spire | earth information

Plans for Long-Term Operational Sea State Monitoring by the Spire GNSS-R Nanosatellite Constellation

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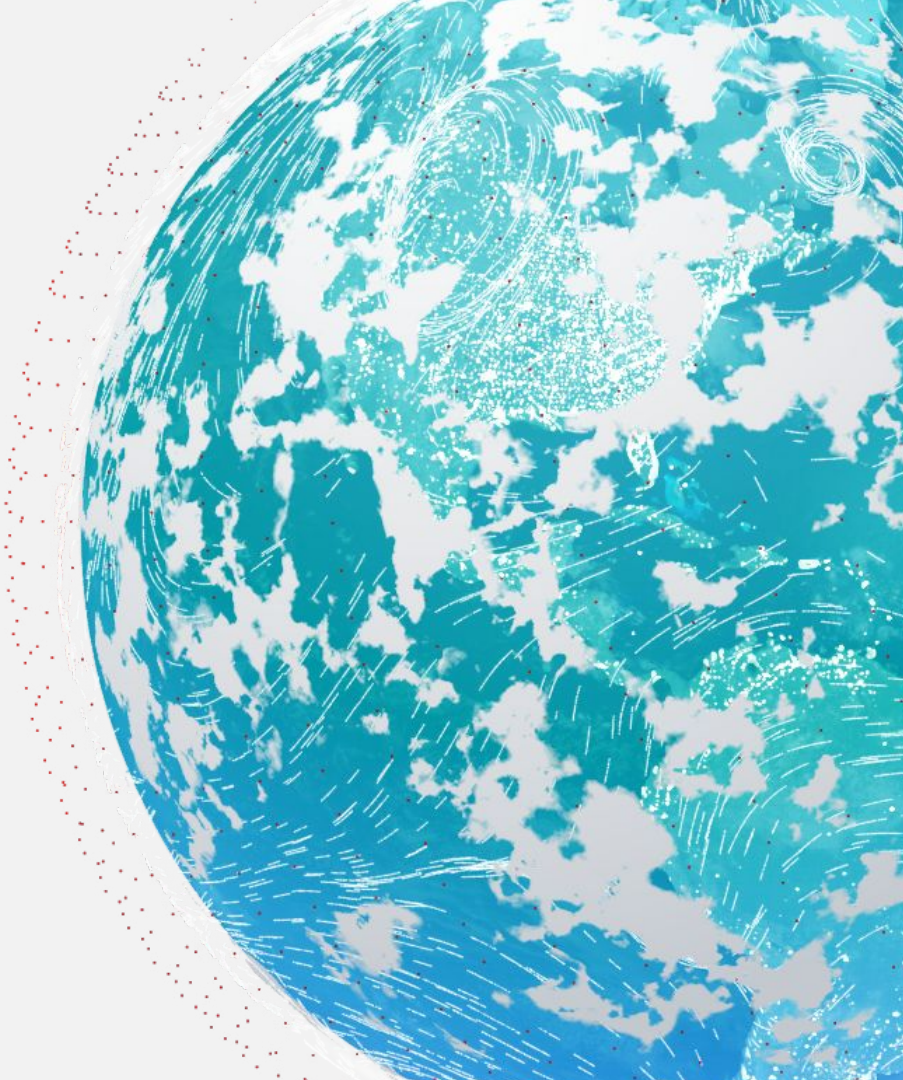
2nd Sea State User Consultation Meeting 23-25 March 2021



Spire EO Experience

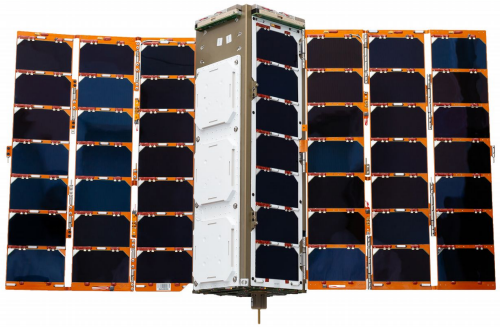
Spire operates the third largest constellation of satellites (110+ nanosatellites and growing)

Established company with ~250 people across six offices

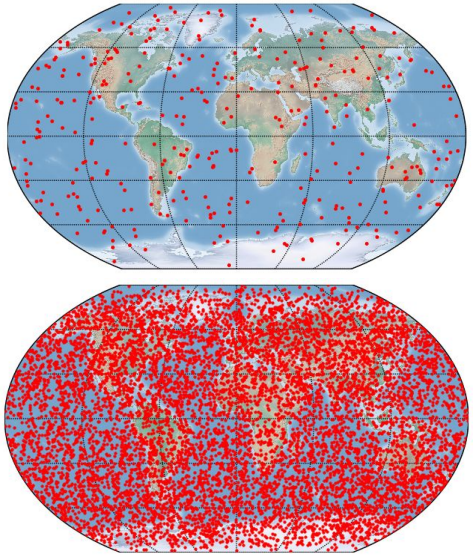
Spire was the first commercial company to collect radio occultation data (atmospheric profiles) and leads in quantity of GNSS-RO and GNSS-R observations

20+ launch campaigns and 29 globally distributed ground stations

Spire GNSS-RO data have been assimilated into the operational forecasts of ECMWF and UK MetOffice



Spire has introduced a faster and more agile paradigm for EO with constellations of nanosatellites



June 2018: 100s RO profiles/day

Feb. 2020: ~10K RO profiles/day (~100x increase)

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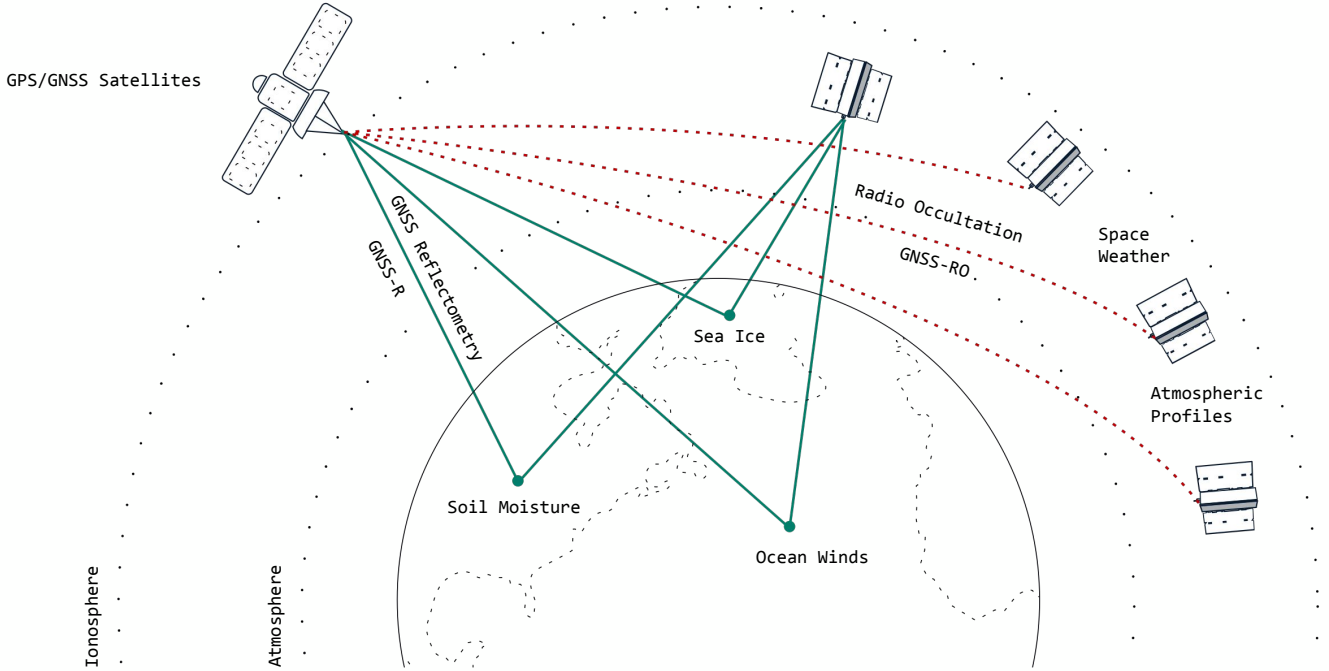
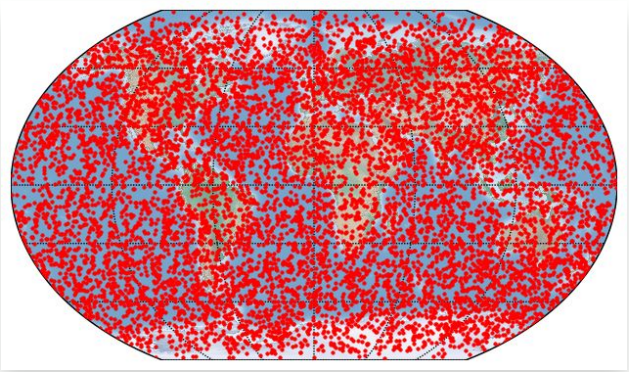
Spire Earth Observations



