

# Introduction to the Muon Space Small Satellite Constellation

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2023 Polarimetric RO Workshop

## *What is Muon Space's mission?*

- We believe there is a lack of knowledge of the Earth 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 one-off pathfinder class missions and large operational weather missions, with a slow (broken?) 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, while still being relatively inexpensive to launch
- **Muon Space is building this small satellite constellation solution**

# Muon Space: An EO Constellation Company



- Muon is deploying global, scientific-grade **constellations of remote sensing satellites for actionable climate intelligence**
- Muon is **vertically integrated**, building full mission solutions to address EO challenges — **from instruments and spacecraft to rapid delivery of data and value-added products**
- Muon also enables climate-focused customers to rapidly **formulate, execute, and deliver sensors, spacecraft, and environmental data** through our Constellation-as-a-Service (CaaS) and hosted payloads opportunities

Founded

**2021**

Team

**60+**

Funding

**\$35M**

Located in

**Mt. View, CA**



# Muon Experience in Small Satellite EO



**Jonny Dyer**  
**CEO**  
Chief Engineer,  
Skybox Imaging  
Principle Engineer,  
Google  
Sr. Director, Lyft  
Level5  
Technical Advisory  
Group, MethaneSat



**Dr. Dan McCleese**  
**Chief Scientist**  
NASA JPL Chief  
Scientist  
Director, JPL  
Innovation Foundry  
Chair, Science  
Advisory Group,  
MethaneSat  
PI, Mars Climate  
Sounder



**Dr. Pascal Stang**  
**CTO**  
Vehicle Tech Lead,  
Loon  
Director AV  
Platform, Lyft  
Avionics Architect,  
Skybox



**Greg Smirin**  
**President**  
Climate Corporation,  
Scuba Analytics, Premise  
Data, VeriSign



**Dr. Reuben  
Rohrschneider**  
**Chief Mission  
Architect**  
Principal Sys. Eng,  
Ball  
Chief Engineer,  
MethaneSat



**Paul Day**  
**COO**  
CPO, Loft Orbital  
P&M Lead, Apple  
AI&T Lead, Skybox



**Jim Martz**  
**VP Engineering**  
Director Eng,  
SpaceX  
Systems Eng, JPL  
Avionics Lead,  
Zipline

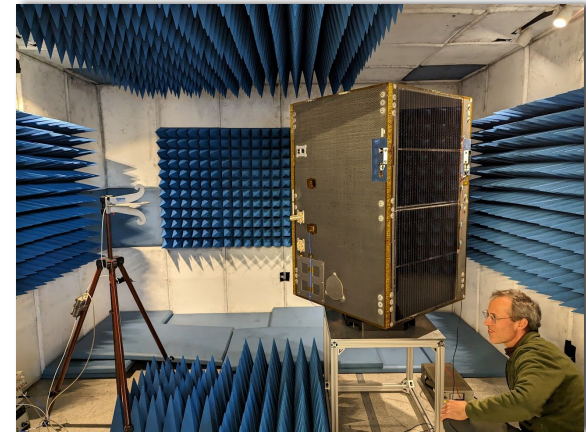


**Dr. Dallas Masters**  
**VP Signals of Opportunity  
Program**  
Director EO, Spire  
Research Scientist, U.  
Colorado  
Project Scientist, NCAR

Former leaders from **Skybox, Google, Planet, Loon, JPL, SpaceX, Ball Aerospace, Climate Corporation, and Spire**, with extensive Earth observation mission experience, from basic science and engineering design to manufacturing and operations.

