

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

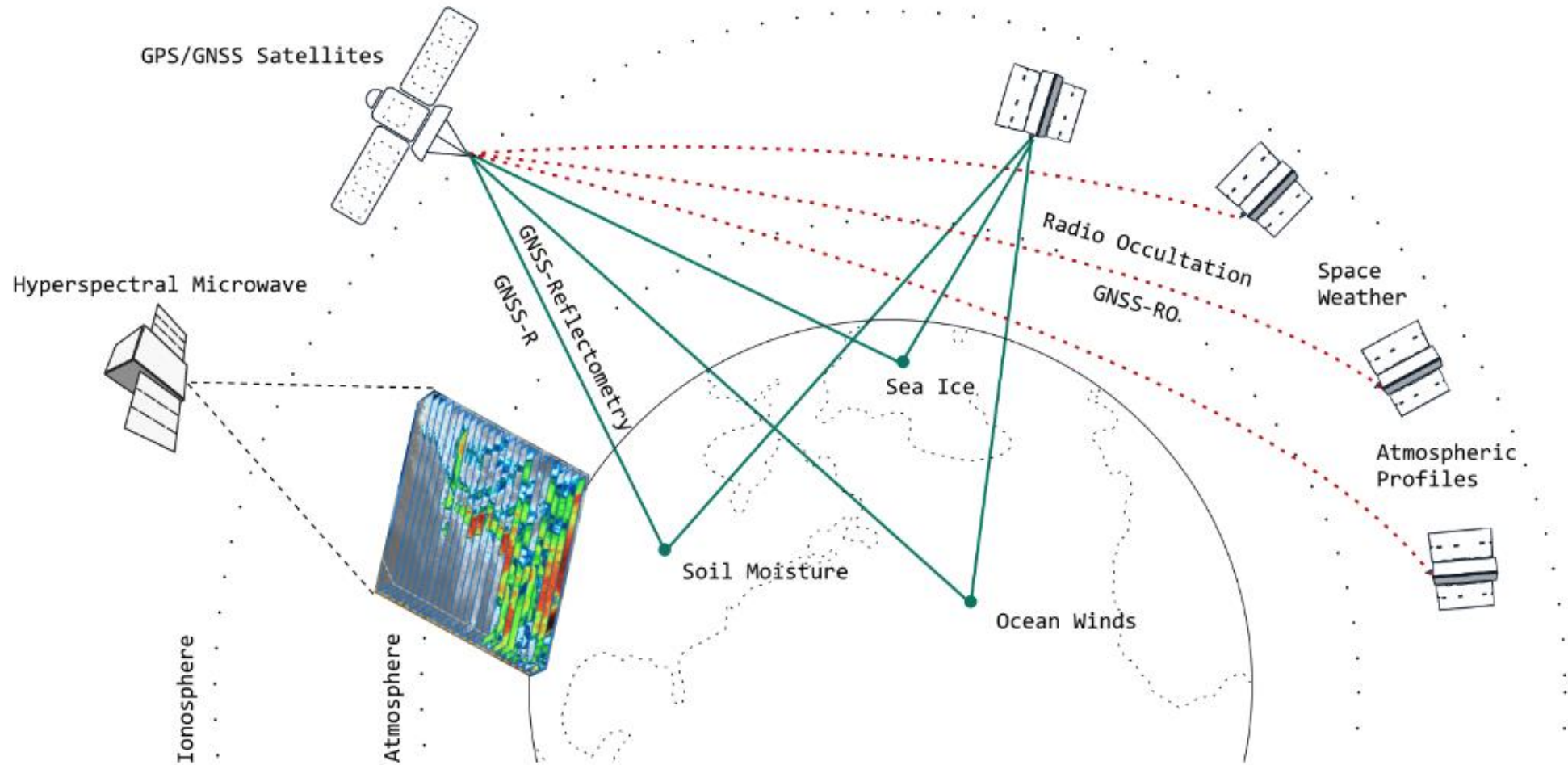
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2024 IROWG

13 September 2024

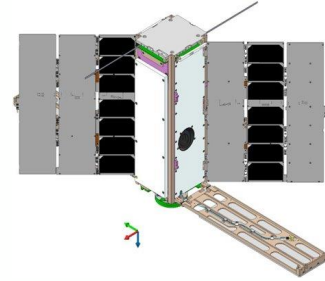
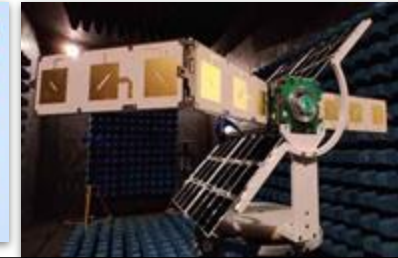
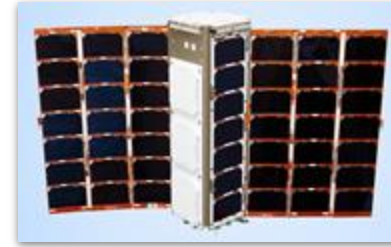
Spire Earth Intelligence Constellation

