

# Muon Space Constellation for GNSS-Based Remote Sensing

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

**GNSS-based observations are being applied to surface remote sensing and space weather applications**

# Muon Signals of Opportunity Program



## ***Building a Great Team of SoOp Experts***

Muon is building a strong team spanning software-defined radios, antenna design, and **GNSS-based science and products** e.g., GNSS-R, GNSS-RO, etc.

## ***Collaborate with Partners & Customers***

For initial satellites, Muon is **partnered with University of Michigan** and **Ohio State University** to leverage and improve upon existing technology developed under the NASA Instrument Incubator Program

## ***Focus on Products***

Muon is focused on **rapidly developing products using machine learning** to solve customer needs



**Dr. Dallas Masters**  
VP, SoOp Program  
Director Earth Observation, Spire



**Dr. Max Roberts**  
Senior Scientist  
Scientist, JPL



**Dr. Clara Chew**  
Senior Scientist  
Scientist, UCAR



**Dr. Steve Lowe**  
Principal Scientist  
Principal Scientist, JPL



**Linus Tan**  
Payload Lead SWE  
Principal SWE, Spire



**Ian Colwell**  
Lead ML Scientist  
ML Scientist, JPL



**Dr. Karl Nordstrom**  
Geospatial Data Engineer  
ML Scientist, Spire

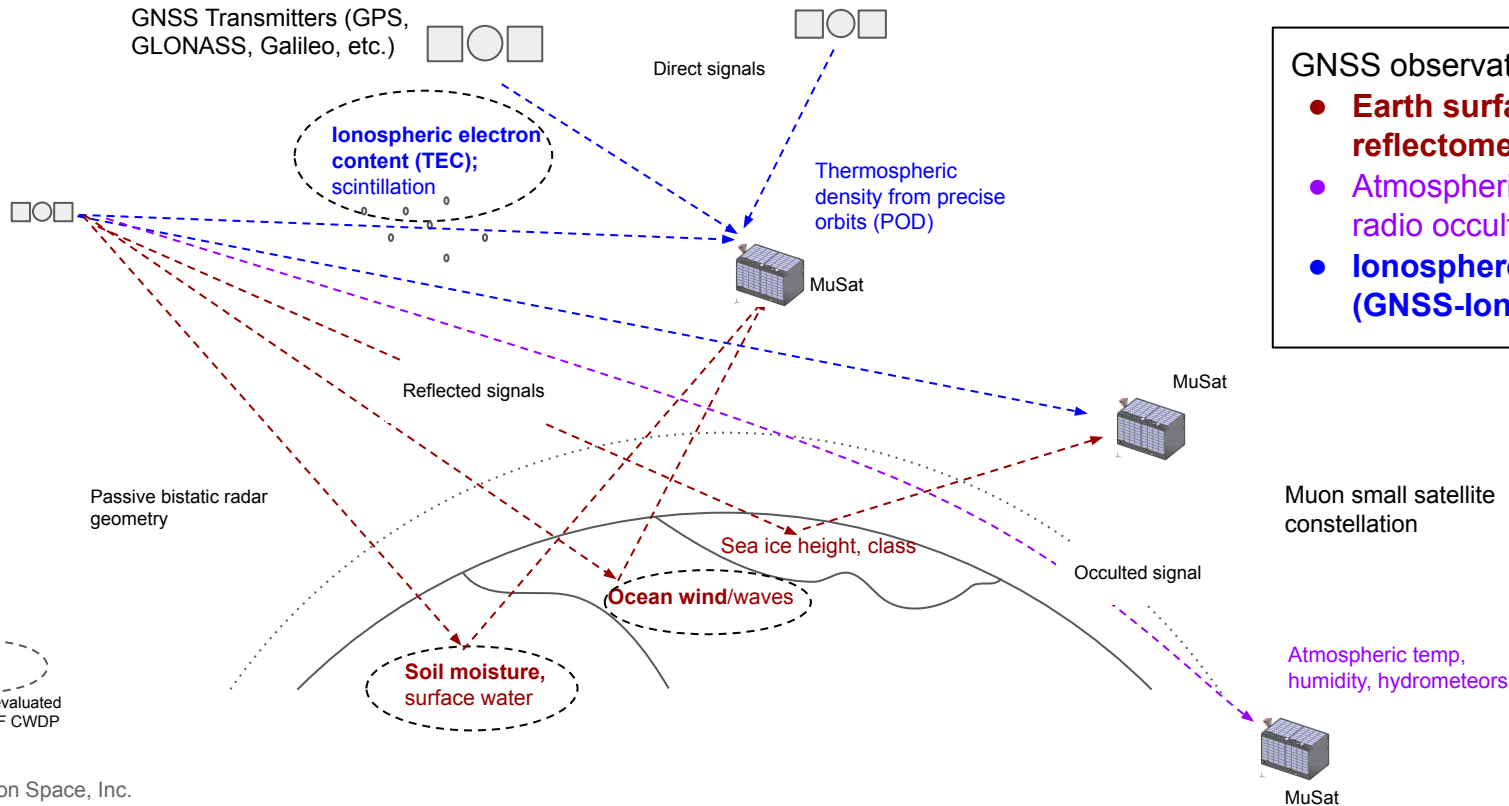


**Prof. Chris Ruf**  
Advisor  
PI NASA CYGNSS Mission

**\* Members of the team with GNSS-RO/TEC experience**

# EO Suited for SmallSat Constellations

Muon is harnessing decreasing launch costs and miniaturization of **technologies suited for remote sensing from small satellites**  
Examples: signals of opportunity (SoOp), e.g., **GNSS reflectometry** and radio occultation for Earth surface products



- GNSS observations and products
- **Earth surface: GNSS reflectometry (GNSS-R)**
  - **Atmospheric sounding: GNSS radio occultation (GNSS-RO)**
  - **Ionosphere/space weather (GNSS-Iono)**

