New Polarimetric GNSS-R Observations of the Water Cycle from the Muon Space MuSat2 SmallSat Mission

Dallas Masters, Stephen Lowe, Linus Tan, Max Roberts, Clara Chew, Ian Colwell, Karl Nordstrom
Dan McCleese, Chris Ruf

Muon Space, Inc., Mountain View, CA, USA

dallas@muonspace.com

©2025 Muon Space, Inc.

Motivation: Sustained L-Band GNSS-R Products

- Recently, commercial **small satellite constellations have been shown to be cost-effective alternatives for providing sustainable Earth observations**
- GNSS reflectometry (GNSS-R) is a passive remote sensing technique (i.e., bistatic radar) that utilizes **reflected L-band signals** from GNSS satellites to measure **soil moisture** & **ocean wind speed**
- GNSS-R soil moisture observations agree well with **SMAP** and in situ sites and show **increased spatial detail compared to SMAP**
- GNSS-R ocean wind speeds agree well with other satellite sensors and in situ buoy measurements, **including in tropical cyclones**
- A **constellation of GNSS-R low Earth orbit satellites** is required to fully sample the Earth surface
- Muon Space is launching a constellation of small satellites and planning to carry GNSS-R payloads to supply **operational** and **sustained** L-band soil moisture and ocean wind speeds
- Muon developed a machine learning algorithm and now retrieves soil moisture and ocean wind speeds from both the **NASA CYGNSS mission** (2018-present) and **Muon's MuSat2** (March 2024-present)
- Muon is launching **two additional GNSS-R satellites in 2025**

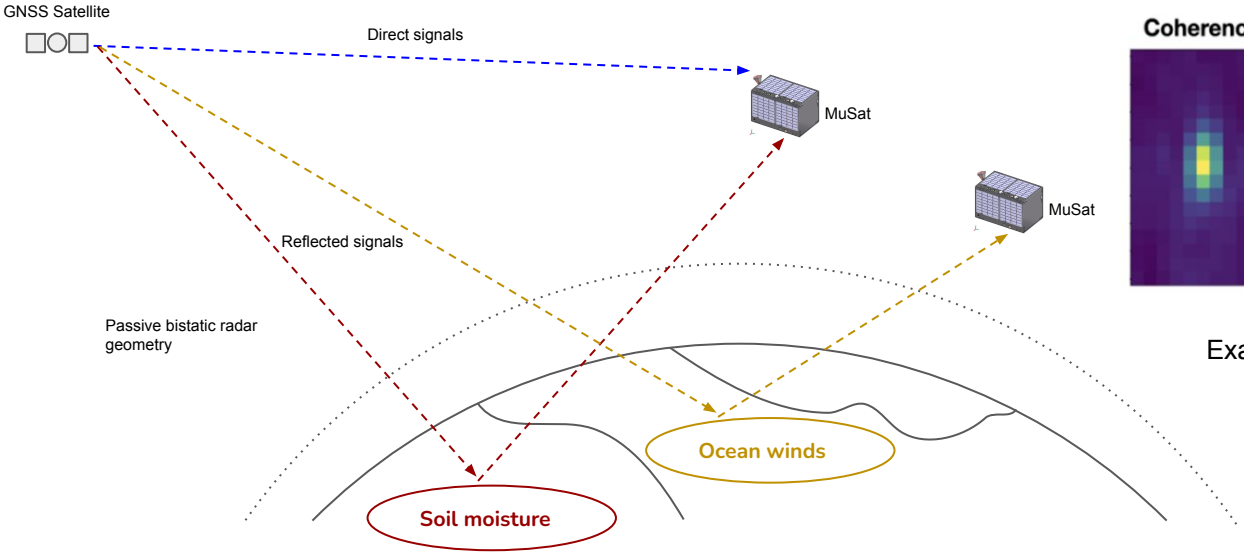


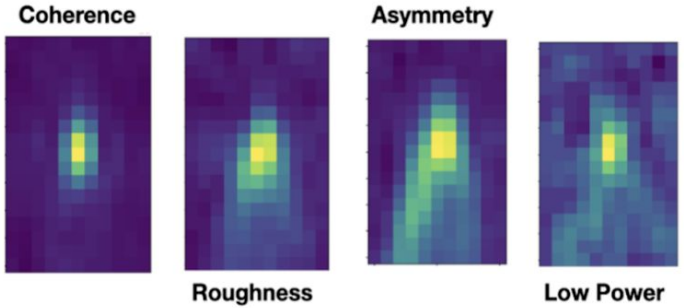
Muon Space **designs, builds,** and **operates** satellite constellations delivering Earth Intelligence

©2025 Muon Space, Inc.

GNSS-R Satellite Measurements

- Primary GNSS-R observable is the **delay-Doppler map (DDM) representing power scattered from a region of the surface** surrounding the specular reflection point at specific delays and Doppler shifts
- Conditions influencing the reflected signal:
  - Surface dielectric properties: **reflectivity (i.e., soil moisture)**, surface water, vegetation
  - Surface roughness/topography: **small-scale roughness (i.e., ocean wind speed)**, topography, land cover
  - Receiver/transmitter: geometry, antenna characteristics, Tx state, Rx configuration





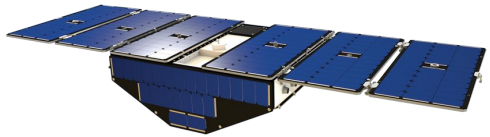
Example DDMs from varying surface properties

©2025 Muon Space, Inc.

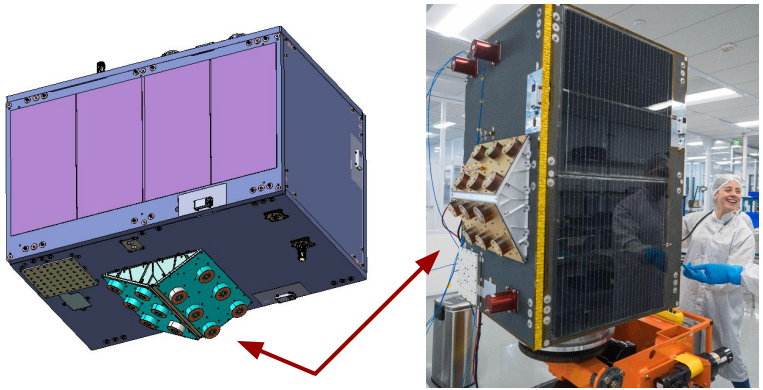
MuSat2 & CYGNSS GNSS-R Missions

- Muon is building GNSS-R products from **two sources**: the NASA **CYGNSS** constellation and the Muon Space constellation (**MuSat2** at present)
- **NASA CYGNSS (2017-present):**
  - Pathfinder GNSS-R mission: 8 small sats carrying GPS-only GNSS-R payload sampling **+/- 37 deg latitude band**
  - Operational data since 2018-present
- **Muon Space MuSat2 (2024/03-present):**
  - Commercial small sat in **polar orbit**
  - **Dual-freq, dual-polarization GNSS-R antennas:**
    - L1/L5, RHCP and LHCP
    - ~14 dBi peak gain (similar to CYGNSS)
    - Designed by OSU under **NASA ESTO IIP**
  - **Muon flexible software-defined radio (SDR) receiver:**
    - Based on state-of-the-art RFSoC technology
    - Multiple, wide-band antenna channels and 32 simultaneous reflections
    - **Relative channel calibration via noise injection**
  - Compared to CYGNSS, **MuSat2 adds dual-pol, dual-freq** (L1/L5) GNSS-R **(akin to ESA's future HydroGNSS mission),** multi-constellation signals (GPS, Galileo, Beidou, QZSS), wider bandwidths, and **tracking all signals in view**

CYGNSS satellite (8 in constellation)



MuSat2 satellite



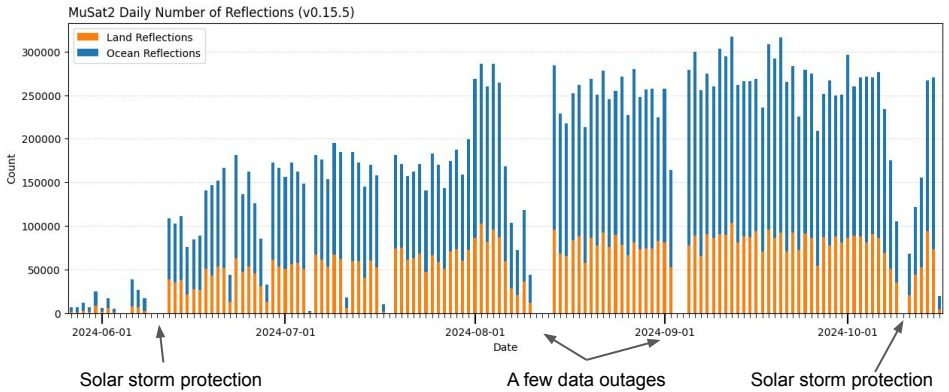
MuSat2 port and starboard nadir **dual-pol R/LHCP, L1/L5** GNSS-R antennas pointing across track and 28 deg off nadir (reflected signal)

©2025 Muon Space, Inc.

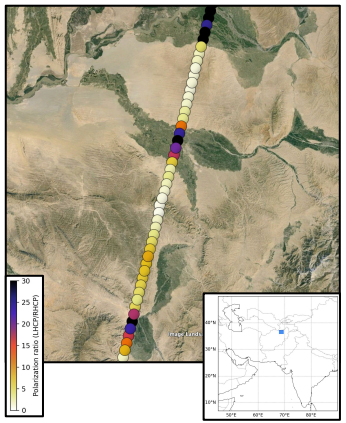
MuSat2 Operational Status

- **All systems healthy**
- Nominal tracking up to 7 simultaneous GPS L1 CA reflections: May 27 - present
- **Currently operating nominally** with duty cycle around 70%
- Collecting **dual-pol (LHCP+RHCP) reflections** all the time
- Galileo E1 and QZSS reflections (~2X data) to be implemented soon to improve spatial sampling density
- SBAS reflections in development

MuSat2 Collection Record



First MuSat2 Dual-Pol Observations



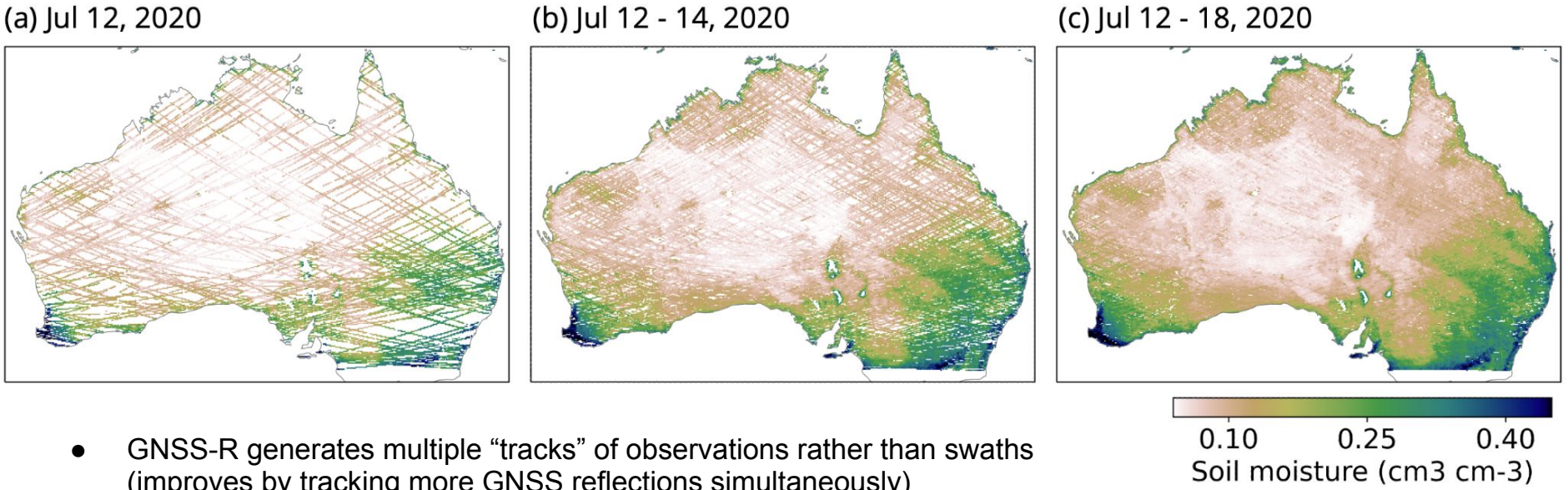
- MuSat2 is collecting **simultaneous LHCP and RHCP surface reflections**
- An example track of the polarization ratio is shown on the right, which crosses over agricultural areas interspersed amongst arid regions in northeastern Afghanistan
- Muon is investigating ability of polarization ratio to help **correct for roughness effects or better understand and correct attenuation caused by vegetation**

©2025 Muon Space, Inc.

