2022

Potential Applications of GNSS Data – Reflectometry and Polarimetry

Presented to CGMS-52 Plenary session, CGMS-52-CGMS-WP-17

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Coordination Group for Meteorological Satellites

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Executive summary of the WP

This presentation provides an overview on GNSS-based remote sensing methodologies beyond ordinary Radio Occultation (GNSS-RO) soundings. These include:

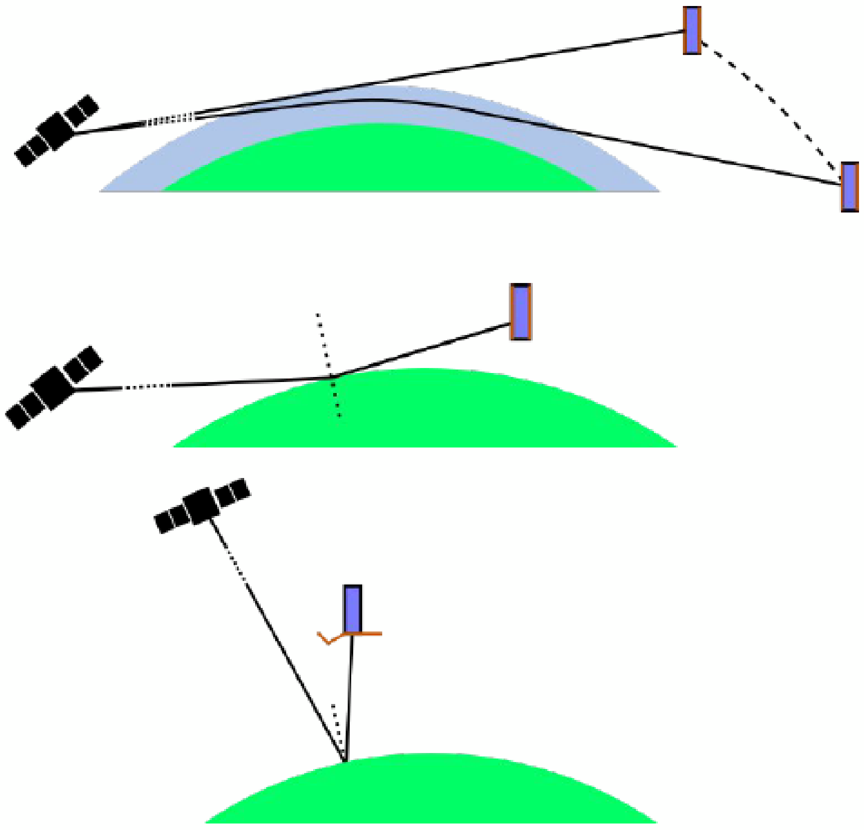
- Polarimetric RO (GNSS-PRO):
  - Heavy precipitation and ice particles in clouds

- GNSS Reflectometry (GNSS-R):
  - Grazing GNSS-R:
    - Sea ice extent, freeboard height and ice characteristics; altimetry over (very) calm surfaces
  - Near-Nadir GNSS-R:
    - Over ocean: surface winds, mean square slope, sea ice extend and characteristics
    - Over land: soil moisture, flooding and inundation, biomass

These methodologies currently experience considerable scientific evolution but are not yet as mature as ordinary RO. GNSS-R measurements, in particular, strongly depend on calibration, which is difficult for GNSS signals.

GNSS-based remote sensing techniques from Space

- **Ordinary Radio Occultations (GNSS-RO)**
  - Temperature, moisture in the neutral atmosphere, electron density in the ionosphere; carrier phase measurements
- **Polarimetric Radio Occultations (GNSS-PRO)**
  - Ordinary RO + information about large hydrometeors: carrier phase measurements
- **GNSS Reflectometry (GNSS-R)**
  - Grazing GNSS-R
    - Sea ice boundary, height and classification; altimetry; coherent reflection of GNSS signals (= carrier phase measurements)
  - Near-Nadir GNSS-R
    - Ocean surface winds, mean square slope,… over the oceans; soil moisture, biomass, wetland detection, flood inundation, snow heights over land; incoherent reflection of GNSS signals (= amplitude/power measurements; no carrier phase)