Products evaluated under USAF CWDP contract

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

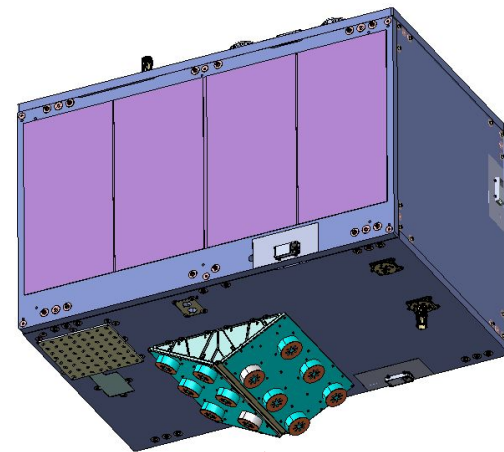
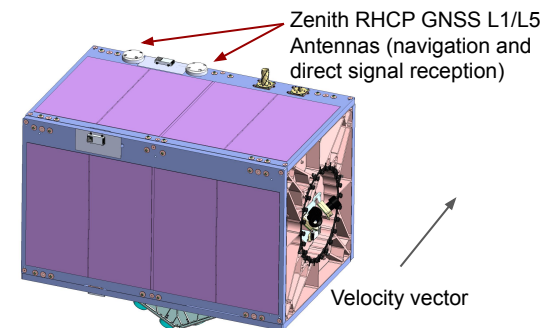


- **MuSat2 GNSS-R payload:**

- **Zenith antenna:** multi-freq RHCP
- **Dual-polarization GNSS-R antennas:**
  - Port and starboard pair
  - L1/L5, RHCP and LHCP
  - ~14 dBi peak gain
  - Designed by OSU under **NASA 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
- 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**

- **MuSat2 GNSS-TEC payload:**

- **Multi-GNSS top-side TEC** derived from separate RHCP antenna and NovAtel navigation receiver

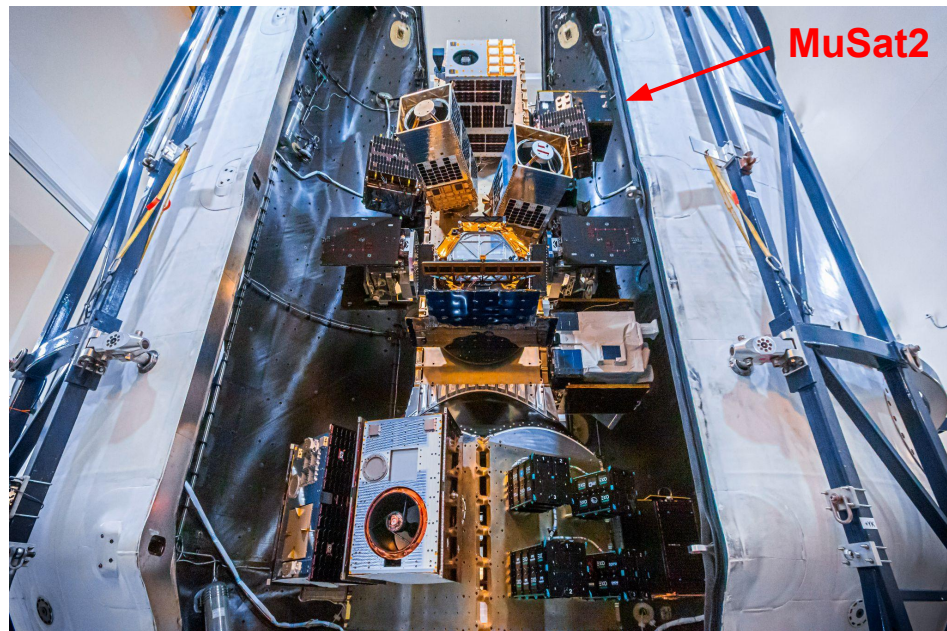
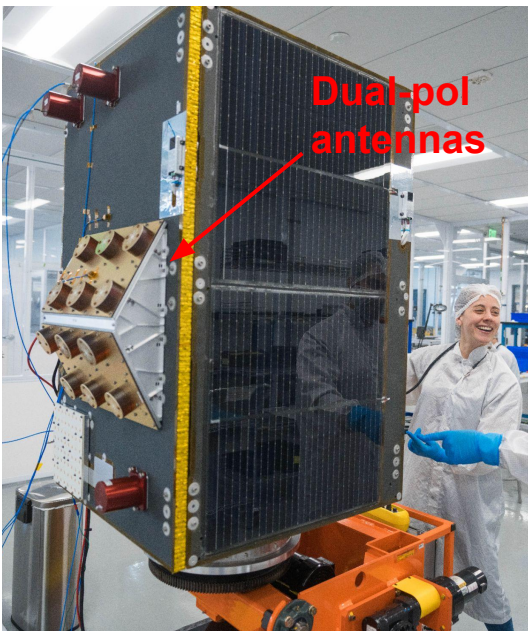


Port and starboard nadir **dual-pol R/LHCP, L1/L5** GNSS-R antennas pointing across track and 28 deg off nadir (reflected signal)

# 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**
- **All systems healthy, and MuSat2 is actively producing dual-pol (LHCP+RHCP) GPS reflections, soil moisture, ocean wind, and TEC products**

