spire | earth intelligence

Initial polarimetric RO results from Spire's nanosatellite constellation

Vu Nguyen, Sergio Tomas, Matthieu Talpe and Philip Jales

2nd PAZ Polarimetric Radio Occultations User Workshop

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Agenda

1. Spire overview
2. Polarimetric RO (PRO) mission
3. Data production and processing
4. In-orbit calibration and validation

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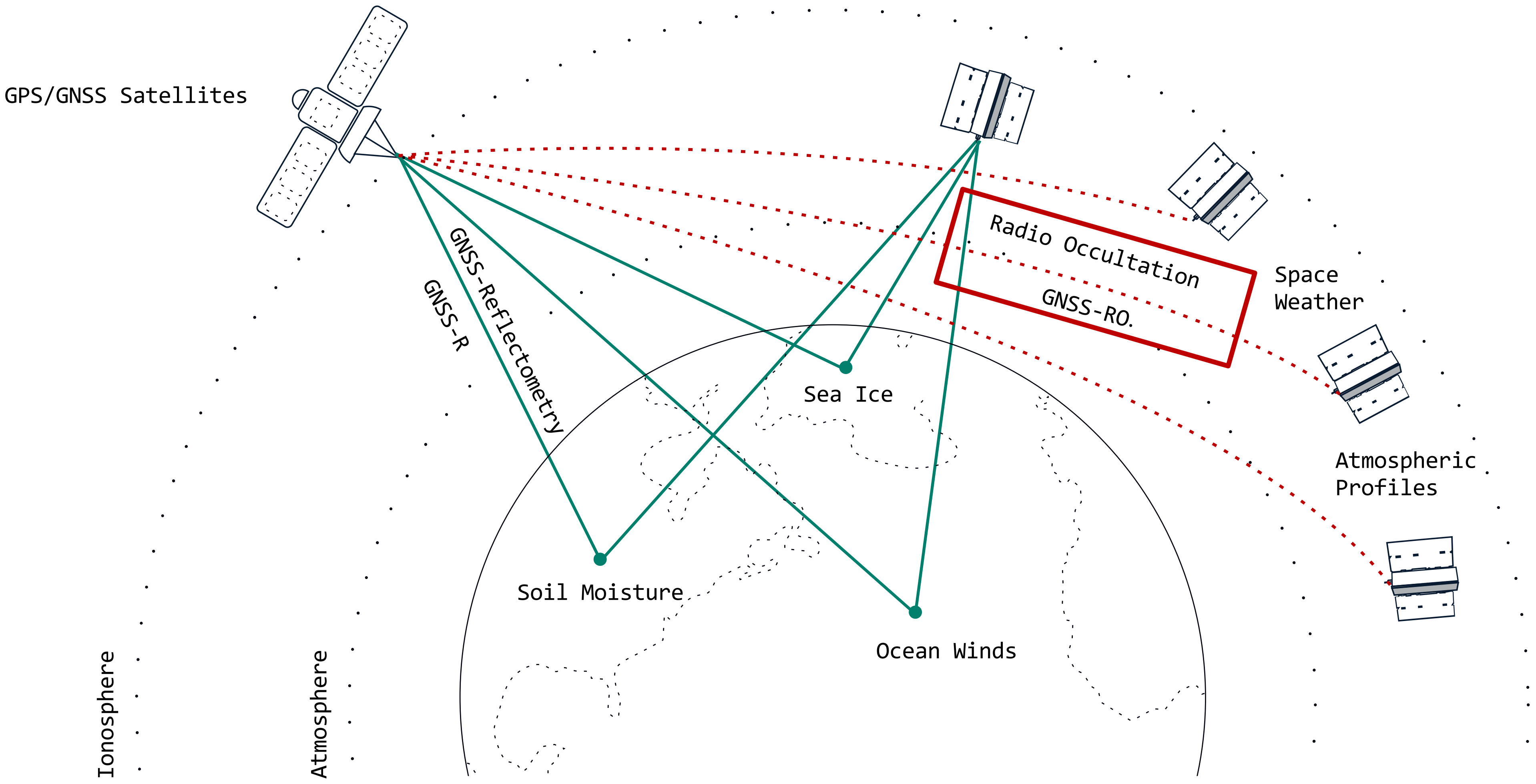
Spire Overview: Earth Intelligence Constellation



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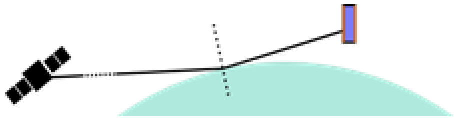
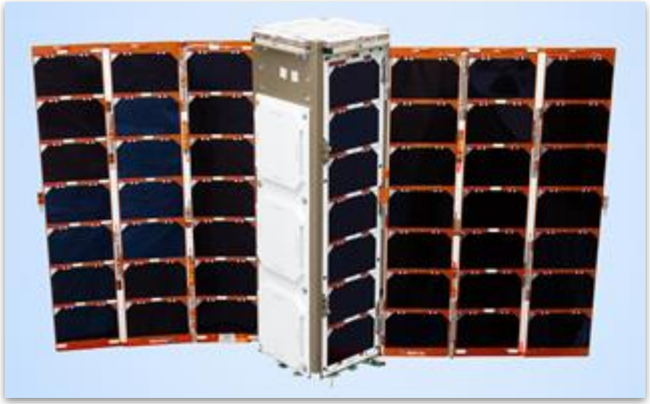
Spire Overview: Satellites In-Orbit

GNSS-RO (Radio Occultation) → Grazing Angle GNSS-R





Up to **40** satellites

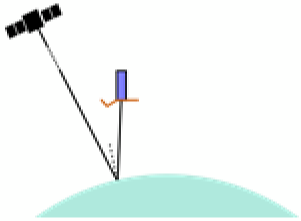
Antennas for RO, re-used for grazing angle reflections (5° - 30° elevation)

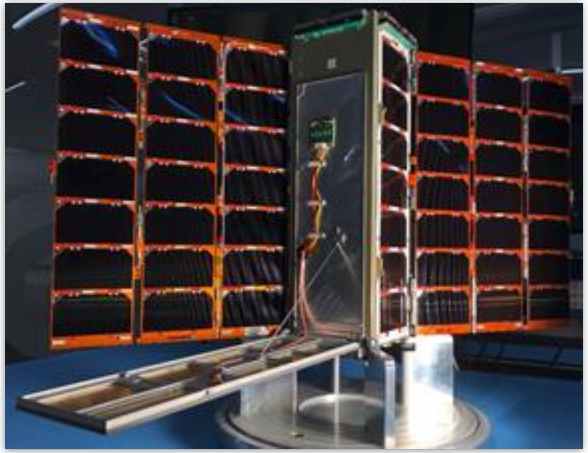
- Dual-frequency RHCP antennas (x2)

Processing

- **Application focus: RO, ice characterization and altimetry, space weather**
- Coherent signal processing - output I/Q at 50 Hz

Near-Nadir GNSS-Reflectometry (GNSS-R)





