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Status and Future Plans of the Spire Satellite Constellation for Neutral and Ionospheric RO Measurements

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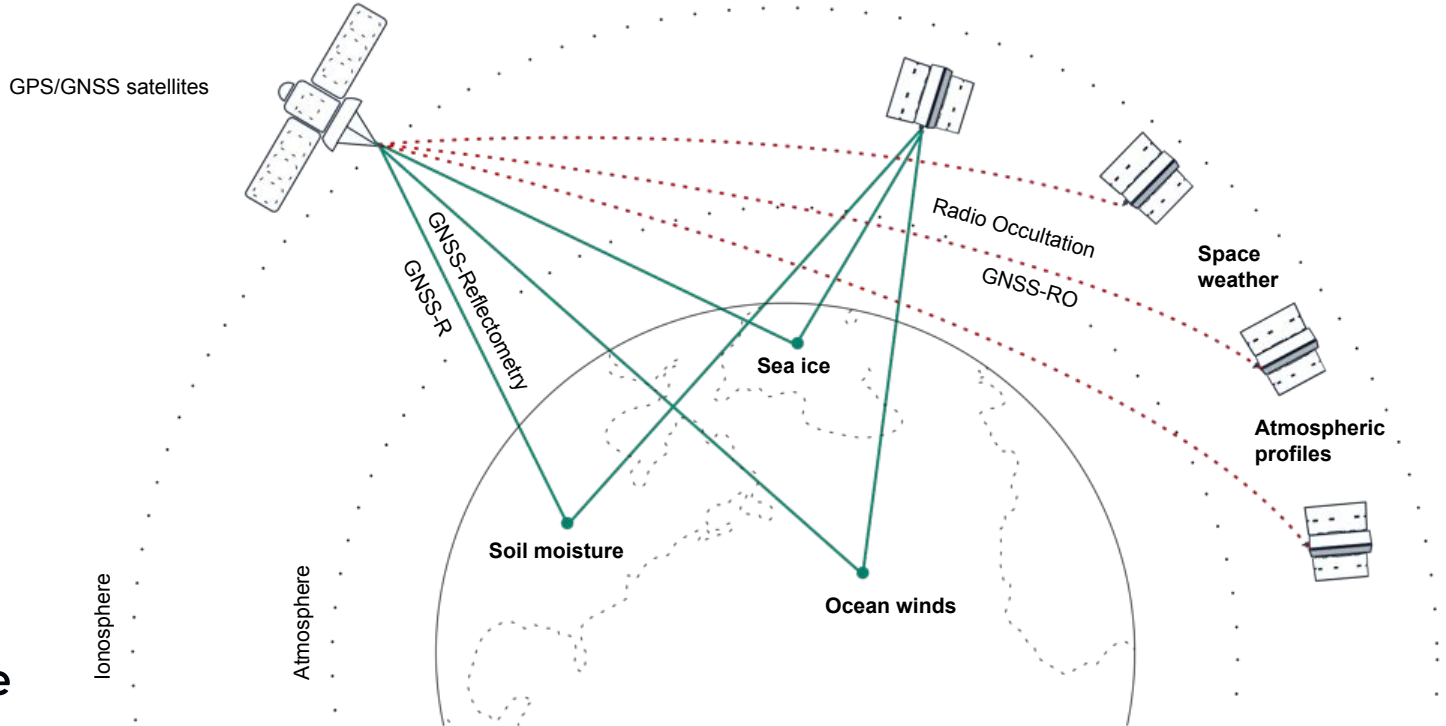
Spire Earth Intelligence Data

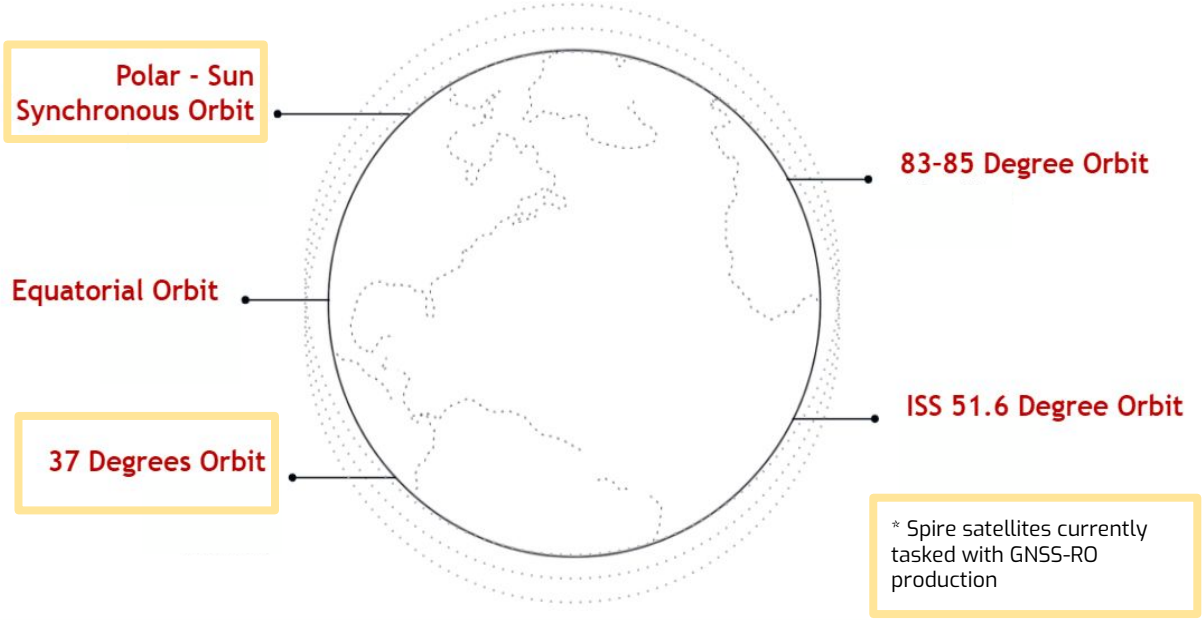
Spire satellites capture Earth observations for various applications: NWP data assimilation, space weather, sea ice, soil moisture, etc.



