spire | earth intelligence

# Status and Future Plans of Spire's GNSS Radio Occultation and Reflectometry Constellation

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2024 IROWG

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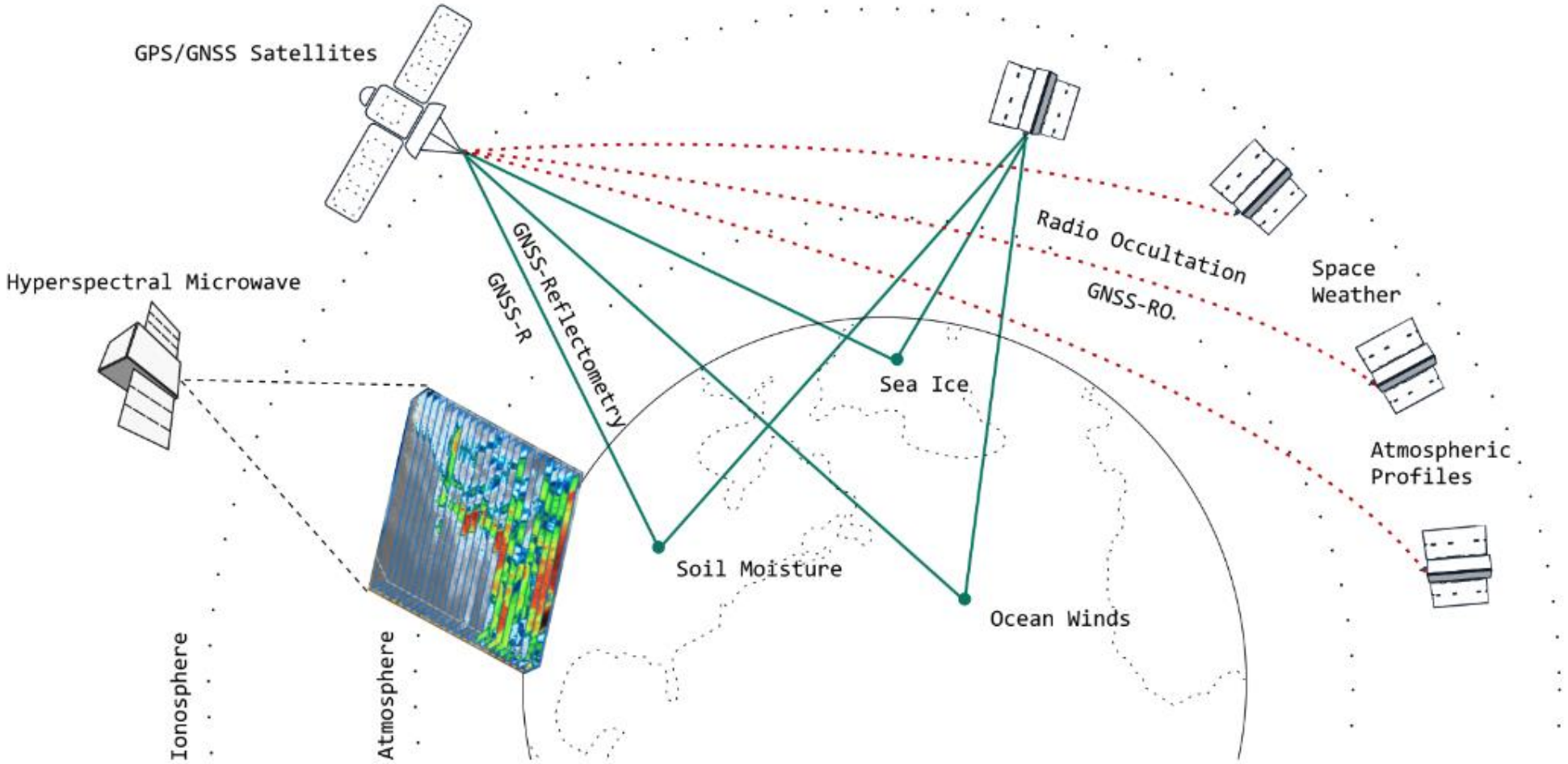
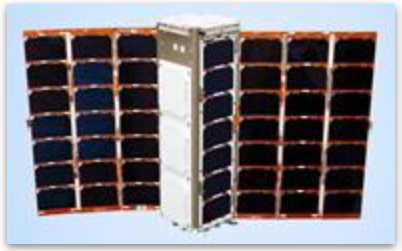
# Spire Earth Intelligence Constellation

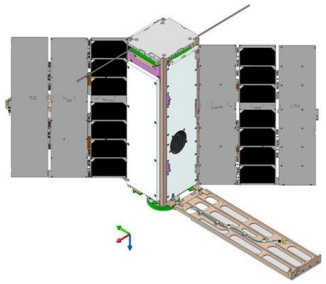
**Spire's operational satellite constellation capture Earth observations for various applications: NWP data assimilation, climate, space weather, sea ice, altimetry, soil moisture, etc.**



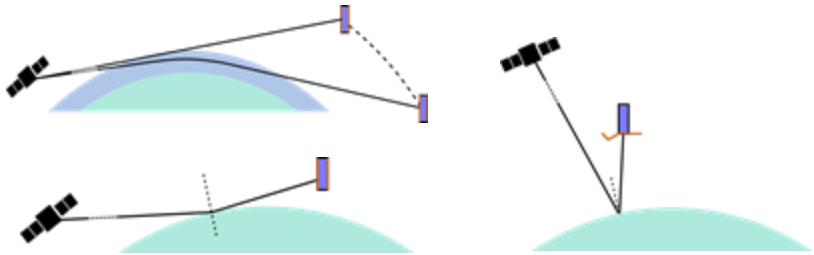
# STRATOS GNSS Antenna and Receiver

- STRATOS payload is common receiver among all applications
- 6 W receiver with ~100% duty cycle
- Antenna solutions targeting -R, -RO, -PRO within the 3U form-factor
- Tracks all major GNSS constellations
  - GPS, GLONASS, Galileo, Beidou
- 4 RF front-ends