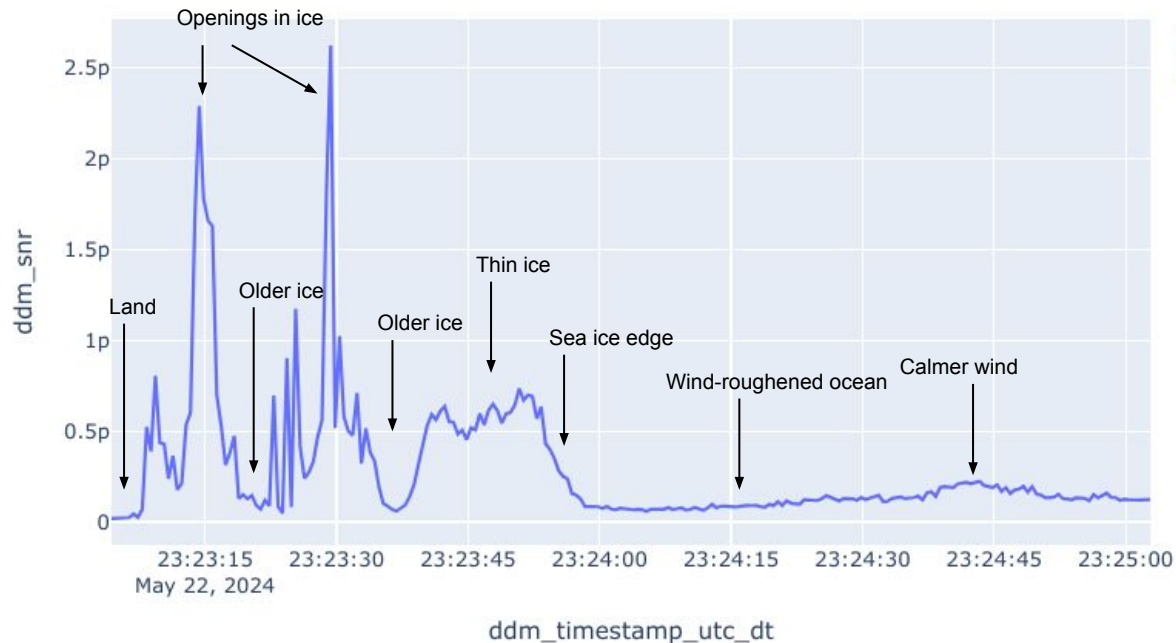
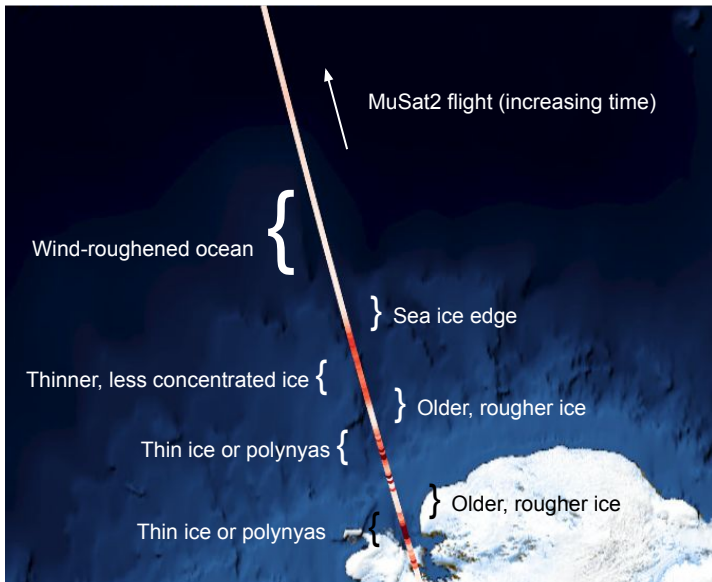


# MuSat2: Early Operations Status

- **Spacecraft bus status:**
  - All systems **healthy**
  - Some issues with stray light in star trackers (similar to CYGNSS)
- **GNSS-R payload status:**
  - All payload components **healthy**
  - Tracking **~6-7 simultaneous GPS L1CA dual-pol reflections** with both nadir antennas (2 more than CYGNSS)
  - Producing 2 Hz DDMs land and ocean (**open loop topography tracker working well**)
  - DDM resolution:  $\frac{1}{8}$  chip, 250 Hz Doppler (**2X finer resolution than CYGNSS**)
  - Nominal data collections started in late May
- **NovAtel receiver (TEC) status:**
  - Nominal data collections started in June
- **Initial product status:**
  - L2 ocean wind speeds generated with machine learning (ML) model
  - L2 soil moisture generated with parameterized model derived from CYGNSS and SMAP (ML model in future)
  - L1b podTEC generated from GPS, Galileo, GLONASS, BDS obs



# First MuSat2 GNSS-R Tracks: May 22 Antarctica



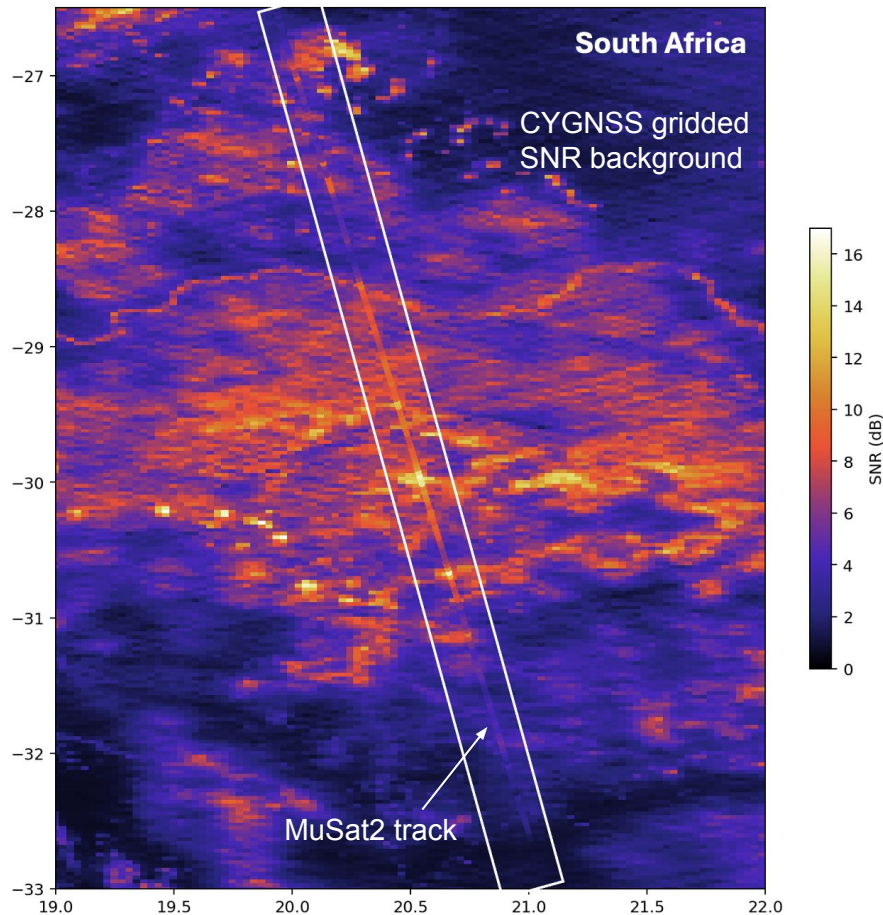
- First scheduled data collections: May 22 captured **transition from land → sea ice → open ocean** in Antarctica
- **Typical reflected power signatures** over each surface type, with sensitivity to highly reflective thin sea ice and older, rougher ice and open ocean, wind-roughened seas