# MuSat Constellation

- Muon Space is developing a line of **small satellites in support of Earth observation constellations**
- The spacecraft (known as “MuSats”) are designed with **modularity and platform flexibility** in mind, supporting a wide range of potential payloads
- **Signals of opportunity (SoOpr) technology will fly as an internally hosted payload on MuSats**, beginning with MuSat-2 in early 2024
- MuSat bus has ample SWaP for **additional rideshare payloads**



## MuSat-1

- First Muon satellite serving as prototype to test core avionics
- Launched in June 2023 and operating nominally



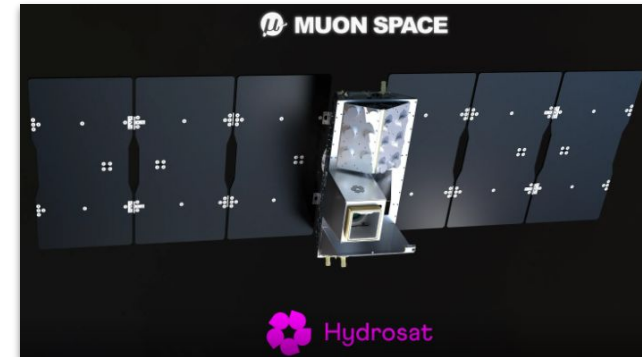
## MuSat-2

- MuSat-1 heritage with **polarimetric GNSS-R** payload
- Launch in March 2024
- **USAF customer of GNSS-R, TEC products**



## MuSat-3 (Hydrosat-1)

- Hosting Hydrosat's multispectral and TIR payloads
- Muon **polarimetric GNSS-R payload**
- Launch in Oct 2024



