spire | federal

Spire's Earth Observations

NASA Lunch & Learn

25 AUG 2021

Introductions

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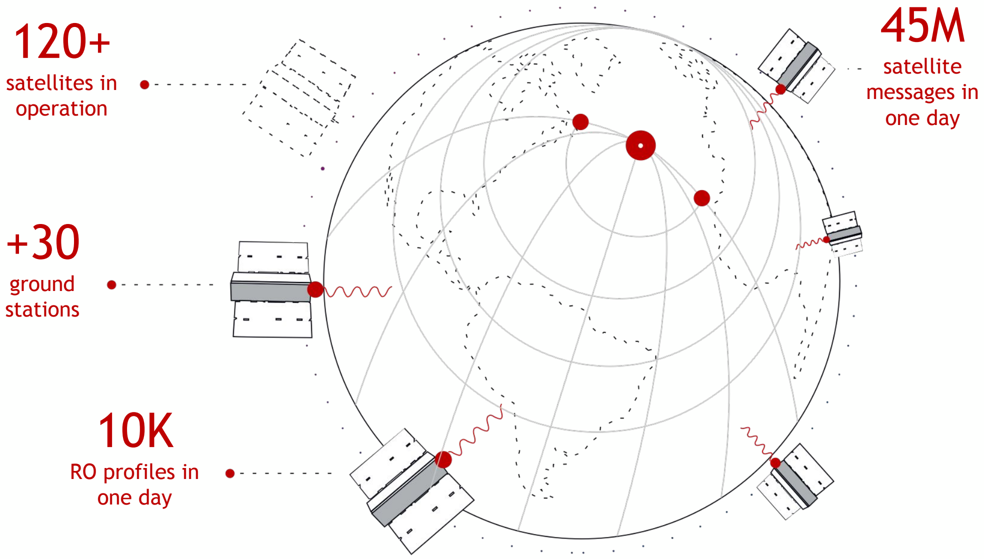
AGENDA

- **Spire Overview**
- EO Satellite Constellation
- CSDA Program Data Products
- EULA and T&Cs
- Accessing the Data & Support

The Spire Constellation

One of the largest private constellations in the world

- The Low Earth Multi-Use Receiver (LEMUR) is Spire's 3U CubeSat platform used to track maritime, aviation, and weather activity from space
- We operate the world's largest RF sensing fleet and are the largest producer of radio occultation and space weather data
- Our data provides a global view with coverage in remote regions like oceans and poles; all data can be refreshed within 15 minute cycles
- We are continuously launching improved sensors and upgrading them in-orbit
- We turn ideas into live feed from space in as little as 6-12 months



Global Ground Station Footprint

We own and operate the most geographically dispersed and largest network for ground stations, which allows us to repatriate our satellite-generated data at record speed

30+

Ground stations

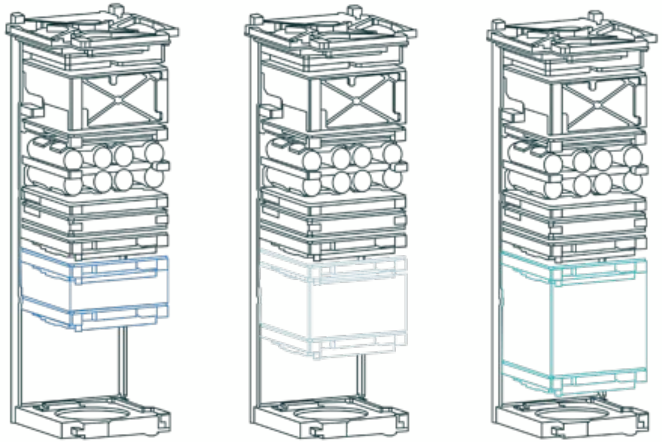
70+

Antenna systems

Spire's Ground Station Network

Spire LEMUR-2 Cube-Satellite Systems

Parameter	6U Carrier Specs	3U Carrier Specs
Empty Carrier Mass	5.4 kg	4.2 kg
Payload Mass	Up to 4.2 kg	Up to 1.4 kg
Total Mass	9.6 kg	Up to 5.6 kg
Payload Power	5W - 12W Orbit Average, 35W Peak	
Data Interface	CAN bus (CS), Ethernet (TCP/IP), UART	
Onboard Storage	1 GB	
Pointing Accuracy	3-degree nadir	



Spire's Core Competencies

Maritime
Leveraging the International Maritime Organization AIS standard, Spire provides constantly-refreshed information on the state of the global waterways