Spire Earth Intelligence Constellation

Data from a constellation of many Spire RO satellites is a resilient and sustainable solution for Earth observation

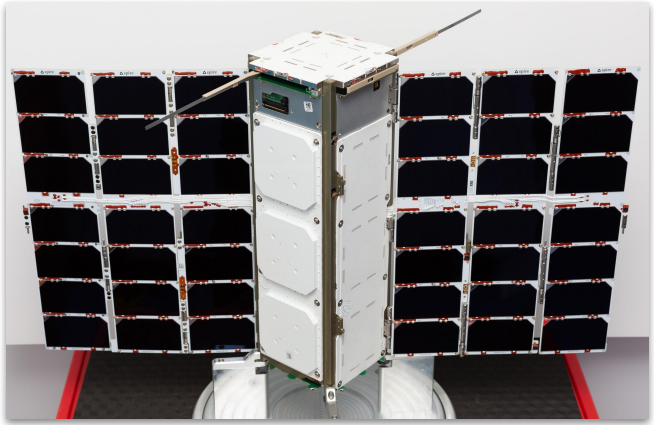
- 100+ LEO nanosatellites in diverse orbits for global coverage, high spatial and temporal sampling, and system redundancy
- 40+ RO-capable sats and 25+ in RO production
- RO satellites also collecting grazing angle GNSS-R observations for sea ice and altimetry applications
- 3 operational GNSS-R sats collecting nadir observations

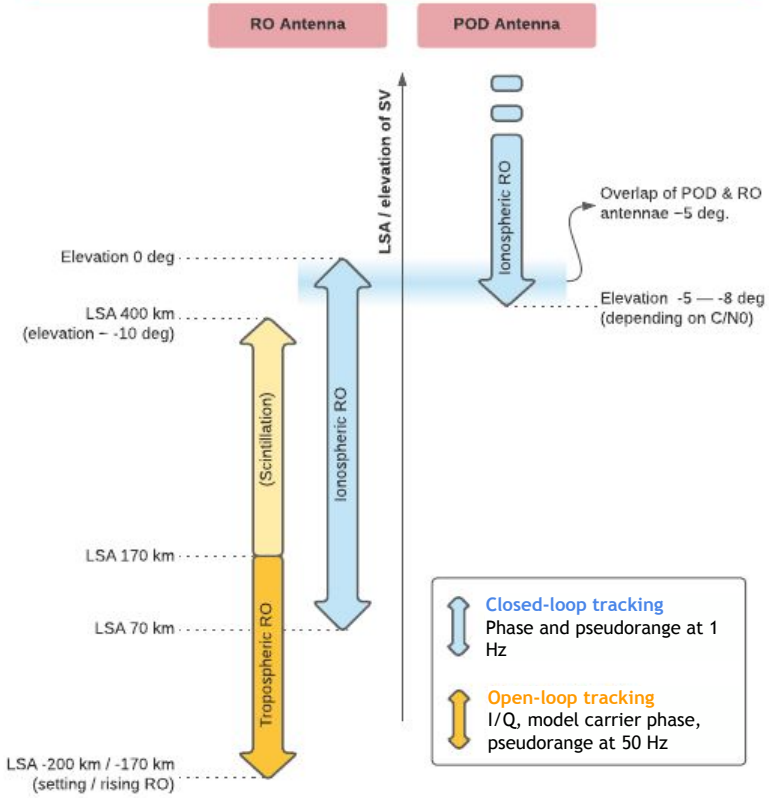


GNSS-RO Collection

Spire GNSS-RO satellites

- Moderate gain, dual antennas (rising/setting)
- Multi-GNSS signals tracked in open-loop
- STRATOS receiver v2 launched and capable of more RO collection
- Polarimetric RO satellites to be launched in near-future

