SPIRE EARTH OBSERVATIONS FOR NASA'S CSDAP

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OUTLINE

- Introduction to the Spire model
- Properties of Spire EO: constellation, satellites, and payloads
- Active Spire EO data products evaluated and available via the CSDAP
    - GNSS radio occultation (RO) atmospheric soundings
    - Grazing angle GNSS-R observations
    - Space weather: total electron content (TEC), electron density profiles, scintillation indices
    - Precise orbit determination for thermospheric density, possible gravity estimation
- Plans for new data types to be considered for the CSDAP
    - Grazing angle GNSS-R sea ice extent, sea ice type
    - GNSS-R scatterometry (CYGNSS-like): soil moisture, ocean wind/waves, sea ice
    - Enhanced space weather observations
    - Evaluation by NASA of future Spire data for the CSDAP
- End User License Agreement (EULA) for Spire CSDAP data
- NASA CSDAP program comments

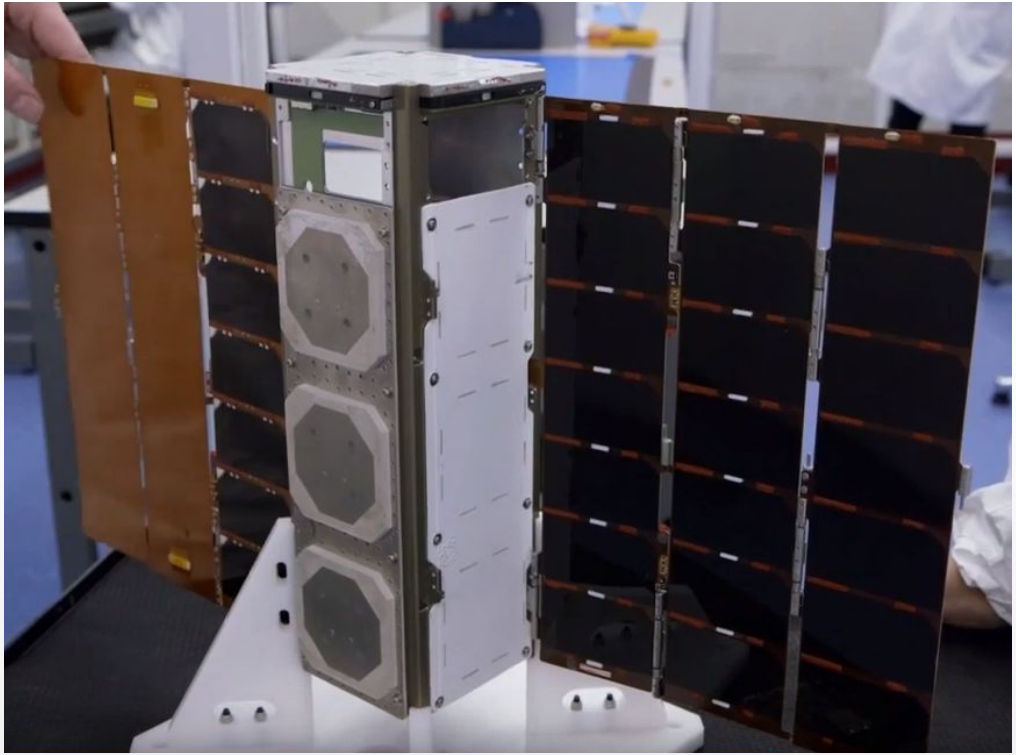
WHO & WHAT IS SPIRE?

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...

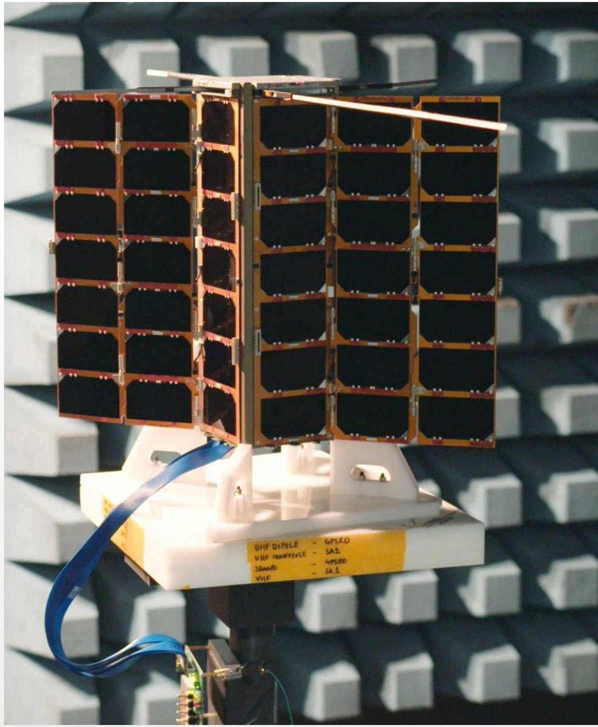
*We're the transformation of a single, crowd-sourced nanosatellite into the **third largest constellation of satellites** in the world.*

We are collecting impactful Earth observations that could impact science and society… TODAY.



SPIRE STATS

- Established company with ~200 people (and growing) across six offices
- Full nanosatellite manufacturing facilities and supply chain
- 85+ operational LEO 3U CubeSats (10x10x30 cm) in orbit
- 20+ launch campaigns with seven different launch providers
- 30+ globally distributed ground stations we own and operate
- Complete global EO coverage in multiple orbit inclinations
- **World's largest GNSS-based constellation for Earth science and weather forecasting**
- World's largest ship tracking constellation
- ADS-B aircraft tracking product
- Various EO research and weather forecast products
- **$200M** raised with top institutional investors



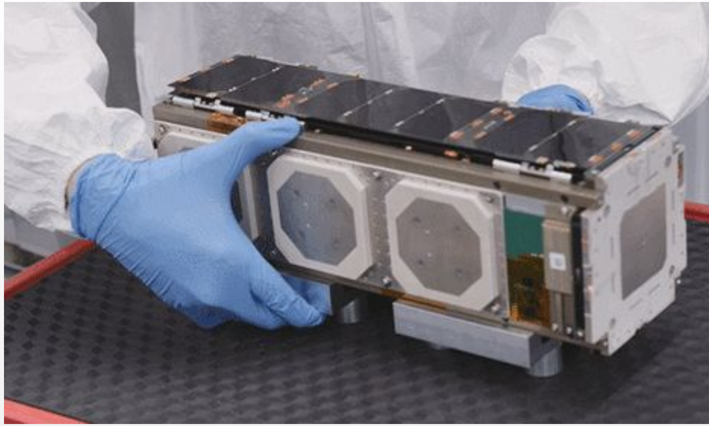
WHAT MAKES SPIRE UNIQUE?

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 commercial RO, first and only operational Galileo and QZSS RO**, phase-delay altimetry, GNSS-R, thermospheric density)

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)

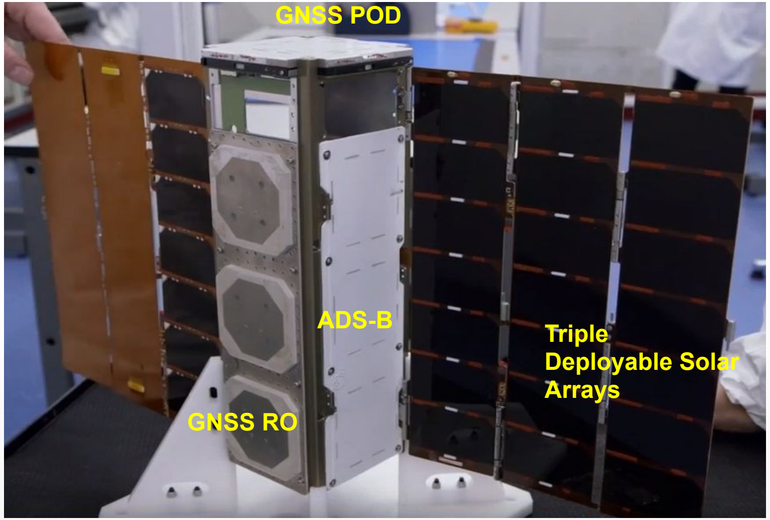


Fast Iteration and Upgrades

New hardware: 6-12 months from idea to launch; currently **launching satellites on average every six weeks**

SPIRE CUBESAT TECHNOLOGY

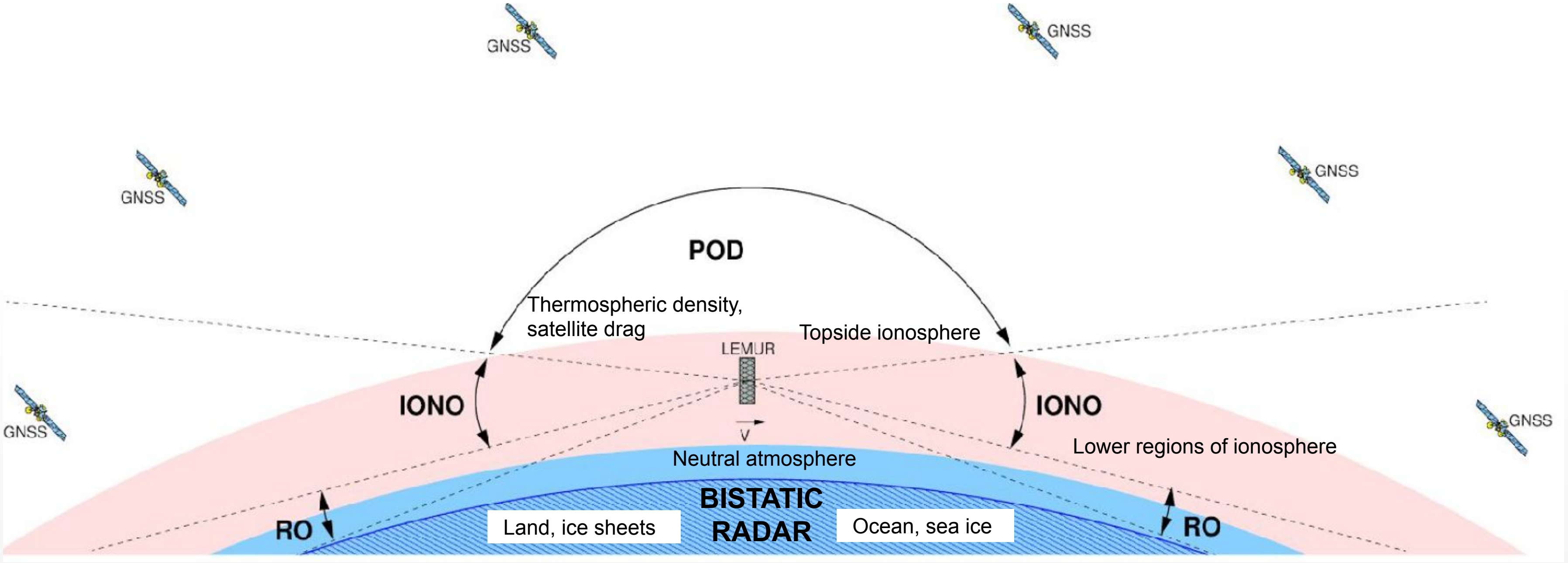
Parameter	Value	
Design Lifetime	2+ years	
Volume	10 x 10 x 30 cm (3U)	
Total Mass	4.7 +/- 0.1 kg	
ADCS	3-axis stabilized (sun sensor, magnetometer, Earth-horizon sensor, 3 reaction wheels, magnetorquers)	
Power	Triple-deploy solar arrays with batteries	
Transmitters	UHF	
	S-band, (X-band soon)	
Receivers	UHF, (S-band soon)	
Payloads	AIS	Ship tracking
	GNSS	**RO, TEC, POD, Scintillation, GNSS-R**
	ADS-B	Aircraft tracking



