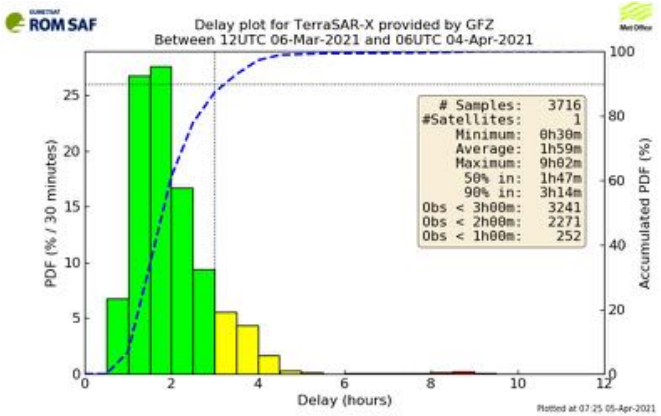
TerraSAR-X
(since 2007)

TanDEM-X
(since 2010)



GRACE-FO
(since 2021)

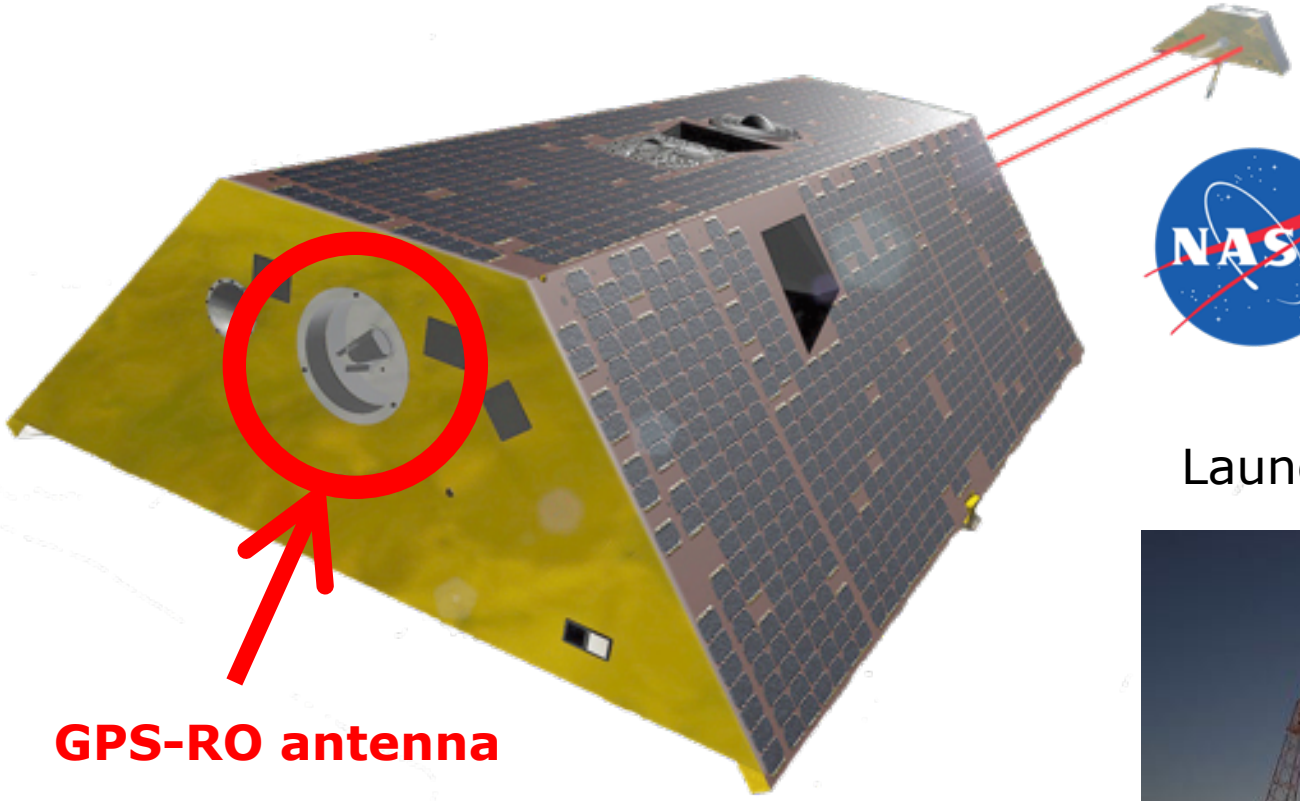




NRT monitoring by ROM SAF @ MetOffice, Sat. April 4, 2021

TerraSAR-X: Average delay: 1h59

GRACE – Follow On



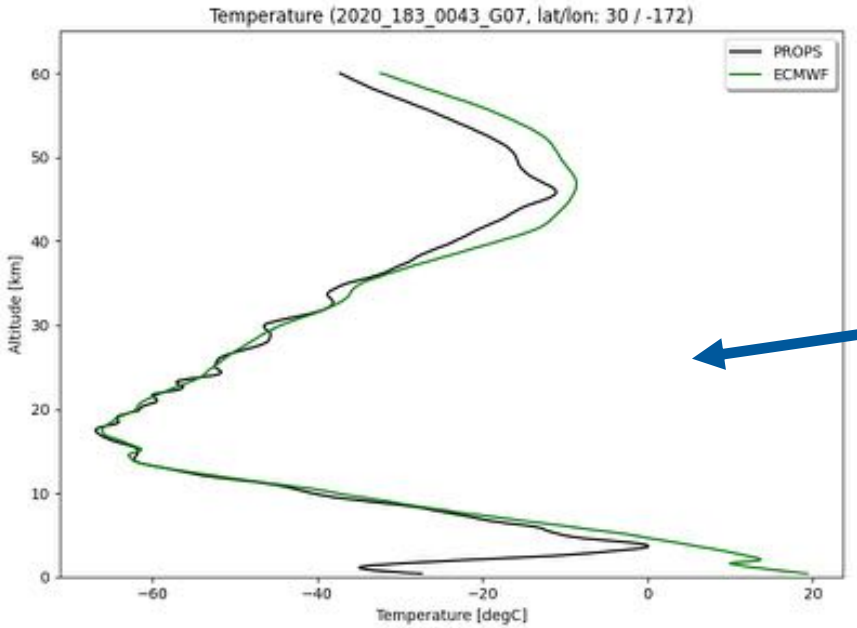
GPS-RO antenna

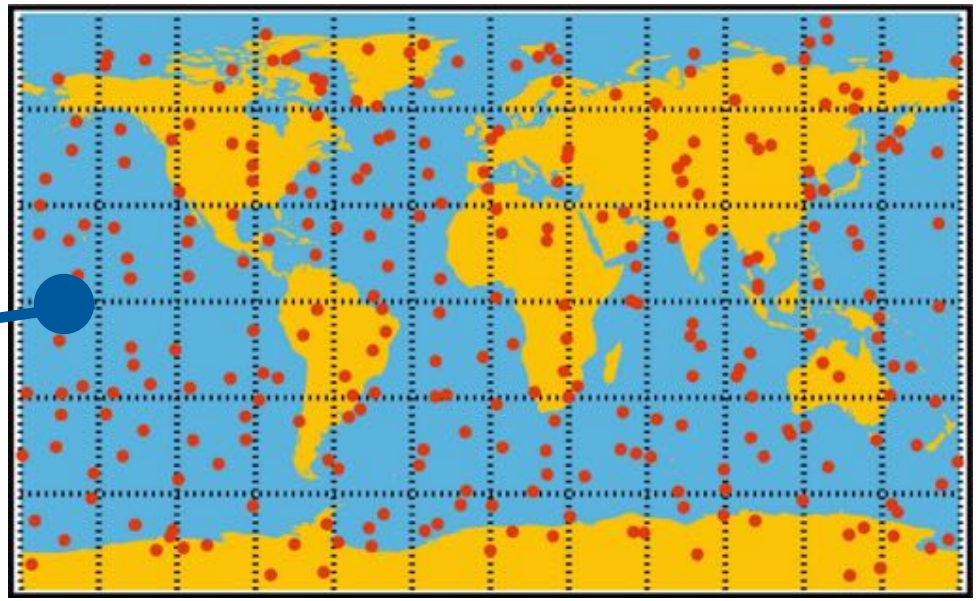
Launch of a **Falcon 9** rocket

The U.S./German Mission GRACE-FO was launched **May 19, 2018**
German Co-PI: F. Flechtner (GFZ)