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

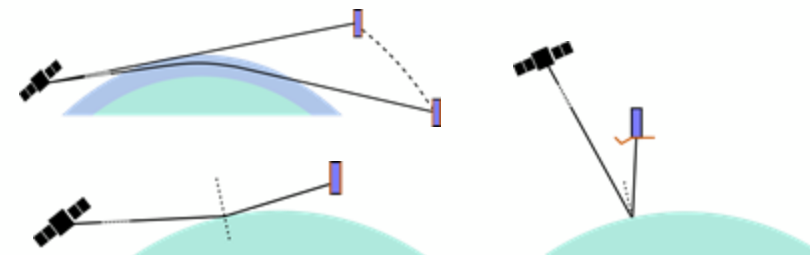


STRATOS GNSS Antenna and Receiver

- 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



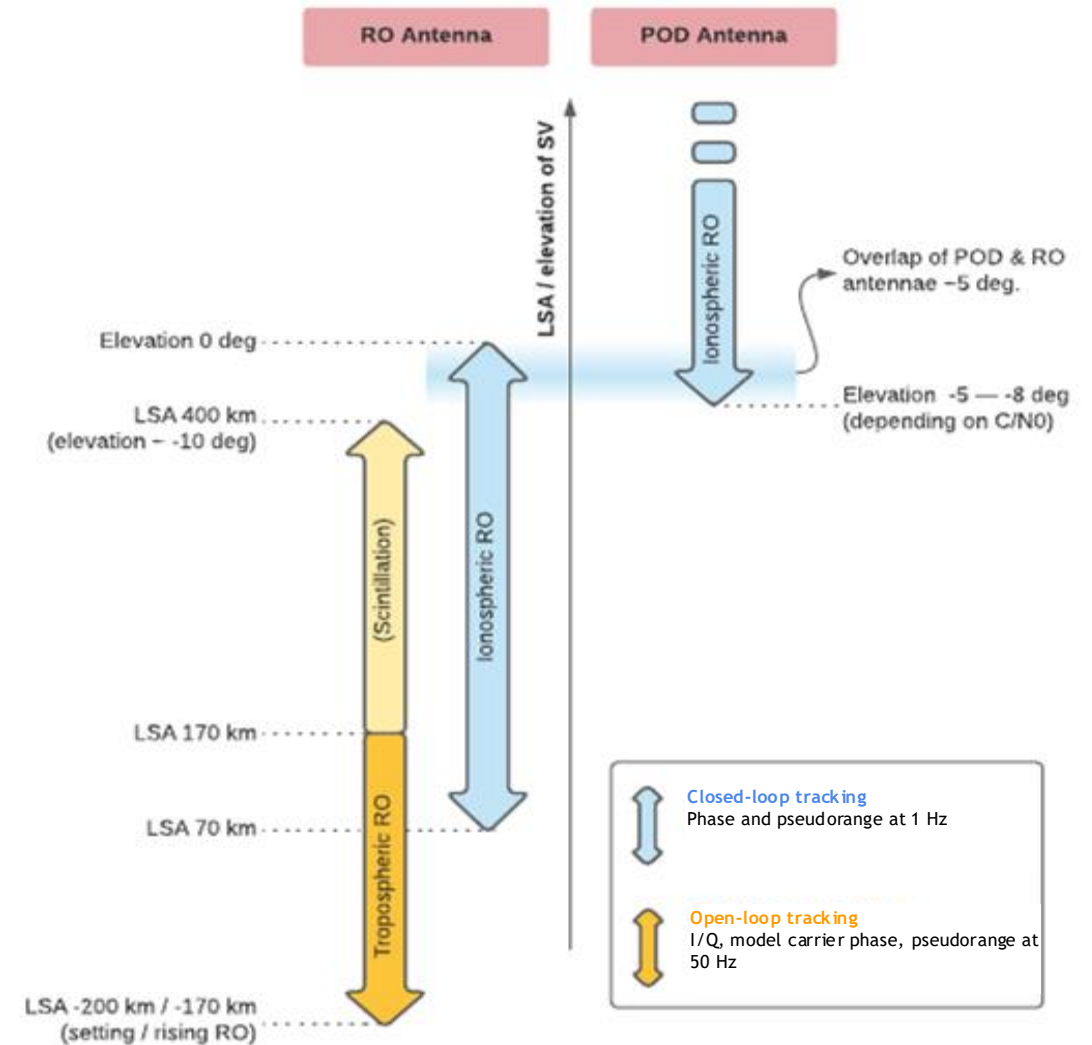
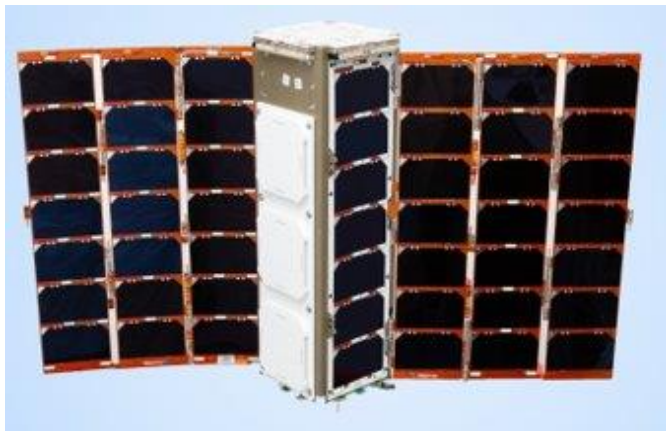
Antenna configuration	GNSS-(P)RO/GA GNSS-R	NN-GNSS-R	GNSS-RO + NN-GNSS-R
Antenna panels	1 or 2	2 or 3	Combines -RO and -R capabilities
Peak antenna gain (@L1)	10 dB	14.5 dB (beamform)	
Polarization	RHCP (H + V for PRO)	LHCP	
Frequency band support	L1/L2/L5	L1	
# of satellites as of Sept 2024	9 (max 30+)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



