The Muon Space Generalized GNSS-R Retrieval Pipeline and Satellite Constellation

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Opportunities to Collaborate with Muon Space

- Muon is forming an **academic partnership program** and is actively seeking collaborations with academic, government, and non-governmental organizations that wish to trial data or discuss opportunities for missions and hosted payloads
- Collaboration can take many forms, including:
  - Mission concepts (other signals of opportunity, e.g., P-band)
  - Payload development
  - Retrieval algorithms
  - Product validation against in situ and other satellite sensors/products
  - Joint proposals to funding agencies
- **Please contact dallas@muonspace.com with collaboration interests**

Motivation

Over the last few years, the plausibility of launching and operating commercial small satellite constellations specifically for Earth observation has been demonstrated. Due to increasing supply and decreasing costs in other commercial space sectors, such as access to space via rideshare and other small satellite launch opportunities, as well as cloud-connected services offered by multiple ground station providers, commercial small satellite companies can now offer viable alternatives to launching new scientific and operational missions through complete constellation services, hosted payloads, or direct data purchases. This paradigm shift attributed to “New Space” companies and their rapid development methodologies can play an increasingly important role in sustaining existing Earth observation records (e.g., climate records), while also enabling new technologies that will be needed to monitor climate change using satellite observations.

Muon Space: Mission Statement

- We believe there is a lack of knowledge of the Earth’s climate, and **satellite observations are required for detection, monitoring, and mitigation of the effects of climate change**
- Our traditional satellite observing systems have been limited to pathfinder class missions and large operational weather missions, with a slow process to bring new and increasing quantities of observations online
- Recently, commercial **small satellite constellations have been shown to be cost-effective alternatives for providing sustainable Earth observations**
- With rapidly decreasing launch costs, small sats are replacing CubeSats, allowing **larger platforms that can host more capable EO payloads** and more payloads on a single satellite
- Muon Space is launching a constellation of GNSS reflectometry (GNSS-R) small sats for sustained L-band bistatic radar observations, including soil moisture and ocean winds
  - GNSS-R is a passive remote sensing technique that utilizes reflected L-band signals from GNSS satellites to measure and analyze Earth surface properties.
- **GNSS-R is a cost-effective means to achieving sustained L-band observations**
- Planned constellation of 50+ satellites for **sustained L-band soil moisture monitoring**

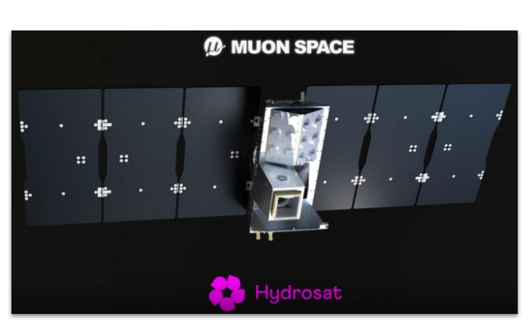
Muon GNSS-R Satellites

MuSat1 (Jun 2023)

- First Muon satellite serving as prototype to test core avionics
- Operating nominally

MuSat2 (Mar 2024)

- MuSat1 heritage with **polarimetric GNSS-R payload**
- First light data collected

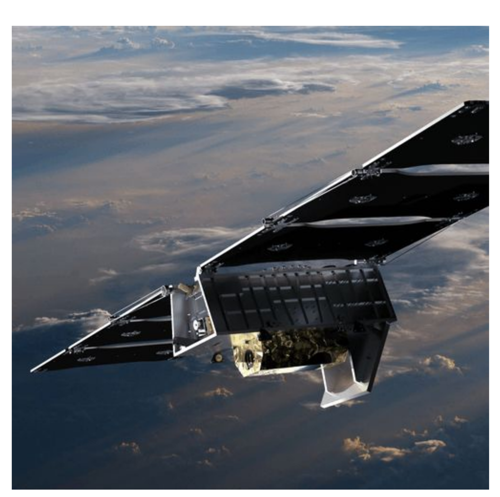


MuSat3 (2025)

- Hosting Hydrosat’s multispectral and TIR payloads
- Muon **polarimetric GNSS-R payload (same as MuSat2)**