Up to **4** satellites

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

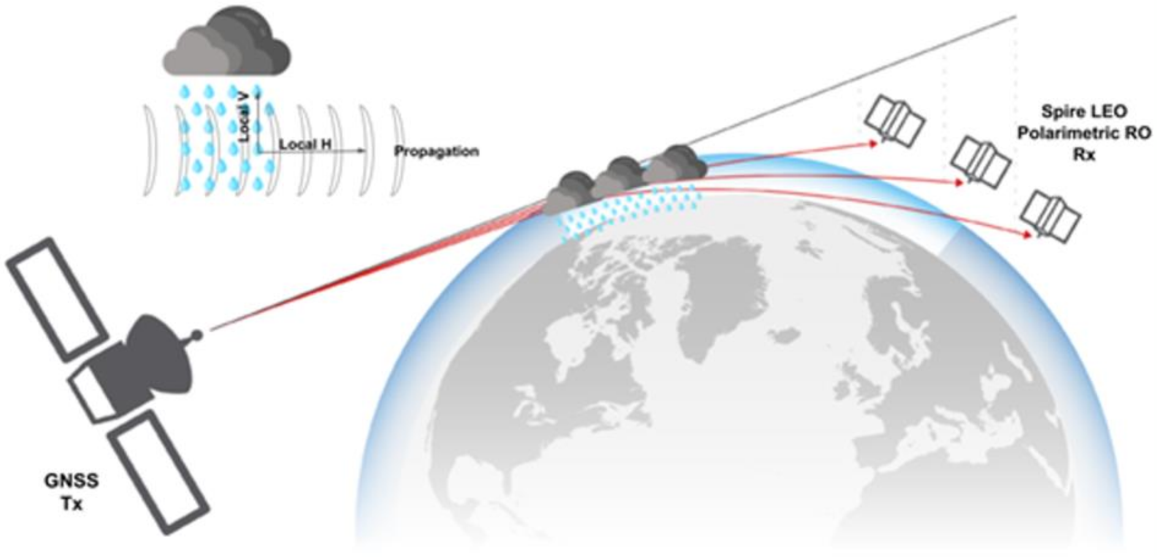
- Single-frequency LHCP nadir-pointing antennas (x2 or x3)

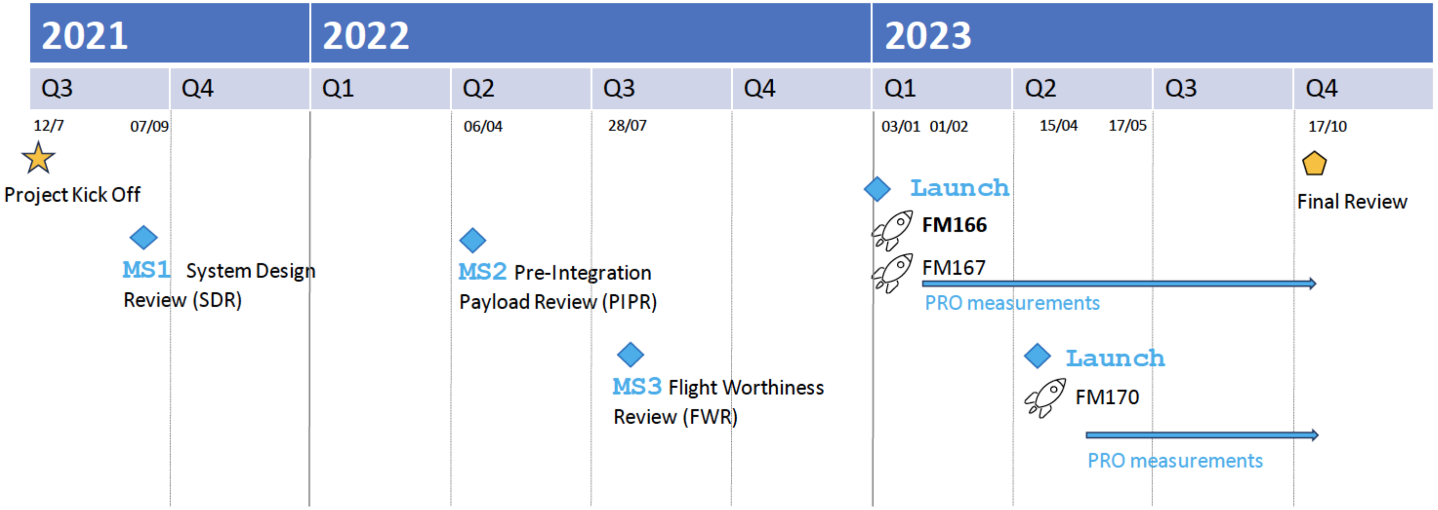
Processing

- **Application focus: Soil moisture and ocean winds**
- Incoherent DDM signal processing – output 1 or 2 Hz
- Calibration signal injection
- Supporting combining antennas with digital beamforming

PRO Mission: Progres.Lu

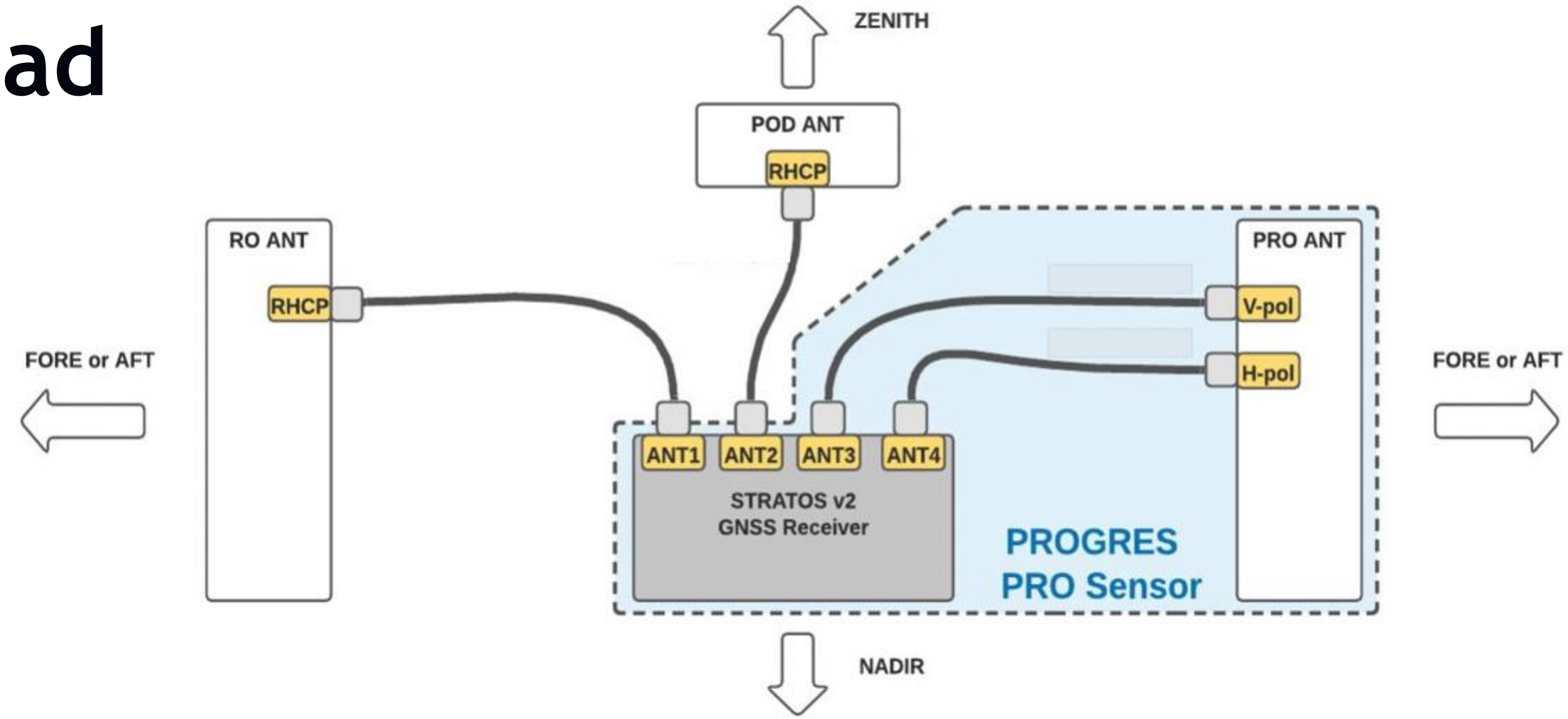
- Funded by ESA InCubed program
- July 2021 – October 2023
- **Primary Goal:**
  - Launch a Spire nanosatellite equipped with a GNSS-PRO sensor that produces measurements sensitive to precipitation
- **Achieved by the following:**
  - Re-design GNSS-RO antenna and receiver system to perform PRO
  - Launch an in-orbit demonstrator of this new sensor
  - Capture, process, and analyze these data to evaluate sensor performance, specifically for ability to extract hydrometeor-related information

