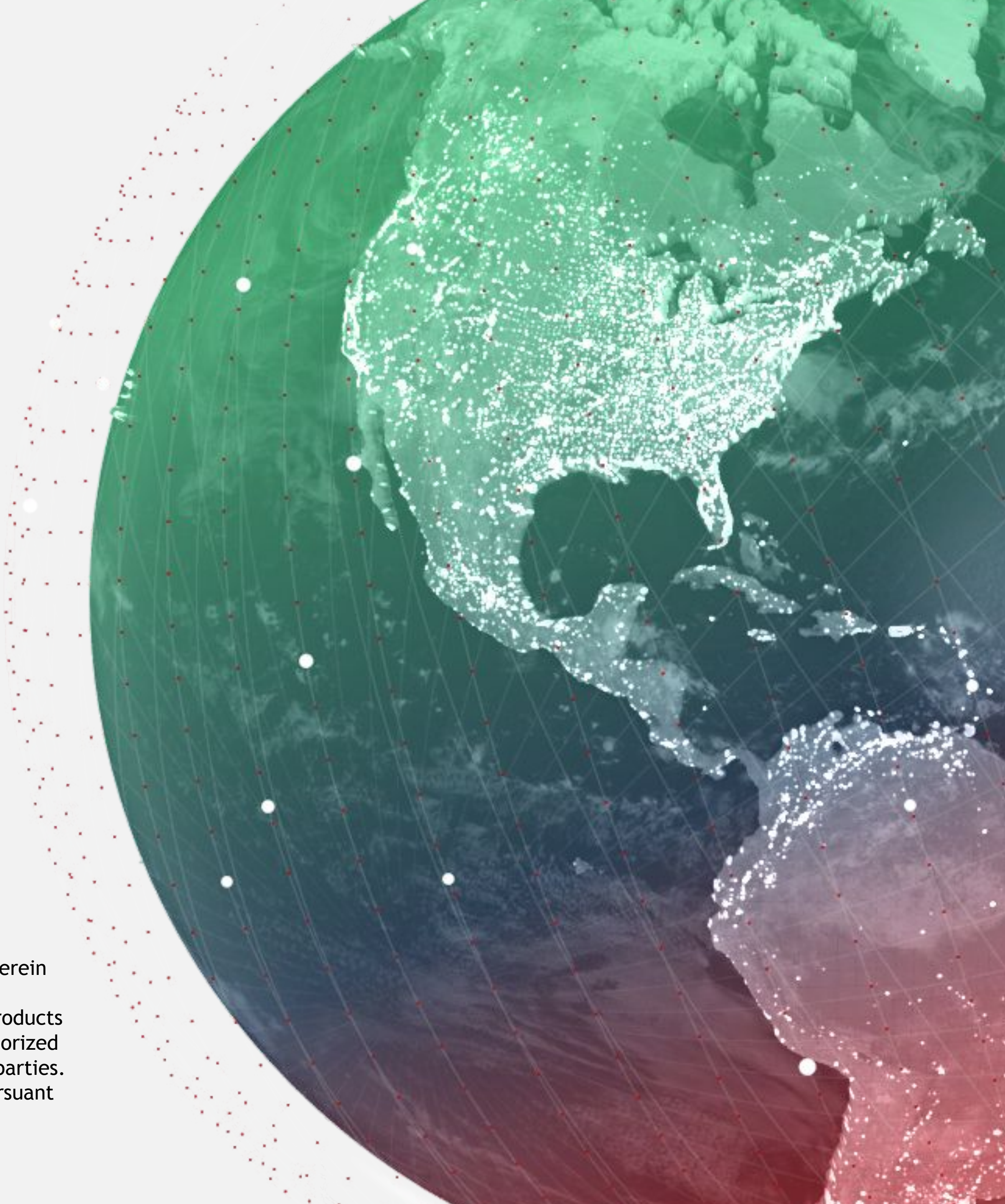
spire | federal

NASA Commercial SmallSat Data Acquisition (CSDA) Program Webinar

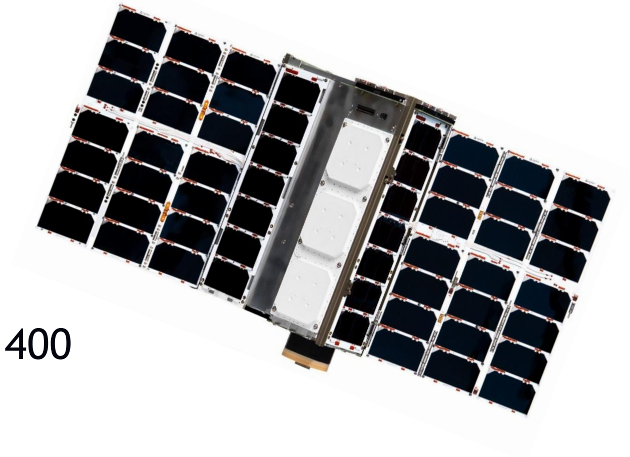


Presented by:

Kris Lindner, Account Executive – Spire Federal
Vu Nguyen, Technical Director – GNSS-RO/PRO Products
Philip Jales, Technical Director – GNSS-R Products
Troy Reisner, CSDA Program Manager (Spire)

November 19th, 2024

Spire Global Company Overview



Building a space-powered global data network

- Spire Global, Inc. (NYSE: SPIR) is a US Company headquartered in Northern Virginia with over 400 employees
- Spire operates wholly owned subsidiaries in Canada, United Kingdom, Luxembourg & Singapore
- Spire Federal (Cage Code: 7JE17) provides products and services to the US Federal Government market.
- Based on revenue and cost of goods, sold Spire remains a small business for Data Processing, Navigation Services, Telecommunications, and R&D NAICS codes (encompassing all commercial offerings).

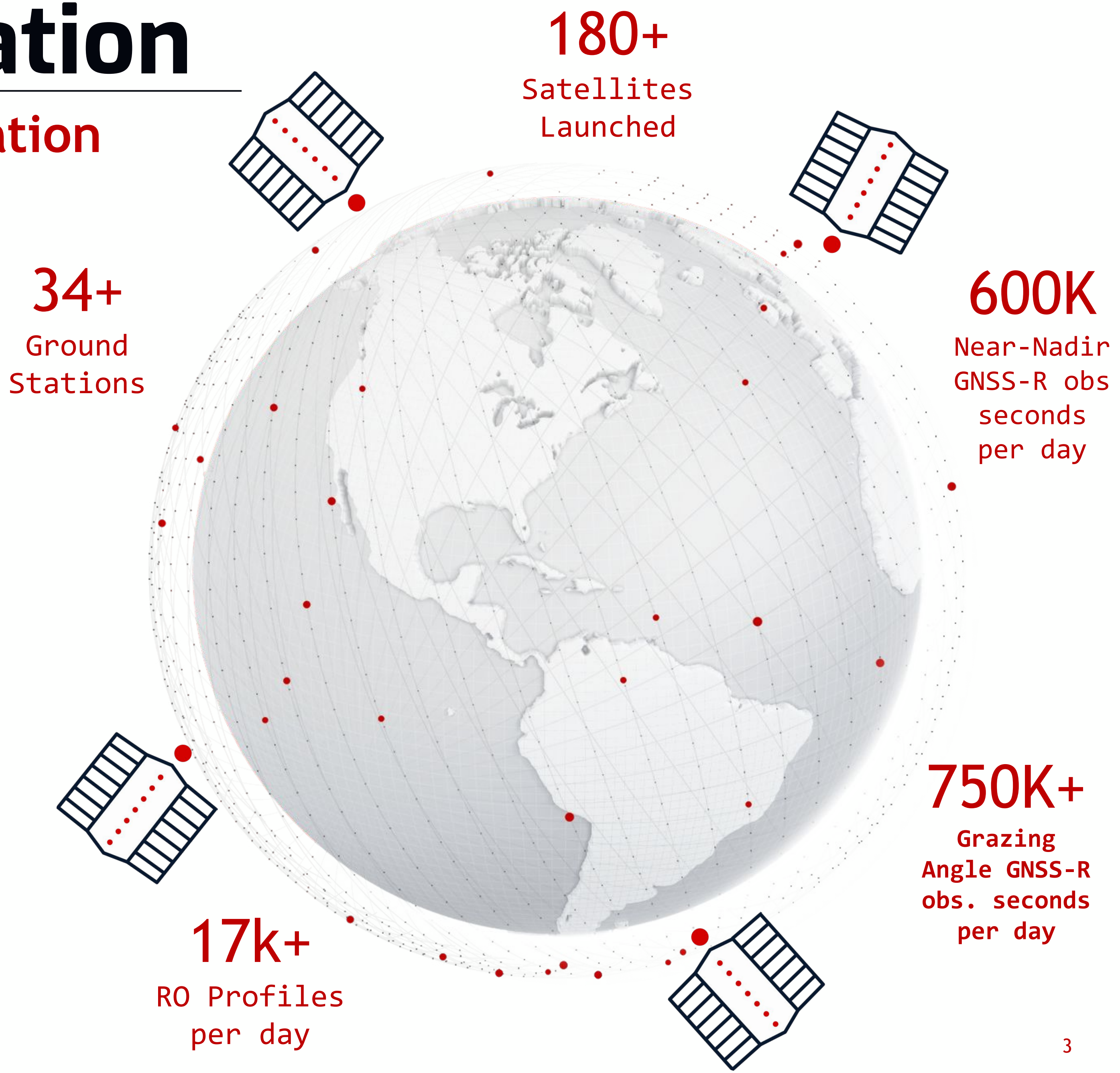
Spire Global's 5 Core Data Products & Space Services

Maritime	Aviation	Weather	Earth / RF Intelligence	Space Services

The Spire Constellation

The largest multipurpose constellation in the world

- The Low Earth Multi-Use Receiver (LEMUR) is Spire's CubeSat platform used to track maritime, aviation, and weather activity from space
- We operate the world's largest RF sensing fleet via a network of over 34 ground stations remotely operated with autonomous constellation management tools used to optimize tasking, collection, contact time & data transfer
- Our data provides a global view with coverage in remote regions like oceans and poles
- We are continuously launching improved sensors and upgrading them in-orbit
- We turn ideas into live feed from space in as little as 6-12 months



Spire Product Summary

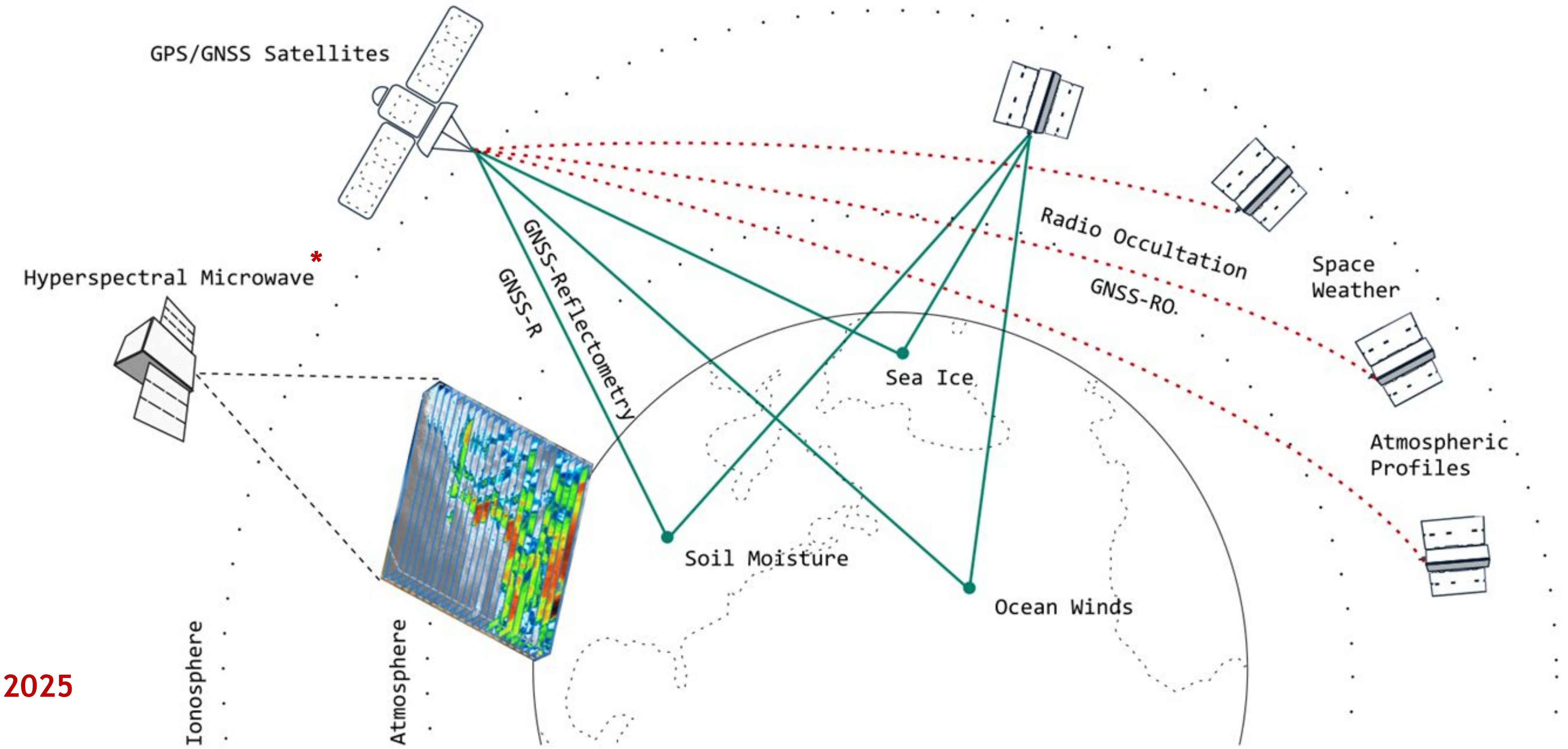
For documentation and more information, please visit https://spire.com/.