- Atmospheric sounding for NWP, climate
- Ionospheric sounding for space weather monitoring
- Thermospheric density and possibly gravity through precise orbit determination
- Grazing angle bistatic radar altimetry with GNSS-RO satellites
- GNSS-R scatterometry: sea ice, soil moisture, **ocean winds, mean square slope**

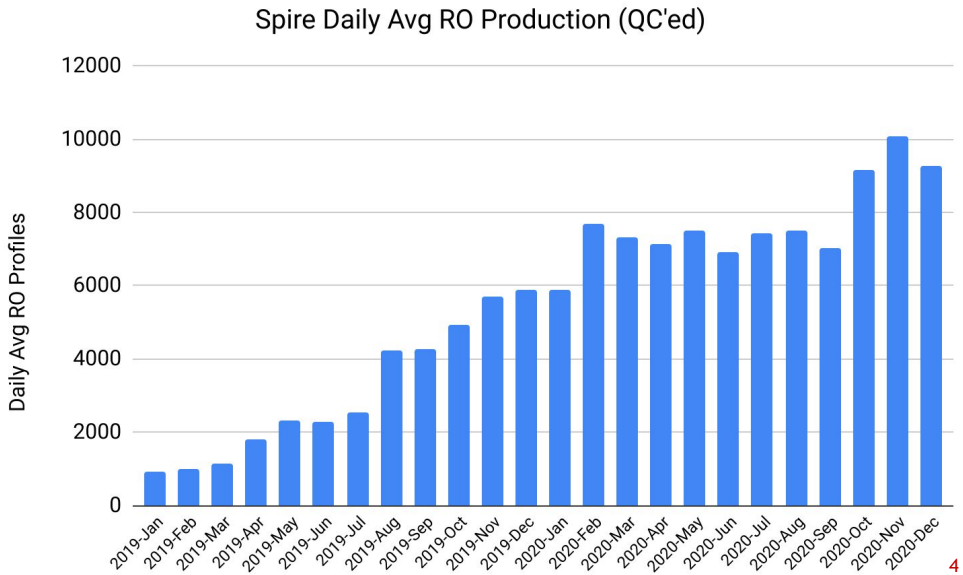
Scaling Earth Observations



~10K profiles per day and global coverage

Spire Earth observation production advancement:

- Quantity increase through launches and additional GNSS constellations tracked
- Continual receiver and bus performance improvements
- Continual data latency reduction
- Spire's constellation is designed for continuous scaling, replenishment, and improvement
- Long-term, sustainable Earth observations to meet societal needs



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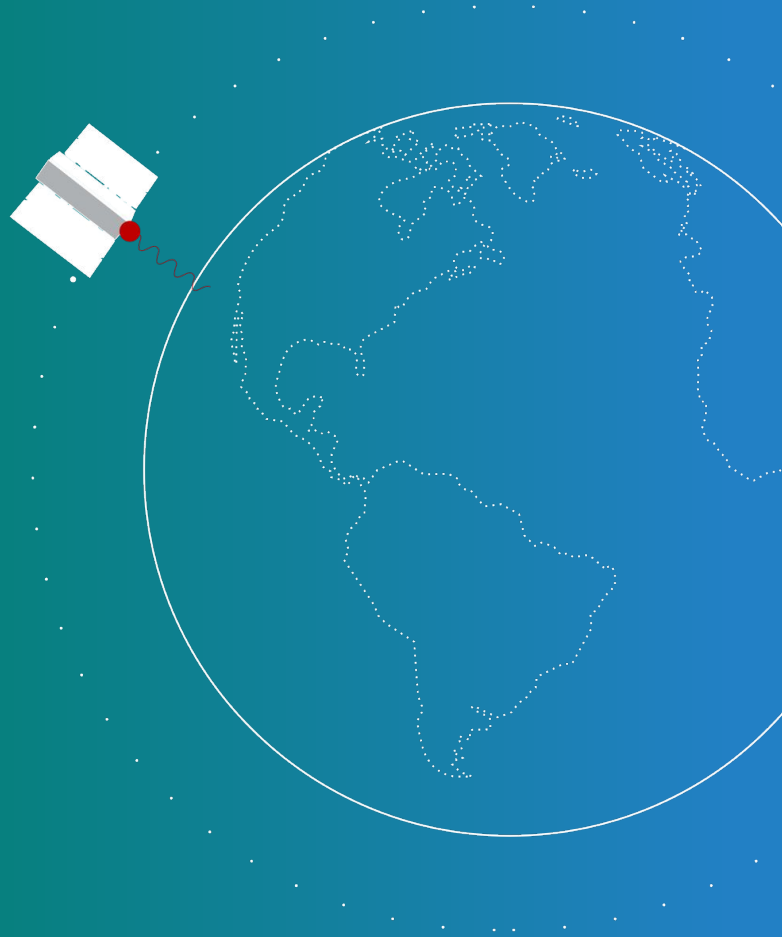
GNSS Reflectometry (GNSS-R)