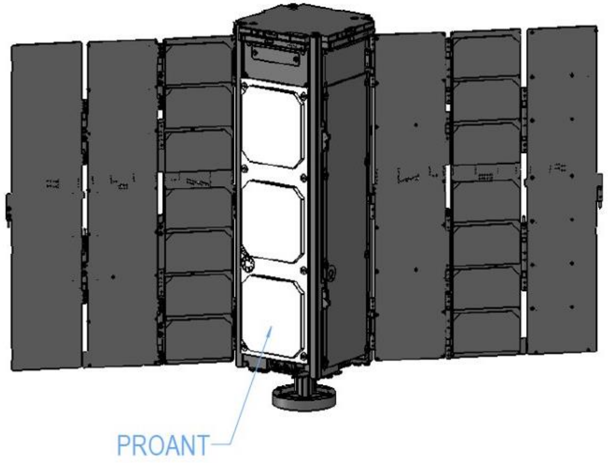




PRO Mission: Payload

- PRO antenna replaces one RO RHCP antenna on existing GNSS-RO bus
  - Contains orthogonal (H-V) linear polarization ports
- Receiver design based on Spire's current standard STRATOS v2 GNSS RO receiver
  - Full open-loop tracking of H/V
  - Rising and setting events
  - Tracks all major GNSS constellations (GPS, GLONASS, Galileo, Beidou)

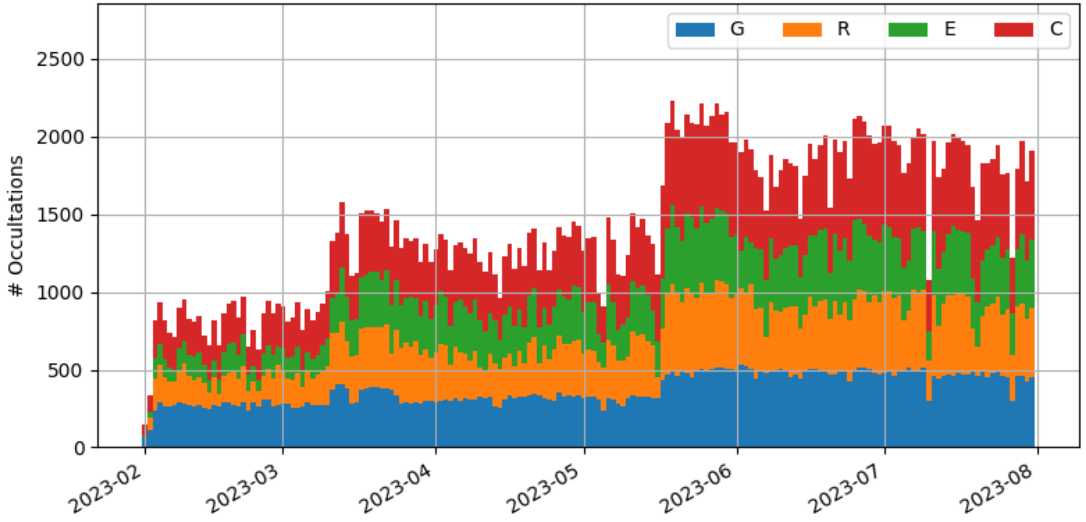




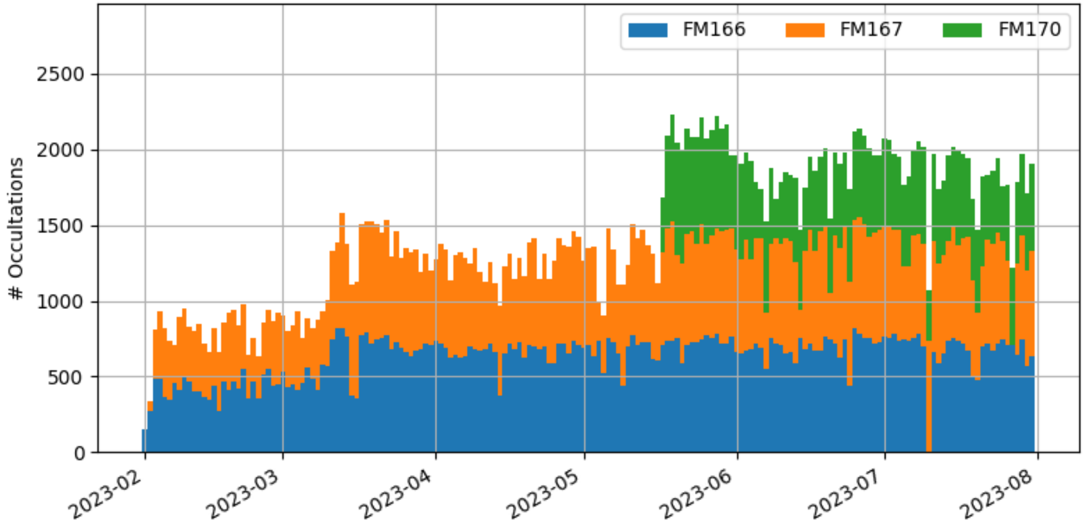
Data Production: Collection Timeline

- **Timeline**
  - **January 2023**: Spire FM166 and 167 launched in 9:30 LT SSO orbit
  - **February 2023**: First PRO profiles collected
  - **April 2023**: FM170 launched into 10:30 LT SSO orbit
- Over 2000 PRO profiles per day collected from 3 Spire satellites, 4 GNSS constellations
  - **10x** amount of data currently available from PAZ mission