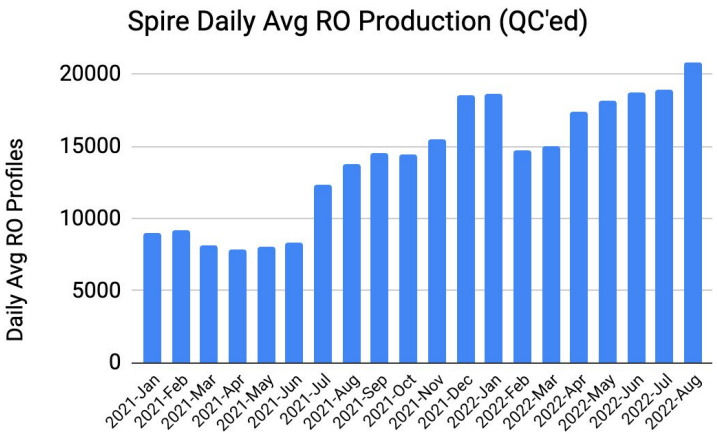




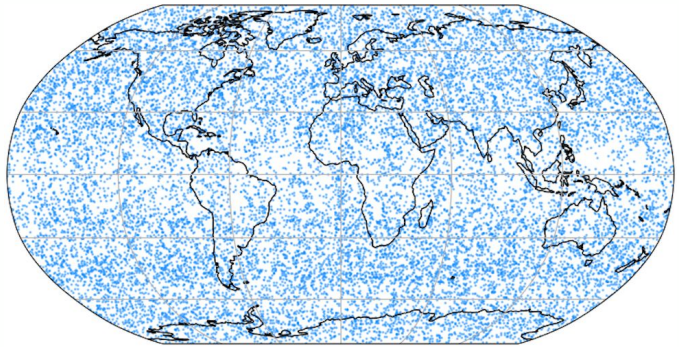
Growing GNSS-RO Volume and Coverage

- Spire constellation is currently producing **20,000+ quality-controlled profiles per day**, satisfying the current established IROWG/CGMS target
  - Ability to scale quickly to meet future demand
- Continual spacecraft bus and and ground station additions and improvements to increase efficiency and decrease data latency

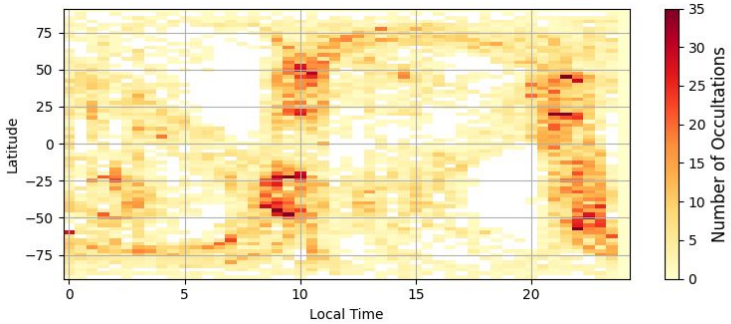
Long-term RO production increase



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



Diverse local time coverage



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GNSS-RO Data and Processing

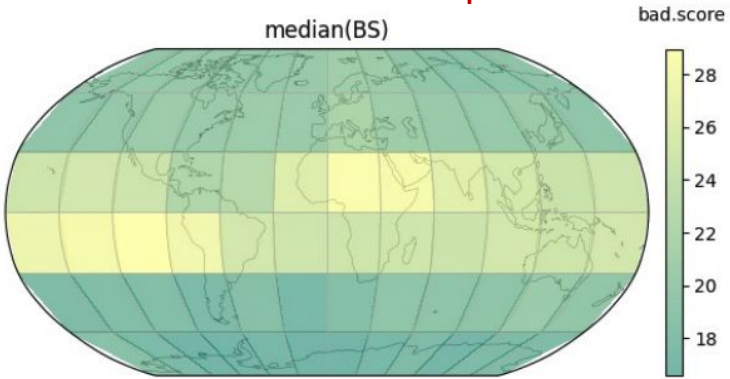
RO Data Processing

- 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)

Quality Control

- Badness score is a data quality metric that is mainly dependent on a) covariance of statistically optimized solution for neutral bending angle and b) signal spectral width
- Passes QC if badness score < 45, SNR > 80 V/V
- Typically > 85% of collected profiles pass QC

