STATUS AND PLANS FOR SPIRE'S GROWING COMMERCIAL CONSTELLATION OF GNSS SCIENCE CUBESATS

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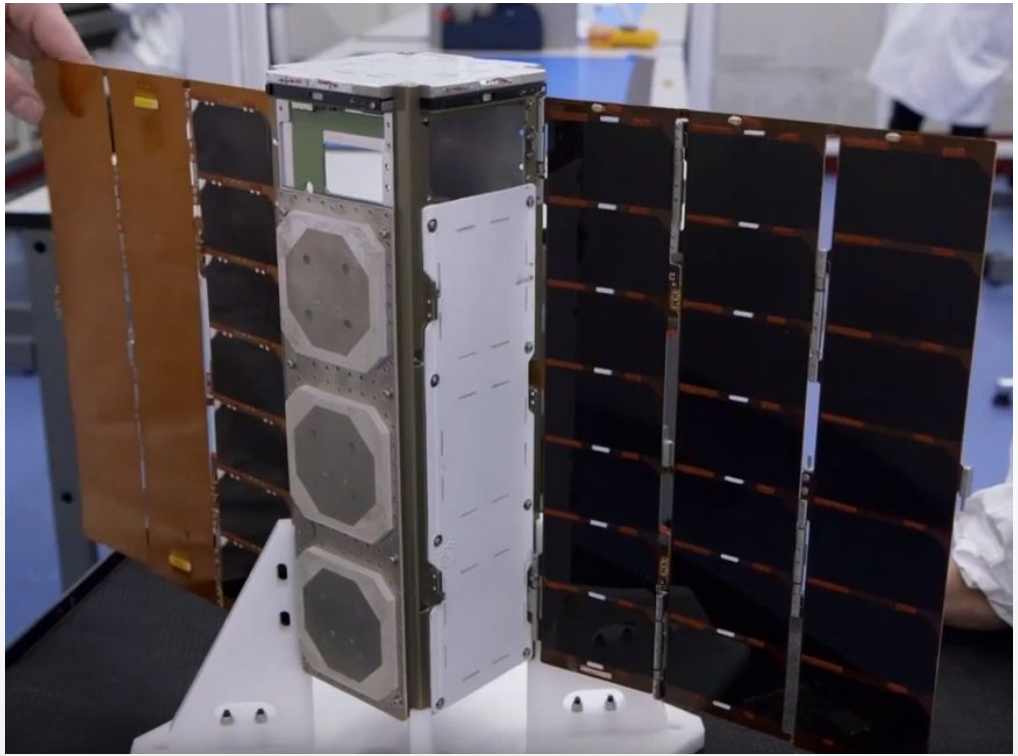
[5] GPS Solutions, USA

WHO & WHAT IS SPIRE?

We're an innovative satellite and data services company or what people refer to as "New Space"...

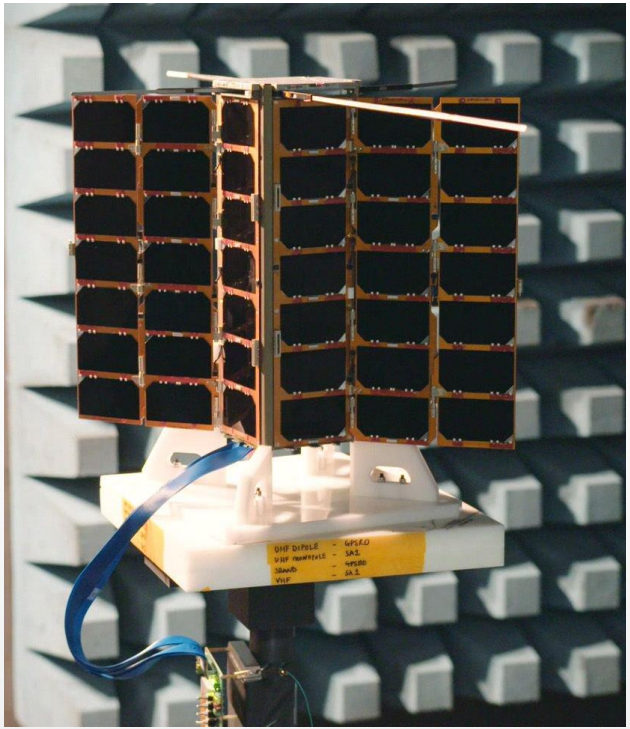
We're what you get when you mix agile development with nanosatellites...

We're the transformation of a single, crowd-sourced nanosatellite into the second largest constellation of satellites in the world.



SPIRE TODAY

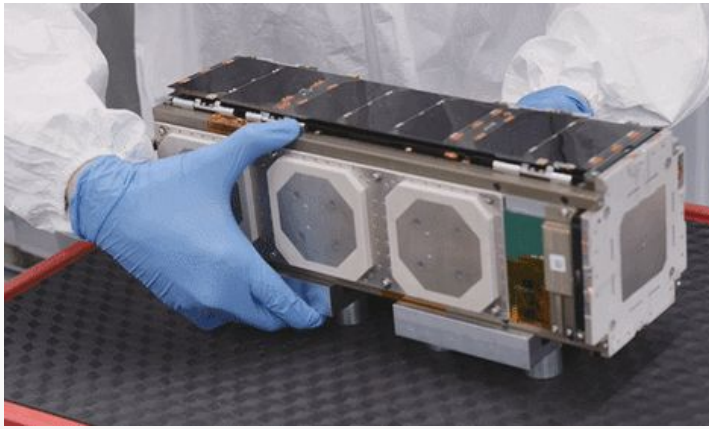
- Established company with 150+ people (and growing) across five offices
- CubeSat manufacturing facility and supply chain
- 80+ LEO 3U CubeSats (10x10x30 cm) in orbit with passive EO payloads
- 20 launch campaigns completed with seven different launch providers
- 31 globally distributed ground stations we own and operate
- Complete global coverage in multiple orbit inclinations
- Deploying new applications within 6-12 month timeframes
- World's largest ship tracking constellation
- World's largest GNSS-based Earth observation (EO) constellation for weather/space weather/GNSS-R data collection
- New ADS-B aircraft tracking product
- $130M+ raised with top institutional investors



WHAT MAKES SPIRE UNIQUE?

Full-Stack Satellites

It's a Spire product from start to finish *(except for the rocket)*; we don't outsource the bus, receiver, nor processing, and this allows us to innovate quickly (e.g., first Galileo RO, conduct phase-delay altimetry, improve open-loop tracking, etc.)