Collected PRO profiles by GNSS Constellation



Collected PRO profiles by Spire satellite



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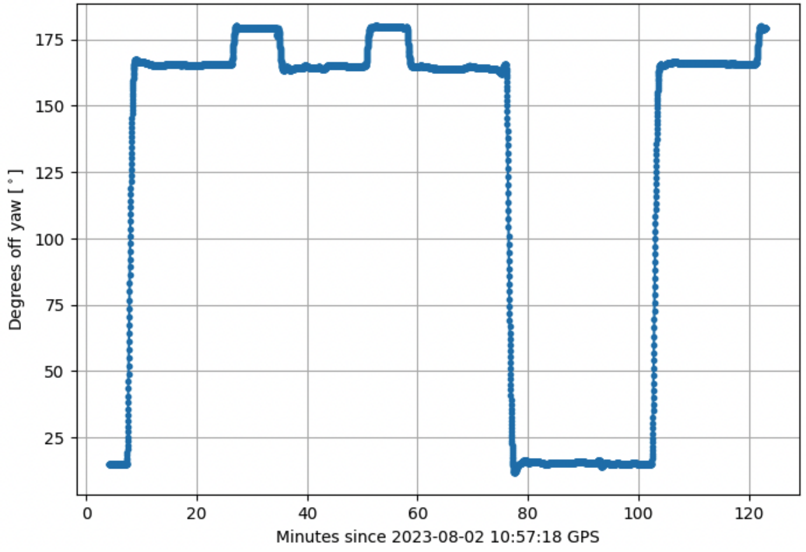
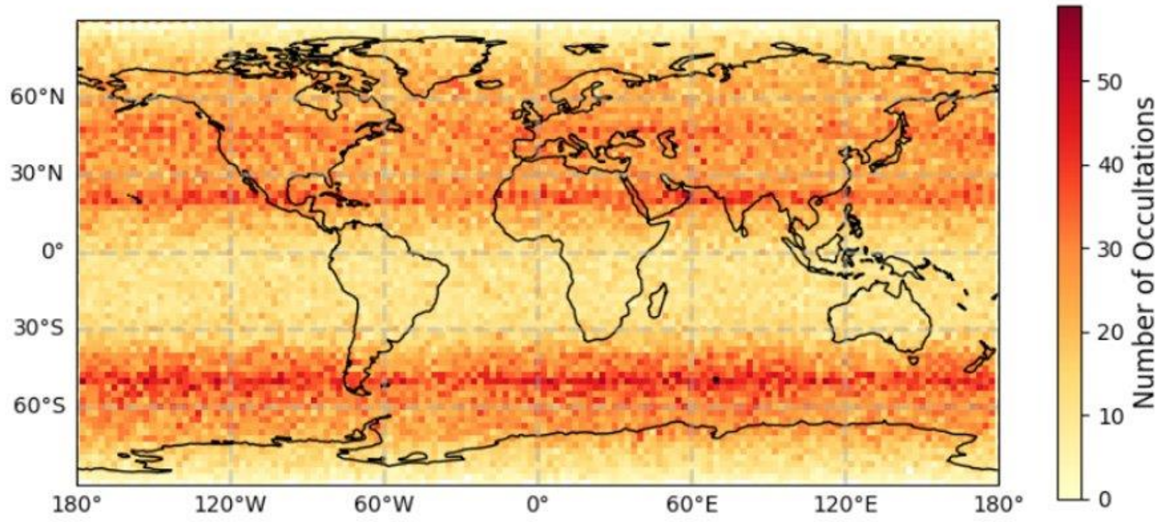
Data Production: Geographic Coverage

- Geographic and rising/setting distribution determined by orientation of the spacecraft
- Spire FMs routinely undergo yaw maneuvers for power optimization
- FM 166/167 collect mostly setting profiles while FM170 collects mostly rising

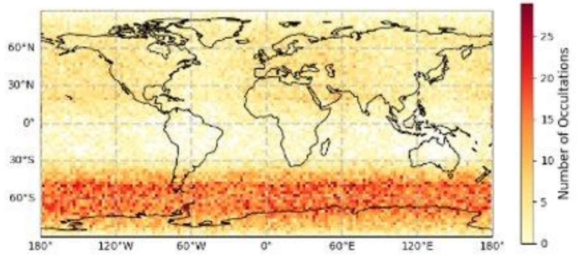
Example of Satellite Orientation During Collection Window



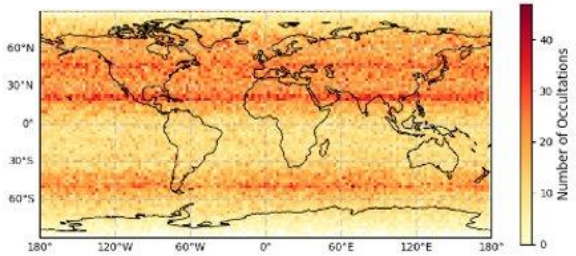
Geographic Distribution for 3 Spire Satellites (Mar-Aug 2023)



All PRO Profiles



Rising PRO Profiles

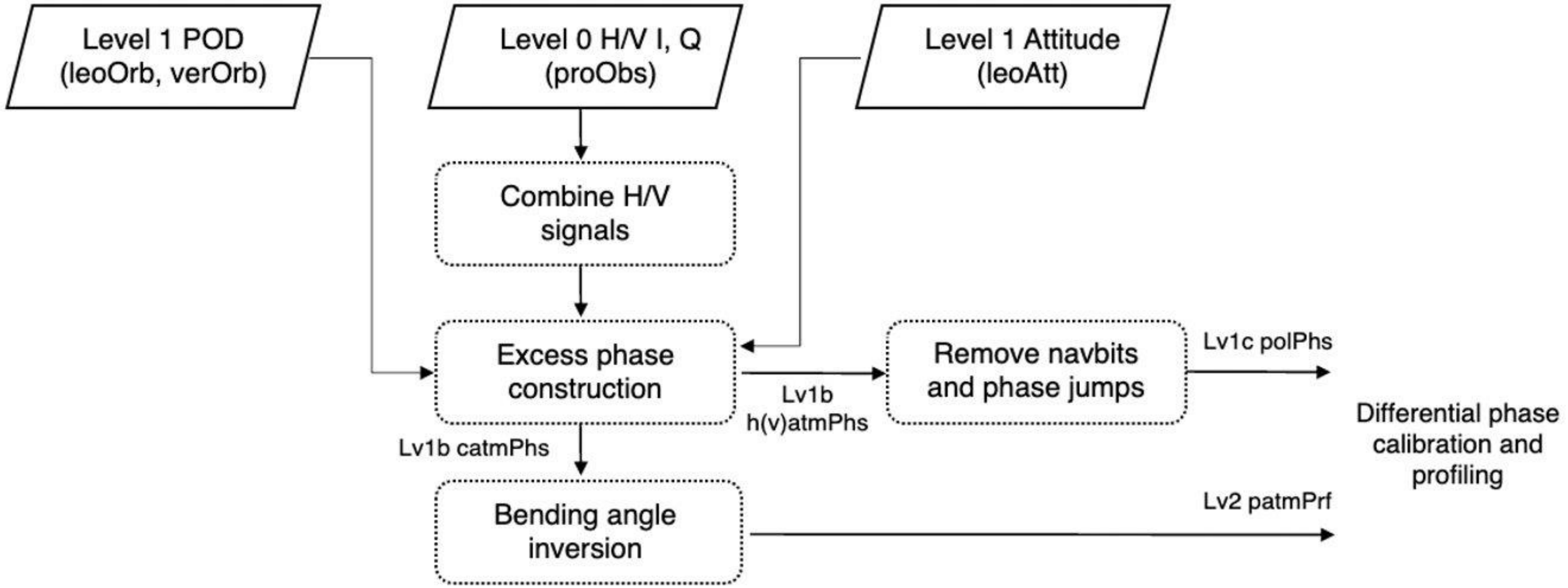


Setting PRO Profiles

Data Processing: Level 1 and RO Retrieval

- An automatic processing chain was developed to ingest raw PRO data and derive higher-order products for downstream PRO and standard RO processing
- For RO processing, the H and V signals are combined (similar to UCAR processing of PAZ data) to form a higher SNR signal

