Muon Space Constellation for GNSS-Based Remote Sensing

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![MuonSpace logo]

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

Muon

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, SoOpr 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
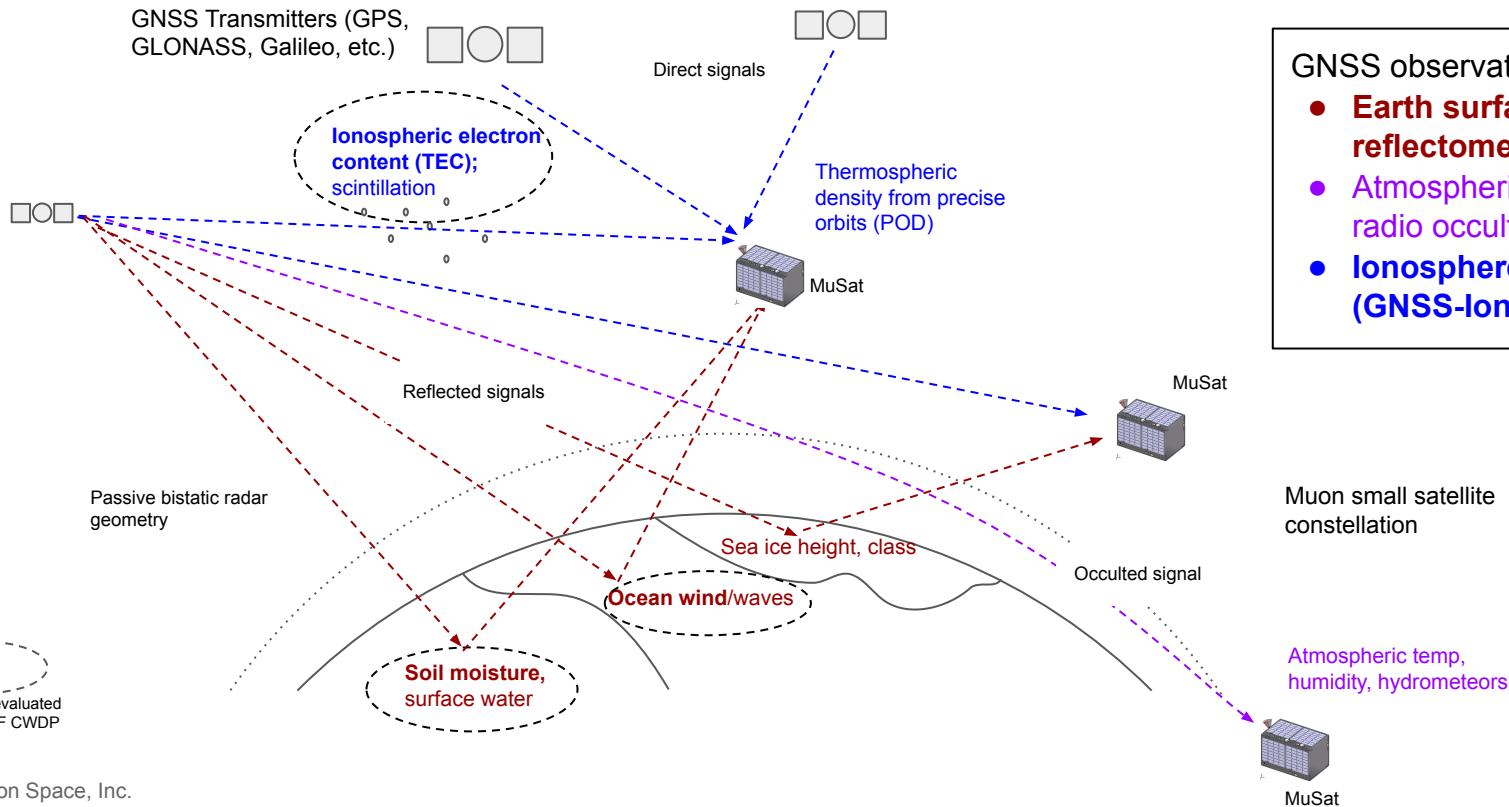**Geospatial Data Engineer**
ML Scientist, Spire

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 Transmitters (GPS, GLONASS, Galileo, etc.)

Direct signals

Ionospheric electron content (TEC); scintillation

Thermospheric density from precise orbits (POD)

MuSat

Reflected signals

MuSat

Passive bistatic radar geometry

Sea ice height, class

Ocean wind/waves

Muon small satellite constellation

Occulted signal

Products evaluated under USAF CWDP contract

Soil moisture, surface water

Atmospheric temp, humidity, hydrometeors

MuSat

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

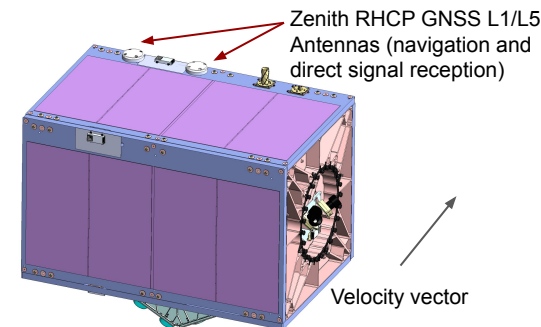# MuSat2: Muon's First GNSS-R & TEC Satellite

- **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

Zenith RHCP GNSS L1/L5 Antennas (navigation and direct signal reception)