Passive RF Sensing Using Software-Defined Radios

Focused on receiving RF "signals of opportunity" for Earth observation (GNSS), ship tracking (AIS), and aircraft tracking (ADS-B)

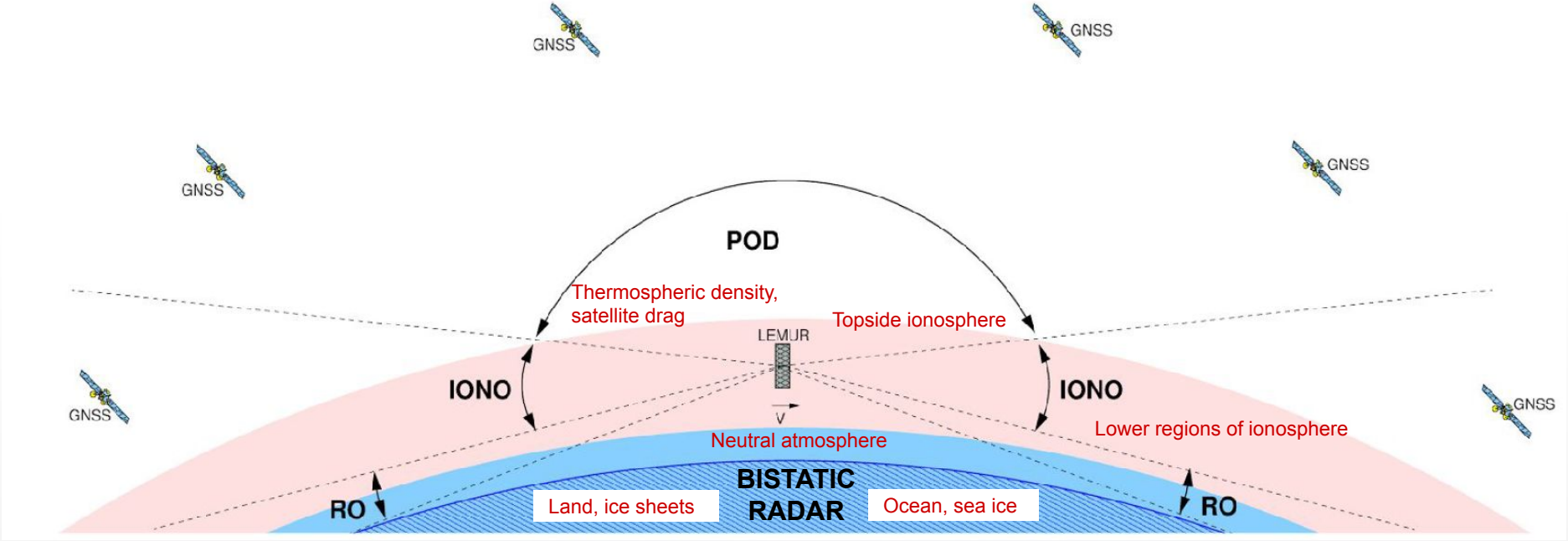
Fast Iteration an Upgrades

New hardware: 6-12 months from idea to launch; currently launching satellites on average **every six weeks**; plans for a constellation to produce 100K RO/day

Consistent On-Orbit Performance Upgrades

Demonstrated rapid improvement in RO quantity and quality

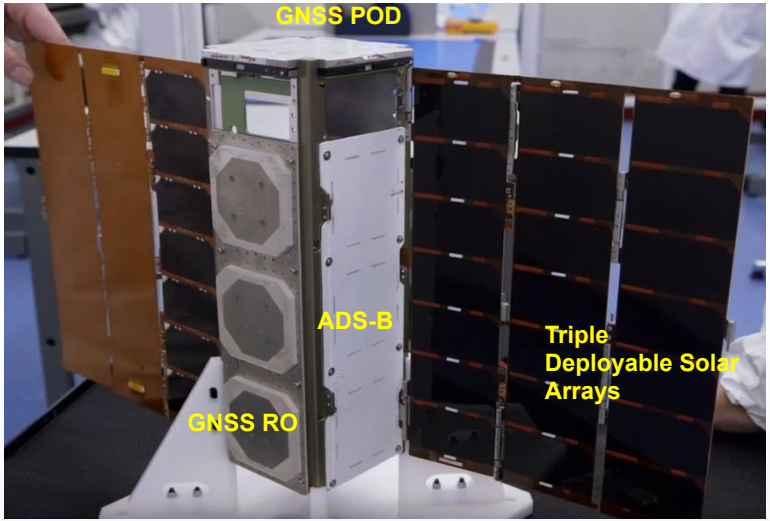
FULL STACK GNSS SCIENCE



Spire leverages the ultra-stable, dual-frequency L-band signals broadcast by GNSS satellites to measure Earth properties that perturb these signals (e.g., refraction, reflection, etc.). These observations have various applications, such as NWP, space weather monitoring, agriculture, etc.

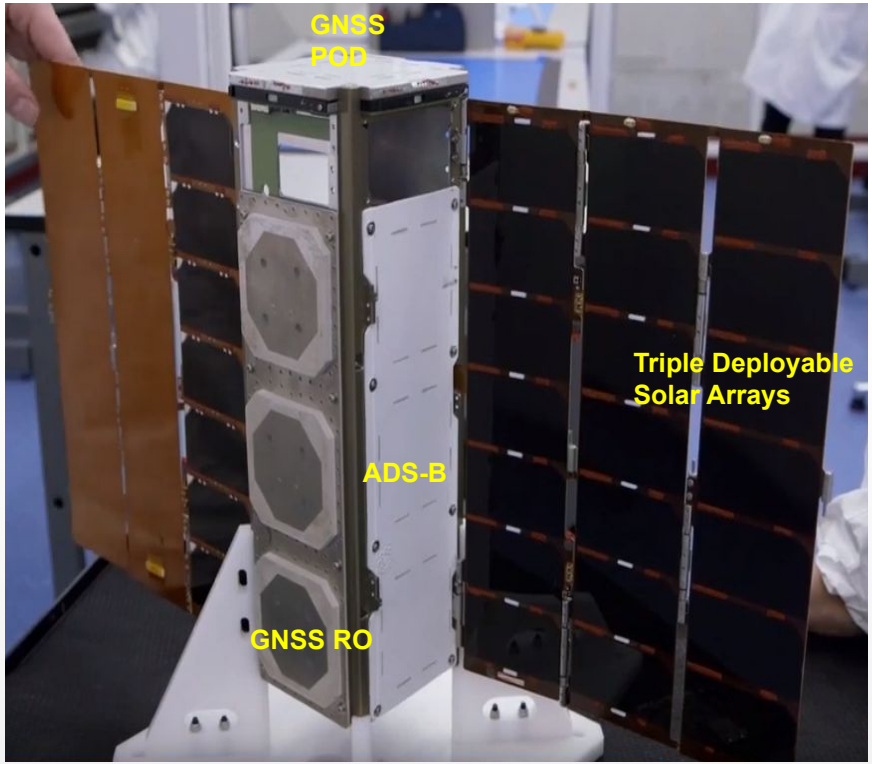
SPIRE EO CUBESAT TECHNOLOGY

Parameter	Value	
Design Lifetime	2+ years	
Volume	10 x 10 x 30 cm (3U)	
Total Mass	4.7 +/- 0.1 kg	
Propulsion	None	
ADCS	3-axis stabilized (sun sensor, magnetometer, Earth-horizon sensor, 3 reaction wheels, magnetorquers)	
Orbit Average Power Usage	Triple-deploy solar arrays with batteries	
Transmitters	UHF	
	S-band, (X-band soon)	
Receivers	UHF, (S-band soon)	
Payloads	AIS	Ship tracking
	GNSS	RO, TEC, POD, Scintillation, GNSS-R
	ADS-B	Aircraft tracking



Spire designs and assembles nearly all of its satellite components in-house, ensuring expert-knowledge of the full satellite HW, SW, and processing stack