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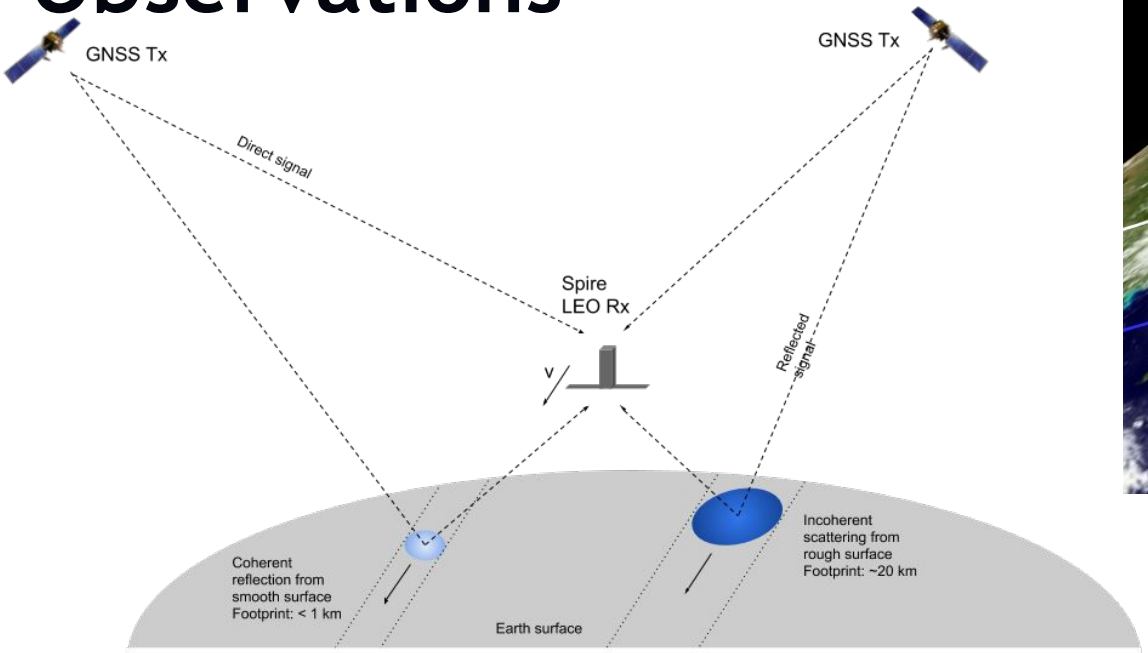
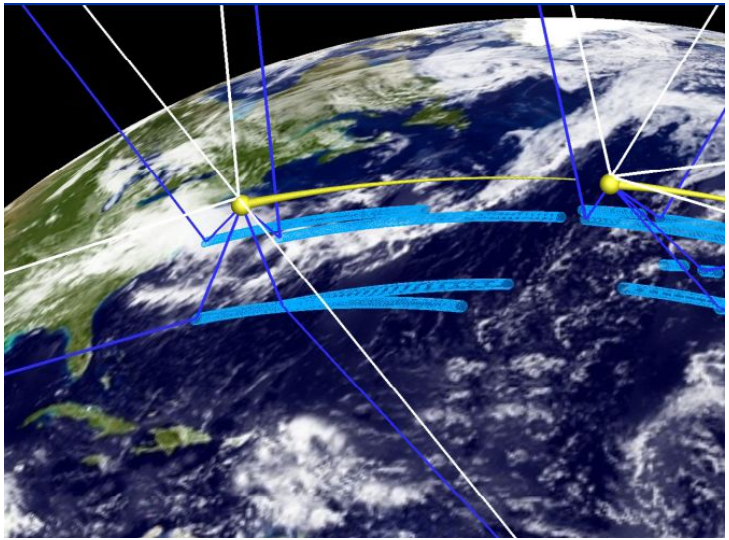
Spire GNSS Reflectometry (GNSS-R) Observations



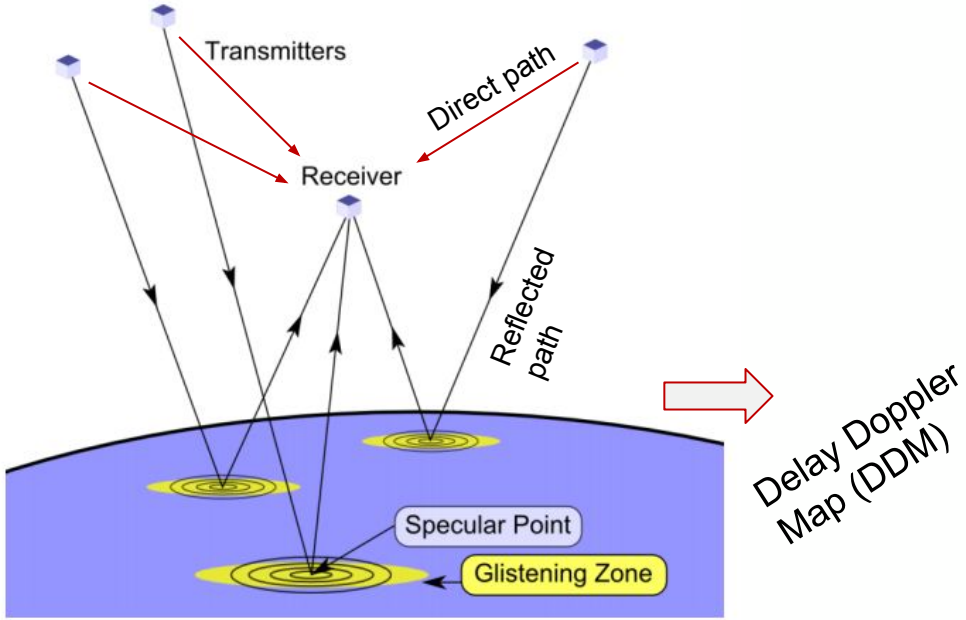


(Credit: NASA CYGNSS Science Team)

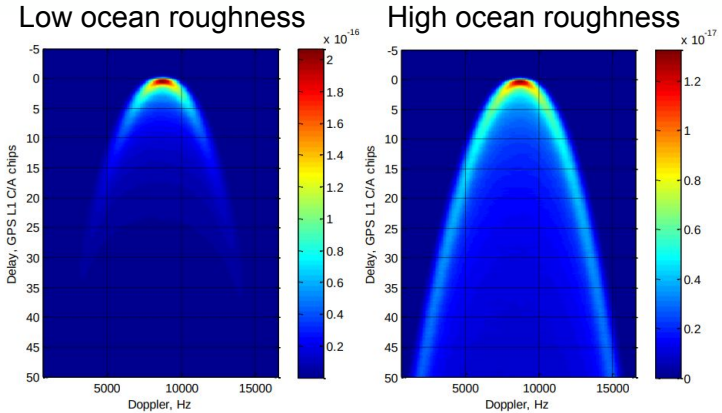
- GNSS-R is a form of bistatic radar using GNSS signals of opportunity (e.g., GPS, Galileo, QZSS, GLONASS) to perform Earth surface scatterometry (ocean roughness estimation, e.g., TDS-1, NASA CYGNSS mission)
- Natural progression from successful Spire radio occultation (RO) satellites to add GNSS-R scatterometer satellites to Spire constellation

Spire's Interest in GNSS-R Ocean Applications

- Ocean Mean Square Slope (MSS) is key to air-ocean gas transfer.
- For NWP a global measure of the wind-wave coupling.
- GNSS-R is directly measuring the surface roughness (MSS) at L-band. This observable can be used as-is, or inferred to surface wind-speed.