Aviation
Sensing the ICAO-backed ADS-B standard, Spire is able to generate near realtime information on the movements of all civilian aircrafts across continents and oceans for a long suite of regulatory and operations applications

Critical Weather Data
Spire generates global space-based weather data at various vertical levels, with critical implications for severe weather events forecast, preparation and management

Weather Modeling
Generating new information over 10,000 times per day, including thousands of daily Radio Occultation profiles, Spire provides agricultural, maritime and aviation customers with a dedicated weather model offering

Soil Moisture
With our reflectometry data, Spire's satellites provide precision agriculture users with a quickly-refreshed database on the soil moisture level of their fields, enabling smart yield-critical decisions

Ionosphere
Spire constantly generates data on the local states of the Earth's ionosphere, the outermost atmospheric layer before outer space, with critical applications for telecoms, mobility and defense entities

Space Services
Spire offers access to its proven LEMUR platform for a wide range of sensing or telecom applications in a variety of all-inclusive packages

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- CSDA Program Data Products
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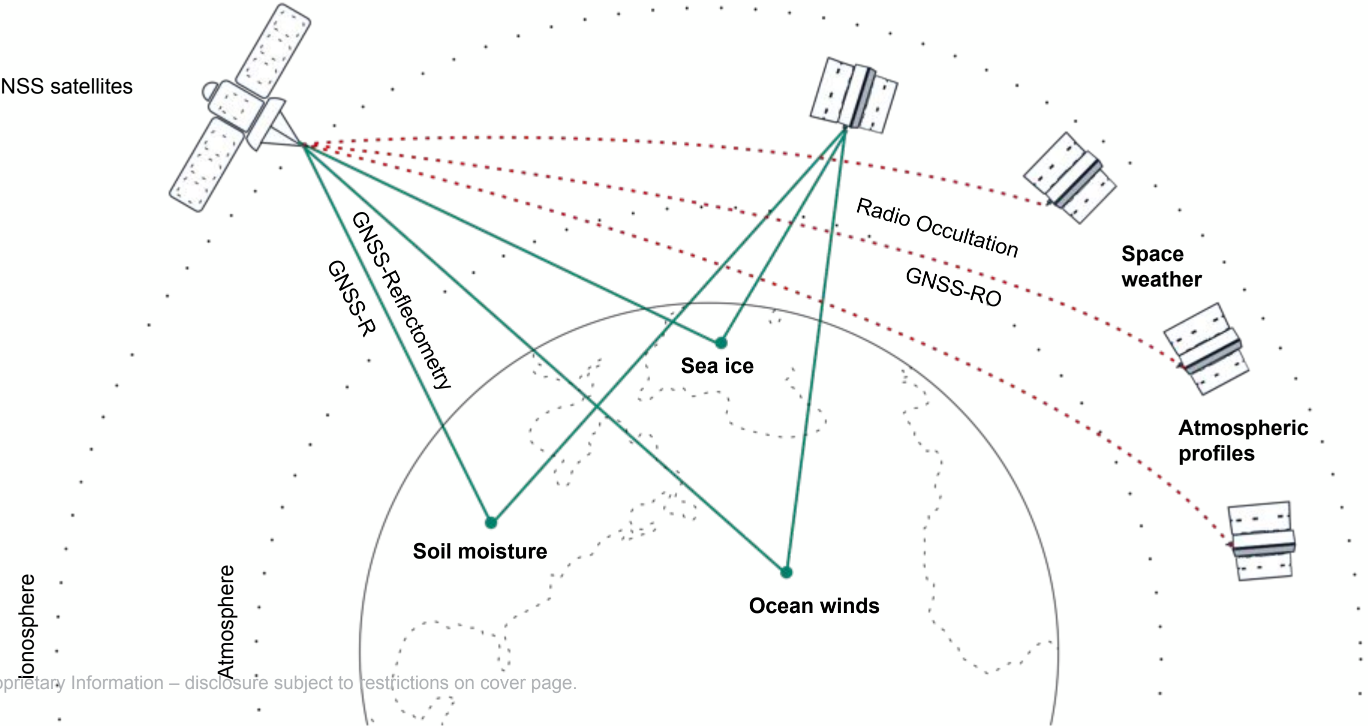
- Accessing the Data & Support