GNSS-RO Collection

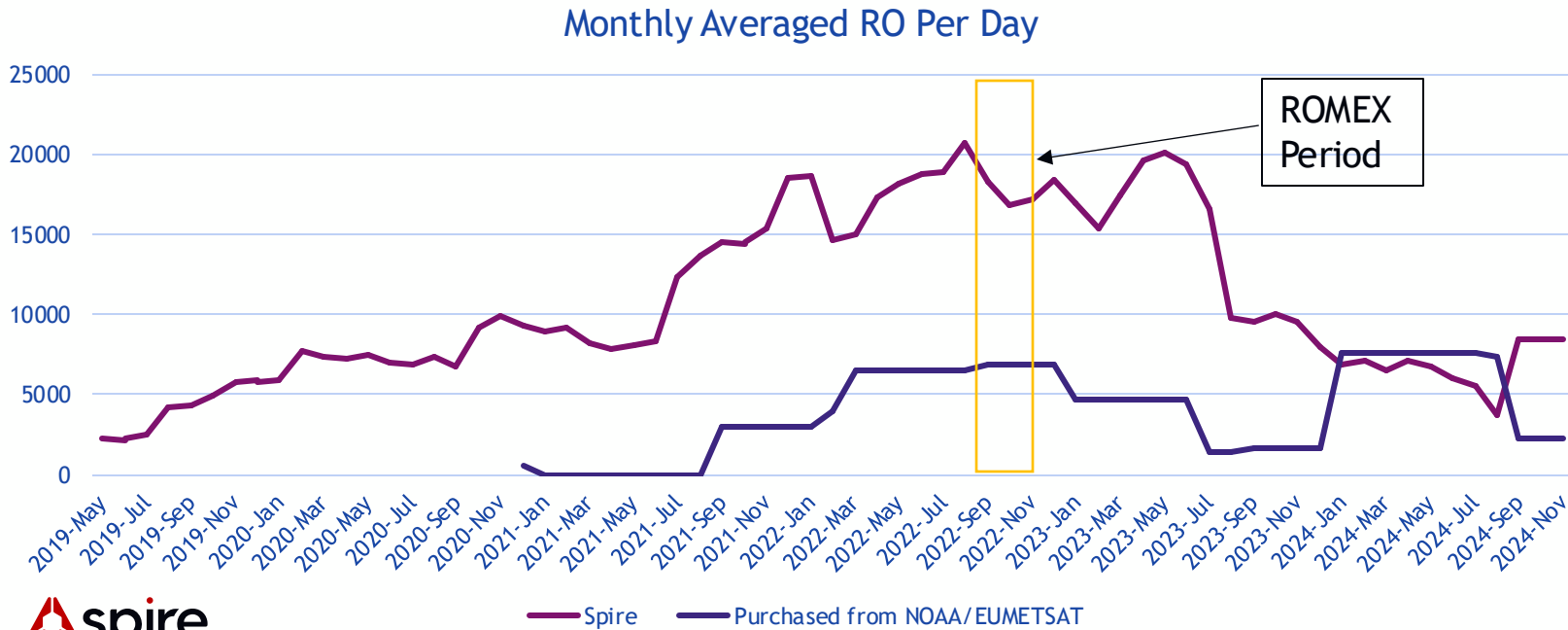
Spire STRATOS GNSS Receiver

- 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

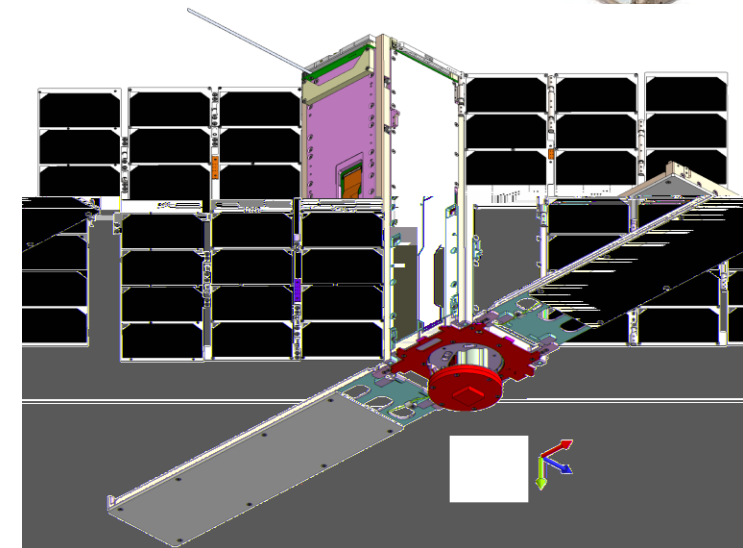
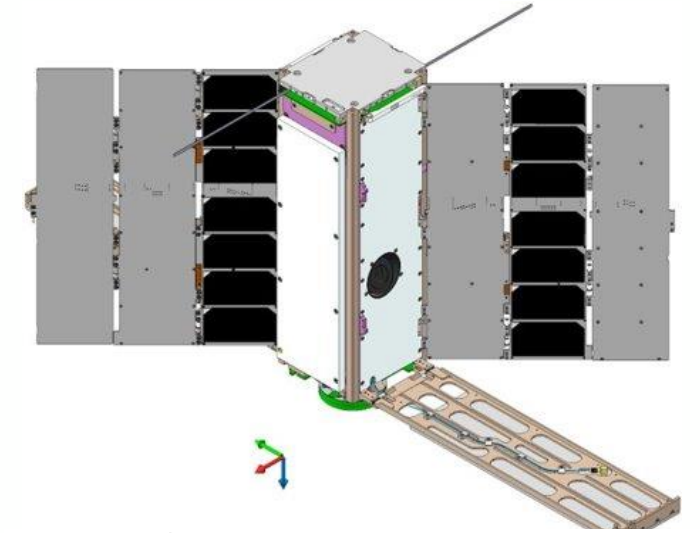