Muon's CYGNSS Soil Moisture Product

©2025 Muon Space, Inc.

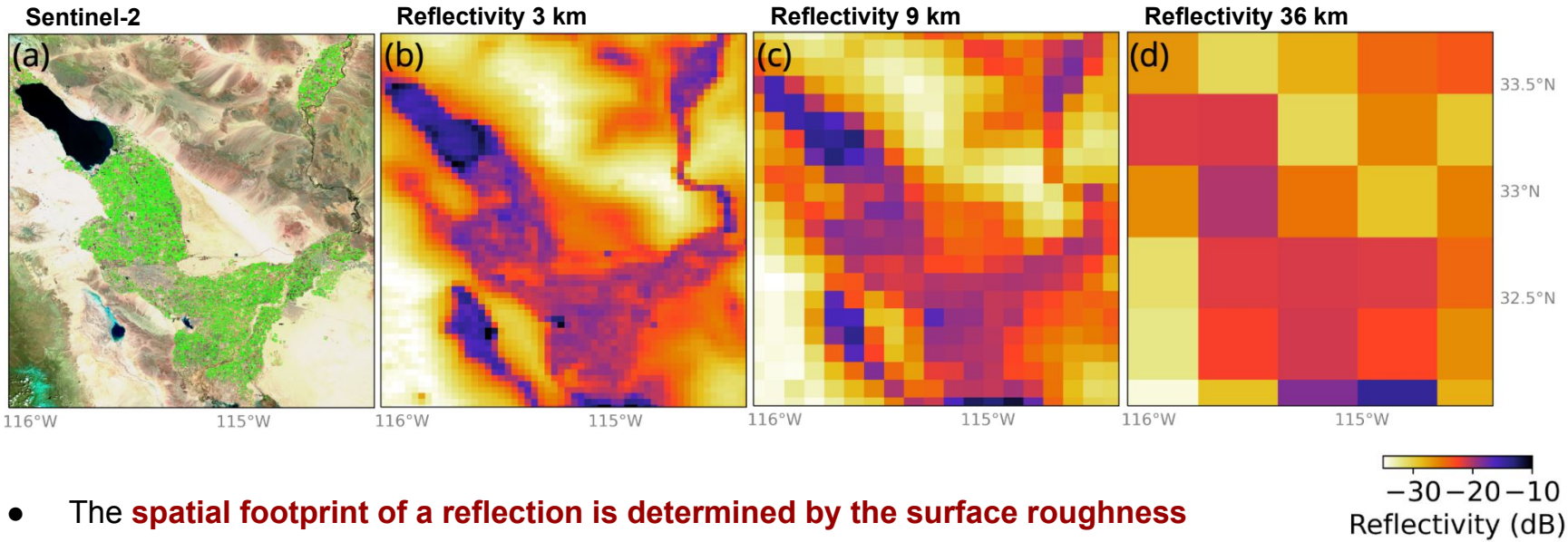
GNSS-R (CYGNSS) Spatiotemporal Sampling



- GNSS-R generates multiple “tracks” of observations rather than swaths (improves by tracking more GNSS reflections simultaneously)
- For soil moisture, choice of gridding technique (9 km above) is a tradeoff between maintaining inherent high resolution footprint (~3 km) vs. density of the resulting gridded product and observing temporal dynamics
- **Constellations of GNSS-R small satellites increase spatiotemporal sampling** and allow generation of gridded products

©2025 Muon Space, Inc.

GNSS-R Spatial Resolution

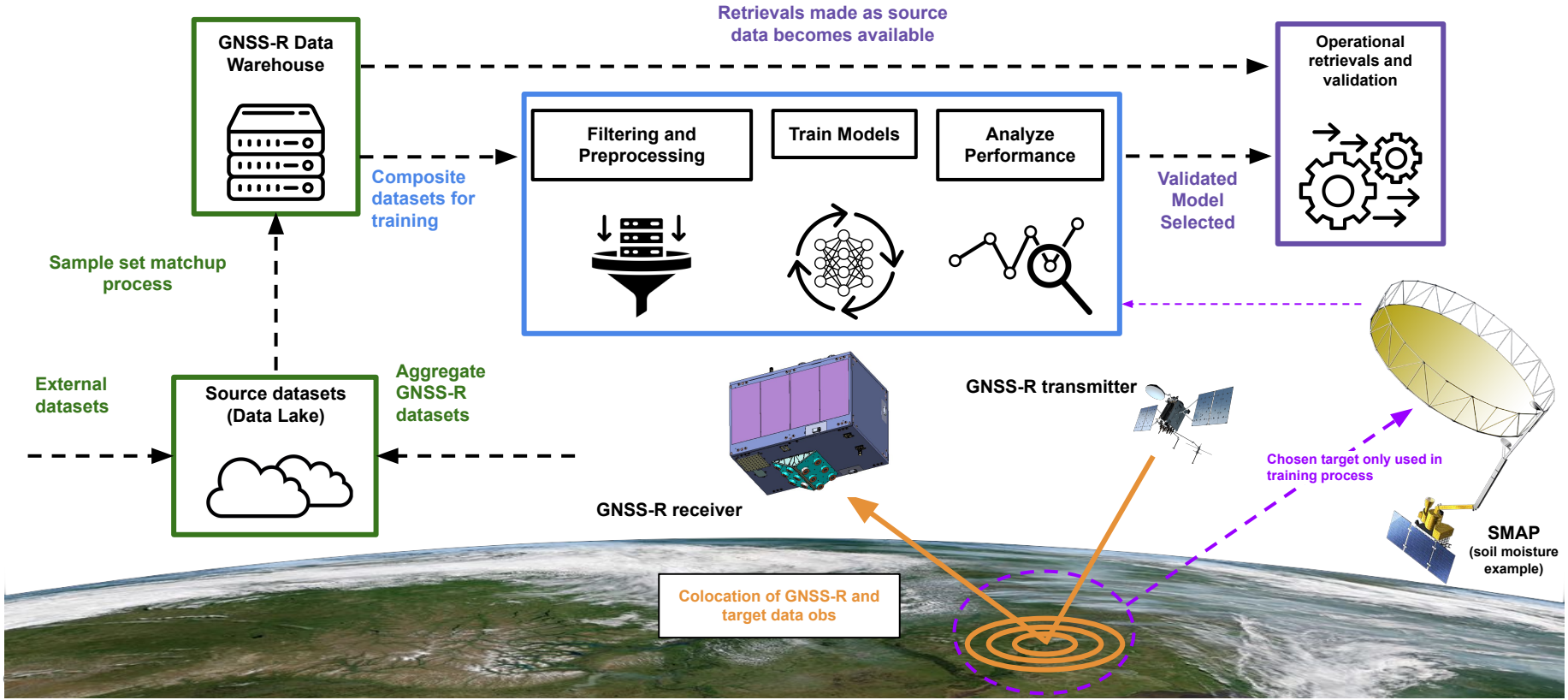


- The **spatial footprint of a reflection is determined by the surface roughness**
- "Smooth" land surfaces (as above) produce mostly coherent reflections: 0.2 - 1.0 km diameter footprint
  - 0.5 sec along-track integration results in **~1.0 x 3.5 km land surface footprint**
- Rougher surfaces (i.e., ocean) increase the footprint up to signal bandwidth: **~20-25 km ocean footprint**
- In training the ML retrieval model, we **match the resolution of ancillary data with the expected footprints**

©2025 Muon Space, Inc.

GNSS-R Retrievals via Machine Learning

- Prior to MuSat2 launch, Muon developed a **generalized machine learning framework to retrieve soil moisture and ocean wind speed** from **CYGNSS DDMs**
- Muon now produces **operational products from both MuSat2 and CYGNSS**



GNSS-R Retrievals via Machine Learning

Muon

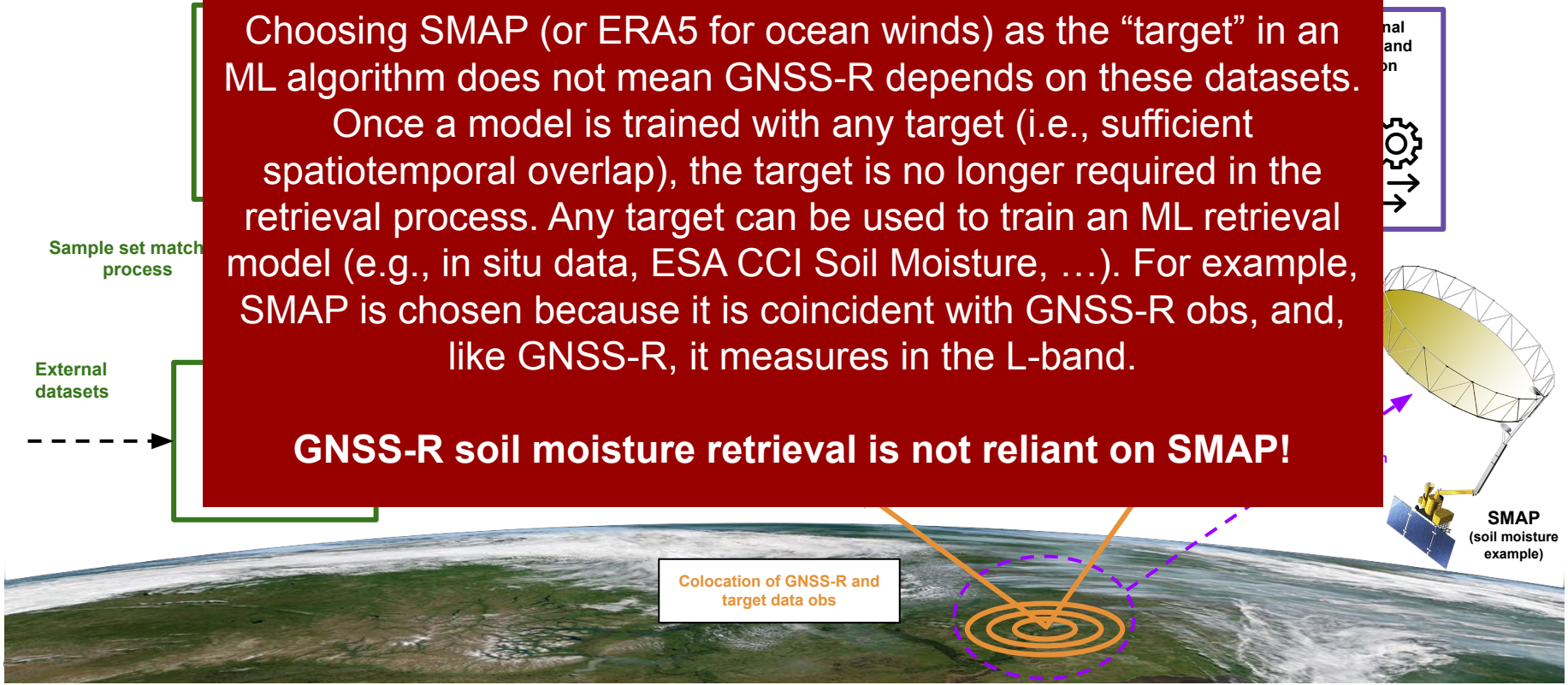
- Prior to
  wind sp
- Muon n

and ocean

Correcting a misconception:

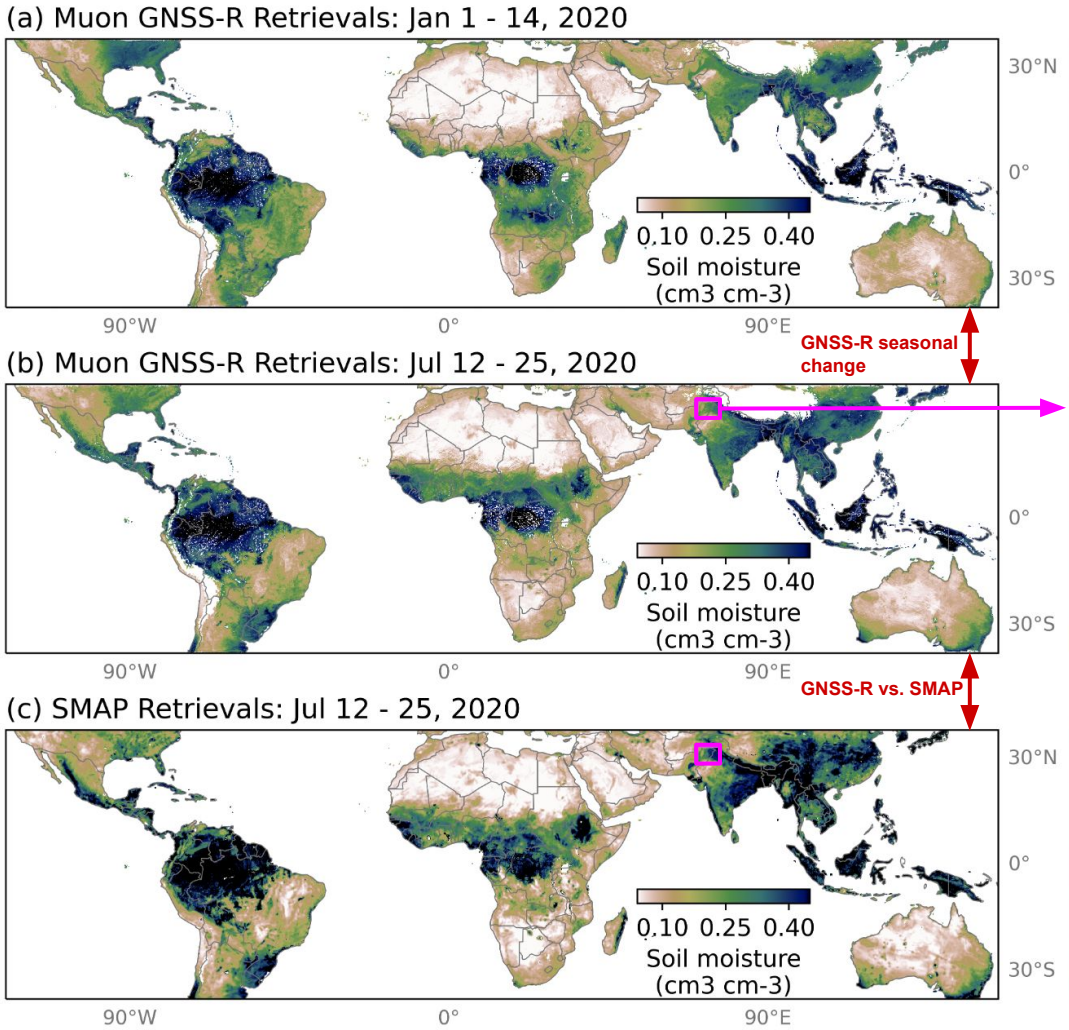
Choosing SMAP (or ERA5 for ocean winds) as the “target” in an ML algorithm does not mean GNSS-R depends on these datasets. Once a model is trained with any target (i.e., sufficient spatiotemporal overlap), the target is no longer required in the retrieval process. Any target can be used to train an ML retrieval model (e.g., in situ data, ESA CCI Soil Moisture, …). For example, SMAP is chosen because it is coincident with GNSS-R obs, and, like GNSS-R, it measures in the L-band.

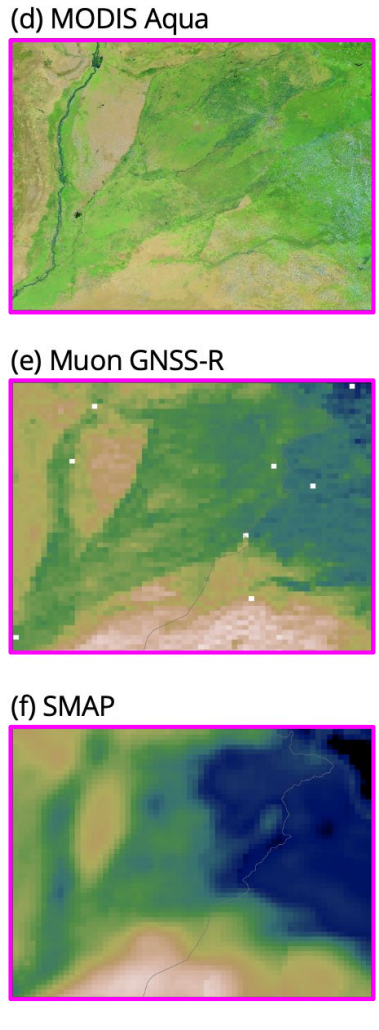
GNSS-R soil moisture retrieval is not reliant on SMAP!



Qualitative Comparison with SMAP

- Gridded 9 km averages of Muon CYGNSS soil moisture and the SMAP L3 Enhanced 9 km product
- The two products show broad spatial similarities, but **GNSS-R SM shows increased spatial resolution**
- (Right column) False-color image from MODIS over the [Punjab region] on the border of India and Pakistan



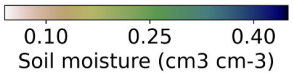


©2025 Muon Space, Inc.

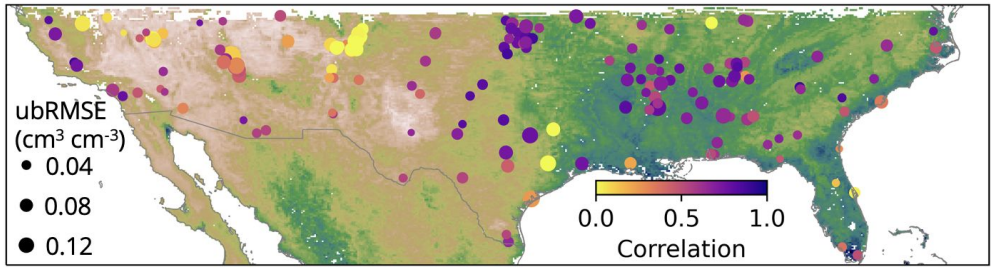
CYGNSS Soil Moisture In Situ Validation

- Muon retrievals and SMAP Enhanced product are upscaled to 36 km to match the official CYGNSS product
- Matchups are established using a 36 km diameter footprint centered on each site
- Daily averages are calculated for matchups
- Spatial patterns of both correlation and ubRMSE are similar across all three products
- All three soil moisture products have mean **ubRMSEs below 0.04 cm3 cm-3** and very low bias

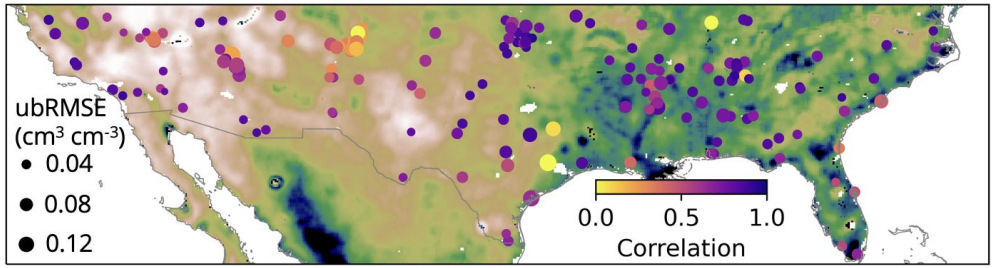
	Correlation			ubRMSE (cm3 cm-3)			Bias (cm3 cm-3)		
Site name	Muon GNSS-R	CYGNSS GNSS-R	SMAP	Muon GNSS-R	CYGNSS GNSS-R	SMAP	Muon GNSS-R	CYGNSS GNSS-R	SMAP
0701 Yanco	0.72	0.66	0.79	0.043	0.039	0.045	0.05	0.04	0.03
1601 Walnut Gulch	0.35	0.46	0.71	0.034	0.033	0.033	0.03	-0.02	0.02
1602 Little Washita	0.86	0.64	0.95	0.023	0.034	0.02	0.02	-0.04	0.01
1603 Fort Cobb	0.84	0.78	0.9	0.031	0.036	0.029	-0.02	-0.04	-0.02
1604 Little River	0.68	0.37	0.77	0.032	0.035	0.046	0.11	0.1	0.1
1902 MonteBuey	0.74	0.42	0.84	0.033	0.046	0.031	-0.01	-0.03	-0.02
4501 Niger	0.81	0.66	0.92	0.026	0.024	0.021	0.04	0.01	0.01
4801 TxSON	0.81	0.71	0.93	0.032	0.038	0.025	-0.01	-0.02	0
Mean of all	0.72	0.59	0.85	0.032	0.035	0.031	0.02	0	0.02



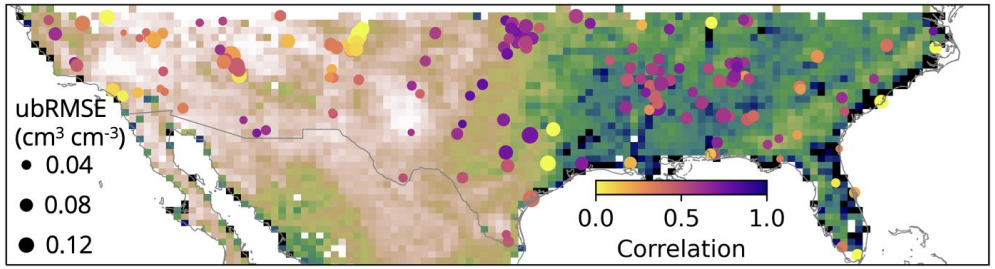
(a) Muon GNSS-R July 2020



(b) SMAP



(c) CYGNSS GNSS-R



©2025 Muon Space, Inc.

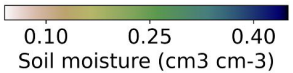
CYGNSS Soil Moisture In Situ Validation

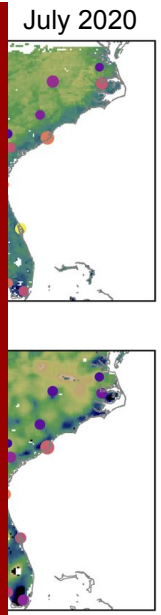
- Muon re
  are upsc
  CYGNS
- Matchup
  diamete
- Daily av
- Spatial
  ubRMSI
- All three
  ubRMS
  bias

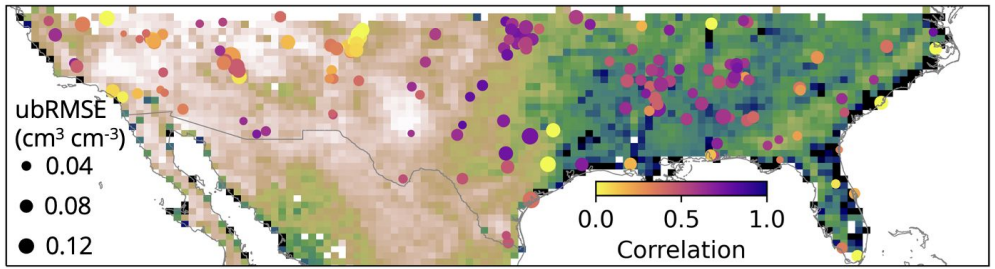
The Muon CYGNSS soil moisture product has been published at https://arxiv.org/abs/2412.00072 and released publicly (https://zenodo.org/records/14172456).