GRACE-FO Initial Results

July 1, 2020, 286 occultations



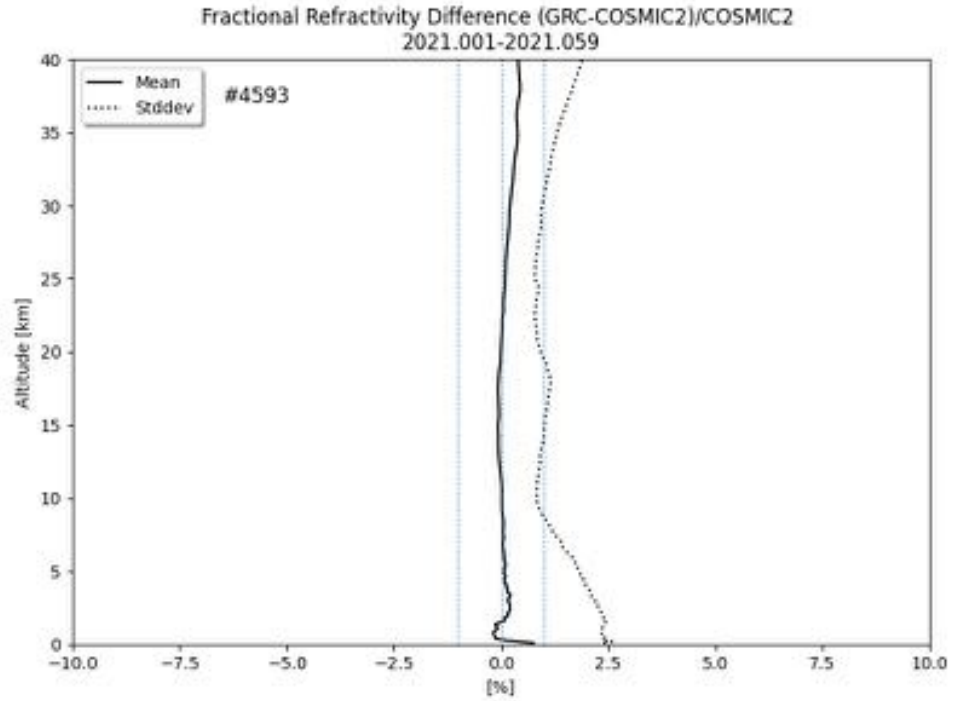


- Multiple carrier frequencies: L1, L2C, L5
- Occultations in polar regions
- Operational test data provision already started

GRACE-FO: Comparison with COSMIC-2

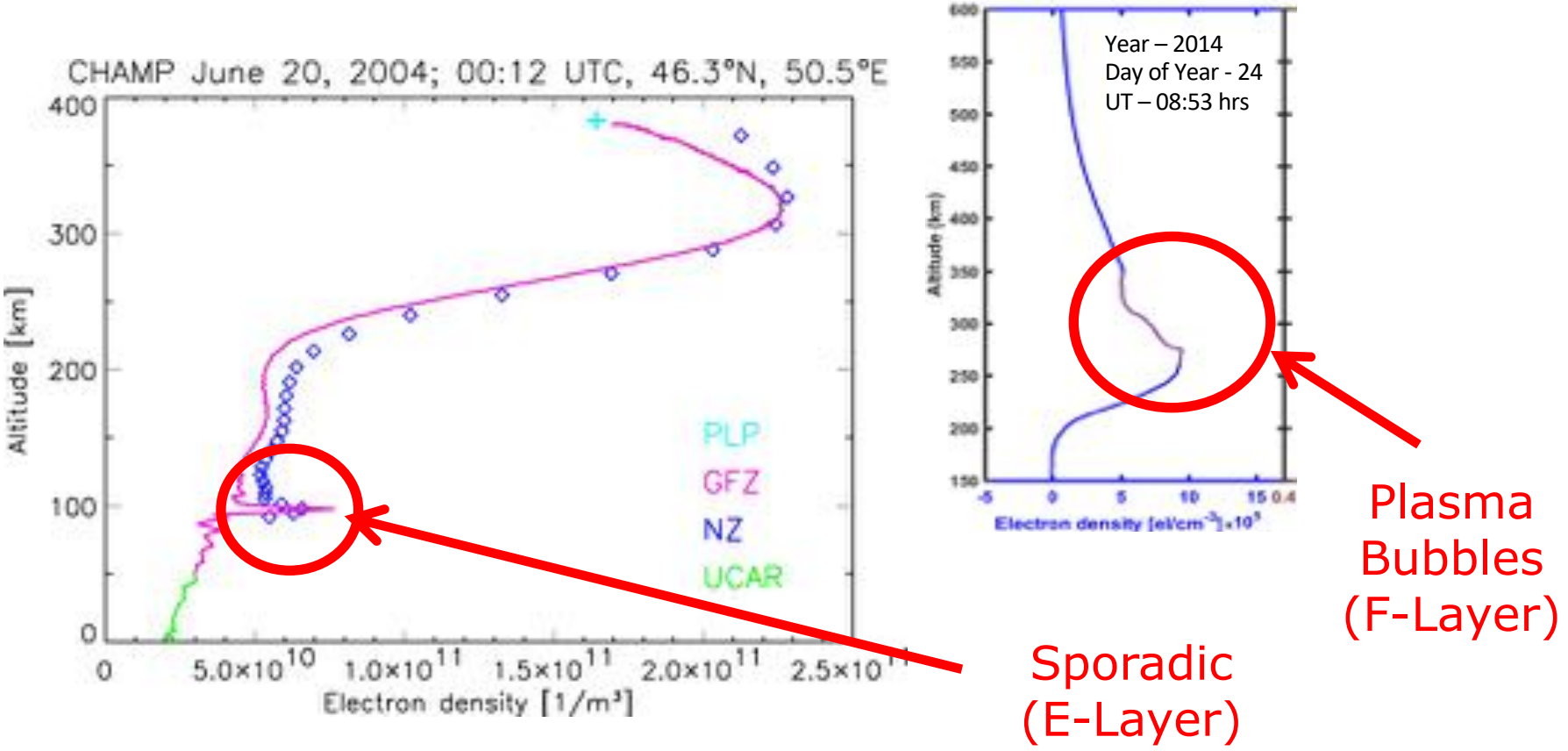
Co-located COSMIC-2 NRT data ($\Delta d \leq 300$ km, $\Delta T \leq 3$ hrs), 1 Jan – 28 Feb 2021

Fractional refractivity (GRFO-COSMIC2)/COSMIC2



Details: T. Schmidt, Monday, April 12, 09:35

Ionosphere: Vertical Electron Density Profiles and Detection of Disturbances



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

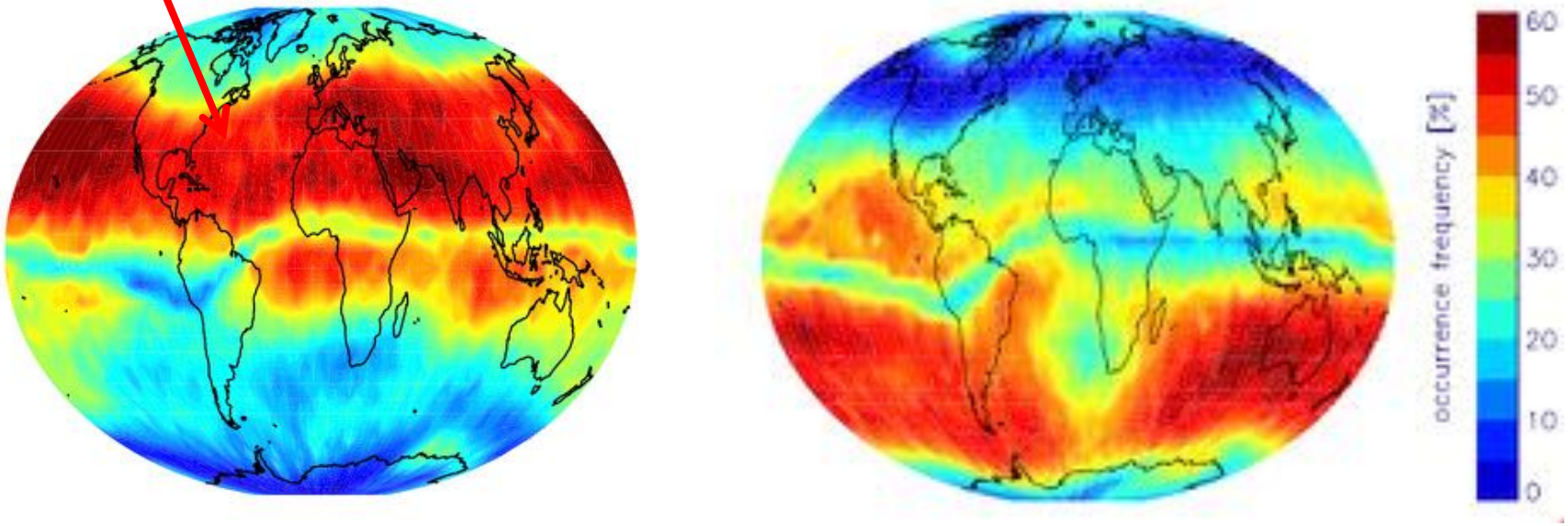
Global Distribution of Sporadic E-Layers