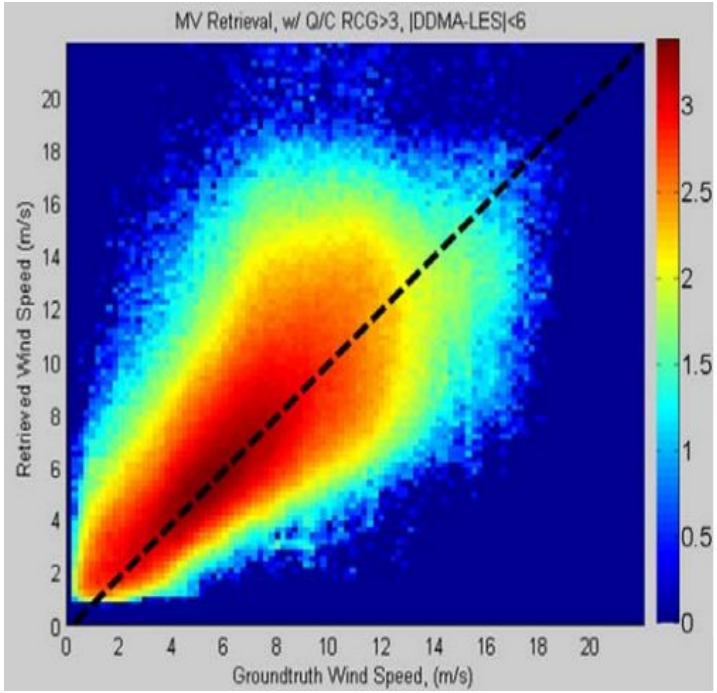


Delay Doppler Map (DDM)



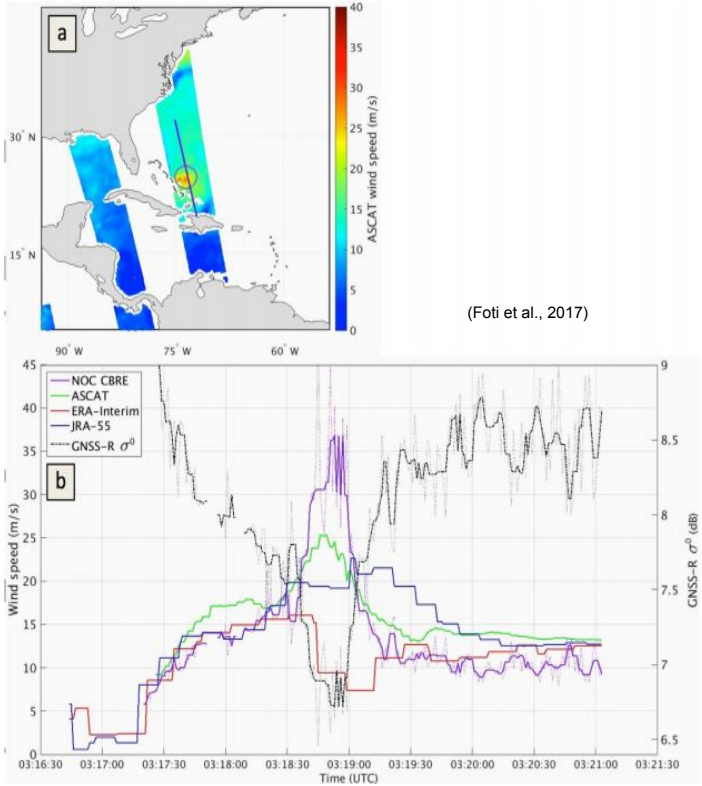
(Gleason et al., 2017)

Spire's Interest in GNSS-R Ocean Applications



CYGNSS wind speed performance

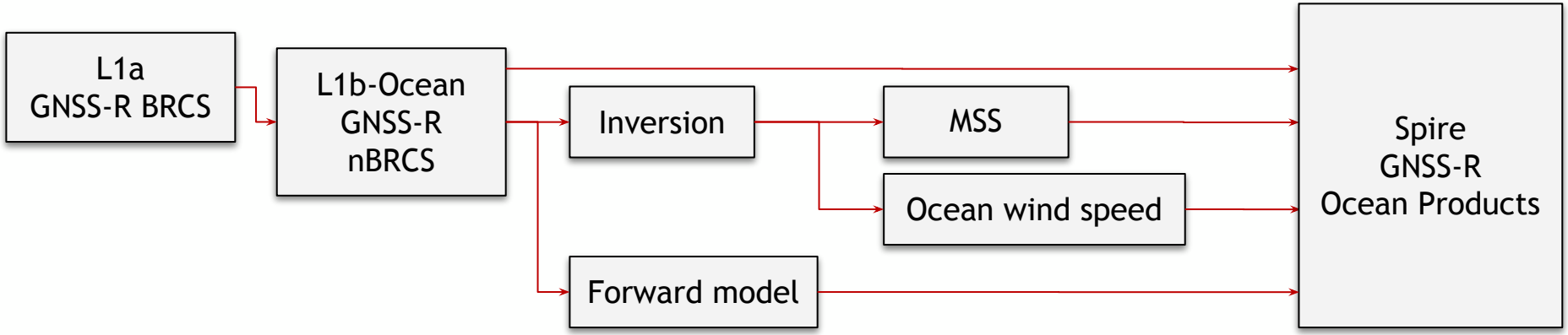
(Ruf et al., 2017)



(Foti et al., 2017)

Ocean roughness and wind speed measurements 2-3 m/s RMSE (with hurricane penetration)

Spire Ocean Product Roadmap



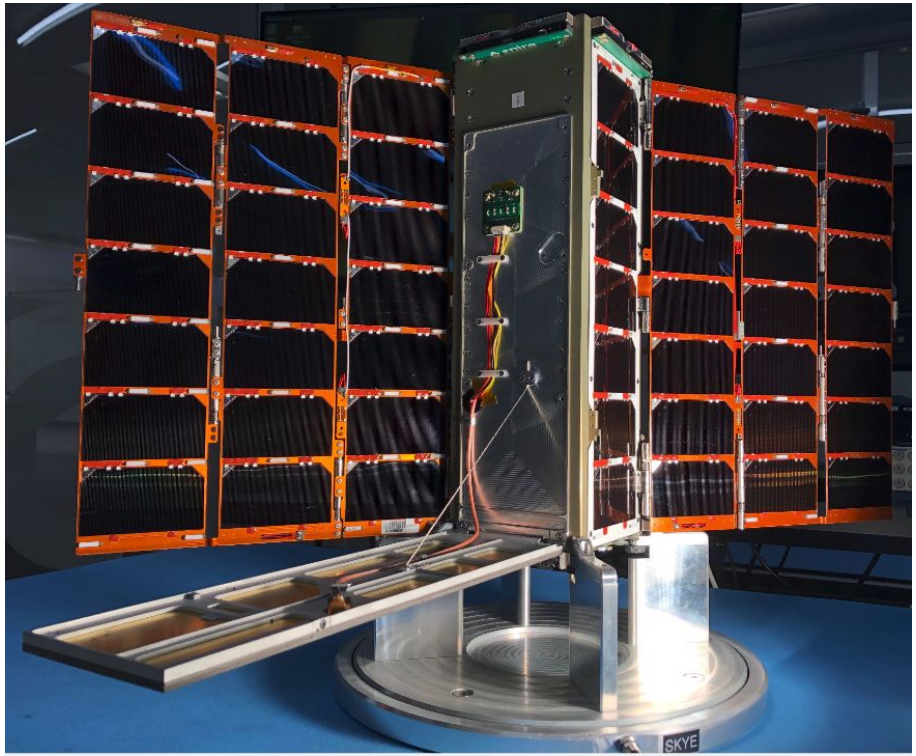
- Preliminary product of Spire GNSS-R ocean reflectivity **inverted** to **MSS** and **ocean wind speed**
- For NWP assimilation we are also generating a **observable** + **forward model** product

Spire Batch-1 GNSS-R Mission (2020)