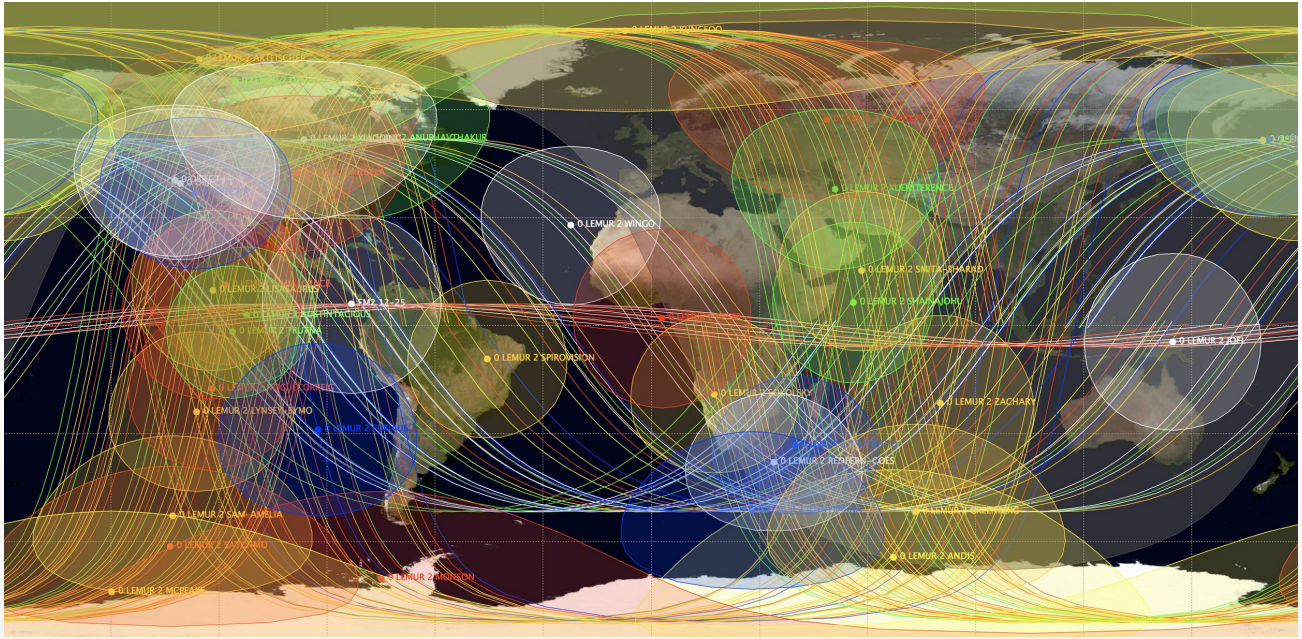
SPIRE GNSS SCIENCE RECEIVER



STRATOS is our advanced, software-defined, dual-frequency, low-power GNSS receiver for remote sensing & precise orbit determination (POD)

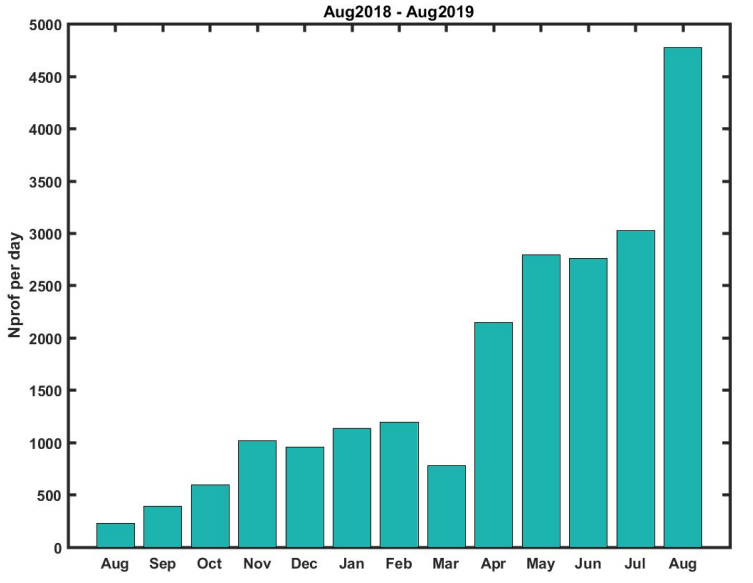
- SDR platform, with FPGA-based acceleration of signal processing
- Performs POD using zenith L1, L2 antenna (orbits ~10-15 cm RMS from overlap analysis)
- Performs radio occultation (RO) on high-gain, forward (rising) and backward (setting) antennas
- Collects GPS, GLONASS, QZSS, Galileo signals
- Enables GNSS applications: atmospheric sounding, space weather monitoring, thermospheric density, time-variable gravity, grazing angle bistatic radar altimetry (GNSS-R)
- Currently modifying STRATOS for GNSS-R scatterometric applications (Earth surface properties: soil moisture, ocean winds, sea ice)

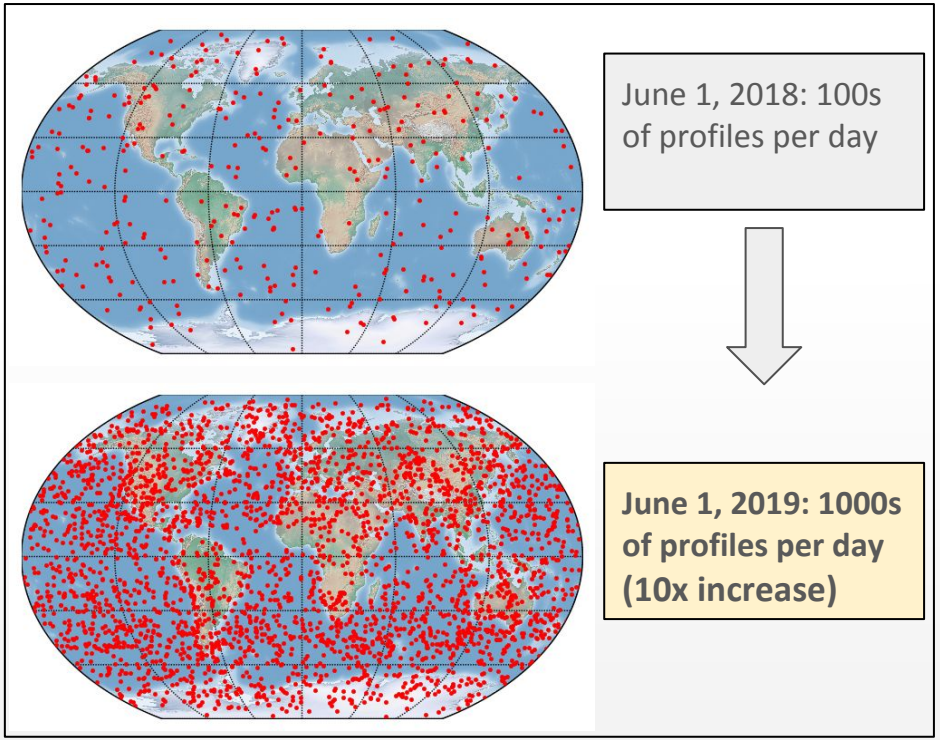
SPIRE CONSTELLATION & OPS



- Currently 80+ satellites in 400-650 km orbits
- Varied orbits for full global sampling
- Mainly sun synchronous and 51.6 deg inc (ISS) orbits
- Some new launches at 85 deg and low inclination orbits
- 30+ ground stations around the world
- 24/7 operations across 4 different time zones