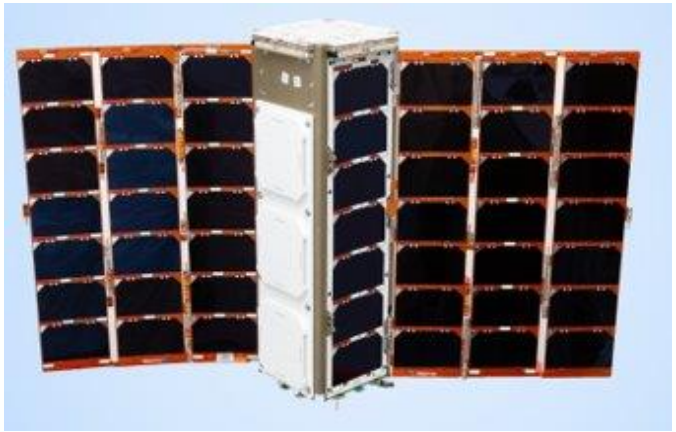
| Antenna configuration | GNSS-(P)RO/GA GNSS-R | NN-GNSS-R | GNSS-RO + NN-GNSS-R |
|---|---|---|---|
| Antenna panels | 1 or 2 | **2 or 3** | **Combines -RO and -R capabilities** |
| Peak antenna gain (@L1) | 10 dB | 14.5 dB (beamform) | |
| Polarization | **RHCP (H + V for PRO)** | **LHCP** | |
| Frequency band support | **L1/L2/L5** | **L1** | |
| # of satellites as of Sept 2024 | **9 (max 30+)** | 1 (max 5) | 2 |
| Applications | Atmosphere, Ionosphere, Earth Surface (ice) | Soil moisture, Ocean Winds | **Combines -RO and -R capabilities** |

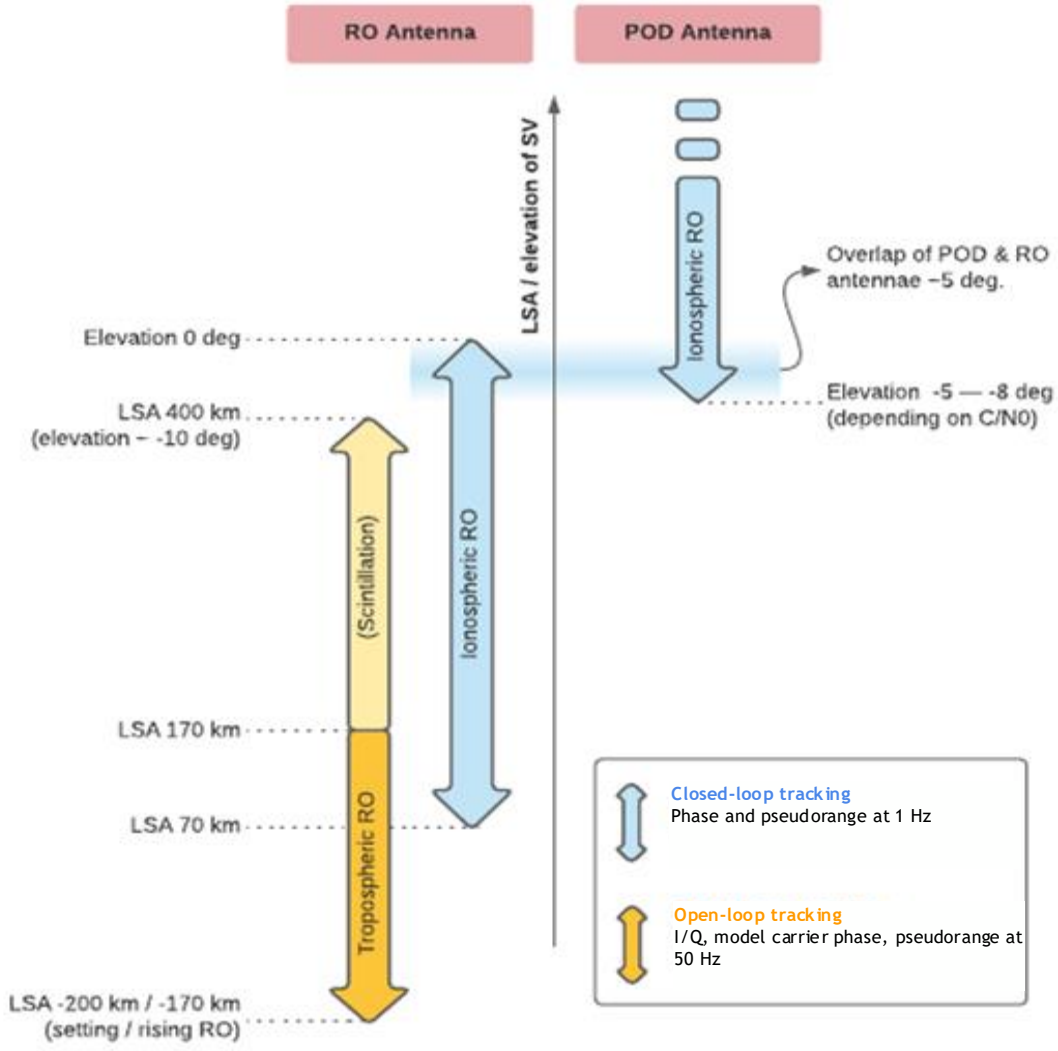


# GNSS-RO Collection

## Spire STRATOS GNSS Receiver

- STRATOS receiver version 1 (Launched 2017-2021)
  - Moderate gain, dual antennas (rising/setting)
  - Multi-GNSS signals tracked in open-loop
  - Demonstrated many "firsts" for RO including producing high-quality profiles from a Cubesat, producing non-GPS profiles, etc.
- STRATOS receiver version 2 (Launched 2022+)
  - Advanced wide-band receiver with relative amplitude calibration (mainly for GNSS-R)
  - More receiver channels allows for more simultaneous RO profiles
    - Up to 2000 collected RO profiles per day