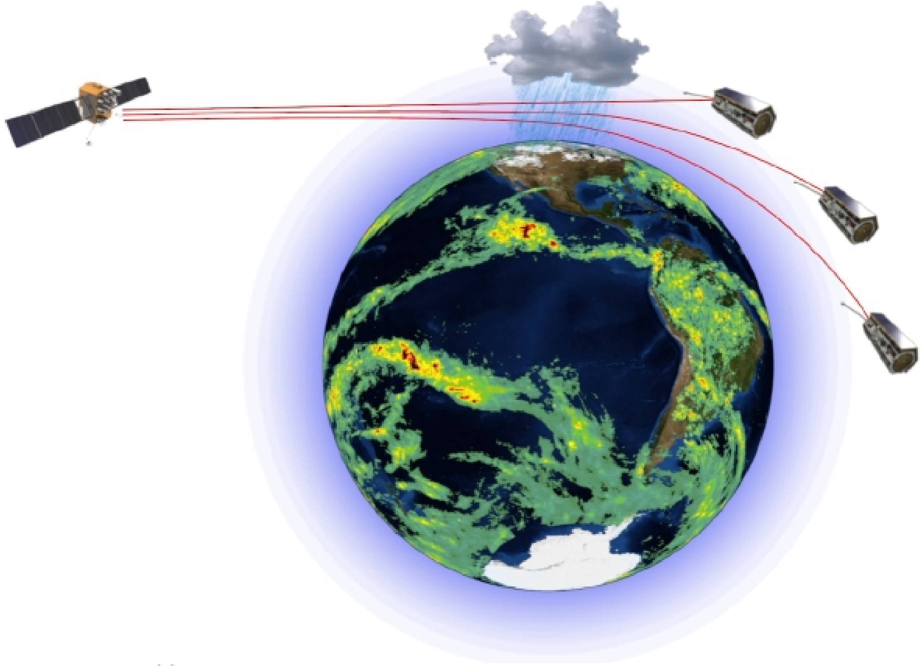
(Figure by P. Jales et al., ESA LPS 2022)

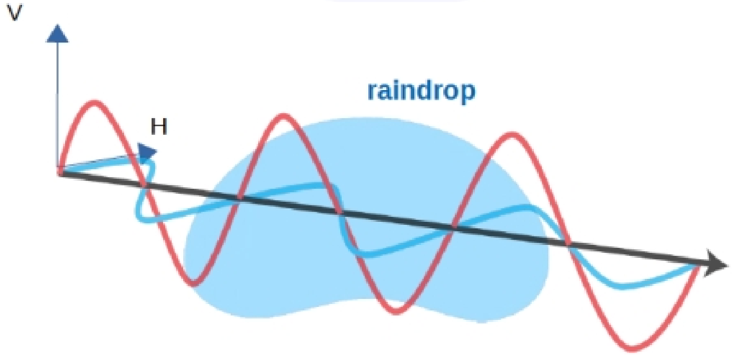
Polarimetric RO (GNSS-PRO)

- GNSS signals are Right-Handed Circular Polarised (RHCP)
- Ordinary RO: H- and V-component are combined by antenna
- Polarimetric RO: Receiver processes H- and V-component independently

- Large hydrometeors (heavy precipitation; ice crystals in clouds) are not spherical, but flattened
- H- and V components experience different delays while propagating through regions with large hydrometeors – differential phase delay is sensitive to large water droplets in heavy precipitation and horizontally oriented ice particles in clouds

- Pioneered by Spanish-US PAZ mission
- Spire currently operates 2 PRO-capable satellites (a third one ended its life in late April 2024); both have a remaining lifetime of 3-5 months.





(Figures by E. Cardellach et. al, IROWG 2022)

Polarimetric RO (GNSS-PRO, cont'd)

- Sensitivity of the measurements to both heavy precipitation (Cardellach et al., 2019) and large ice and snow particles (Padulles et al., 2022) has been demonstrated using PAZ data.

For use in NWP:

- EUMETSAT ROM SAF / ECMWF initiated the development of a forward operator;
- Forward modelling of differential phase delays depends on the availability of parameters from cloud microphysics schemes;
- Actual positive impact on forecasts still needs to be demonstrated.