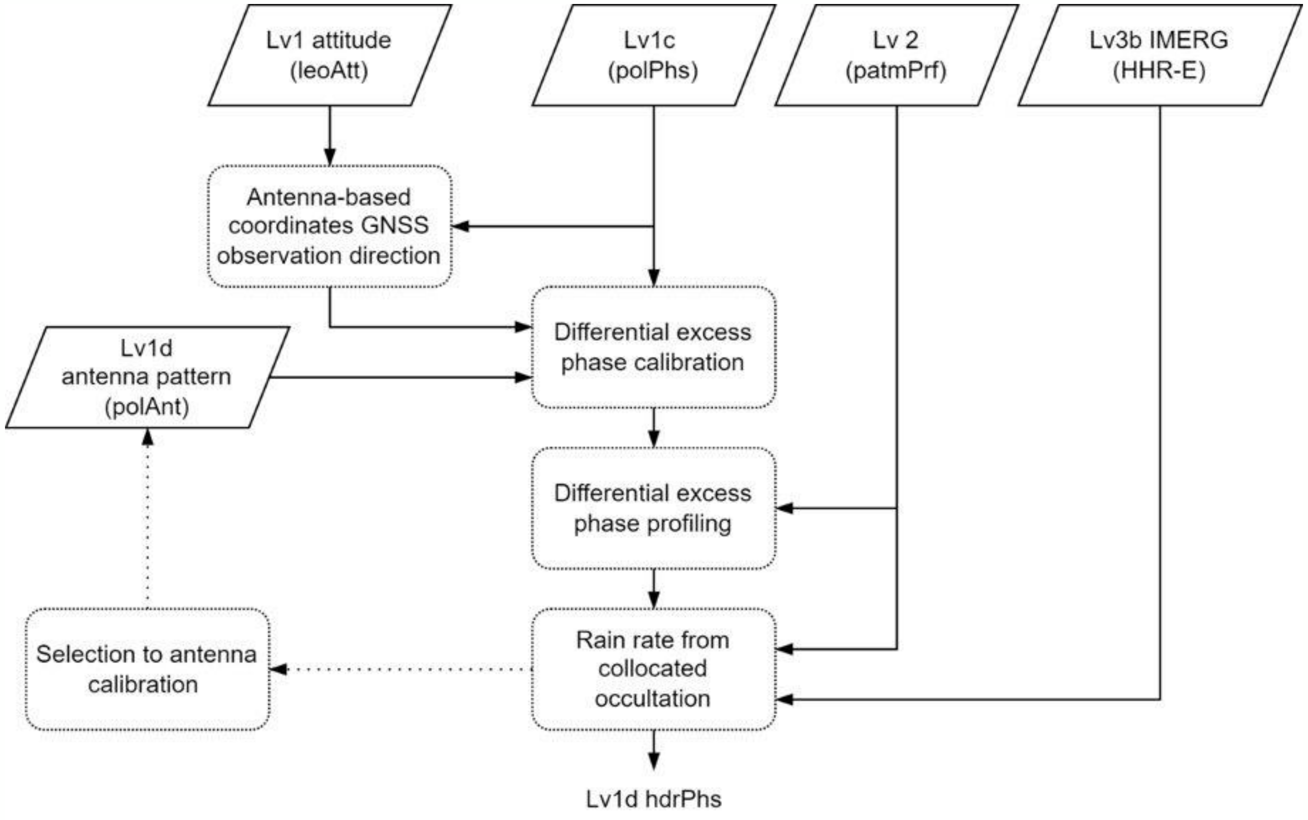
Spire Level 1 PRO Products (processed in near-real-time)



Data Processing: Differential Phase Shift

- Main PRO observable is height-based profile of calibrated differential (H-V) phase shift (**Lv1d hdrPhs**)
- Lv1d hdrPhs inputs originate from real-time processing chain and include:
  - Attitude quaternions (leoAtt)
  - Connected atmospheric excess phase for each polarization (polPhs)
  - Tangent point height (patmPrf)
- Surface rain rate from IMERG precipitation product is used to collocate with PRO profiles for antenna calibration and validation

Spire Differential Phase Processing (hdrPhs)



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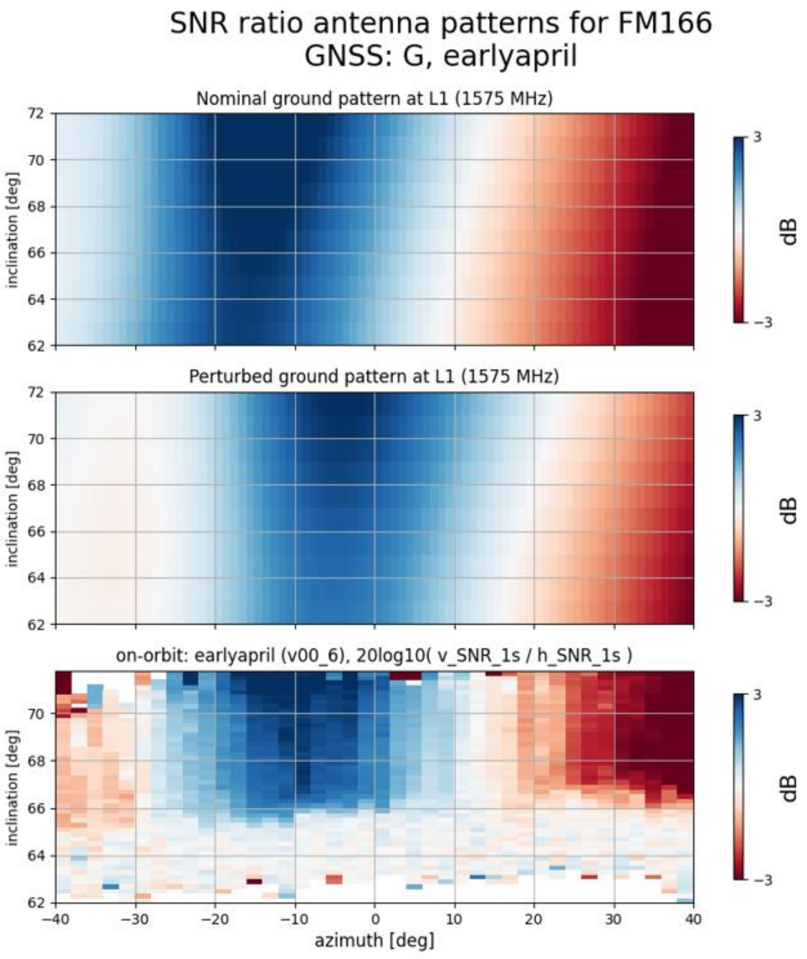
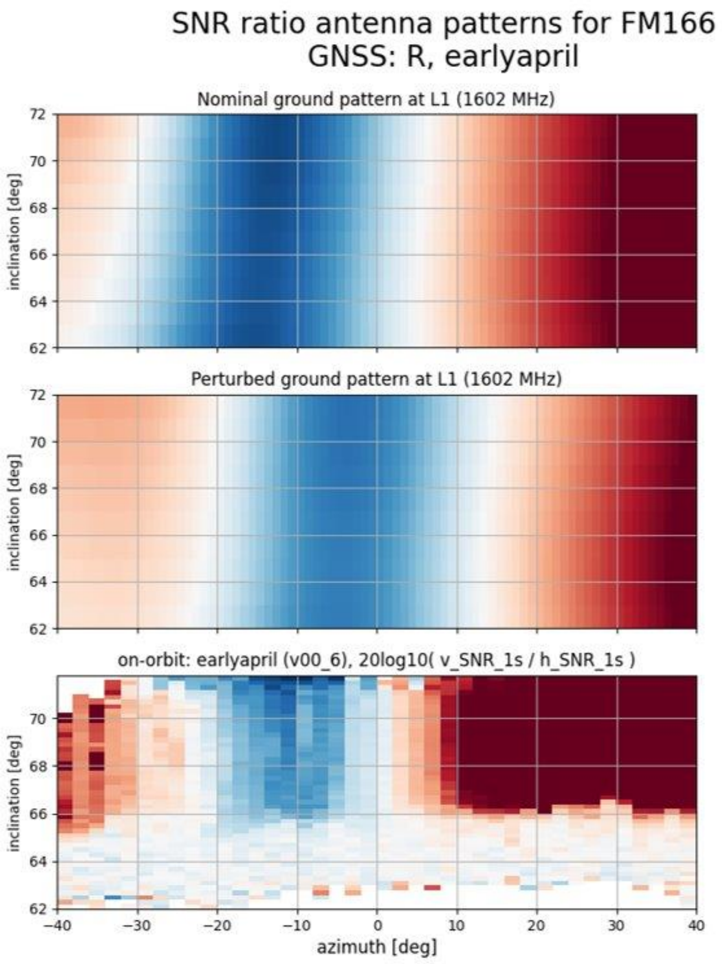
Antenna Calibration: Ground Comparison