Measurement/Product Type	Derived Variables in Spire NASA CSDA Products	Example Applications	Time Range Available Through NASA CSDA
Radio Occultation	Atmospheric profiles of bending angle, temperature, water vapor	NWP assimilation, Planetary boundary layer studies	2019 to present
Navigation	Precise orbit estimates of Spire receiver	Thermospheric density, Gravity field recovery	2019 to present
Ionospheric	Total electron content, scintillation indices, electron density profiles	Ionospheric morphology (global, E-/F-region, topside), Event detection	2019 to present
Grazing angle GNSS-R	Relative surface altimetric height mainly over ice, Sea ice presence/type	Cryosphere, Lake/calm sea altimetry, River width/slope, Tropospheric water vapor	2019 to present
Near-nadir GNSS-R	Ocean wind and mean-squared slope, soil moisture	Ocean wind / wave state, Soil moisture, Surface freeze / thaw, Vegetation and biomass, Cryosphere	2020 to present
Polarimetric RO	Polarimetric phase difference sensitive to precipitation + RO variables	Precipitation monitoring	2023 to present
AIS	Vessel location, dynamic characteristics	Maritime domain awareness, fleet management, GPS spoofing detection and geolocation, predictive analysis	N/A
ADS-B	Aircraft location, dynamic flight data, aircraft characteristics	Air domain awareness, fleet management, predictive analysis	N/A
Weather Observations/Forecasting	Historical weather data, hyper accurate weather observations and forecasting	Weather and Earth science research, standard and custom forecasting, severe weather alerts	N/A
RF Geolocation	Detect and geolocate RF signals of interest	Dark vessel, GNSS jammer, PTT radio, etc. detection and geolocation	N/A
Hyperspectral Microwave Sounding	Atmospheric property profiles	Numerical weather prediction, storm tracking, climate forecasting	N/A
Space Services	N/A	Hosted payloads for numerous space-based applications	N/A

Spire Earth Intelligence Data

Our satellites capture data relevant for weather and climate monitoring
- Space weather: Ionosphere corrections for navigation, and thermospheric density
- Neutral atmosphere: Profiles of temperature, pressure and humidity
- Surface: Ocean wind, soil moisture and ice

delivered to CSDA to support NASA's Earth science research mission.

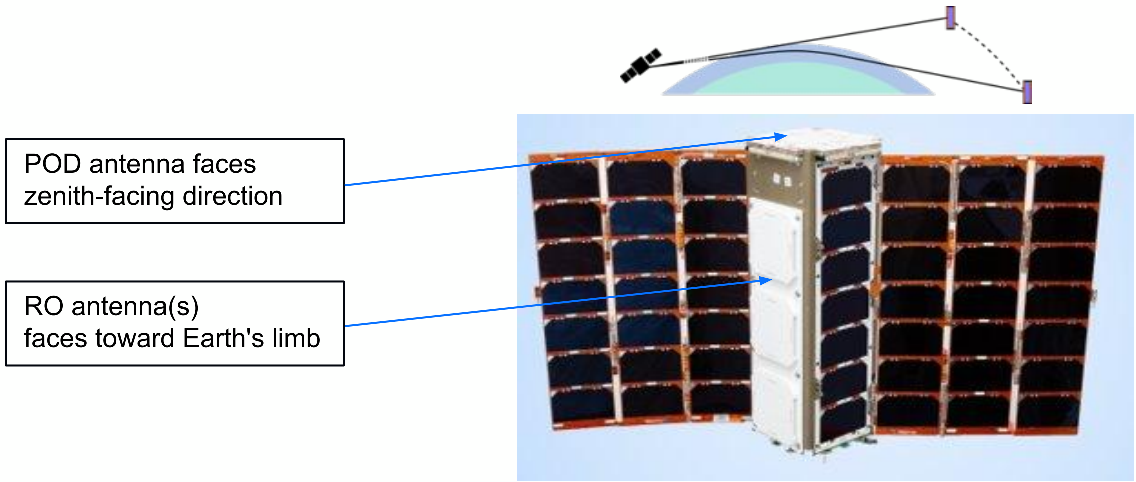


*Launching in 2025

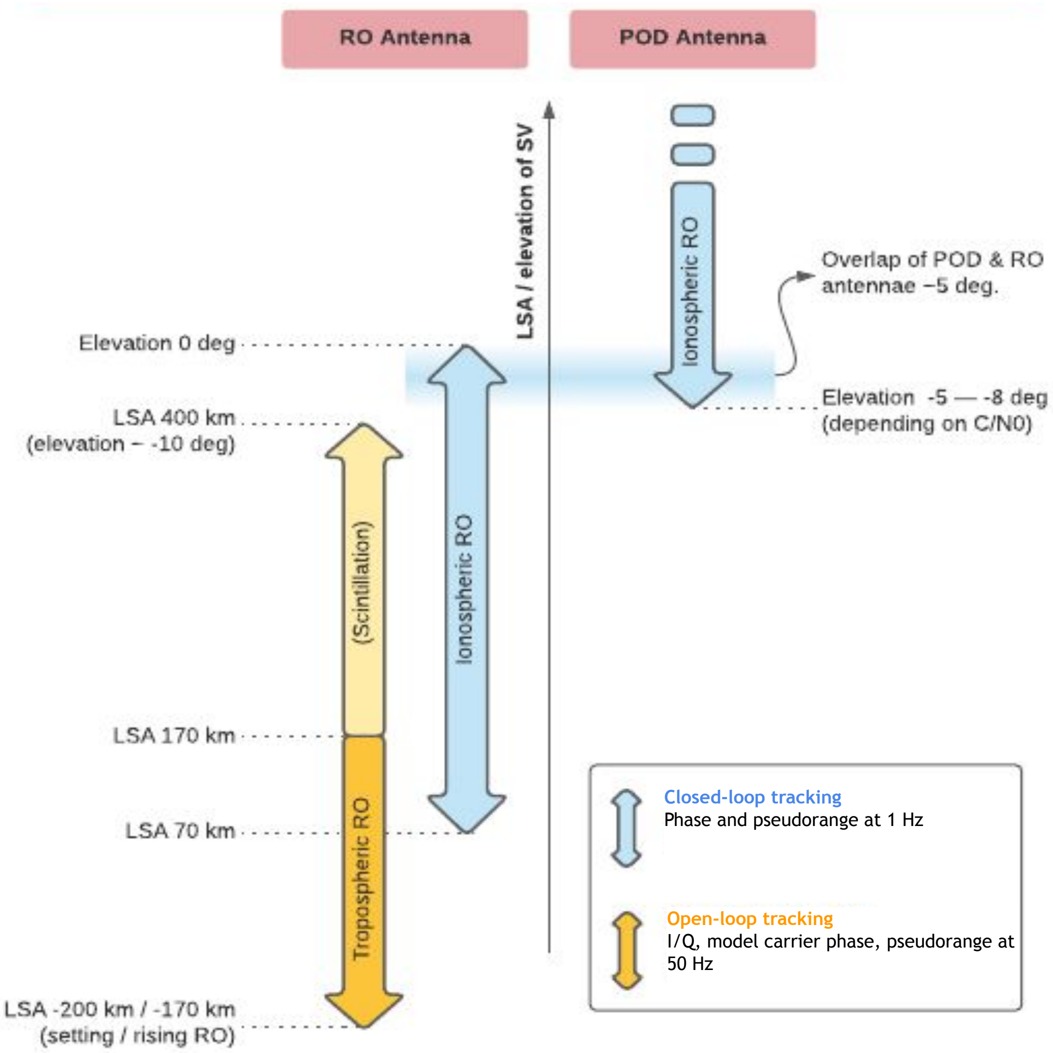
GNSS-RO Collection

- RO technique measures the phase change in the GNSS signal as it passes through the Earth's atmosphere
  - Amount of signal bending is sensitive to atmospheric properties (temperature, water vapor) with benefits to operational NWP
  - Setting/rising of Spire satellite produces vertical profile of Earth's atmosphere with ~100-meter vertical resolution, < 0.1 K accuracy
- GNSS signals collected with in-house built STRATOS receiver
  - Multi-GNSS, dual-frequency signals tracked in open-loop
  - Demonstrated many "firsts" for RO including producing high-quality profiles from a Cubesat, producing non-GPS profiles, etc.

Spire GNSS-RO 3U Satellite Bus



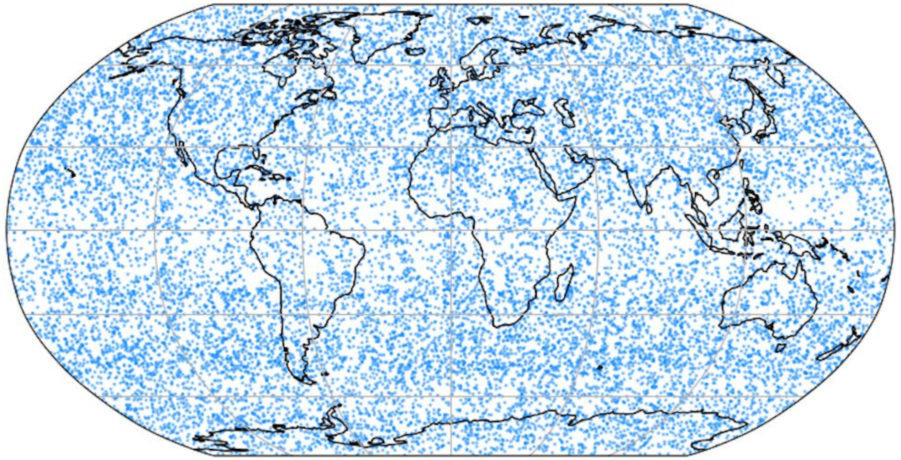
RO Measurement Configuration



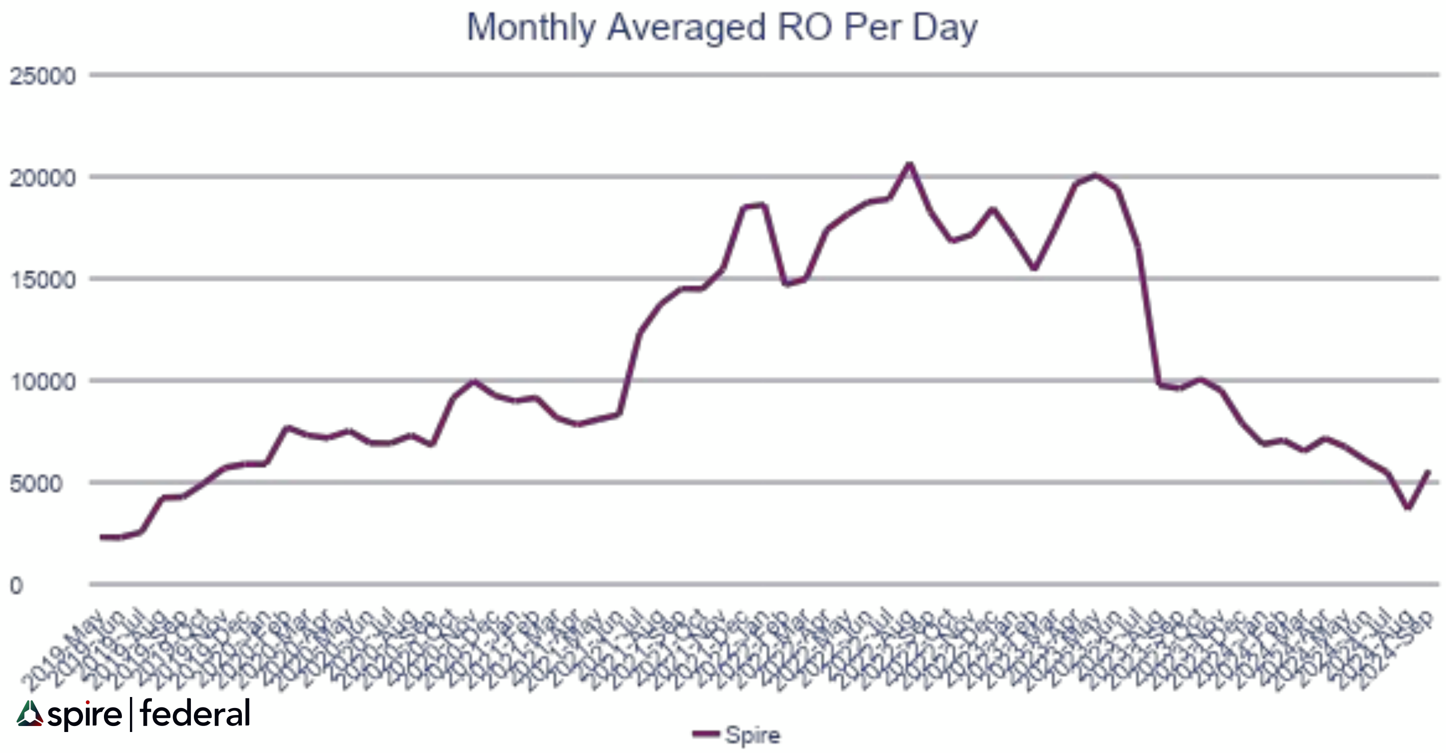
GNSS-RO Production

- Spire constellation has demonstrated the capability of producing over 20000+ quality-controlled profiles per day
    - Global coverage achieved over multiple orbital local times
- Continual spacecraft bus and ground station additions and improvements to increase efficiency and decrease data latency