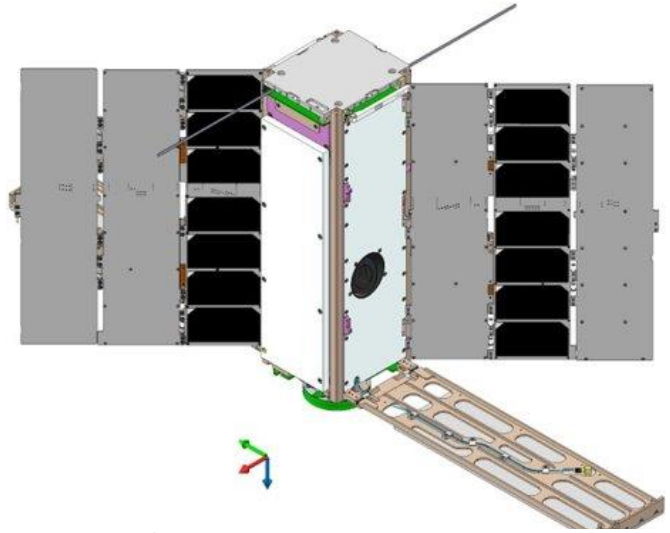


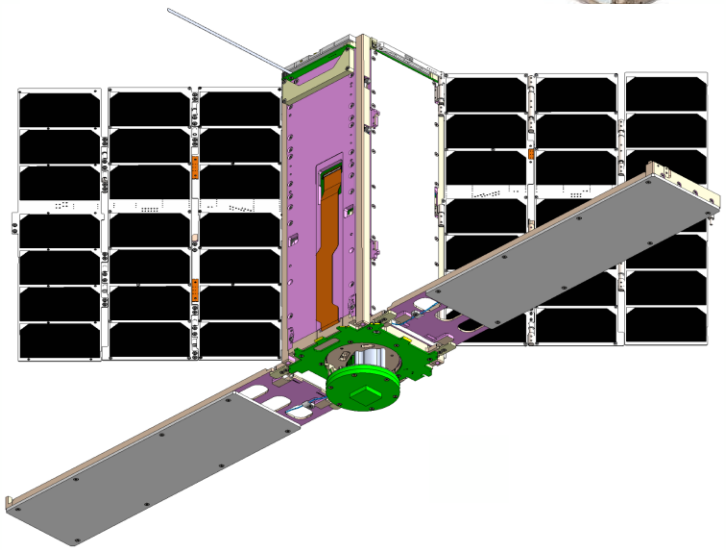


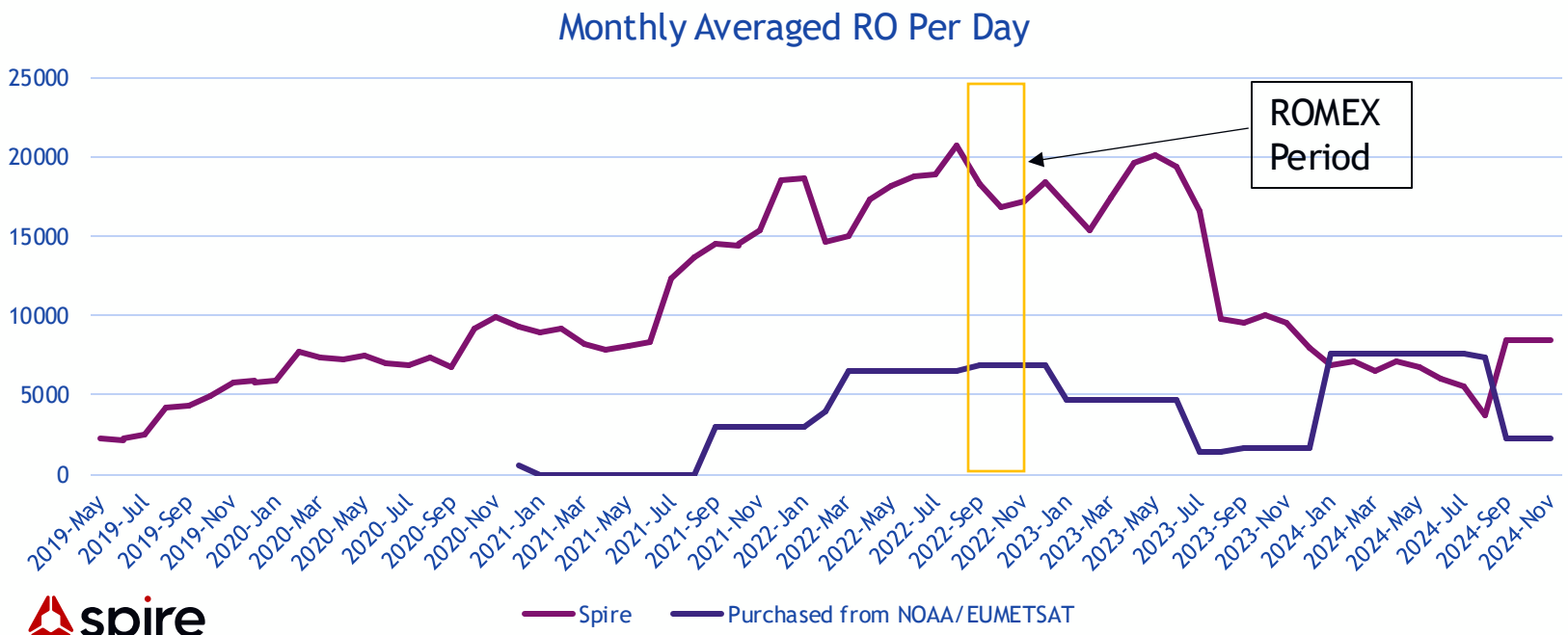
# GNSS-RO Production

- Spire constellation has demonstrated the capability of producing over 20000+ quality-controlled profiles per day
- About 17.5k profiles/day produced for ROMEX (50% of total profiles)
- RO production has decreased over the past year mainly due to satellite de-orbit, launch slips and constellation reallocation
- August launch introduced 6 new satellites into orbit including the first two satellites with combined GNSS RO and NN GNSS-R capabilities (right)