- Antenna patterns for each frequency and satellite are estimated in-orbit by accumulating profiles without the presence of rain
  - 2-degree resolution inclination-azimuth map can be achieved within several days
- In-orbit collections match well with ground-measured patterns

Mean V/H SNR Ratio for GPS L1



Mean V/H SNR Ratio for GLONASS L1



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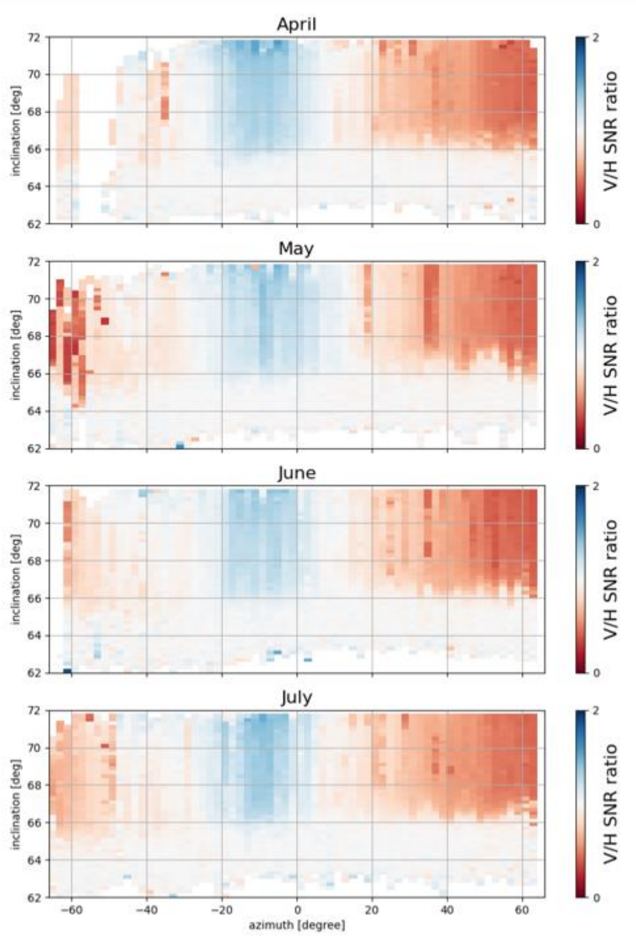
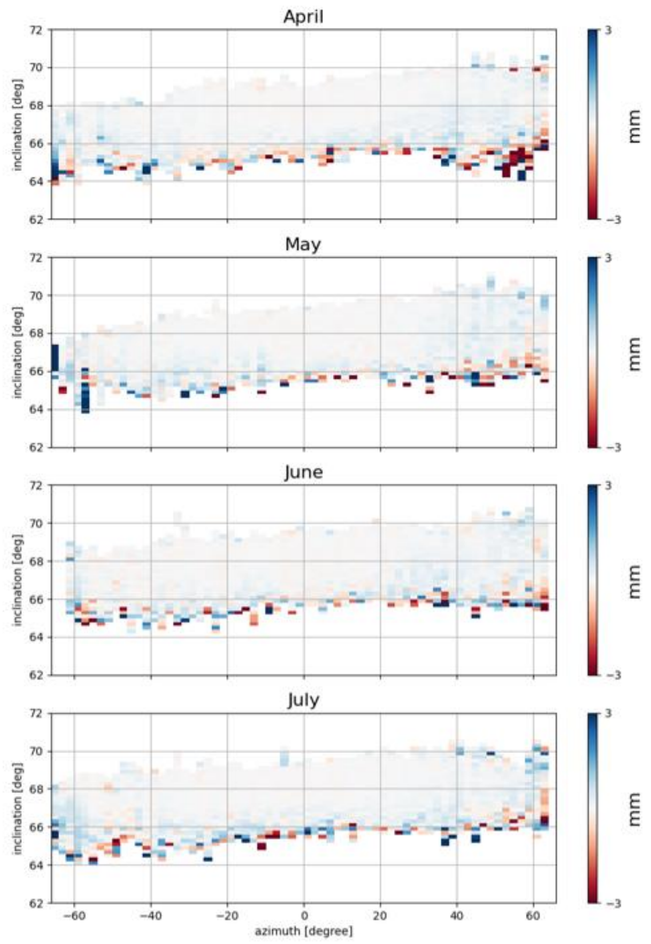
Antenna Calibration: Temporal Stability

- The antenna patterns of SNR ratio and phase shift remain consistent between April and July 2023.
- Antenna induced phase shifts are small (tenths of mm, smaller than PAZ)
- Including antenna calibration in the differential phase shift is **not necessary for validation**

Mean V/H SNR Ratio for GPS L1



Mean H-V Phase Shift for GPS L1



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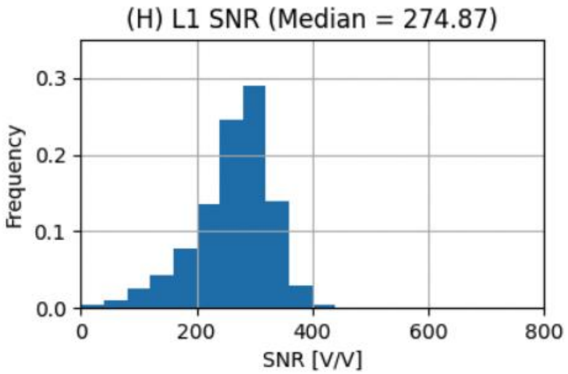
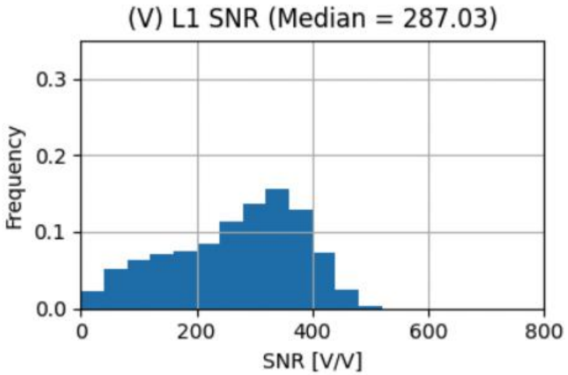
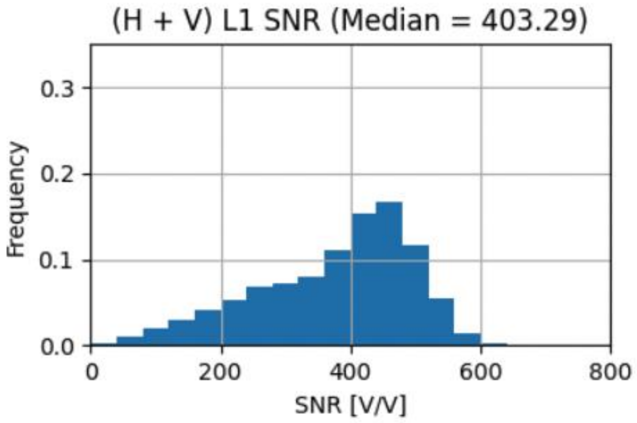
Validation: RO Retrieval