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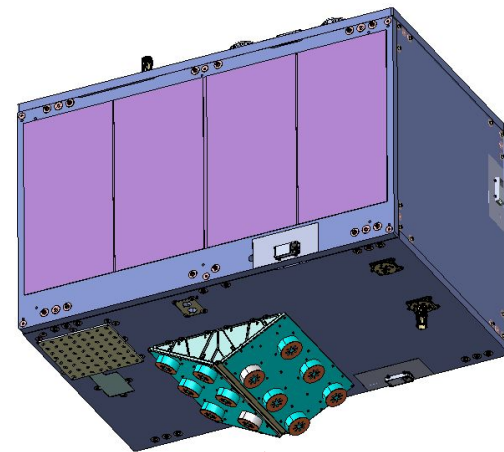
Port and starboard nadir **dual-pol R/LHCP, L1/L5** GNSS-R antennas pointing across track and 28 deg off nadir (reflected signal)

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**


Dual-pol antennas
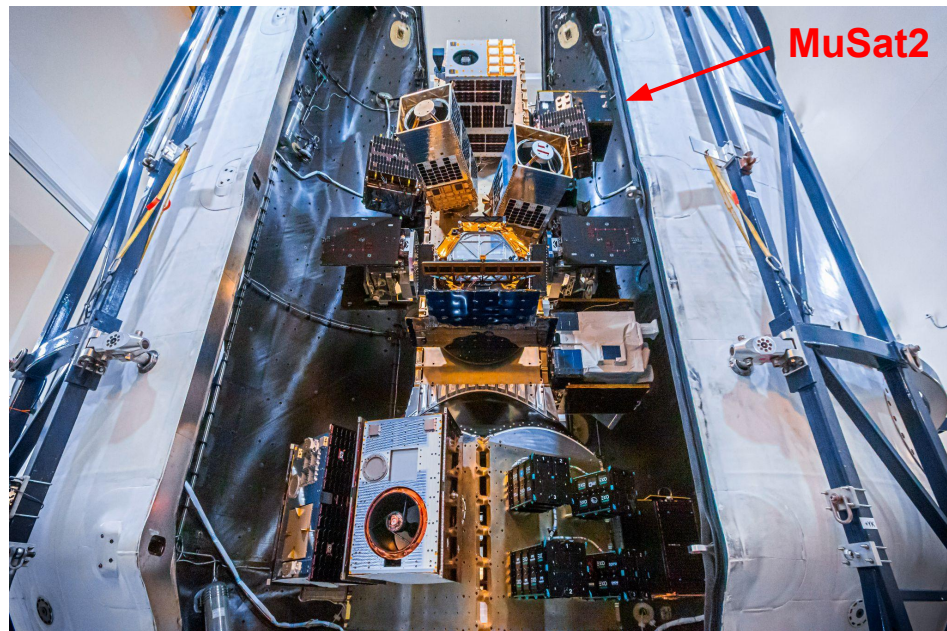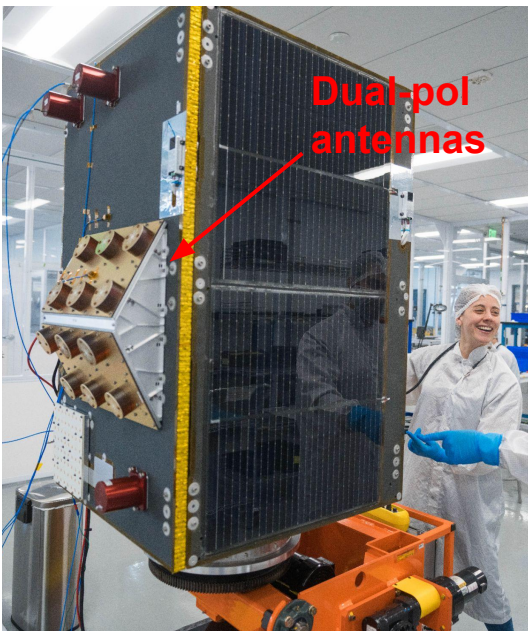
MuSat2