# MuSat2 Early Results: Comparisons to CYGNSS Muon

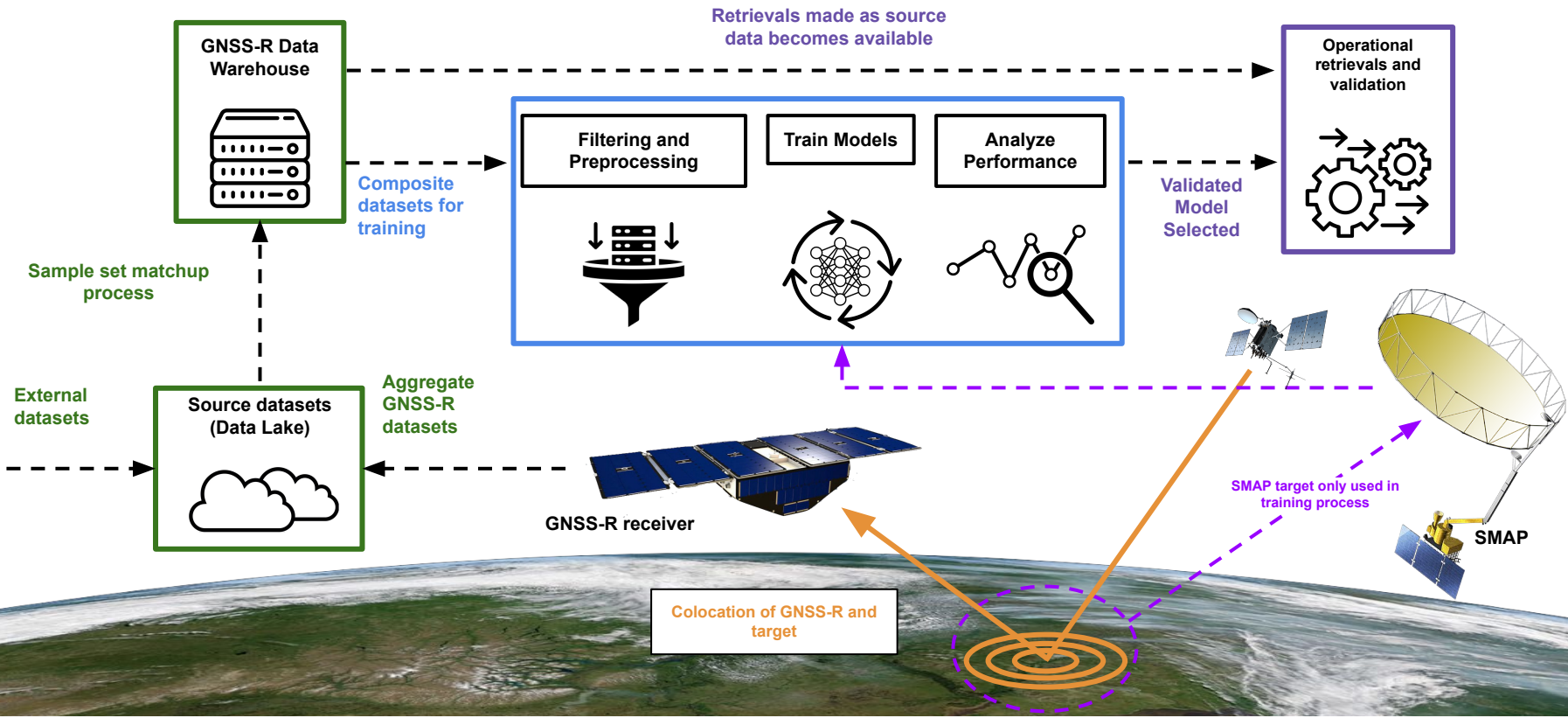
**Good agreement between MuSat2 and CYGNSS land reflections:** MuSat2 reflected SNR track over South Africa overlaid on top of 3 km gridded SNR from CYGNSS

If you're having trouble finding the track, it's because **the MuSat2 SNR values are pretty much the same as CYGNSS** (white box outlines the track)



# Operational Products Built Using CYGNSS Data Muon

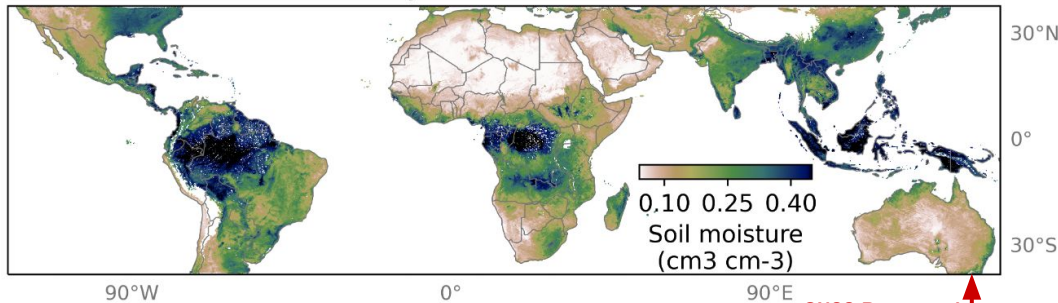
- Prior to MuSat2 launch, Muon developed a **generalized machine learning framework** and developed its own **CYGNSS soil moisture** (example shown) and **CYGNSS ocean wind speed** products
- Eventually, Muon products will **merge MuSat2 data with CYGNSS** and other GNSS-R mission data