**New Combined GNSS-RO+R Satellites Launched Aug 2024**







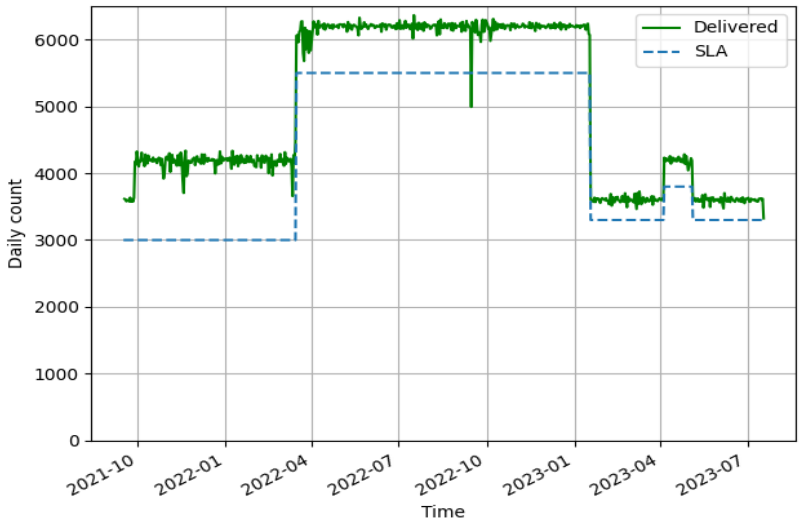
# Operational RO Data Deliveries

- **EUMETSAT**
  - Consistent delivery of 1000-1600 RO/day since 2022. Transition to new contract in August 2024 (1400 RO/day)
  - Delivery of real-time PRO data initiated in May 2024
- **NOAA**
  - Operational deliveries since 2020 spanning two IDIQ contracts, consistently exceeding requirements for years
  - Under-delivery in current period due to reduced RO capacity and mismatch between short-term changes in customer demand and long-term constellation planning needs
    - Improvements over the past 6 months to boost numbers include Beidou signal-tracking improvements and delivery latency reduction

**Current Spire RO Operational Deliveries**

| Customer | Operational Delivery Period | Data Volume | Latency Requirement | Data Access |
|---|---|---|---|---|
| NOAA CWDOB | 2020-present | Up to 6000 profiles/day | 140 minutes | Global Reshare (since 2023) |
| EUMETSAT | 2022-present | Up to 1600 profiles/day | 140 minutes | Global Reshare |
| NASA CSDA | 2019-present | Up to 20000 profiles/day | 48 hours (as of June 2024) | US-based researchers |

**Spire RO Delivered Per Day to NOAA 2021-2023**

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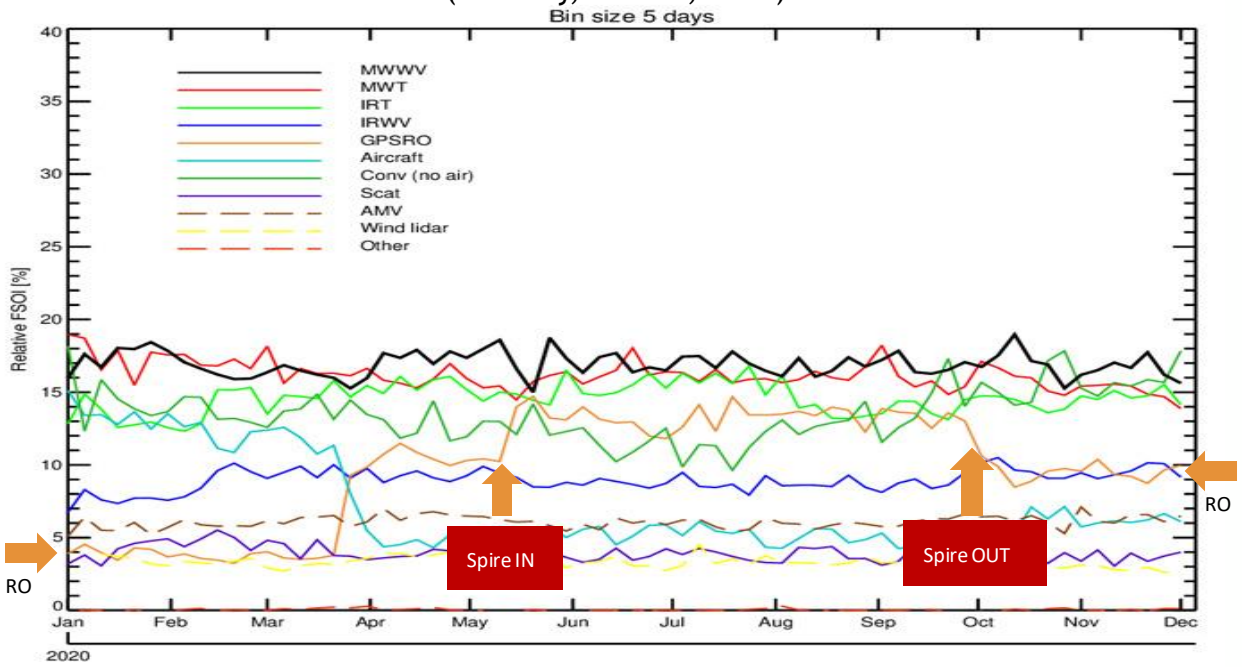
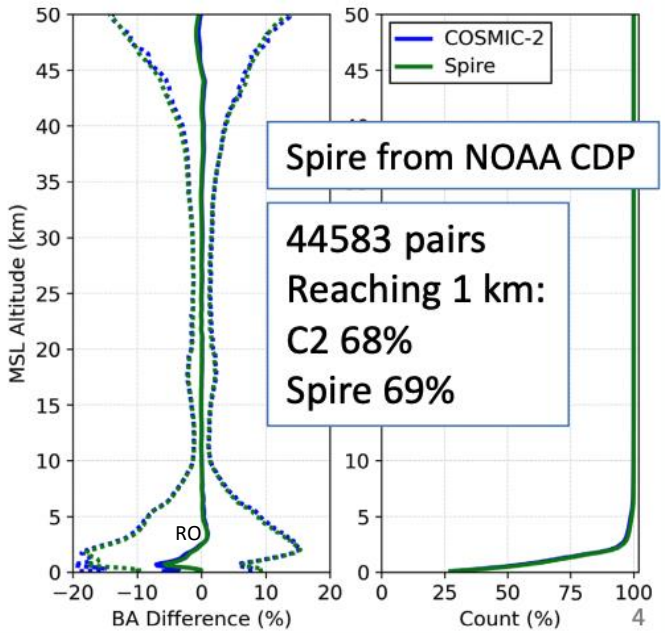
# External Evaluations

- Years of third-party evaluations from EUMETSAT, UCAR, NOAA, and NASA have shown Spire RO data to be of high-quality and exceeding performance of many legacy missions
- Demonstrated positive impact of Spire RO data on NWP systems