GNSS-RO Production

- 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

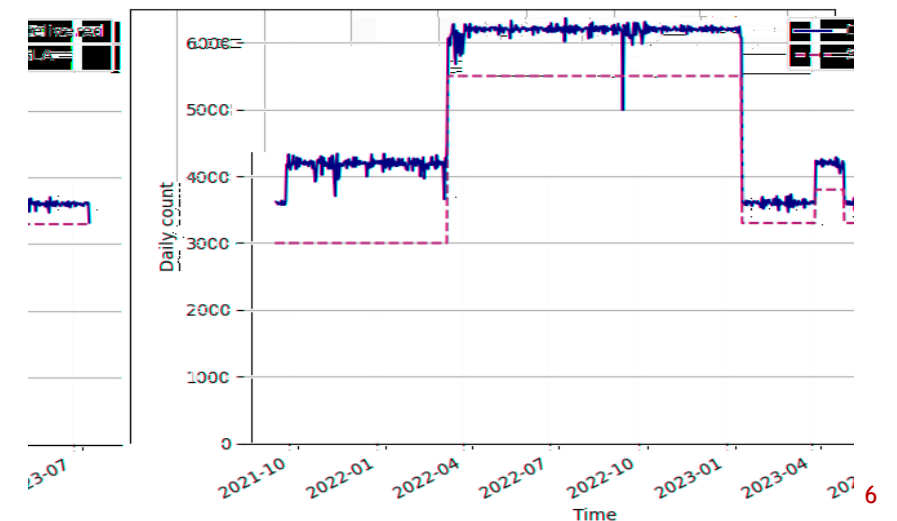
- **EUMETSAT**
 - Consistent delivery of 1000-1600 RO/day since 2022. Transition to new contract in August 2024 (1400 RO/day)
 - Delivery of real-time PRO data initiated in May 2024
- **NOAA**
 - Operational deliveries since 2020 spanning two IDIQ contracts, consistently exceeding requirements for years
 - 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



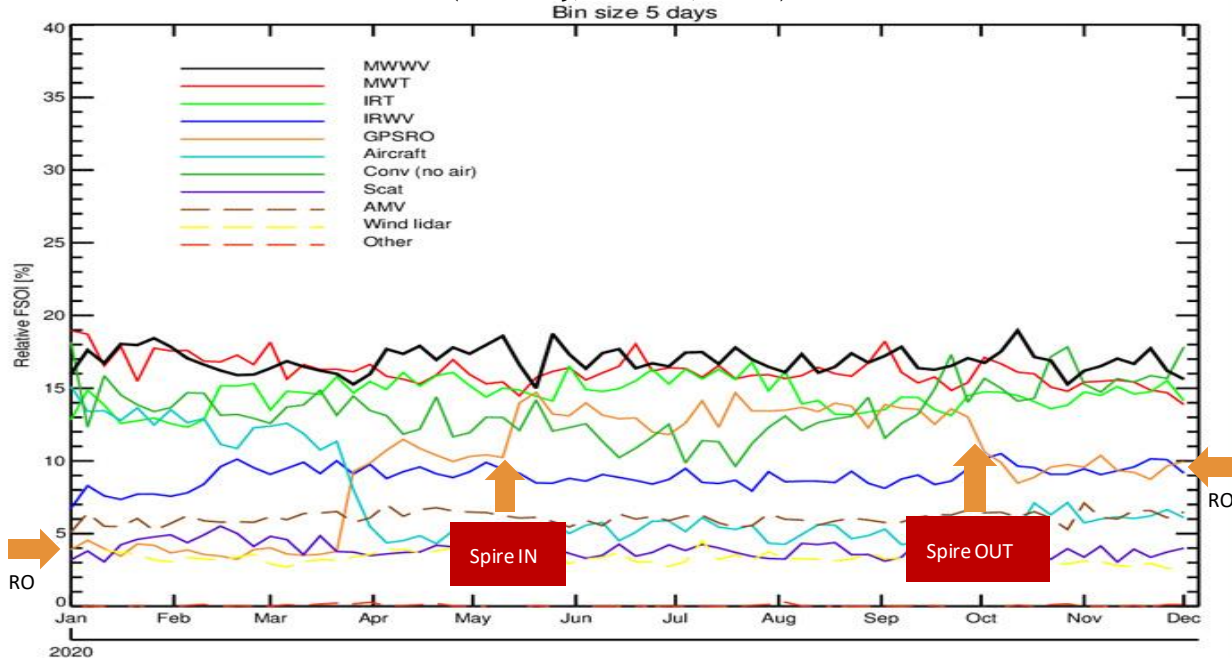
Spire RO Delivered Per Day to NOAA 2021-2023