2007-2019, 5°x5° resolution, COSMIC-1 data

Important phenomenon:
~50% occurrence frequency

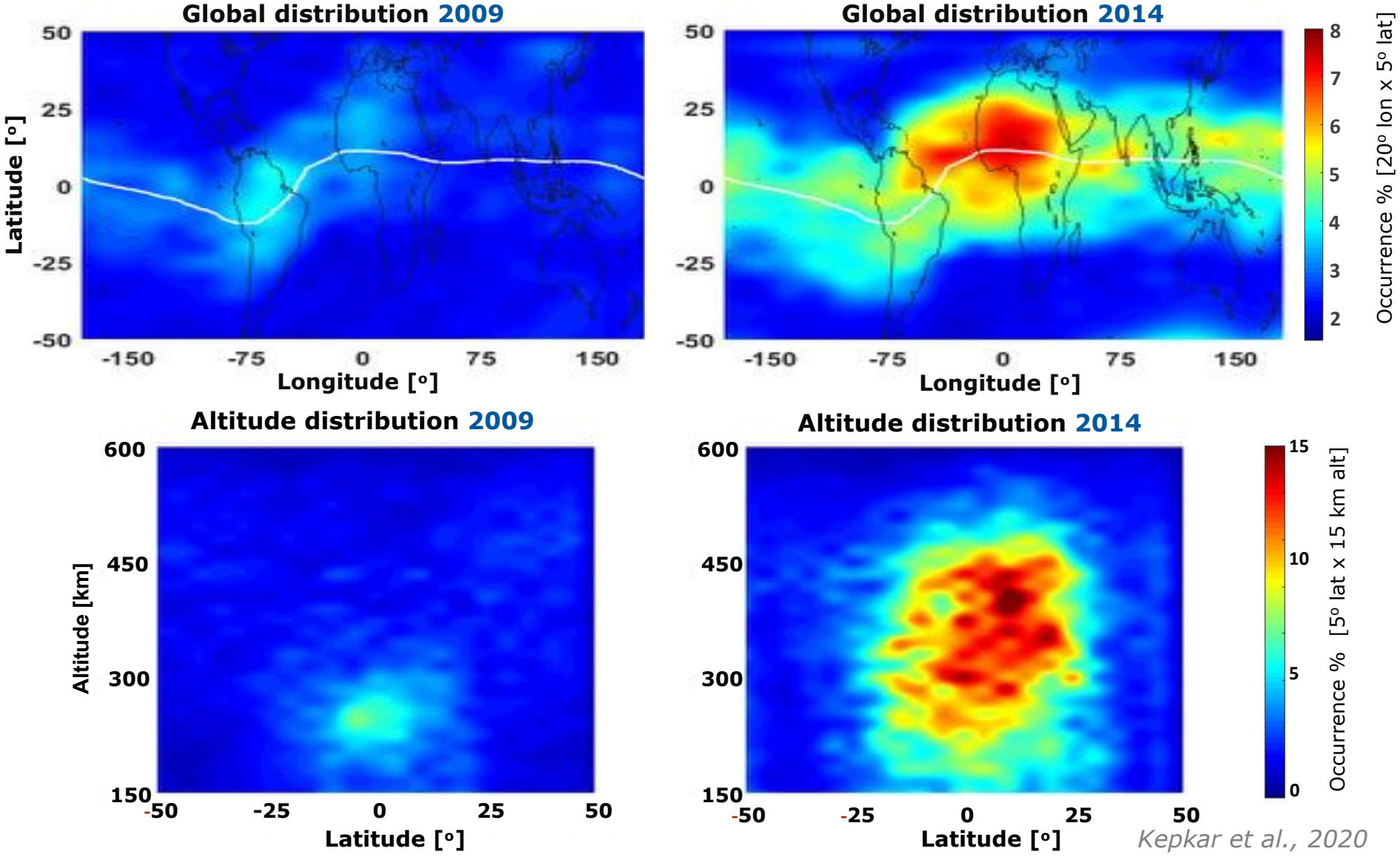
JJA

DJF



- Several DFG research projects
- Provision of extensive data set to NASA (Prof. Bilitza) in 2020 for inclusion to the **I**nternational **R**eference **I**onosphere

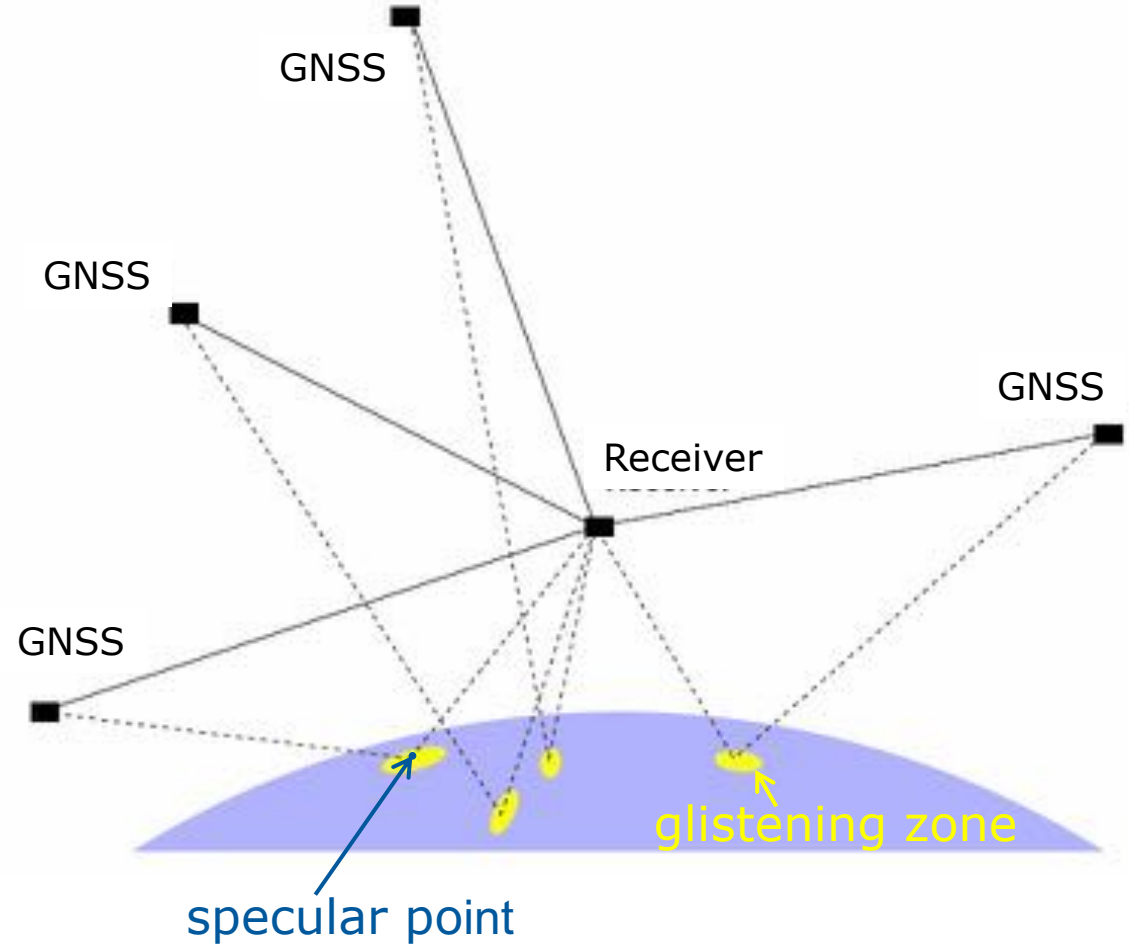
Equatorial Plasma Bubbles



Kepkar et al., 2020

GNSS Reflectometry: Complementary Observations to GNSS RO

GNSS Reflectometry

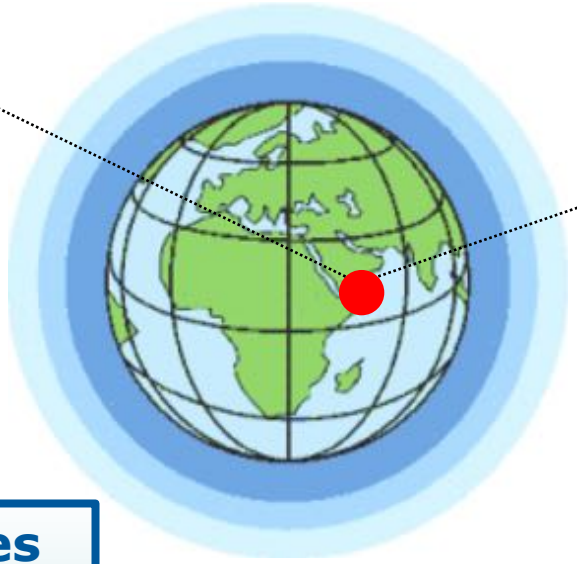


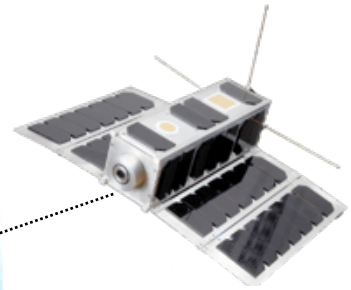
- Multistatic radar
- Transmitters ~120, signals „free of charge"
- High rain transmissivity
- Reflections over oceans, land, ice, snow

GNSS Reflectometry: Versatile Earth Observation

Weather
Wind, humidity, precipitation, …

Ionosphere and Space Weather
Electron density





Climate
Sea level, sea ice, salinity, …

Disasters
Tsunamis, flooding, hurricanes, ...