**ECMWF FSOI increase after assimilating Spire RO (~5-7k/day) in 2020**
(S. Healy, ECMWF, 2020)

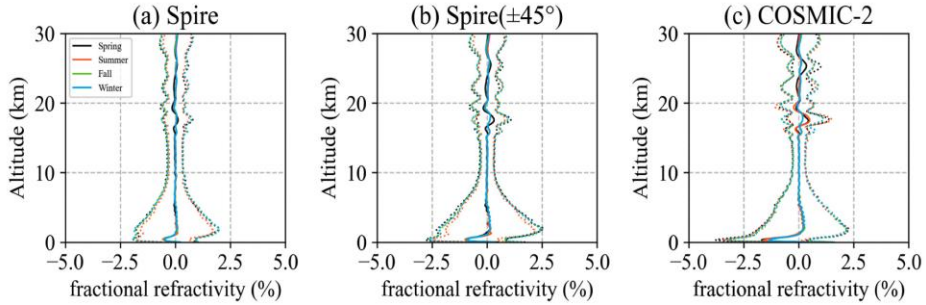



**Spire vs. COSMIC-2 Bending Angle Differences from ECMWF**
(*J. Weiss et al., 2022 IROWG*)



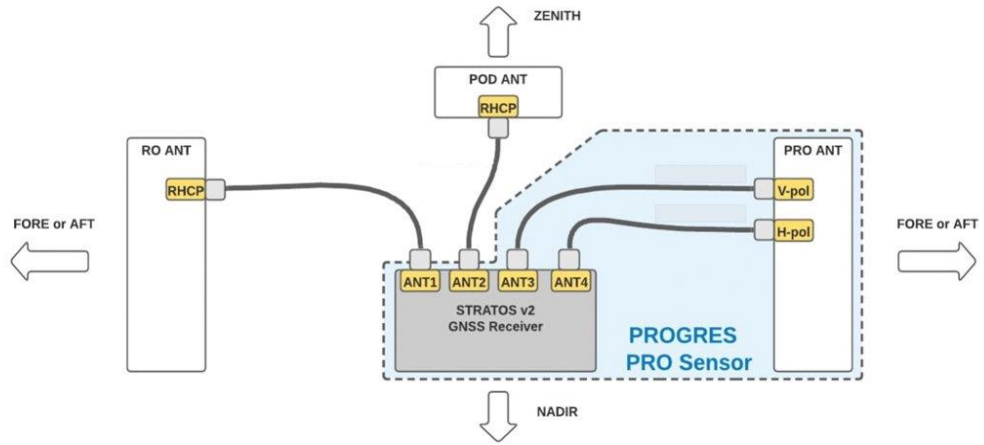

From UCAR retrievals of NOAA Spire Data

**Spire vs. COSMIC-2 Refractivity Differences from ERA5**
(*Qiu et al., 2023*)

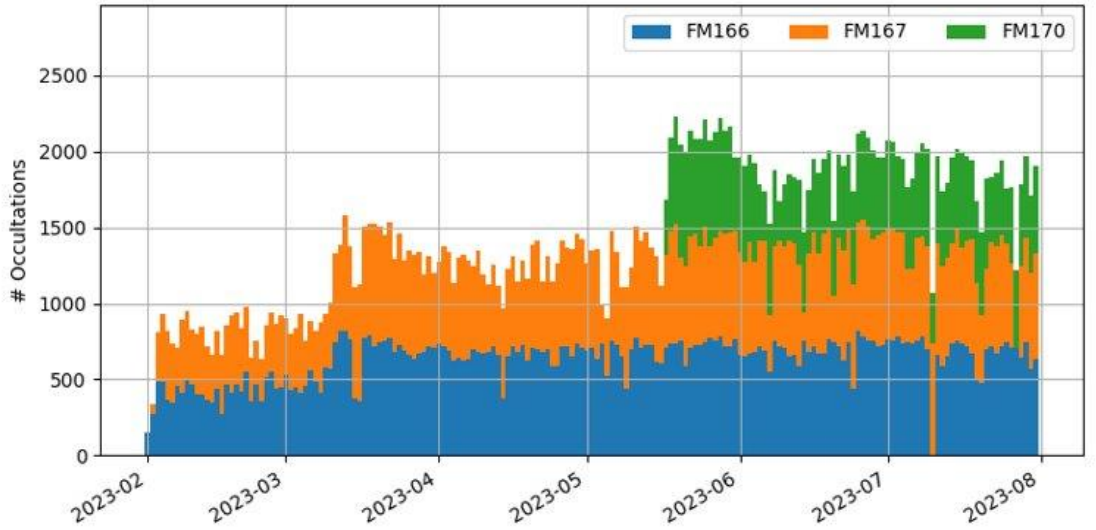


# Polarimetric Radio Occultation

- First Spire PRO-capable satellites launched in 2023
- Over 2000 PRO profiles per day collected from 3 Spire satellites, 4 GNSS constellations
  - **10x** amount of data currently available from PAZ mission
- Polarization phase shifts demonstrate clear sensitivity to precipitation and are minimally affected by the antenna. Ongoing development.
- Bending angle profiles can be derived from PRO data with similar quality to Spire's operational RO