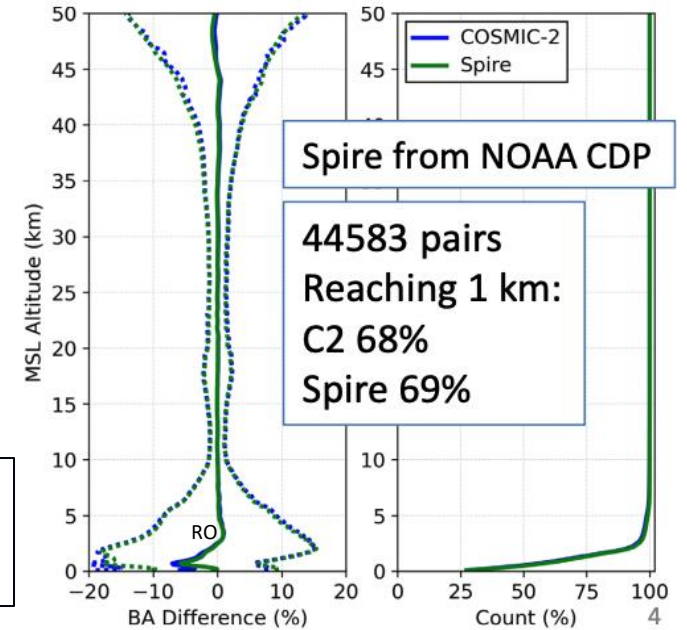
External Evaluations

- 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)

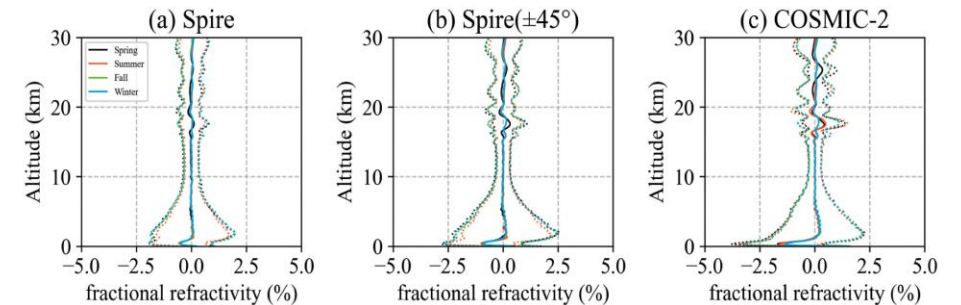


Spire vs. COSMIC-2 Bending Angle Differences from ECMWF
(J. Weiss et al., 2022 IROWG)



From UCAR retrievals of NOAA Spire Data

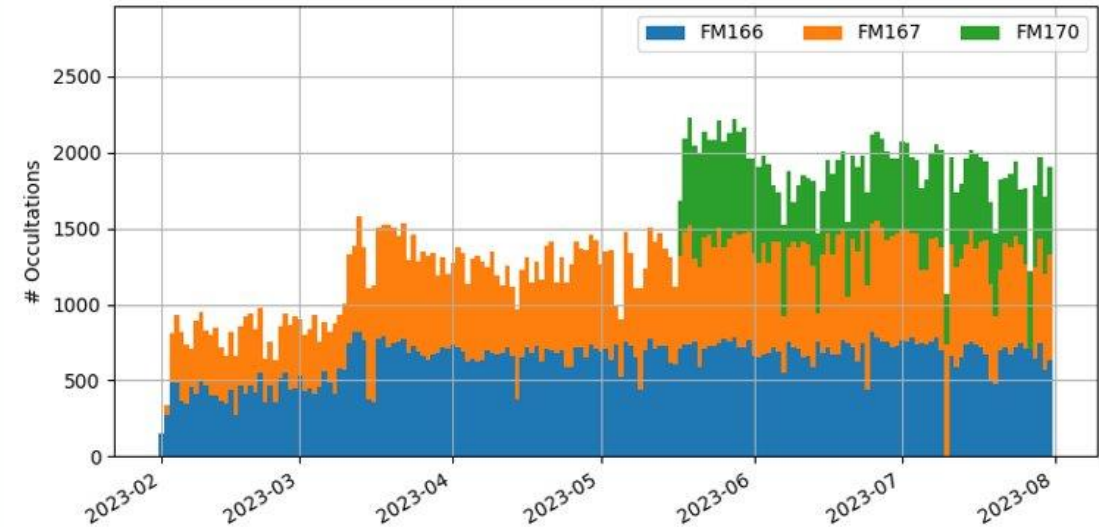
Spire vs. COSMIC-2 Refractivity Differences from ERA5
(Qiu et al., 2023)