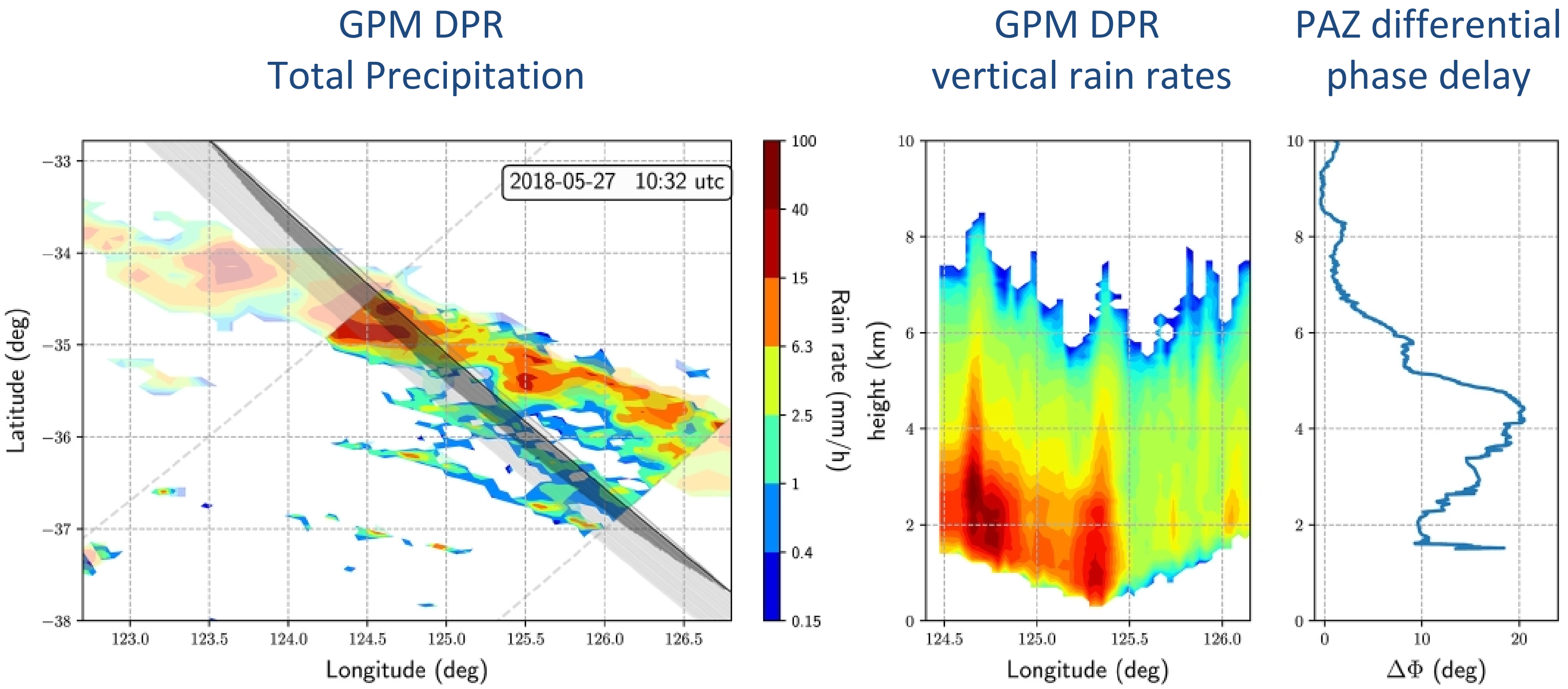


Figure from E. Cardellach et al. (2019), Sensing heavy precipitation with GNSS polarimetric radio occultations. Geophysical Research Letters, 46, 1024–1031. https://doi.org/10.1029/2018GL080412