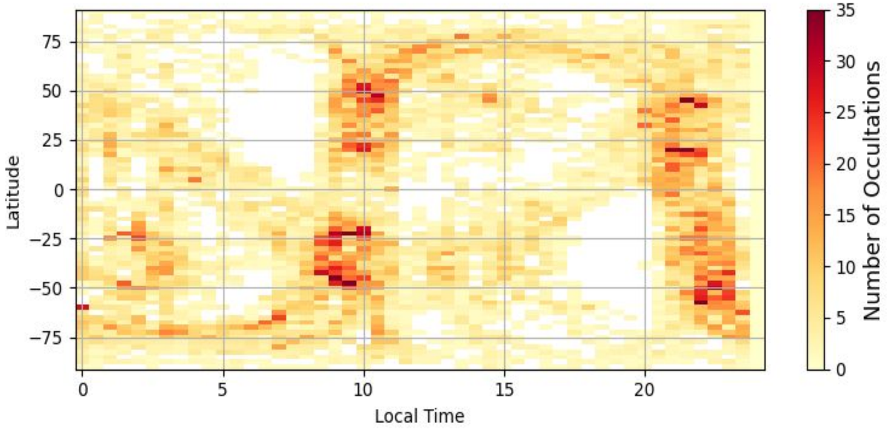
World's largest producer of RO profiles
(24 hr coverage in 2022 shown below)



Monthly Averaged RO Available Through NASA CSDA



Diverse local time coverage



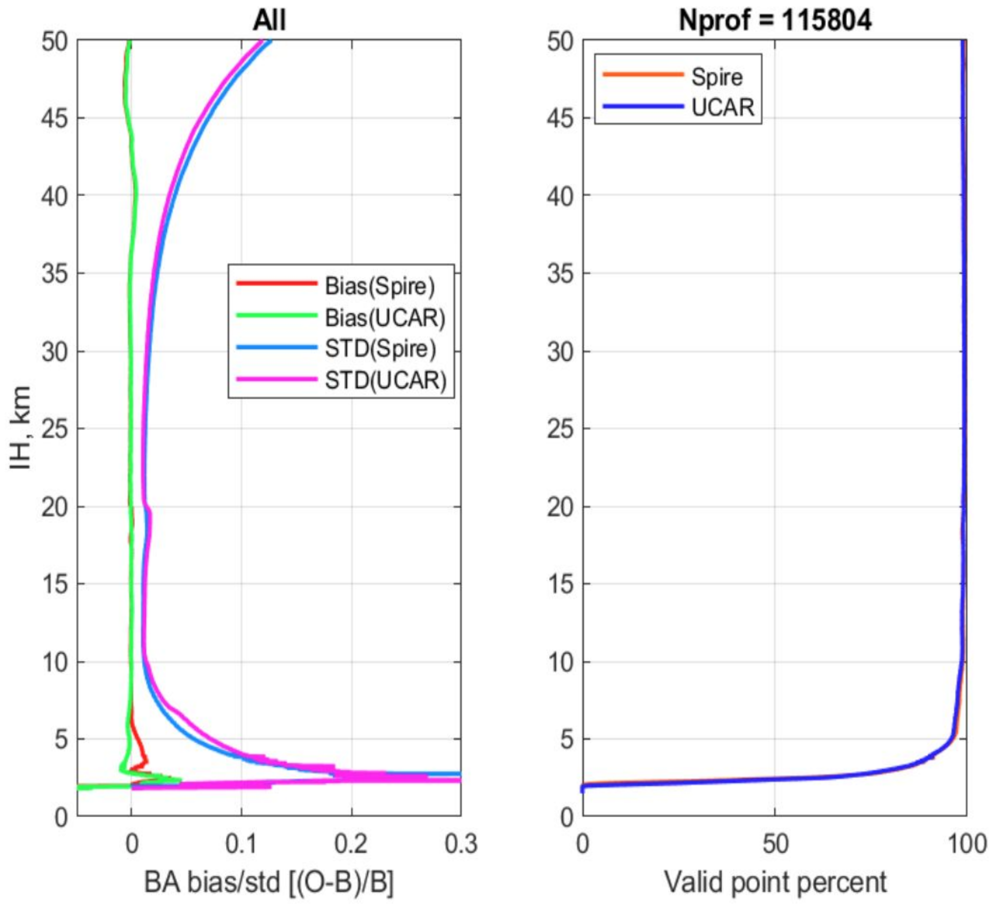
GNSS-RO Data and Processing

RO Data Processing

- Spire RO data are downloaded and processed into all data levels using a state-of-the-art processing system
- Mainly follows CDAAC conventions and includes:
    - Level 0 Low-level 50 Hz data (custom netCDF, opnGns)
    - Level 1B Excess phase (atmPhs)
    - Level 2 Atmospheric profiles (atmPrf, bfrPrf)
    - Navigation data
        - Level 1A RINEX data (podObs)
        - Level 1A Attitude data (leoAtt)
        - Level 1B Precise orbit estimates (leoOrb)

Spire vs. UCAR processing compared to ECMWF

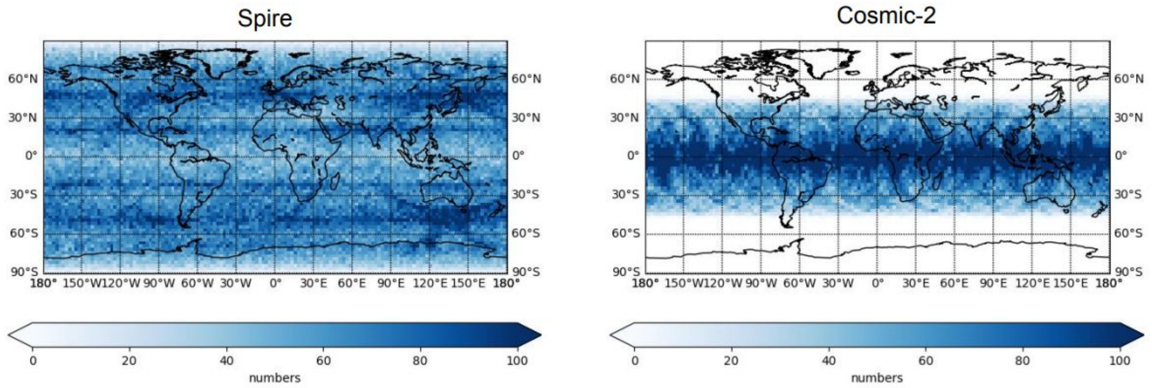
(Dec 2021 for NOAA CWDOB DO3)



External Evaluations

At the <u>2021 International RO Working Group</u> meetings, independent users showed Spire RO is similar in quality and impact to institutional RO missions

ECMWF compared Spire to COSMIC-2 sampling and impact

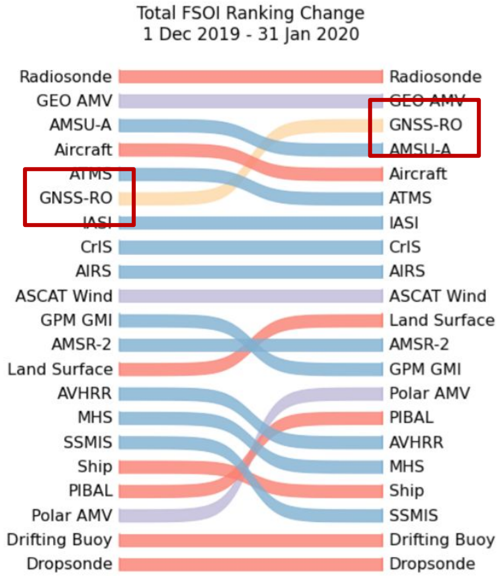


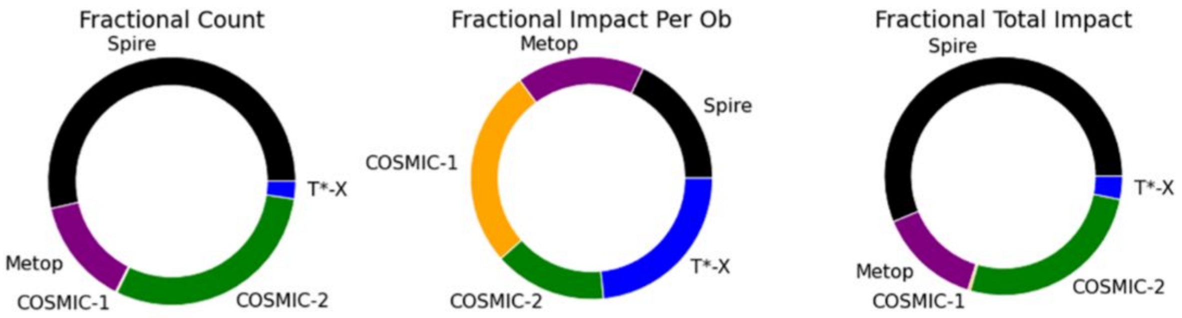
Source: K. Lonitz, ECMWF, 2021 (2021 IROWG)

NOAA showed Spire matches COSMIC-2 penetration depths

	10N-10S	10N-30N	30S-10S	30N-45N	45S-30S	45N-60N	60S-45S	60N-90N	90S-60S
COSMIC-2	0.85	0.90	0.75	1.35	1.10				
GeoOptics	0.95	1.05	1.10	0.70	0.80	0.35	0.40	0.55	0.20
SPIRE	0.90	0.90	0.75	0.80	0.55	0.45	0.25	0.45	0.20
KOMPSAT-5	1.85	1.50	1.15	0.40	0.95	0.35	0.40	0.25	0.20
PAZ	2.65	1.85	2.05	0.90	1.30	0.45	0.45	0.35	0.25

Source: B. Ho, NOAA, 2021 (2021 IROWG)





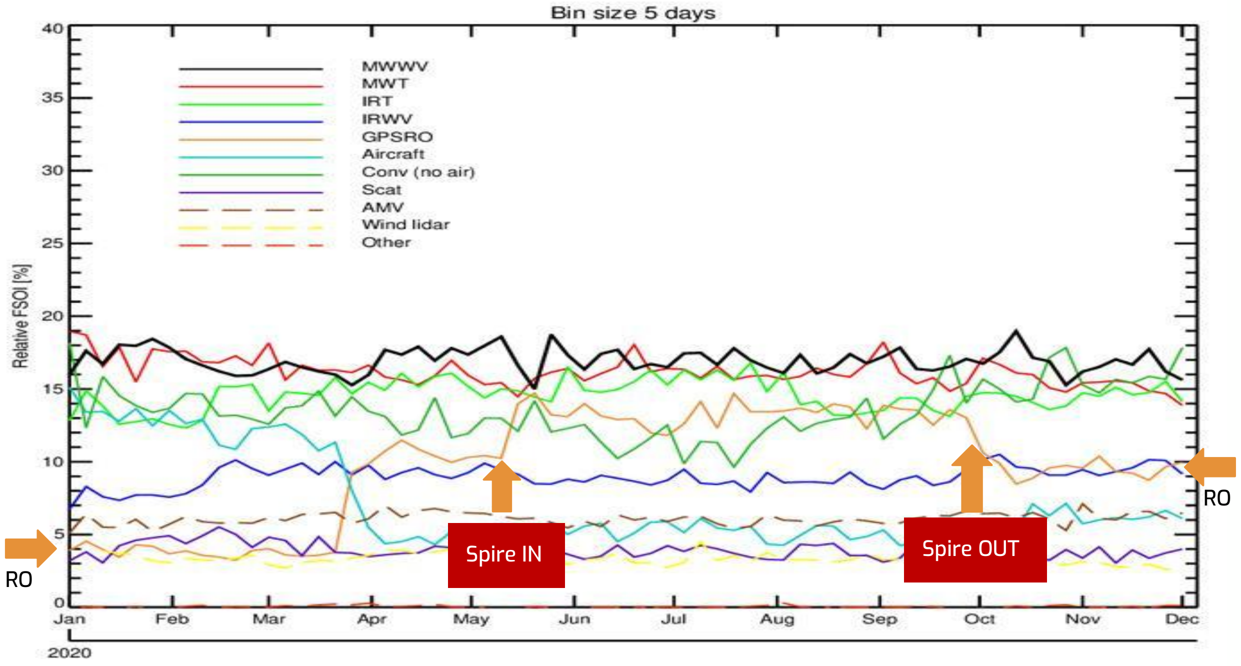
NASA showed Spire data moved RO FSOI to third place among all observations and **Spire led in fractional total impact**