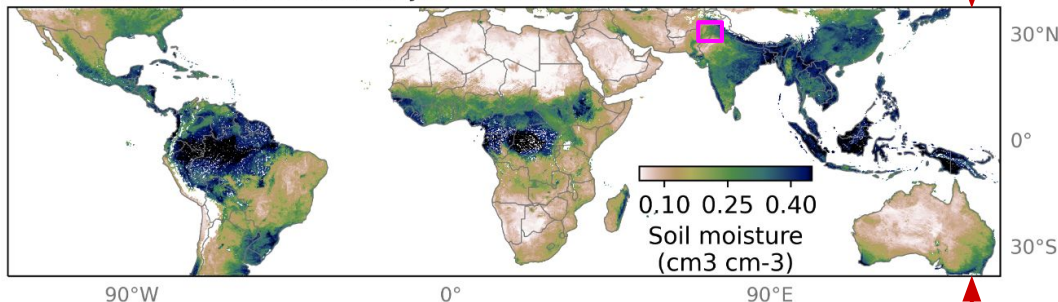
# Comparison of Muon's CYGNSS SM with SMAP

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

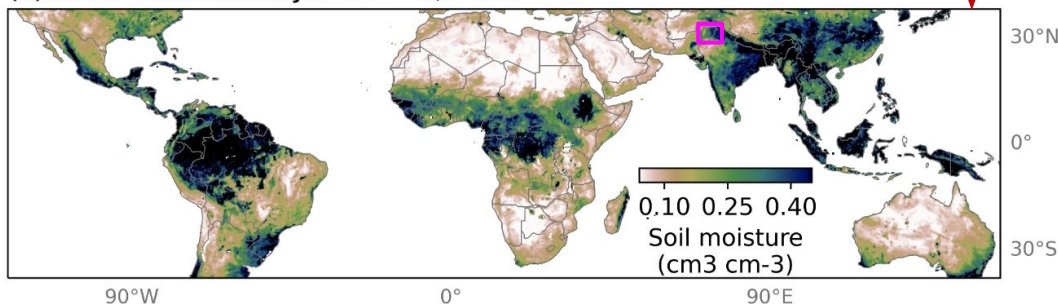
(a) Muon GNSS-R Retrievals: Jan 1 - 14, 2020



(b) Muon GNSS-R Retrievals: Jul 12 - 25, 2020



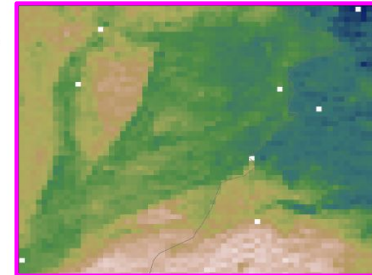
(c) SMAP Retrievals: Jul 12 - 25, 2020



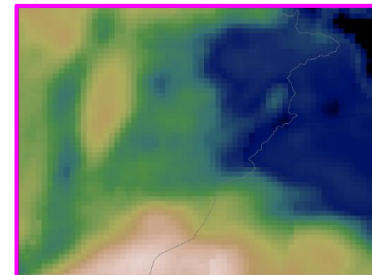
(d) MODIS Aqua



(e) Muon GNSS-R



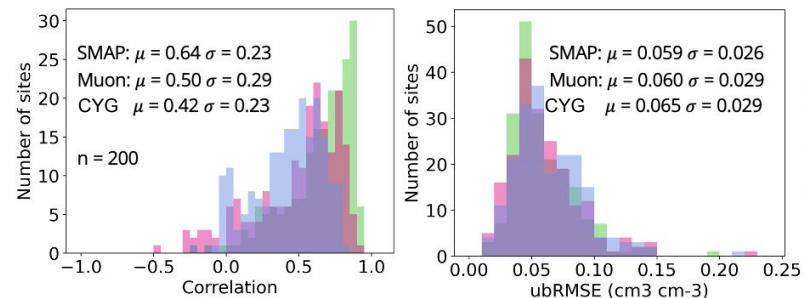
(f) SMAP



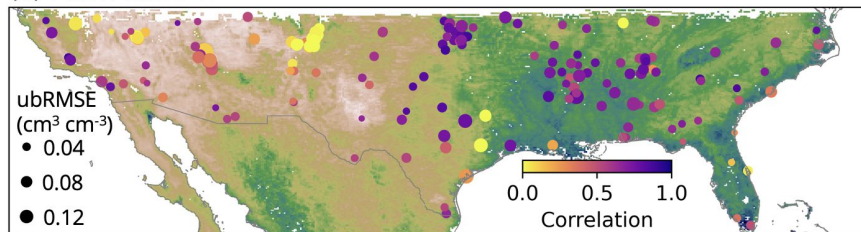
# Validation of Muon's CYGNSS Soil Moisture



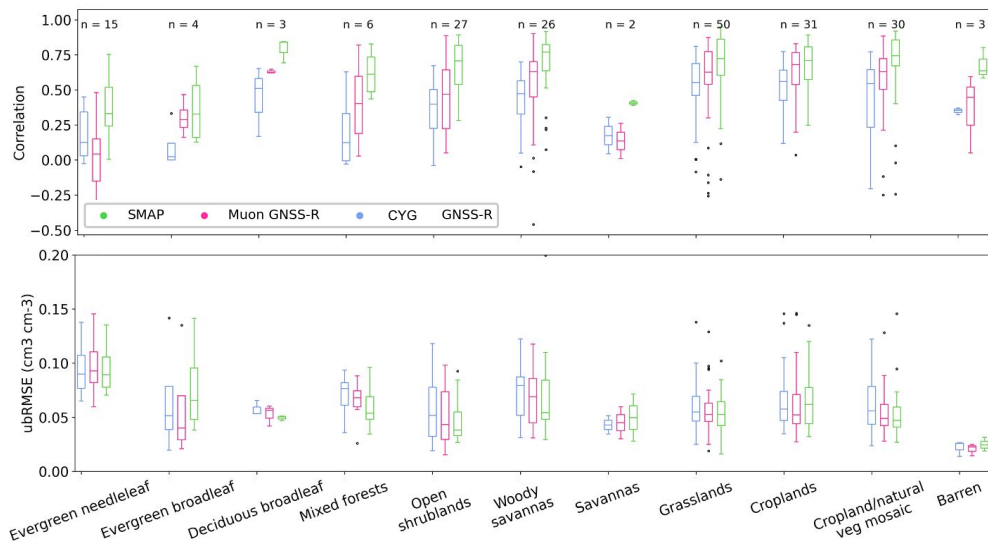
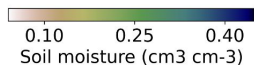
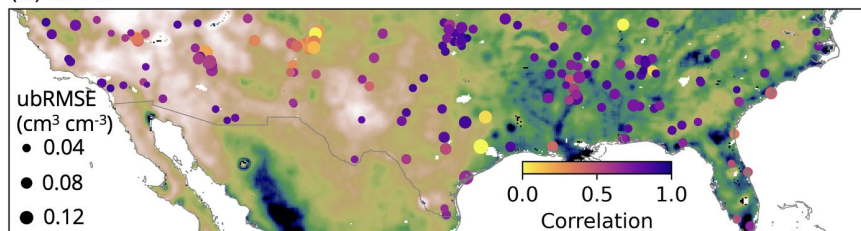
We are finalizing a manuscript detailing our CYGNSS GNSS-R soil moisture product and its validation. These show some of the statistics at in situ sites in CONUS (labeled Muon GNSS-R), with equivalent statistics from SMAP and the official CYGNSS SM product for context (labeled CYG)