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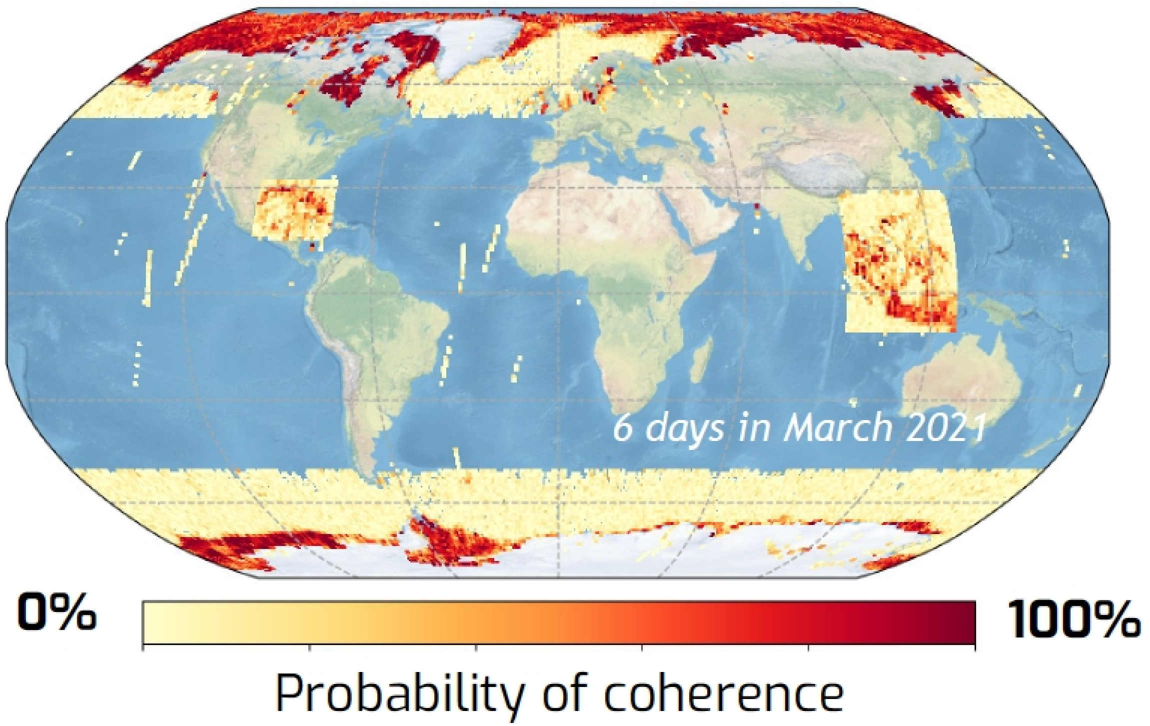
Grazing GNSS-R

- At low elevation angles (< 20-25°) and over calm surfaces, GNSS signals are coherently reflected; carrier phase information can still be tracked
- Altimetric measurements, sea ice border, freeboard height, ice classification
- Altimetry was demonstrated with raw CYGNSS data, but uncertainties are in the order of 7-10 cm – not competitive to conventional altimeters.

- However, sufficiently calm surface conditions are rare; in practice, measurements are limited to
  - high latitudes close to the sea ice boundary
  - two areas over the open ocean.

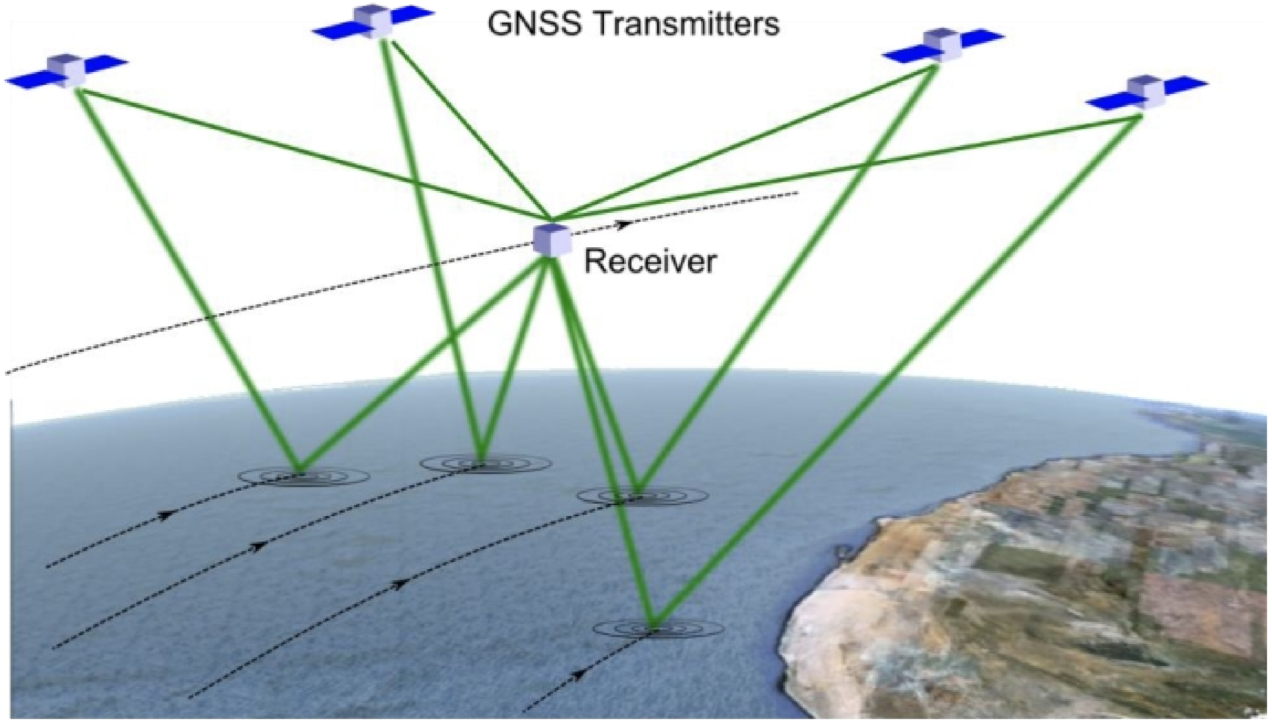
- Spire operates grazing GNSS-R from all its RO satellites.