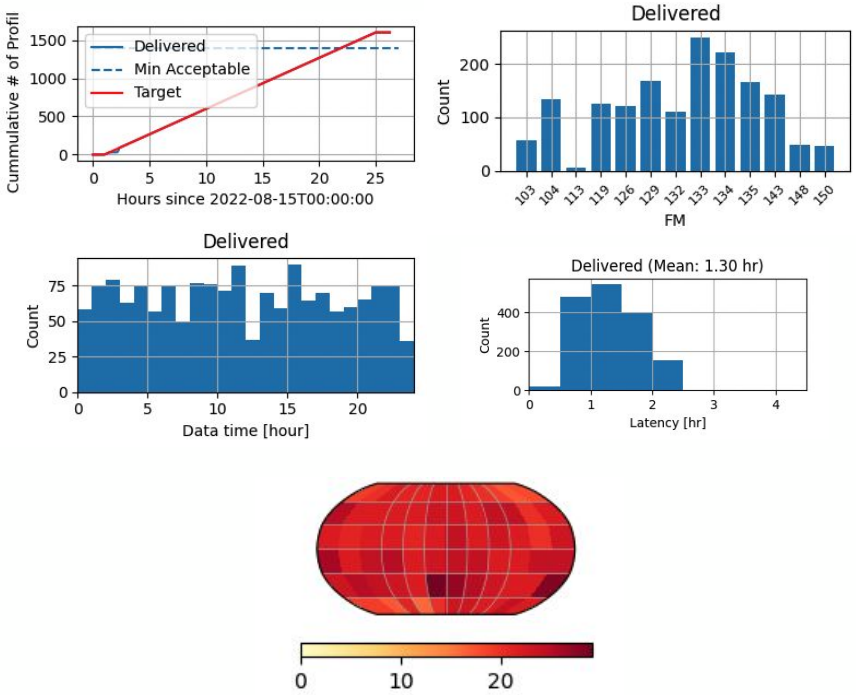
Median Badness Score of Spire Profiles



RO Data Deliveries

- Spire is delivering raw and processed data in near-real-time to major processing centers for further dissemination to NWP centers and users
- Delivering real-time L0/L1/L2 RO data to EUMETSAT for the past year
  - Initial 6 month evaluation period
  - SNR > 80 V/V, Latency < 140 minute requirements
  - Currently delivering over 1400 profiles per day with global redistribution rights
- Delivering all data types for intended research use with a 30-day delay. Historical data available through
  - NASA Commercial Smallsat Data Acquisition Program for US gov't-funded researchers at no-cost
  - ESA Earth Online

Daily RO delivery statistics for EUMETSAT
(Aug 15, 2022)

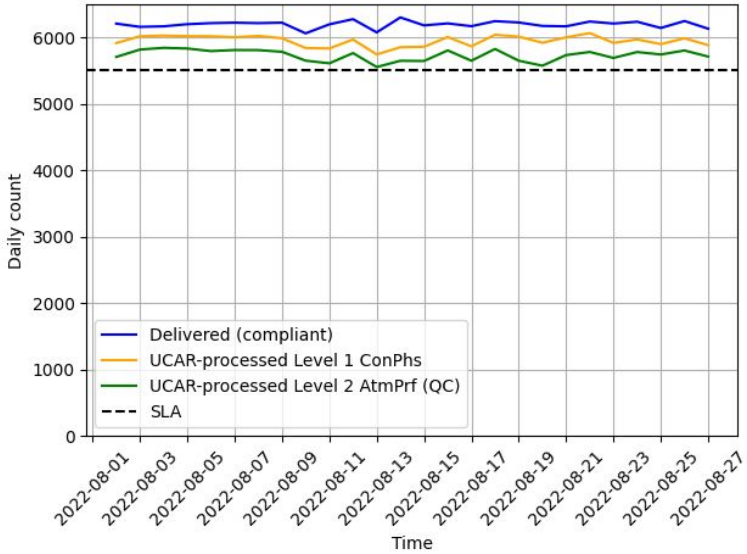


# of RO profiles collected and delivered in each cell

NOAA RO Deliveries

- Delivering RO data to NOAA through multiple Commercial Weather Data Pilots and Operational Buys since 2017
- Since March 2022, Spire is delivering L0/L1 data for at least 5500 profiles per day for Delivery Order 4
  - All delivered profiles satisfy the contract requirements including > 200 V/V and < 140 minute latency reqs.
- **Stable and consistent deliveries**
  - Has met the daily delivered minimum for 100% of the days during the operational buys by consistently over-delivering
- **High quality of data delivered**
  - All Spire profiles pass internal quality control before being delivered in addition to meeting contract reqs.
  - Typically, 90-95% of delivered Spire RO profiles lead to a QC-passed Level 2 retrieval by CDAAC

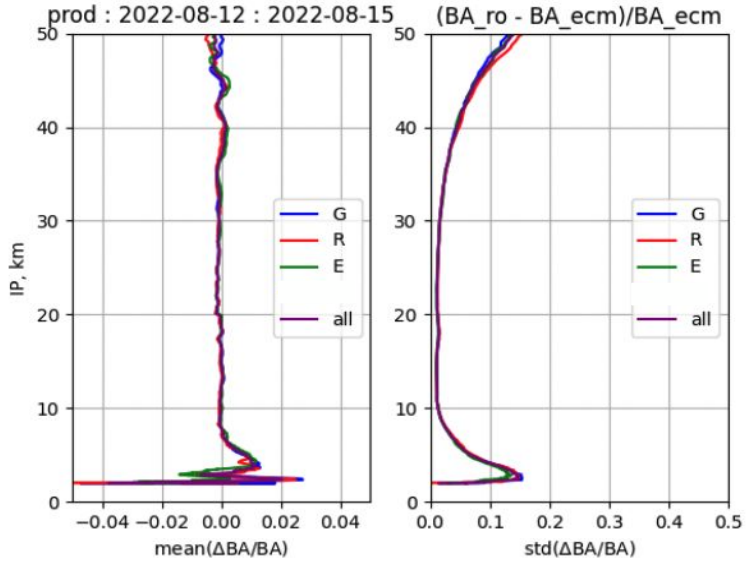
Daily Spire delivery and UCAR processing statistics
(August 2022)