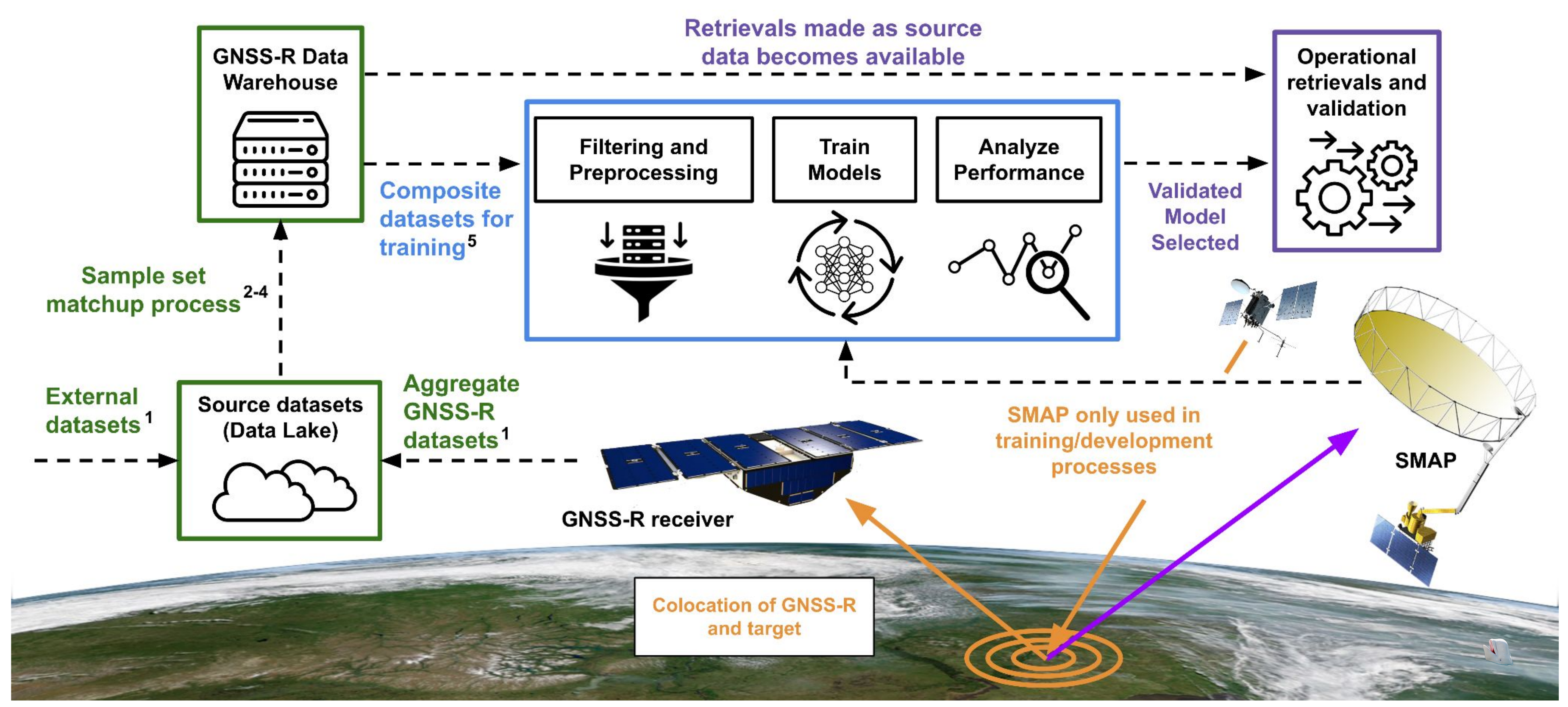
MuSat4 (2025)

- Addition of **high-gain GNSS-R payload to measure soil moisture under canopy** and TC winds