Source: W. McCarty, NOAA, 2021 (2021 IROWG)

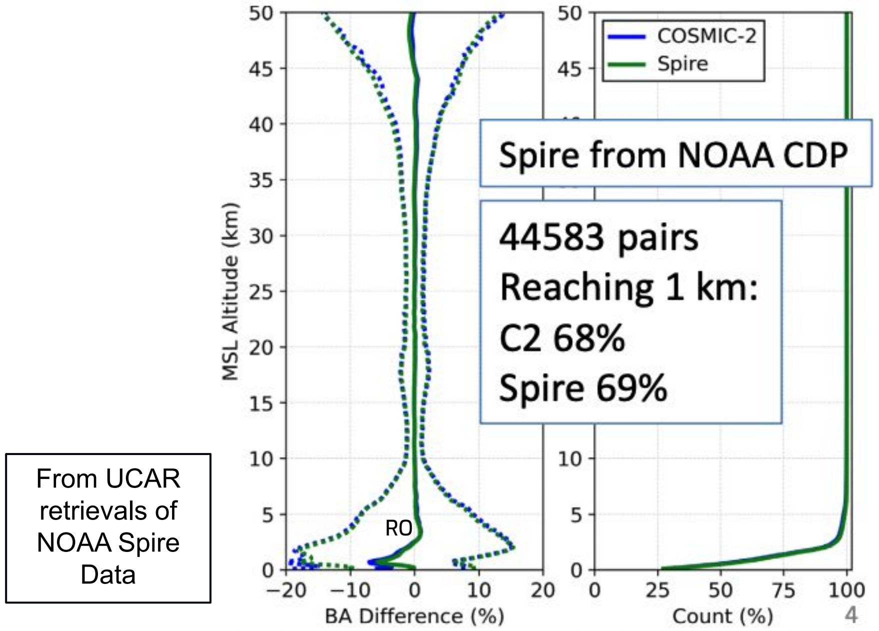
External Evaluations

- 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

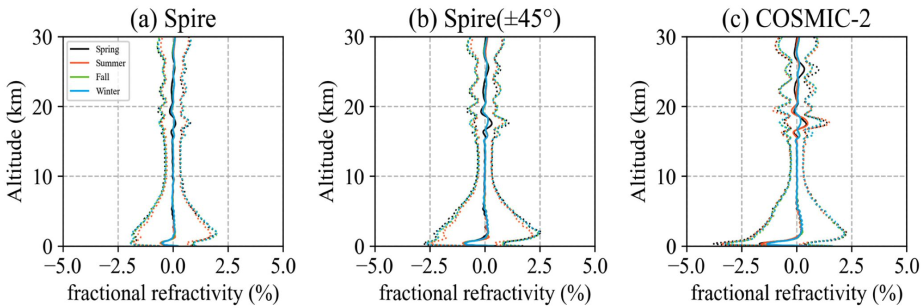
ECMWF FSOI increase after assimilating Spire RO (~5-7k/day) in 2020
(S. Healy, ECMWF, 2020)



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



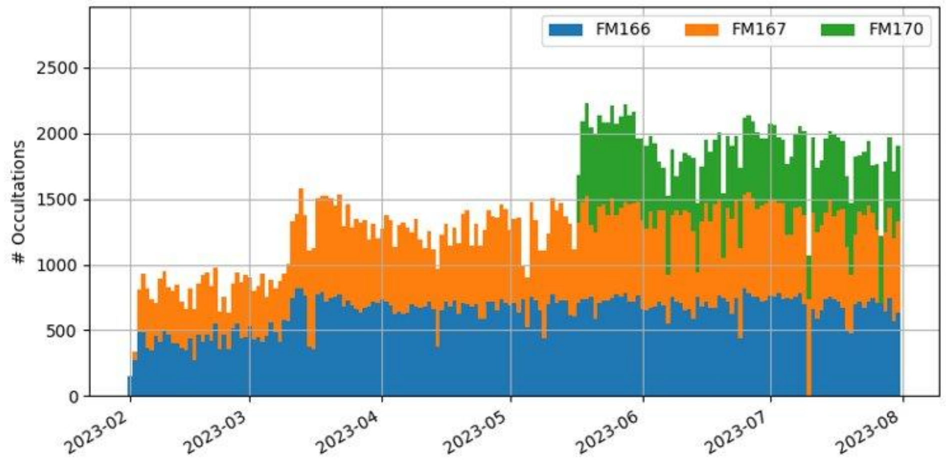
Spire vs. COSMIC-2 Refractivity Differences from ERA5
(*Qiu et al., 2023*, https://doi.org/10.3390/rs15215082)



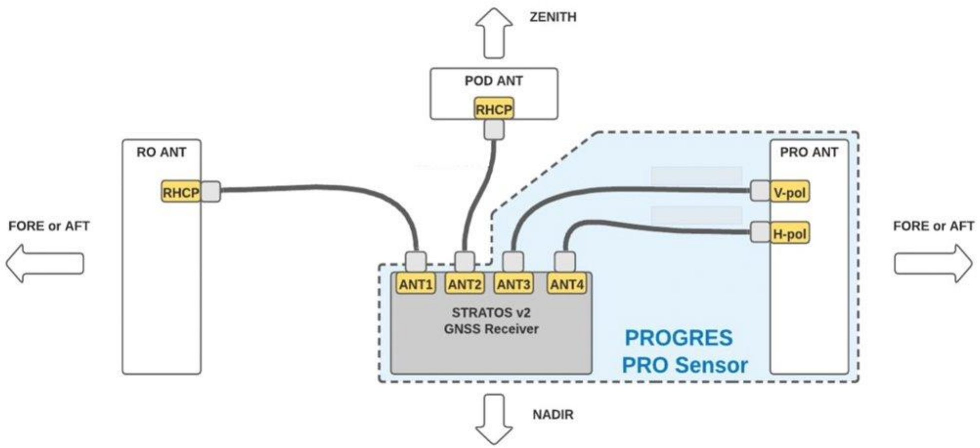
Polarimetric Radio Occultation

- 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
- Bending angle profiles can be derived from PRO data with similar quality to Spire's operational RO

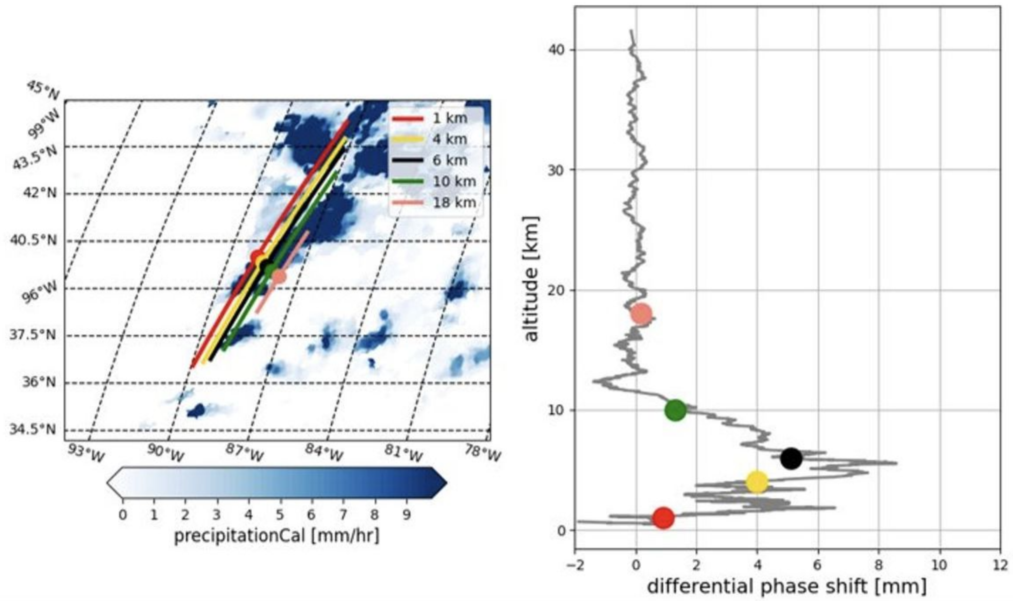
Collected PRO profiles by Spire satellite



Spire Polarimetric RO payload



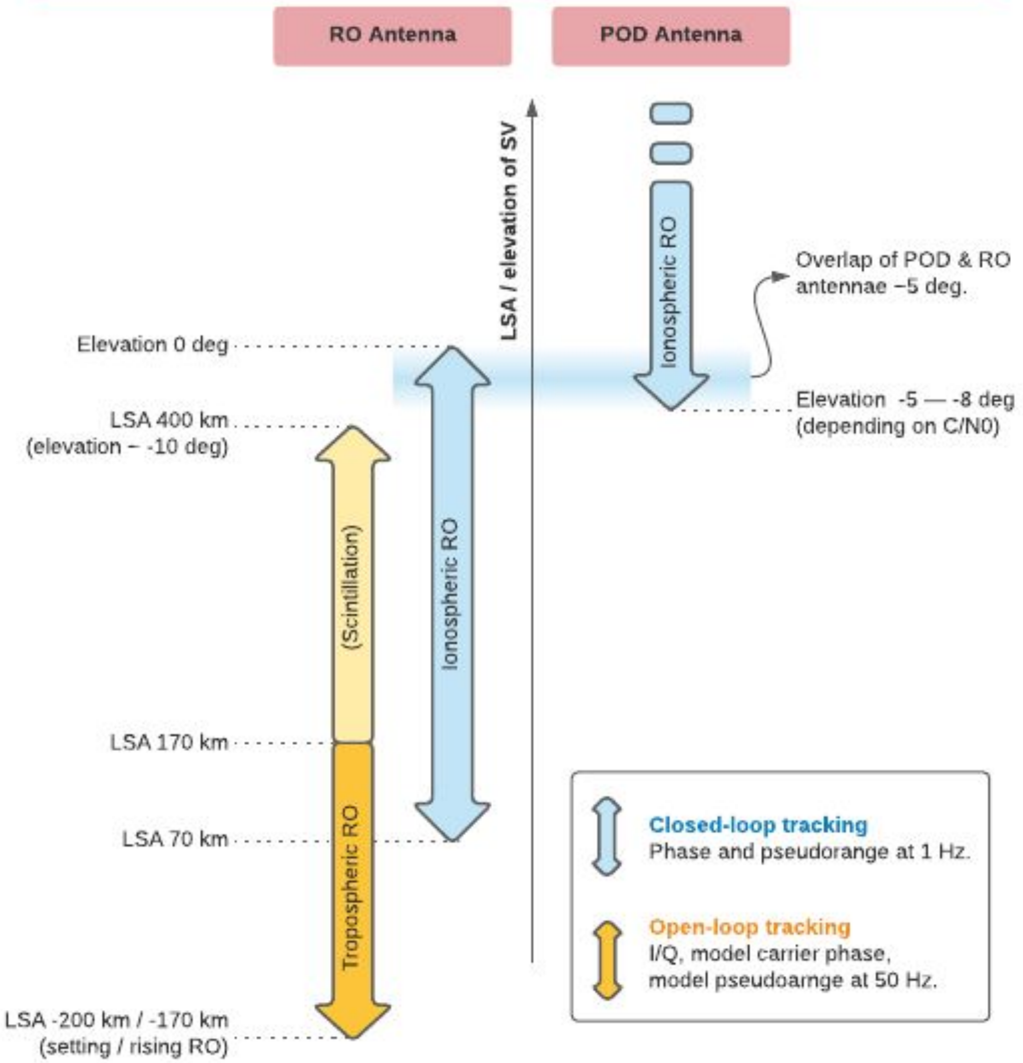
PRO Measurements Compared to IMERG Precipitation



spi

Ionospheric Data Collection and Products

- SpWx relevant data collected from both POD and RO antennas
  - POD antenna: 1-Hz closed loop tracking
  - RO antennas: 1-Hz closed loop tracking and 50 Hz open loop tracking
  - Observation range overlap between POD and RO antennas
- Data Products
  - **Level 0 Raw:** GNSS phase, pseudorange, navigation solution and onboard scintillation indices are contained in short segment netCDF files to minimize latency
  - **Higher-order products** include GNSS observables in RINEX format (podObs), TEC estimates (podTec, ionTec), scintillation indices (scnLv1), and electron density profiles (ionDen)