Spire's constellation is designed for **continuous scaling, replenishment, and improvement**

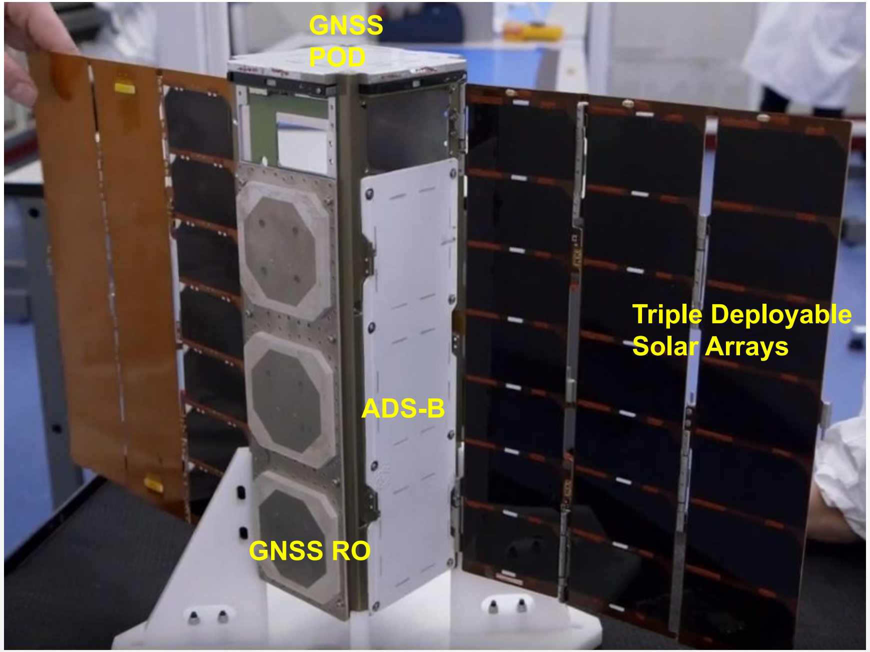
Long-term, sustainable Earth obs

CURRENT GNSS EARTH OBSERVATIONS



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

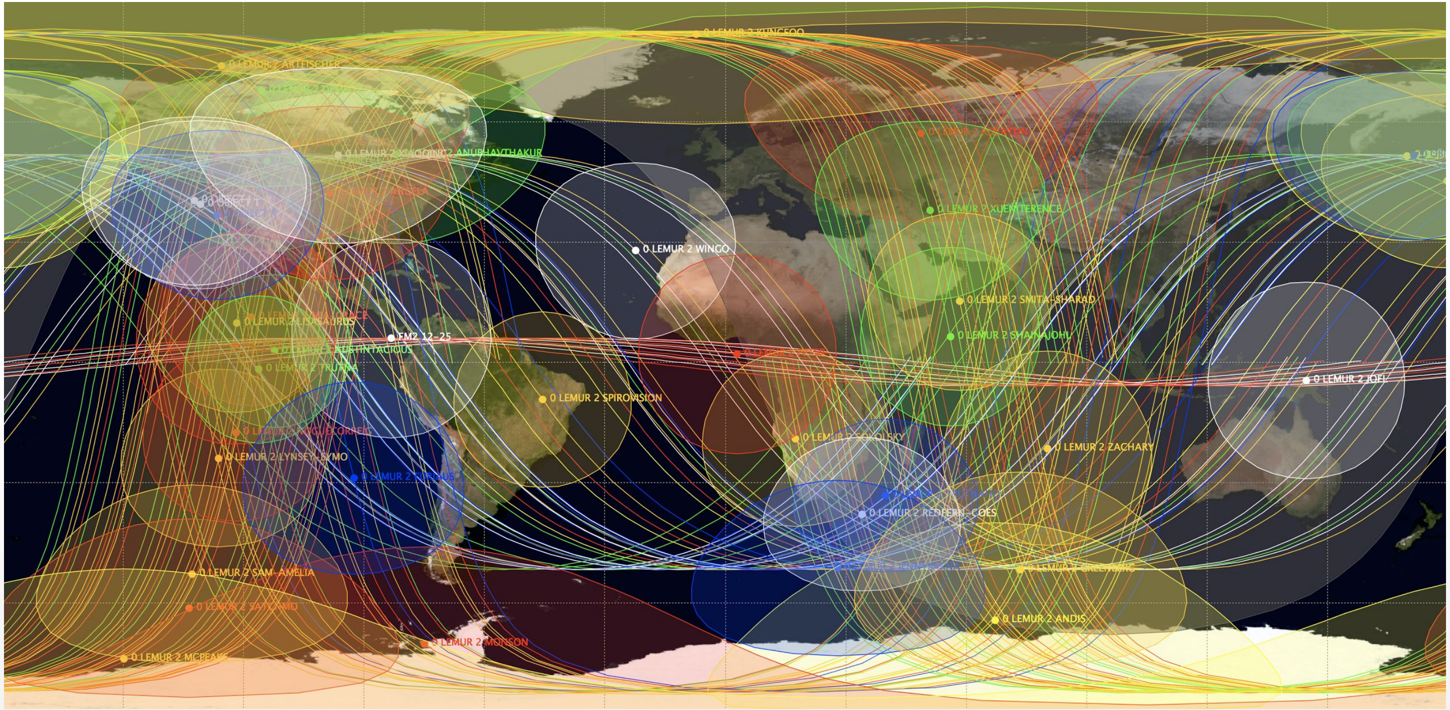
SPIRE GNSS SCIENCE RECEIVER



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

- FPGA-based acceleration of signal processing
- Performs POD using zenith L1, L2 antenna (orbits ~10-15 cm RMS)
- Performs radio occultation (RO) on high-gain, forward (rising) and backward (setting) antennas
- Collects **GPS, GLONASS, QZSS, Galileo, SBAS signals**
- Enables GNSS applications: atmospheric sounding, space weather monitoring, GNSS-R, and possibly thermospheric density, gravity
- **All processing done in-house using state-of-the-art algorithms on resilient, rapidly-scalable, cloud-based system**

SPIRE CONSTELLATION & ORBITS



- Currently 80+ sats in 400-650 km orbits; **plans for 100+ operational EO sats**
- Varied orbits for dense global and temporal sampling with low data latency (10s minutes)
- Sun synchronous (SSO) with varying local times, 85 deg, 51.6 deg (ISS), 37 deg, low inclination orbits

SPIRE DATA EVALUATED IN 2019 PILOT

- Spire participated in the NASA Commercial Smallsat Data Acquisition Pilot (CSDAP Pilot)
  - Spire constellation data from 2018 and 2019 were made available to expert researchers selected by NASA to evaluate and "to help determine their utility for advancing NASA's science and applications development goals"
  - Evaluations are available:
    - The Use of Spire Radio Occultation Measurements in the GEOS Atmospheric Data Assimilation System. Will McCarty, Global Modeling and Assimilation Office/Goddard.
    - Data Processing and Scientific Evaluation of Spire GNSS RO Data for the NASA Commercial Data Buy Program. Bill Schreiner, UCAR COSMIC Program.
    - Phase-Delay Altimetry from Reflected GNSS Signals for Resolving Mesoscale Ocean Circulation Features. R. Steven Nerem, University of Colorado.
    - Spire POD/Neutral Density Assessment. Eric Sutton, Space Weather Technology, Research, and Education Center/Univ. of Colorado.
- **All data products evaluated deemed appropriate for inclusion in CSDAP, and data evaluated in pilot are part of CSDAP holdings**

SPIRE DATA AVAILABLE IN THE CSDAP

- NASA procured access to data types evaluated during the pilot for the dates starting from **2019/11/01 to 2021/04/30 (18 months)**
- Data are made available with a 30-day delay (i.e., delivered 30 days after collection)
- Historical data delivery in late July after provenance info added to manifests
- Current Spire products available in the CSDAP include:

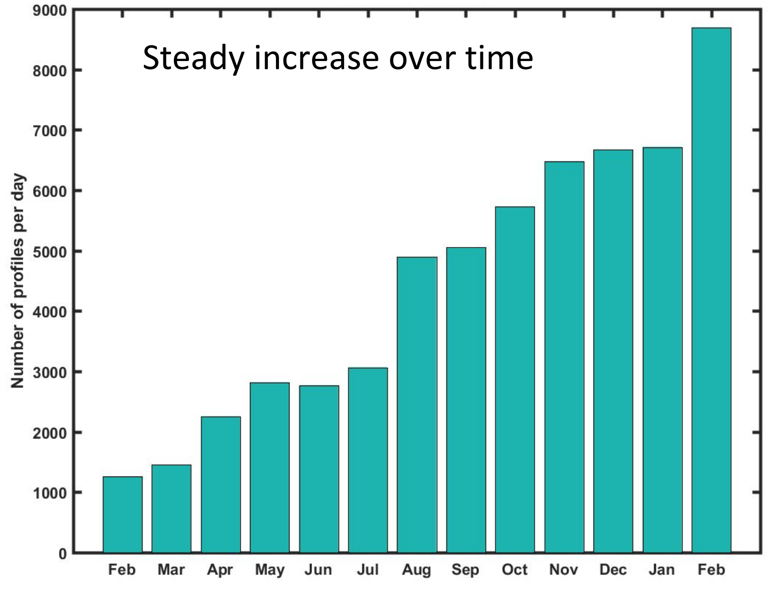
Data Type	Date Range
GNSS Radio Occultation	9/24/2018 - 12/9/2018; 12/14/2018 - 3/8/2019; 11/1/2019 - onward
Grazing Angle GNSS-R	1/09/2019 - 4/18/2019; 11/1/2019 - onward
Raw IF GNSS-R (A limited number of low-level, raw intermediate frequency (IF) data collected by both RO satellites (for grazing angle reflections) and GNSS-R satellites are also available.)	2020 (various captures)
Satellite Precise Orbit Determination	9/24/2018 - 4/18/2019; 11/1/2019 - onward
Space Weather (TEC, EDP, scintillation)	11/1/2019 - onward
Magnetometer (simple sensor data)	11/1/2019 - onward