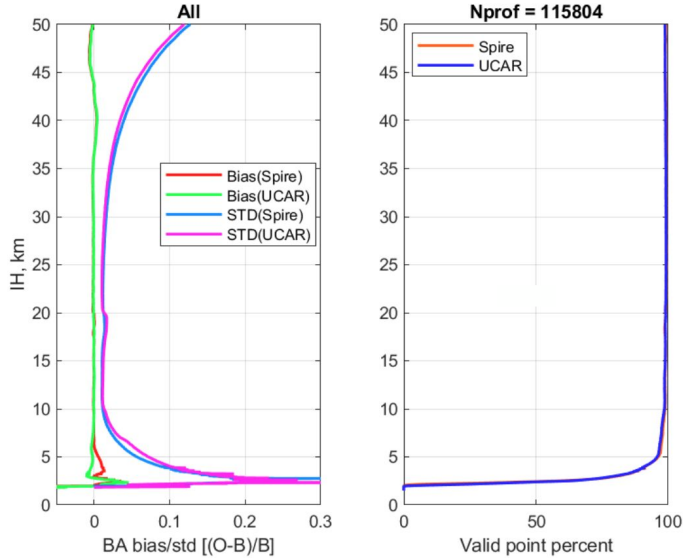
GNSS-RO Statistics and Comparison

- Bending angle retrievals from Spire RO data are of high-quality and comparable to other operational RO missions
- Spire processing results produce similar results to other centers with minor differences due to quality-control and processing parameters applied.

Spire RO statistics and ECMWF comparison
(Spire-processed, Jan 17, 2022 for NOAA CWDOB DO3)



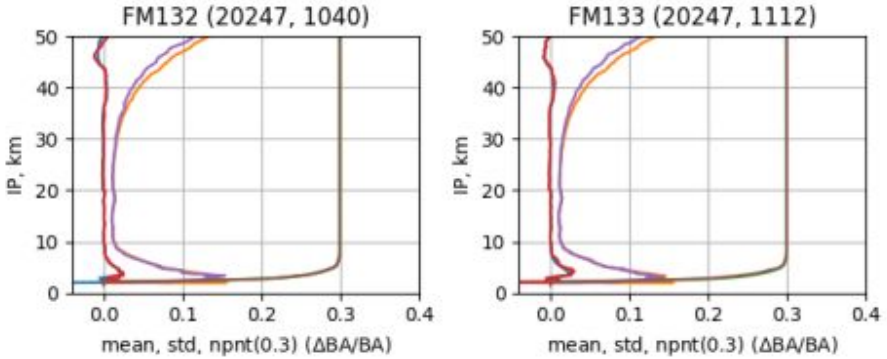
Spire vs. UCAR processing compared to ECMWF
(Dec 2021 for NOAA CWDOB DO3)



GNSS-RO Statistics and Comparison

- Newer satellites are equipped with latest receiver version that can track more RO events simultaneously and more stable clock oscillator
- Penetration depth statistics are similar to COSMIC-2 and exceeds many legacy missions within similar region of sampling

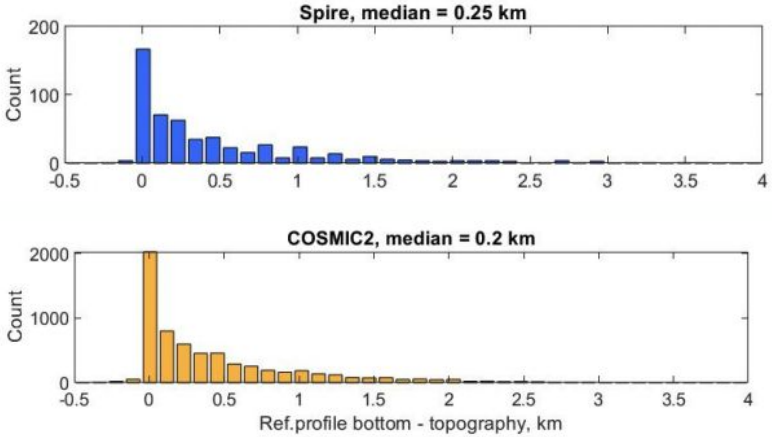
New Spire GNSS receiver with more capabilities



Bending angle comparison to ECMWF analysis for Spire satellites with newest receiver version. Orange (purple) line represents standard deviation of differences for all (STRATOS v2) Spire satellites. Statistics for Spire-processed profiles on Jan 17, 2022

RO penetration depth statistics

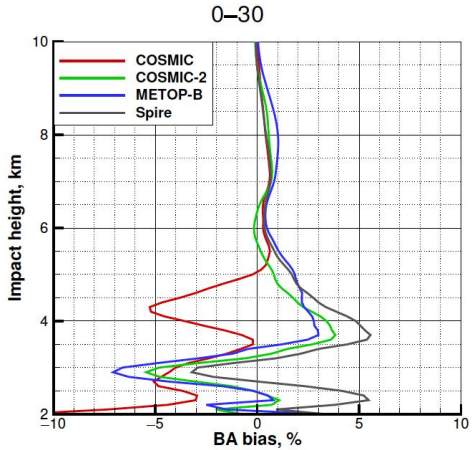
(COSMIC-2 Latitudes, UCAR-processed, Jan 1-2, 2021)