(Figure by P. Jales et al., ESA LPS 2022)

Near-Nadir GNSS-R

- Exploiting GNSS signal reflected incoherently by the Earth's surface (both ocean and land)
  - Elevation angles > 20°
- Typical integration times ~ 1 second
  - ~ 6-7 km along the ground track
- Under best circumstances (coherent reflection), reflected signals primarily from 1st Fresnel zone
  - ~ 400 m across ground track;
  - Much larger (~ 25 km) when incoherent
- Missions:
  - TDS-1 (UK) – experimental, first GNSS-R measurements in large numbers (2014 – 2019)
  - CYGNSS (US) – 8 sats, low inclination; 2016 – …
  - Spire (US/EUR) – 4 satellites



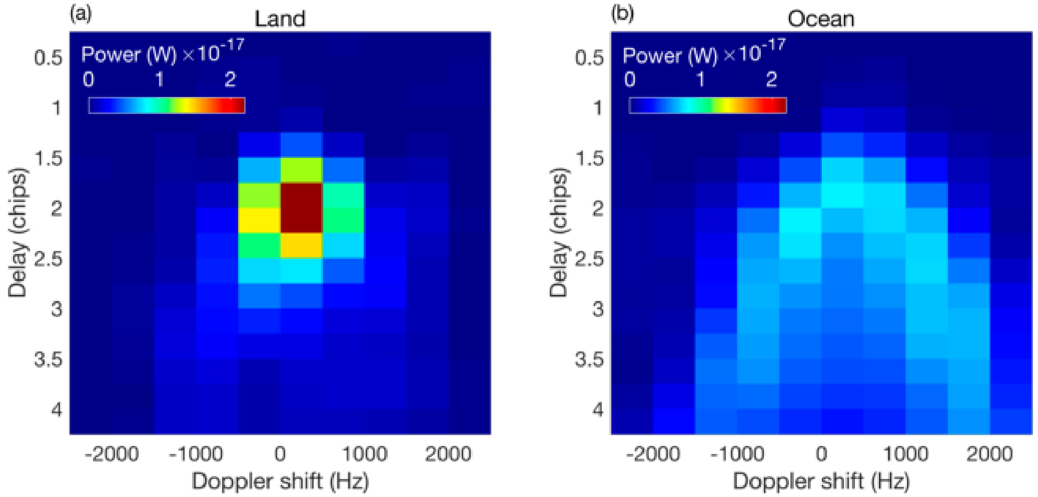
Near-Nadir GNSS-R – ocean surface winds

- GNSS receivers produce pseudorange measurements by correlating the observed signal with replicas of the transmitter code, recording delay and doppler shifts.
- GNSS-R receivers generate Delay-Doppler Maps (DDMs), typically averaged over ~ 1 second.

- Both the waveform shape and the peak of the correlation depend on surface characteristics such as (over the ocean) sea surface roughness (which depends on sea surface winds), but also significant wave height, incidence angle, antenna gains, transmitter power, …

- For ocean surface winds, DDMs are converted to Normalised Bistatic Radar Cross Section (NBRCS), or σ_0.

- σ_0 is converted to wind speeds using empirically derived Geophysical Mapping Functions (GMFs)



CYGNSS DDMs recorded over land (left) and ocean; Chew and Small, *Remote Sens.* **2020**, *12*(10), 1558; https://doi.org/10.3390/rs12101558

- Measurements of wind speed only, although there are attempts to derive wind direction as well.