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: ⅛ 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
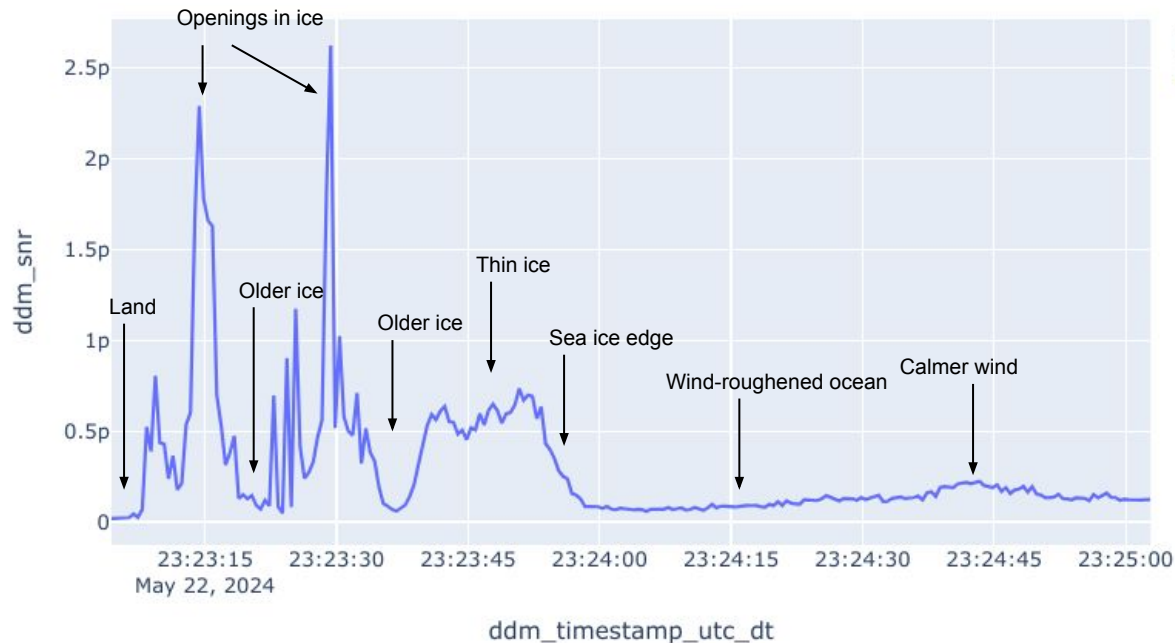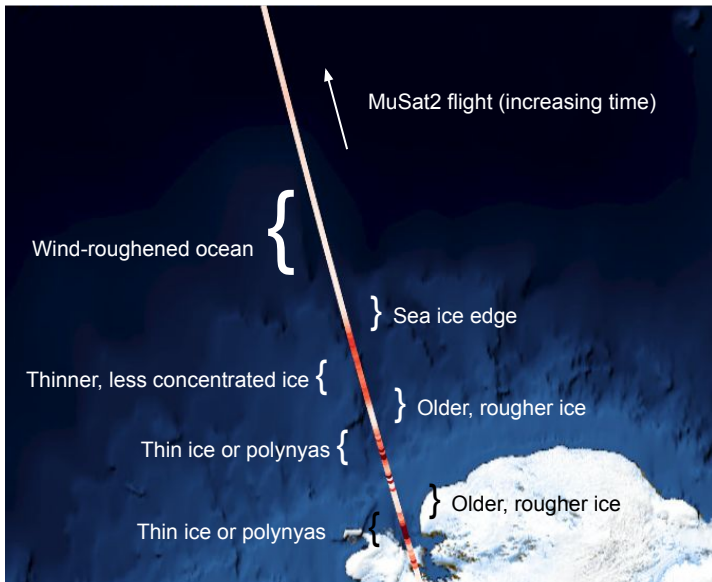
- First scheduled data collections: May 22 captured **transition from land → sea ice → open ocean** in Antarctica
- **Typical reflected power signatures** over each surface type, with sensitivity to highly reflective thin sea ice and older, rougher ice and open ocean, wind-roughened seas

MuSat2 Early Results: Comparisons to CYGNSS 𝓾 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)

South Africa

CYGNSS gridded SNR background

MuSat2 track
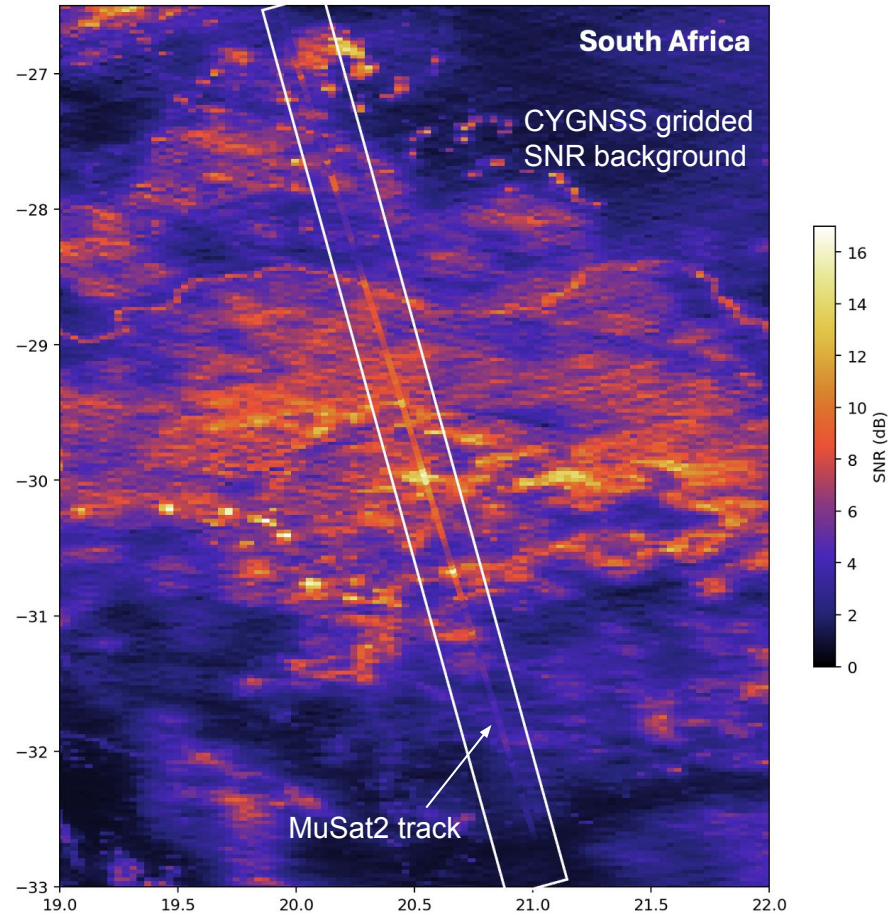
Operational Products Built Using CYGNSS Data