GROWING DATA VOLUME & COVERAGE





June 1, 2018: 100s of profiles per day

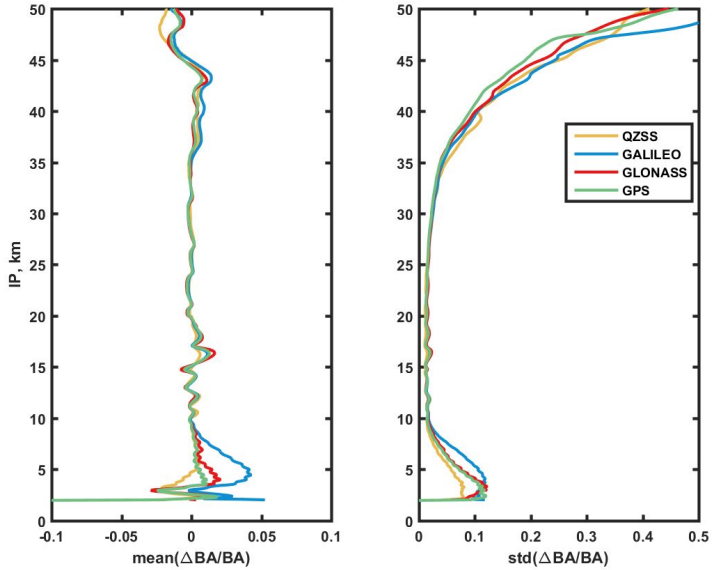
June 1, 2019: 1000s of profiles per day (10x increase)

Daily RO production continues growing/improving:

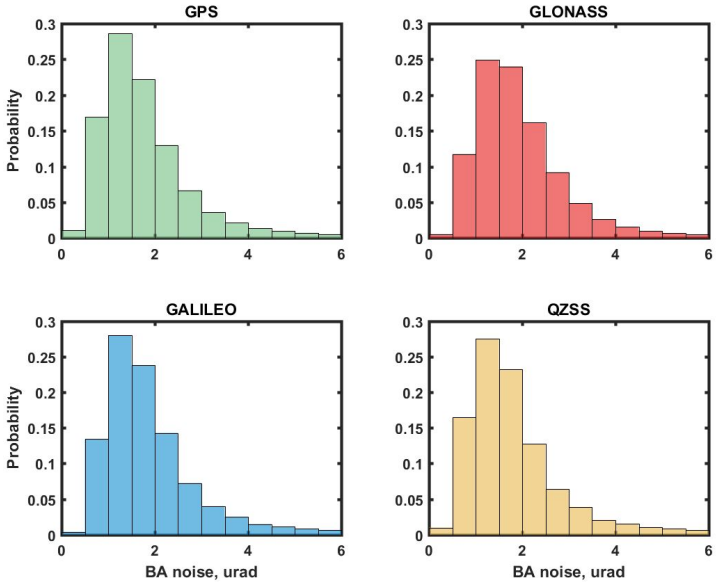
- Satellite launches continue
- Receiver performance improvements
- Satellite bus performance improvements
- Additional GNSS constellations tracked

GPS, GLONASS, GALILEO, QZSS RO

BA Bias & STD vs. GFS



Distribution of the bending angle noise

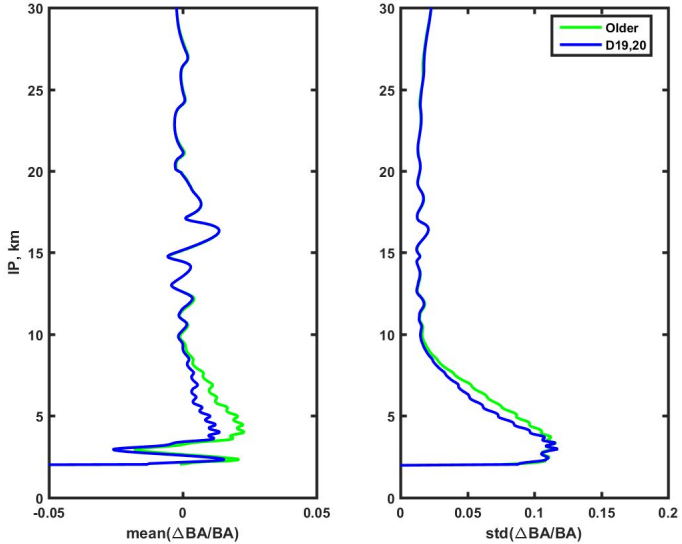


- First commercial provider of four constellations and the only provider of Galileo profiles
- Similar statistics for different GNSS, but differences due mainly to transmissions, spatial sampling
- Galileo (faster chipping rate) open-loop tracking improvements have recently been implemented
- BA noise meets Metop requirements (2 urad) for all constellations

See "Radio Occultation Observations and Processing from Spire's CubeSat Constellation" - Vladimir Irisov, Spire, Fri., Poster15

CONTINUOUS RO IMPROVEMENT

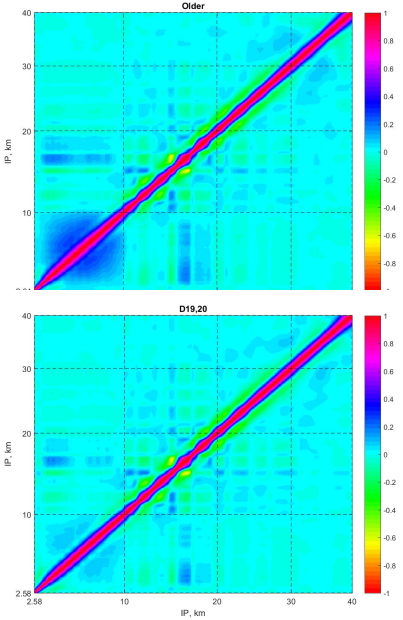
BA improvement on newer satellites



Vertical correlation

Older satellites

Newer satellites

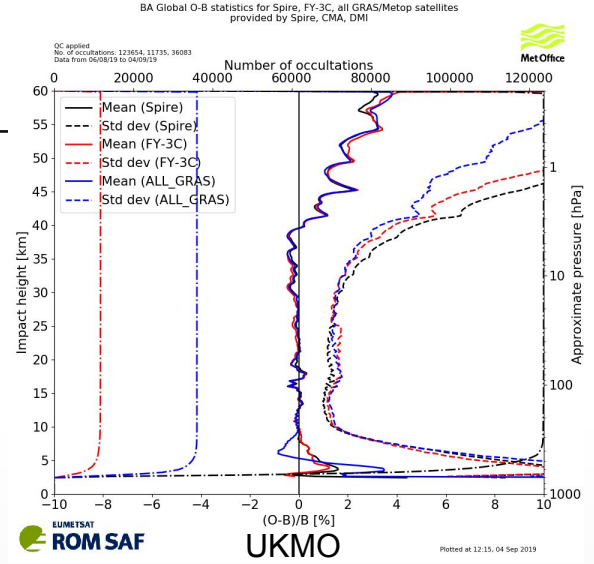


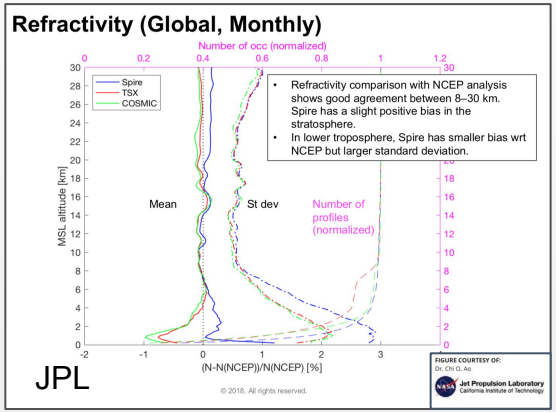
- Spire has the unique ability to improve RO quality/quantity due to rapid launch cycle
- Examples:
  - Improved receiver performance on newer satellites shows better BA statistics (left) and lower vertical correlations in troposphere (right)
- Rapid improvement is also a topic of IROWG discussion: *How shall we collaborate to benefit from rapid improvements without burden on users (.e.g, retuning NWP DA)?*