Spire Earth Intelligence Data

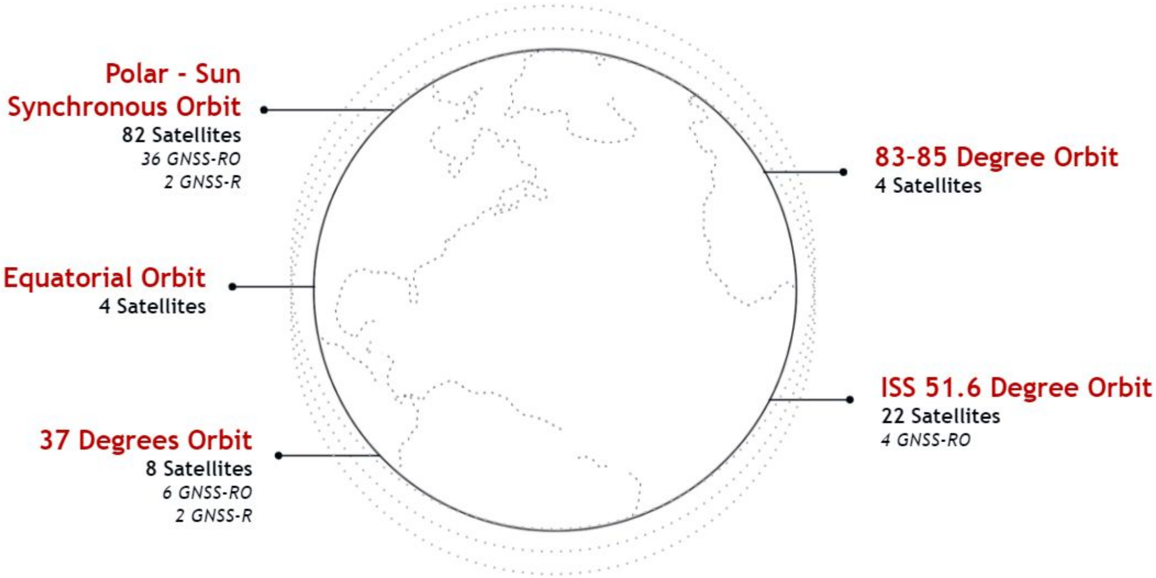
Our satellites capture Earth observations for various applications: NWP data assimilation, ocean winds, soil moisture, space weather, etc.



Spire Earth Intelligence Data

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

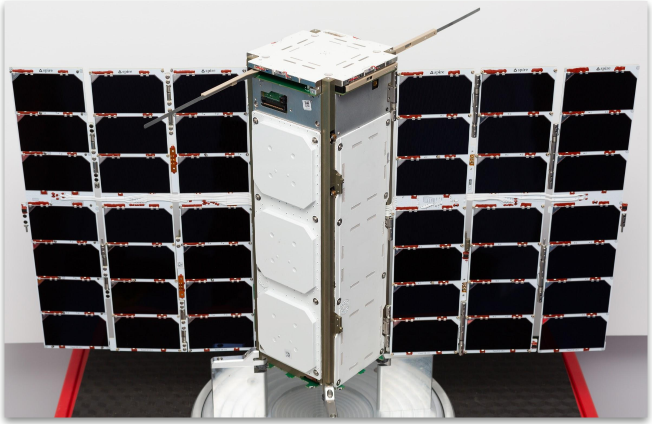
- 120+ LEO nanosatellites in diverse orbits for **global coverage**, high spatial and temporal sampling, and system redundancy
- 40+ RO-capable sats and **30+ in RO production**
- New GNSS-R sats in 37° and **SSO orbits**



Spire GNSS Earth Observation Satellites

Spire GNSS-RO satellites

- 3U form factor
- Moderate gain, dual antennas (rising/setting RO)
- Multi-GNSS signals tracked
- Rapid on-orbit innovation

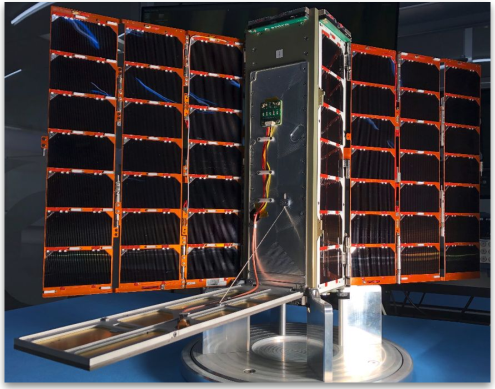


Spire GNSS-R satellites

- 3U form factor

Batch 1

- Dual nadir antennas
- Multi-GNSS signals tracked
- 30 simultaneous reflections
- Launched **DEC 2019**