(a) Muon GNSS-R

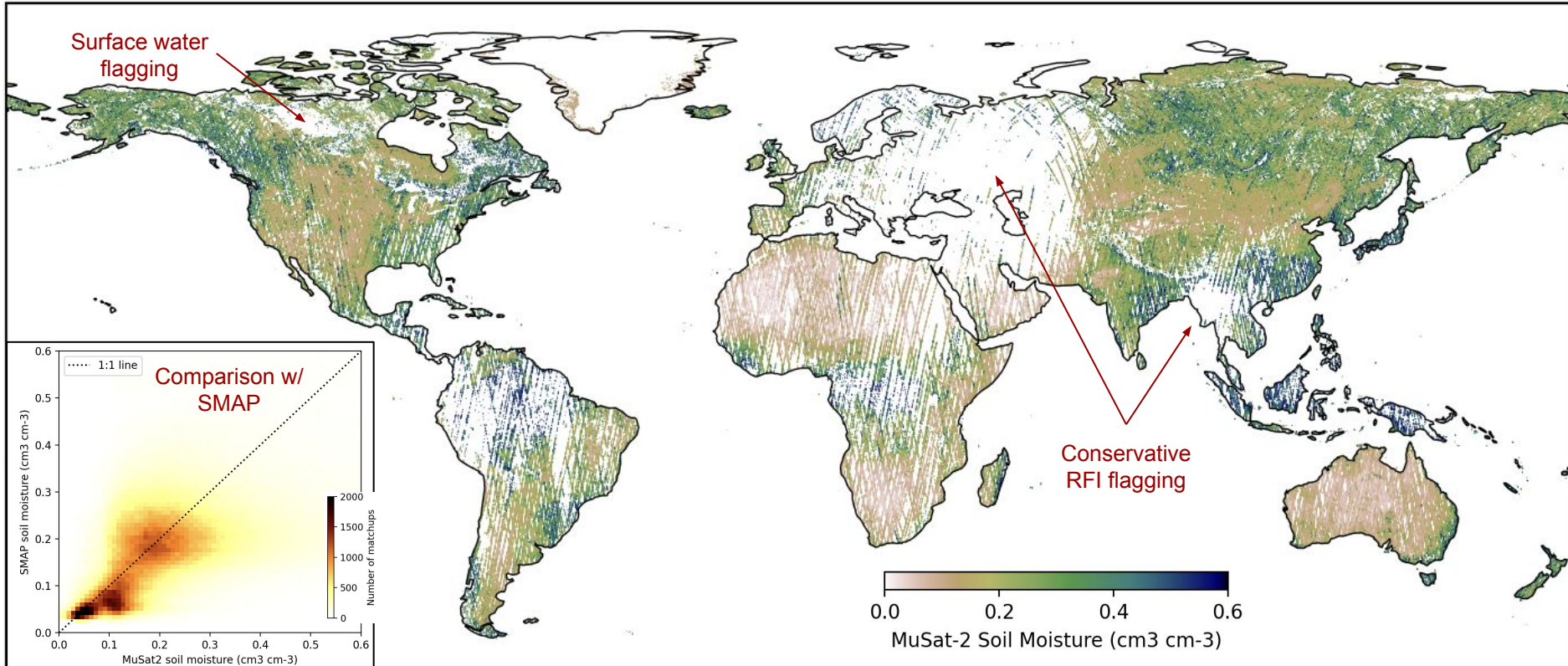


(b) SMAP



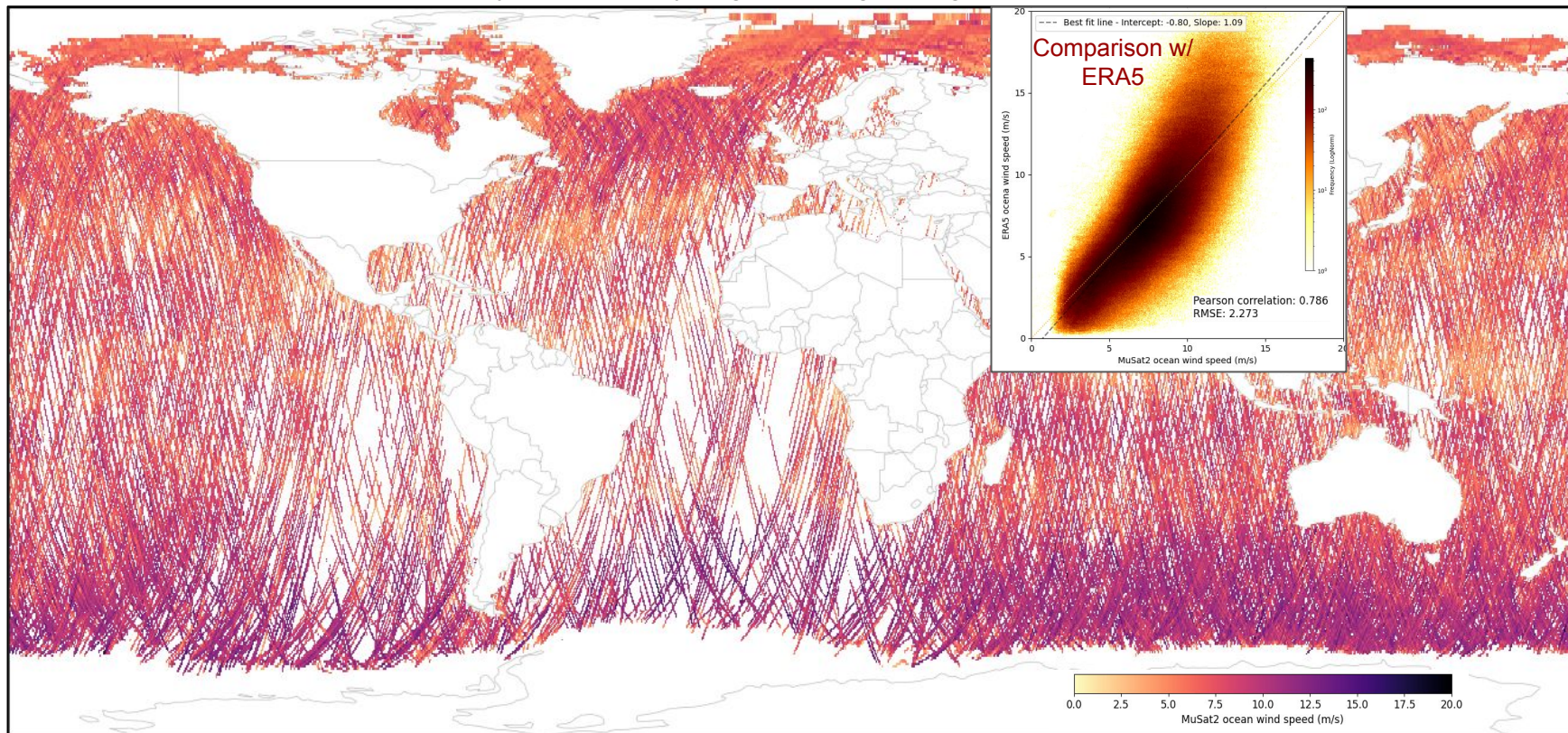
# Initial MuSat2-Only Soil Moisture Retrievals

LHCP-only initial soil moisture retrievals May 27 - August 19, 2024, retrieved with temporary empirical approach and filtered with a preliminary set of quality flags, show