- 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
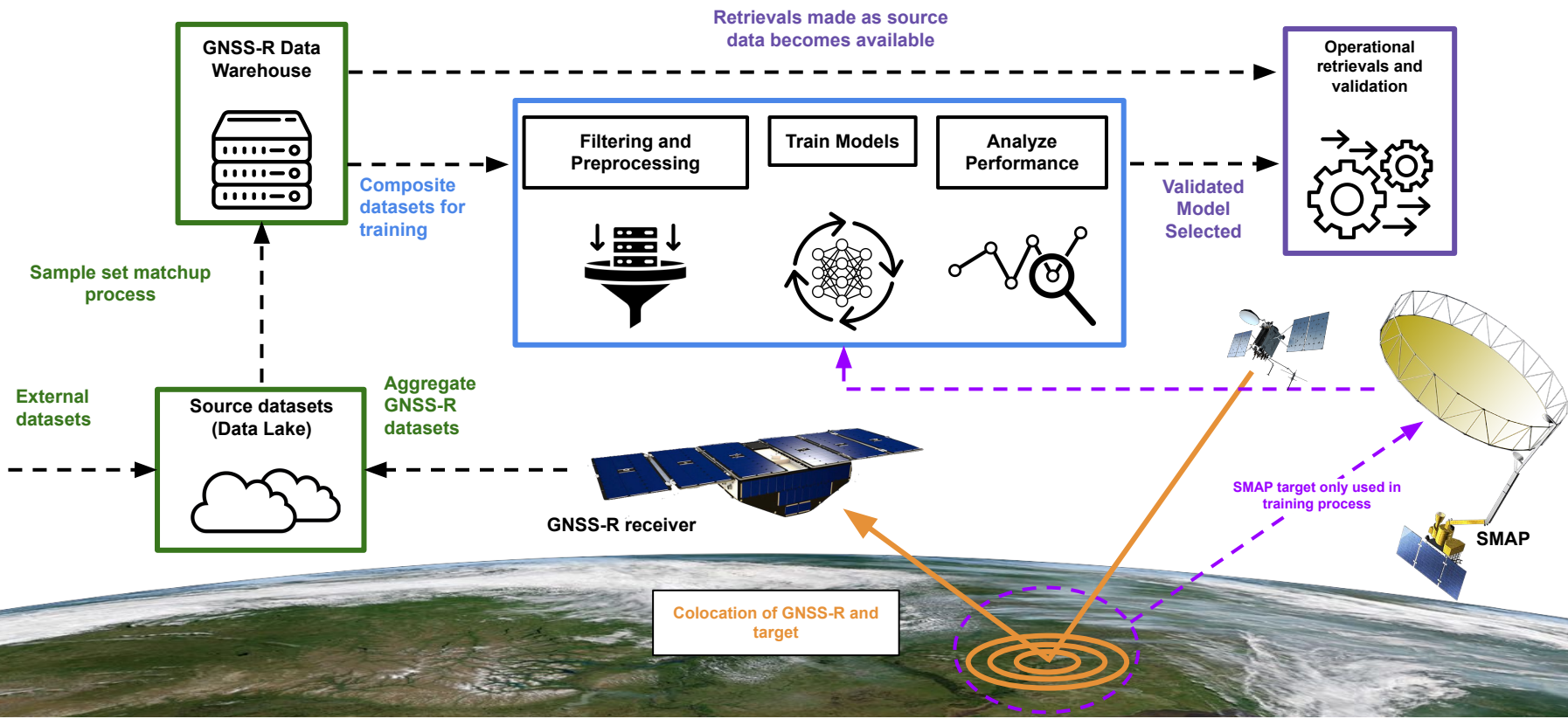
Comparison of Muon's CYGNSS SM with SMAP