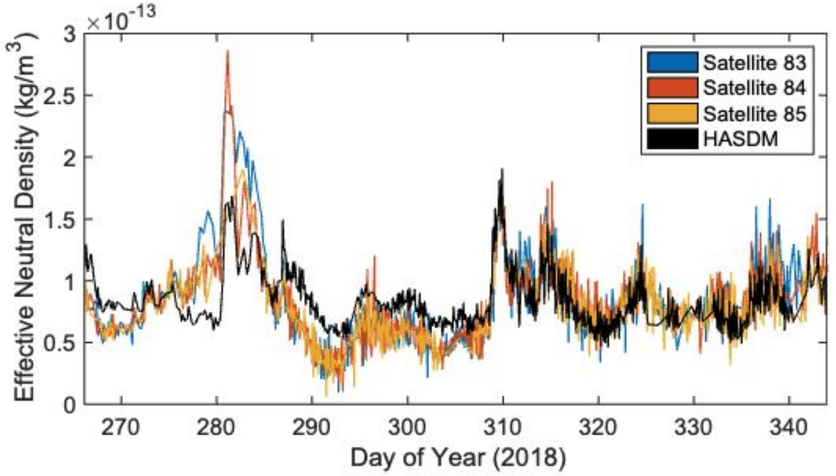


More details at Angling et al. Sensing the ionosphere with the Spire radio occultation constellation, *J. Space Weather Space Clim*, 2022 https://doi.org/10.1051/swsc/2021040

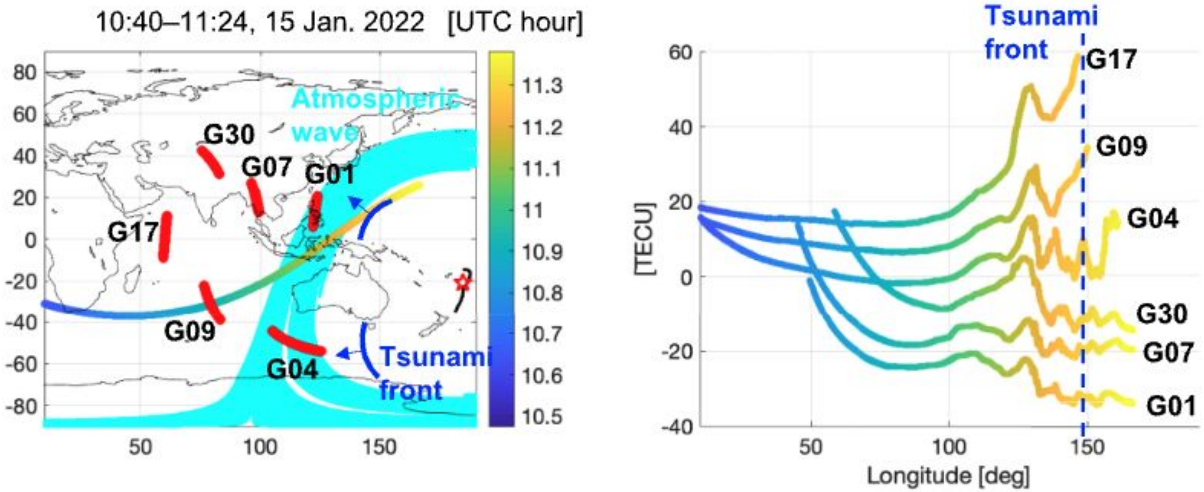
Space Weather Applications

- Spire's constellation of dual-frequency GNSS receivers in different orbital planes enables unique observations of the ionosphere-thermosphere system
- Examples of ionospheric applications include ionospheric disturbance detection, model data assimilation, climatology, storm-time analysis, etc.
- Precise orbit determination estimates can also be used for thermospheric density derivation, gravity field recovery, and potentially more

Thermospheric density estimates derived from Spire POD
(Sutton et al., 2021, https://doi.org/10.1029/2021SW002736)

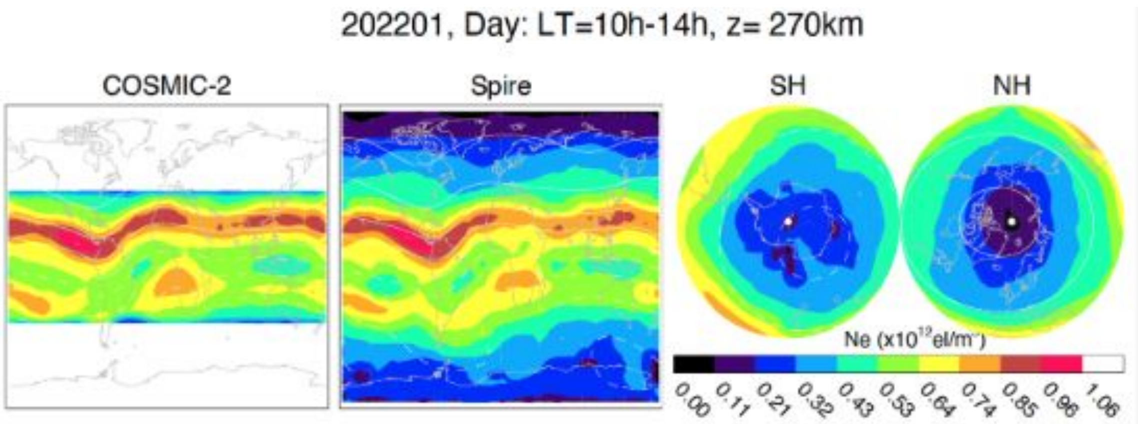


Ionospheric wave detection from Spire TEC data after Hunga-Tonga Eruption
(Han et al., 2023, https://doi.org/10.1029/2022EA002586)



Left: Ground tracks of Spire satellites (colors representing hours of flight) and GPS satellites (red). Cyan lines represent atmospheric wave propagation. Predicted tsunami wavefront shown in blue and Hunga-Tonga volcano represented by a star. **Right**: Time series of Spire TEC measurements along the longitude of the Spire trajectory.

Ionospheric electron density estimates derived from Spire data
(Wu et al., 2023, https://doi.org/10.3390/rs15133245)

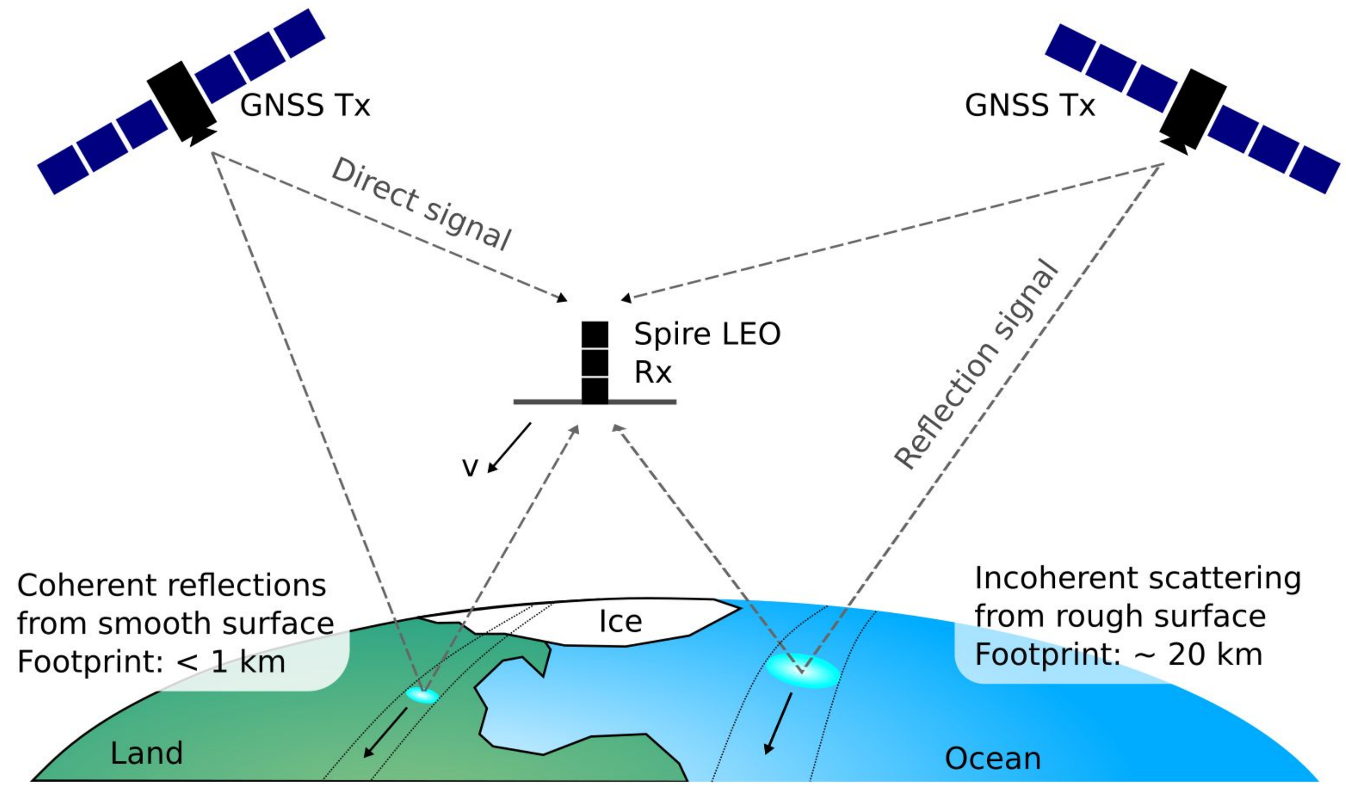


Spire Near-Nadir GNSS-Reflectometry

Spire deployed GNSS-R constellation

GNSS-R is a form of bistatic radar using GNSS signals of opportunity (e.g., GPS, Galileo, QZSS, Beidou) to perform Earth surface scatterometry (reflectivity and roughness estimation)

Reflectivity is sensitive to surface state
- Roughness -> **Ocean wave / wind**
- Dielectric -> **Soil moisture, flooding**
- Covering Volume -> **Biomass**
- Time delay -> **Surface altimetry**