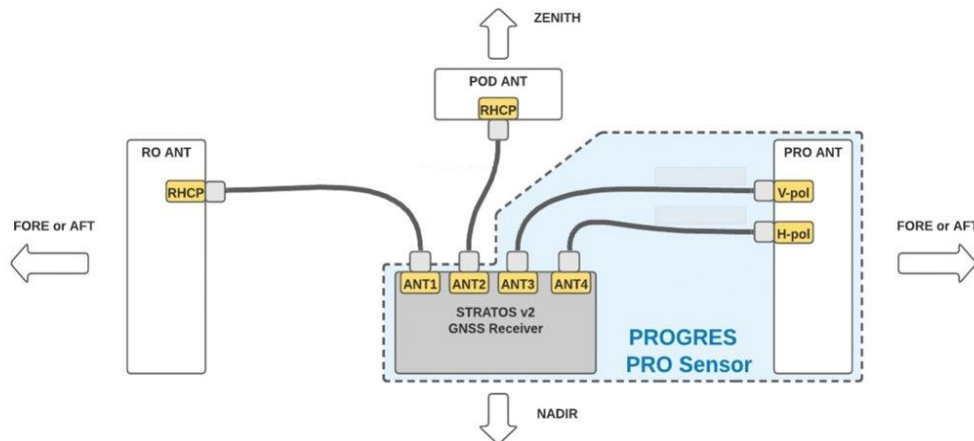
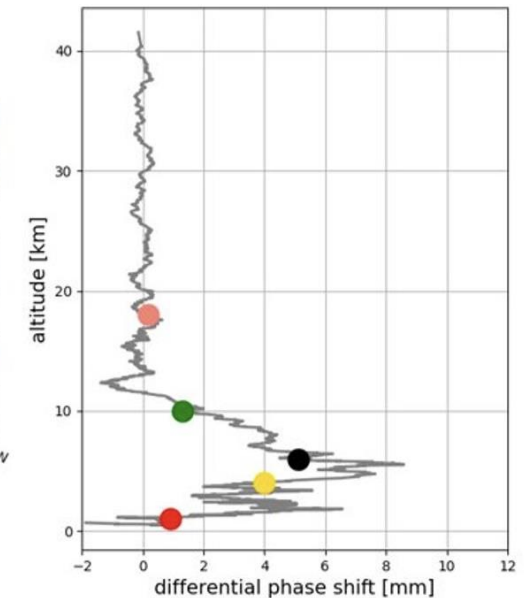
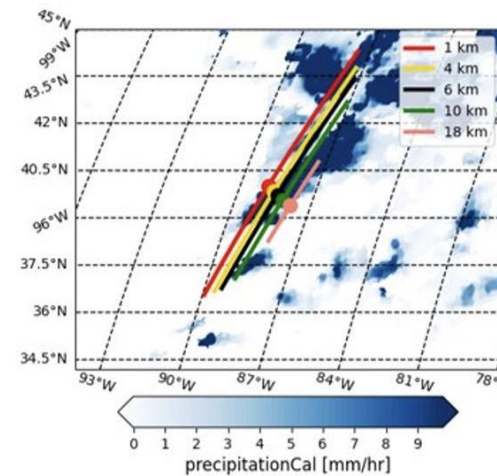
Polarimetric Radio Occultation

- 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



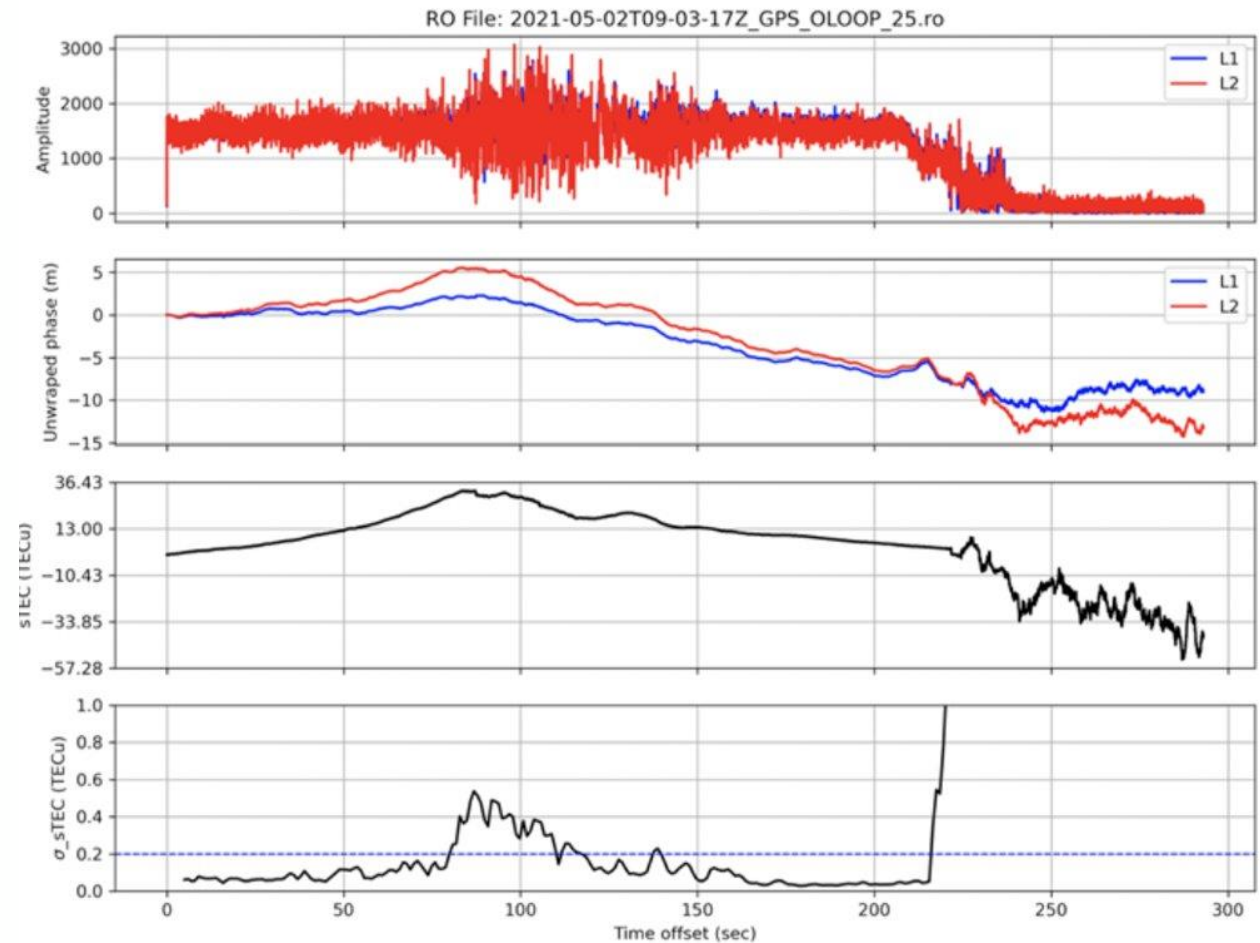
2023-04-01T01-42-03
FM166 GALILEO E30



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

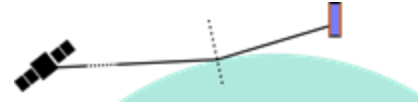
Example of Sigma-phi Computation from Spire Data