- 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

Soil moisture (cm3 cm-3) 0.10 0.25 0.40

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

Soil moisture (cm3 cm-3) 0.10 0.25 0.40

GNSS-R seasonal change

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

Soil moisture (cm3 cm-3) 0.10 0.25 0.40

GNSS-R vs. SMAP
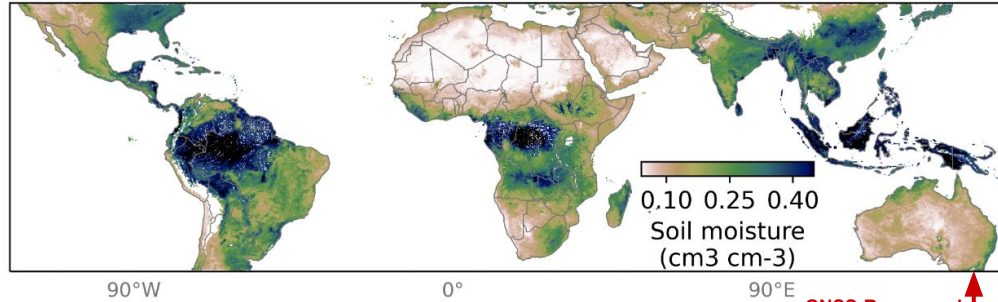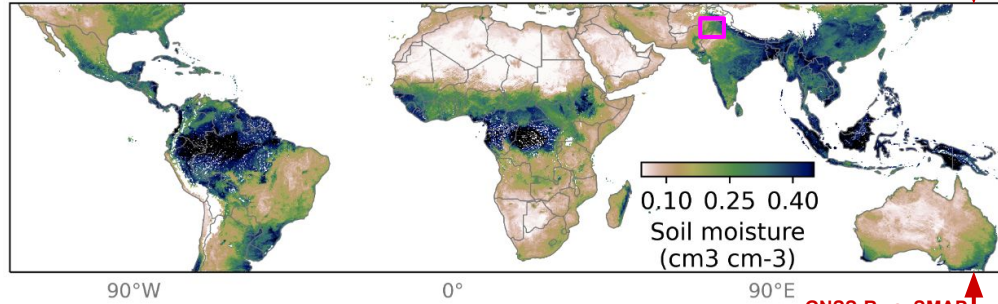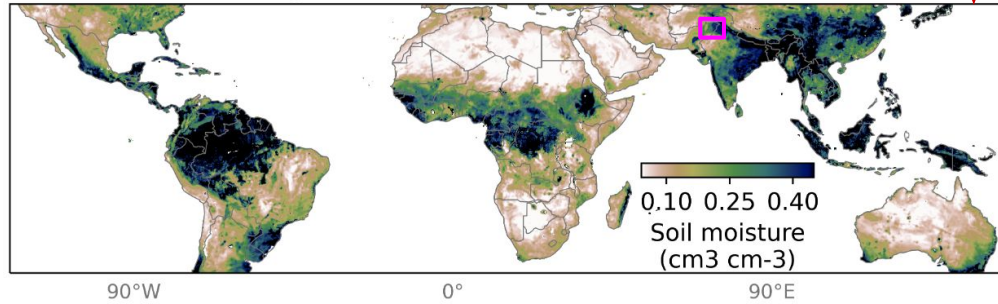
(d) MODIS Aqua
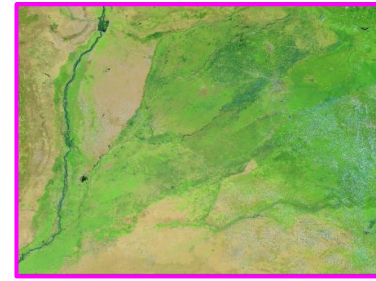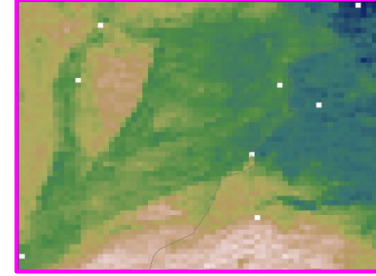
(e) Muon GNSS-R

(f) SMAP
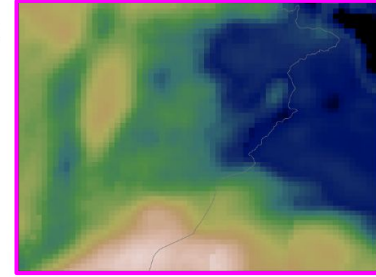
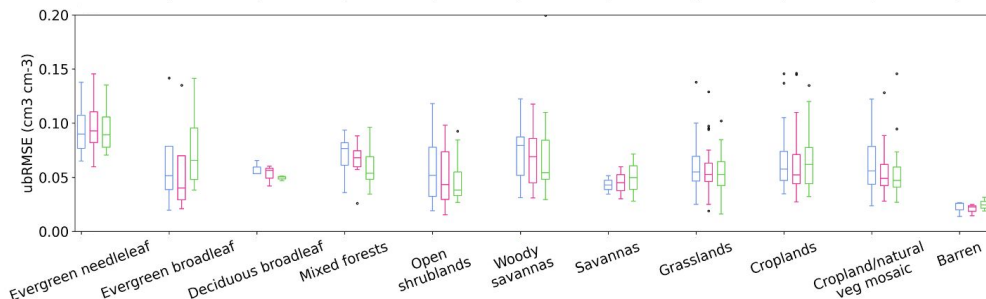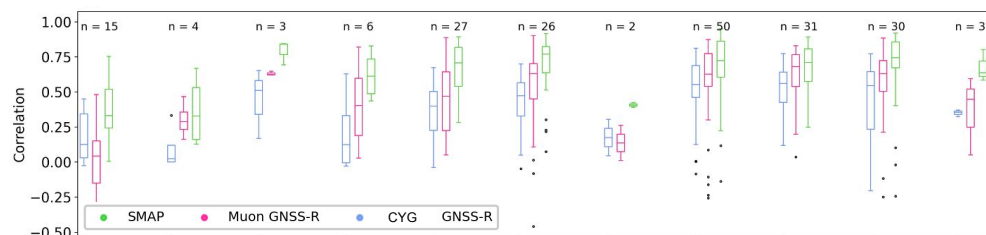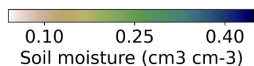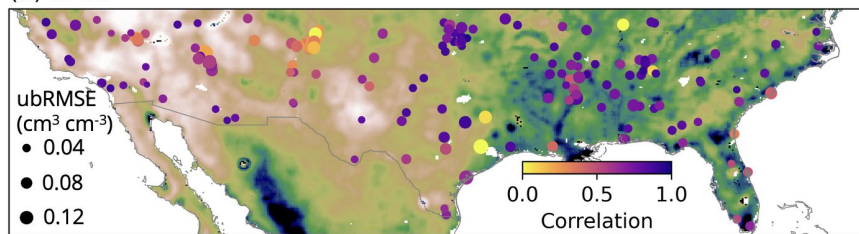# Validation of Muon's CYGNSS Soil Moisture