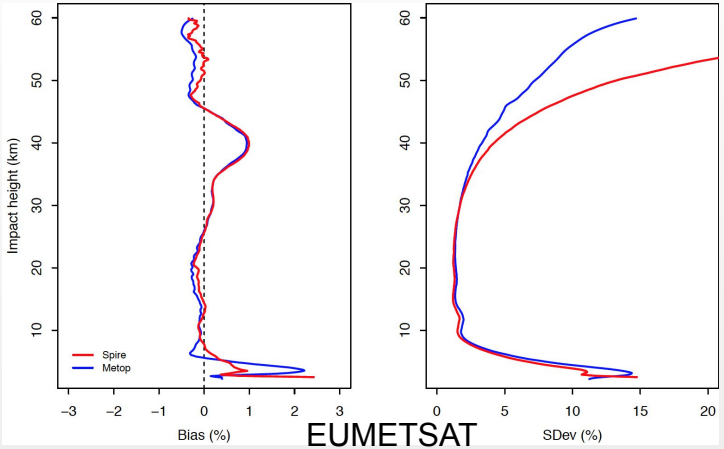
SPIRE DATA ASSESSMENTS

External assessments show similar results: latest Spire RO data are very similar to other RO missions in quality

- At right, UKMO and EUMETSAT assessments *(presentations to follow); JPL below*
- In core region, Spire performs excellently
- In troposphere, Spire in between FY-3C and GRAS
- In upper atmosphere, Spire data has some issues with higher STD *(partial POD cause/fix discussed on slide 19)*
- Similar initial results from US assessments by both NOAA and US Air Force

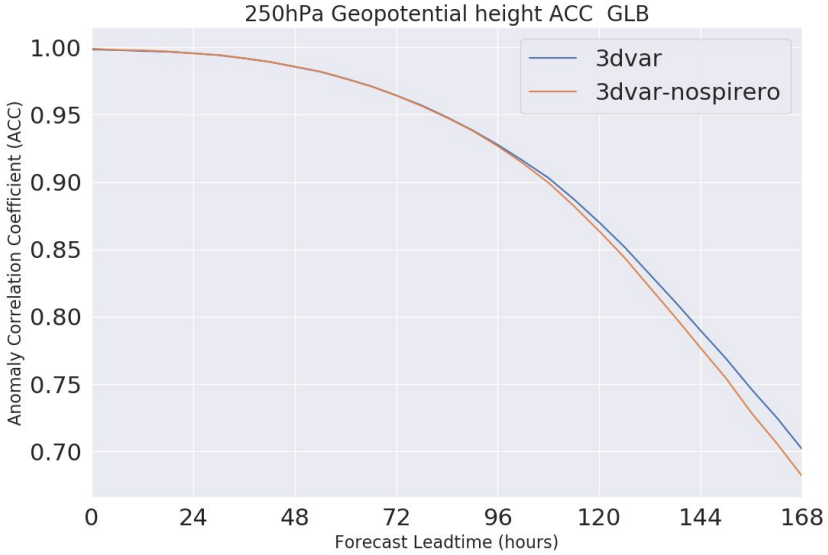


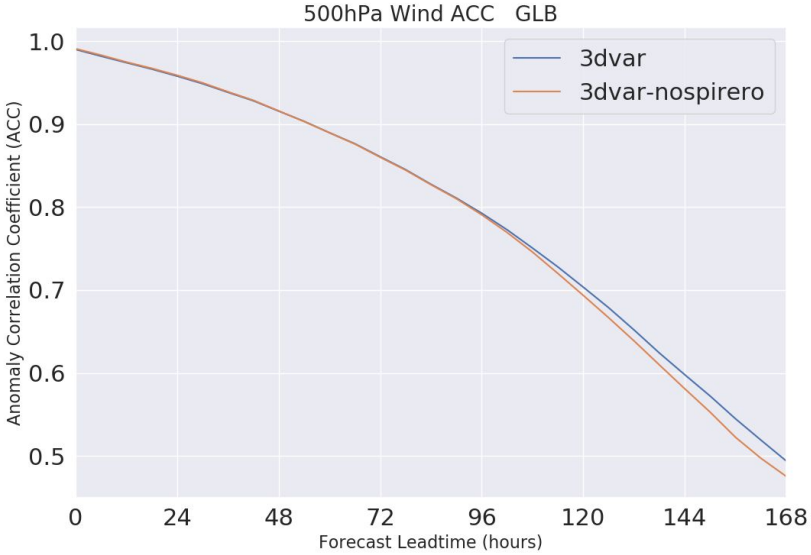




IMPACT OF SPIRE RO DATA ON NWP

- Test period: July 25-31, 2019
- Assimilation of all NOAA observations (conventional, MW, IR) + Spire RO
- 3DVar data assimilation (GSI) on top of NOAA GFS 6h background forecast with 6h data assimilation cycle
- ~ 900-1000 Spire RO profiles assimilated
- Impact on 7-day FIM forecast: mean anomaly correlation scores with GFS analysis as “truth”





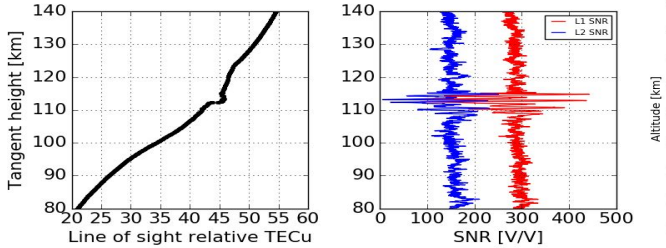
Higher is better

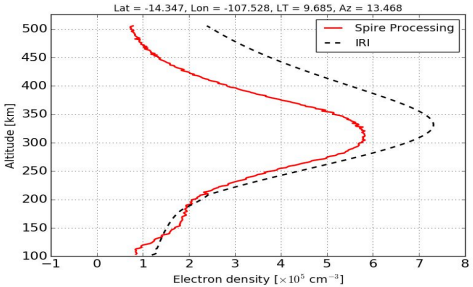
Significant impact on 250 hPa (geopotential) and 500 hPa (wind) levels