SPIRE GNSS-R "Batch-1" Satellites

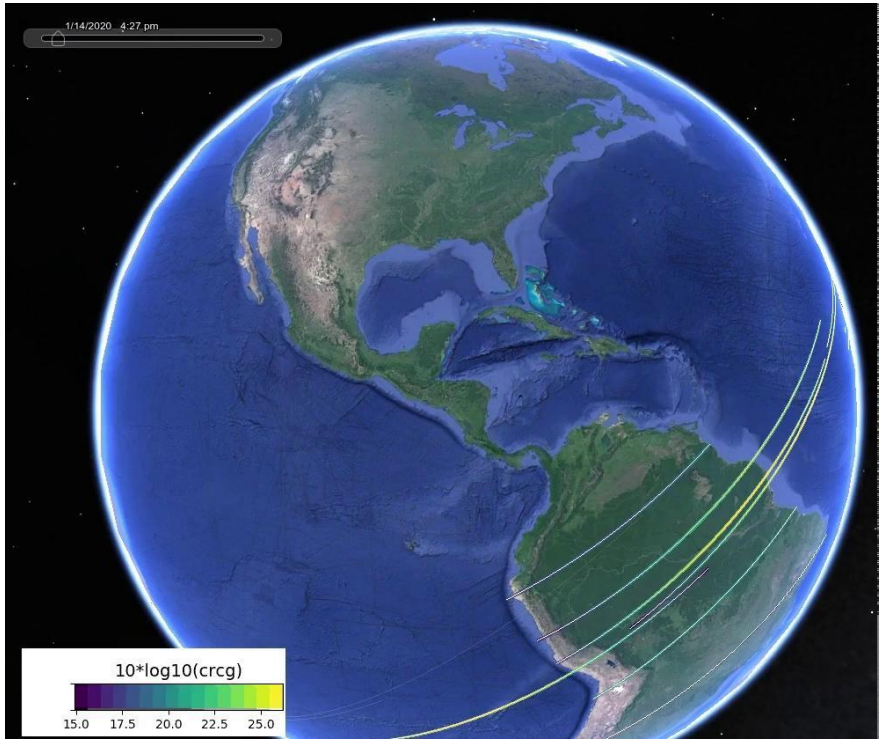
- **Launched two satellites in December 2019**
- Novel relative power calibration method
- Digital beamforming between antennas

Parameter	NASA CYGNSS	Spire GNSS-R Batch-1
Simultaneous reflections observed	4	**30**
GNSS Constellations tracked	GPS	**GPS, QZSS, Galileo, SBAS**
Direct antenna	L1 Single patch	L1/L2 single patch
Reflection antenna	2, 3x2 L1 LHCP array (off-nadir)	2, 3x1 L1 LHCP array (nadir), **beamforming**
Mass	25 kg	5 kg
Orbit	35 deg, 510 km	37 deg, 571 km
Expected lifetime	2 years	2 years

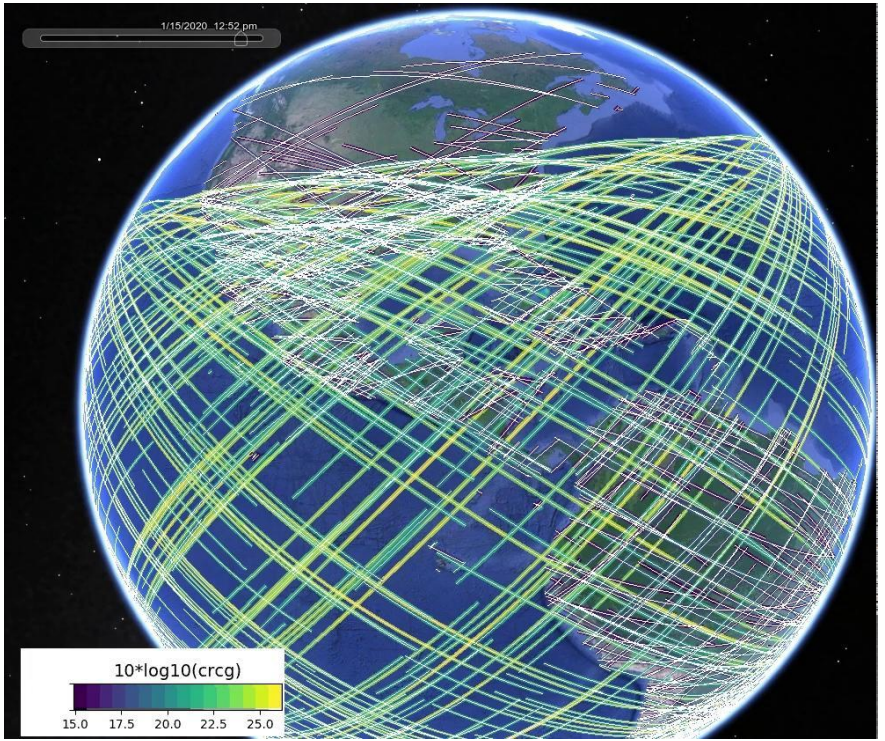


Increased Coverage with All GNSS Reflections

GPS reflections only (CYGNSS-like)



Spire: GPS+Galileo+QZSS+SBAS reflections



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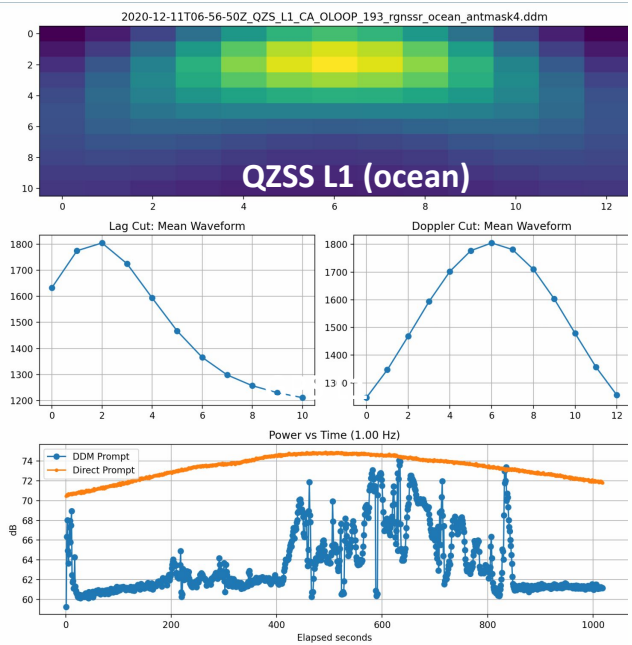
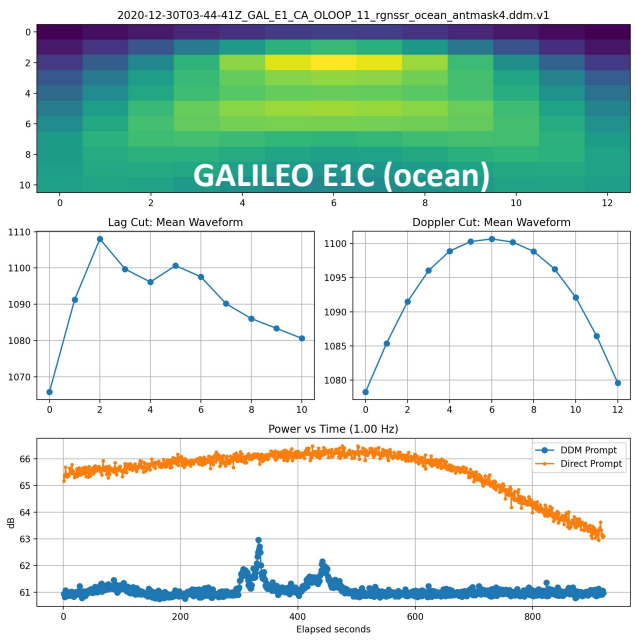
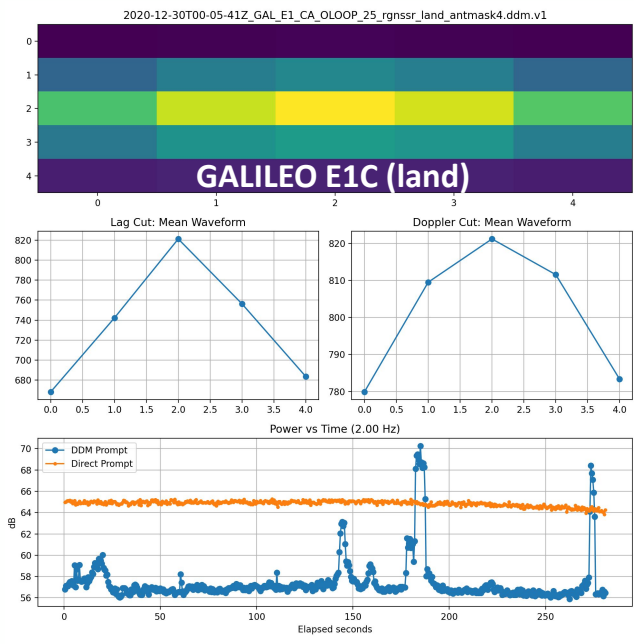
Tracking More GNSS Constellations