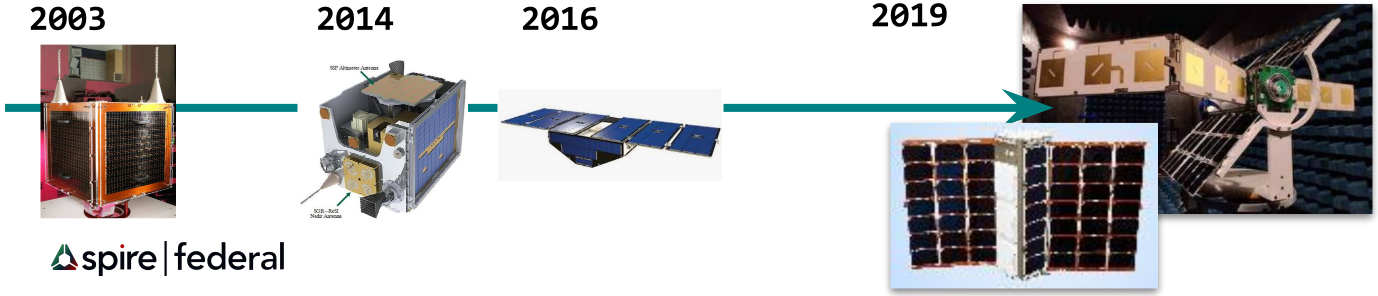
GNSS-R Timeline

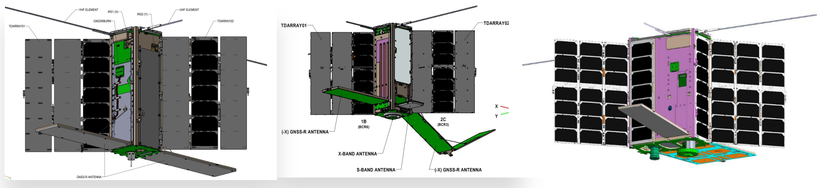
UK-DMC 2003

TDS-1 2014

NASA CYGNSS 2016

Spire 2019





GNSS-R Processing

- Key observable is reflectivity at the *surface*

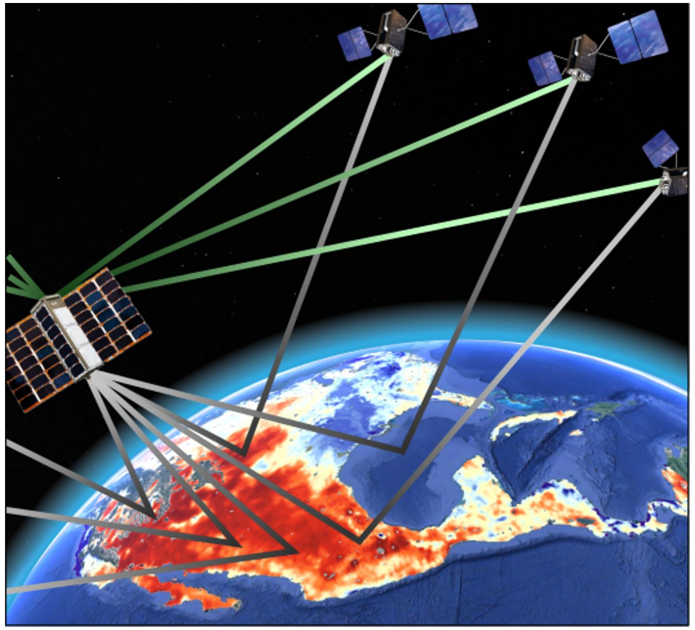
  Reflection power / Incident power

- Receiver is observing at the *satellite*

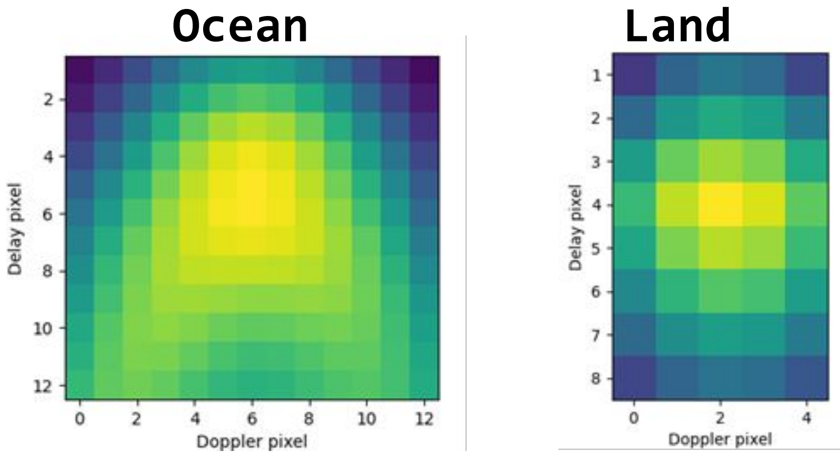
  Reflection (Delay Doppler Map) / Direct power

Calibration is correcting for:

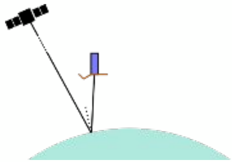
- Receiver gain (Using active calibrations system)
- Antenna gains
- Free-space path losses
- Surface scattering area



Delay Doppler Maps

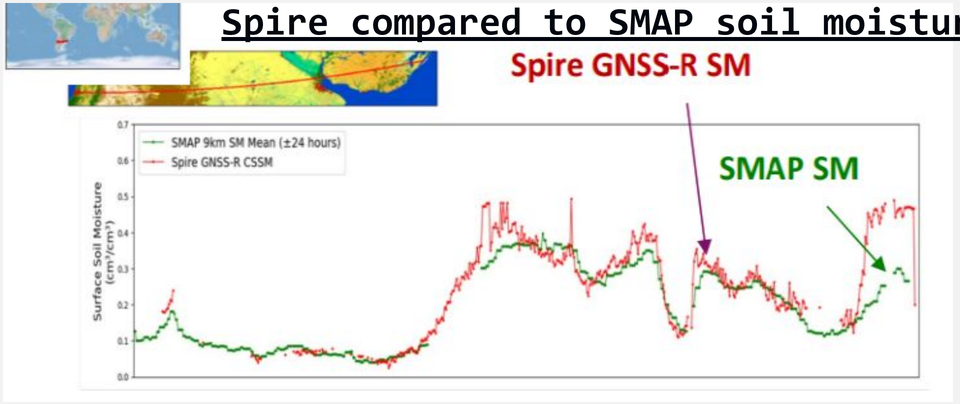


Spire Soil Moisture Data Products



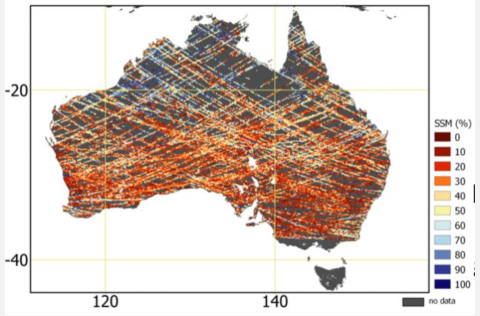
How GNSS-R differentiates from soil moisture from radiometers such as SMAP & SMOS

High similarity for climate observation continuity



GNSS-R can provide robust temporal coverage

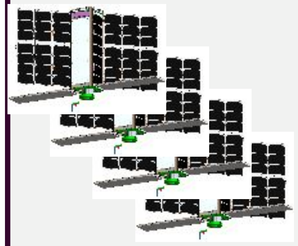
Capturing **precipitation events** and **diurnal cycle** only feasible using small-satellites

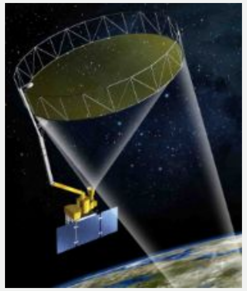


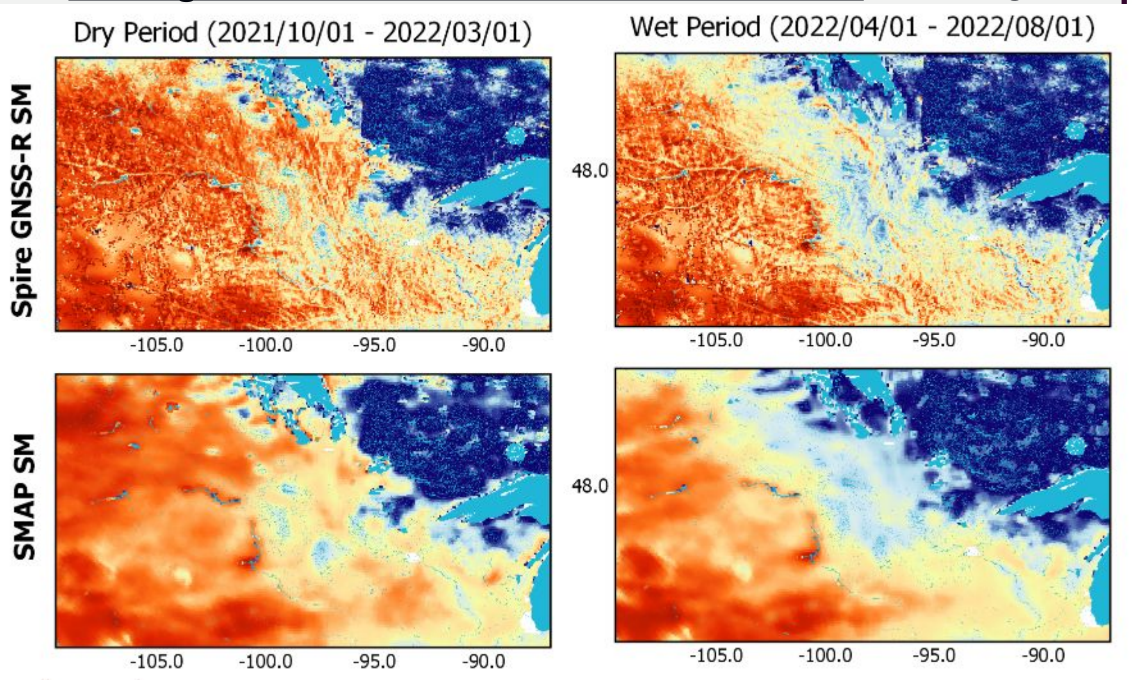
Spire "gbrSSM"

GNSS-R provides higher spatial resolution information

(Footprint **3 to 6 km** vs. SMAP **36 km**)





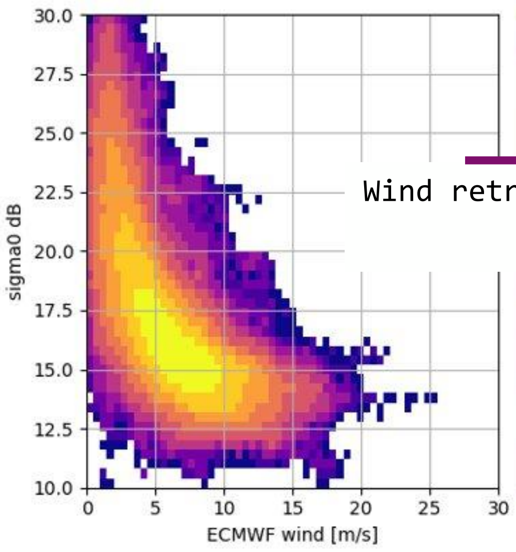


GNSS-R Ocean Wind / Wave

- Ocean wind is impactful in operational weather forecasts & high impact events
- Why GNSS-R?
  - Views ocean in all precipitation conditions
  - Can add rapid revisit of developing weather systems
- Ocean wind retrieved from normalized bi-static radar cross-section σ_0
  - Along-track filtering to 25 km
  - Mean Square Slope (MSS)

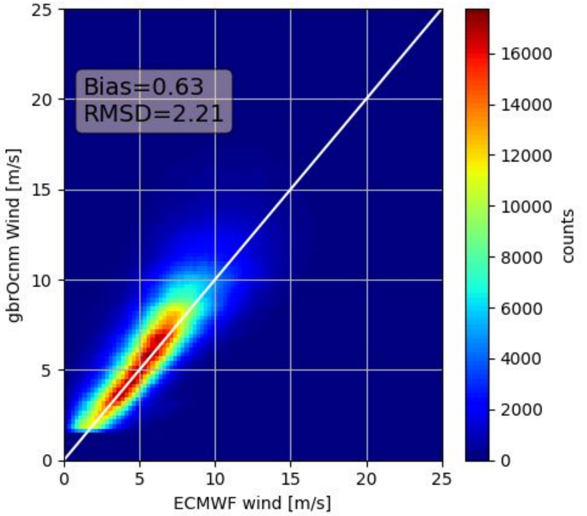
Comparison to ECMWF U10 wind speed

Sigma-0

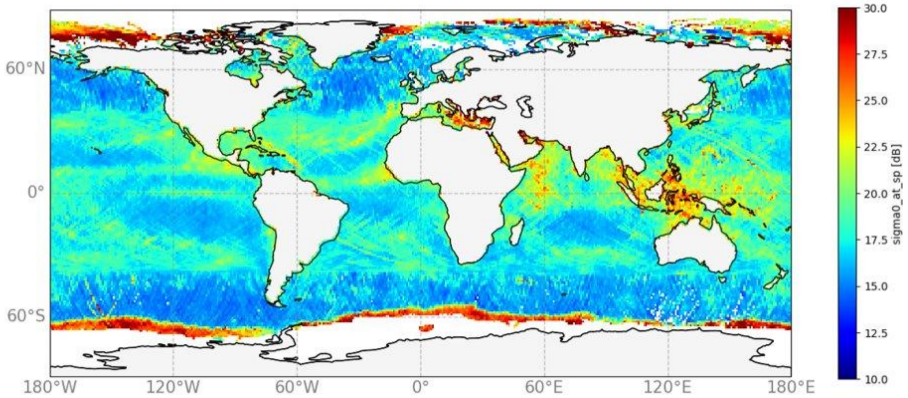


Wind retrieval →

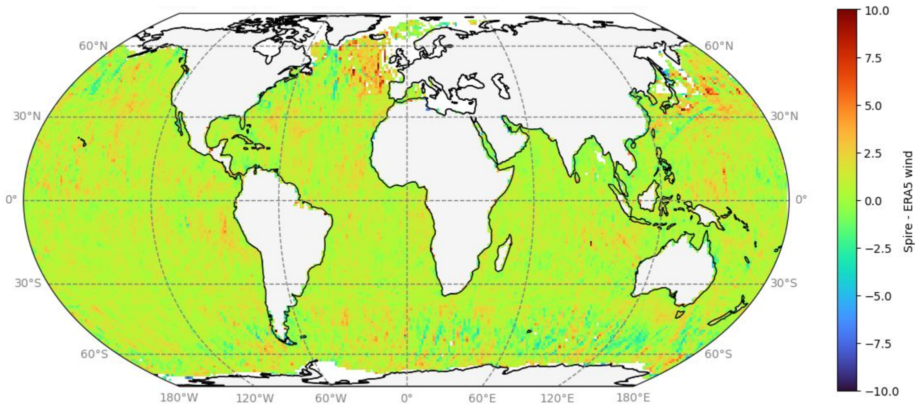
Spire wind "gbrOcn"