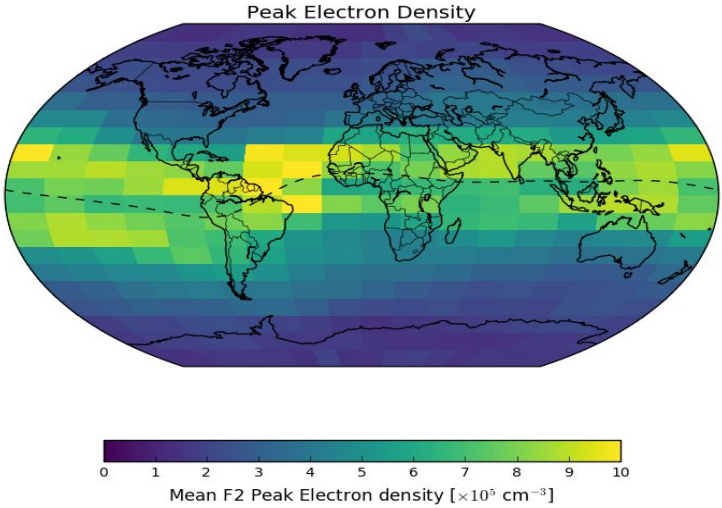
Matthew Hei, Spire Global

SPIRE SPACE WEATHER PRODUCTS

- Ionospheric information can be derived from delay of dual-frequency GNSS signals
  - Line-of-sight total electron content (TEC)
  - Scintillation detection
- Assimilation into upper atmospheric models for improved space weather forecasting predictions







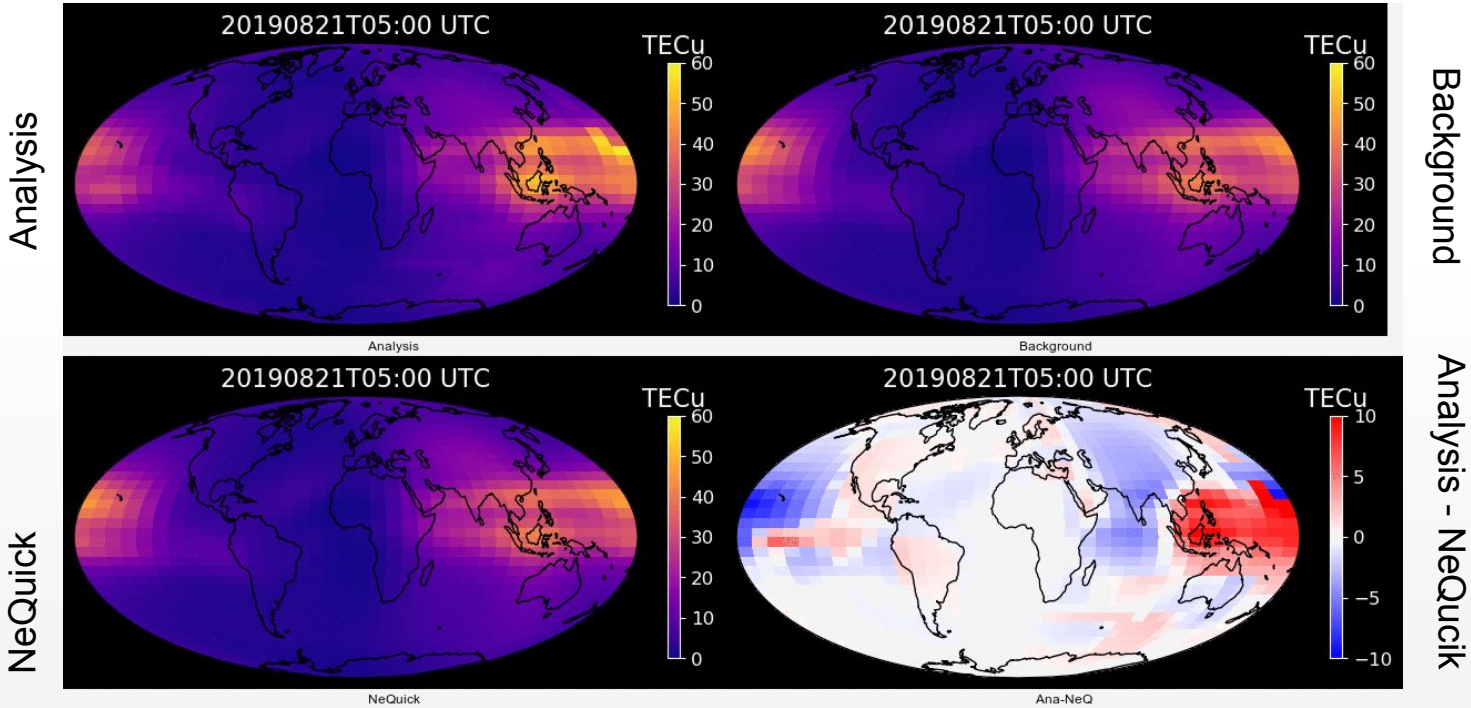
Example of E-region ionospheric scintillation event as observed in Spire TEC measurements and SNR perturbations

Electron density profiles derived from line-of-sight TEC measurements and comparison to climatological model (IRI)

Monthly mean daytime ionospheric peak electron density derived from TEC values. Diversity of Spire orbits allows for global spatial coverage of the ionosphere.

See "Space Weather Observations from Spire's Growing Cubesat Constellation" - Vu Nguyen, Spire, Mon., 10:20-10:40

SPIRE IONOSPHERIC DA MODEL



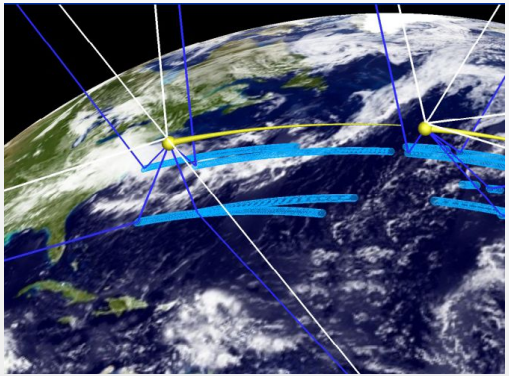
- Spire is expanding its space weather products with in-house modeling and assimilation
- Matt Angling recently joined to build Spire TEC Assimilative Model (STEAM)
- Addressing many applications of ionospheric anomaly detection

SPIRE GNSS-R PROGRAM: SCATTEROMETER

Spire is planning a fleet of GNSS-R scatterometer satellites like GNSS-RO

Two prototype GNSS-R satellites ready for launch in late 2019

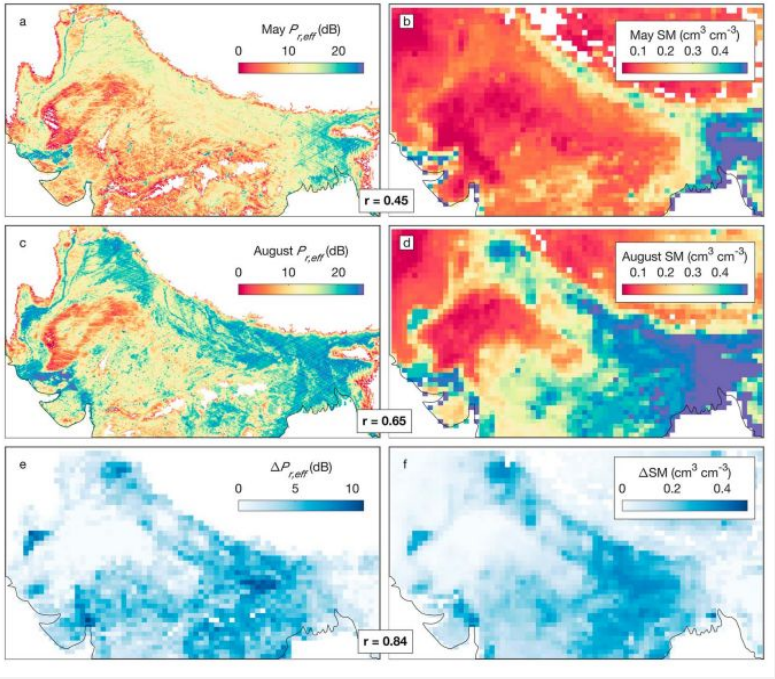
- Utilizes existing LEMUR2 bus and STRATOS GNSS-RO receiver
- Performing raw IF and delay-Doppler map processing
- To be followed by operational GNSS-R missions