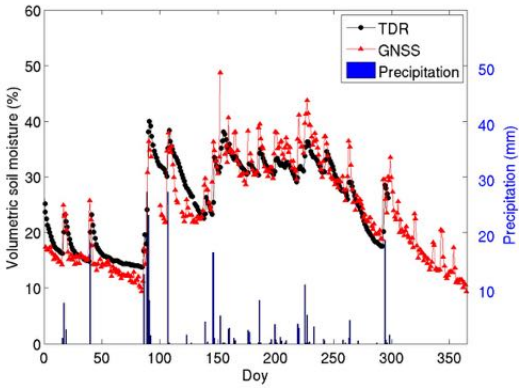
Land surfaces
Soil moisture, biomass, snow, ...

Infrastructure
Ship monitoring

Wickert et al., EU report GfG², 2012

Soil Moisture

Sutherland, South Africa

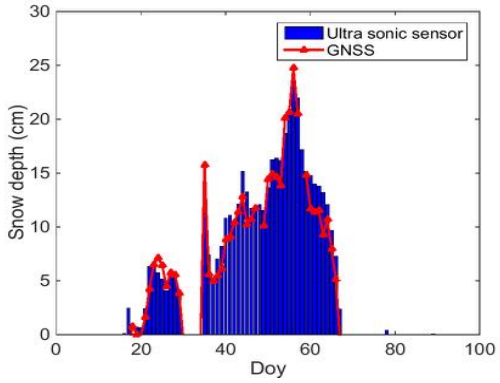


Precipitation events and evapotranspiration well visible

Vey et al., 2016

Snow Height

Wettzell, Germany



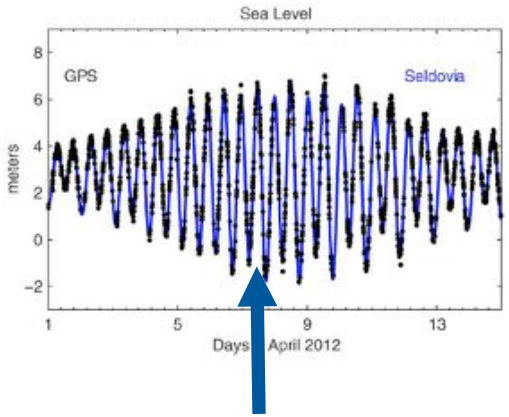
GNSS vs. ultra sonic sensor

RMSE 1.7 cm

Vey et al., 2016

Sea Level

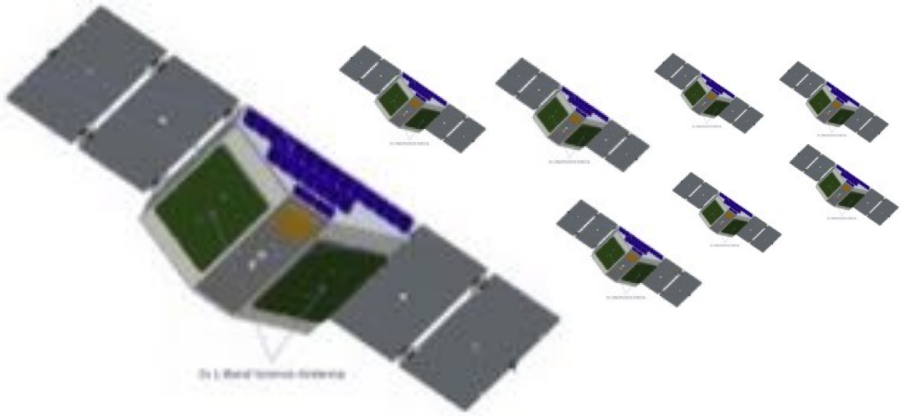
Kachemark Bay, Alaska



Nine meters tide amplitude

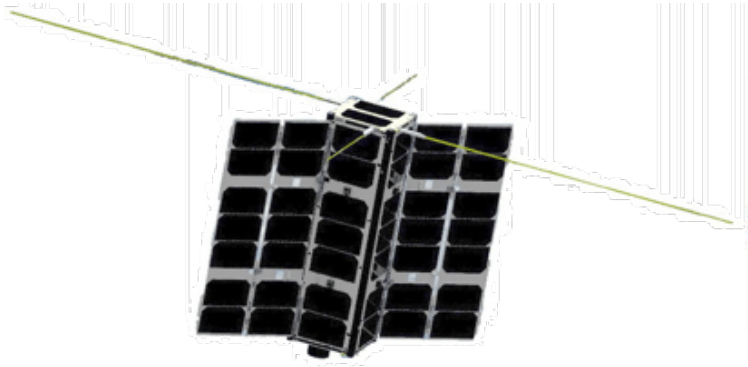
Thanks K. Larson

Selected current GNSS-R missions



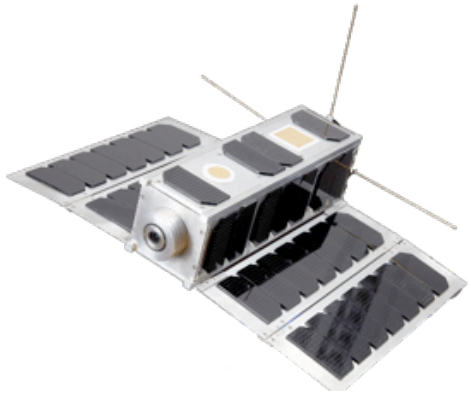
CYGNSS (8, since 2016)

TDS-1 (since 2014)



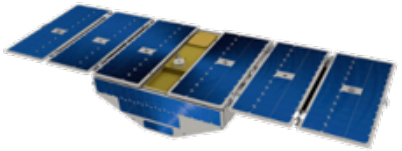
LEMUR (100+ in Orbit)

FY-3E (launch 2021)

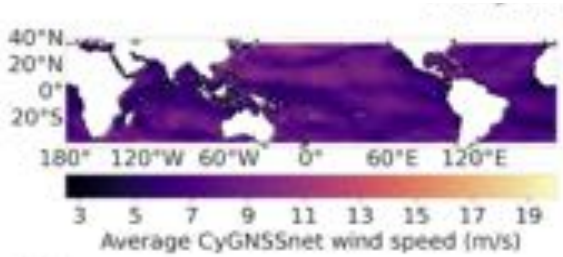
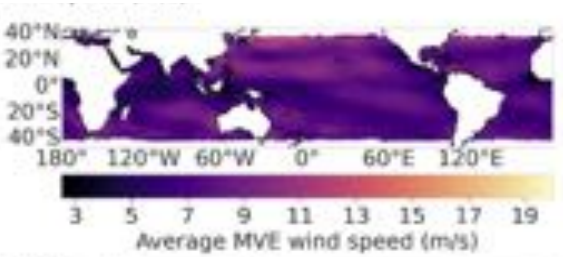
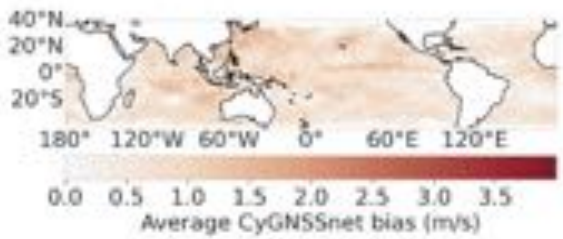
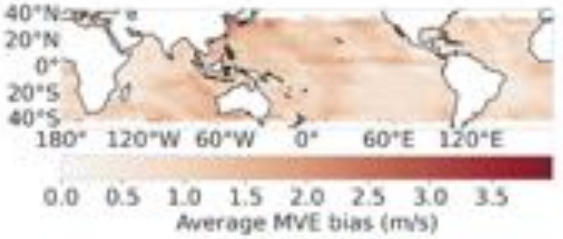
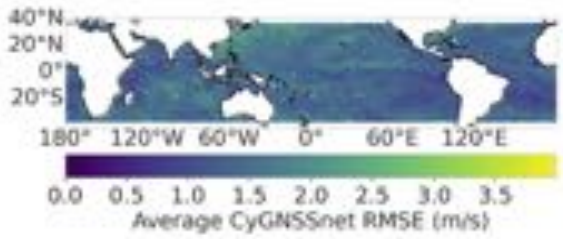
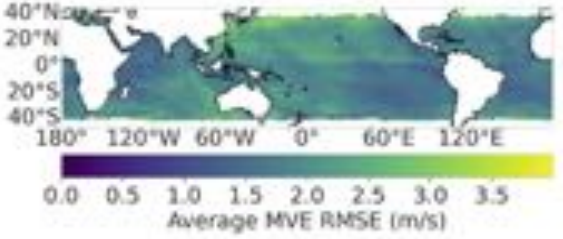


PRETTY (launch 2022)