- GPS signals tracked since launch
- First operational DDM collections of non-GPS signals
- QZSS L1 (4 more transmitters) and Galileo E1C (22 more transmitters) added in December 2020
- SBAS signals (~14 more transmitters) in mid-2021

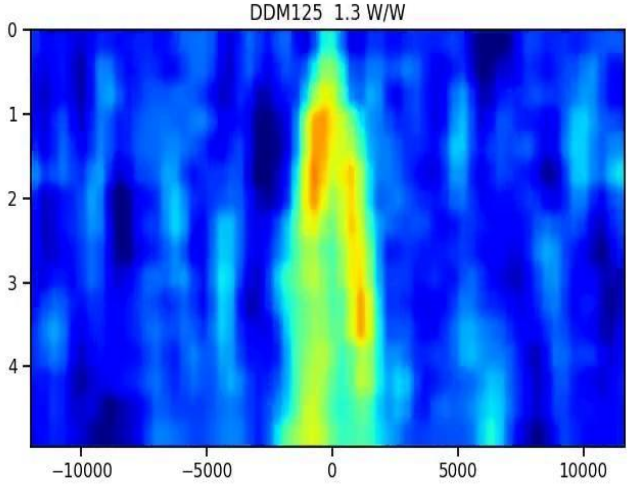


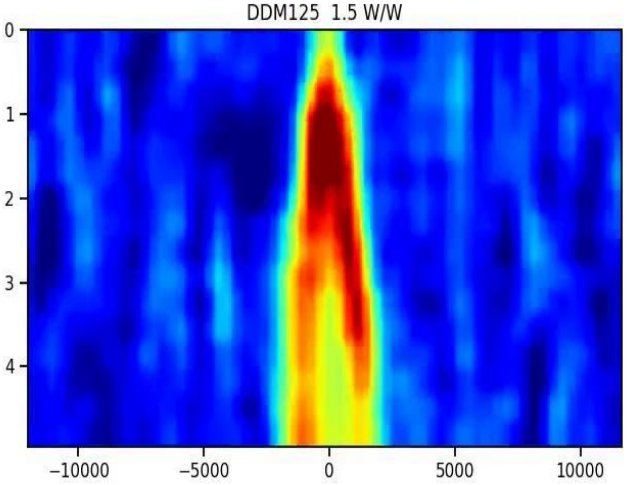


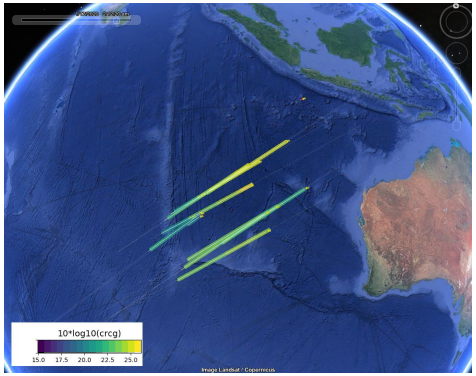


Spire GNSS-R: First to Beamform

- Demonstration of beamforming to increase SNR from coherent combination of multiple antennas. Currently beamforming only for short durations in ground processing. Single antenna (Left) vs. beamformed (Right). Color scale is fixed.





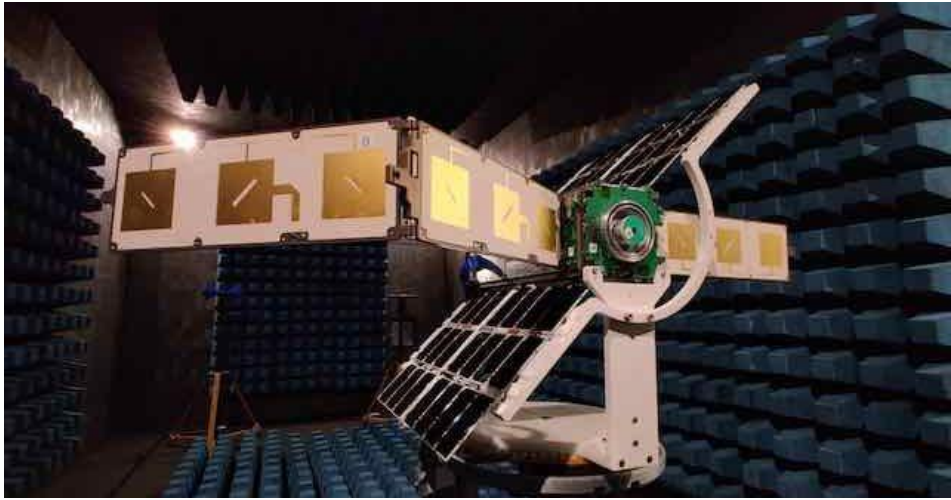


Spire Spire Batch-2 GNSS-R Mission (2021)

SPIRE GNSS-R "Batch-2" Satellites

- **Two satellites launched in January 2021**
- Sun synchronous (polar) orbit
- 3-panel, wide FOV antenna; direct sampling GNSS receiver

Parameter	Spire GNSS-R Batch-1	Spire GNSS-R Batch-2
Simultaneous reflections observed	**30**	**45**
GNSS Constellations tracked	GPS, QZSS, Galileo, SBAS	**GPS, QZSS, Galileo, SBAS**
Direct antenna	L1/L2 single patch	L1/L2 single patch
Reflection antenna	2, 3x1 L1 LHCP array (nadir), beamforming	**3, 3x1 L1 LHCP array (nadir, 35 deg off-nadir, and beamforming**
GNSS receiver	STRATOS v1	**STRATOS v2 (direct sampling, onboard calibration, larger FPGA)**
Mass	5 kg	5 kg
Orbit	37 deg, 571 km	**SSO: 9:30 LTDN**, 500 km



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Comparison between Spire and CYGNSS

- Comparison of GNSS-R normalised bistatic radar cross-section (nBRCS) to ECMWF u10 wind speed
- Preliminary like-for-like comparison between Spire and CYGNSS: GPS-only, 1 Hz nBRCS.