Batch 2

- Triple GNSS-R antennas
- Multi-GNSS signals tracked
- 45 simultaneous reflections
- Advanced calibration
- Launched **JAN 2021**

AGENDA

Data Available Under CSDA Program

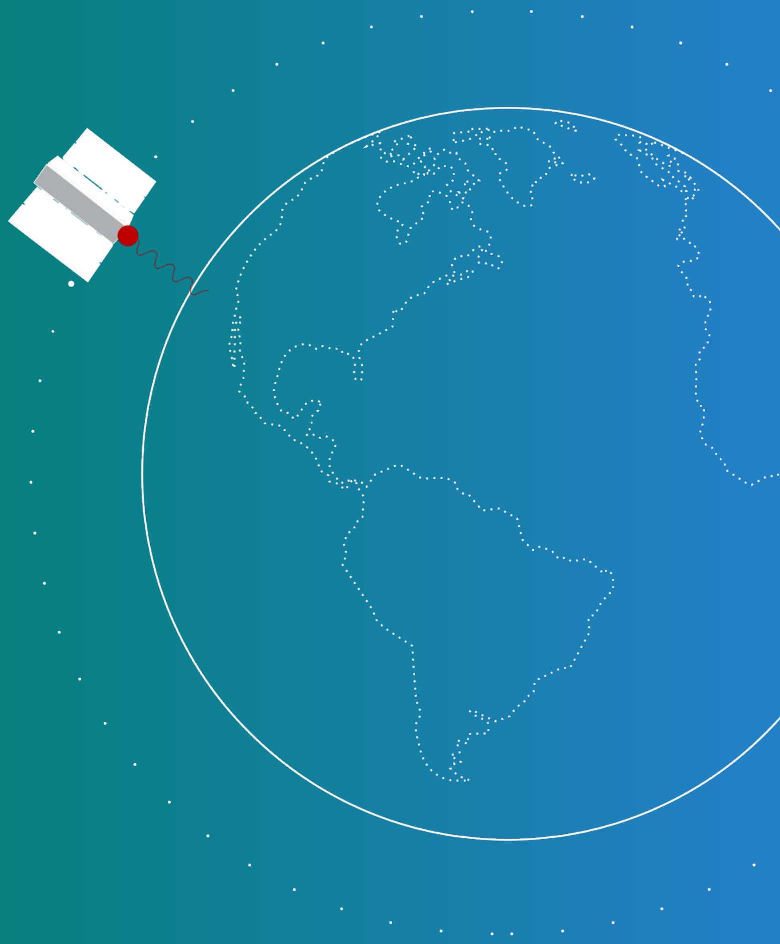
Data available from both NASA CSDA Program task orders and older NASA CSDA pilot program

- NASA procured access to data types starting **01 NOV 2019** through to **17 MAY 2022**
- Data available with a 30-day delay (i.e., 30 days after collection)
- Current Spire products available under the NASA CSDA Program
- New products undergo NASA evaluation
- Product improvements made available as developed

Data Type	Date Range
GNSS Radio Occultation (L0-L2 atmos. prf)	24 SEP 2018 - 14 DEC 2018 14 DEC 2018 - 08 MAR 2019 **01 NOV 2019 - present**
Grazing Angle GNSS-R (L0-L2 sea ice type & altimetry)	09 JAN 2019 - 18 APR 2019 **01 NOV 2019 - present**
Conventional GNSS-R (L0-L2 soil moisture, ocean winds & MSS) (under evaluation)	TBD (under evaluation)
Raw IF captures (GNSS-R)	Various
Precise Orbit Determination (L0-L1)	24 SEP 2018 - 18 APR 2019 **01 NOV 2019 - present**
Space Weather (TEC, EDP, Scintillation) (L0-L2)	**01 NOV 2019 - present**
Magnetometer (simple sensor data) (L0)	**01 NOV 2019 - present**