CYGNSS: Global wind speed with AI



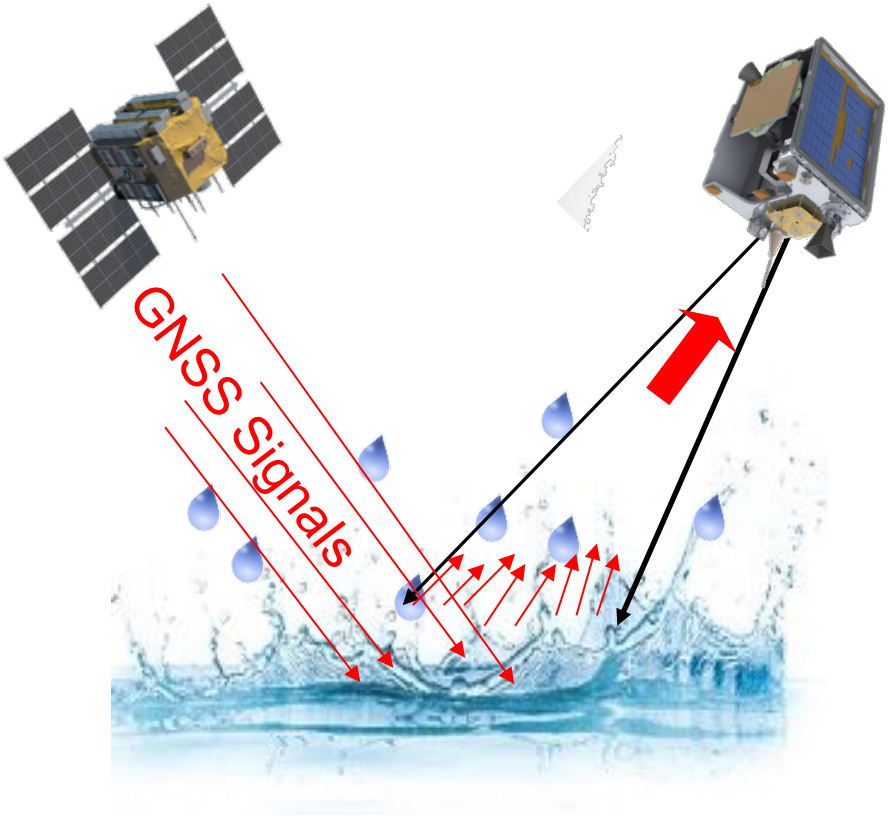
October 2018 – February 2019

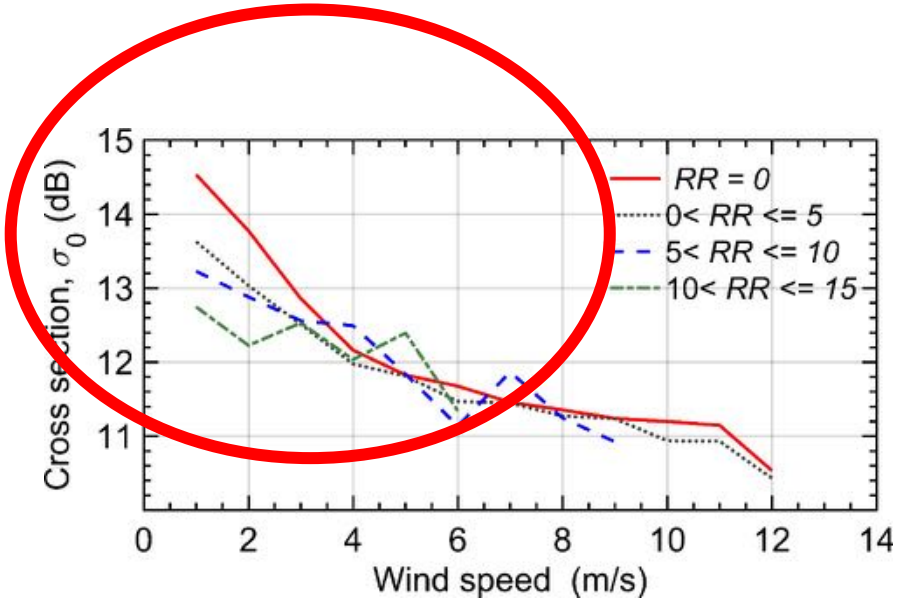
	CyGNSSnet	Conventional method CyGNSS Level 2
Average Wind Speed		
Bias		
RMSE		

The best quality of global wind products so far:
RMSE of 1.4 m/s using deep learning over a test dataset

Asgarimehr et al., 2021

GNSS-R can detect precipitation over oceans





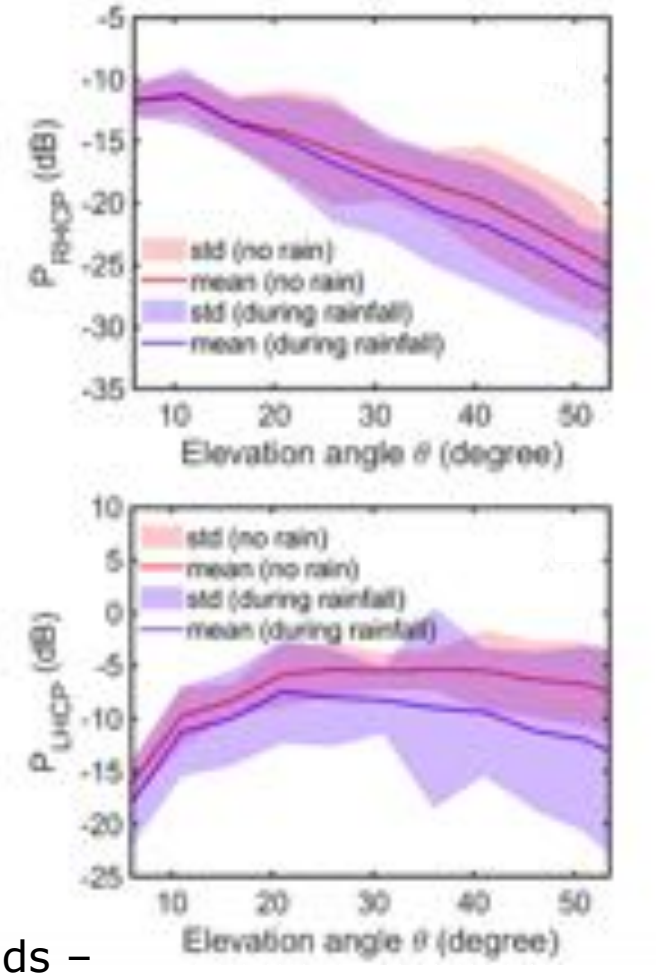
Average bistatic radar cross section versus wind speed at different rain rates (RR).

Considerable splash effect at winds lower than 6 m/s

Asgarimehr et al., 2018

Rain – dual polarization observations

Onsala Space Observatory



Rain signatures in polarimetric measurent at low winds – proof of concept for future space missions

Asgarimehr et al., 2021

HydroGNSS:

A new ESA mission

for GNSS reflectometry

(provided by M. Unwin/E. Cardellach)

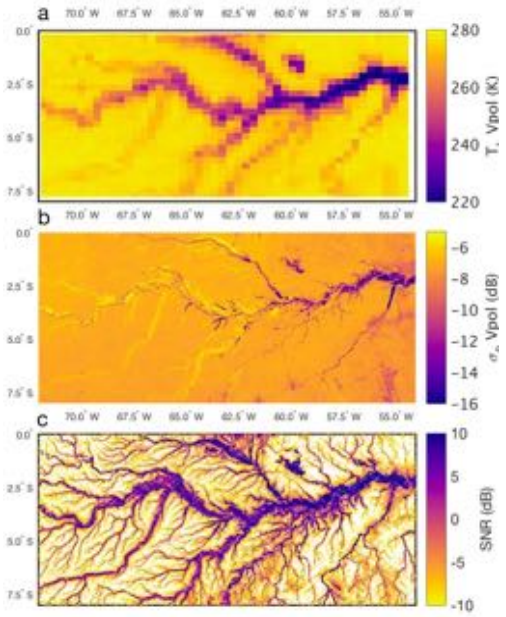
HydroGNSS

- Presence of **water over land** impacts weather, climate, ecosystems, human welfare and agriculture
  - Water systems currently inadequately measured
  - Global Climate Observing System requiring better measurements
  - Special needs at higher latitudes incl. permafrost, biomass
  - Vital SMOS and SMAP L-Band missions have no immediate successors
- **HydroGNSS to sense 4 ECVs**
  - Soil Moisture
  - Inundation / wetlands
  - Freeze / Thaw state
  - Biomass
- **ESA Scout opportunity**
  - Science driven mini-Explorer
  - HydroGNSS selected to proceed