Three Muon GNSS-R sats operating by Feb. 2025

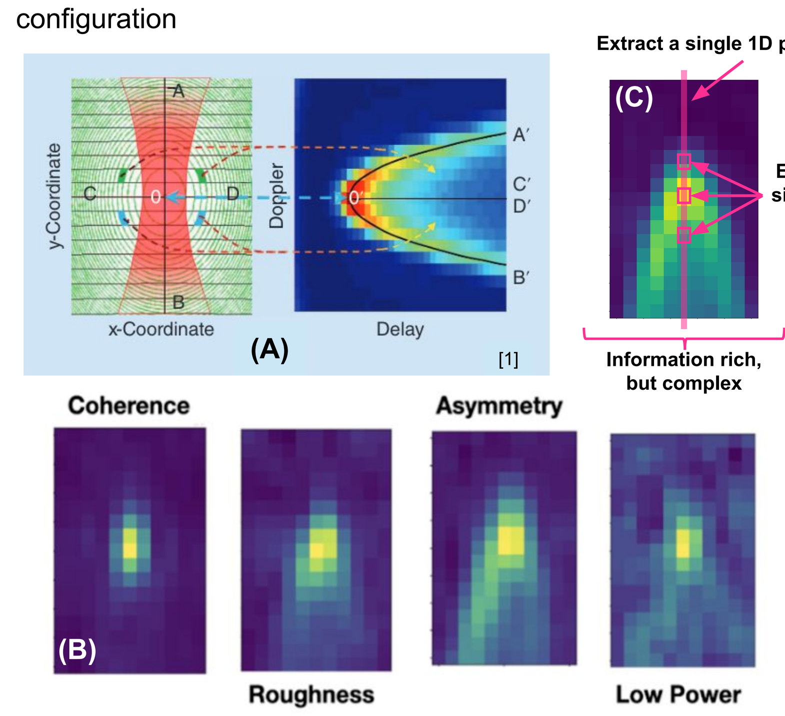
Generalized GNSS-R Retrieval Pipeline



A) The primary GNSS-R measurement is the delay-Doppler map (DDM) representing reflected power at a specific delay and Doppler shift from scattering points along the ground track. GNSS bistatic radar geometry is roughly illustrated in orange above.

B) Conditions influencing the reflected signal:

- Surface dielectric properties: soil moisture, surface water, vegetation
- Surface roughness/topography: DEMs, land cover, vegetation, swell
- Receiver/transmitter: geometry, antenna characteristics, Tx state, Rx configuration



C) Traditional methods for observable extraction often throw out the majority of *information* in a delay-Doppler map.

- 2D array contains analytically complex data
- Extracted metrics ignore majority of data
- Structure contains information on surface state
- Discarded data could be interpreted with sufficient contextual input