- Combined H + V SNR from PRO antenna is larger than Spire's RO RHCP antenna SNR
  - Higher percentages of quality-control pass
  - Similar statistics of bending angle and penetration depth

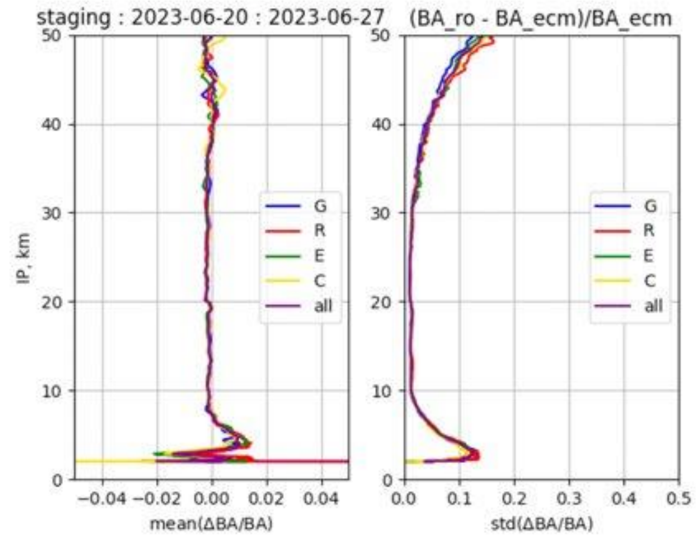




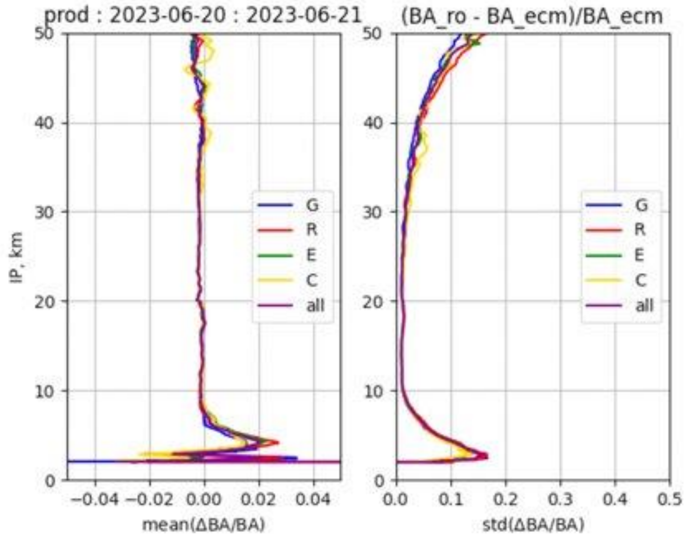
Peak combined PRO SNR is about 1.2 dB (15%) larger than RHCP RO SNR



BA Derived from ***Spire PRO Data***
Compared to ECMWF



BA Derived from ***Spire RO Constellation***
Compared to ECMWF



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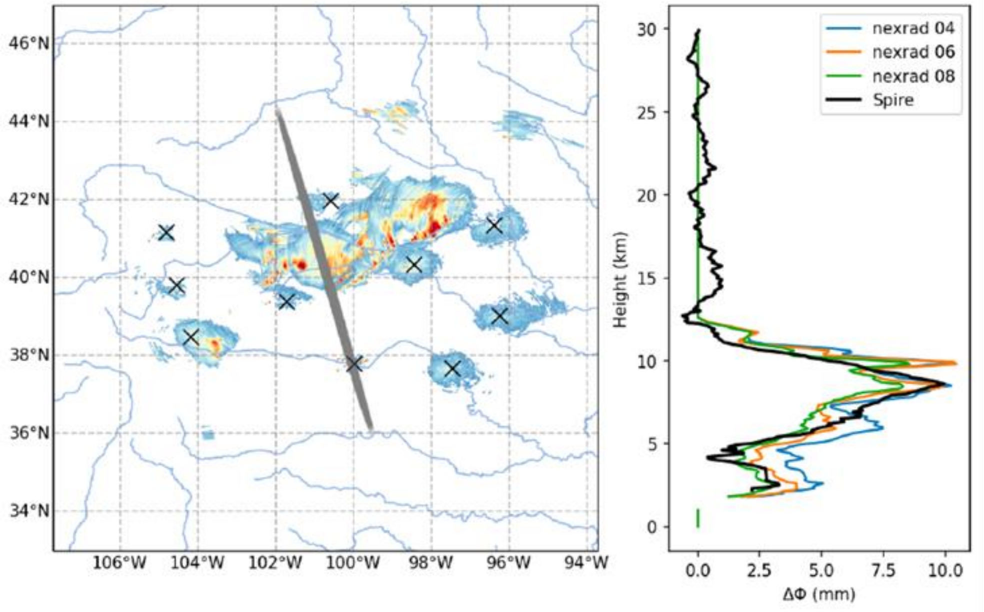
Validation: Precipitation Sensitivity

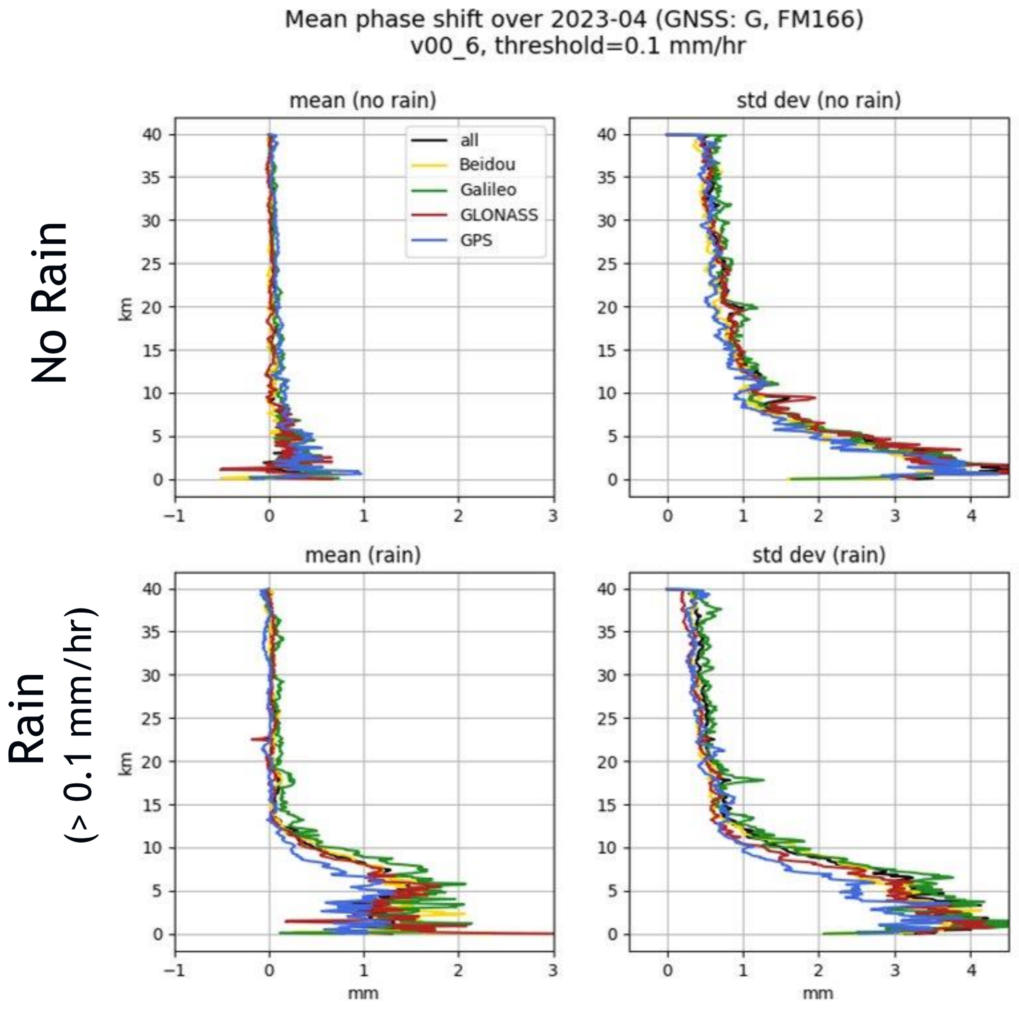
- At high altitudes, where hydrometeors are not expected, uncalibrated differential phase shifts show
  - Means spanning –0.1 to 0.1 mm for all GNSS measurements
  - Standard deviations on the order of ~0.5 mm