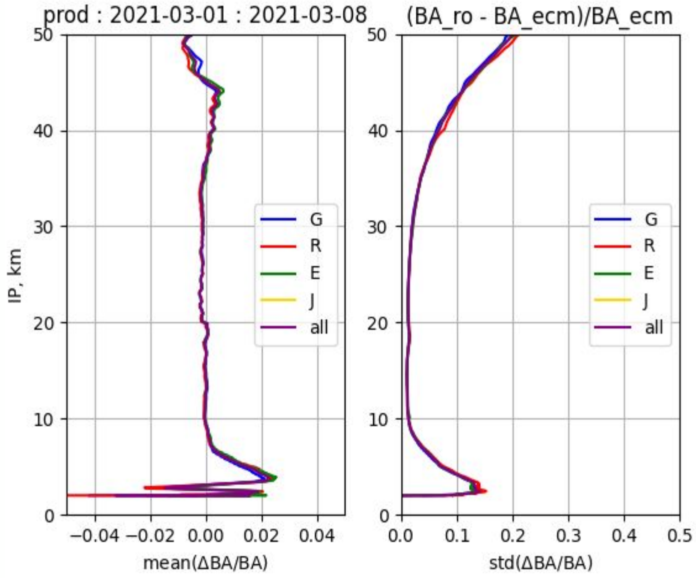
Radio Occultation

NASA CSDA Program



GNSS-RO Data in the CSDA Program

- Collected operationally for NWP customers
- 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 (1 Hz leoAtt in CHAMP format during RO, 0.1 Hz CSV)
  - Ancillary information (e.g., antenna phase centers, CoM)
- Provenance information included in the files and manifest
  - Used to identify all data going into processing GNSS-RO events



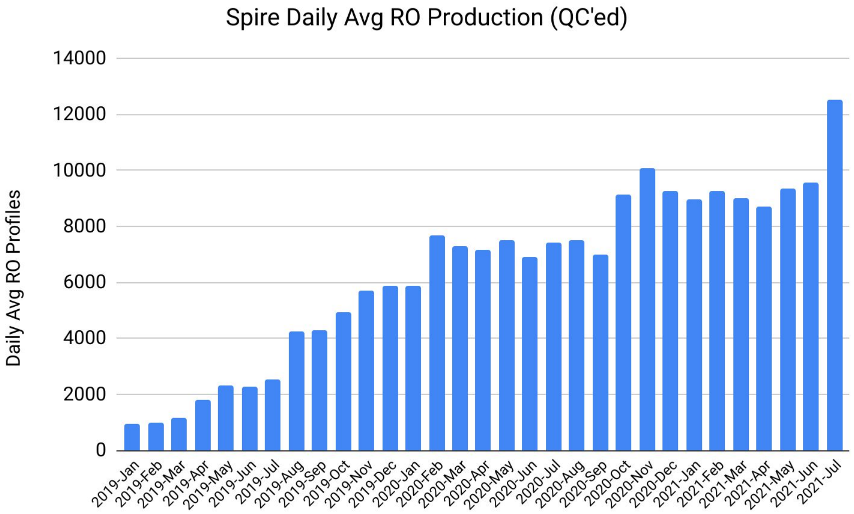
Similar quality rising/setting profiles from multiple GNSS

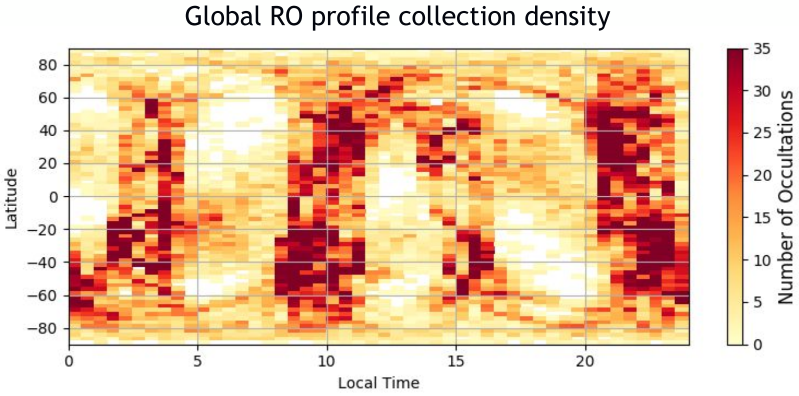
Growing Volume and Coverage

Spire is consistently improving global RO production

Continual RO production growth

- New receiver in validation to become operational in 2021 to **track all RO in view**
- Continual bus and ground station latency performance improvements