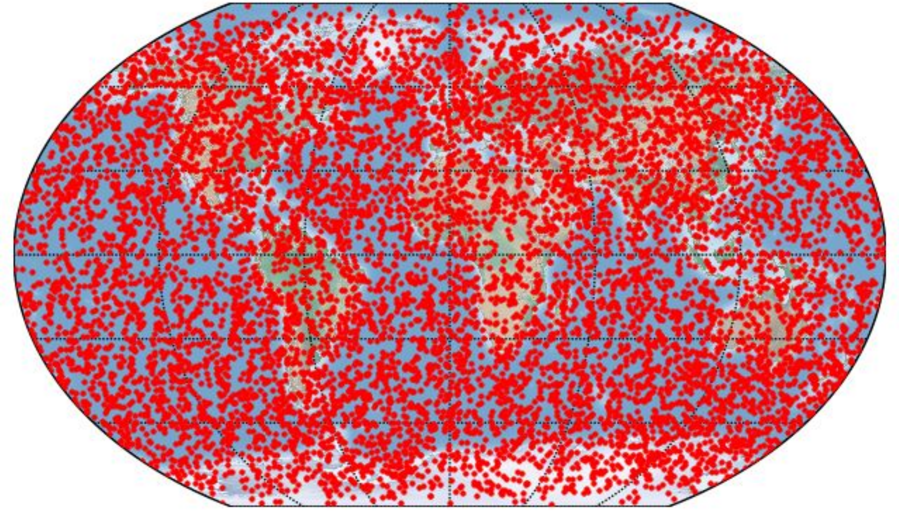
RADIO OCCULTATION DATA

SPIRE GNSS-RO DATA IN THE CSDAP

- Spire GNSS-RO products are collected operationally for NWP customers
- The product types follow COSMIC conventions (CDAAC) and include:
  - Low-level 50 Hz data (opnGns format)
  - Excess phase (atmPhs nc4 format)
  - Atmospheric profile (atmPrf nc4 and bfrPrf BUFR formats)
  - Navigation data (leoOrb precise orbits in SP3 format, RINEX data)
  - Attitude data (leoAtt in CHAMP format)
  - Ancillary information (e.g., antenna phase center)
- The provenance information to identify all data going into processing a GNSS-RO event is included in the files and the manifest
- GNSS transmitter precise orbits/clocks and navbits are not included but available from other sources

GROWING DATA VOLUME & COVERAGE





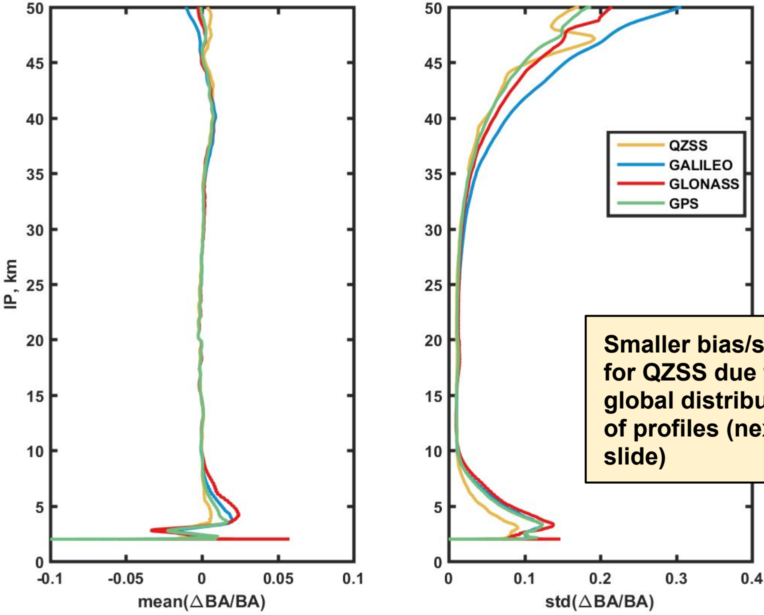
Feb 15, 2020: ~10K profiles per day

RO production advancement:

- Quantity increase through launches and additional GNSS constellations tracked
- Receiver performance improvements
- Satellite bus performance improvements
- **Continual data latency reduction**

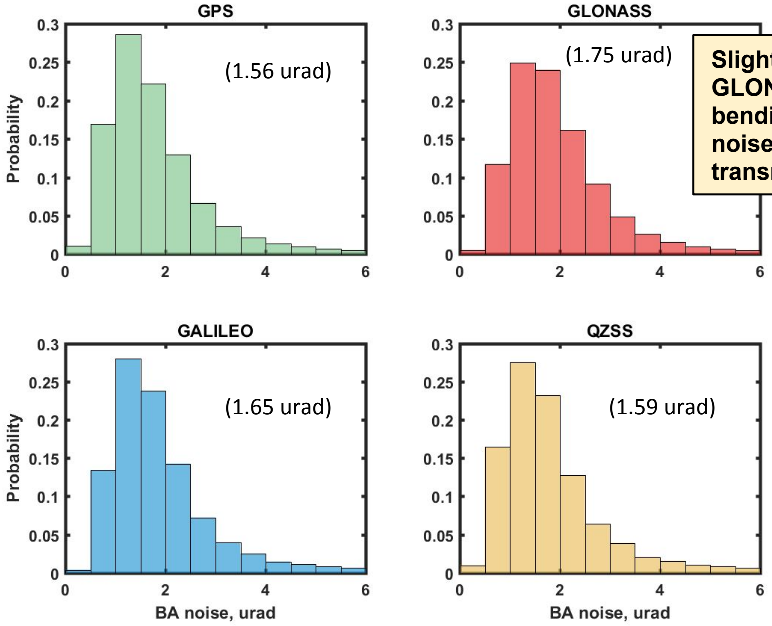
WORLD'S ONLY GPS, GLO, GAL, QZSS RO

Bending angle bias & STD vs. ECMWF



Smaller bias/std for QZSS due to global distribution of profiles (next slide)

Distribution of the bending angle noise (median)

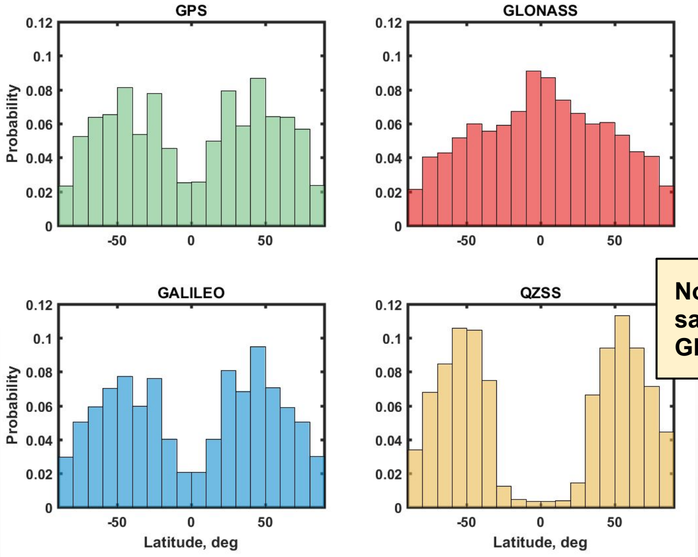


Slightly higher GLONASS bending angle noise due to transmitter clock

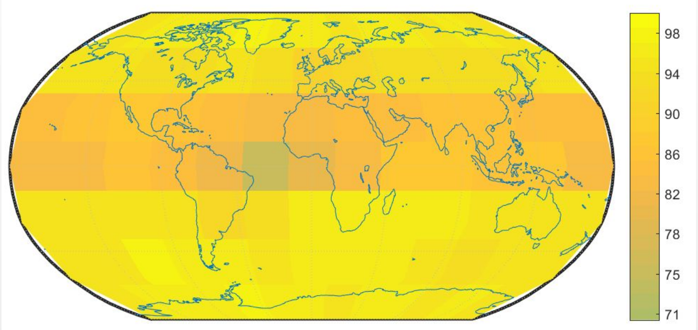
- First commercial provider of four constellations and the only provider of Galileo and QZSS data
- Galileo-based RO (faster chipping rate) is fully functional after open-loop tracking improvements
- **Spire RO difference statistics vs. ECMWF match current operational RO missions**
- **BA noise meets COSMIC-2 and Metop requirements (2 urad) for all GNSS constellations**

GLOBAL DISTRIBUTION OF RO PROFILES

- Multiple GNSS constellations provide uniform **global RO coverage**
- Latitude distributions differ for different GNSS constellations due to combinations of GNSS and LEO orbits
- Smaller fraction of QZSS occultations in tropics explains better bias and STD statistics
- **Comparison between constellations or with other RO sensors must account for geographic sampling differences**



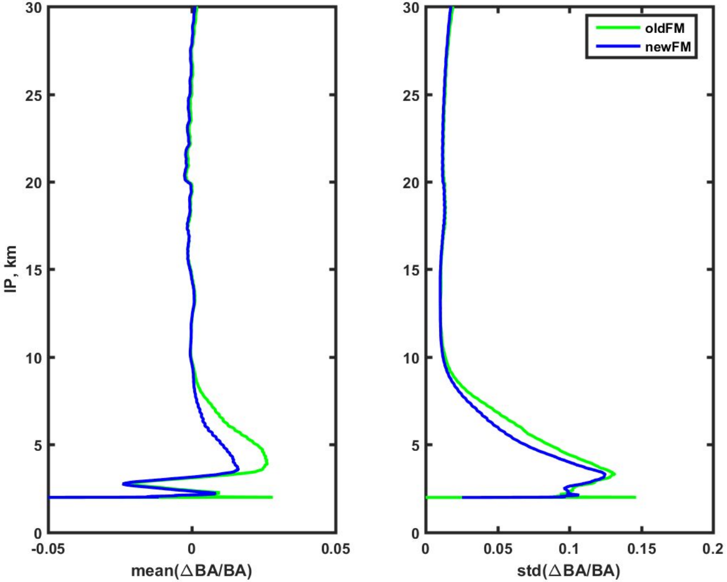
Note: geographic sampling bias by GNSS constellation



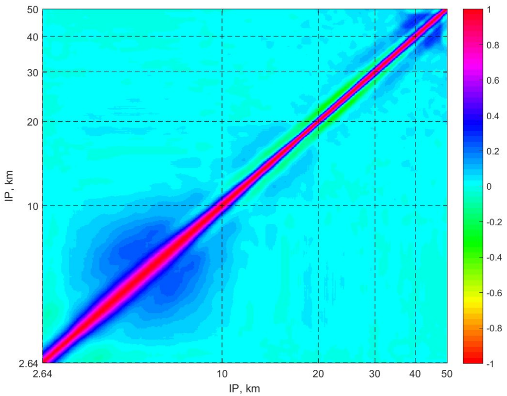
High percentage of Spire data pass QC (exceeds COSMIC-2 req of 73%)

CONTINUOUS RO IMPROVEMENT

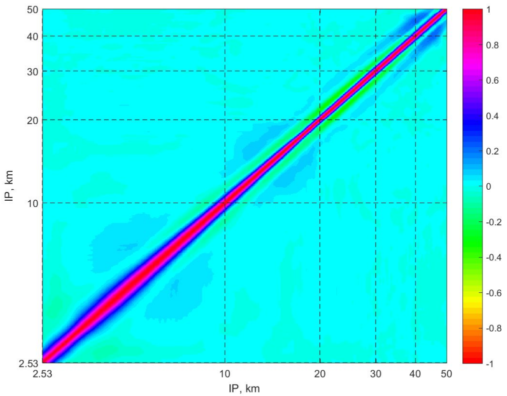
RO improvement on newer satellites



Improved vertical correlation statistics



Older Satellites



Newer Satellites

- **Spire has the unique ability to improve EO quality/quantity due to rapid launch cycle**
- Example: improved receiver performance on newer satellites shows better statistics (left) and lower vertical correlations in troposphere (right)
- Rapid improvement is also a new paradigm for users: ***How shall we collaborate so users benefit from rapid improvements*** *(e.g., retuning NWP DA when obs improve)?*