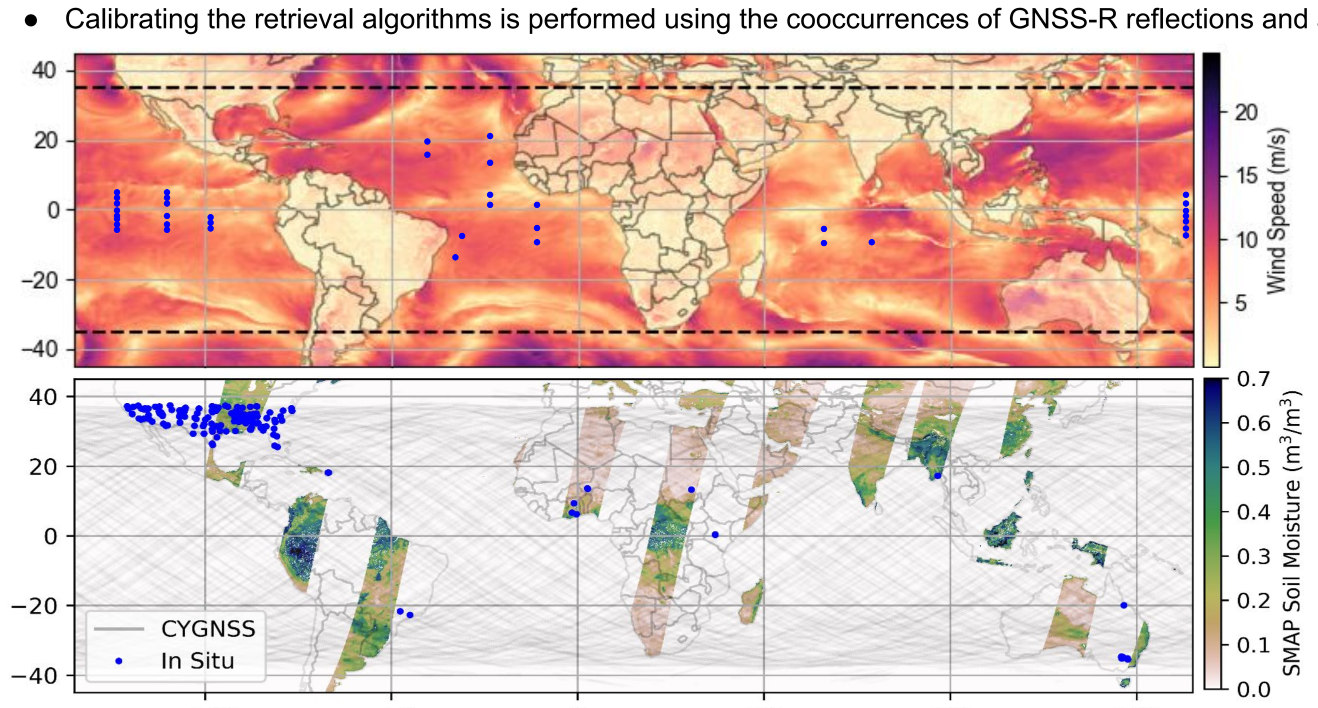
SOLUTION

- Build **data driven** models that ingest the **entire DDM** to find the important observables
- Include **ancillary information** to help disambiguate confounding variables

While the utility for DL-based models is higher over the complex, heterogeneous surfaces present with soil moisture retrievals, using this same architecture for a variety of retrieval types, such as ocean wind speed, has benefits including allowing for higher-dimensional relations than are possible with traditional techniques. Additionally, having a single, unified architecture for the interpretation of GNSS-R measurements allows for the production of multiple products with a degree of parallelization, where research and development into one retrieval type often benefits other retrievals.

Target Datasets

- The SMAP L3 Enhanced Radiometer-based soil moisture (bottom, color map) serves as the target variable used to calibrate the Muon GNSS-R **soil moisture** algorithm. Similarly, ECMWF Reanalysis v5 (ERA5) wind speed (top) is used to calibrate of the Muon GNSS-R **ocean wind** retrieval algorithm.
- Observations from CYGNSS GNSS-R receivers are spatially distributed pseudo-randomly in the form of “tracks” (bottom, grey curves).
- Calibrating the retrieval algorithms is performed using the cooccurrences of GNSS-R reflections and a given target. While we do study the performance of the GNSS-R retrieval compared against the target for periods of time outside the calibration period, comparing retrievals against relevant in situ data provides a separate estimate of performance. For soil moisture, retrievals are compared against sparse in situ sites from the International Soil Moisture Network (ISMN) (bottom, blue) as well as SMAP core validation sites which averages multiple probes. The Global Tropical Moored Buoy Array, specifically TAO/TRITON,PIRATA, and RAMA (blue, top) arrays, provide in situ measurements for evaluating ocean wind speeds.