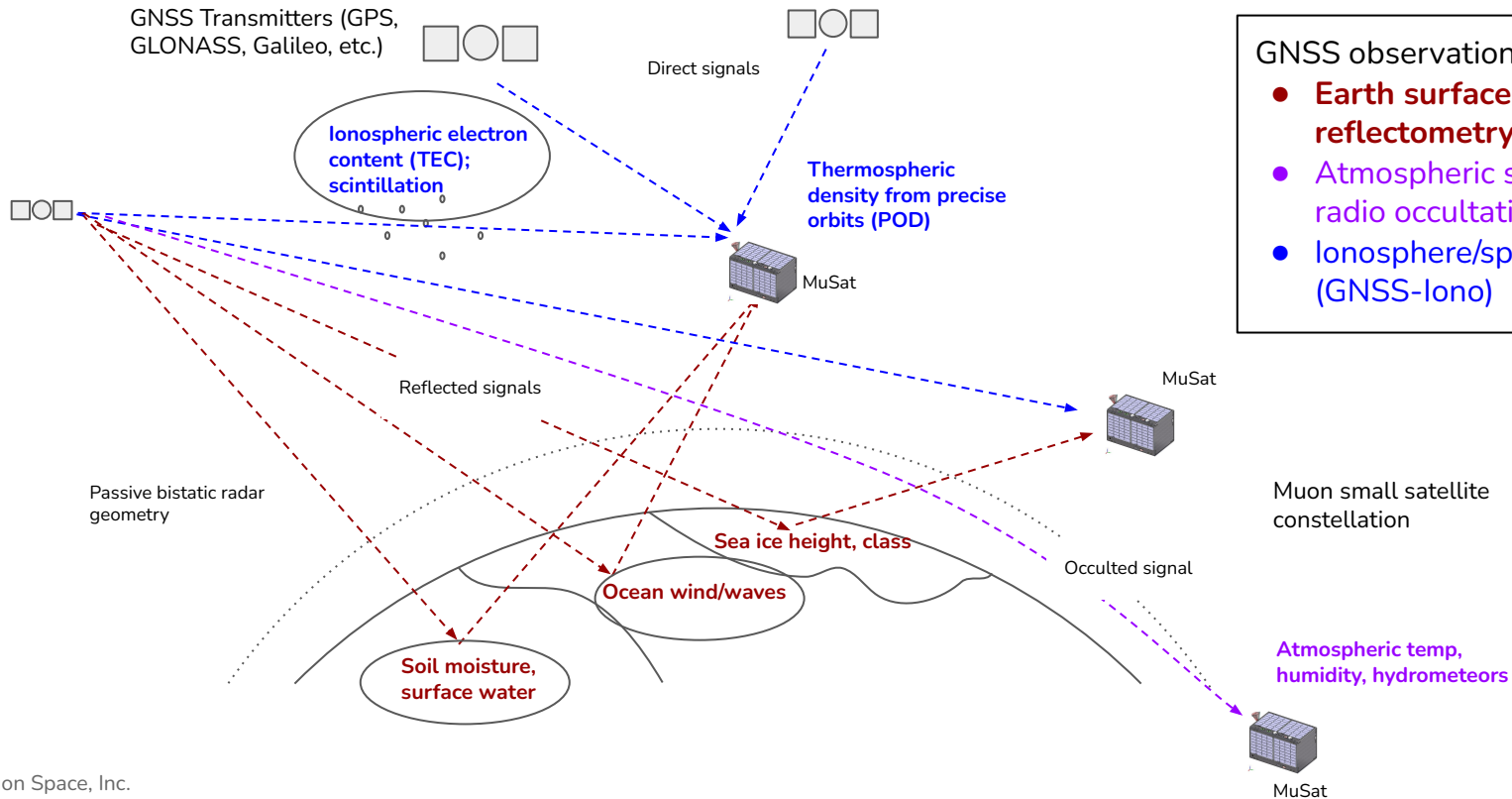
# MuSat-1 Launched June 12, 2023



MuSat-1 is serving as a testbed for the vertically integrated MuSat spacecraft. **First contact made and telemetry successfully received in about six minutes.** All systems healthy.

# EO Suited for Small Sat Constellations

Muon is harnessing decreasing launch costs and miniaturization of **technologies suited for remote sensing from small satellites**  
Examples: **signals of opportunity (SoOpr)**, 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)**

Muon small satellite constellation



# Muon Signals of Opportunity Program



## Muon “SoOpr” Program Goals

### *Build a Great Team of SoOpr Experts*

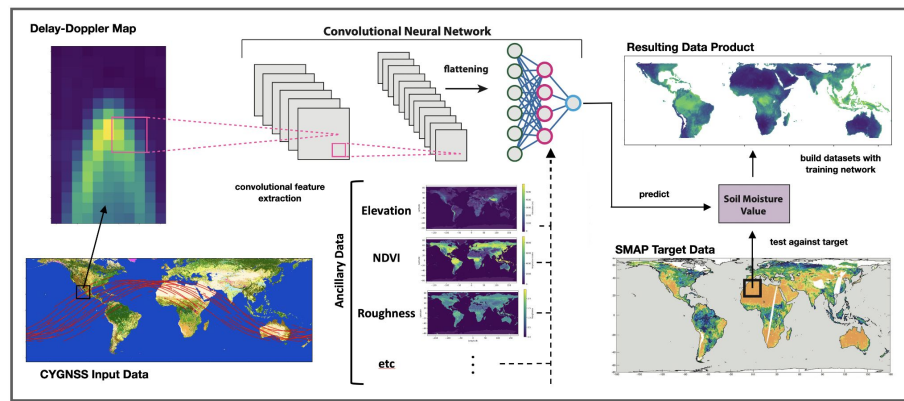
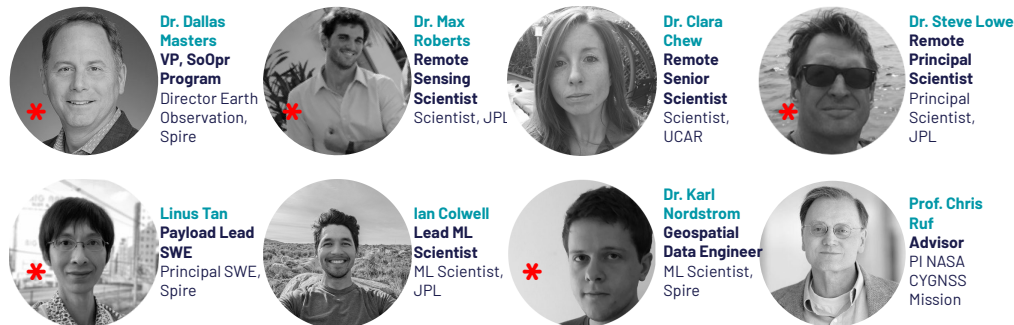
Muon is building a strong team spanning software-defined radios, antenna design, and **SoOpr science and products** e.g., GNSS-R, GNSS-RO, etc.