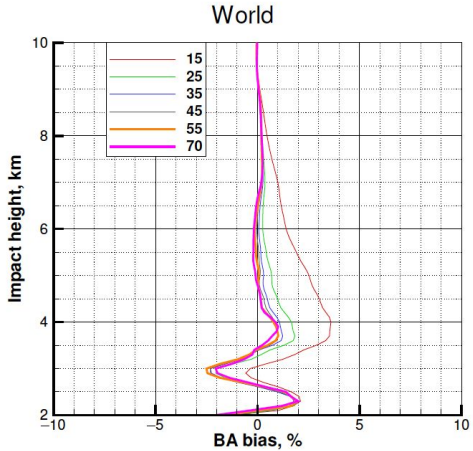
Comparison to Other Missions

- Spire and other operational RO missions show comparable bending angle and penetration depths statistics despite Spire's smaller satellite form factor
- Lower tropospheric statistical quality only weakly dependent on SNR (Gorbunov et al., 2022, Anthes et al., 2022, Chang et al., 2022, etc.)
- Noise floor values should be calibrated across missions for effective SNR dependence studies and QC thresholding

Mean bending angle (BA) difference from GFS analysis for 0-30 N by mission



Spire BA bias vs. normalized SNR



Most probable noise floors by mission (V/V)
(Divide reported SNR by NF values to normalize)

	G	R
COSMIC	11.1	-
METOP-A	11.6	-
METOP-B	12.0	-
METOP-C	11.8	-
COSMIC-2	18.4	14.6
Spire	9.64	9.93

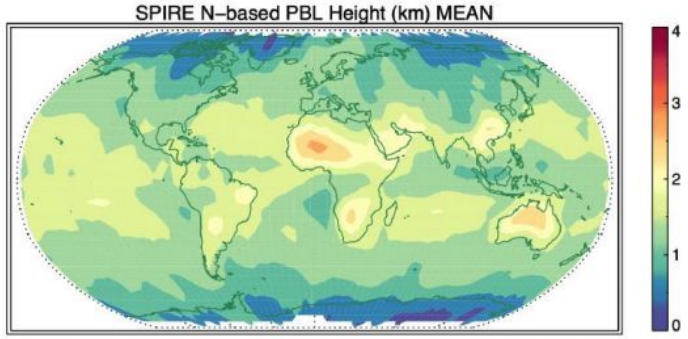
Figures from Gorbunov et al., (2022), *Remote Sensing:*

(1) Noise Floor and SNR of RO Observations: A Cross-Mission Statistical Comparison
(2) Influence of the SNR upon RO Retrievals.

External Evaluations

- Several 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
  - Near real-time results available at ROMSAF and JCSDA
- Demonstrated positive impact of Spire RO data on NWP systems from evaluators at NOAA, NASA, ECMWF, UK Met Office

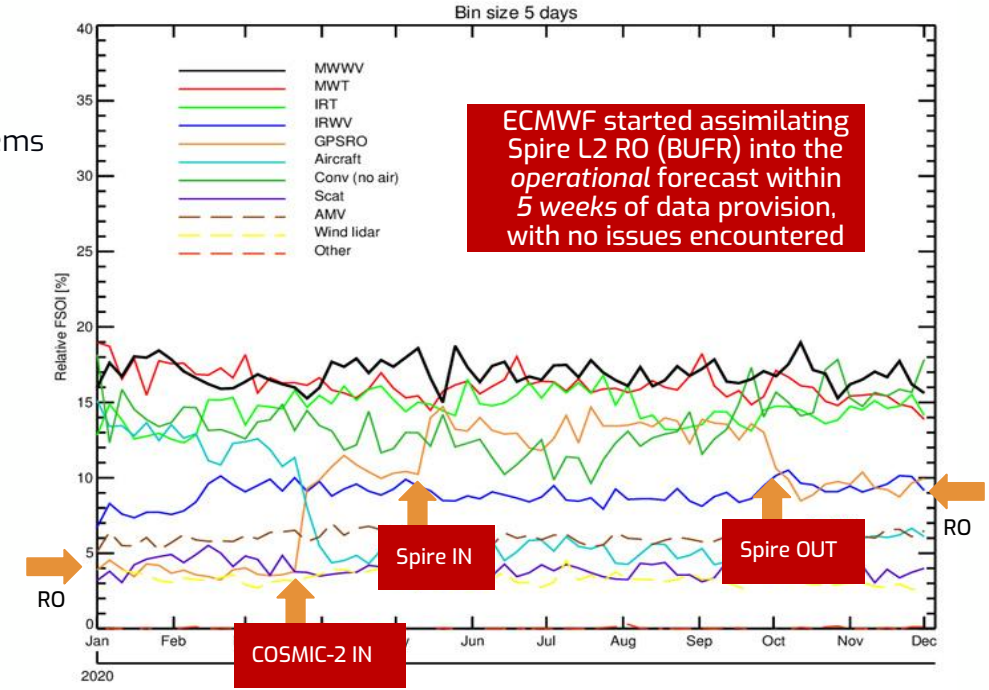
UCAR study on planetary boundary layer from Spire data



Mean PBL height as detected directly from Spire data. It is noted that Spire's penetration depth exceeds heritage, making this measurement possible.