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

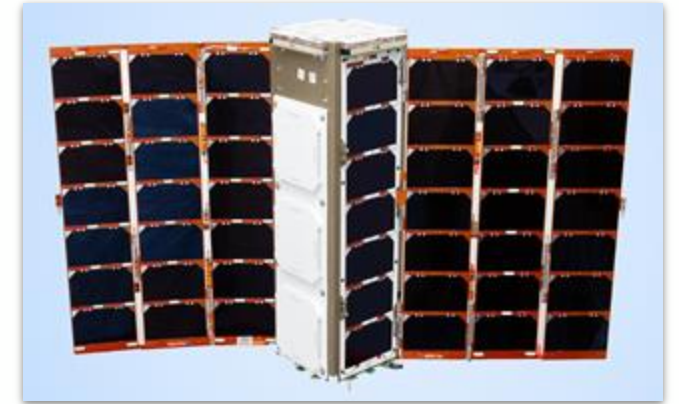


Antennas for RO, re-used for grazing angle reflections (5° - 30° elevation)

- Dual-frequency RHCP antennas (x2)

Processing

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



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

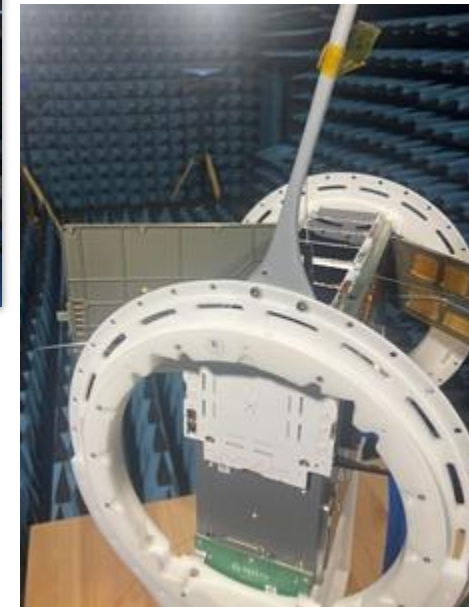
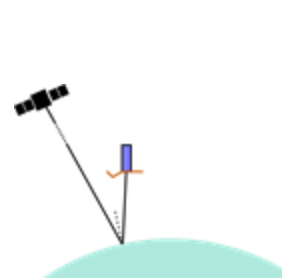
- Collaboration with ESA through the ARTES Pioneer Programme
- Have launched 7 satellites (2019 & 2020 & 2023 & 2024)

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

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

Processing

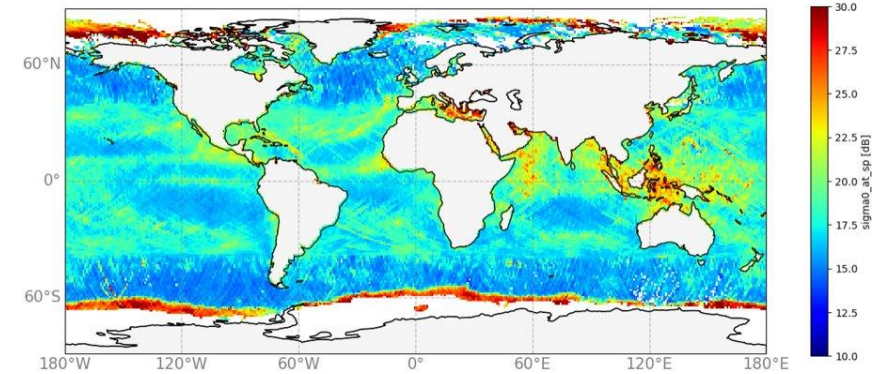
- Incoherent Delay-Doppler map (DDM) signal processing (up to 30 channels)
- Application focus: Soil moisture and ocean winds