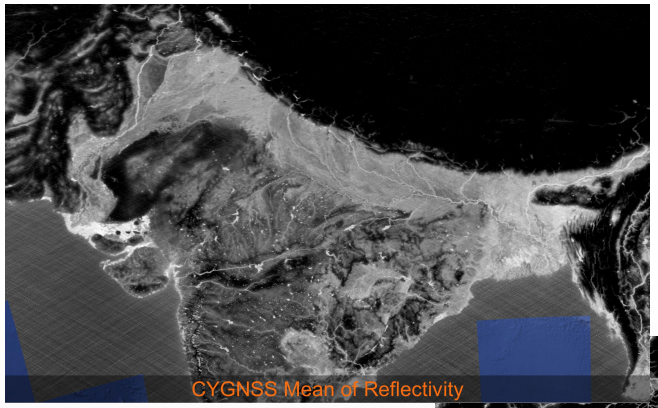
(NASA CYGNSS Science Team)

GNSS-R PROGRAM: SOIL MOISTURE

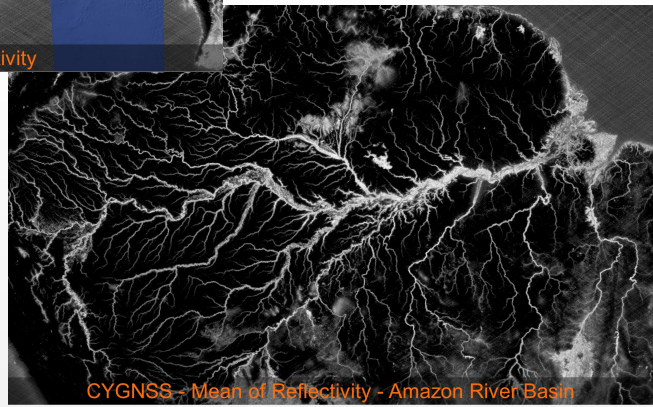
GNSS-R SMAP



(Chew & Small., 2018)



From Spire GNSS Team



Surface water, flood mapping

- Soil moisture measurements at potentially much finer (0.2-25 km) spatio/temporal resolution than SMAP ($1B NASA mission)
- Like RO, impactful when assimilated into NWPs

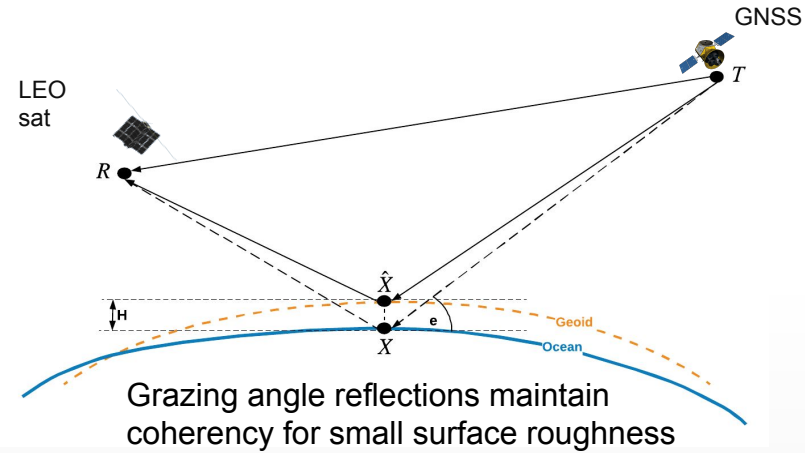
GNSS-R FROM AN RO CONSTELLATION

Spire is also pursuing GNSS-R with its current GNSS-RO constellation

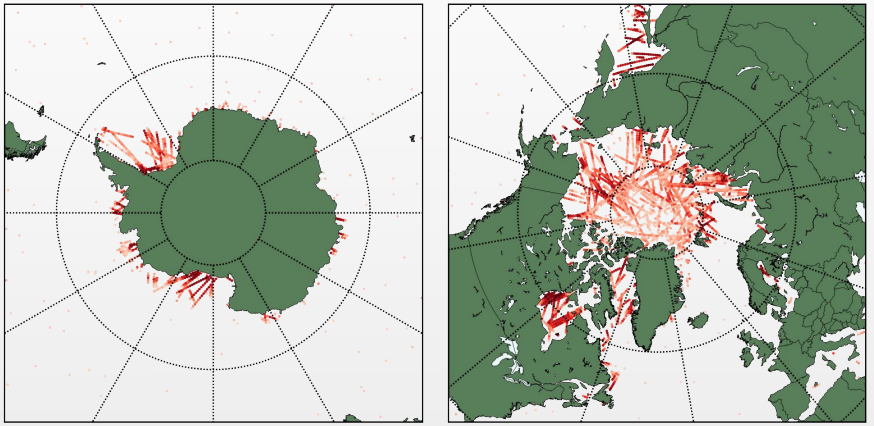
Phase-delay altimetry is a type of GNSS-R that uses coherent reflections of GNSS signals at low grazing angles (5-30 deg) to estimate sea surface and sea ice heights

Within two months, Spire reprogrammed RO sats open-loop tracker to collect thousands of dual-frequency, RHCP, grazing angle reflections

Funding from NOAA OPPA Technology Maturation Program

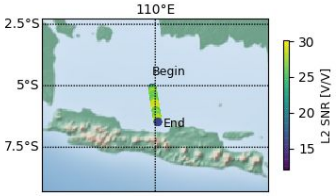


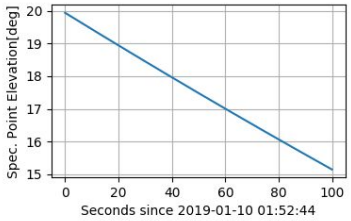
Grazing angle reflections maintain coherency for small surface roughness



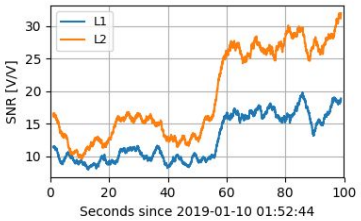
Sea ice map from two Spire RO sats in early 2019