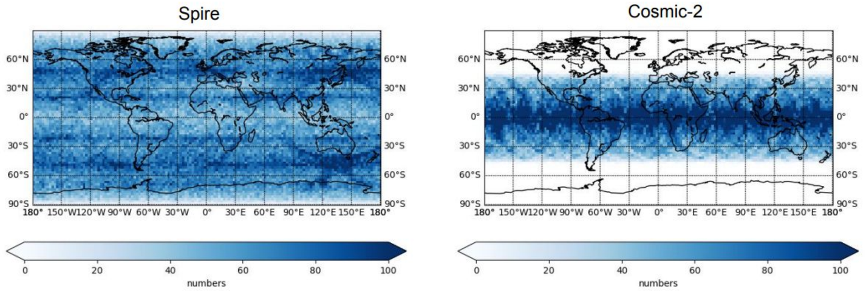


Improving local time sampling through orbit diversity

Spire GNSS-RO

At the biannual April 2021 International RO Working Group meeting, independent users showed Spire RO is similar in quality and impact to institutional RO missions

ECMWF compared Spire to COSMIC-2 sampling and impact

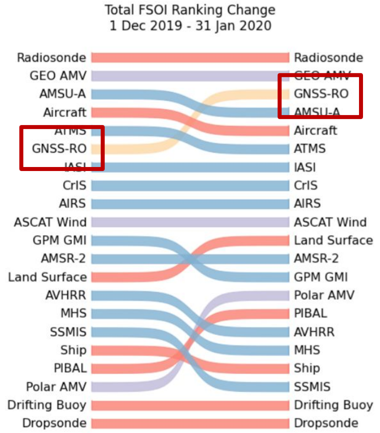


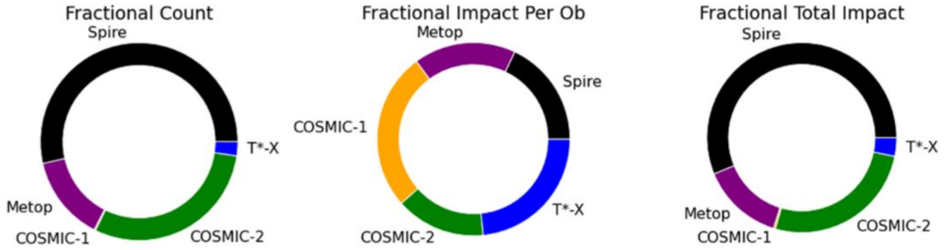
Katrin Lonitz (ECMWF) IROWG link

NOAA showed Spire matches COSMIC-2 penetration depths

	10N-10S	10N-30N	30S-10S	30N-45N	45S-30S	45N-60N	60S-45S	60N-90N	90S-60S
COSMIC-2	0.85	0.90	0.75	1.35	1.10				
GeoOptics	0.95	1.05	1.10	0.70	0.80	0.35	0.40	0.55	0.20
SPIRE	0.90	0.90	0.75	0.80	0.55	0.45	0.25	0.45	0.20
KOMPSAT-5	1.85	1.50	1.15	0.40	0.95	0.35	0.40	0.25	0.20
PAZ	2.65	1.85	2.05	0.90	1.30	0.45	0.45	0.35	0.25