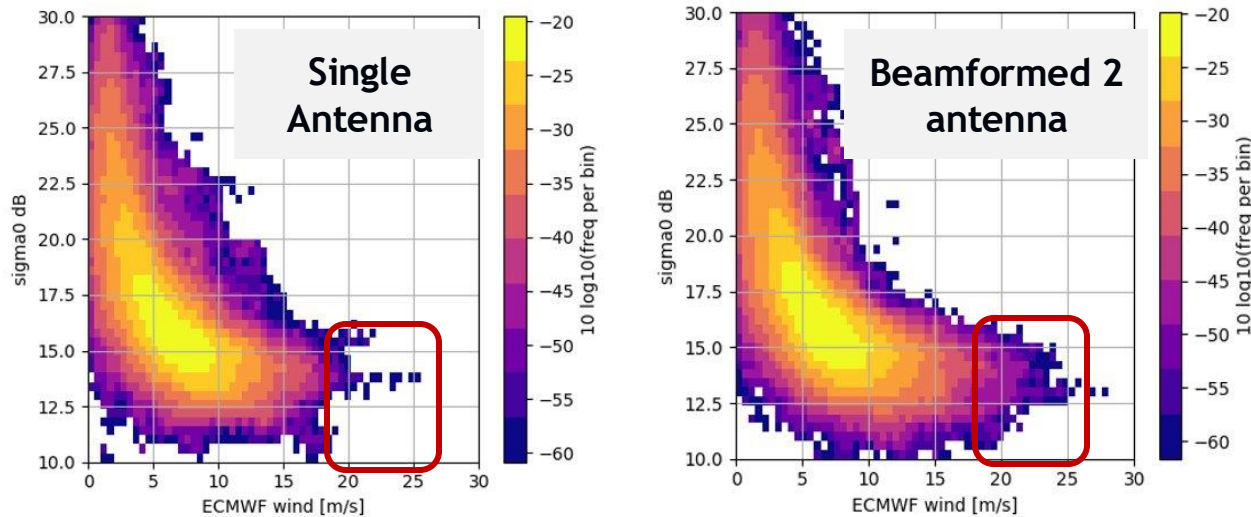
NOAA GNSS-R Ocean Winds Data Pilot

- 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)

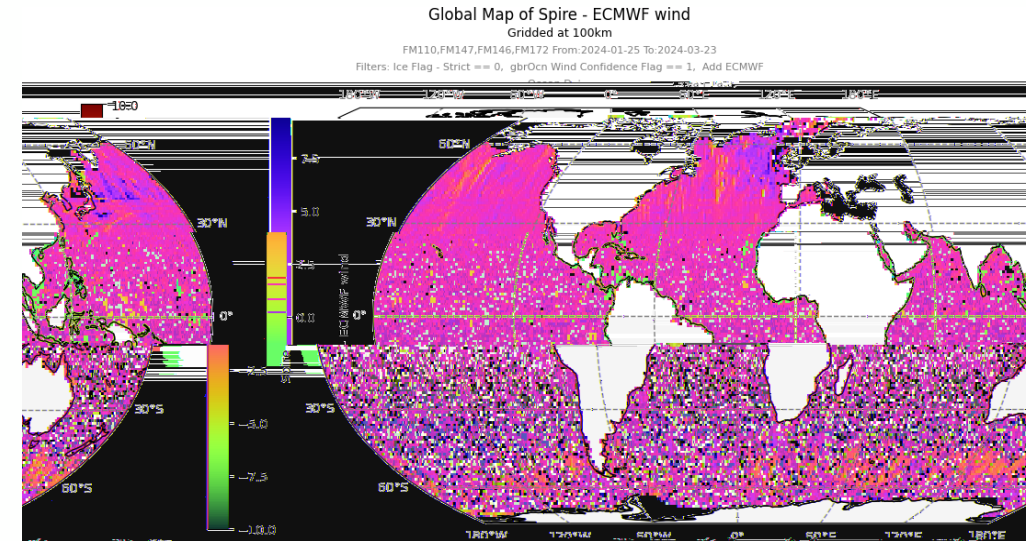
**Sigma-0 averaged
(showing wind climatology)**



Calibrated Sigma-0 vs. ECMWF wind-speed



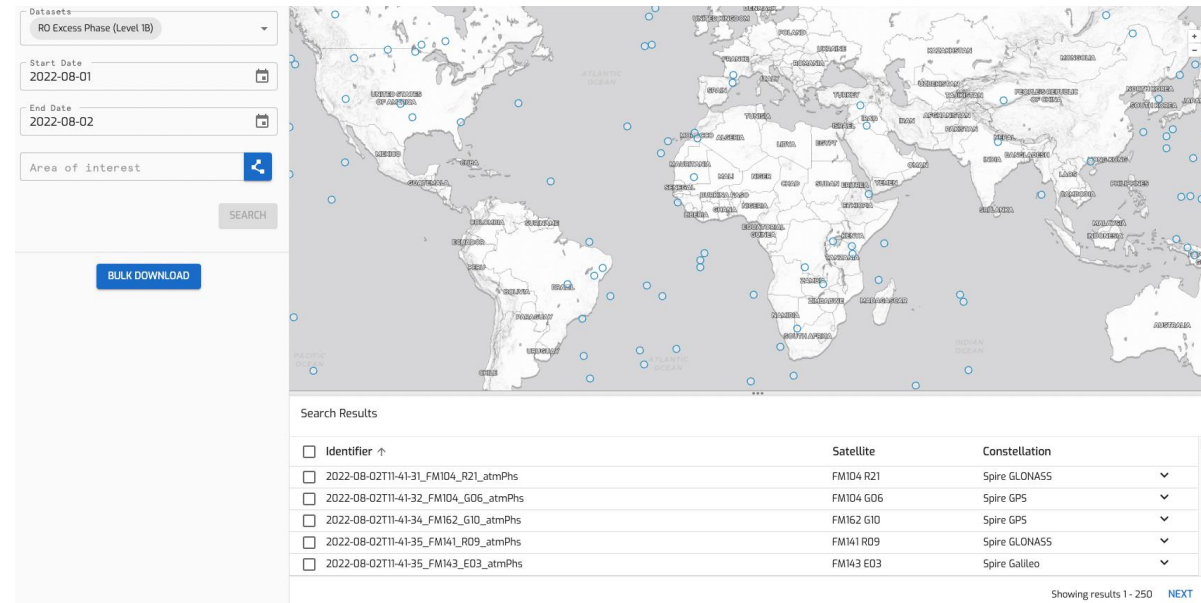
**ECMWF - Spire RMSE 2.2 m/s
(showing wind error distribution)**



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) 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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