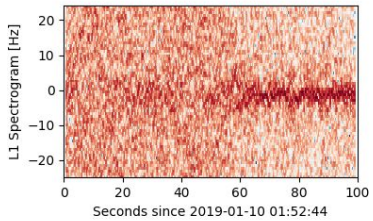
GRAZING ANGLE ALTIMETRY EXAMPLES

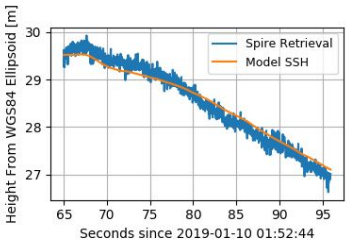


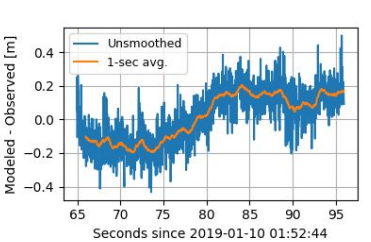


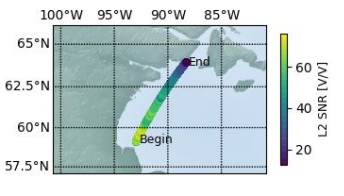
Java Sea (open water)

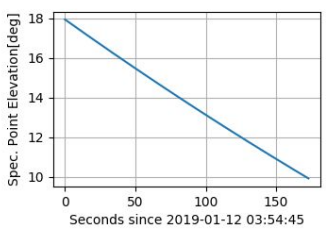




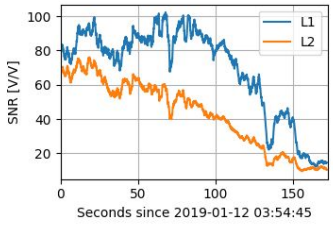


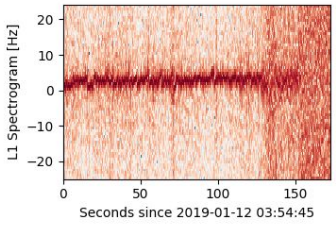


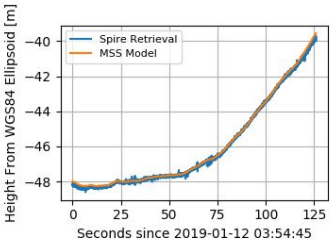


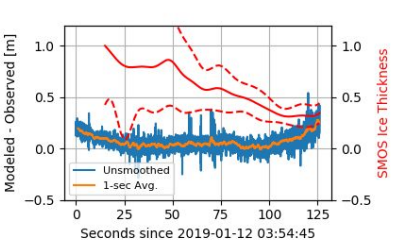


Hudson Bay (sea ice)









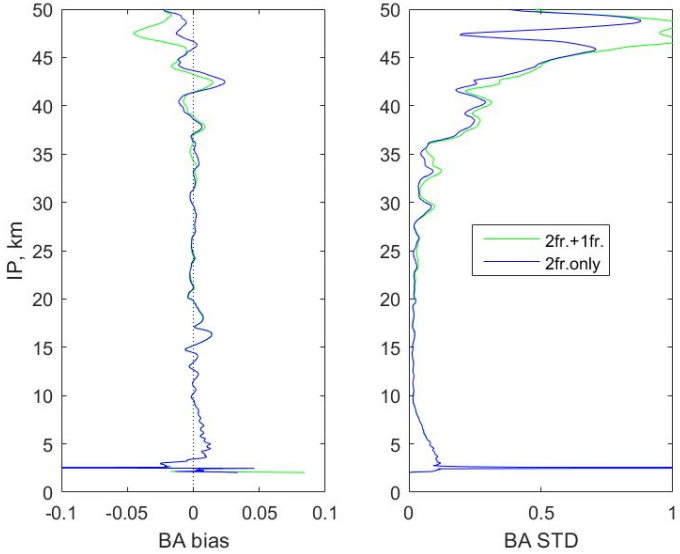
Initial results demonstrated < 10 cm RMSE height retrieval over sea ice and < 20 cm over open ocean

COMMUNITY COLLABORATION

Spire is actively engaged with the RO community and benefiting from collaborations and feedback

- Only commercial company to provide RO in first NOAA Commercial Weather Data Pilot (CWDP-1)
- Currently providing RO and iono obs to:
  - NOAA CWDP-2
  - US Air Force CWDP-1
  - NASA Private Sector Small Constellation Satellite Data Product Pilot (BPA)
  - ESA-sponsored assessments by UK MetOffice, EUMETSAT, and WEGC (results to follow)
  - ESA Earthdatanet trial
  - Many university and commercial collaborations
- NASA PIs can request Spire RO/SpWx data through BPA
- Data samples available upon direct request
- Near real-time access via AWS cloud-based API

Ex: POD Improvement through collaboration



- BA statistics for the original Spire POD processing using both single and dual freq. observations (green) and improved dual-frequency-only POD processing (blue)
- Spire/EUMETSAT/WEGC collaboration resulted in identifying POD improvements

SPIRE DATA AT IROWG

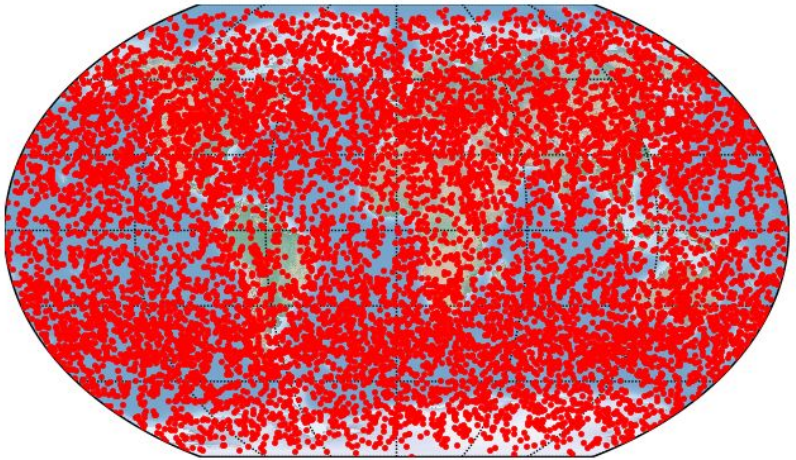
A number of IROWG presentations/posters highlight Spire data and quality

- **“Initial assessment of GNSS-RO data from Spire”** - Neill Bowler, UK Met Office, Thu., 14:20 - 14:40 (next talk)
- **“Assessment of Spire Commercial RO Data”** - Christian Marquardt, EUMETSAT, Josef Innerkofler, WEGC, Thu., 14:40-15:00 (2nd next talk)
- **“Radio Occultation Observations and Processing from Spire's CubeSat Constellation”** - Vladimir Irisov, Spire, Fri., Poster15
- **“Space Weather Observations from Spire's Growing Cubesat Constellation”** - Vu Nguyen, Spire, Mon., 10:20-10:40
- **“Generalized Canonical Transform Method”** - Michael Gorbunov, A.M.Obukhov Institute of Atmospheric Physics, Tue., 13:40-14:00

KEY TAKEAWAYS

- Spire's current constellation is one of the largest producers of RO and SpWx measurements ever launched
  - Currently producing **~ 6000 RO profiles and 5M+ TEC** measurements per day and **increasing**
- External assessments agree that Spire data quality is consistent with other RO satellites
- Internal and external analyses have highlighted the positive impact of assimilation of Spire RO and ionosphere data
- **Spire will provide consistent, long-term GNSS-based Earth observations as a service**

Expected Daily Spire RO Coverage in 2020



For more questions or information please contact dallas.masters@spire.com

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