### *Collaborate with Partners & Customers*

For initial satellites, Muon is **partnered with University of Michigan** and **Ohio State University** to leverage and improve upon existing **dual-freq, dual-pol antenna** and **next-gen GNSS-R receiver** 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



GNSS-R CNN Soil Moisture Retrieval Algorithm  
Developed Max Roberts and Ian Colwell

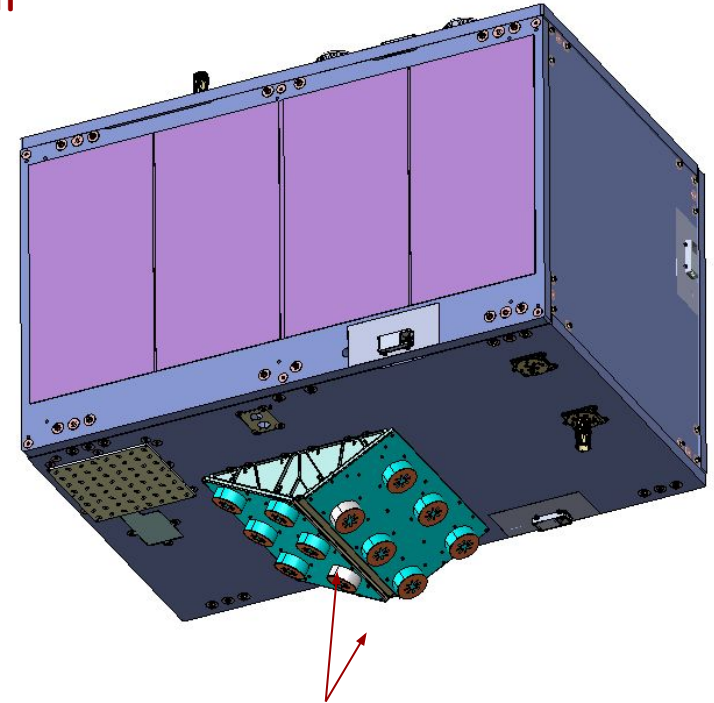
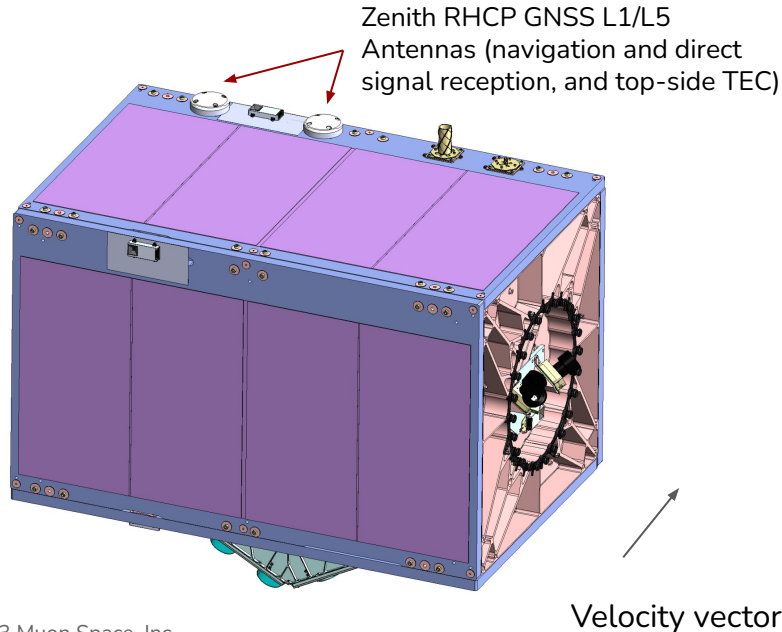
[Roberts et al., 2022]

\* Members of the team with GNSS-RO experience

# MuSat-2: Muon's First GNSS-R Satellite

MuSat-2 will sustain and **improve upon the CYGNSS mission**

- Launch: March 2024 on SpaceX Transporter 10
- Orbit: 500-600 km, SSO, LTAN 22:00-23:00
- Full global coverage to **observe all surface types**