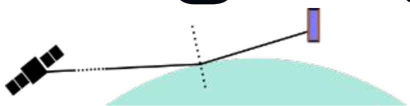
Average sigma0

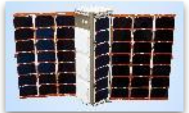


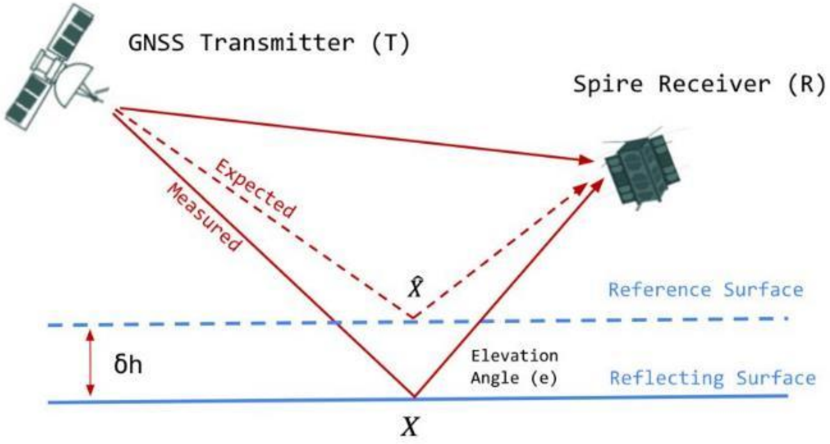
Comparison to ERA5



Grazing Angle GNSS-R



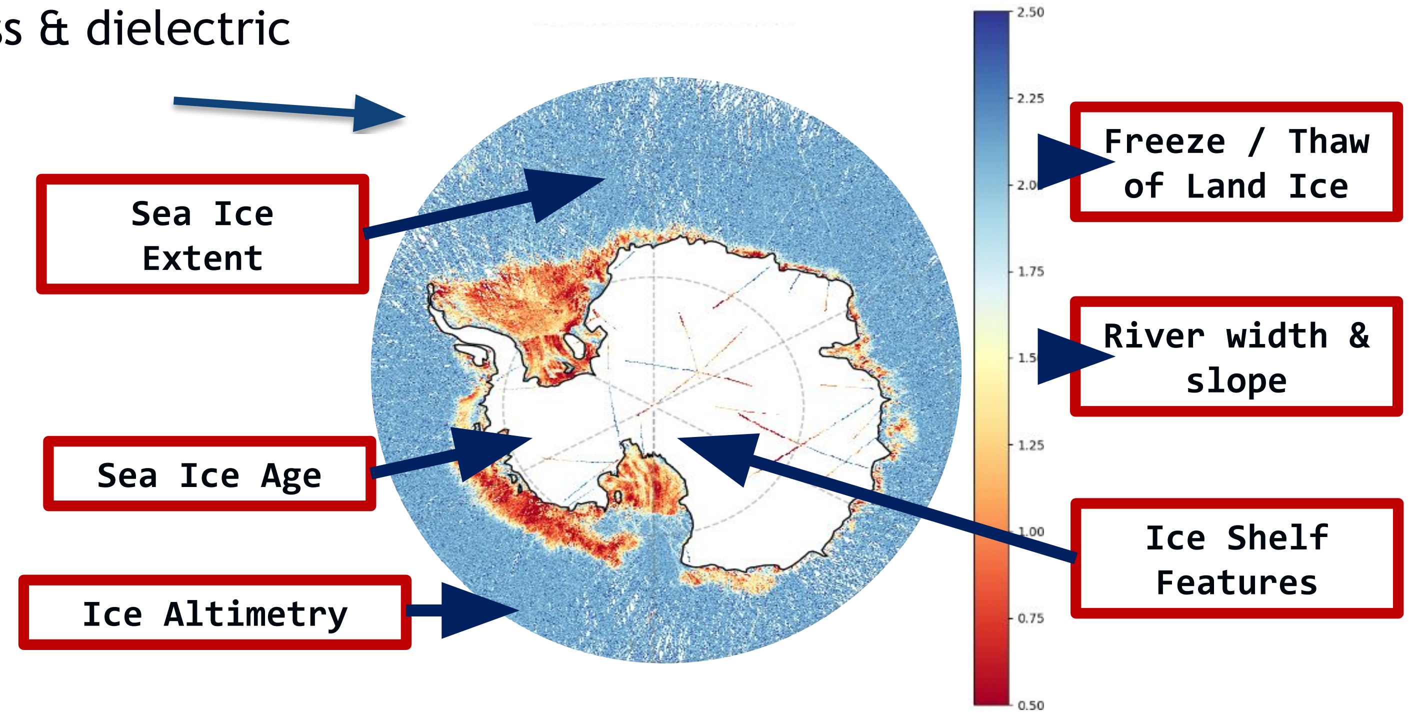




- Spire's operational measurements use the **spare capacity of** the GNSS-RO satellites
  - Following first grazing reflections seen by CHAMP in 2001
- Where the surface is smooth reflections are **coherent**
  - Which enables **carrier phase delay altimetry**
  - Spire altimetry data: **16 cm RMSD to model surface altitude**
  - Processing: Outputs at 50 Hz, Dual frequency L1/L2 or E1/E5
- Additionally retrieves the surface roughness & dielectric properties

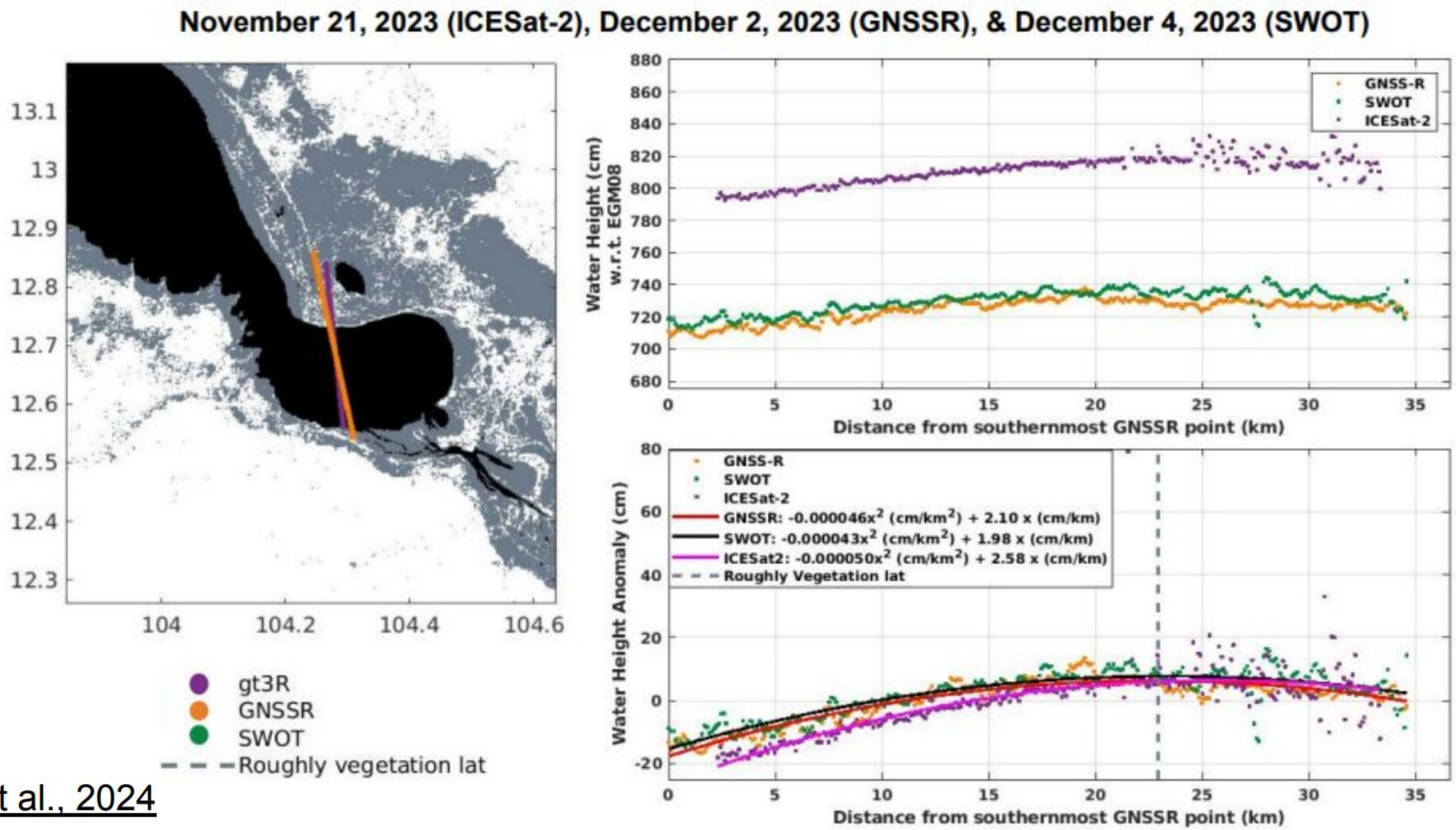
- **Spire data products**:
  - **Level 1: Observations (Refl. Phase)**
  - **Level 2: Height profiles**
  - **Level 2: Sea-ice extent and classification**

    ...
  - **Potential for sensing many more geophysical properties**



Spire GNSS-R Applications

Lake (Geoid) Slope



Scott et al., 2024

Selected Publications

Radio Occultation

- Lonitz et al. (2021). Assimilating Spire and COSMIC-2 data into the IFS. ECMWF Newsletter #169, 25-32.
- McCarty, W. (2021). Science utilizing data from Spire Global as part of the NASA Commercial SmallSat Data Acquisition Program. In 2021 IEEE Geoscience and Remote Sensing Symposium IGARSS.
- Qiu, C. et al. (2023). Comparative Assessment of Spire and COSMIC-2 Radio Occultation Data Quality. Remote Sensing.

Space Weather

- Weiss, J. et al. (2022). COSMIC-2: Highlights from 3 Years in Orbit. Presented at Joint OPAC-7 and IROWG-9. Leibnitz, Austria, September 8, 2022.
- Han et al. (2023). CubeSat GPS Observation of Traveling Ionospheric Disturbances After the 2022 Hunga-Tonga Hunga-Ha'apai Volcanic Eruption and Its Potential Use for Tsunami Warning. Earth and Space Science.
- Cheng et al. (2024). Detection of traveling ionospheric disturbances triggered by 2022 Tonga volcanic eruptions through CubeSats coherent GNSS-reflectometry measurement. Journal of Geophysical Research: Space Physics.
- Grombein, T. et al. (2023). Gravity field recovery based on GPS data of CubeSats from the Spire constellation. 28th General Assembly of IUGG, Berlin, Germany, July 11-20, 2023.
- Lei et al., (2023). Assessment of storm-time ionospheric electron density measurements from Spire Global CubeSat GNSS radio occultation constellation. GPS Solutions.
- Sutton et al. (2021). Toward Accurate Physics-Based Specifications of Neutral Density Using GNSS-Enabled Small Satellites. Space Weather.
- Wang et al. (2021). Ionospheric total electron content and disturbance observations from space-borne coherent GNSS-R measurements. IEEC Transactions on Geoscience and Remote Sensing.

- Wu et al. (2023) Optimal Estimation Inversion of Ionospheric Electron Density from GNSS-POD Limb Measurements: Part I-Algorithm and Morphology.

Selected Publications

Grazing Angle GNSS-R

- Anderson et al. (2024). GNSS-Reflectometry-Based Mapping of Antarctic Ice Shelf Surface Characteristics. Presented at IROWG-10.
- Buendia et al. (2023). Ice sheet height retrievals from Spire grazing angle GNSS-R. Remote Sensing of the Environment.
- Bhattacharya et al. (2023). Detection of Surface Water Using Spire Grazing Angle GNSS-R Data. 2023 International Geoscience and Remote Sensing Symposium.
- Roesler, C. et al. (2023). Gulf of Mexico loop-current signature observed from GNSS-R phase altimetry based on Spire Global CubeSat data. IEEC Transactions on Geoscience and Remote Sensing.
- Wang et al. (2023). Troposphere Sensing Using Grazing-Angle GNSS-R Measurement From LEO Satellites. Geophysical Research Letters.
- Wang et al. (2022). Observation of the Mississippi River Surface Gradients from Spire's GNSS-R CubeSats. 2022 International Geoscience and Remote Sensing Symposium.
- Yanez, C. et al. (2024). Lake Water Level Estimation from Grazing GNSS-Reflectometry and Satellite Radar Altimetry over the Great Lakes. IEEE Geoscience and Remote Sensing Letters.