Ben Ho (NOAA) IROWG link



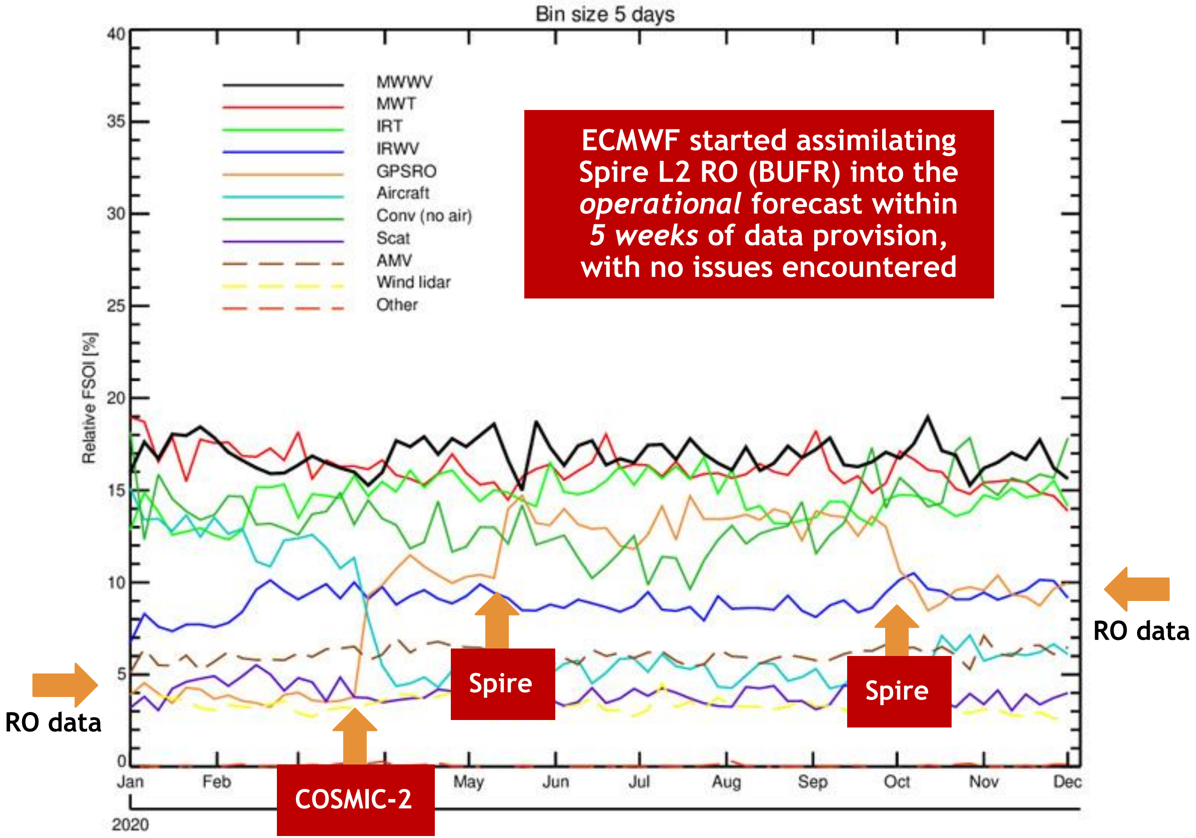


NASA showed Spire data moved RO FSOI to third place among all observations and **Spire led in fractional total impact**

Will McCarty (NASA) IROWG link

Spire RO in ECMWF Operational NWP

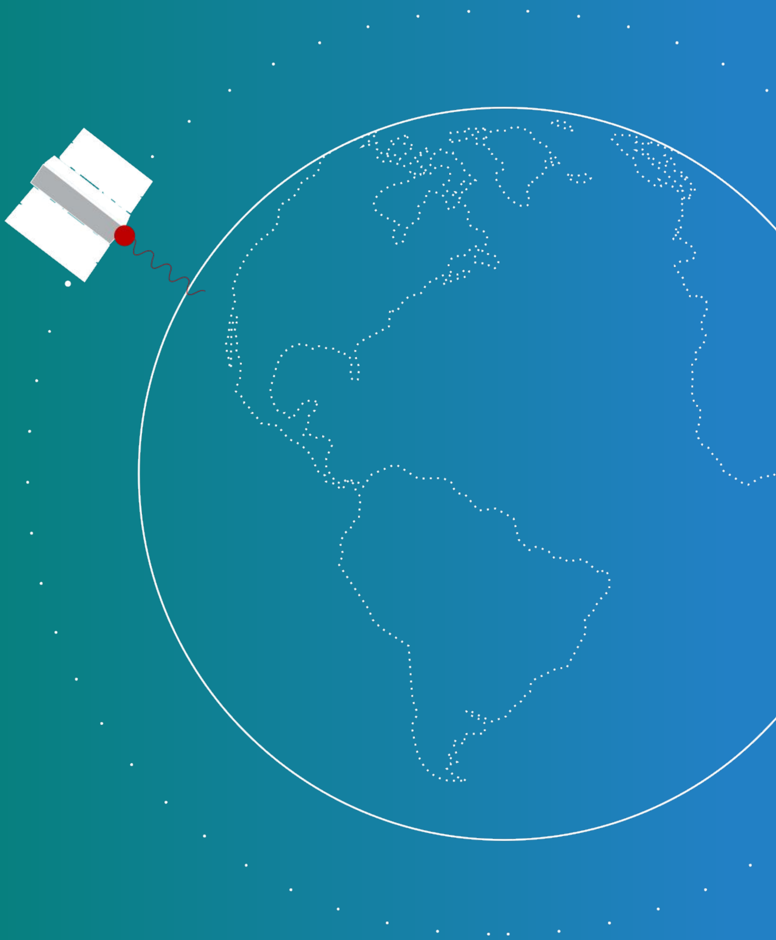
- Spire provided all (>7000) **daily L2 RO prfs** (BUFR) to the **ECMWF, UK Met Office, and US Air Force during the COVID-19 pandemic** to compensate for lack of aircraft measurements (incl. QZSS, Galileo RO)
- **ECMWF saw significant increases in relative forecast sensitivity to observation impact (FSOI)** when COSMIC-2 RO was assimilated in March and again when **Spire RO was assimilated in May**
- Ongoing ESA-sponsored combined ECMWF / UK MetOffice impact study will be completed in Sept. 2021