- Scatterometers like ASCAT use multiple directions / beams to infer wind direction (with ambiguity).

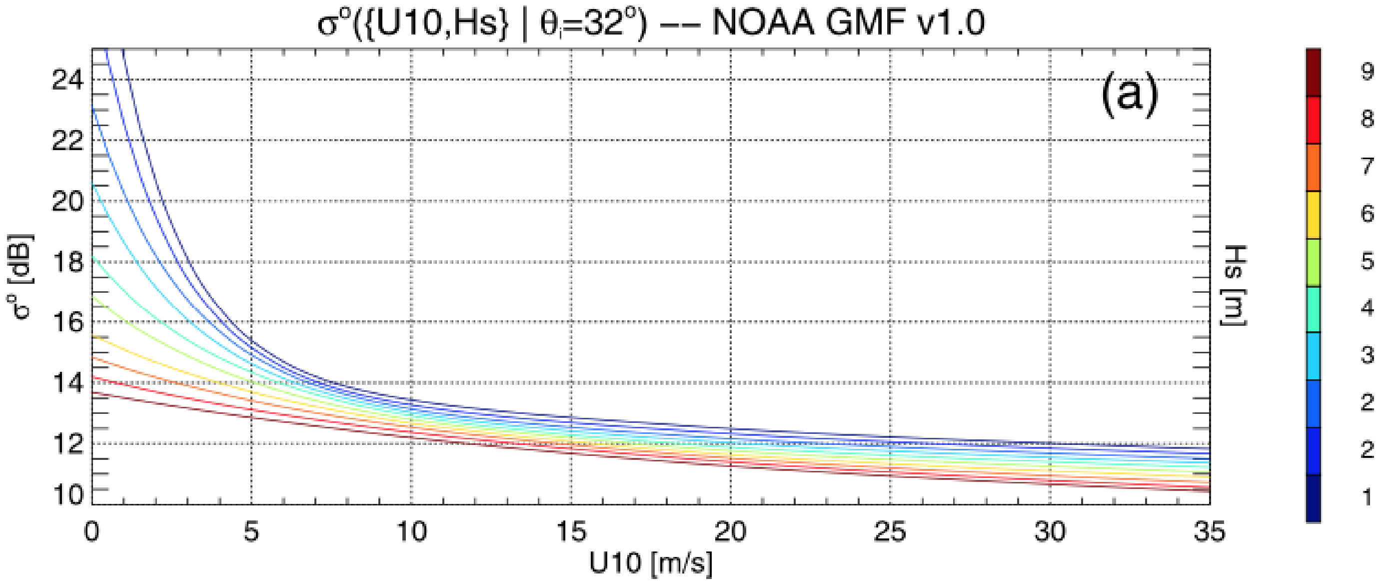
Near-Nadir GNSS-R – ocean surface winds (cont'd)

- σ_0 is highly sensitive below 5 m/s...
- ...but opposite is true above 15 m/s

- Calibration of power levels is key – but difficult:
  - GNSS transmit power is not as well characterised as for scatterometers
  - Different power levels for different GPS satellites ("blocks")
  - Flexpower – GPS power levels change abruptly over certain regions of the world
  - Track-wise bias correction?

- Additional GNSS constellations, beam forming, … make things even more complicated.

- This is an area of active research, for both instruments and the processing/calibration.



CYGNSS σ_0 GMF as function of 10 m winds (ECMWF) for different significant wave heights H_s (colour) and incidence angle of 32°; F. Said et al., *IEEE Trans. Geoscience and Remote Sensing*, **2022**, 60, 4202524, DOI: 10.1109/TGRS.2021.3087426.