NASA SMAP
L-Band Passive

NASA SMAP
L-Band Active

NASA CYGNSS
L-Band GNSS-R

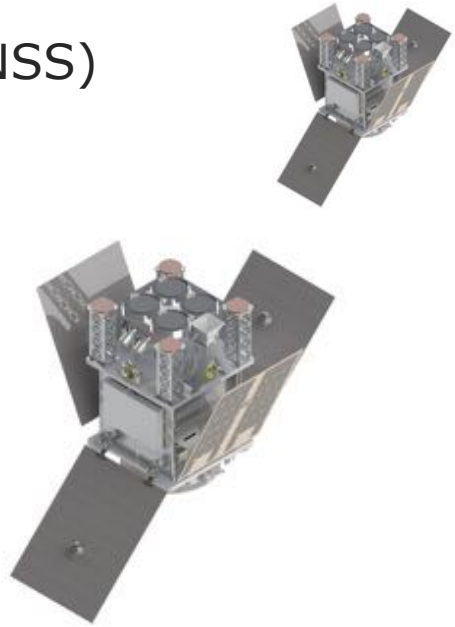


Satellite observations of streams and tributaries across the Amazon basin *(Chew et al. 2018)*

HydroGNSS Instrument & Mission

Innovative GNSS-R measurements

- New GNSS-R Instrument (based on TDS-1/CYGNSS)
- Multi-GNSS reception, including Galileo and GPS
- Left and Right Polarisation DDMs
  - Mitigation of vegetation and soil roughness
- Higher rate coherent complex channel
  - Separation of diffuse / coherent terms
  - Fine scale mapping over wetlands, rivers,
- Dual frequency L1/E1 and L5/E5



Platform

- SSTL-21, 40 kg, 5 year life target
- Up to 160 Mbps X-band downlink via Svalbard
- Payload Data Ground Segment built upon www.merrbys.org

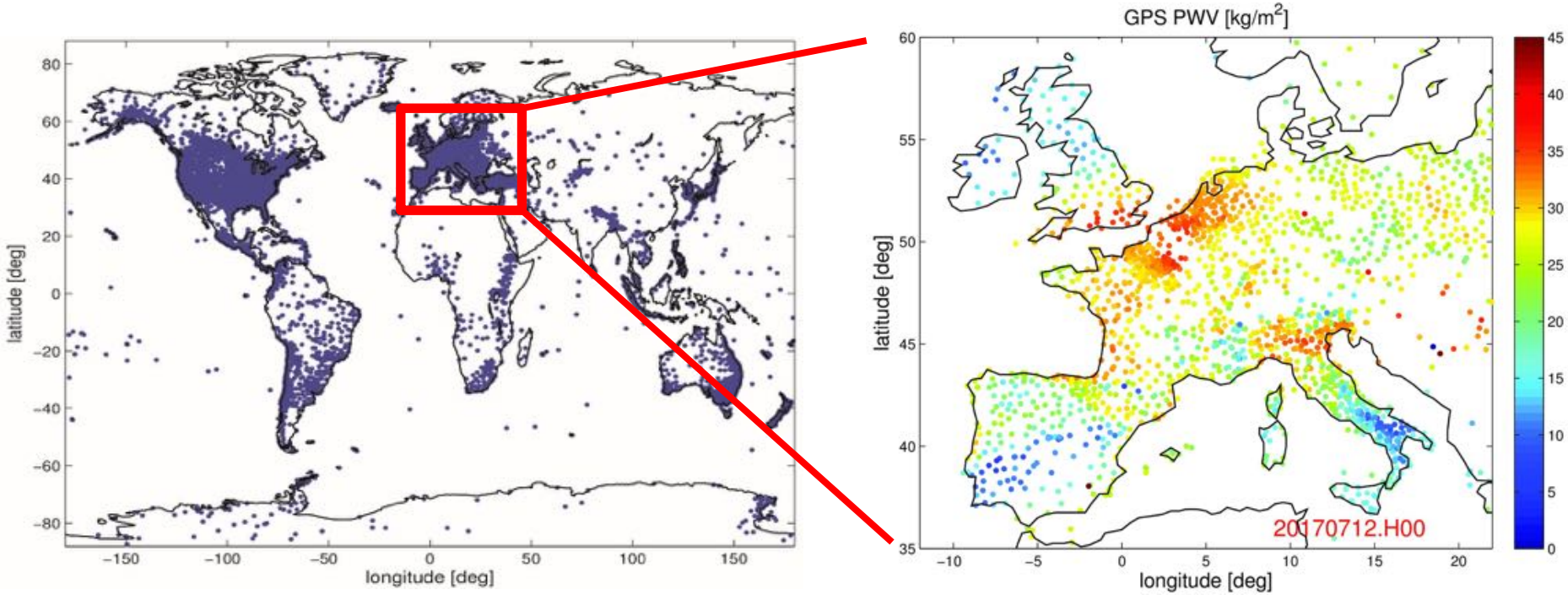
Constellation

- 1 or 2 satellites
- Global coverage every 15 days
- More frequent at high latitudes
- Suitable for upscaling to larger (12+) constellation to achieve daily coverage

Selected future Developments

More than 18,000 GNSS Stations Globally

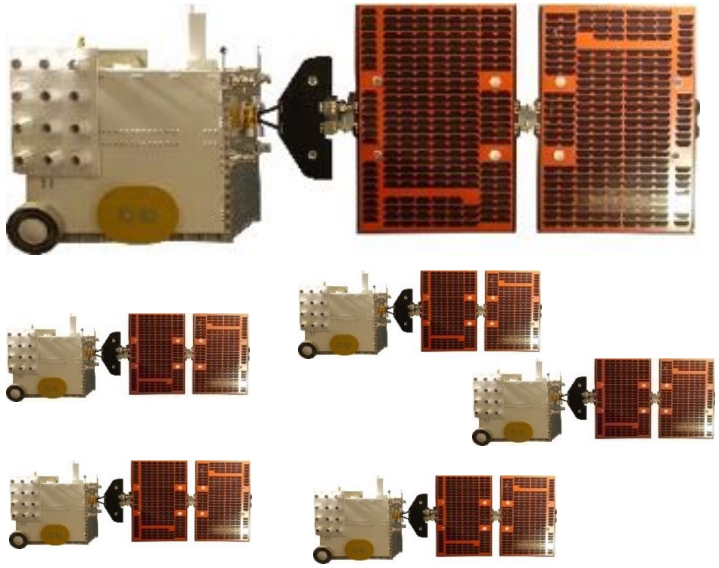
(as of 12.01.2021)



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

Thanks J. Blewitt, geodesy.unr.edu

COSMIC-2 Launch June 25, 2019 Falcon Heavy

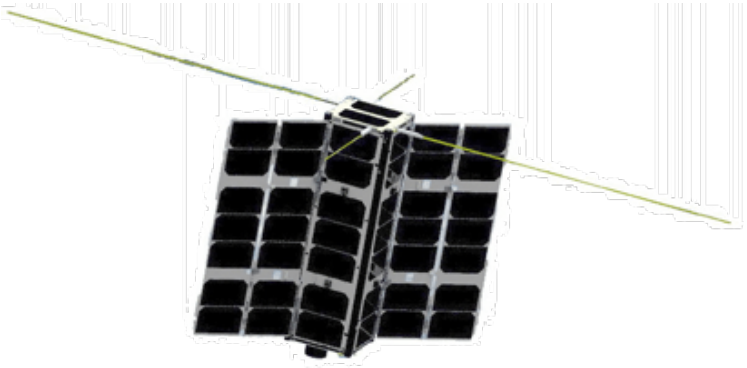


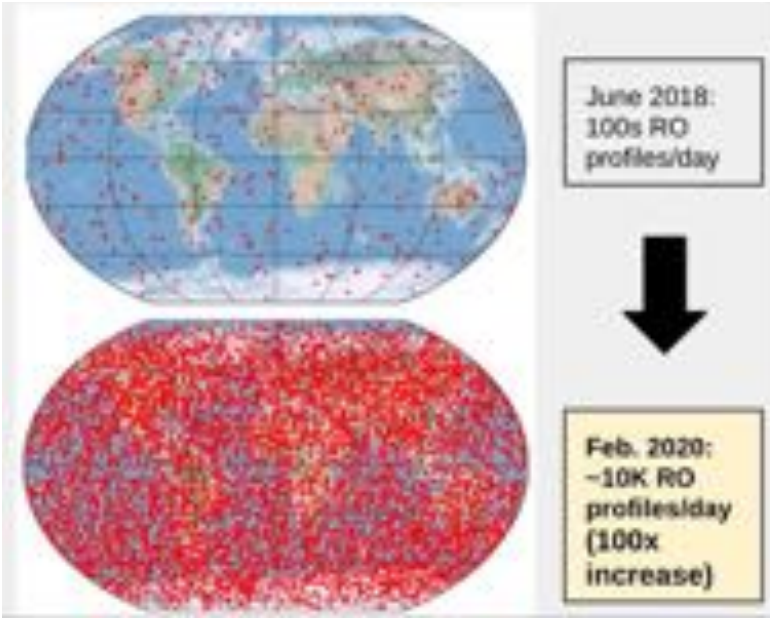
- Tracking GPS, GLONASS, and Galileo
- 6 satellites in low inclination orbit (24^{o} at 520 km)
- > 8,000 RO soundings per day

Thanks B. Schreiner (UCAR)