Collected PRO profiles by Spire satellite




2023-04-01T01-42-03
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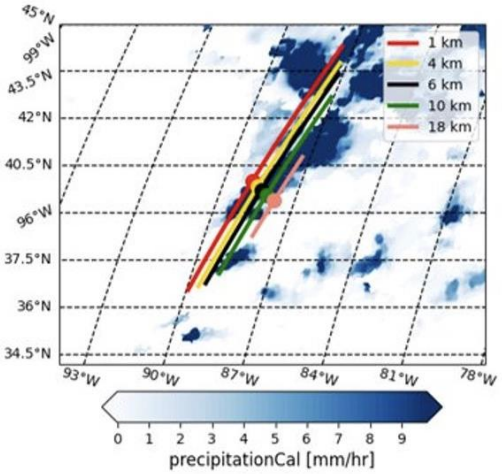
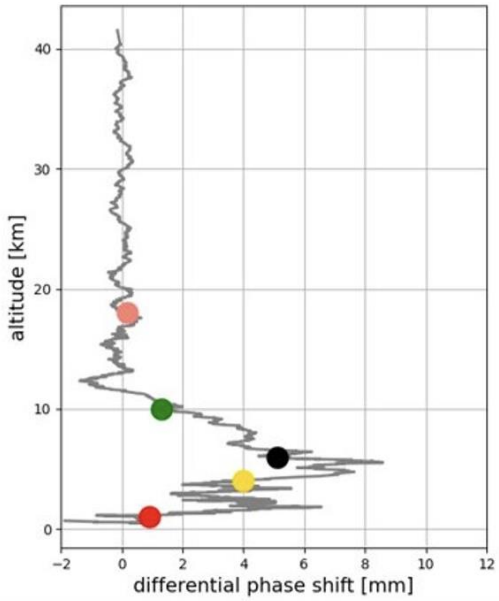
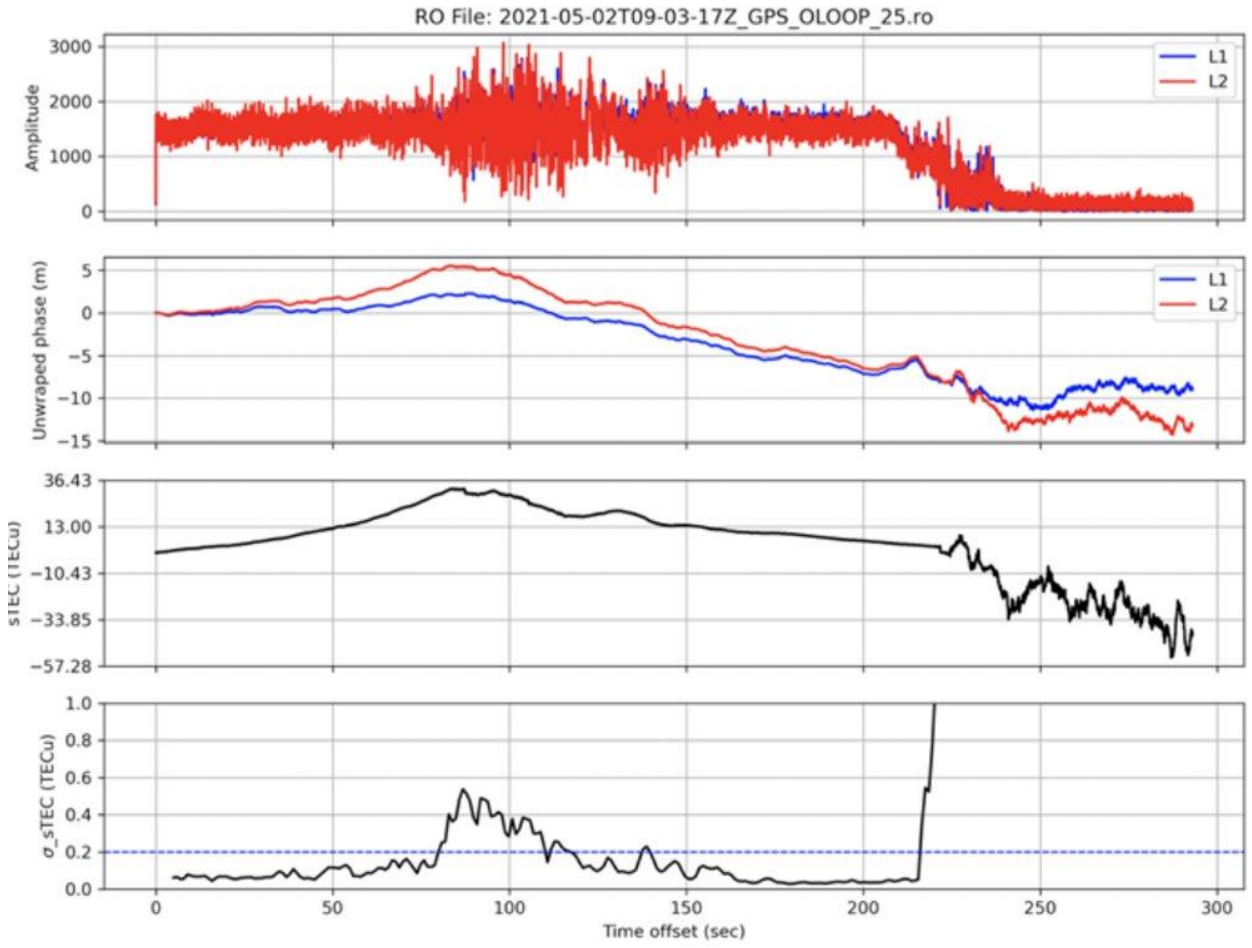


# Ionospheric Updates

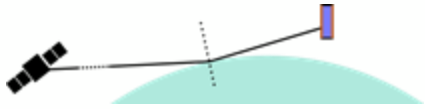
- Participated in NOAA SpWx Data Pilot (2022-2023)
- **Total Electron Content**
  - Observations (1-Hz) across POD and RO antennas combined to produce longer ionospheric tracks
  - Currently tracking mainly GPS in closed-loop mode. Plan to add other constellations.
- **Scintillation**
  - On-board estimate of S4 computed every second from 10-second block of I/Q data sampled at 1 kHz
  - 50-Hz data from orbit altitude downlinked if scintillation threshold exceeded
  - Plan to add on-board estimate of sigma-phi based on detrended geometry-free combination
  - Plan to include additional flagging to allow separation of RFI from scintillation

**Example of Sigma-phi Computation from Spire Data**

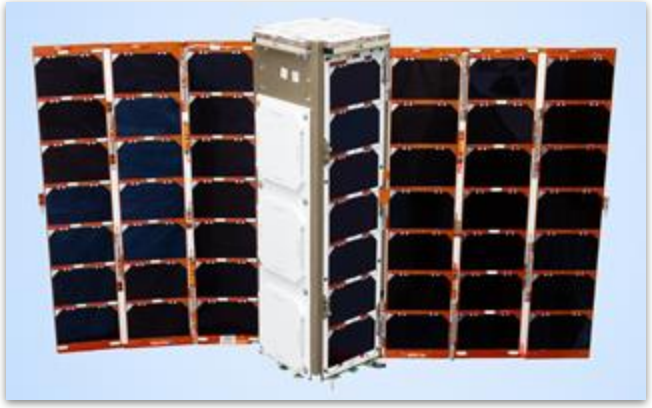


# Spire GNSS-Reflectometry Constellation

## Grazing Angle GNSS-R (GA-GNSS-R)



- Same spacecraft bus as RO satellites using the **spare capacity** of the GNSS-RO satellites