expected spatial patterns and agreement with SMAP



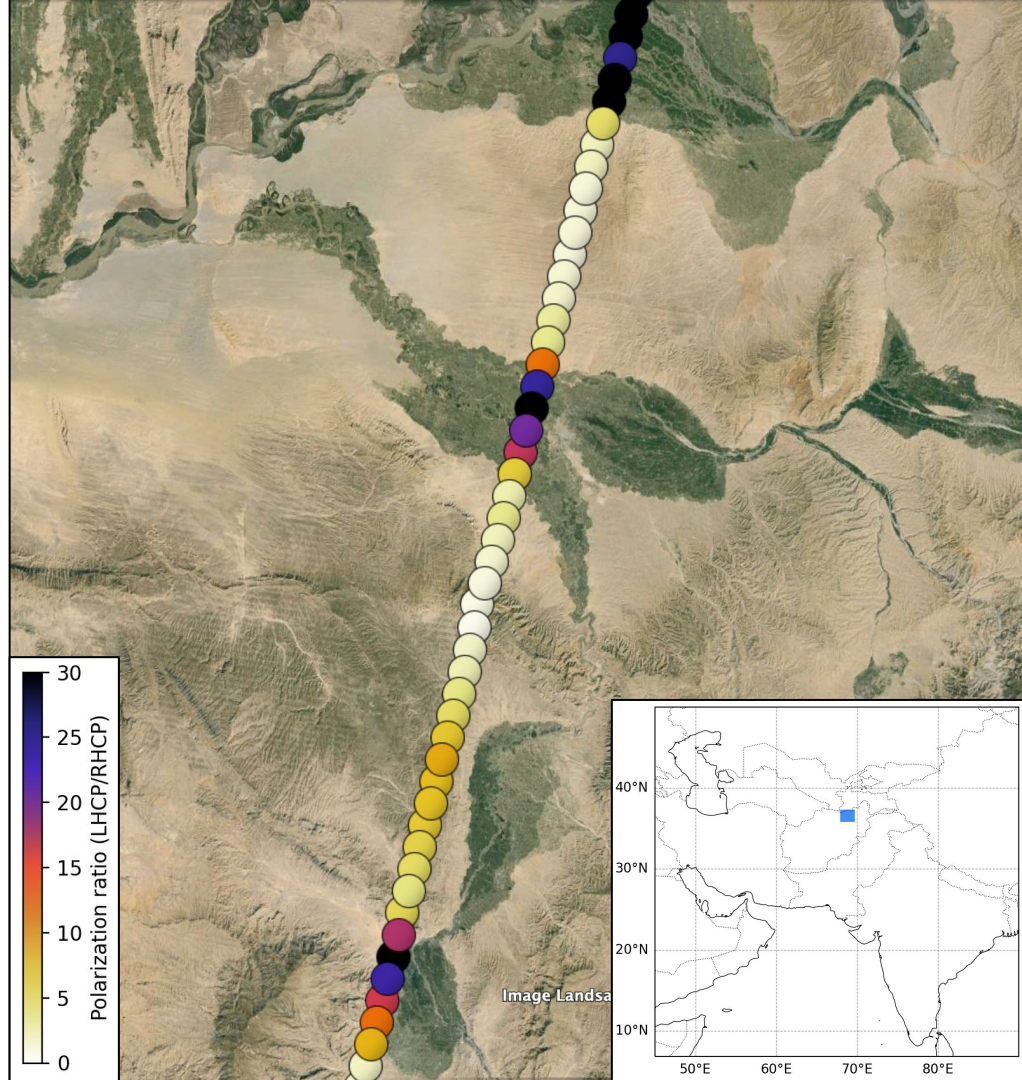
# Initial MuSat2-Only Ocean Wind Speeds

LHCP-only initial ocean wind speed retrievals May 27 - August 19, 2024, based on ML, limited training data, and filtered with a preliminary set of quality flags, show good agreement with ERA5 winds