An operational version updated daily will be available in February 2025.

Site name	Muon GNSS-R	CYG GNS							
0701 Yanco	0.72	0.							
1601 Walnut Gulch	0.35	0.							
1602 Little Washita	0.86	0.							
1603 Fort Cobb	0.84	0.78	0.9	0.031	0.036	0.029	-0.02	-0.04	-0.02
1604 Little River	0.68	0.37	0.77	0.032	0.035	0.046	0.11	0.1	0.1
1902 MonteBuey	0.74	0.42	0.84	0.033	0.046	0.031	-0.01	-0.03	-0.02
4501 Niger	0.81	0.66	0.92	0.026	0.024	0.021	0.04	0.01	0.01
4801 TxSON	0.81	0.71	0.93	0.032	0.038	0.025	-0.01	-0.02	0
Mean of all	0.72	0.59	0.85	0.032	0.035	0.031	0.02	0	0.02







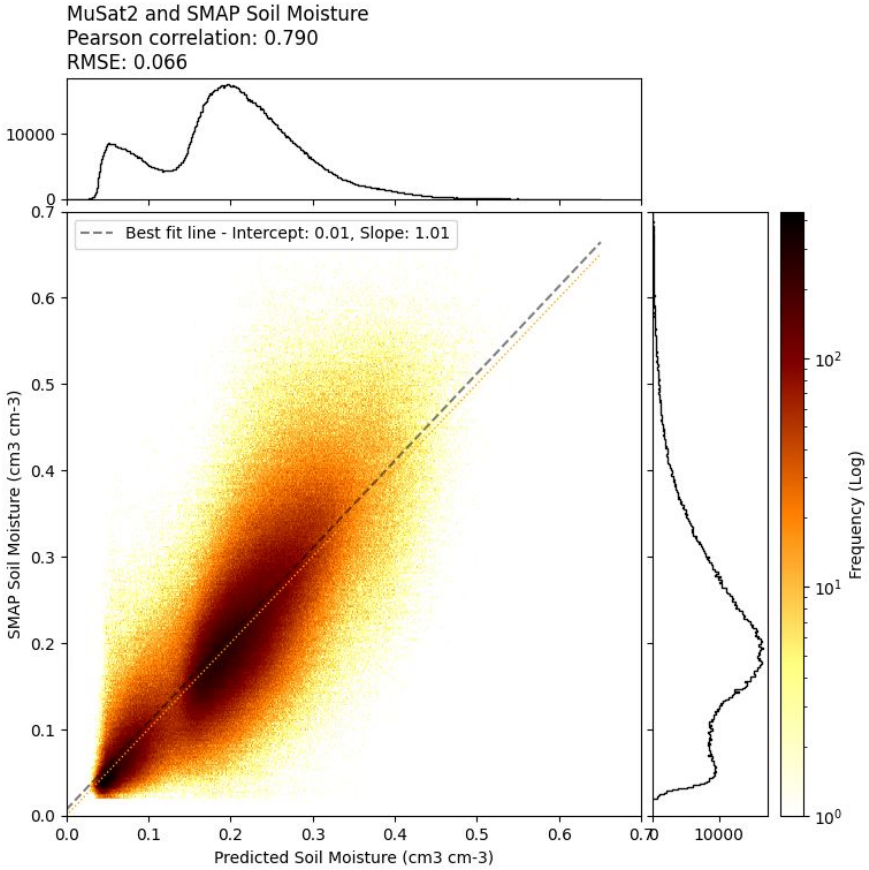
©2025 Muon Space, Inc.

MuSat2 + CYGNSS Soil Moisture Product

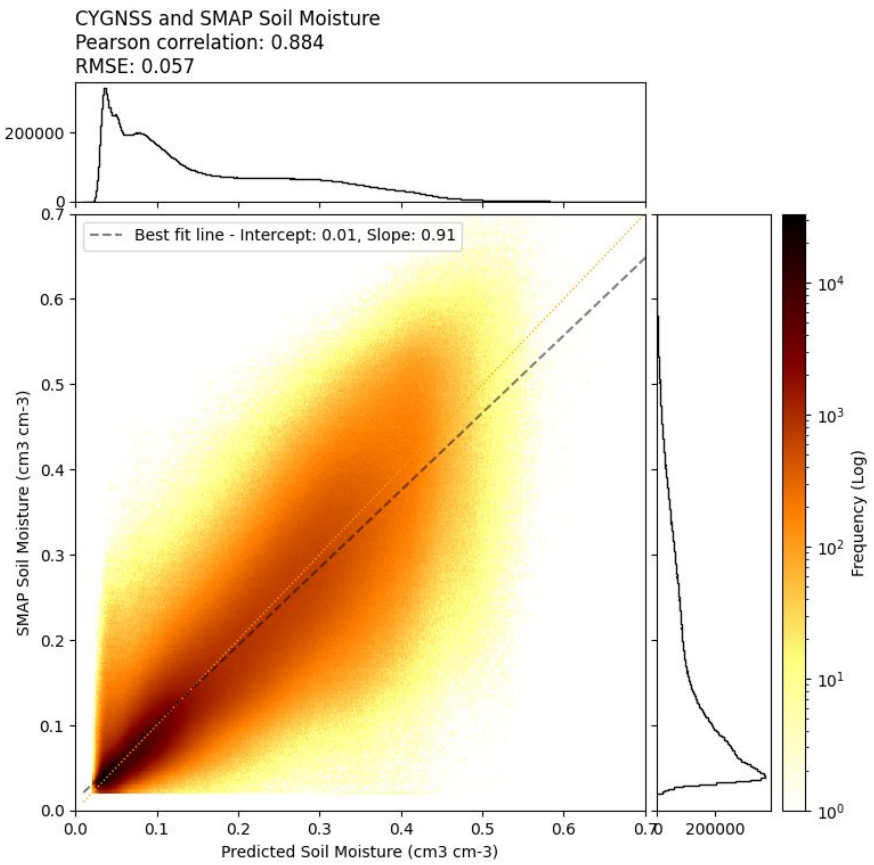


©2025 Muon Space, Inc.

Prelim. MuSat2 Soil Moisture: 2024-05-27 to 2024-10-15



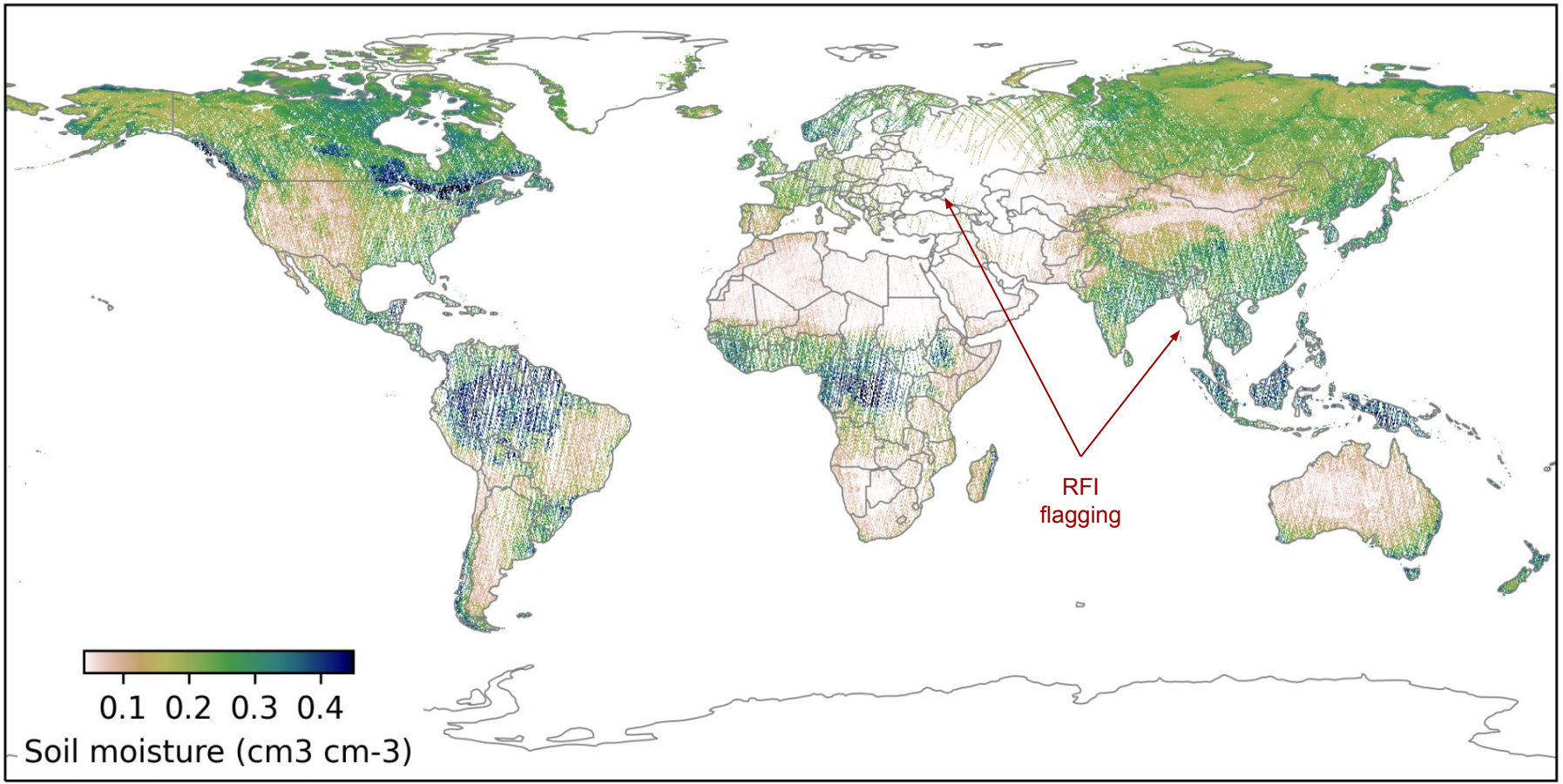
MuSat2



CYGNSS (for comparison)