- Good agreement between Spire and CYGNSS nBRCS for given wind-speed
- Still some work to improve validation and quality flagging

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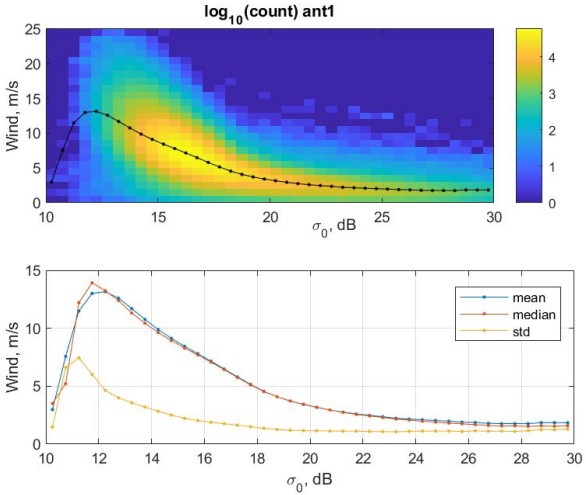
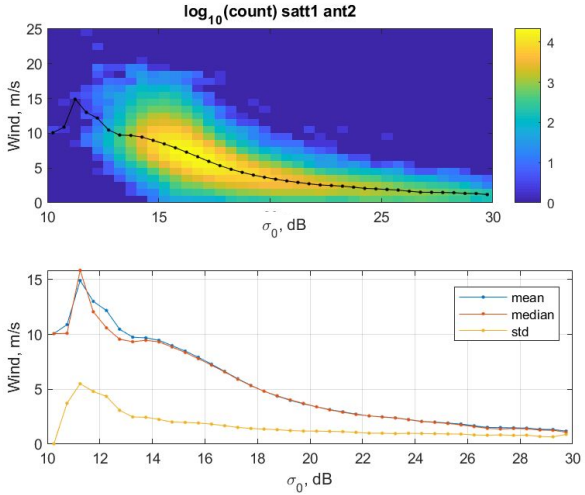
Batch-1: FM109 antenna 1, Nov 2020 - Jan 2021



CYGNSS

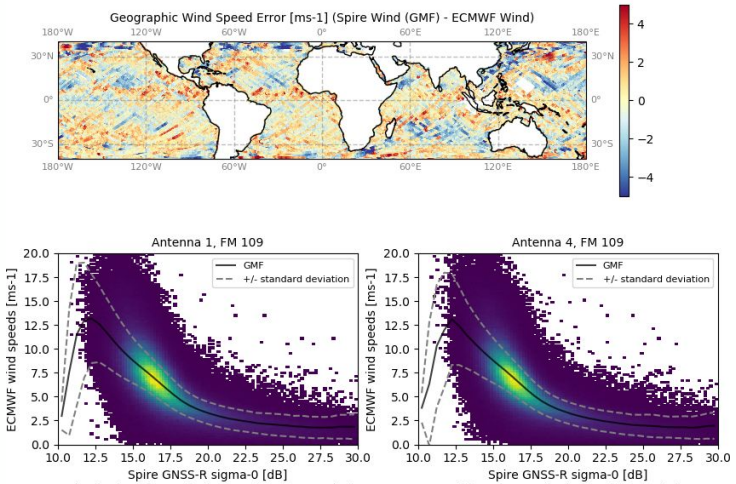
CYGNSS-1 antenna 2 v3.0 (8 days in Oct 2020)



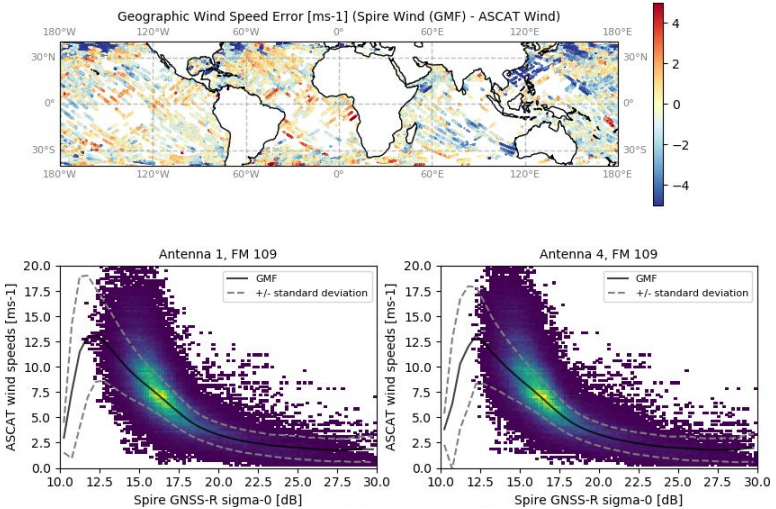
Comparison of Spire GNSS-R, ECMWF and ASCAT

- Inversion to ocean wind and MSS are under development. Here is a preview showing the good sensitivity of Spire nBRCS to ECMWF background wind for 1 Hz observations.
- Showing Dec 2020
  - (Left Panel): Comparison of Spire nBRCS to ECMWF background
  - (Right Panel): Comparison of Spire nBRCS to ASCAT

Spire nBRCS to ECMWF comparison



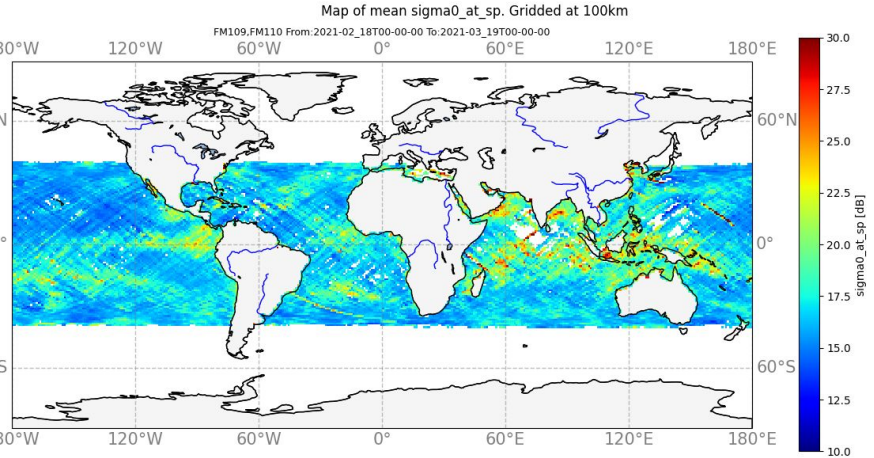
Spire nBRCS to ASCAT comparison



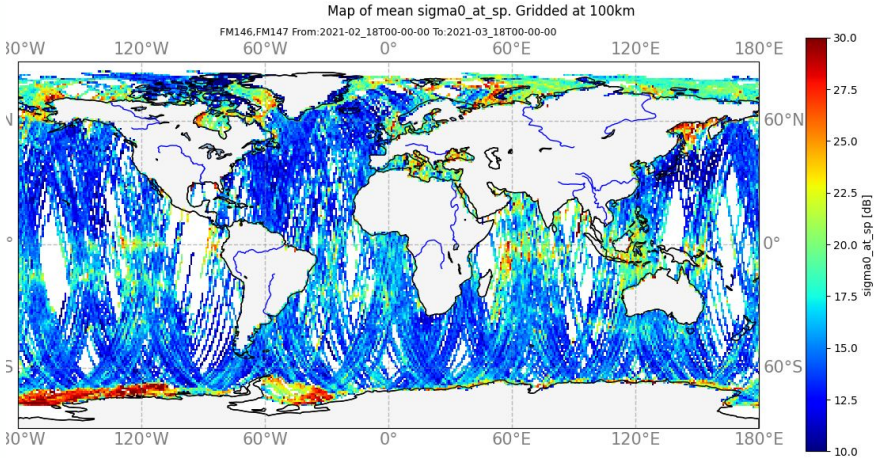
Batch-1 and Batch-2 nBRCS Maps

- The plots below show ocean sigma-0 maps over the ocean for Batch-1 and Batch-2.
  - For the 1 month period: 18 Feb 2020 - 18 March 2021
- Batch-1: utilising GPS, Galileo, QZSS
- Batch-2: utilising GPS only > These are preliminary results during cal/val (without quality control (QC)). Coverage rate will scale x2-3 (add GNSS systems) x2 (duty-cycle).