PRO Data Match Well with Ground-based Radars (NEXRAD)



Credit: IEEC researchers in Barcelona

Differential Phase Shift Statistics by GNSS Constellation (April 1-8, 2023; FM166)

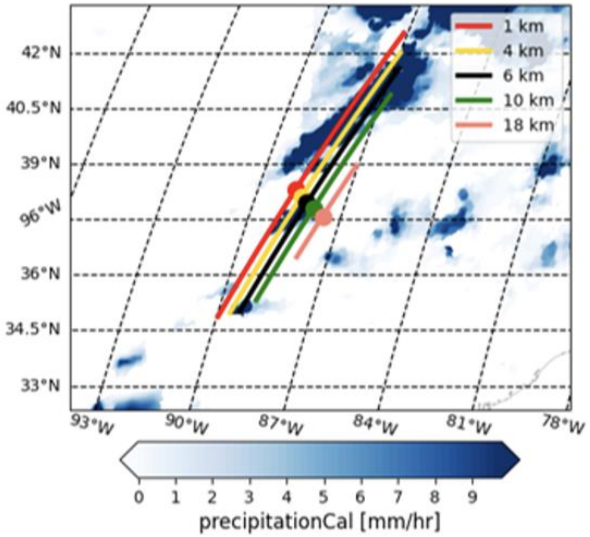


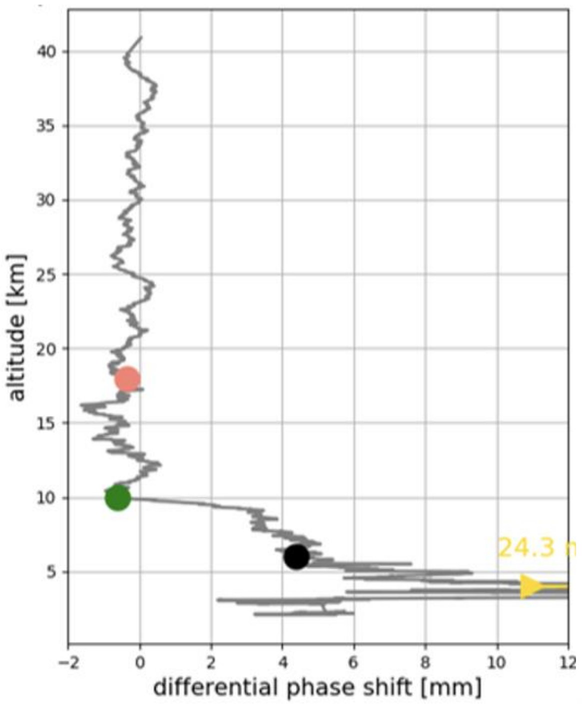
Validation: Individual Case Studies

- Collocating IMERG maps with Spire-derived profiles of PRO sheds light on convective systems.
- Multiple Spire FMs in same orbital plane + multi-GNSS constellations increases amount of "cluster" observations, which can constrain horizontal extent of precipitation cells

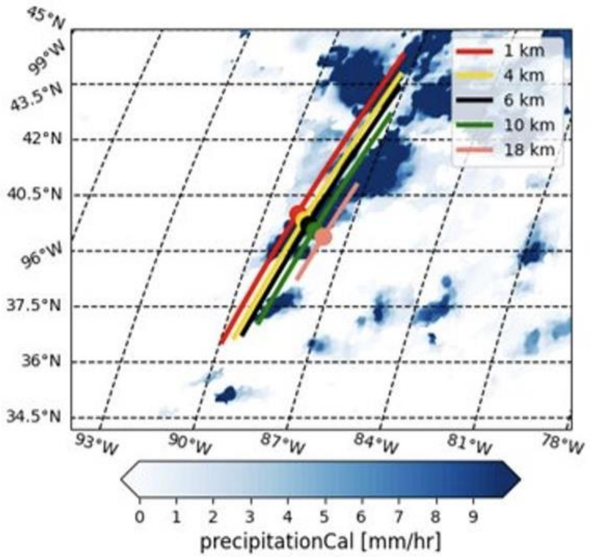
Two PRO profiles over US Midwest (separated by 6 minutes)

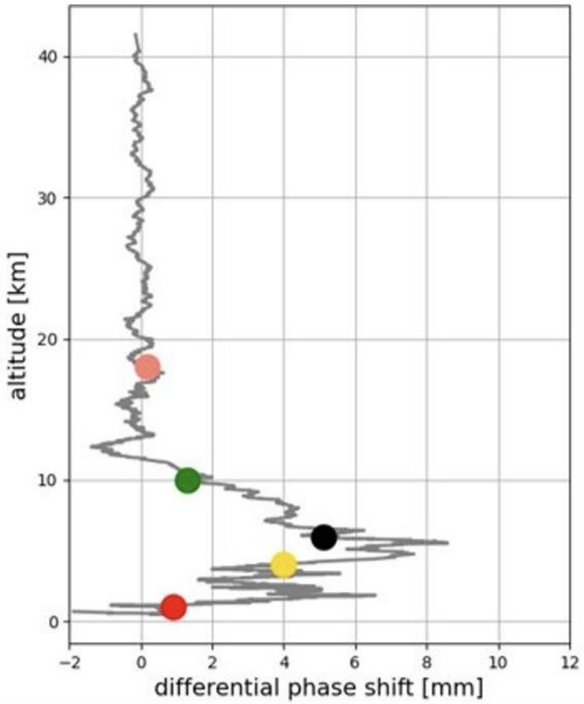
2023-04-01T01-36-21
FM166 GPS G12





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





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vu.nguyen@spire.com

Summary

- Spire has 3 satellites with a PRO payload in-orbit, capable of producing over 2000 profiles per day from all 4 major GNSS constellations
- PRO polarization phase shifts demonstrate clear sensitivity to precipitation and are minimally affected by the antenna. Resulting in low sensitivity to antenna calibration.
- Bending angle profiles can be derived from PRO data with similar quality to Spire's operational RO

What next?

- Collaborative efforts to demonstrate the value of PRO data in NWP models
- PRO capabilities may be added to future Spire RO satellites pending community feedback

Thank you to ESA and IEEC-Barcelona for collaboration via the Progres.Lu project

Thank you!

From our team, to yours.

Appendix

Additional Assets