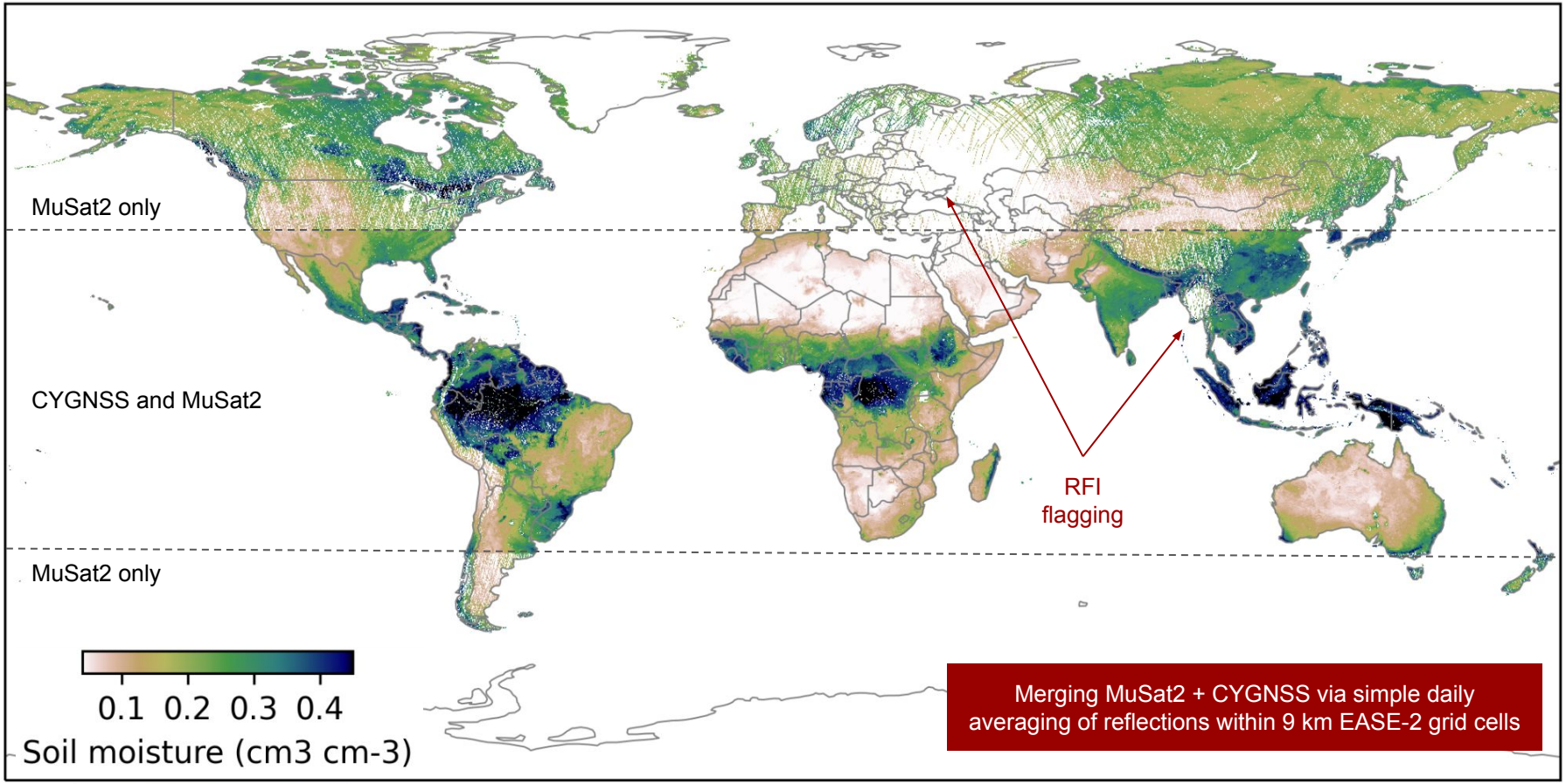
©2025 Muon Space, Inc.

Prelim. MuSat2 Soil Moisture: 2024-05-27 to 2024-10-15



©2025 Muon Space, Inc.

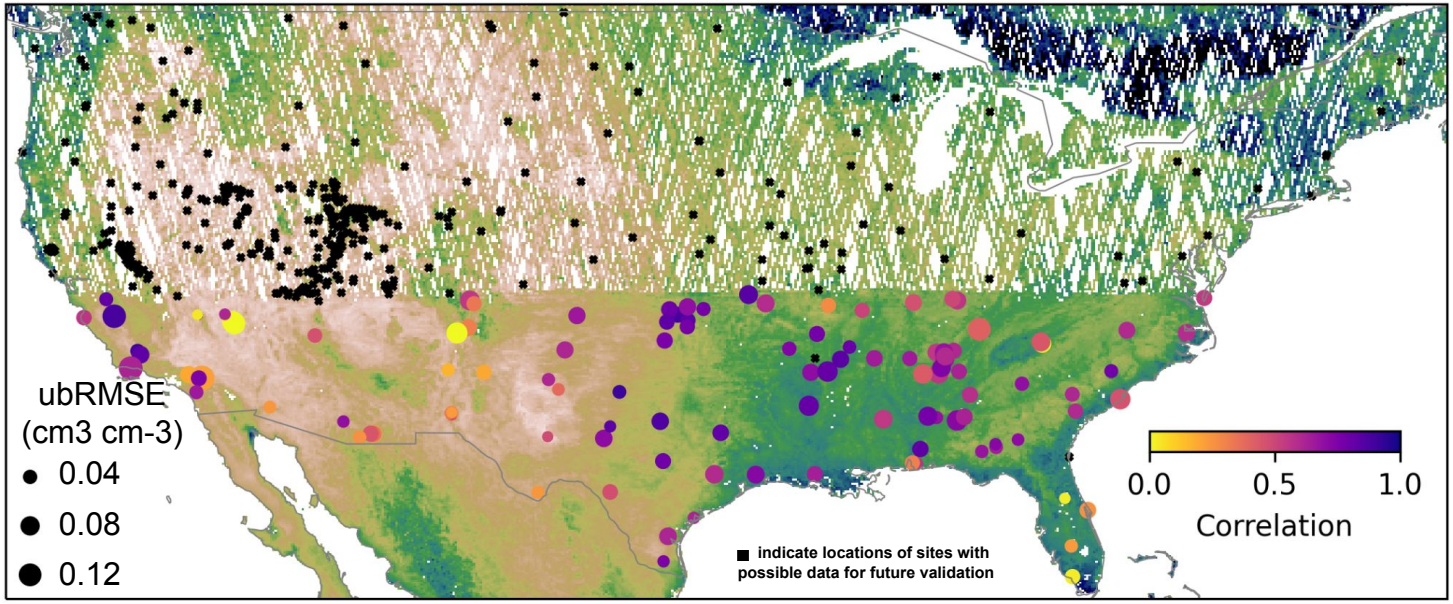
Merging MuSat2 + CYGNSS for Global SM Coverage

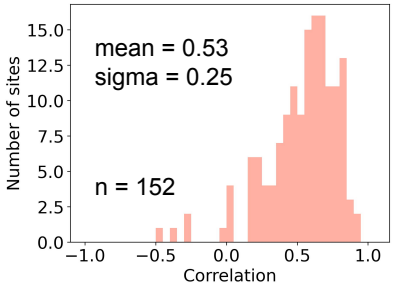


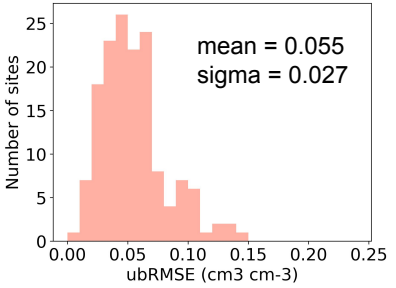
©2025 Muon Space, Inc.

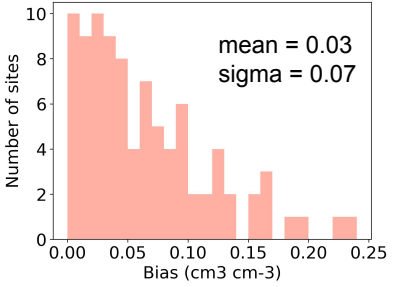
Validation of Muon Merged GNSS-R Soil Moisture

Currently there are not enough repeat MuSat2 observations at higher latitudes to quantify performance at in situ sites.









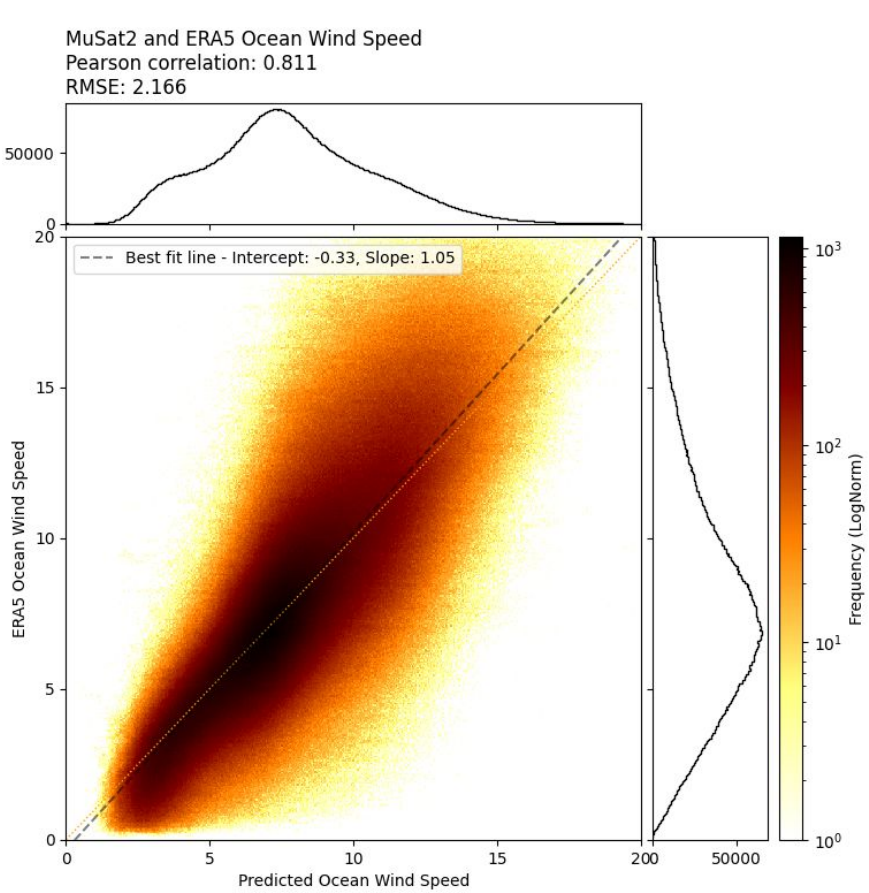
©2025 Muon Space, Inc.

MuSat2 + CYGNSS Ocean Wind Speed Product

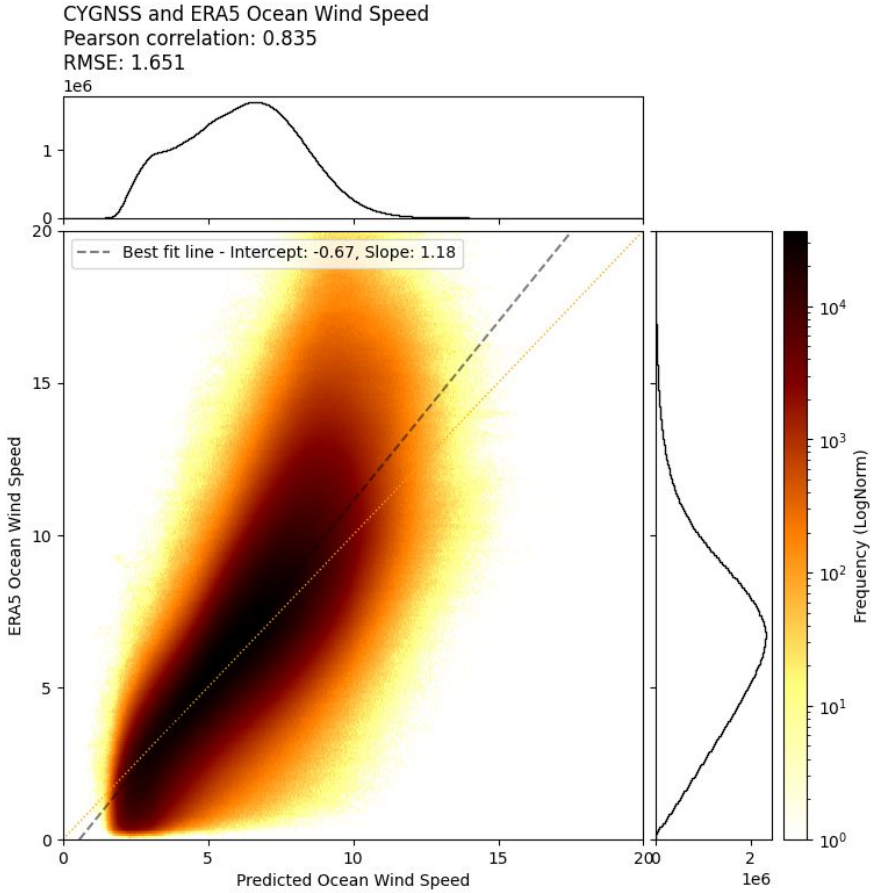
©2025 Muon Space, Inc.