Image from W. Schreiner, 2021 (Data Processing and Scientific Evaluation of Spire GNSS RO Data for the NASA CSDA)

ECMWF FSOI increase after assimilating Spire RO in 2020

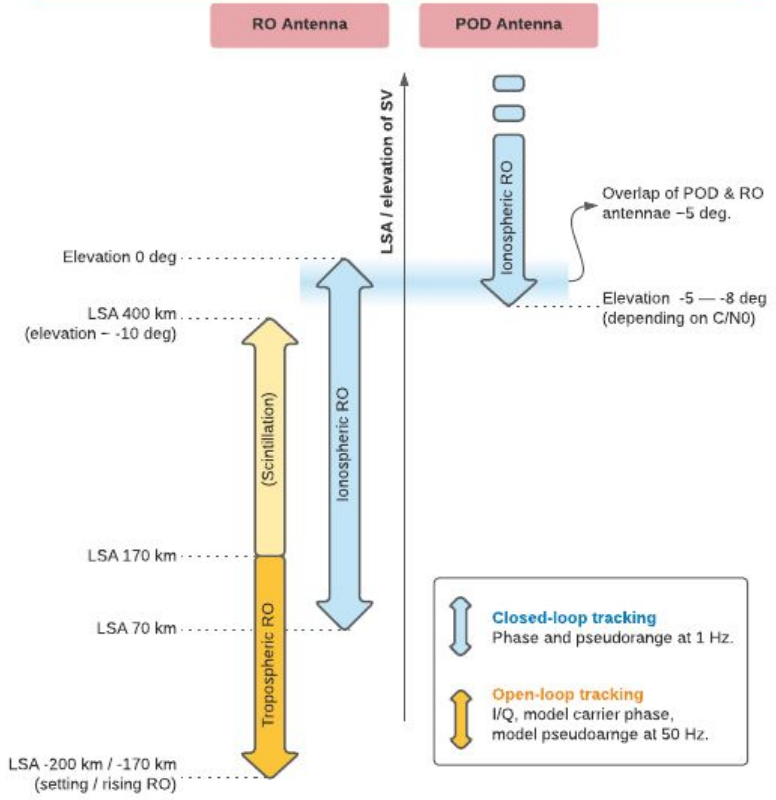


(Courtesy of S. Healy, ECMWF, 2020)

Ionospheric Data Collection

- 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)

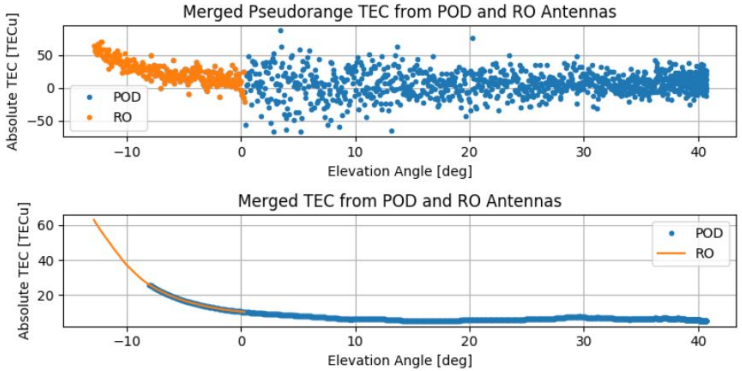
More details at Angling et al. Sensing the ionosphere with the Spire radio occultation constellation, *J. Space Weather Space Clim*, 2022



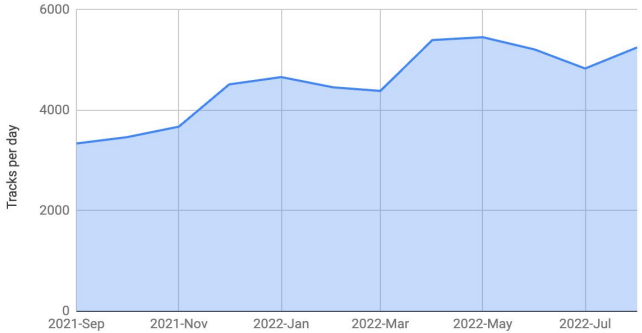
TEC Estimates

- Closed-loop dual-frequency pseudorange and phase observations used to derive TEC measurements through each antenna
  - Standard procedure applied: Weighted levelling, cycle slip correction and estimation of differential code biases
  - Stored in CDAAC **podTec** format
- GNSS observations/TEC estimates can be combined across POD and RO antennas to produce longer ionospheric tracks (**ionTec)**
  - Over 5000 ionospheric tracks per day spanning from maximum elevation to less than 90 km altitude
  - Over 500 ionospheric tracks per day satisfying median latency of 30 minutes required by NOAA SpWx Data Pilot
  - Currently only tracking GPS in closed-loop mode. Can add other constellations to increase number of ionospheric tracks.