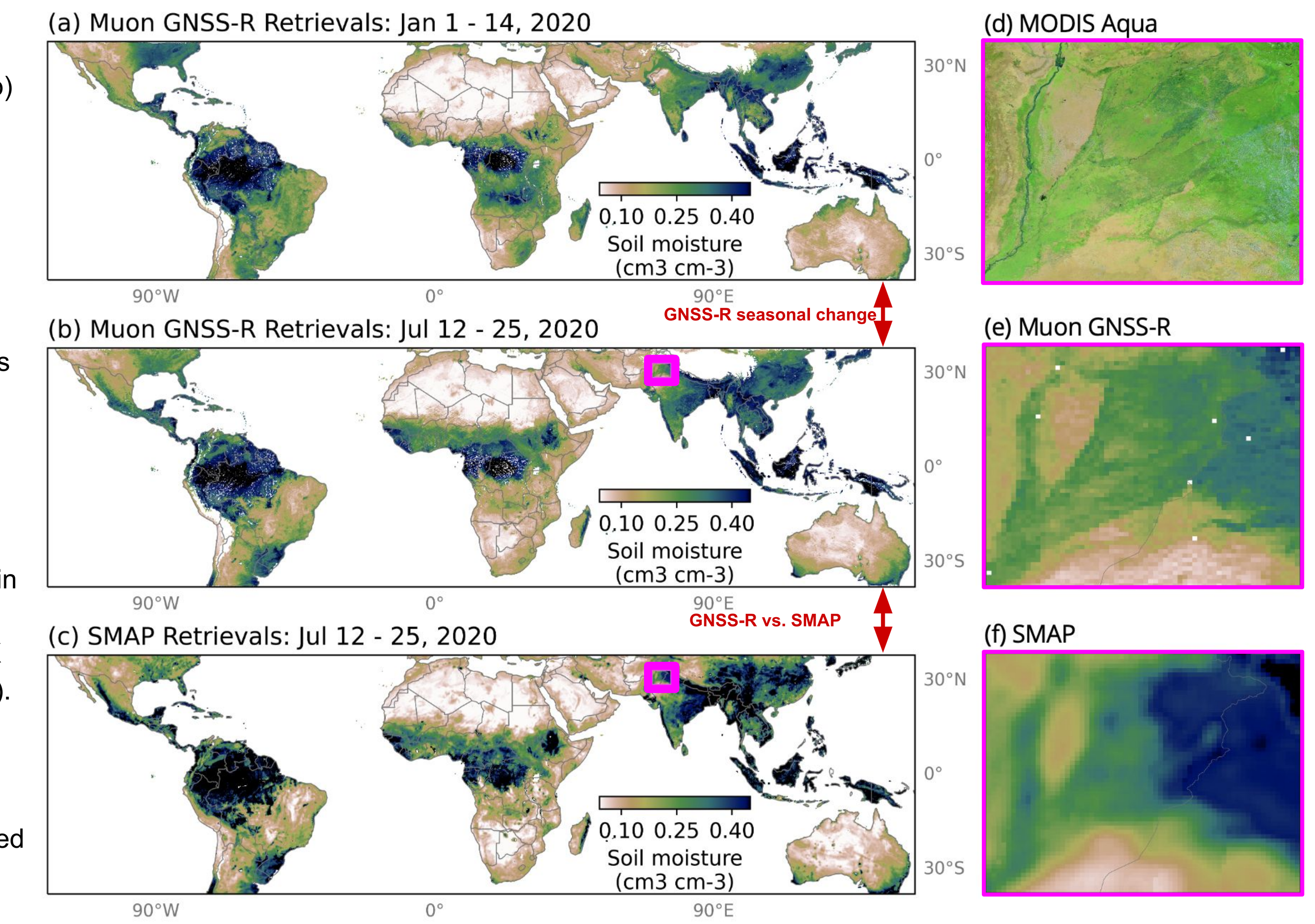
Soil Moisture

Averaged Muon L3 retrievals (a, b) are compared against (c) mean retrievals from the SMAP L3 Enhanced 9-km product.

(a) and (b) highlight temporal differences in soil moisture. The eastern US, southern AF, and northern AU show drying, whereas the Sahel and many parts of IN show wetter conditions in July.

Spatial patterns agree between SMAP and Muon retrievals.

Small-scale differences are seen in (d-f) - MODIS (d) over the Punjab region on the border of IN and PK along with Muon (e) and SMAP (f). (e) has sharper delineations between desert and agricultural regions than (f). Although the SMAP Enhanced product is gridded to 9 km, its inherent spatial resolution is >30 km.