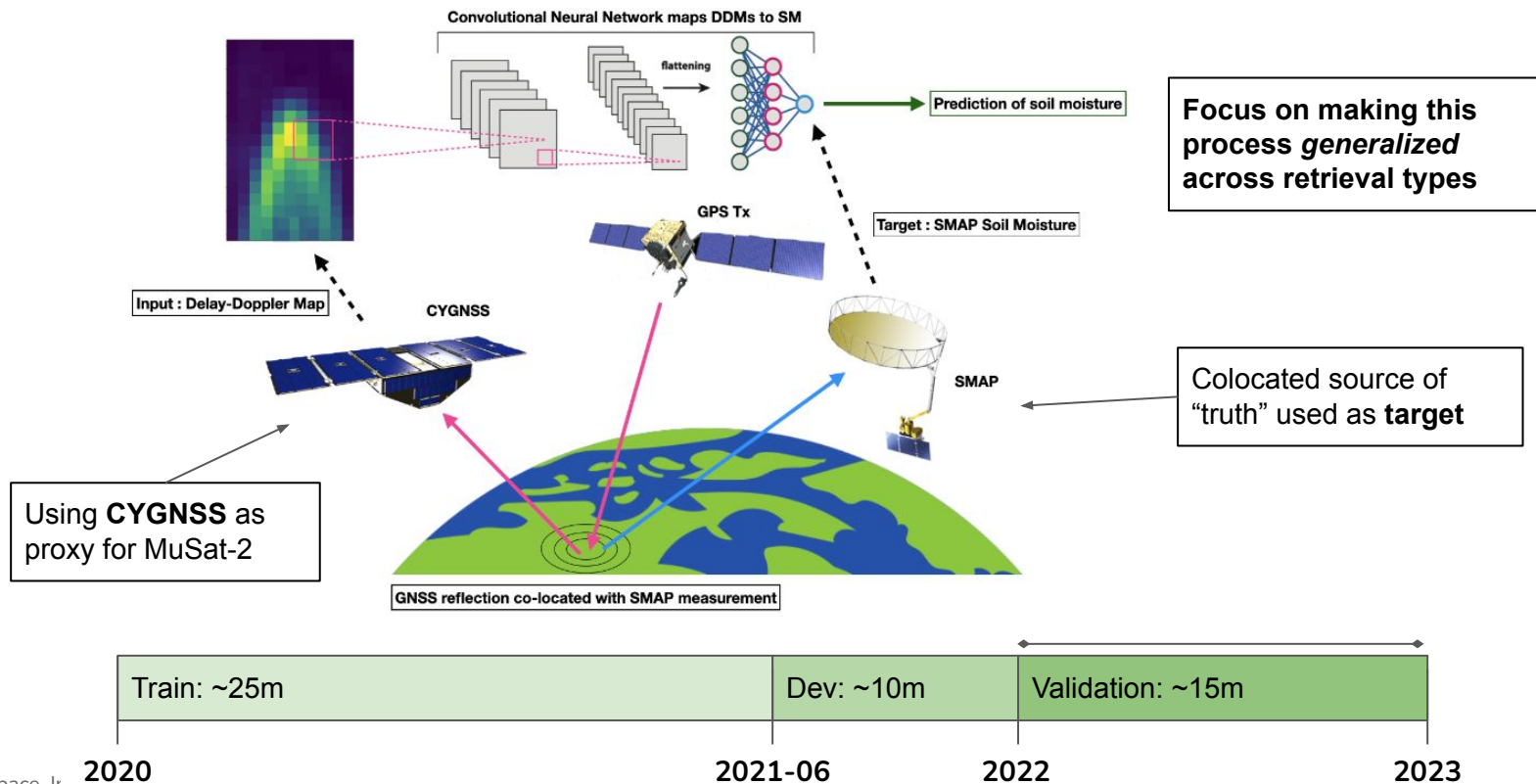
# MuSat-2: Leveraging NASA Technology

- MuSat-2 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 software-defined radio (SDR) receiver
    - Based on state of the art technology
    - Multiple channels, wide bandwidths, on-board compute
    - Leverages UM NGRx developed under NASA IIP
- Compared to CYGNSS, **MuSat-2 will add dual-pol, dual-freq (L1/L5) GNSS-R (similar to HydroGNSS), multi-constellation signals (GPS, Galileo, Beidou, QZSS), wider bandwidths, and tracking all signals in view**