SPIRE DATA ASSESSMENTS

External assessments show similar results: **latest Spire RO data are comparable quality to operational RO missions and exceed operational quantities, resulting in high NWP impact**

- **UKMO forecast impact study deemed Spire RO is comparable to MetOp-C**
- NASA pilot study also found Spire RO comparable to operational missions
- NOAA study concluded Spire RO data ready for purchase

*"Removing data from Metop-C and at the same time including an equivalent number of observations from Spire leaves the system approximately unchanged. **Therefore we conclude that the two data sources are of similar quality.**"* - UK Met Office study

*"[RO observations] were also found to be effective in retrieving the height of the planetary boundary layer, as **their penetration depths were assessed as being particularly good**. In fact, they were determined to exceed those of heritage RO observing systems (e.g., COSMIC-1) and as **comparable to those of modern RO science missions (e.g., COSMIC-2)**."* -- NASA CSDAP study

GRAZING ANGLE GNSS-R DATA

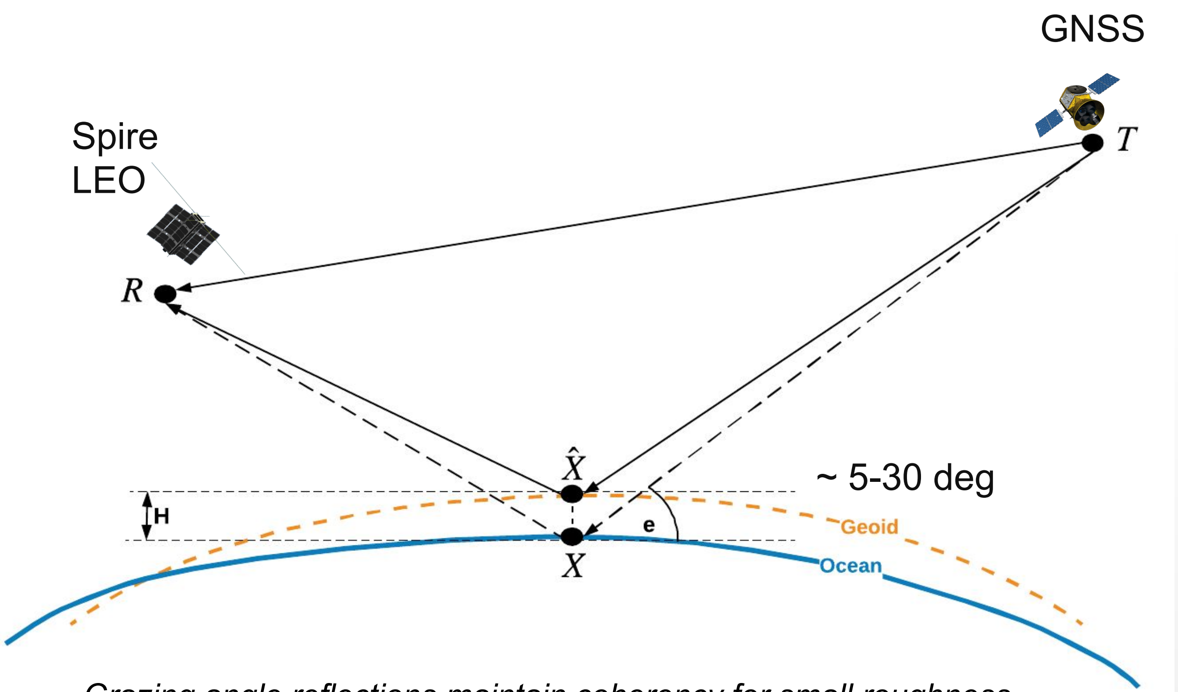
GNSS-R GRAZING ANGLE ALTIMETRY

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 cm-level heights of smooth surfaces

Common terms in combination of direct/reflected path lengths cancel

Dual-frequency allows iono delay estimation

Spire radio occultation satellites can observe RHCP grazing angle reflections during RO production, adding a valuable new measurement of sea/sea ice surface heights



Grazing angle reflections maintain coherency for small roughness

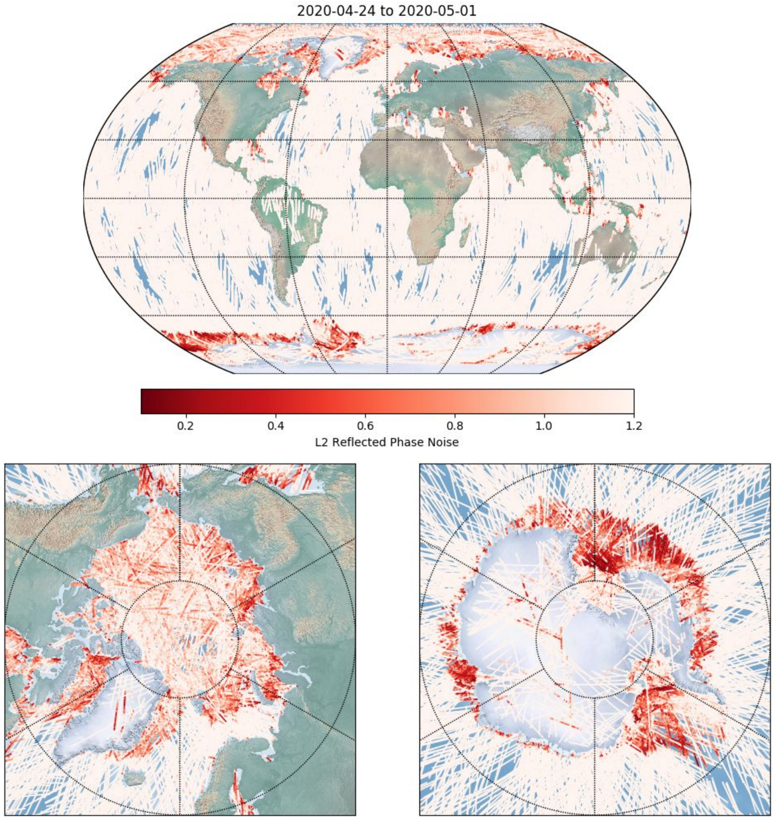
Funding for development: NOAA OPPA Technology Maturation Program

SPIRE GRAZING ANGLE GNSS-R DATA IN THE CSDAP

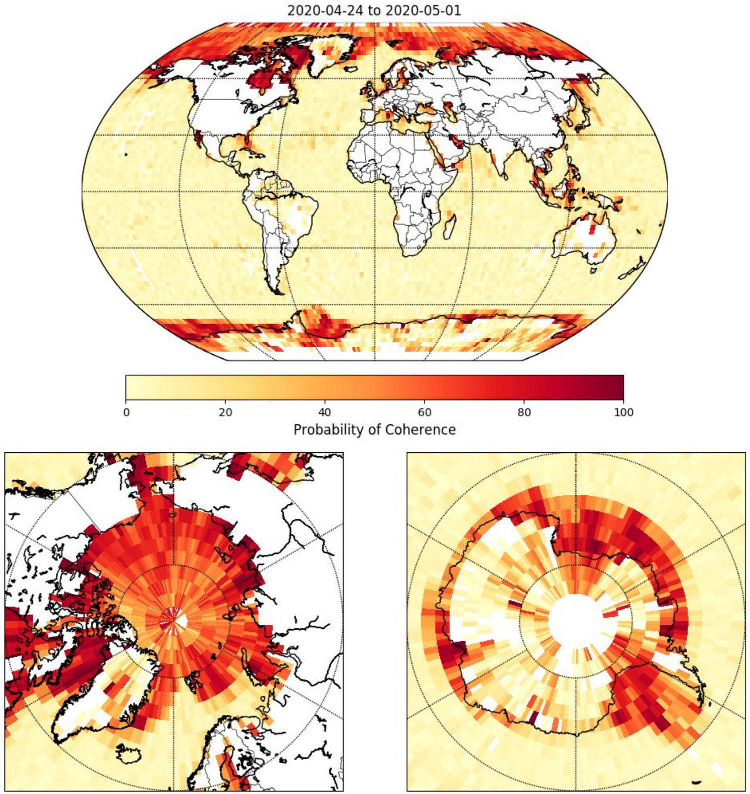
- **Spire grazing angle GNSS-R products are collected operationally by RO satellites**
- The product types are Spire-defined and include:
    - Low-level 50 Hz data open-loop tracked I/Q data (direct and reflected signal in RO antenna (L1A base data in nc4 format)
    - Georeferenced reflection (L1B data nc4 format)
    - Navigation data (leoOrb precise orbits in SP3 format, RINEX data)
- GNSS transmitter precise orbits/clocks and navbits are not included but available from other sources

LEVEL 1 MEASUREMENT COVERAGE

Total Measurement Coverage over 1 Week



Coherence Probability Map over 1 Week



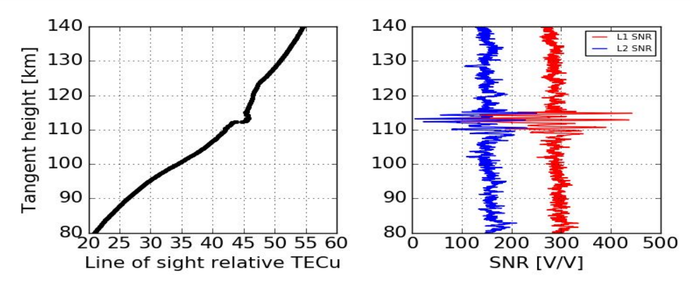
SPACE WEATHER DATA

SPIRE SPWX DATA IN THE CSDAP

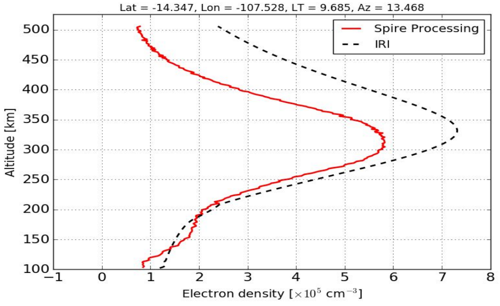
- Spire GNSS SpWx products are collected operationally by all sats
- The product types follow COSMIC conventions (CDAAC) and include:
  - Slant TEC (podTEC, RINEX)
  - Ionospheric density profile (ionPrf)
  - Navigation data (leoOrb precise orbits in SP3 format, RINEX data)
- The provenance information to identify all data going into processing a SpWx event is included in the files and the manifest
- GNSS transmitter precise orbits/clocks and navbits are not included but available from other sources