Muon

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)
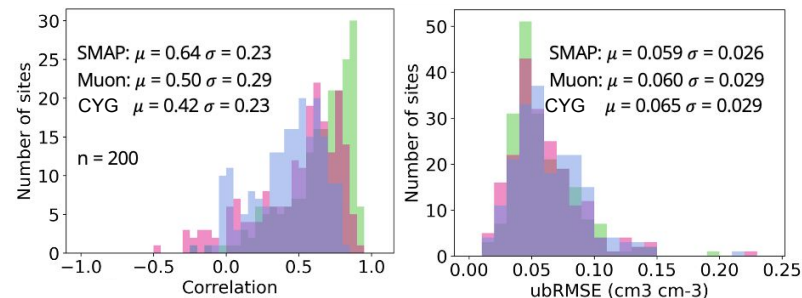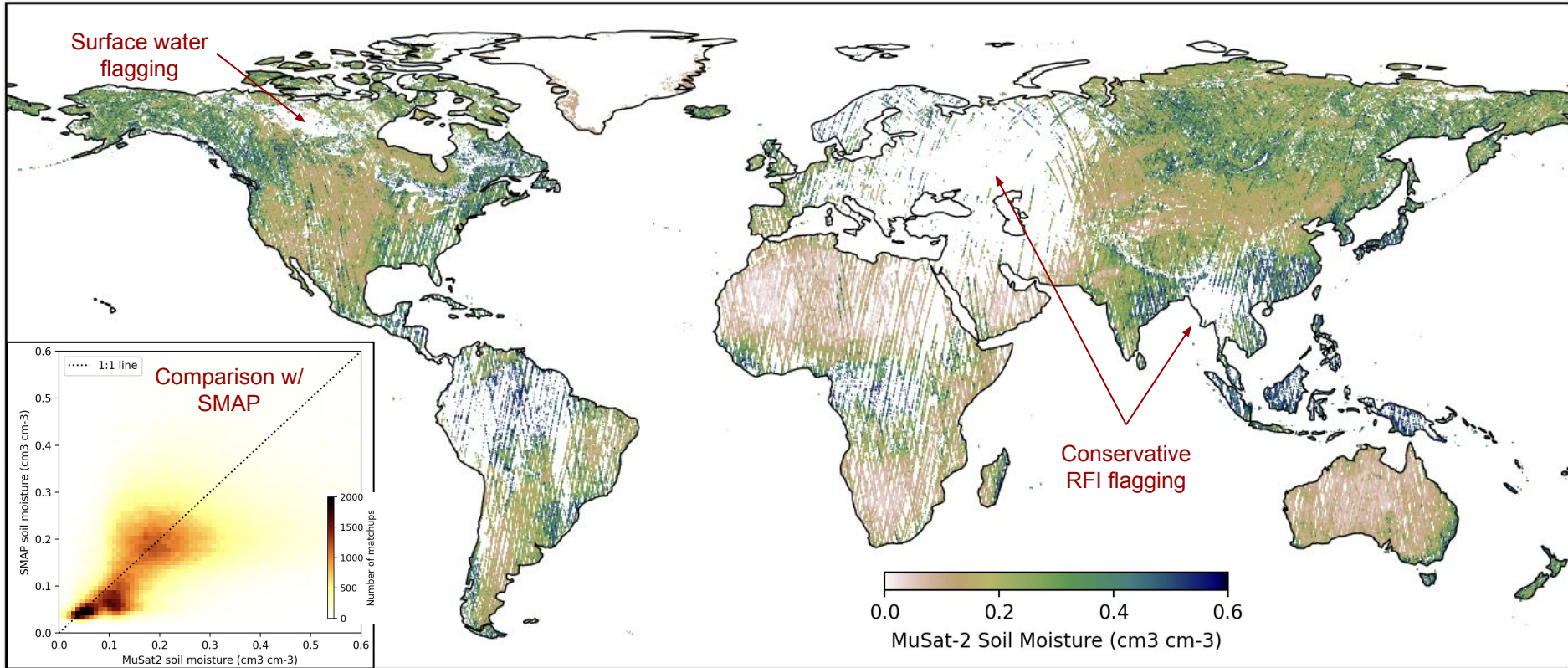