Prelim. MuSat2 Ocean Winds: 2024-05-27 to 2024-10-15

Muon



MuSat2

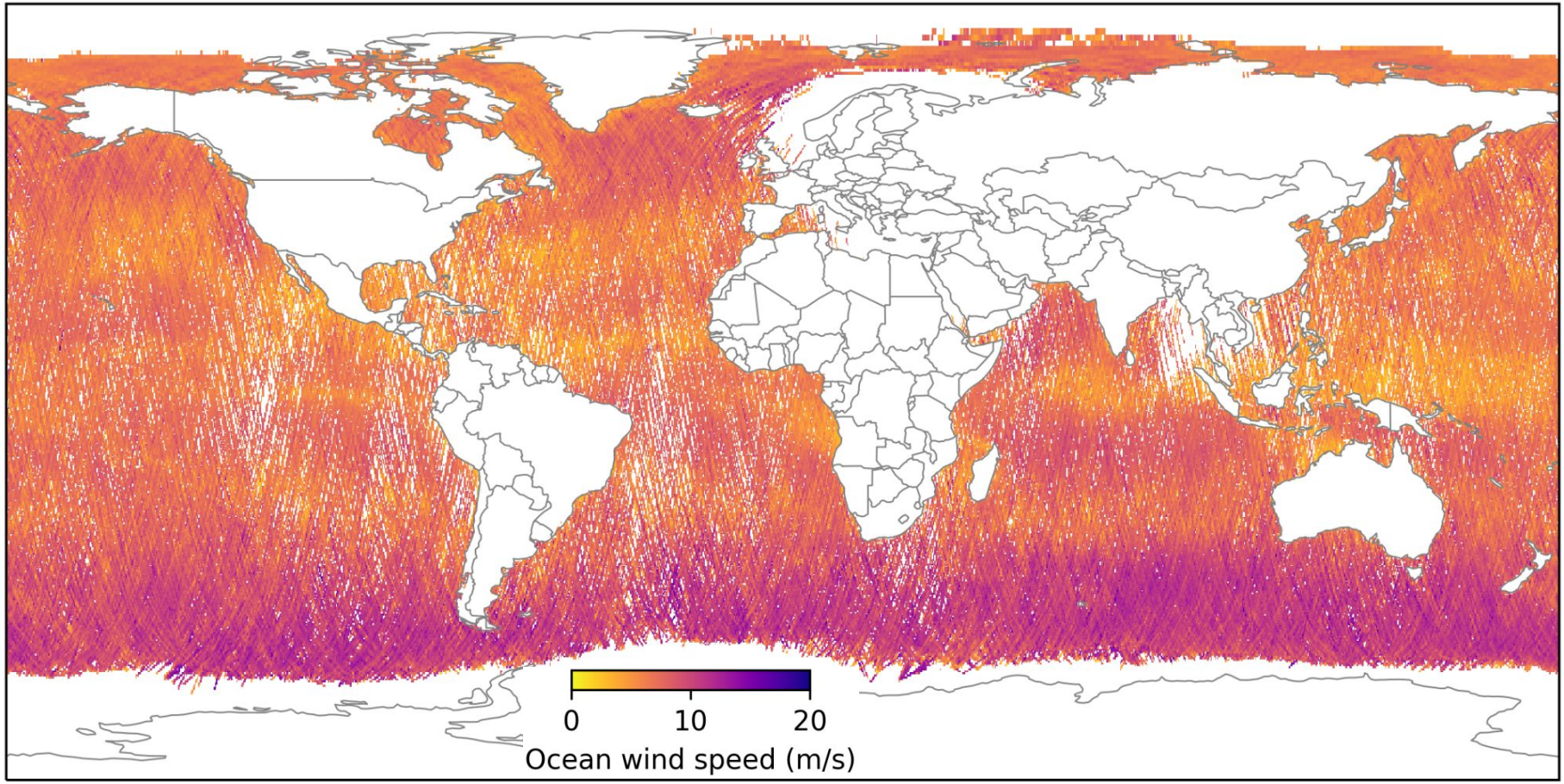


CYGNSS (for comparison)

©2025 Muon Space, Inc.

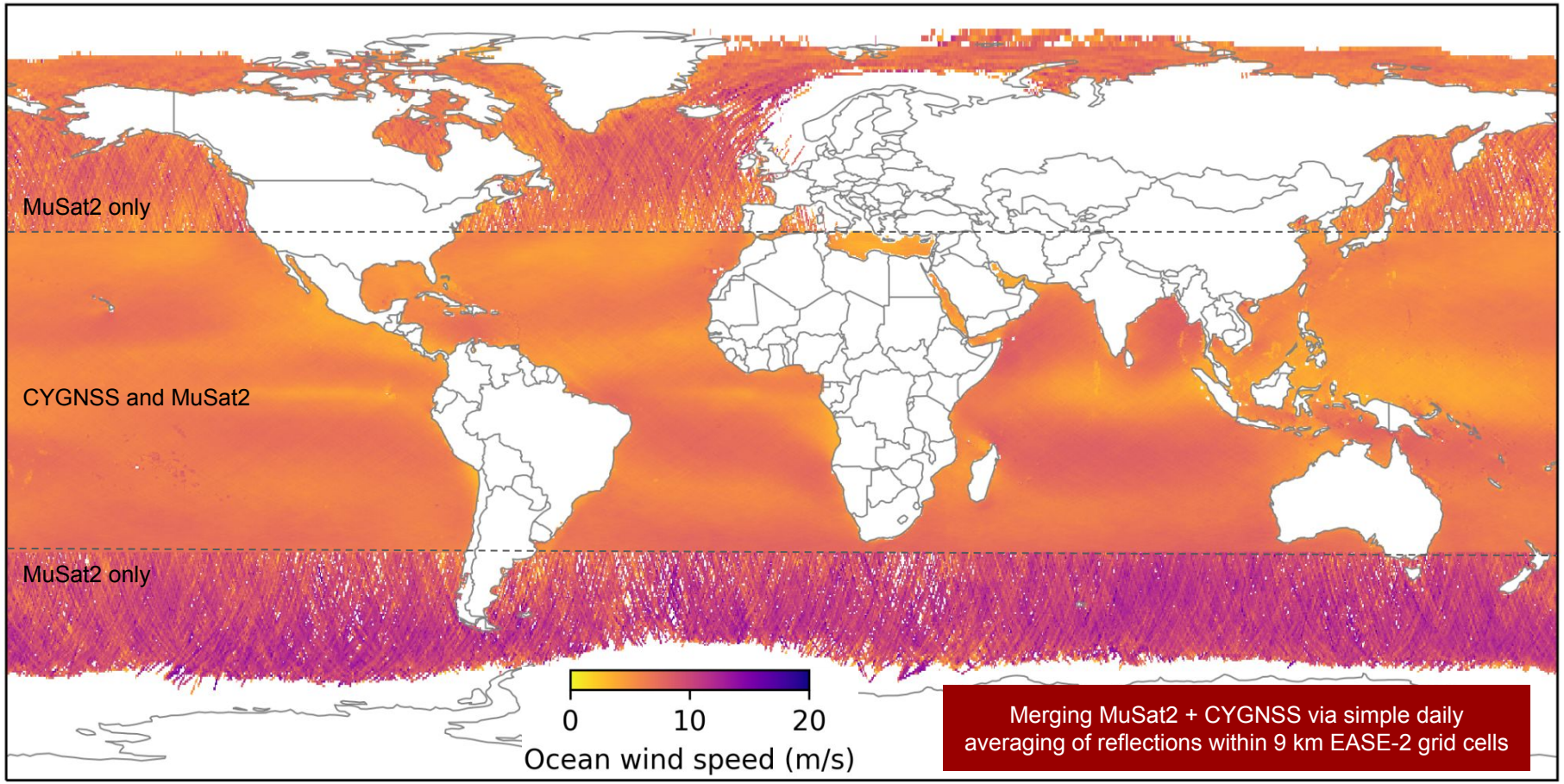
Prelim. MuSat2 Ocean Winds: 2024-05-27 to 2024-10-15

Muon



©2025 Muon Space, Inc.

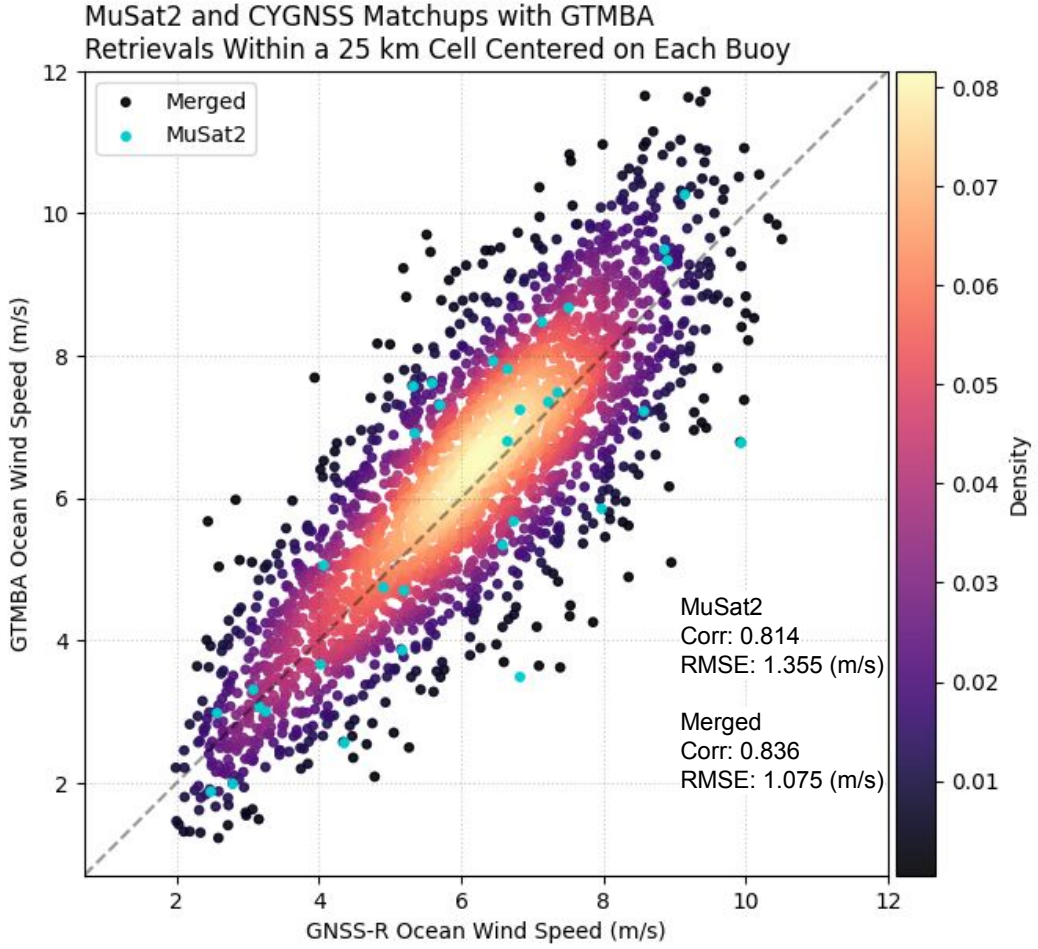
Merging MuSat2 + CYGNSS for Global OW Coverage

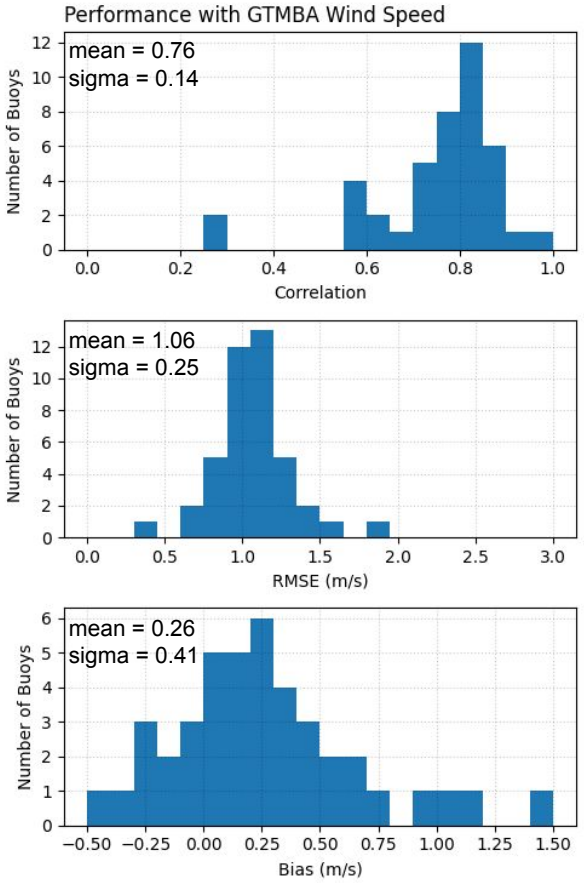


©2025 Muon Space, Inc.