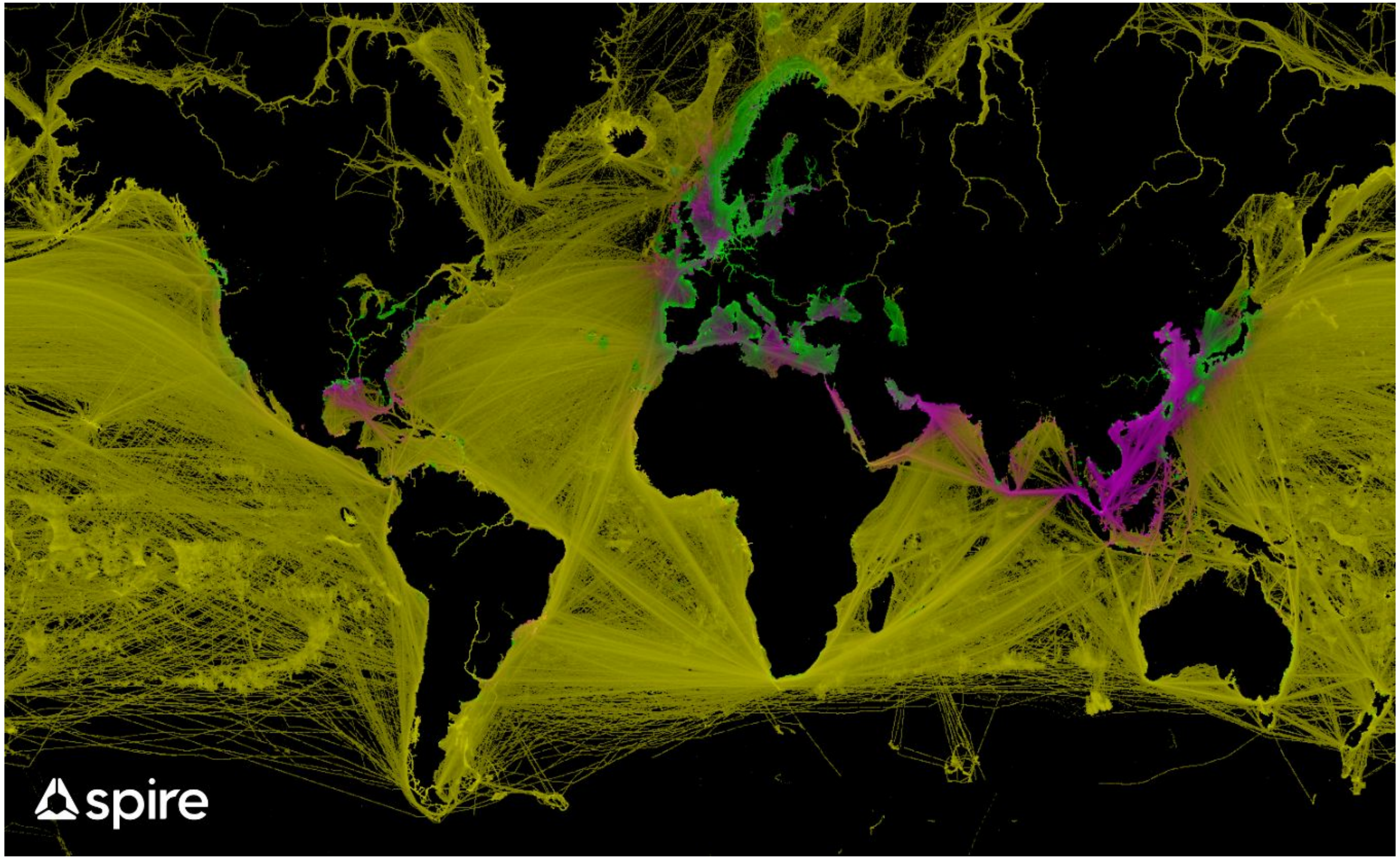
Near-nadir GNSS-R

- Setti et al. (2023). Evaluation of Spire GNSS-R reflectivity from multiple GNSS constellations for soil moisture estimation. International Journal of Remote Sensing.

Spire Non-CSDA Capabilities

Global Maritime Awareness

Large scale commercial vessel-tracking data



4.8B AIS messages collected over the course of 60 days by Spire's combined AIS feed. Colored by source;
Satellite – yellow
Enhanced – purple
Terrestrial - green

TCP Output Format	NMEA 0813 + Tags
API Output Format	JSON

Global Aviation Awareness

Large scale commercial aircraft-tracking data

121.5M ADS-B messages collected over the course of 60 days by Spire's satellite constellation, visualized in the Heavy.ai platform as a density point map

API Output Format	JSON

RF Detection & Geolocation Collection Assets

Detect, collect, and geolocate RF signals from LEO with single- & multi-satellite techniques.

- **Over 100 active satellites in orbit**
  - Dedicated RF payloads for VHF, UHF, L-band, and S-band
  - 2-, 3-, and 4-ball satellite clusters available for tighter geolocation accuracy
  - Upcoming Ku/Ka-band & X-band capabilities
- **450+ years of cumulative flight-proven heritage**
  - Onboard edge-based AI/ML computing with high-performance GPU processors
  - Wideband RF collection with tunable SDR modules
  - High-data rate intersatellite computing with RF-ISL and Optical-ISL
- **34+ active ground stations worldwide**
  - UHF, S-band, and X-band capabilities, with upcoming Ku/Ka expansion for faster downlink
  - Over 70,000 monthly contacts & over 320,000 monthly contact minutes
- **6+ orbital planes**
  - High-revisit and low-latency downlink, including coverage in remote regions
- **30+ daily RF collections** (depending on location, frequency, bandwidth)
  - Multiple revisits per day, e.g., Northern Russia 91-min revisit rate
- **Upcoming Spire RF Intelligence capabilities**
  - January 2024: Commissioned 4-Ball RF Detection & Geolocation Cluster
  - Mid 2025: launching 3-Ball RFGL Cluster w/ Imaging Capability for moving target indication (MTI)
  - Late 2025: launching 3 Ball RFGL Cluster w/ Added SATCOM Spectrum

Spire Frequency Collection Bands	MHz/GHz
VHF	130-183
UHF	310-508
GPS L1	1575.42
GPS L2	1227.6
GPS L5	1176
L-Band (ADS-B)	1085-1095
L-Band (GNSS)	1160-1610
L-Band (SATCOM)	1616.5-1636.5 1610-1675
S-Band	2020-2200
Ku/Ka-Band	10.7-12.75 17.3-20.2 13.75-14.5 27.6-29.1 29.5-30
X-Band	8.0-12.0

Spire Weather Solution

Our weather product portfolio is accessible through our historical archives and our suite of RESTful API endpoints

Historical Weather Data

30+ years of weather reanalysis data available anywhere on the planet and 3 years of forecasts

Single Coordinate Forecasts

Weather forecast for a single coordinate or an array in JSON format, for anywhere on the planet

Global Area Forecasts

Global area forecasts for pre-bundled variables in industry-standard GRIB2 format on a 12km grid

Forecast Visualizations

Integrate weather visual data into your GIS platform or application in minutes with the WMS endpoint

Current Weather Observations

Analysis of the weather currently happening for a single coordinate, a region, or the globe on a 3km grid

Point & Route Format	JSON
Area Format	GRIB2
Imagery Format	WMS
Weather Data Format	JSON or GRIB2

Future Capability

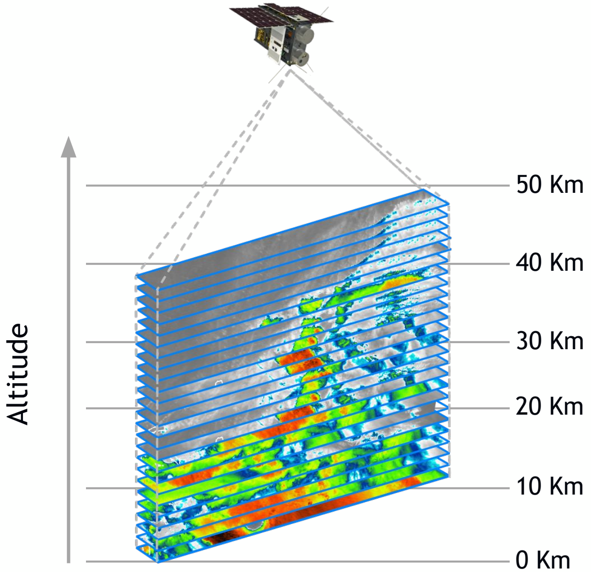
Hyperspectral Microwave Sounder (HyMS) vs. Microwave Sensors

HyMS

<40 kg Dedicated Platform

>1000 Channels

Updated every 3 Years



Benefits

1 Improved **Accuracy**

2 Better **RFI Noise Mitigation**

3 Higher **Vertical Resolution**

4 Increased **Hydrometeor Characterization**

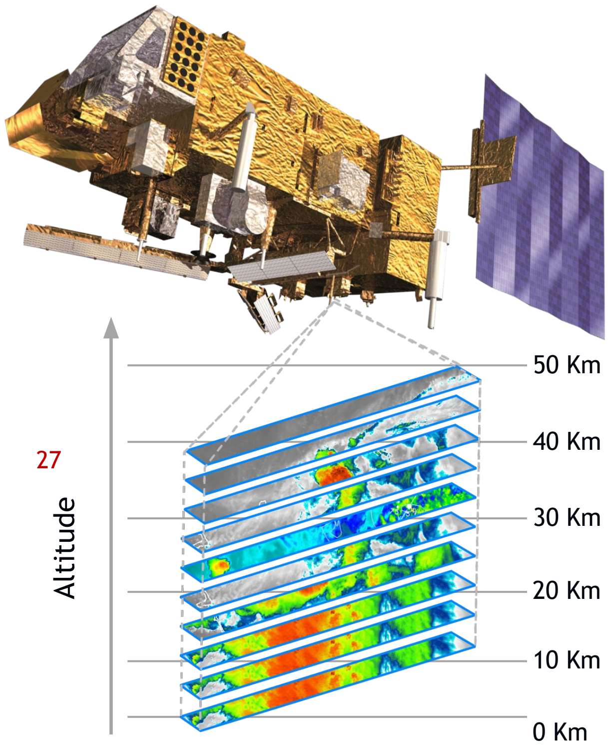
5 Improved wind profile, boundary layer, & upper atmosphere information

MetOP SG MWS Instrument

>4000 Kg Multi-sensor Platform

24 Channels

Updated every 20 Years



Spire Space Services | Proven satellite platform & facilities

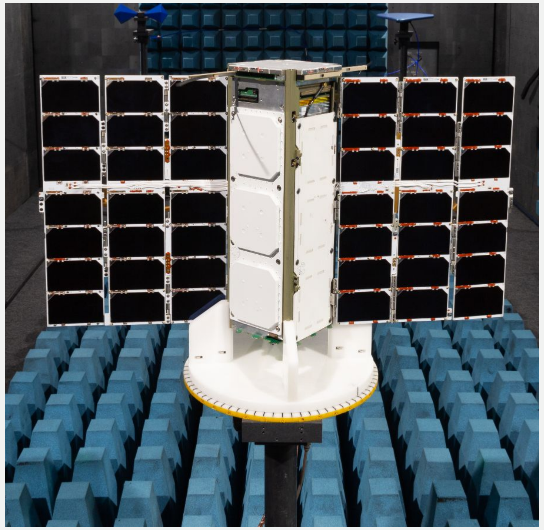
180+
Satellites launched

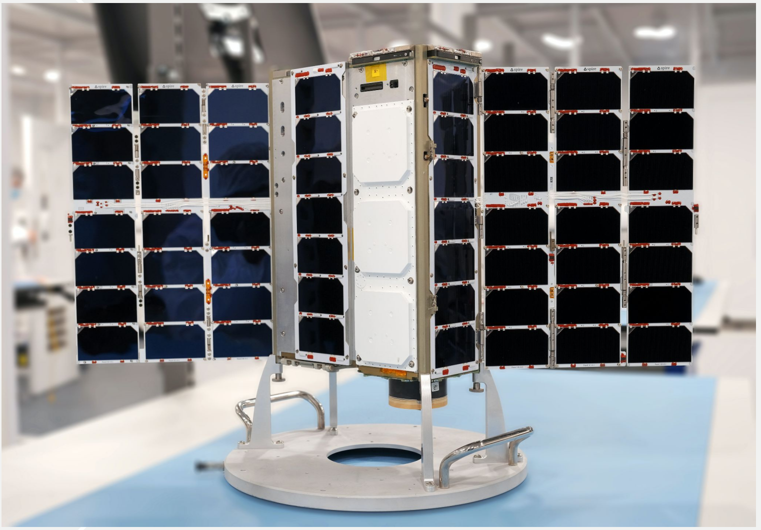
25
Satellite design iterations

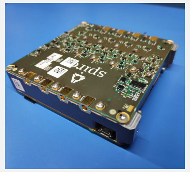
Multi payload capability
ADS-B / AIS
GNSS-RO / GNSS-R
AI/ML / SDRs & RF Systems

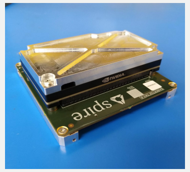
Full vertical integration
In-house engineering, manufacturing, and testing

Software upgradable & cloud native
Fully integrated space, ground and network / cloud segments









Thank you

From our team, to yours.

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