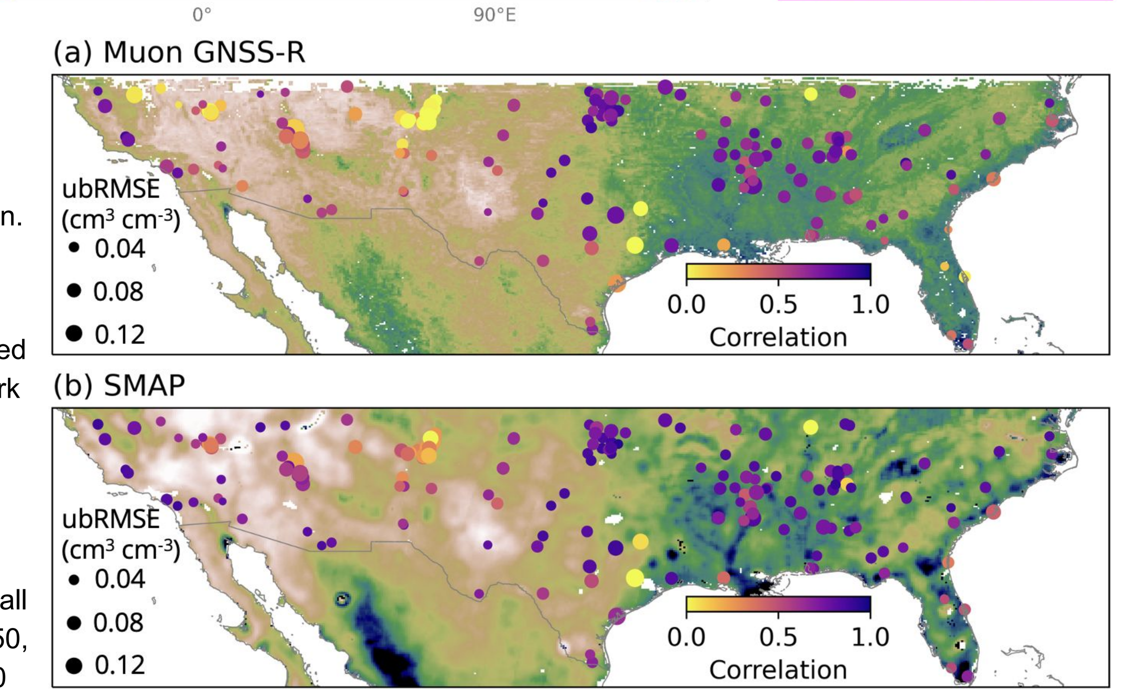


In Situ Validation

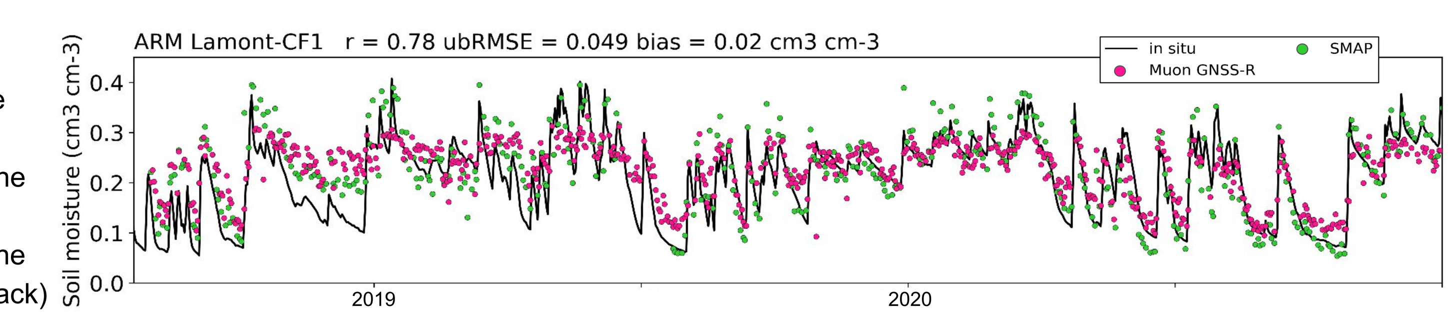
Muon and SMAP daily averaged retrievals are calculated for all observations that fall within a 36 km diameter footprint centered on each in situ site location. In situ soil moisture observations are averaged at the same time interval for comparison.

The underlying map shows the Muon retrievals, gridded to 9 km, for the month of July 2020 and sparse network validation statistics (colored dots). (b) Same as (a), except for the SMAP Level 3 Enhanced Product, also gridded to 9 km.

Broadly, spatial patterns of both correlation and ubRMSE are similar across Muon and SMAP. Across all in situ sites, Muon’s mean correlation coefficient is 0.50, while SMAP’s is 0.64; Muon’s mean ubRMSE is 0.060 and SMAP’s is 0.059.