SPIRE SPACE WEATHER PRODUCTS

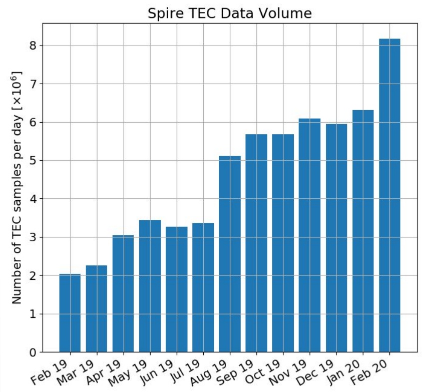
- Ionospheric information derived from delay of dual-frequency signals
  - Line-of-sight total electron content (TEC)
  - Electron density profiles
  - Scintillation detection
- Assimilation into upper atmospheric models for improved space weather forecasting predictions

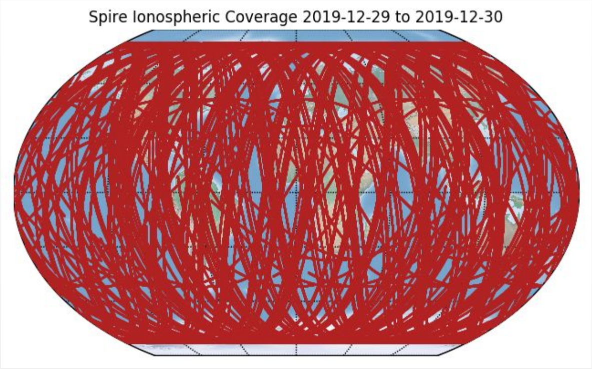


Example of E-region ionospheric scintillation event as observed in Spire TEC measurements and SNR perturbations



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

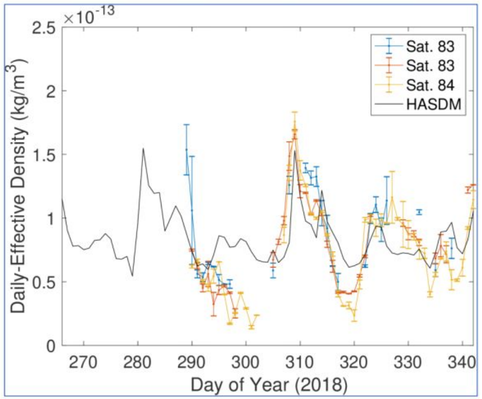




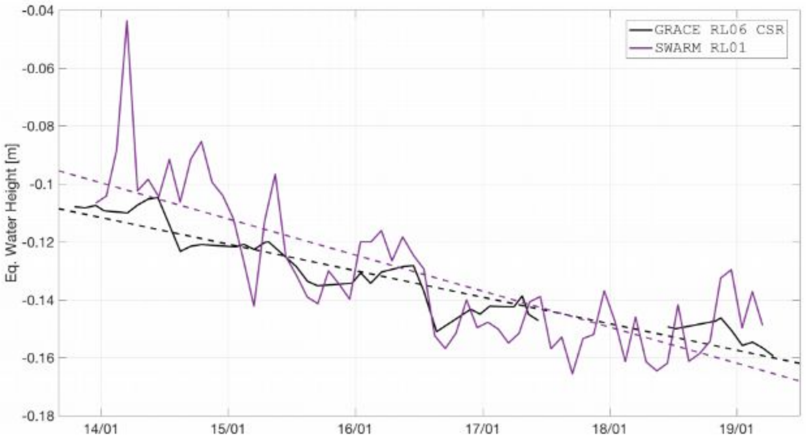
PRECISE ORBIT DATA

SPIRE POD DATA IN THE CSDAP

- Spire GNSS precise orbit products are collected operationally by all sats
- The product types follow COSMIC conventions (CDAAC) and include:
  - Navigation data (leoOrb precise orbits in SP3 format, RINEX data)
- Possible applications:
  - These data have been successfully used to estimate thermospheric density through satellite drag (left plot, E. Sutton, CSDAP report)
  - Mass change trend signals and annual signals for different recovered by GPS receivers in LEO using POD techniques (right, da Encarnação et al, 2019)



The daily-effective density retrieved from the satellite POD for three different satellites as compared to the USAF HASDM model.



FUTURE DATA EVALUATION AND AVAILABILITY VIA CSDAP

POSSIBLE FUTURE CSDAP PRODUCTS

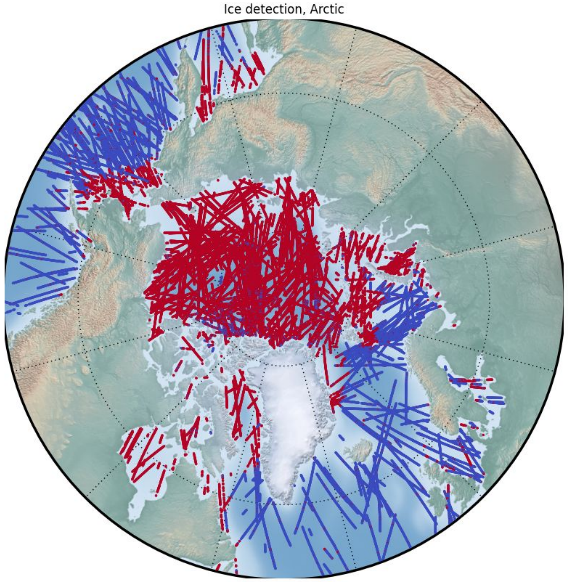
- Spire is developing new EO products that will be evaluated by NASA for possible inclusion into the CSDAP
- The new products include:
  - **Grazing angle GNSS-R sea ice extent, sea ice type**
  - **GNSS-R scatterometry (CYGNSS-like): soil moisture, ocean wind/waves, sea ice**
  - Enhanced space weather observations
- Time frame is dependent on development and NASA evaluation of data

FUTURE GRAZING ANGLE GNSS-R SEA ICE PRODUCTS

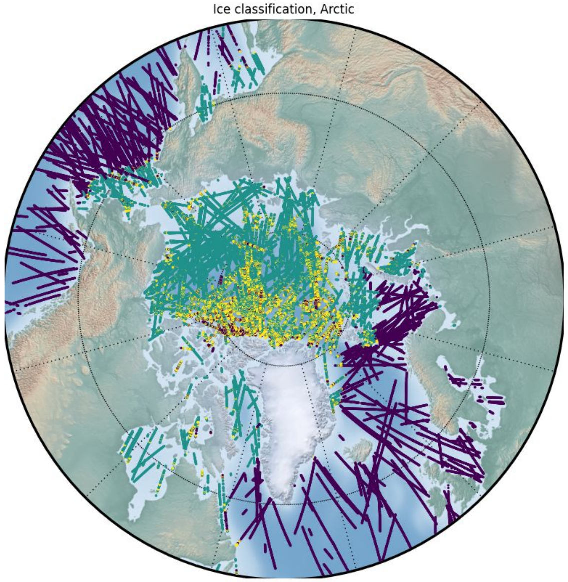
SEA ICE CLASSIFICATION

- High resolution and measurement coverage of Spire grazing angle measurements can be valuable products in the near-future
- A two week testing period showed that **95%** of OSI SAF ice/water classification and **75%** of first year/multi year ice classification is correctly predicted by Spire data

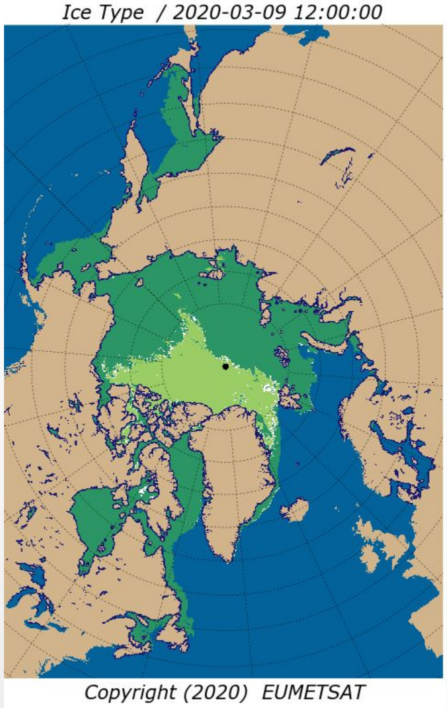
Spire Water/Ice Detection (03/02 to 03/15)



Spire Ice Type Detection (03/02 to 03/15)



OSI SAF Ice Type Classification

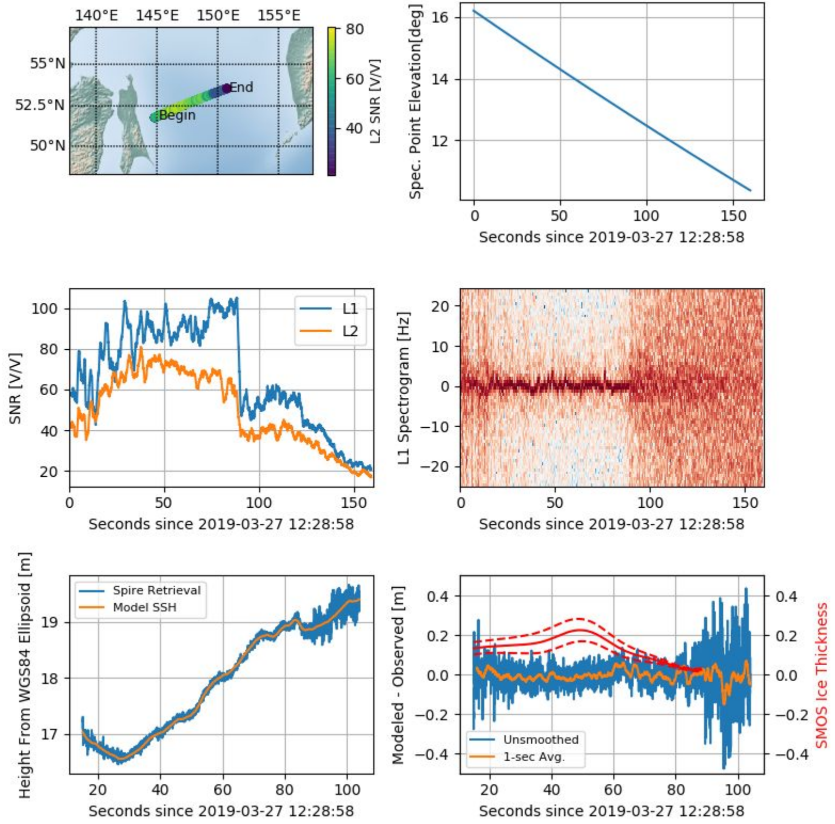


SEA ICE ALTIMETRY

Initial results indicate strong coherent events over sea ice

Reflection event over Sea of Okhotsk

- L1 & L2 SNR correlated and show transition from sea ice to open ocean around 80 seconds
- Estimated reflector height again follows expected mean sea surface (DTU18) with tides (TPX09-atlas) removed
- Residual shows little gradient along the track (**< 3 cm RMSE**)
- SMOS thickness estimate is larger in center of track
- Reflection is likely occurring off the top of the ice