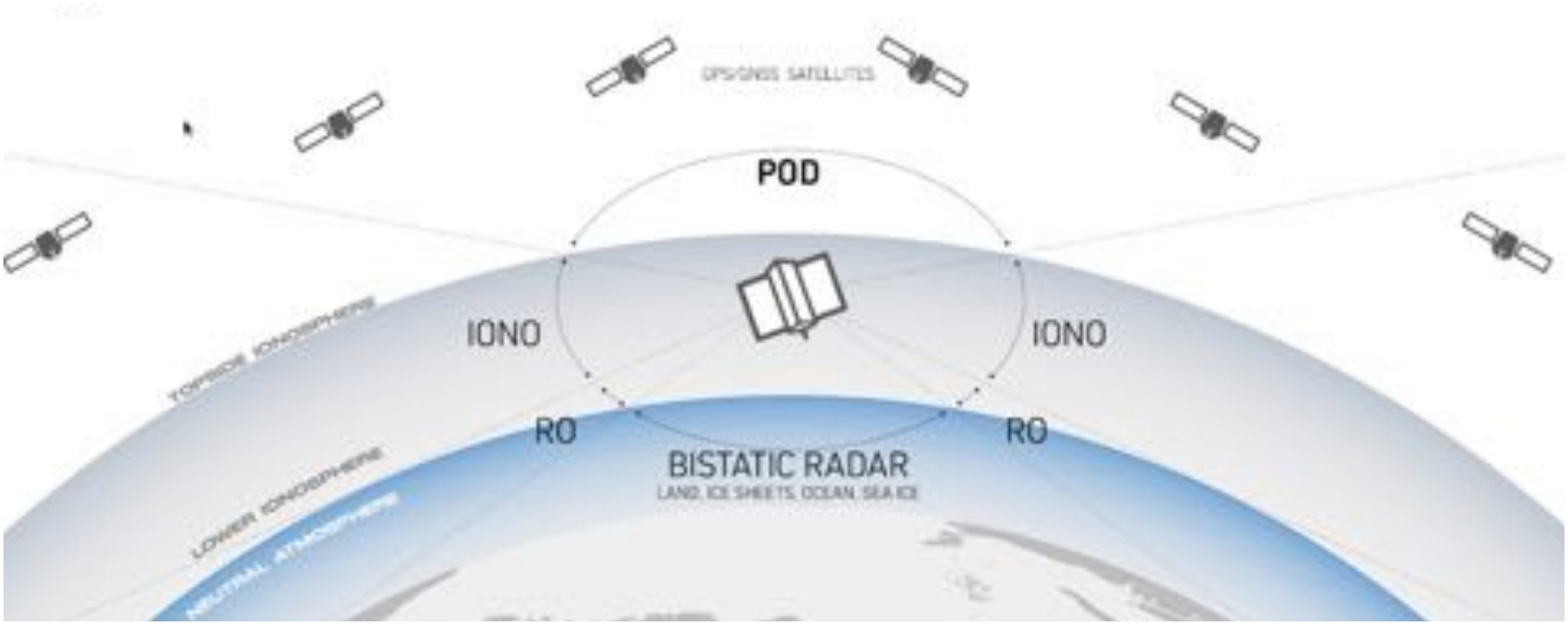
Commercial RO becomes reality

- Spire operates the third largest constellation of satellites (100+)
- Established company with 250 people (growing) across six offices
- Spire first commercial company collecting RO data, 20+ launch campaigns, 30+ ground stations
- Two talks (D. Masters, V. Nguyen)
- Two posters (V. Irisov, V. Nguyen)





Spire Earth Observation with GNSS

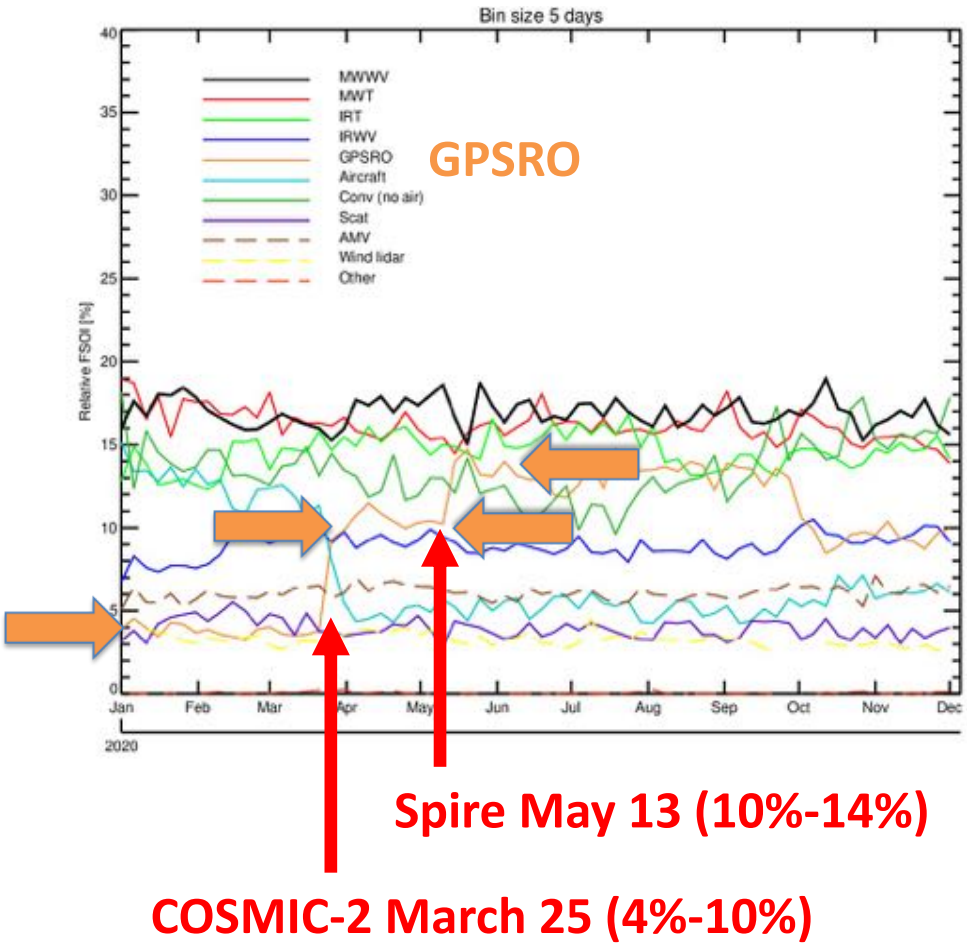


- Atmosphere sounding (NWP, Climate)
- Ionosphere sounding for Space Weather
- Thermosphere density, gravity through POD
- Scatterometry (soil moisture, ocean winds, sea ice)
- Grazing angle altimetry with RO satellites

Integrated measure of 24 hour forecast impact: time series in 2020

- Spire provided RO data to ECMWF, UK MetOffice, U.S. Air Force during Covid19 to compensate for lack of aircraft measurements

- ECMWF saw significant increase in relative forecast sensitvity to observation impact (FSOI) when COSMIC-2 was assimilated in 2020 and again when Spire RO were assimilated in May

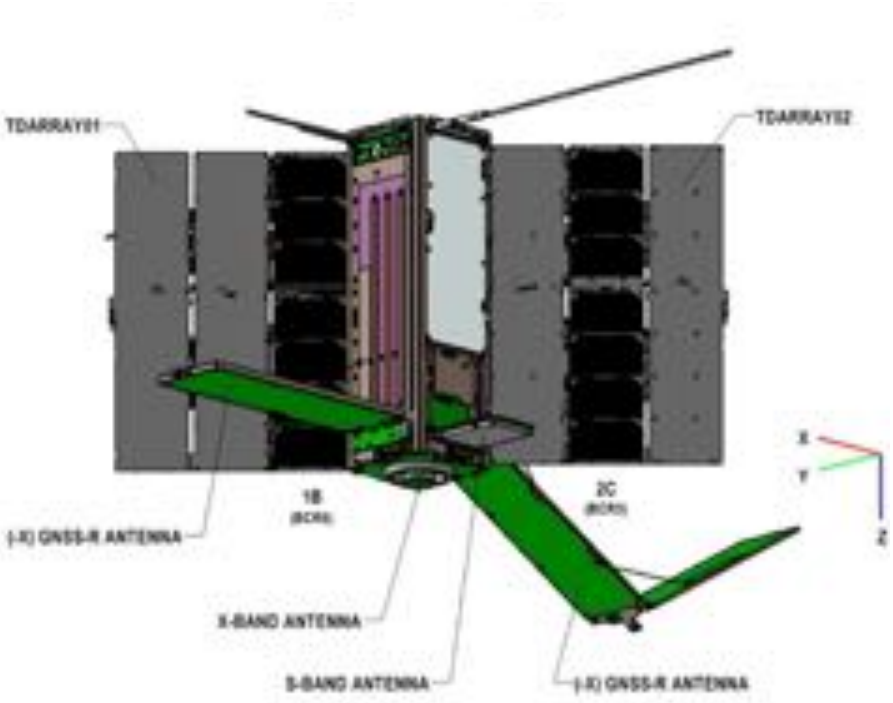


Spire Batch-2 GNSS-R mission 2021

SPIRE GNSS-R "Batch-2" Satellites

- To be launched two satellites in January 2021
- Sun synchronous (polar) orbit
- 3-panel, wide FOV antenna; direct sampling GNSS receiver