(a) Muon GNSS-R
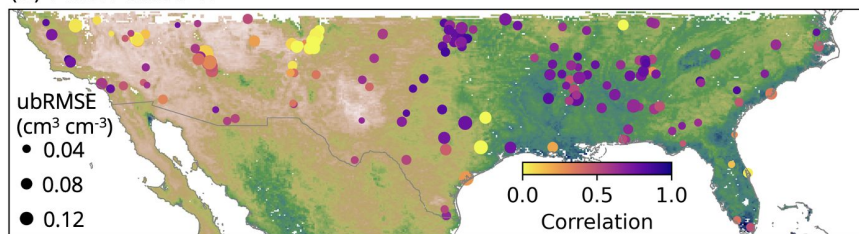
(b) SMAP

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
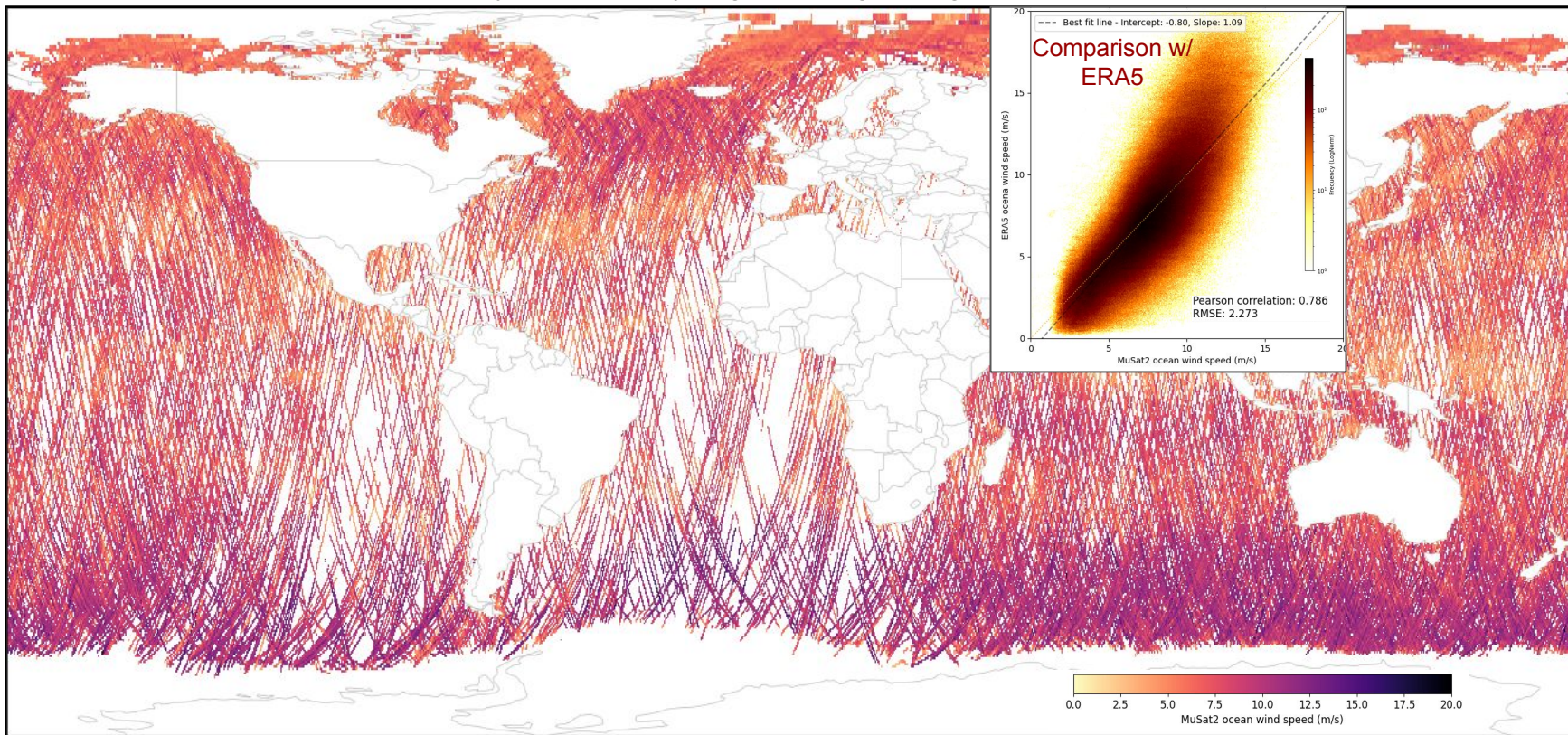
First Peek at MuSat2 Dual-Pol Observations

- 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**


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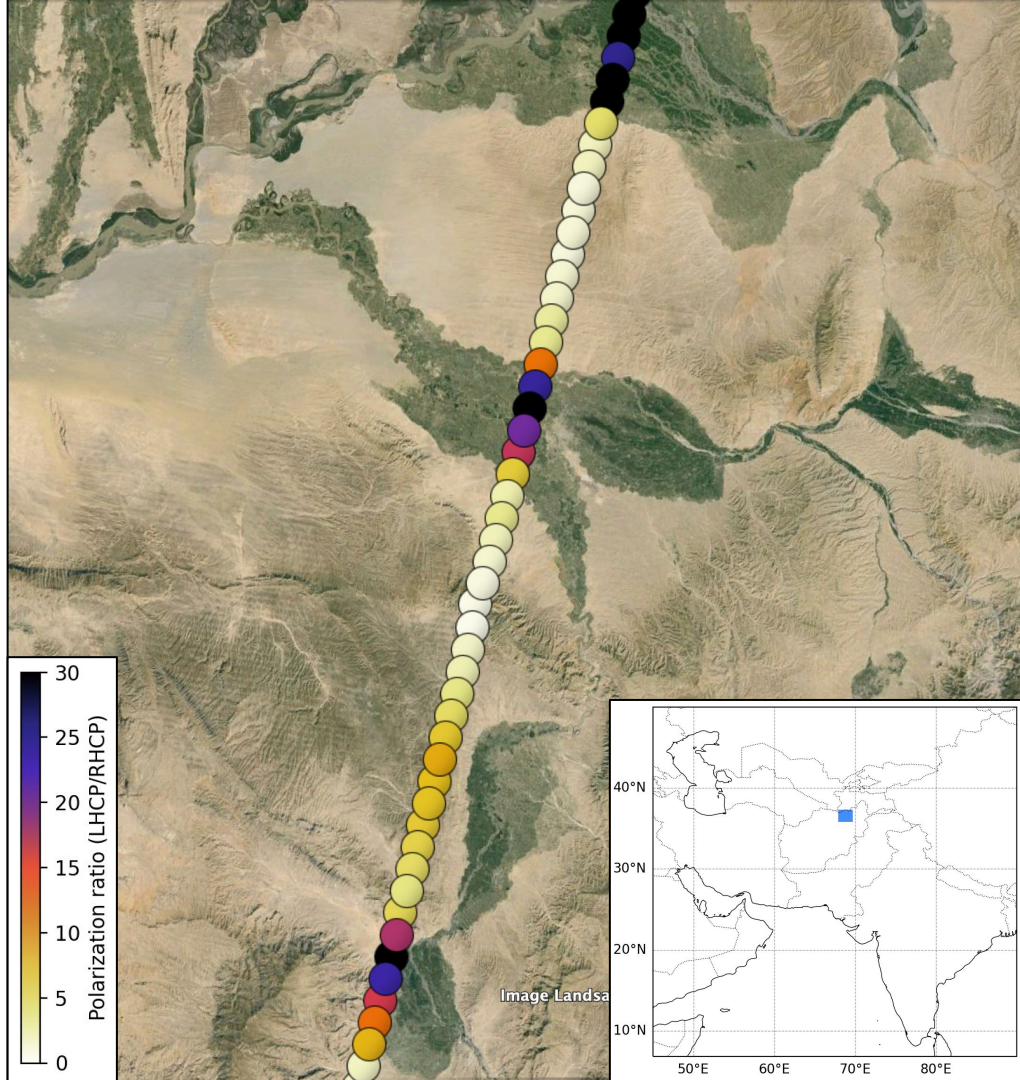
Initial MuSat2 TEC Product