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Near-Nadir GNSS-R – ocean surface winds (cont'd)

- Coverage of GNSS-R, compared with ASCAT

  (figure from Pu et al., *Remote Sens.*, **2022**, 14(9), 2118; https://doi.org/10.3390/rs14092118)

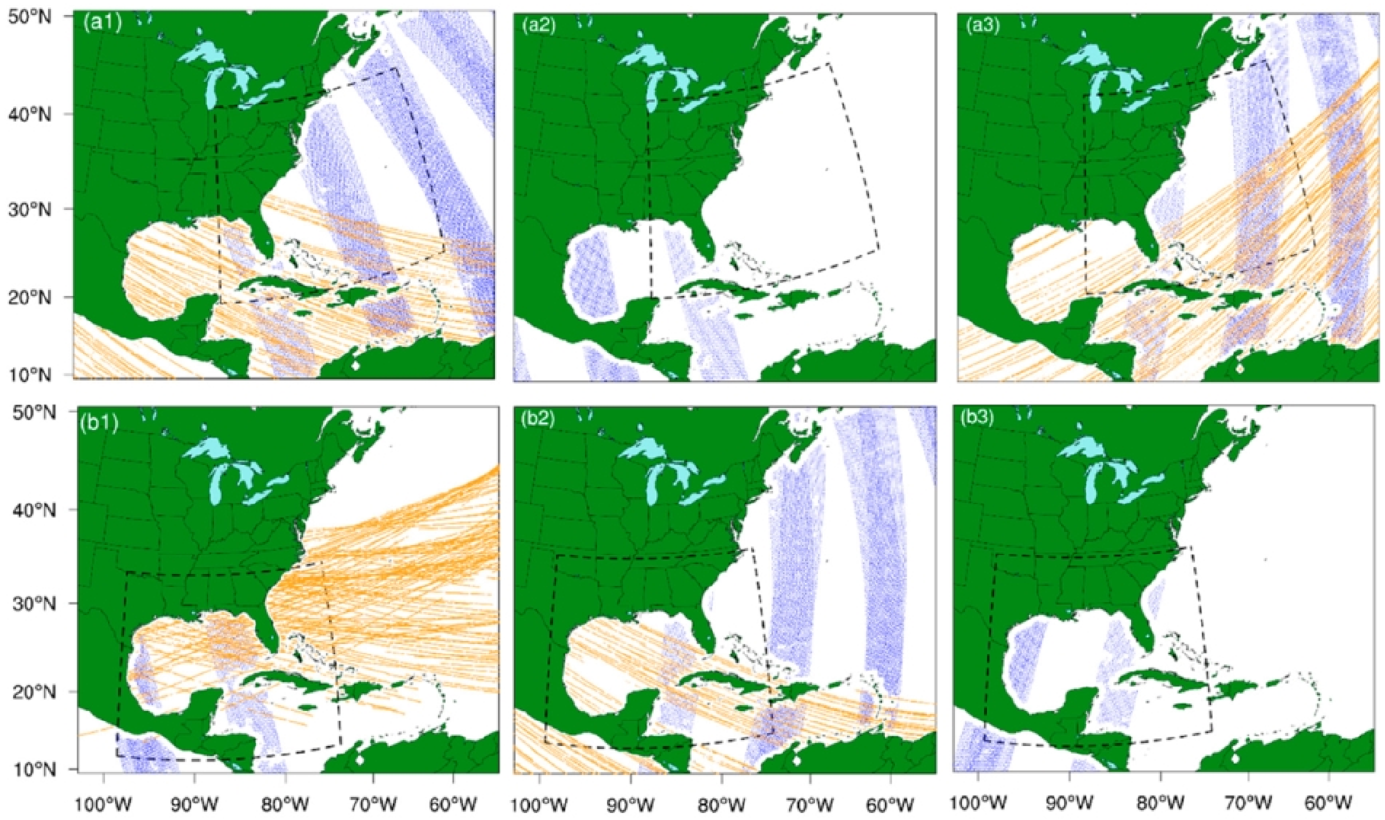


Figure 1. Available ASCAT and CYGNSS v2.1 data distribution for Florence and Michael at different assimilation times: (**a1–a3**) are, respectively, at 0000, 0600, and 1200 UTC on 13 September 2018; (**b1–b3**) are, respectively, at 0600, 1200, and 1800 UTC on 09 October 2018. Blue dots represent locations for ASCAT data and orange dots represent locations for CYGNSS data. The black dashed frames are the HWRF ghost domain for d02.

- Overall, GNSS-R ocean surface winds appear to be an interesting complement to scatterometer data, though there are still many open science questions.