Example of combining TEC across multiple antennas

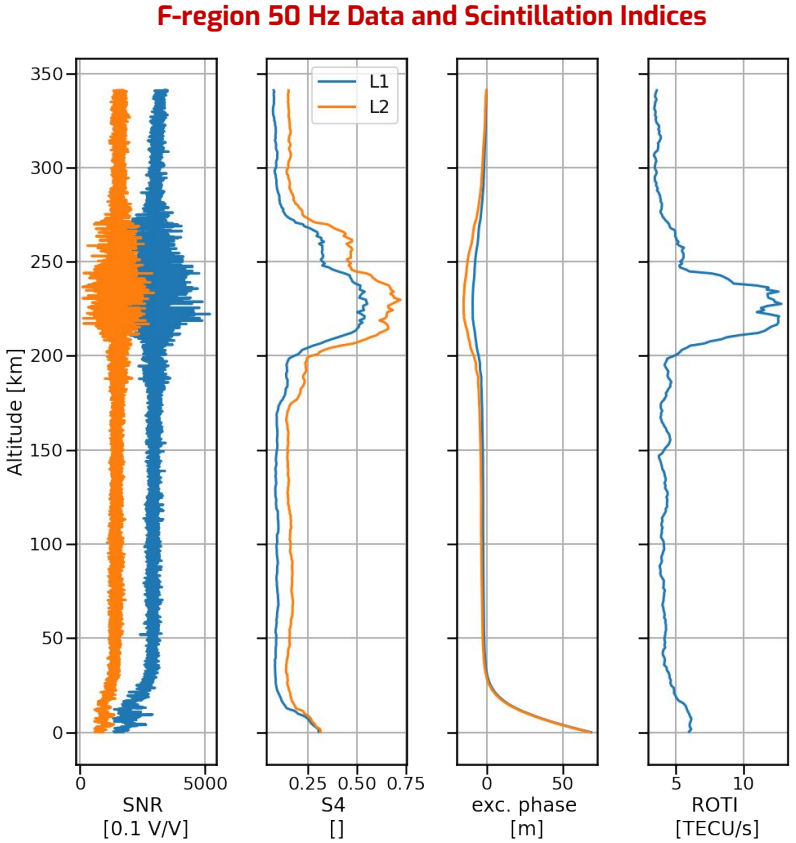


Monthly averaged ionospheric tracks per day



High-Rate Data and Scintillation

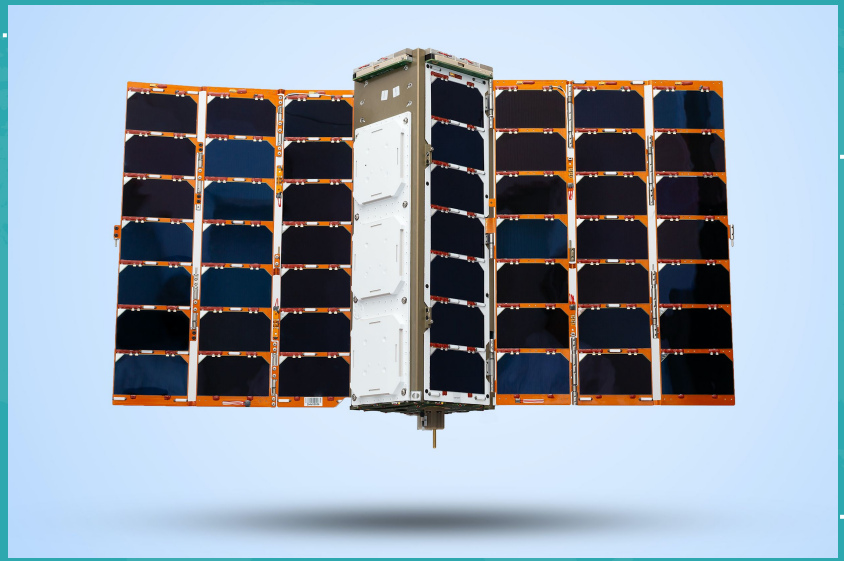
- High-rate (50-Hz) open-loop phase data are collected through RO antennas
  - Spans at least from 150km and downward
  - Multi-constellation
- On-board estimate of S4
  - Computed every second from a 10 second block of I and Q data sampled at 1 kHz
  - Computed on both frequencies through the RO antennas
  - 50-Hz data from orbit altitude is downlinked if S4 > 0.3 for at least 10 seconds



Key Takeaways

1. GLOBAL & SUSTAINABLE CONSTELLATION

Spire has built a resilient, operational Earth observations constellation to improve weather forecasting today through generation of **20k+ profiles per day** and growing, and external analyses have shown comparable data quality to "institutional" missions. Spire has the ability to scale up quickly to meet future demand.



2. OPERATIONAL CONSISTENCY

Spire has years of demonstrated excellence in delivering low-latency, real-time RO data to processing centers for impactful data assimilation into NWP models.

3. CONTINUED IMPROVEMENT

Spire aims for continuous scaling, replenishment, and improvement for sustainable and cost-effective long-term Earth observations

Thank you!

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