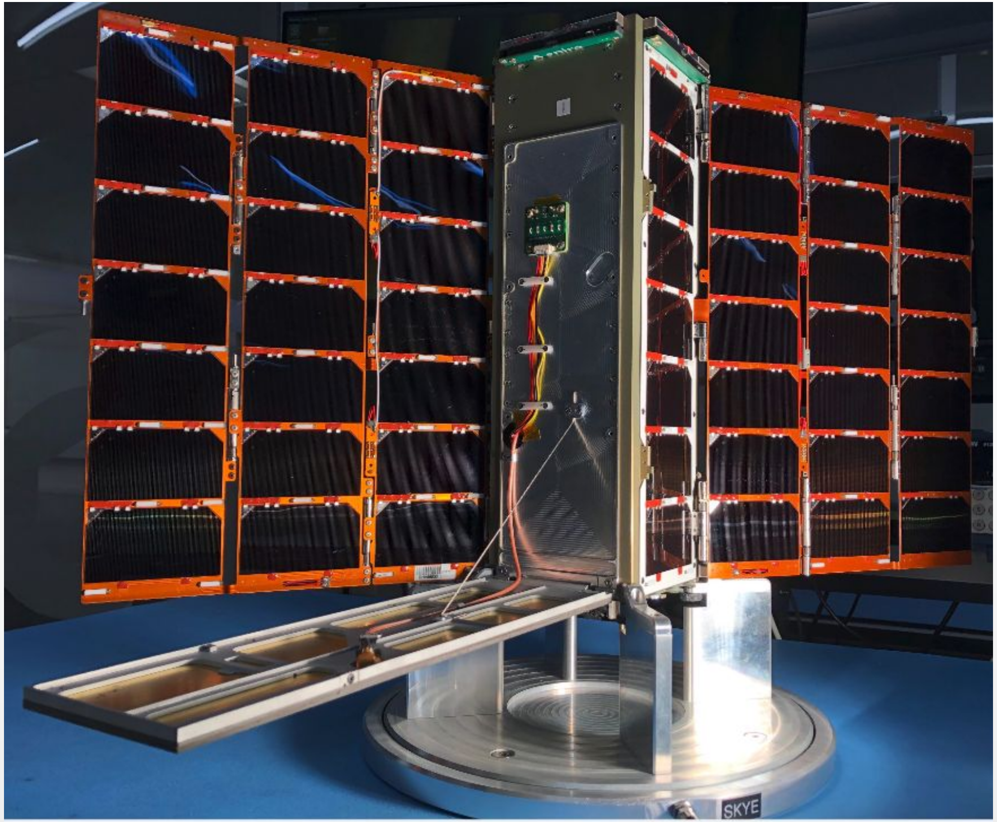
FUTURE GNSS-R SCATTEROMETRY DATA

SPIRE GNSS-R BATCH-1 MISSION

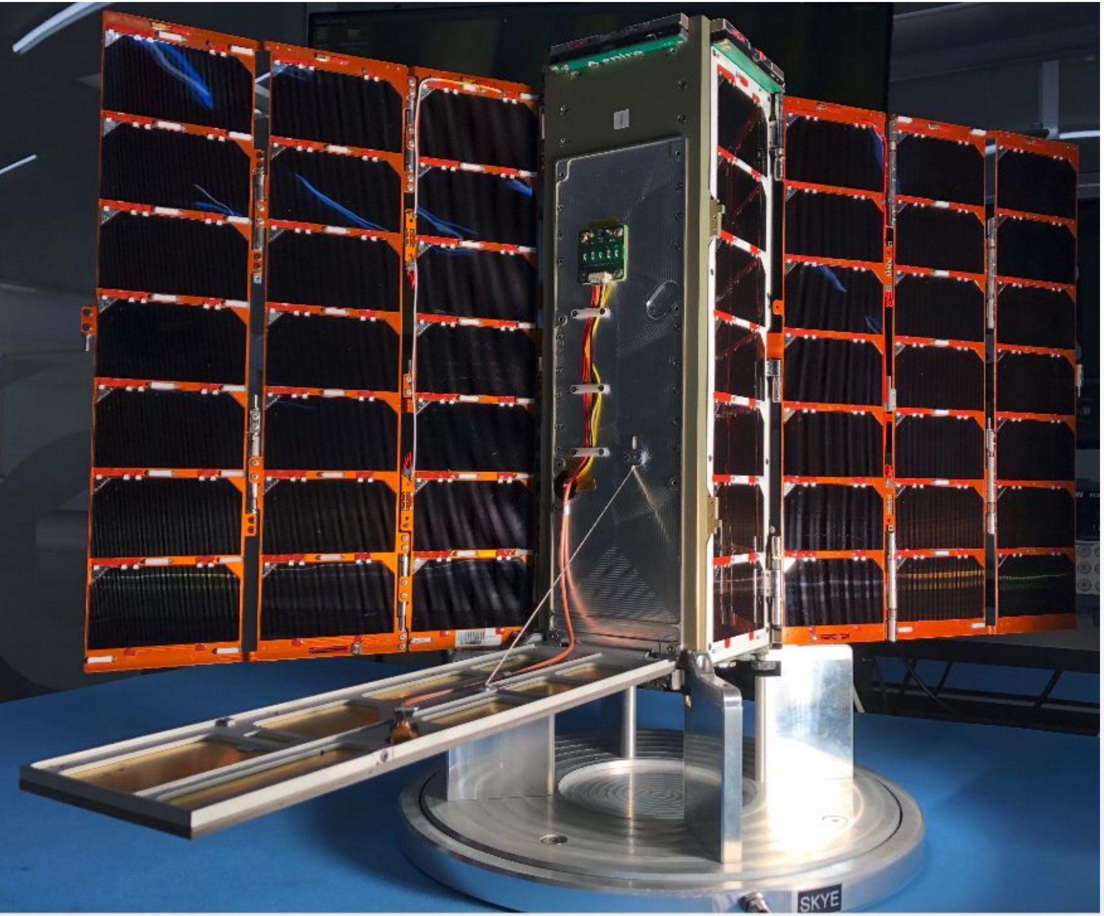
Spire GNSS-R "Batch-1" satellite design

- Co-funded by ESA Pioneer and UKSA
- Two identical "prototype" satellites
- Derivative of successful Spire RO 3U bus
- Modified subsystems:
    - STRATOS GNSS receiver relative calibration system
    - RO antennas replaced by deployable reflection antennas
- Direct signal collected using zenith POD antenna
- Two identical, deployable L1, single polarization reflection antennas both oriented nadir to **realize more effective gain via beamforming**
- Low-level GNSS-R products: raw IF, onboard DM and DDM generation, phase observable, multiple beams

Spire GNSS-R Batch-1 satellite

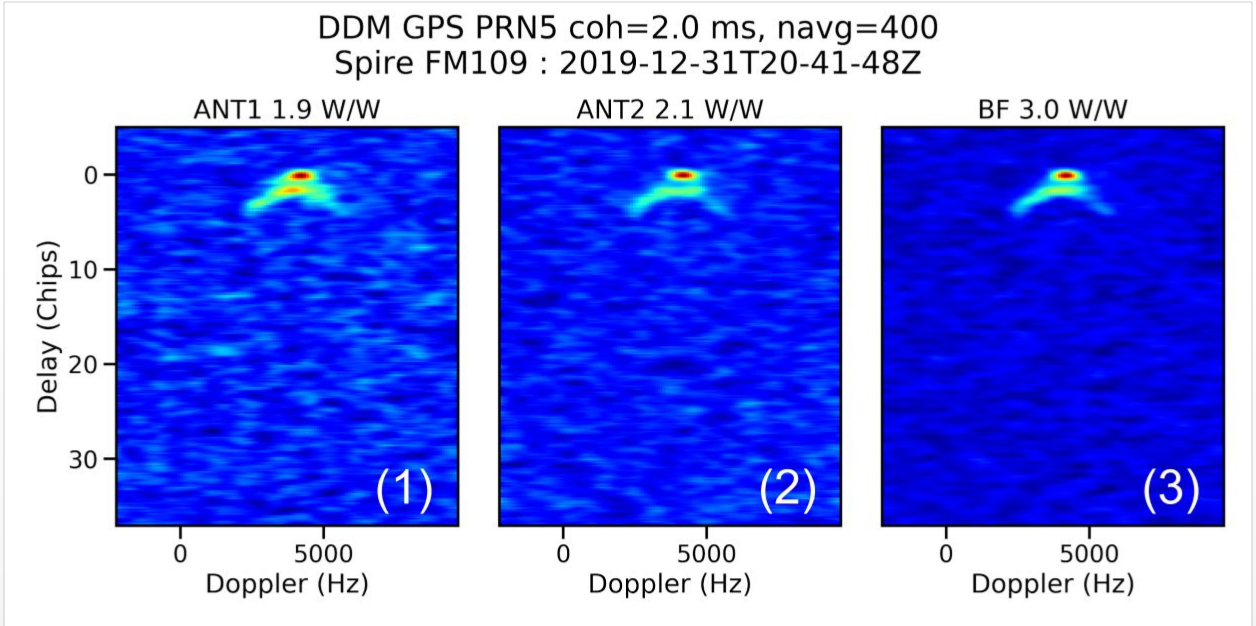


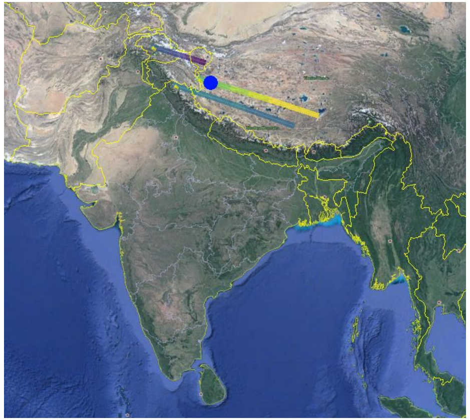
BUILDING ON THE CYGNSS PATHFINDER

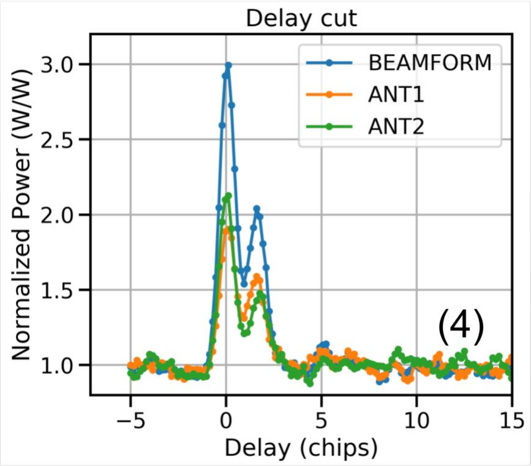


Parameter	CYGNSS	Spire GNSS-R Batch-1
Simultaneous reflections observed	4	**30**
GNSS constellations tracked	GPS	**GPS, QZSS, Galileo, SBAS,** possibly GLONASS
Calibration	Blackbody loads	**Direct/reflected relative channel monitoring**
Direct antenna	L1 single patch	L1/L2 single patch
Reflection antenna	2, 3x2 L1 LHCP array (off-nadir)	2, 3x1 L1 LHCP array (nadir), **beamforming**
Mass	25 kg	5 kg
Orbit	35 deg, 510km	37 deg, 571 km
Expected lifetime	2 yr	2 yr