Parameter	Spire GNSS-R Batch-1	Spire GNSS-R Batch-2
Simultaneous reflections observed	16	48
GNSS Constellations tracked	GPS, QZSS, Galileo, SBAS	GPS, QZSS, Galileo, SBAS
Direct antenna	L1/L2 single patch	L1/L2 single patch
Reflection antenna	2, 3x1 L1 LHCP array (nadir), beamforming	3, 3x1 L1 LHCP array (nadir, 35 deg off-nadir, and beamforming
GNSS receiver	STRATOS v1	STRATOS v2 (direct sampling, onboard calibration, larger FPGA)
Mass	5 kg	5 kg
Orbit	37 deg, 571 km	SSO: 9:30 LTDN, 500 km

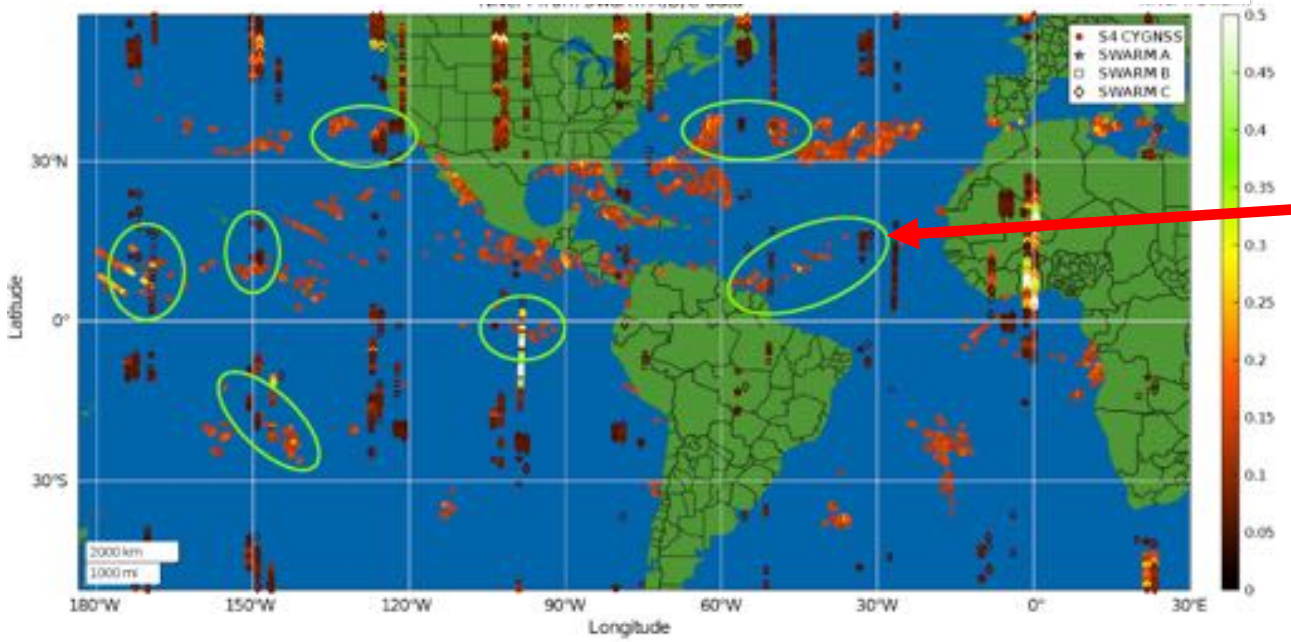


- Two satellites already launched in January 2021
- Going operational later this year

Ionosphere monitoring using GNSS-R

Initial idea already in 1996
(Katzberg/Garrison)

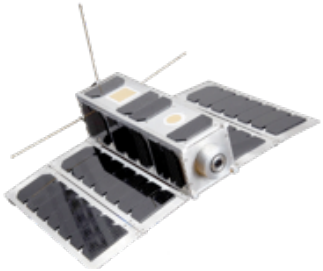
August 24, 2017, 00:00-24:00 UTC



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

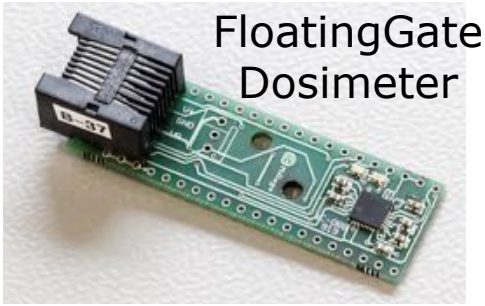


ESA Small Satellite PRETTY

- Cubesat 10/10/30cm³ (lead RUAG)
- GNSS Reflectometry
- Space Weather Payload
- Launch planned for 2022
- GNSS-R Science Team
  Uni Trondheim, DLR, GFZ, IEEC

Antenna Array:
8 segments, L1, RHCP, 16 db

RadFET Dosimeter

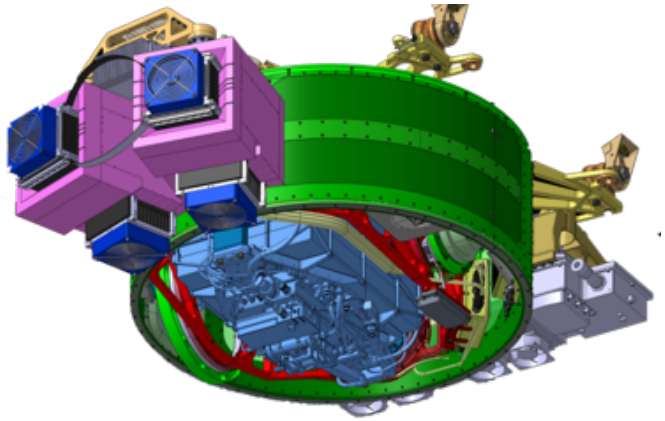


FloatingGate
Dosimeter

+ Particle Detection

ATMOSAT: New Mission with RO

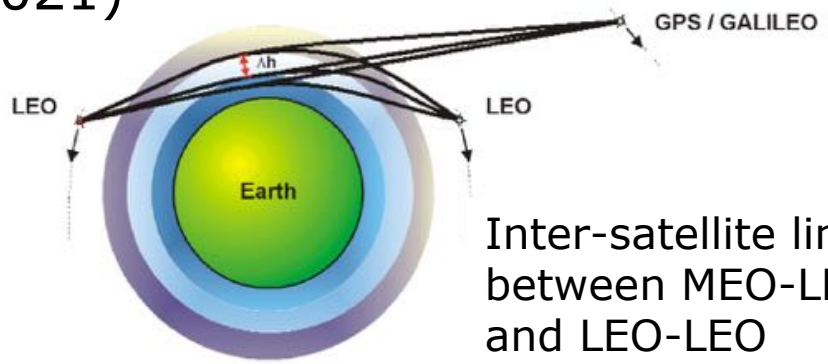
- Improvement of regional climate and mid term weather prediction
- KIT/FZJ leading, GFZ contributing
- Proposed 2016 within large research structure investments in Germany (>50 Mio€)
- Scientific evaluation with highest possible result (2017), not yet funded
- Key payload: GLORIA (3D atmosphere mapping); GFZ: TriG RO receiver (Atmosphere/Ionosphere, Reflectometry)
- Recent activities to prepare iterated proposal



TriG RO receiver

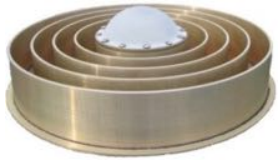
Galileo: Next Generations

- GNSS Science Advisory Board
  (J. Wickert member since 2021)
- Scientific exploitation of GNSS
  for Earth, navigational and physical sciences
- GNSS policy in Europe

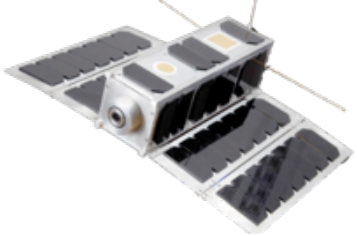


Inter-satellite links between MEO-LEO and LEO-LEO

- Future missions and new projects (calls, ITT), workshops
- Selected aspects under investigation: intersatellite links, inclusion of LEOs, ionosphere correction/sounding, additional payloads (accelerometers), Kepler concept (Günther et al.) with optical links



Conclusions and Outlook



- Overview on selected GNSS remote sensing activities with focus on satellite based activities was given
- Ground based atmosphere sounding is operationally applied for weather forecast and part of the Global Climate Observing system, operational TEC observations provided
- Selected recent GNSS RO activities from GFZ reviewed, e.g. GRACE-FO, ionospheric irregularities (sporadic E, EPB)
- GNSS reflectometry introduced as synertgetic complement to RO and novel and versatile Earth Observation technique with examples
- Selected new developments in GNSS Earth Observation/Remote Sensing and missions ideas briefly introduced (e.g. HydroGNSS, Spire small satellites)

Thank you !