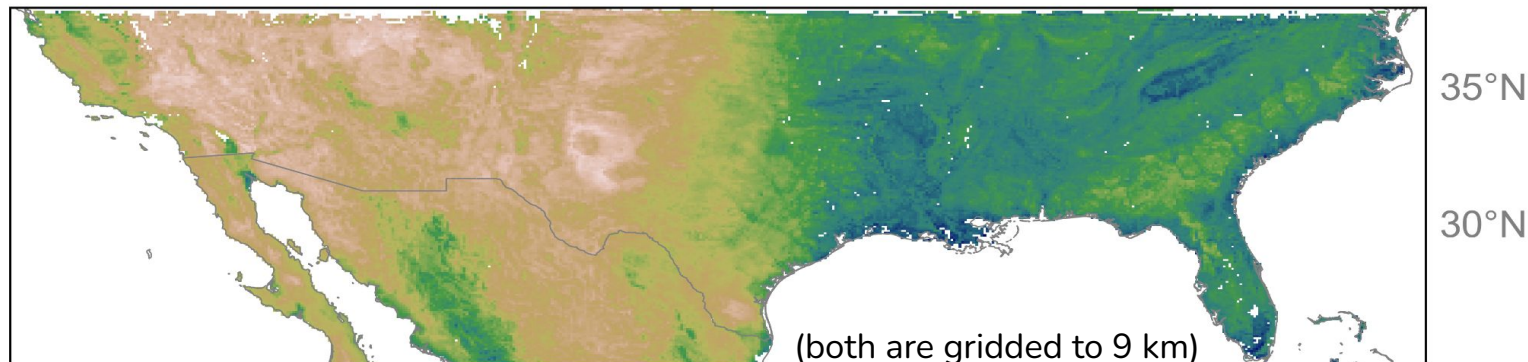
# MuSat-2: GNSS-R Product Development

Product development uses a **general machine learning framework** to address multiple products and applications  
Example GNSS-R soil moisture from CYGNSS:

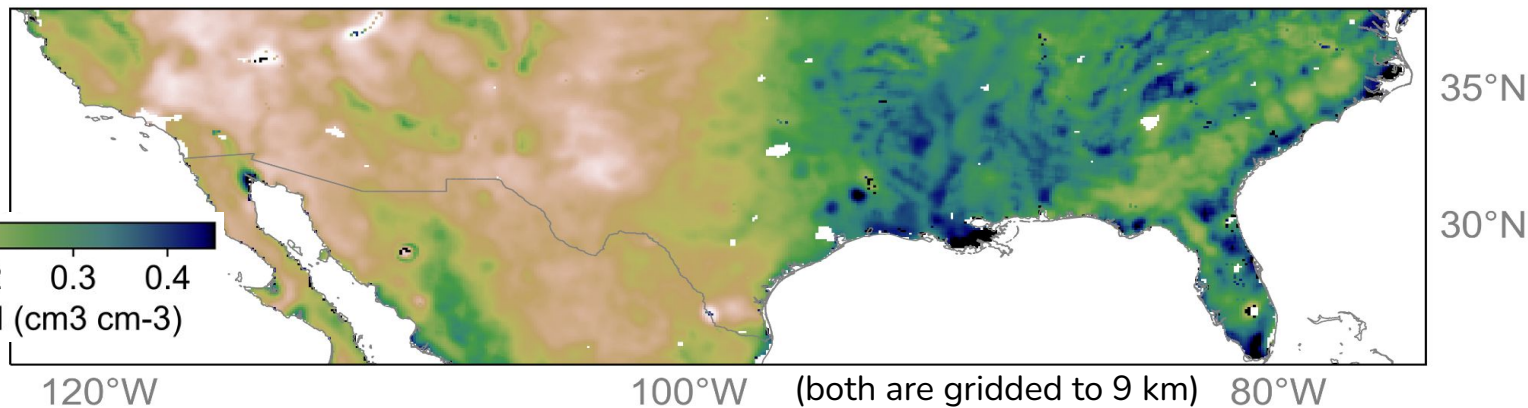


# Muon GNSS-R Soil Moisture

Muon GNSS-R Retrievals

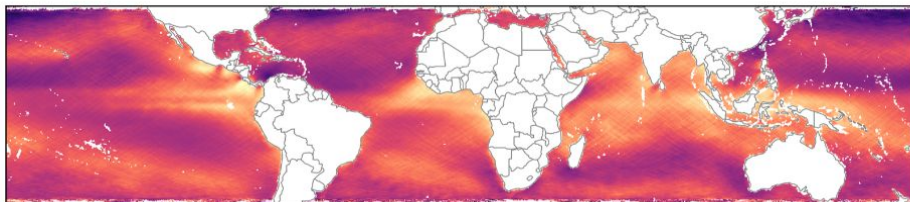


SMAP Retrievals

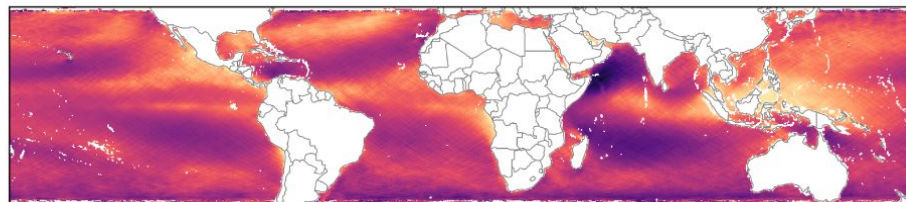


# Muon GNSS-R Ocean Surface Winds

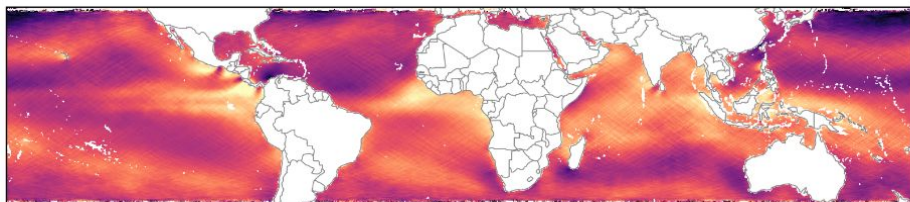
Muon GNSS-R



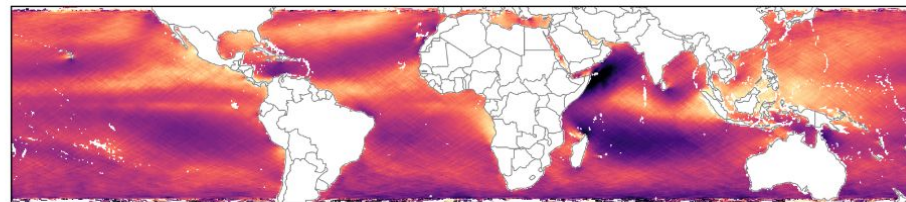
Muon GNSS-R



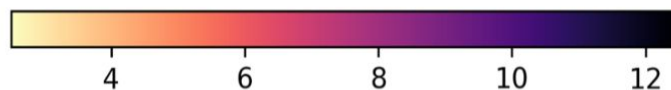
ERA5



ERA5



Jan/Feb/Mar 2022



Mean Wind Speed, (m/s)