GNSS-R BATCH-1 FIRST DATA: LAND

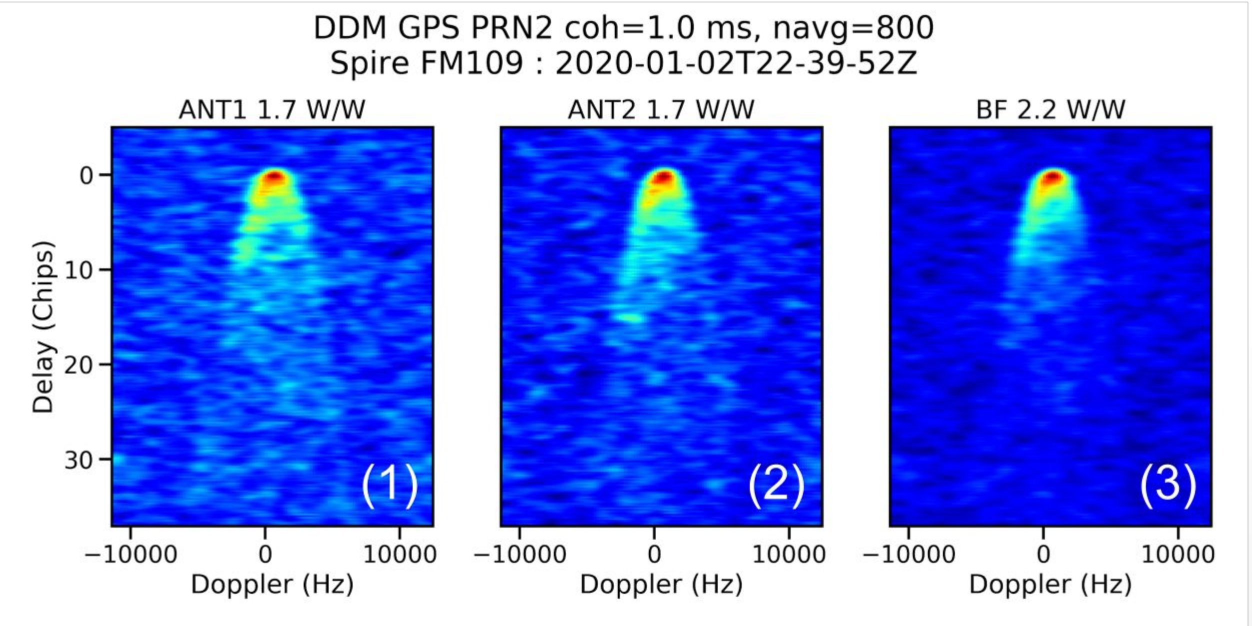


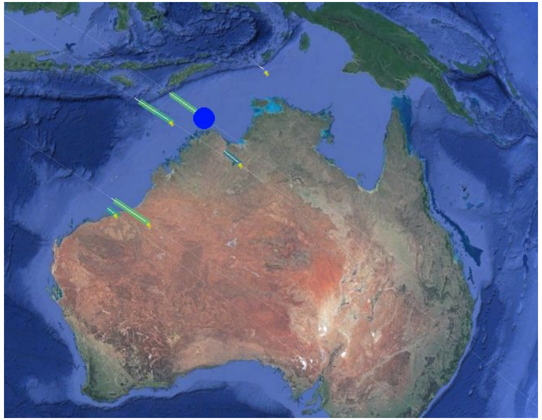


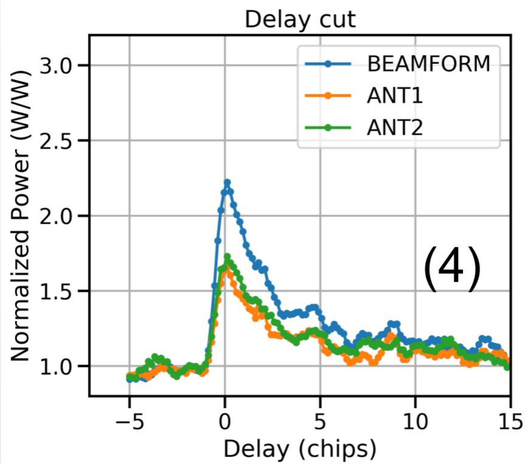


First light land DDM collected while over the Tibetan plateau. Panel (1) and (2) show DDM from each nadir-pointing antenna, while (3) shows the observation after digital beamforming. Panel (4) is a delay-cut through the peak waveform. Panel (5) Map showing the location of the collection with the blue dot indicating the specular point at the displayed time.

GNSS-R BATCH-1 FIRST DATA: OCEAN







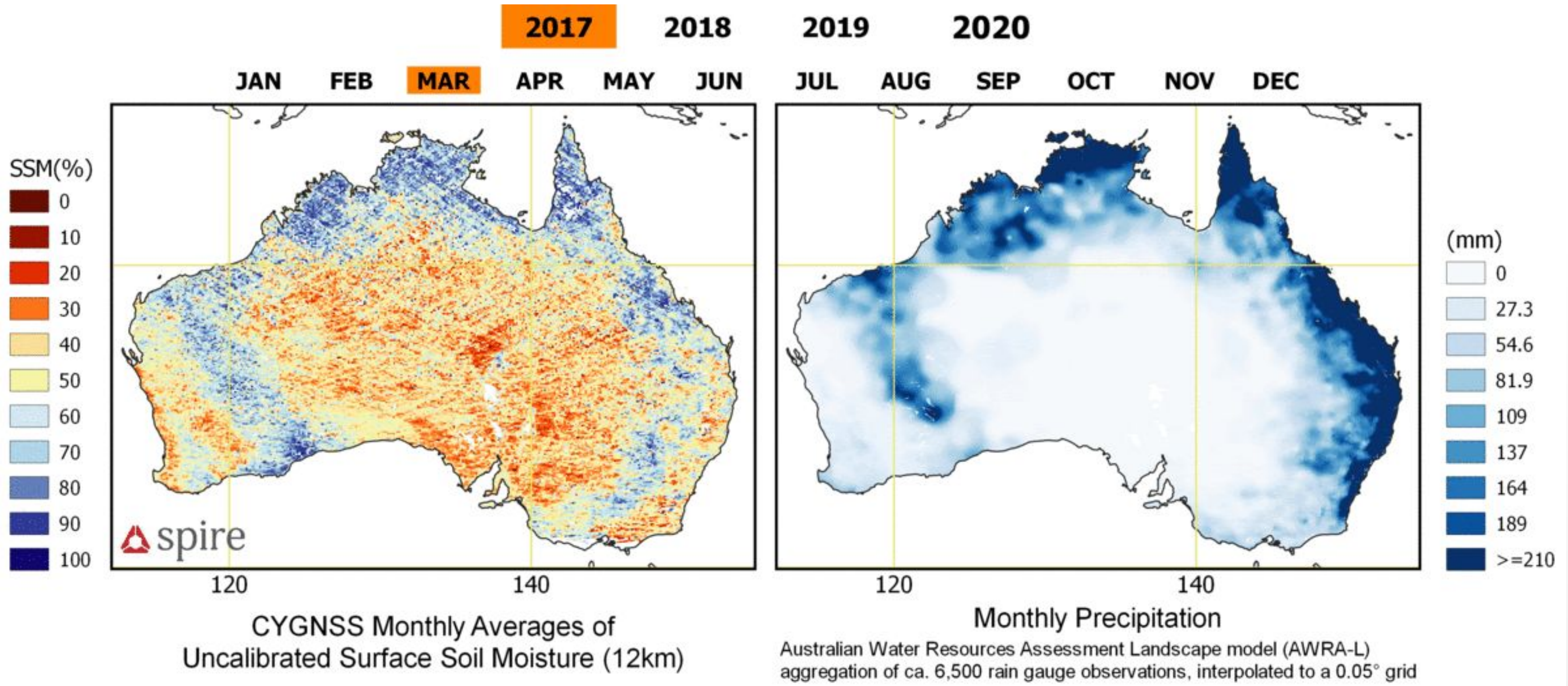
First light ocean DDM collected while over the Timor Sea. Panel (1) and (2) show DDM from each nadir-pointing antenna, while (3) shows the observation after digital beamforming. Panel (4) is a delay-cut through the peak waveform. Map indicating the location of the specular points collected. The displayed time is highlighted with a blue dot.

FM109 Comparison to CYGNSS

- Spire from 1 track at 2 Hz
- CYGNSS is averaged 1 Hz and 2 Hz data

- Cropland rainfed
- Cropland rainfed - Herbaceous cover
- Cropland rainfed - Tree or shrub cover
- Cropland irrigated or post-flooding
- Mosaic cropland (>50%) / natural vegetation (tree/shrub/herbaceous cover) (<50%)
- Mosaic natural vegetation (tree/shrub/herbaceous cover) (>50%) / cropland (<50%)
- Tree cover broadleaved evergreen closed to open (>15%)
- Tree cover broadleaved deciduous closed to open (>15%)
- Tree cover broadleaved deciduous closed (>40%)
- Tree cover broadleaved deciduous open (15-40%)
- Tree cover needleleaved evergreen closed to open (>15%)
- Tree cover needleleaved evergreen closed (>40%)
- Tree cover needleleaved evergreen open (15-40%)
- Tree cover needleleaved deciduous closed to open (>15%)
- Tree cover needleleaved deciduous closed (>40%)
- Tree cover needleleaved deciduous open (15-40%)
- Tree cover mixed leaf type (broadleaved and needleleaved)
- Mosaic tree and shrub (>50%) / herbaceous cover (<50%)
- Mosaic herbaceous cover (>50%) / tree and shrub (<50%)
- Shrubland
- Shrubland evergreen
- Shrubland deciduous
- Grassland
- Lichens and mosses
- Sparse vegetation (tree/shrub/herbaceous cover) (<15%)
- Sparse tree (<15%)
- Sparse shrub (<15%)
- Sparse herbaceous cover (<15%)
- Tree cover flooded fresh or brakish water
- Tree cover flooded saline water
- Shrub or herbaceous cover flooded fresh/saline/brakish water
- Urban areas
- Bare areas
- Consolidated bare areas
- Unconsolidated bare areas
- Water bodies
- Permanent snow and ice

SPIRE'S CYGNSS SOIL MOISTURE



Spire has produced a soil moisture product from CYGNSS data and has operationalized it to prepare for data product derived from Spire GNSS-R satellites

KEY TAKEAWAYS & FAQ

- Spire has built an operational Earth observations constellation (80+ sats) that is **enabling new Earth science and applications**
- Having proven RO, Spire is **now expanding to more SpWx science, GNSS-R applications, and new payloads**
- More information is available via the [CSDAP program] and a [Spire CSDAP Data FAQ]

Spire CSDAP Data FAQ

What types of data do Spire satellites collect and are being made available in the CSDAP holdings?