Batch-1 (FM109, FM110)



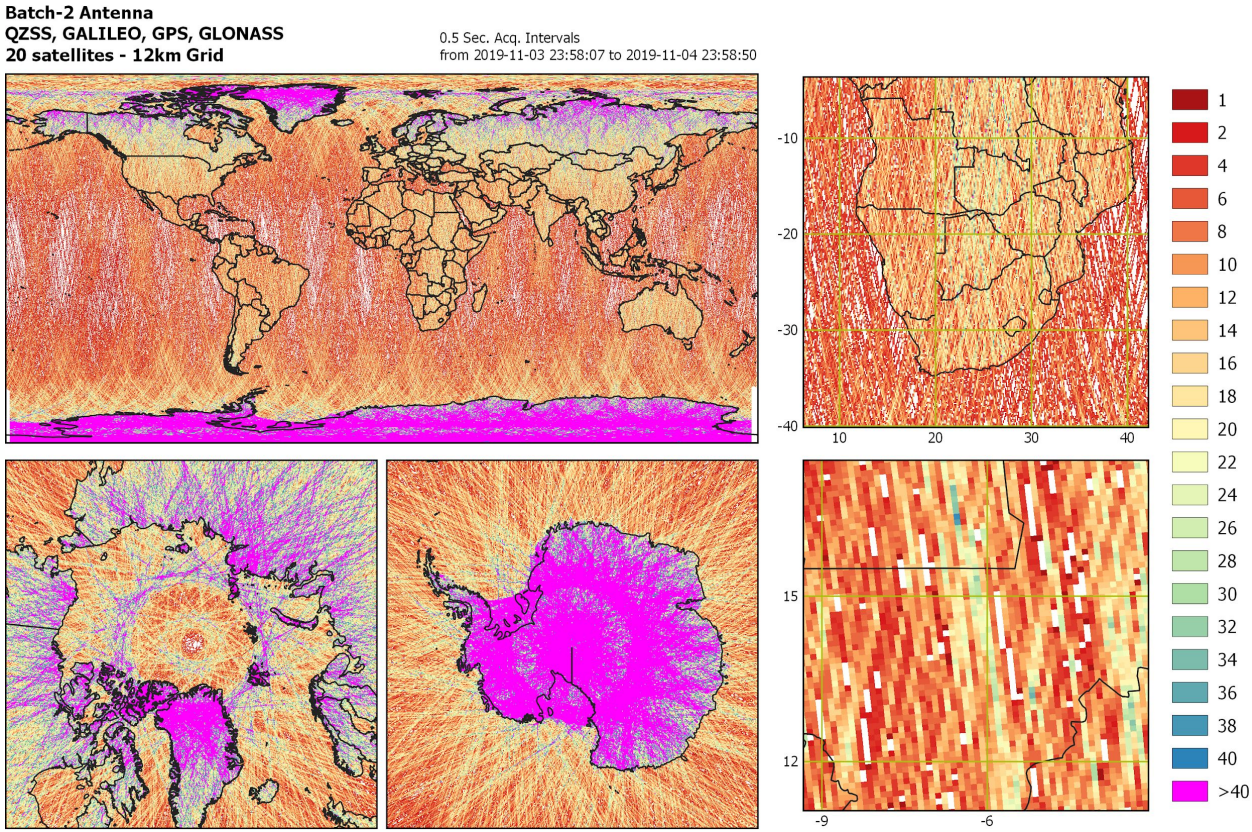
Batch-2 (FM146, FM147) (no QC)



- Batch-1 orbit mid-inclination higher update rate, Batch-2 global coverage

Spire GNSS-R Program Status

- Two GNSS-R Batch-1 satellites in operation producing onboard DDMs **from multiple GNSS**
- **Two new GNSS-R Batch-2 satellites (new receiver and antennas) are in operation with cal/val in progress.**
- **Operational GNSS-R products (e.g., L1 nBRCS, reflectivity, and L2 soil moisture, sea ice, surface water, ocean wind and MSS) operational in 2021**
- Increased temporal and spatial sampling as Spire GNSS-R constellation builds out *(example at right)*



Simulated coverage/revisit for 20 Spire GNSS-R Batch-2 CubeSats (> 10 daily samples per 12 km cell)

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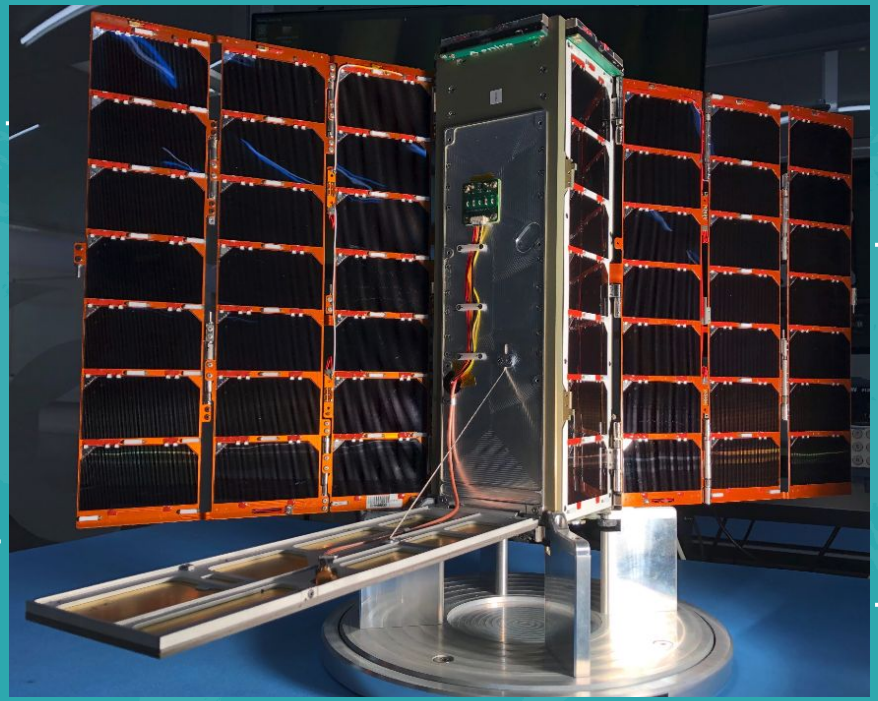
Key Takeaways

1. GLOBAL CONSTELLATION

Spire has built an operational Earth observations constellation (110+ sats). The Spire-RO measurements of the atmosphere are **improving weather forecasting** and **external analyses have proven the positive impact of assimilation of Spire data**. With this platform we are **building a GNSS-R constellation for measuring the surface.**



2. INCREASED SAMPLING & COVERAGE

We cost-effectively harness nanosatellites to collect large quantities of Earth observations to positively impact applications that **benefit from high spatial and temporal sampling and low-latency**

3. GNSS-R QUALITY

Spire GNSS-R data producing **comparable measurements to CYGNSS and TDS** and can exceed operational quantities

4. CONTINUED IMPROVEMENT

Spire aims for continuous scaling, replenishment, and improvement for sustained, long-term Earth observations

Spire data are available to funded researchers through the NASA CSDAP and ESA Earthnet programmes. For more info, contact earth-obs@spire.com.

Thank you!

Philip Jales

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