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- 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
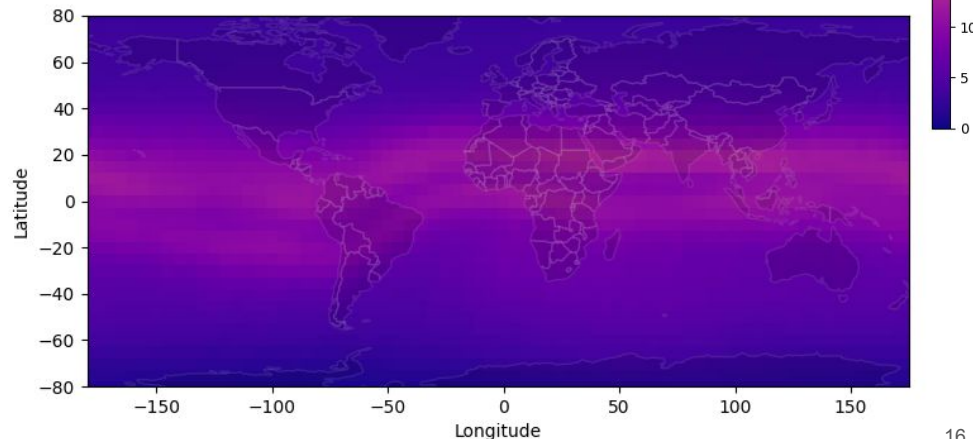
Quantity of MuSat2 TEC Arcs/Day
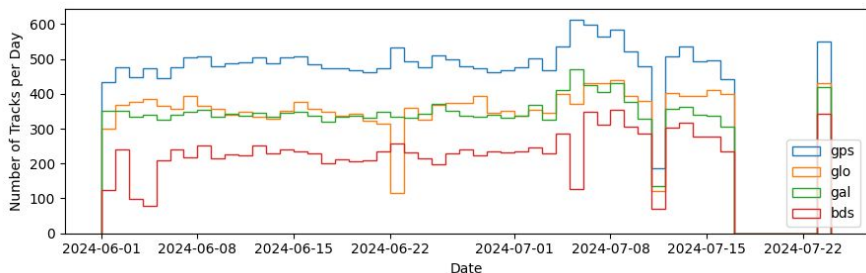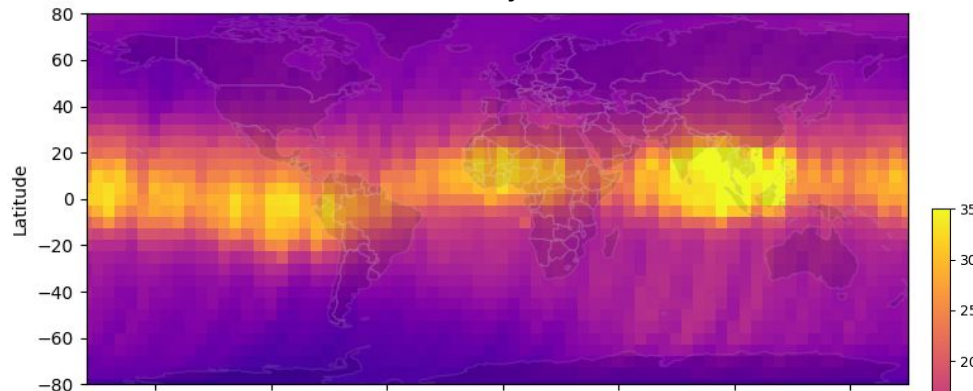
Plan for Muon GNSS Satellites

Muon

MuSat1 (June 2023)

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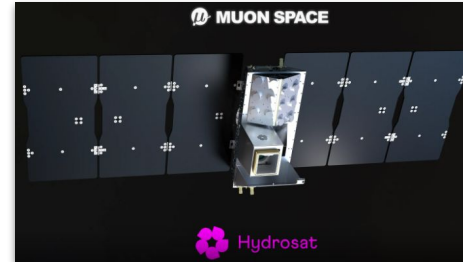- Operating nominally

MuSat2 (Mar. 2024)

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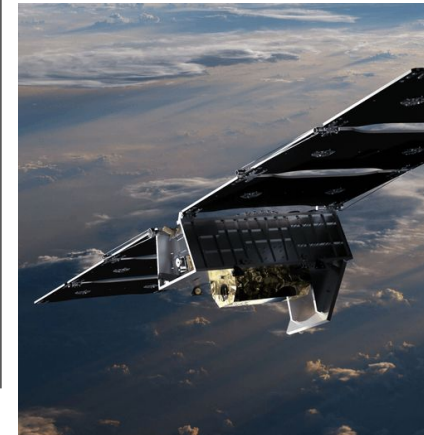- First data collections under review

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

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 for opportunities.