Validation of Muon Merged GNSS-R Ocean Winds

Muon





Plan for Muon GNSS-R Satellites

MuSat1 (June 2023)

- First Muon satellite serving as prototype to test core avionics



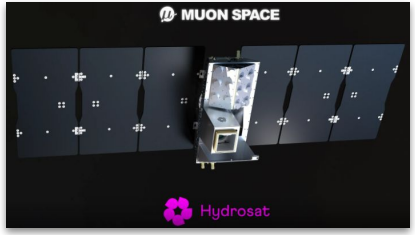
MuSat2 (Mar. 2024)

- MuSat1 heritage with **polarimetric GNSS-R** payload
- **Operational soil moisture and ocean wind products**



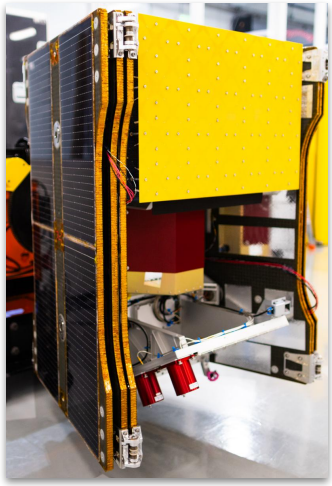
MuSat3 (2025)

- 2nd generation bus hosting Hydrosat's multispectral and TIR payloads
- Muon **polarimetric GNSS-R payload (same as MuSat2)**



MuSat4 (2025)

- **High-gain, beamforming GNSS-R payload** to measure **soil moisture under canopy** and **cyclone winds**



Three Muon GNSS-R sats operating in 2025

Muon is actively seeking collaborations with academic, government, and non-governmental organizations that wish to use our data or discuss opportunities for missions and hosted payloads.
Please contact dallas@muonspace.com for opportunities.

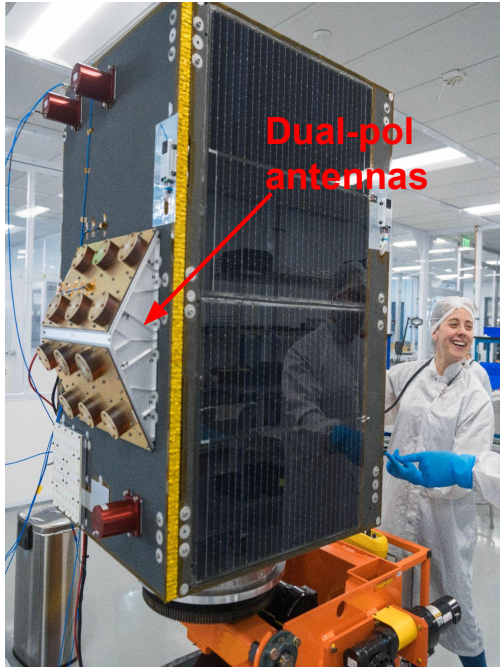
©2025 Muon Space, Inc.

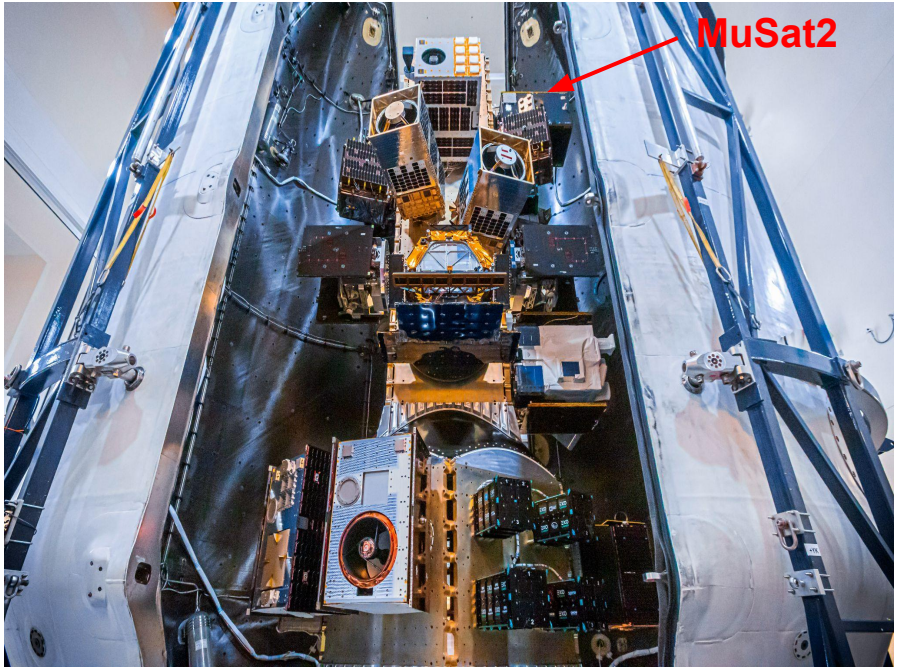
Supplemental Material

©2025 Muon Space, Inc.

MuSat2: Muon's First GNSS-R & TEC Satellite

- Launch: March 4, 2024 on SpaceX Transporter 10 in to **polar orbit**: 500-600 km, SSO, LTAN 22:00-23:00
- Full global coverage to observe all surface types
- **Commercial Weather Data Pilot contract with US Air Force Weather** to provide **GNSS-R soil moisture, ocean wind speeds,** and **GNSS TEC**



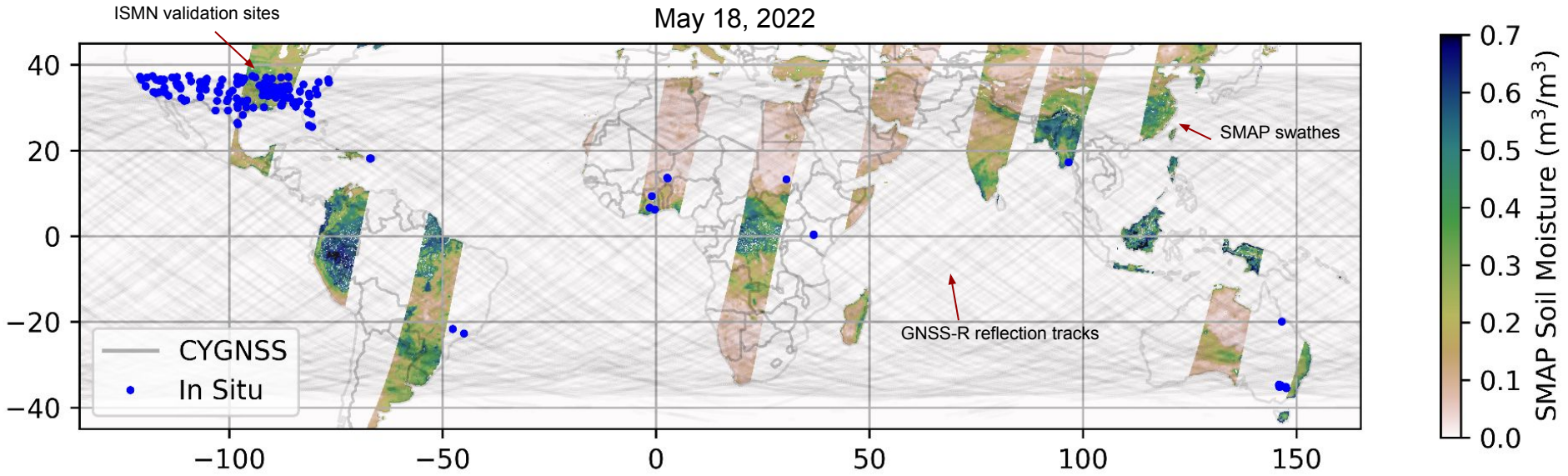




©2025 Muon Space, Inc.

Soil Moisture Example: GNSS-R Obs & SMAP “Truth”

Muon

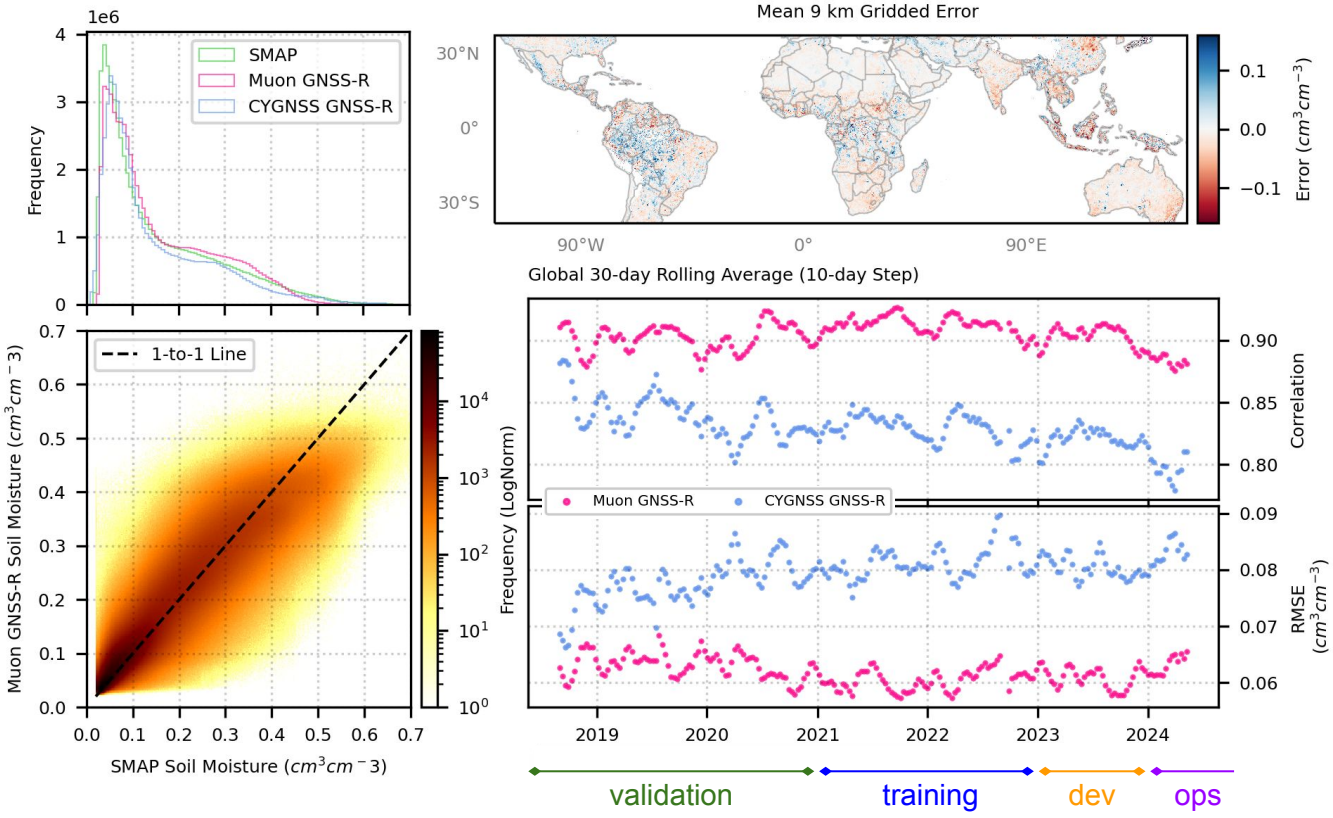


- Datasets used for training and validation of ML model to retrieve GNSS-R soil moisture:
  - **Primary input:** delay-Doppler maps from randomly spatially-distributed “tracks” (grey curves in plot)
  - **Truth (“target”) dataset:** SMAP 9km L3 Enhanced Radiometer-based soil moisture retrievals (swath data)
  - **Ancillary inputs:** bistatic geometry (e.g., incidence angle), soil texture, NDVI, surface water fraction, LULC
  - **Validation dataset:** International Soil Moisture Network validation (blue dots)

©2025 Muon Space, Inc.