**Antennas for RO, re-used for grazing angle reflections (5°-30° elevation)**

- Dual-frequency RHCP antennas (x2)

**Processing**

- Coherent signal processing - output I/Q at 50 Hz
- **Application focus: Ice characterization and altimetry**

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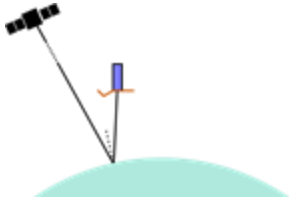
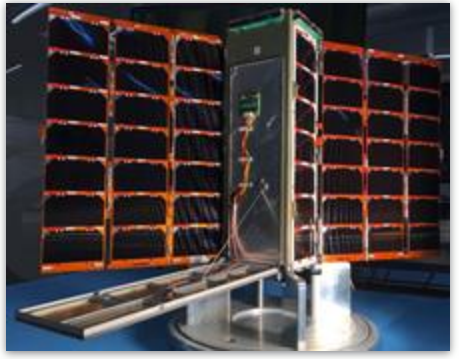
## Near Nadir GNSS-R (NN-GNSS-R)

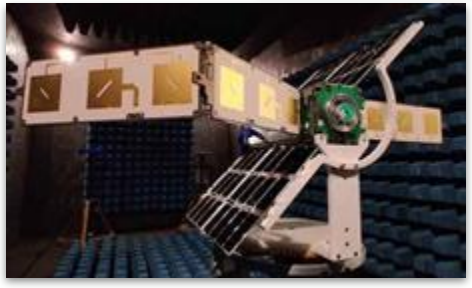


- Collaboration with ESA through the ARTES Pioneer Programme
- Have launched 7 satellites (2019 & 2020 & 2023 & 2024)



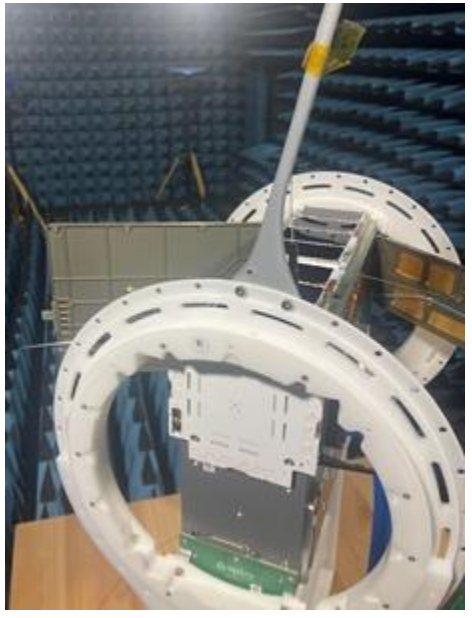
**Antennas Near-nadir pointing (20°-90° elevation)**

- Single-frequency LHCP nadir-pointing antennas (x2 or x3)



**Processing**

- Incoherent Delay-Doppler map (DDM) signal processing (up to 30 channels)
- **Application focus: Soil moisture and ocean winds**



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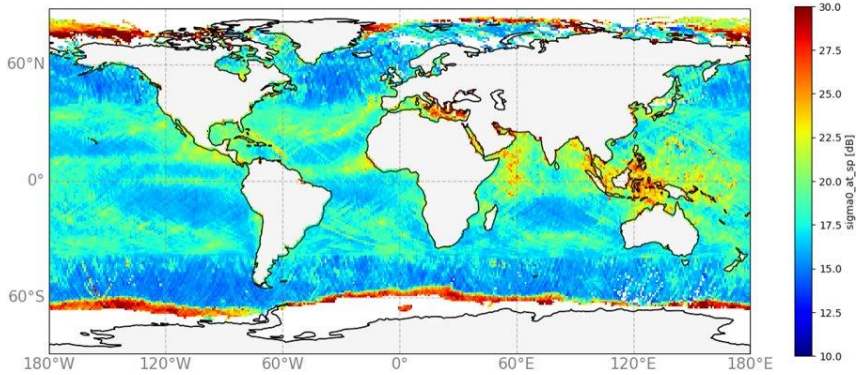
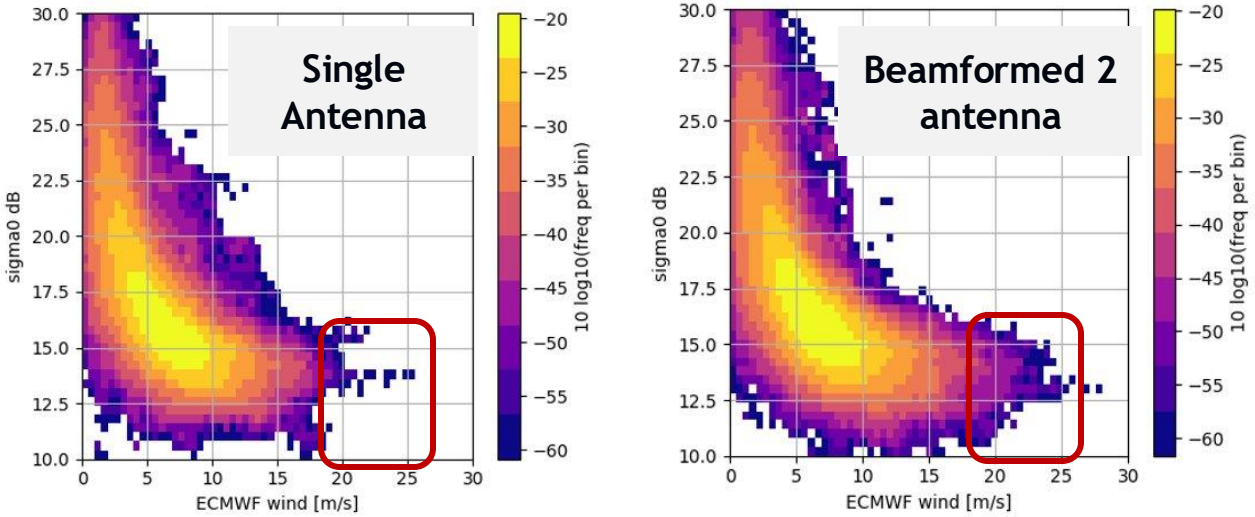
# NOAA GNSS-R Ocean Winds Data Pilot