Spire satellites primarily collect data using a science-grade, dual-frequency GNSS receiver. The Spire GNSS receiver collects primarily both rising and setting radio occultation observations using fore and aft facing "RO" antennas. A third dual-frequency zenith antenna collects observations for precise orbit determination (POD). Typical RO data products include:

- *Low-level 50 Hz data (opnGns format)*
- *Excess phase (atmPhs)*
- *Atmospheric profile (atmPrf and bfrPrf)*
- *Slant TEC (podTEC)*
- *Ionospheric density profile (ionPrf)*
- *Precise orbit determination (leoOrb)*
- *Scintillation indices (scnLv1)*

Grazing angle GNSS reflections from the Earth surface are also observed in the fore and aft RO antennas to perform a new type of GNSS-R. These observations include both the direct and reflected signals and allow precise altimetry under conditions of coherent reflections. These data are derivations of and similar to traditional 50 Hz RO data.

A limited number of low-level, raw intermediate frequency (IF) data collected by both RO satellites (for grazing angle reflections) and GNSS-R satellites are also available.

Each Spire satellite also collects attitude (leoAtt) and raw magnetometer data from the attitude determination and control system (ADCS).

As new data types are created by Spire, such as from the recent launch in Dec. 2019, of two GNSS-R specific satellites, these data will undergo evaluation by NASA prior to their inclusion into the CSDAP holdings.

What is the time period of the data provided to the CSDAP?

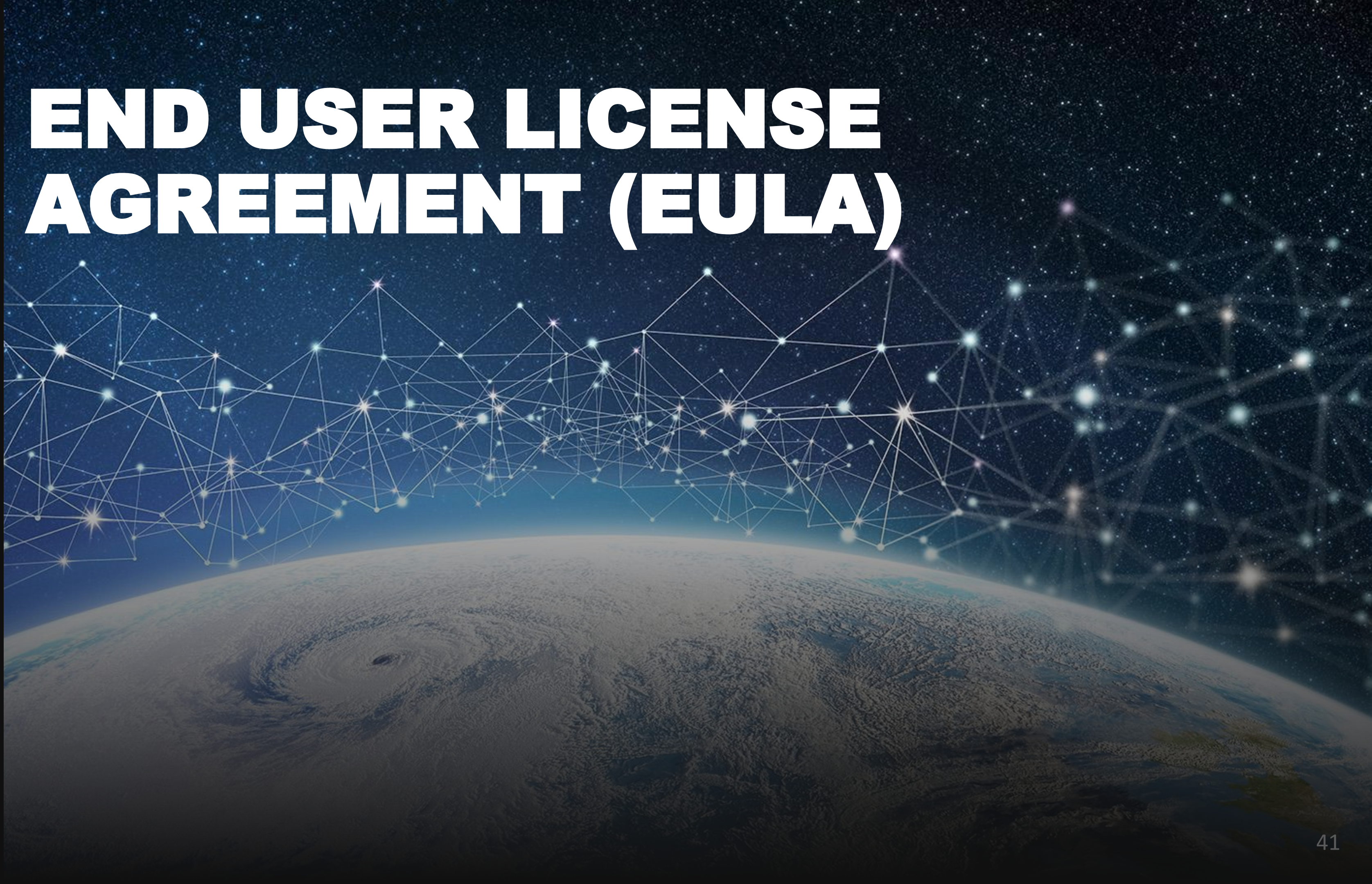
Spire is supplying data from Nov. 1, 2019 through April 30, 2021. Not all data types are available at earlier dates.

What are the characteristics of the Spire constellation?

Spire launches 3U CubeSats into a variety of orbits, including sun synchronous polar orbits with varying local time sampling and orbits of various inclinations (e.g., 83 deg, 51.6 deg (ISS), 37

Page 1 of 2 spire

END USER LICENSE AGREEMENT (EULA)



CSDAP TERMS & CONDITIONS OF USE OF SPIRE DATA

- Commercial Data is the exclusive property of Spire
- Commercial Data is provided only for NASA scientific use
- Commercial Data cannot be published or disclosed without Spire consent
- Commercial Data is not for Commercial use
- Commercial Data is not guaranteed in terms of Accuracy (spatial, temporal, spectral), Currency, or Completeness
- Derivatives may be published but are not for Commercial use
- Derivative publications must include a copyright notice, e.g., “Includes copyrighted material of Spire Global, Inc. All rights reserved.”
- Courtesy copies of reports and publications shall be provided to NASA and Spire for informational purposes, preferably prior to publication
- Derivatives cannot disclose Commercial Data, enable it to be reverse engineered or extracted, or be capable of use as a substitute
- Users must comply with all laws, rules, and regulations, including export control regulations

NASA CSDAP PROGRAM COMMENTS

National Aeronautics and
Space Administration

EXPLORE EARTH

Spire Integration into the SmallSat Data Explorer

NASA Commercial SmallSat Data Acquisition Program (CSDAP)
Will McCarty, CSDAP Project Scientist
Global Modeling and Assimilation Office
NASA Goddard Space Flight Center

Distributing Spire Data for CSDAP

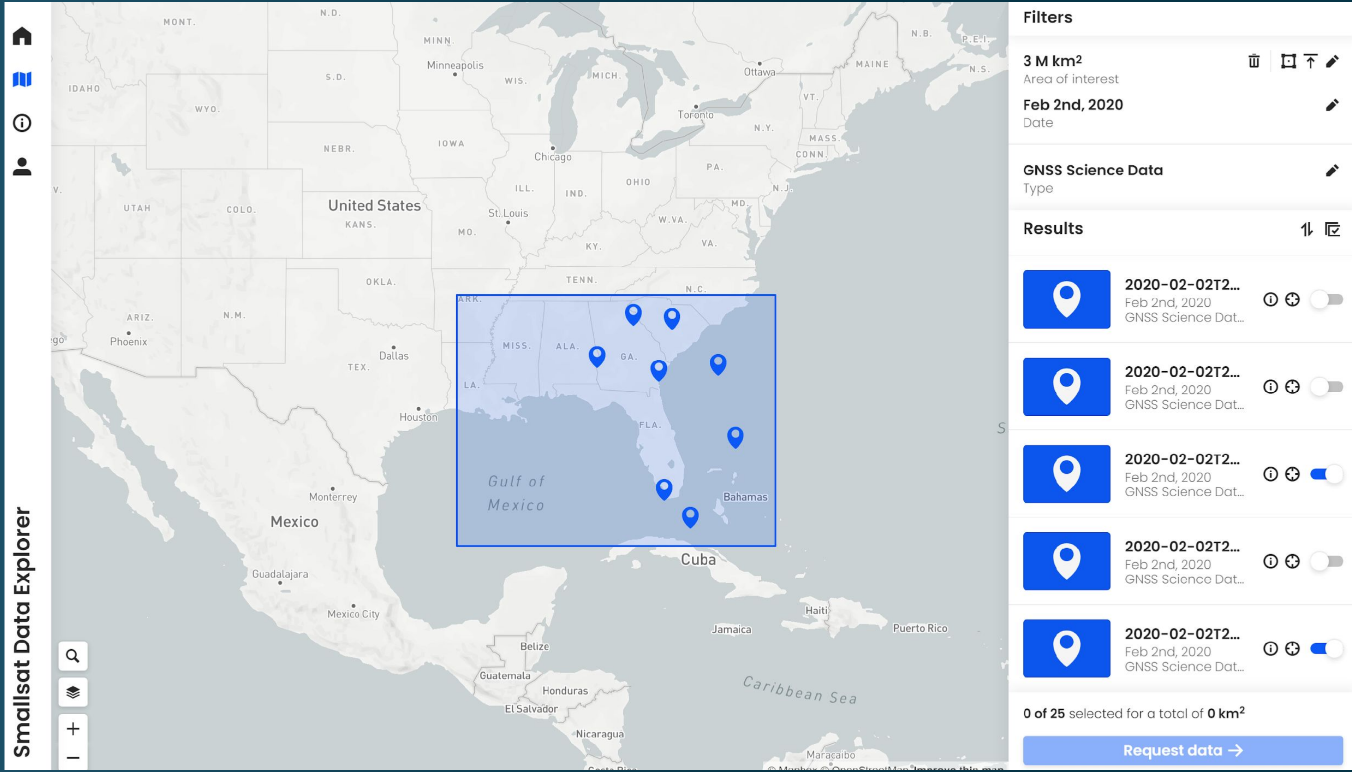
With the purchase of the Spire data, it is being integrated into the CSDAP SmallSat Data Explorer (SDX)

- Integrating Spire data into the SpatioTemporal Asset Catalog (STAC) specification
- Allow for search, discovery, and access to Spire data
- Aim of reaching both new and power users
- Will populate every day with the delivery of new data

SDX Advantages:

- Searchable in space and time
- Controllable access – access requires verification of NASA funding and acceptable of End User Licensing Agreement (EULA)

Distributing Spire Data for CSDAP



Distributing Spire Data for CSDAP

SDX Spire “Golden Day” – 2 Feb 2020, in production

- Radio Occultation Only for now
- CSDAP data management team is adding additional selection criteria
- Will soon expand to grazing angle reflectometry, navigation, attitude, ionospheric, and magnetometry data

Looking for testers and feedback!

- If interested in providing feedback, reach out to me at will.mccarty@nasa.gov
- Looking for the full range of new and experienced users

https://earthdata.nasa.gov/esds/csdap/

https://earthdata.nasa.gov/esds/csdap/sdx (requires EarthData login)

Special thanks goes to the CSDAP Data Management team and Spire for their hard work on this