# First Peek at MuSat2 Dual-Pol Observations

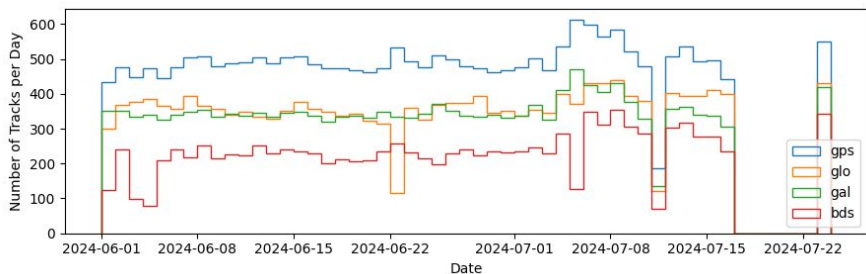
- MuSat2 is collecting **simultaneous LHCP and RHCP surface reflections**
- An example track of the polarization ratio is shown on the right, which crosses over agricultural areas interspersed amongst arid regions in northeastern Afghanistan
- Muon is investigating ability of polarization ratio to help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



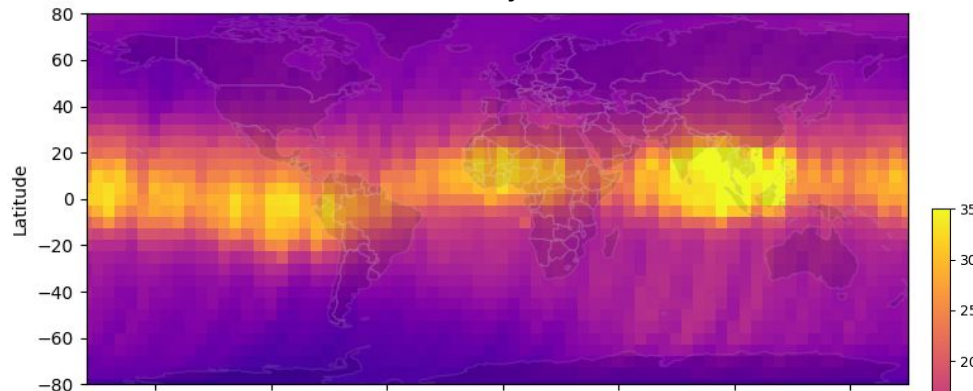
# Initial MuSat2 TEC Product

- Mapped from sTEC to vTEC above satellite [Foelsche & Kirchengast, 2002]
- Expected temporal/geographic trends observed
- Maps use 10% of all obs from June 1-July 22
- Day assumed to be local time between 6 am and 6 pm
- Longitudinal oscillations are an artifact of MuSat2 SSO orbit and solar activity

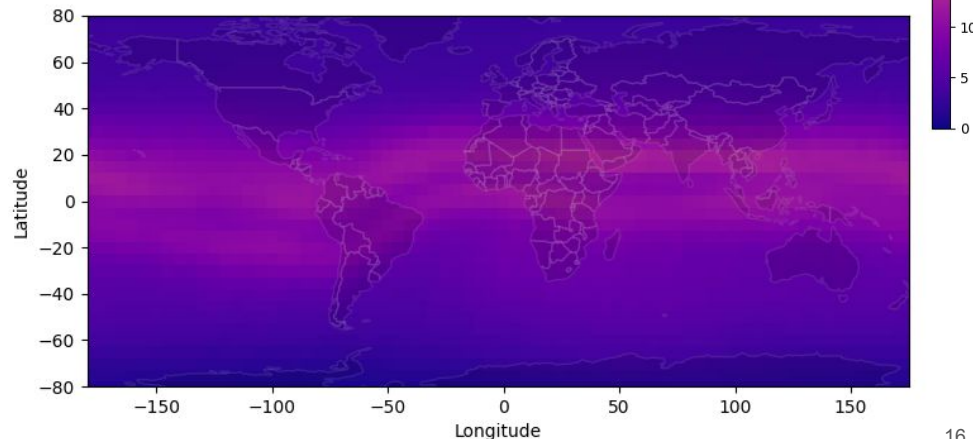
### Quantity of MuSat2 TEC Arcs/Day



### Day



### Night





# Plan for Muon GNSS Satellites

## MuSat1 (June 2023)

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



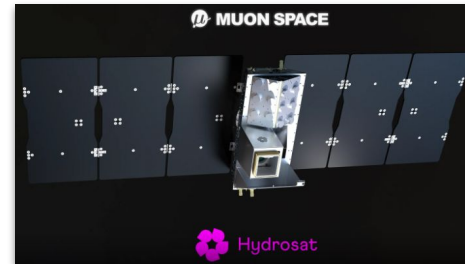
## MuSat2 (Mar. 2024)

- MuSat1 heritage with **polarimetric GNSS-R** payload
- First data collections under review



## 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 **TC winds**



**Three Muon GNSS-R sats operating in 2025**

# Summary

- Muon Space, a new small satellite company, has started launching GNSS-based payloads on its **satellite constellations for sustained Earth observations**
- **MuSat2**, launched March 4, 2024 into a **polar orbit**, merges NASA-developed antennas with Muon's software-defined radio (SDR) GNSS receiver to perform GNSS-R
- The MuSat2 payload can perform **dual-polarization (LHCP & RHCP)** and **dual-frequency (L1 & L5) GNSS-R observations** with similar gain and FOV as CYGNSS
- MuSat2 is **healthy** and continuously collecting **dual-pol GPS L1CA reflections**
- Muon has developed GNSS-R soil moisture, ocean wind, and TEC products for an ongoing **USAF Commercial Weather Data Pilot (CWDP) contract**, including **operational CYGNSS-based products**
- **MuSat2 soil moisture, ocean wind speed, and TEC products** are being produced and supplied to the USAF and NOAA
- Muon will continue launching GNSS-R payloads, including a **high-gain, beamforming LHCP antenna in early 2025 on MuSat4**, and likely as a secondary payload on a large constellation for fire monitoring



# MuonSpace

Thanks your attention!

Muon is actively seeking collaborations with academic, government, and non-governmental organizations that wish to trial data or discuss opportunities for missions and hosted payloads.

Please contact [dallas@muonspace.com](mailto:dallas@muonspace.com) for opportunities.