- Only commercial provider to participate in NOAA Ocean Surface Winds Pilot contract (2023-2024)
- Successful delivery of at least 500 GNSS-R tracks/day (Lev-0 to Lev-2, near-nadir and grazing angle)
- NOAA-sponsored groups currently evaluating products
- New developments to increase sensitivity: antenna beamforming, multi-code Galileo (E1B & E1C

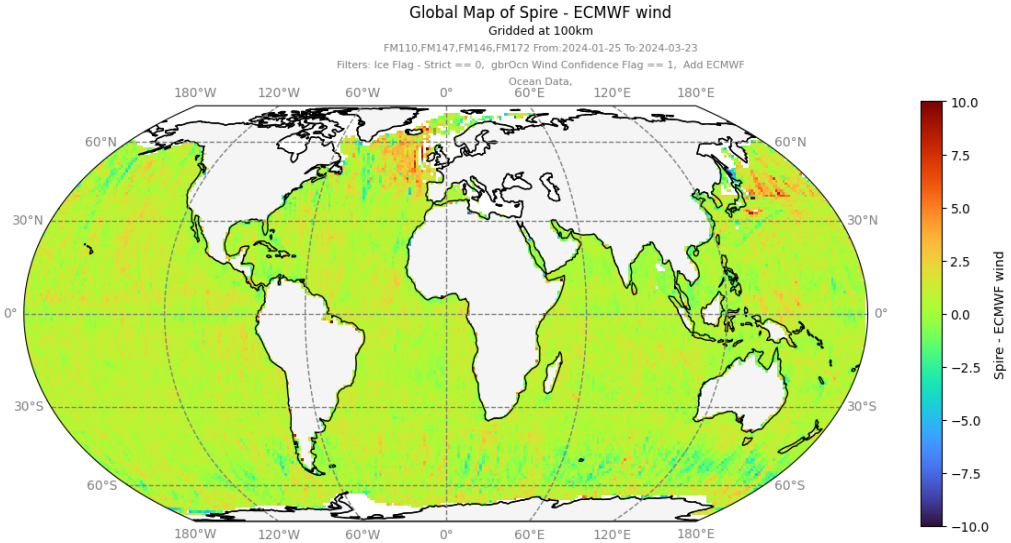
**Sigma-0 averaged (showing wind climatology)**




**Calibrated Sigma-0 vs. ECMWF wind-speed**




**ECMWF - Spire RMSE 2.2 m/s (showing wind error distribution)**

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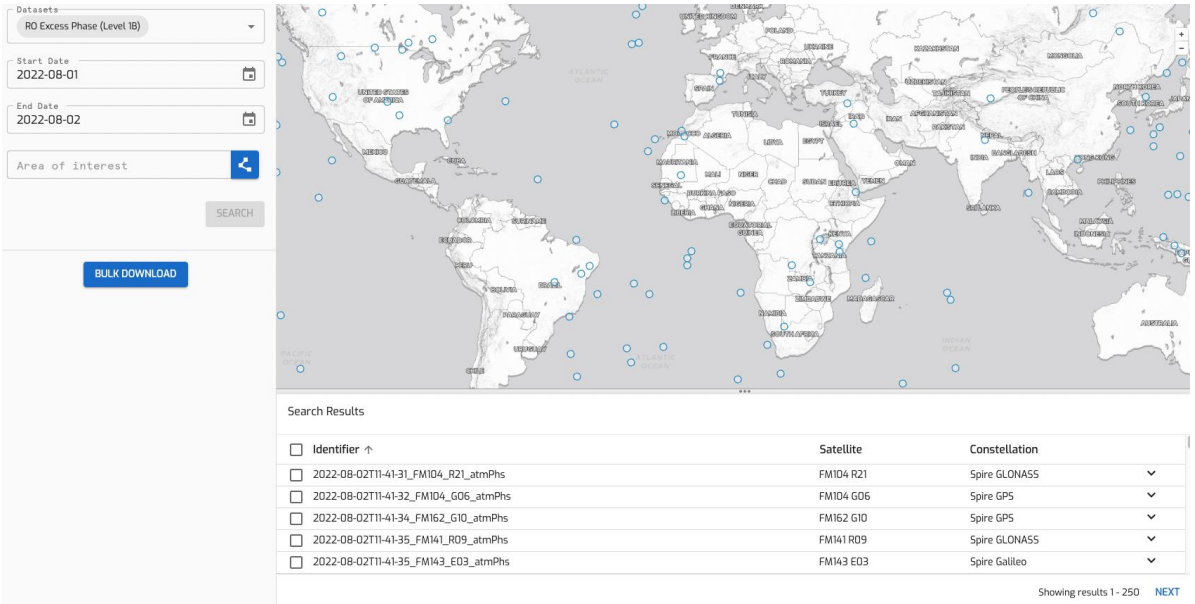
# Data Access and Outlook

- Spire currently has 10 satellites in-orbit capable of collecting 8000+ QC profiles/day
  - Satellite/ground infrastructure being optimized to produce more data from a single platform
- Spire has demonstrated production of 20k RO/day historically and can scale up RO production to meet demand with advanced notice
- Multiple avenues to access Spire data summarized below

**New Spire-developed User Interface for NASA CSDA Access**




| | Contains | Available to | Time Period | Link |
|---|---|---|---|---|
| NASA CSDA | All GNSS-RO, -R L0-L2 data | US gov't researchers | 2019-present | https://nasa-csda.wx.spire.com/ (after granted access) |
| EUMETSAT Data Store | Raw and processed RO data delivered through EUMETSAT | All users | 2022-present | https://data.eumetsat.int/ |
| ESA Third Party Mission | PRO, NN/GA GNSS-R | Worldwide institutions for R&D | May-Nov 2023 (PRO)<br>Jan-Jul 2024 (GNSS-R) | https://earth.esa.int/eogateway/catalog/spire-live-and-historical-data (follow steps) |
| UCAR | Raw and processed RO data delivered through NOAA | All users | 2020-present | https://data.cosmic.ucar.edu/ |

# Thank you!

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