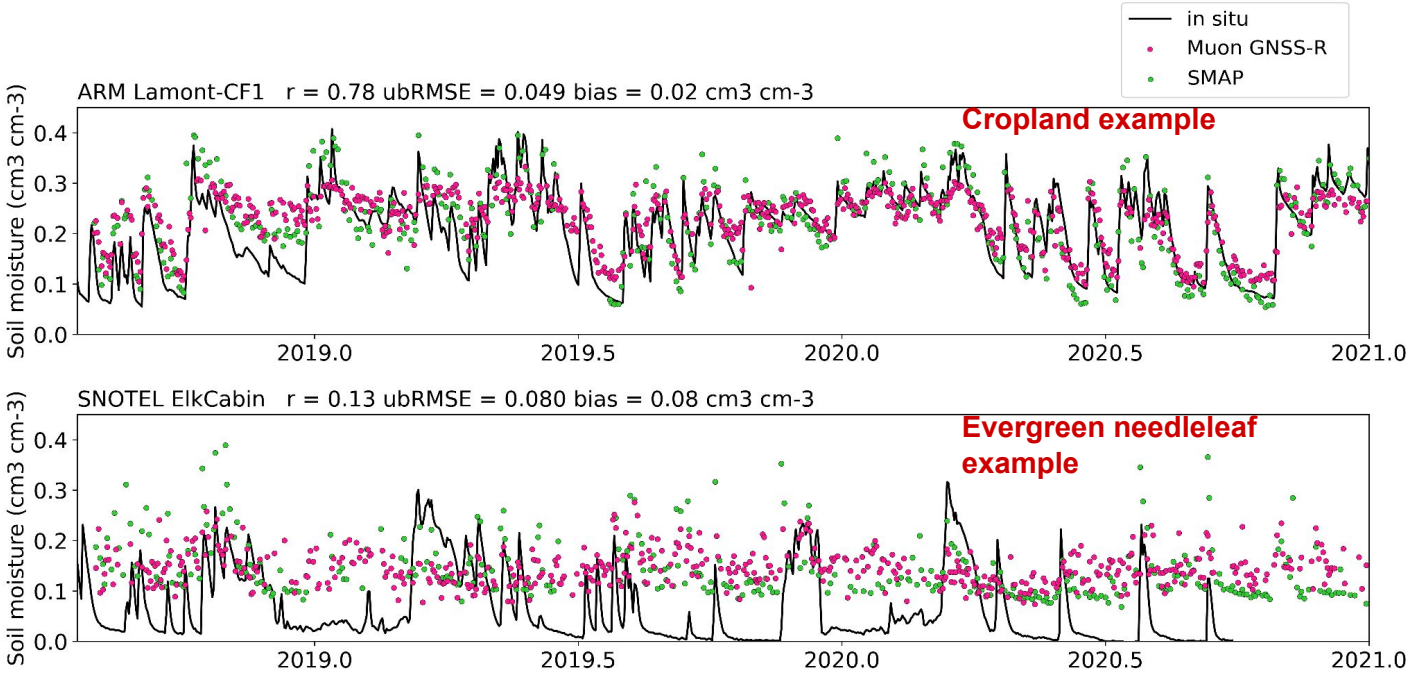
CYGNSS Soil Moisture Performance Evaluation

- **Comparison of Muon's CYGNSS SM, official CYGNSS SM, and SMAP**
- Muon's CYGNSS SM agrees well with SMAP during validation period (2018-2021) & performs better than official CYGNSS SM product
- Dry bias in highly vegetated areas (Amazon and Central and Eastern Africa)
- Global moving average GNSS-R soil moisture tracks well with SMAP; performance is consistent across time



©2025 Muon Space, Inc.

CYGNSS SM In Situ Validation Examples

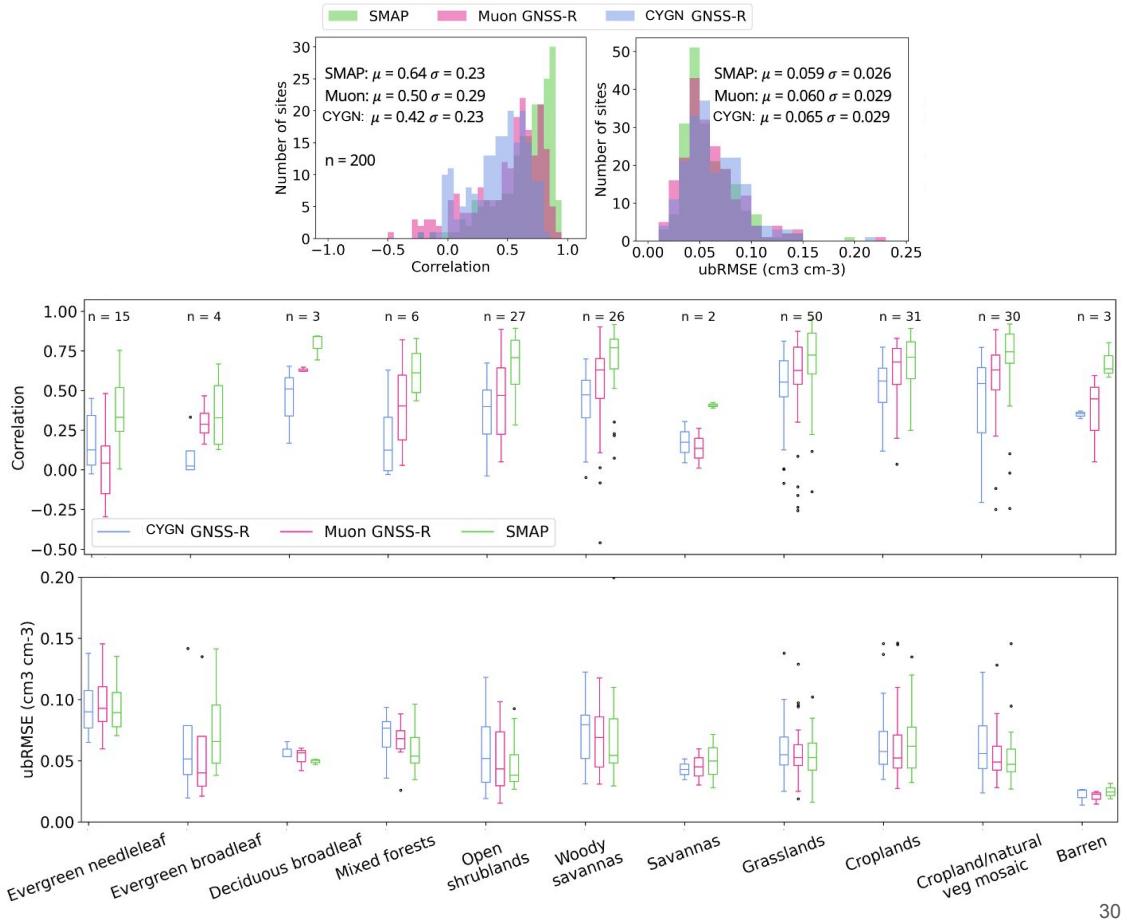


- Example site time series chosen because they had close to the Muon GNSS-R median correlation as found for sites within their land cover class: **croplands (top)** and **evergreen needleleaf forests (bottom)**
- **Similar performance of GNSS-R and SMAP retrievals** in these examples (retrievals have not been bias corrected)

©2025 Muon Space, Inc.

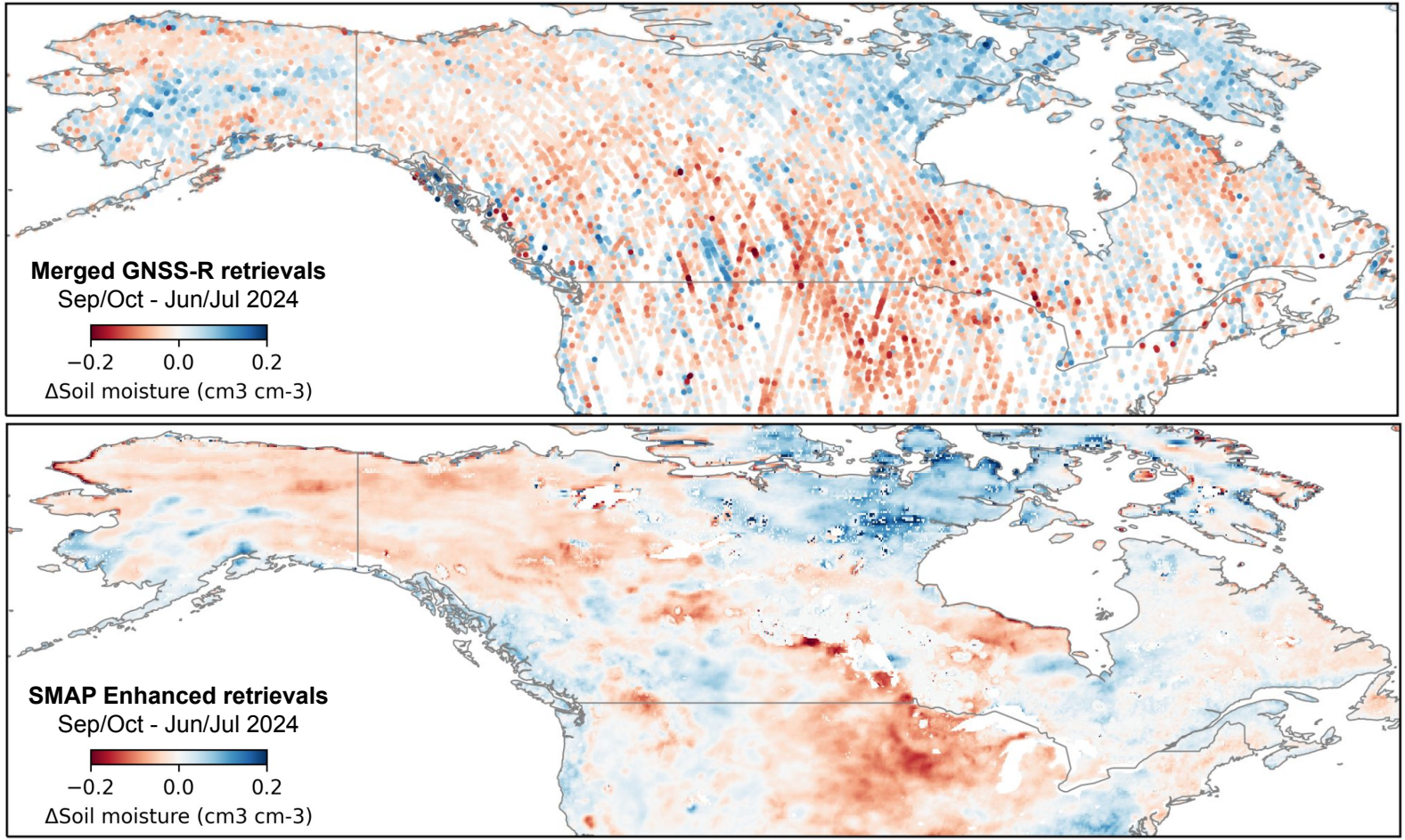
CYGNSS SM In Situ Validation

- In low to moderately vegetated areas, Muon GNSS-R approaches SMAP performance
- Retrievals are challenging in forested, mountainous terrain, where the reflected signal strength is weak
- **Future Muon GNSS-R antenna gains beyond the 14 dBi of CYGNSS will improve soil moisture retrievals in areas of heavy vegetation and terrain**



©2025 Muon Space, Inc.

Prelim. High-Latitude Seasonal Change in MuSat2 Soil Moisture



©2025 Muon Space, Inc.