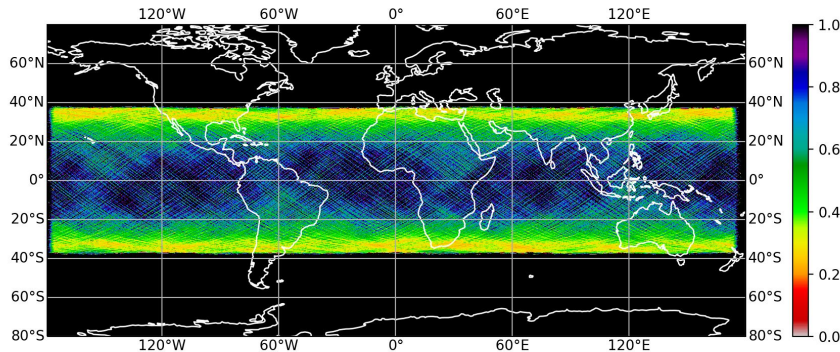
Jun/Jul/Aug 2022

# Muon Payload & Constellation Trajectory

Future Muon satellites will significantly improve upon CYGNSS and MuSat-2:

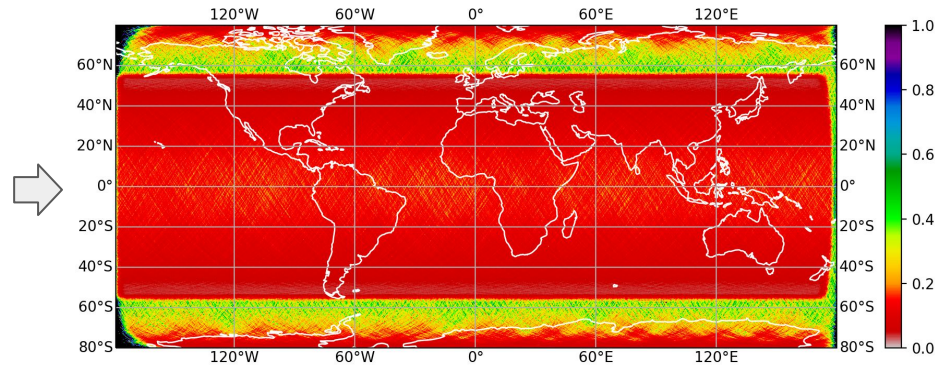
- High-gain, beamformed antennas will address **> 30 m/s ocean winds** and **potentially 3 km soil moisture**
- Better onboard calibration will reduce wind speed and soil moisture error caused by GNSS signal fluctuations
- Dual-polarization GNSS-R will potentially **correct soil moisture error due to vegetation, volume scattering**
- Full constellation will provide **rapid sub-diurnal revisits to track TC growth** and **soil moisture evolution**
- **Polar and diverse orbits** will achieve globally dense spatio-temporal sampling for improved DA impact
- **Potential to add polarimetric GNSS-RO antennas to existing payload**

CYGNSS sampling



CYGNSS limited coverage and daily revisit period

Muon sampling



Expected 24-sat Muon daily coverage and revisit period

(1/4° cell revisit period (in days) with 45° incidence mask)

# Summary of Muon Small Sat EO Program



- Muon Space is building constellations of Earth observation satellites to provide **sustainable data products that improve our knowledge of climate, weather, and the environment.**
- Muon's first SoOpr Earth observation satellites will **advance GNSS-R observations and begin launching in 2024**, with the goal of producing sustainable, operational EO products.
- Muon's **initial primary payload harnesses "signals of opportunity"** will measure properties of passively collected signal transmissions using GNSS remote sensing techniques to generate products such as soil moisture, ocean wind speeds, ionospheric density
- Similar measurements have been demonstrated on **government-funded pathfinder missions (e.g., CYGNSS) but have critical gaps in coverage, performance, and continuity** required to reliably feed operational weather models.
- With an experienced team of remote sensing scientists and engineers, control of our satellite design-build process, \$35M in funding, and three scheduled launches, **Muon is on track to produce valuable, demonstrated data products for commercial, government, and NGO customers.**



# Opportunities to Collaborate with Muon



- Muon is starting 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, **including interest in polarimetric RO**
- Collaboration can take many forms, including:
  - Mission concepts (other signals of opportunity, e.g., P-band)
  - Payload development
  - Retrieval algorithms
  - Derived product development
  - Product validation against in situ and other satellite sensors/products
  - Joint proposals to funding agencies
- **Please contact [dallas@muonspace.com](mailto:dallas@muonspace.com) with collaboration interests**