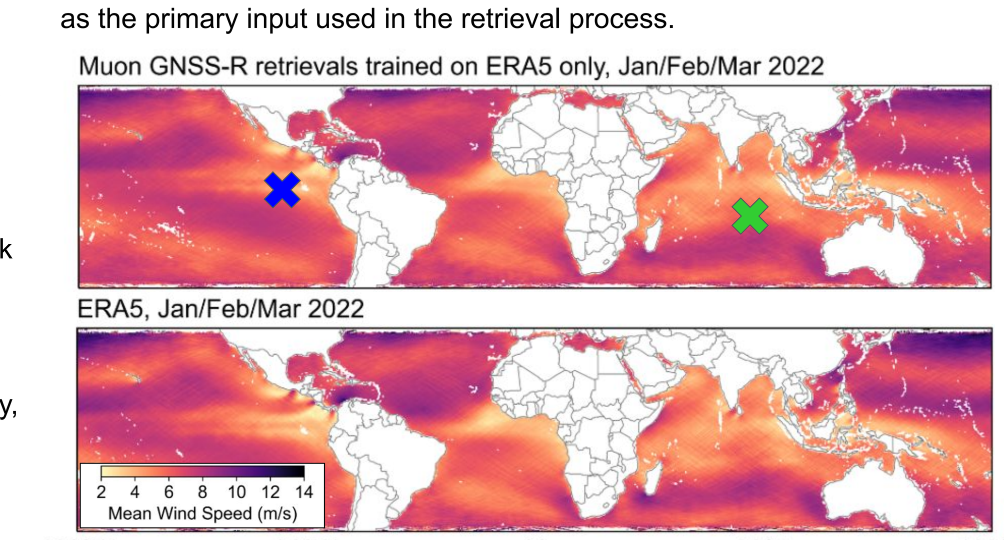
The time series to the right highlights a case where the Muon (pink) and SMAP (green) retrievals capture the temporal dynamics of soil moisture similar to that of the in situ soil moisture site (black)



Ocean Winds

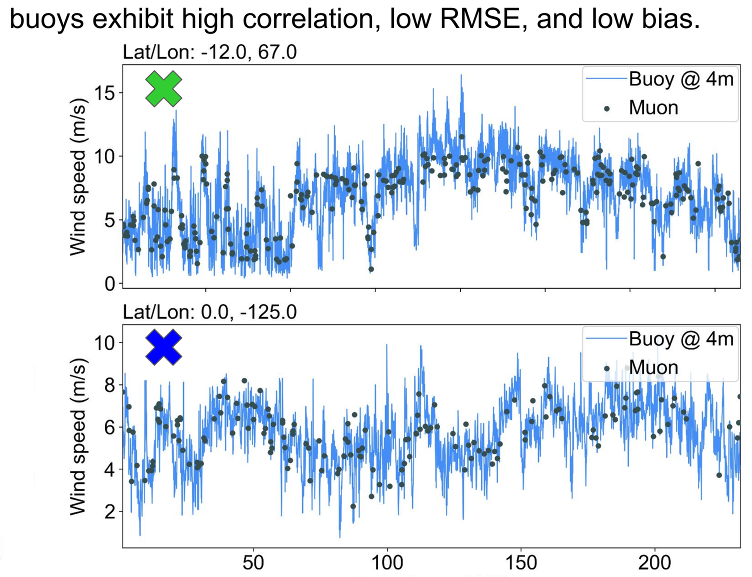
Level 2 ocean surface wind speed was the initial focus of GNSS-R observations since L-band GNSS signals penetrate through precipitation, unlike higher-frequency scatterometers that are attenuated by heavy rain. CYGNSS was designed as a pathfinder to investigate the utility of GNSS-R observations to retrieve winds in tropical cyclone conditions.

The Muon CYGNSS-based GNSS-R ocean surface wind speed retrieval was developed with much of the same approach as the soil moisture retrieval. Input ancillary data and the target change, but the DDM persists as the primary input used in the retrieval process.



Below are averaged wind speeds for the first three months of 2022 for Muon (top) and ERA5 (bottom). Broad spatial similarities between average wind speeds are present between the two products.

Hourly wind speeds for buoys are calculated as well as hourly GNSS-R wind speed within a 25 km radius of each buoy. The average correlation and RMSE for Muon against the matchups with buoys is 0.82 and 1.17 m/s, respectively. The majority of buoys exhibit high correlation, low RMSE, and low bias.



[1] V. U. Zavorotny, S. Gleason, E. Cardellach and A. Camps, "Tutorial on Remote Sensing Using GNSS Bistatic Radar of Opportunity," in *IEEE Geoscience and Remote Sensing Magazine*, vol. 2, no. 4, pp. 8-45, Dec. 2014, doi: 10.1109/MGRS.2014.2374220. keywords: {Tutorials;Remote sensing;Bistatic radar},