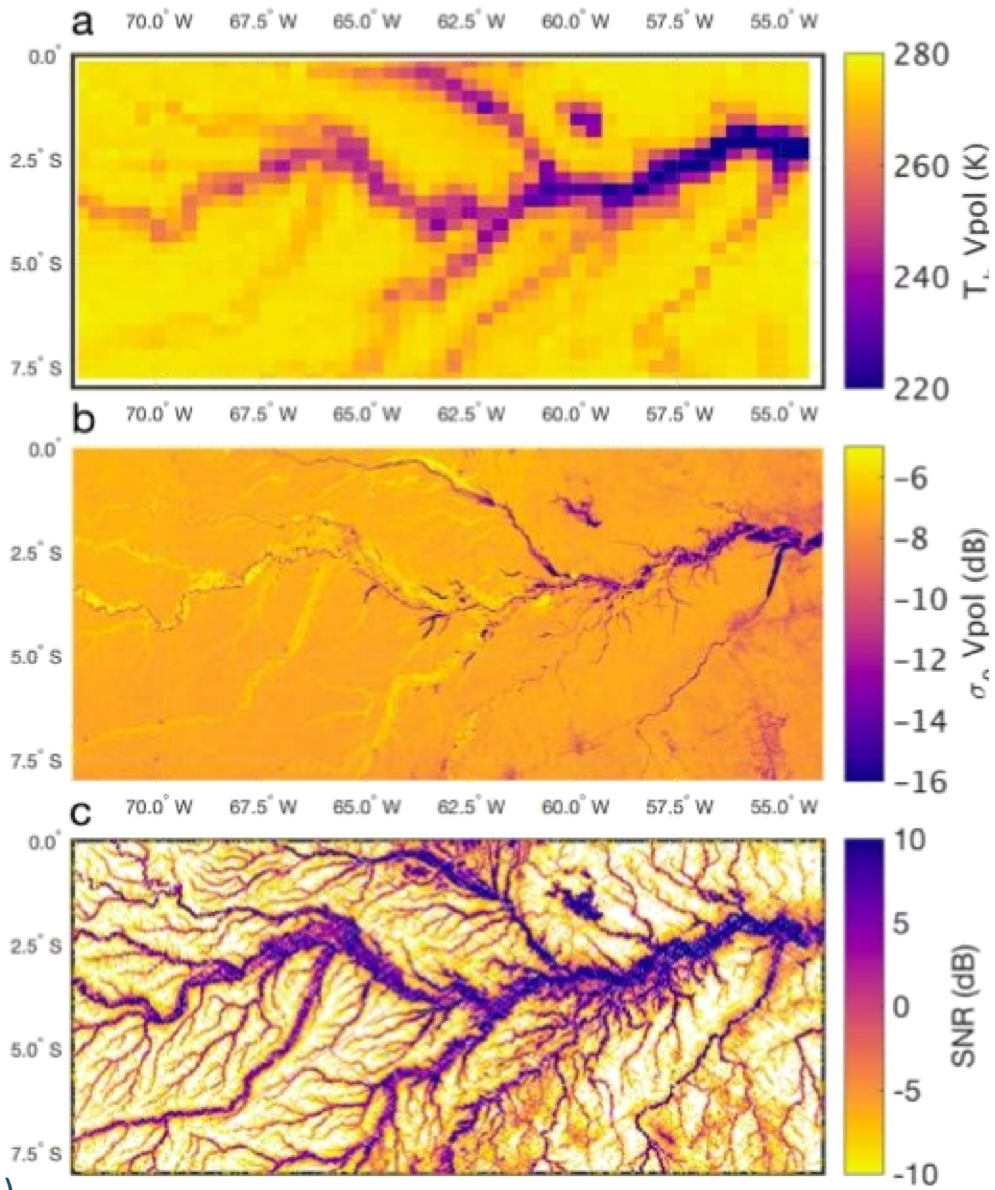
Near-Nadir GNSS-R – land

- Over land, GNSS reflections consist of both coherent reflections and incoherent scatterometry.
- Reflectivity over land is linked to the dielectric constant, which relates to soil moisture and freeze/thaw conditions.
- The higher resolution is attributed to the signal characteristics in the L-band, enabling better penetration below the canopy.
- Currently, GNSS-R data over land is also utilised to create flooding and inundation maps, as well as biomass estimates.
- Data in figures averaged over a several months (see Chew et al., 2018, https://doi.org/10.1109/IGARSS.2018.8517971)

SMAP
Passive MW
~30 km

SMAP
Active Radar
~5 km

CYGNSS GNSS-R
SNR
~500 m



(Figures by C. Chew et al.)

Summary

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Thank you!