Sean Healy, ECMWF

Grazing Angle GNSS-R

NASA CSDA Program



spire

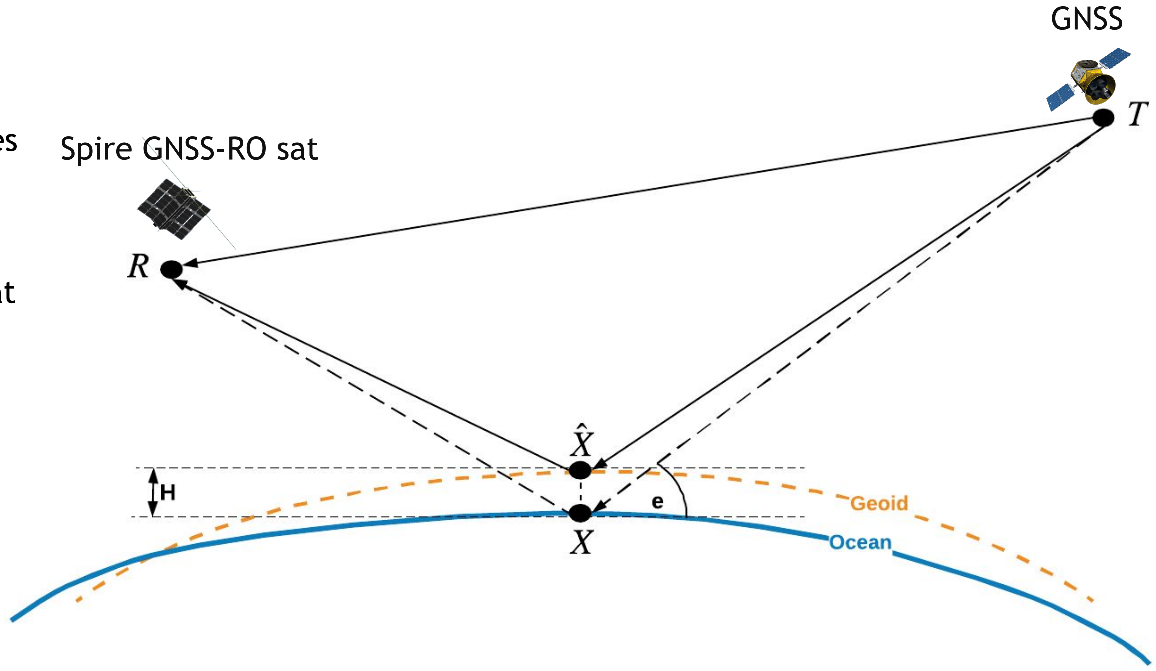
Grazing Angle GNSS-R Technique

Phase-delay altimetry is a type of GNSS-R that uses <u>coherent</u> reflections of GNSS signals at **low grazing angles (5-30 deg)** to estimate cm-level heights of smooth surfaces

Grazing angle GNSS-R altimetry has the ability to collect large quantities of relative height profiles of sea ice with precisions that approach traditional altimeters (< 10 cm RMSE @ 50 Hz) and can potentially complement these other altimeters to fill gaps

Uniquely, Spire satellite data within the same orbit plane are collocated in time/space for "self-validation"

These data are very new and only being produced by Spire satellites, but their potential has been demonstrated



Grazing angle reflections maintain coherency for small roughness

Grazing Angle GNSS-R in CSDA Program

- Spire grazing angle GNSS-R products are collected operationally by GNSS-RO satellites (targeting polar, Gulf of Mexico, and Indonesian areas)
- 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)
  - **Derived products (beta) available in Sep. 2021:**
    - grzIce (L2 sea ice extent & classification)
    - grzAlt (L2 surface altimetry)

Geophysical Research Letters

Research Letter

Initial GNSS Phase Altimetry Measurements From the Spire Satellite Constellation

Vu A. Nguyen, Oleguer Nogués-Correig, Takayuki Yuasa, Dallas Masters, Vladimir Irisov

First published: 08 July 2020 | https://doi.org/10.1029/2020GL088308

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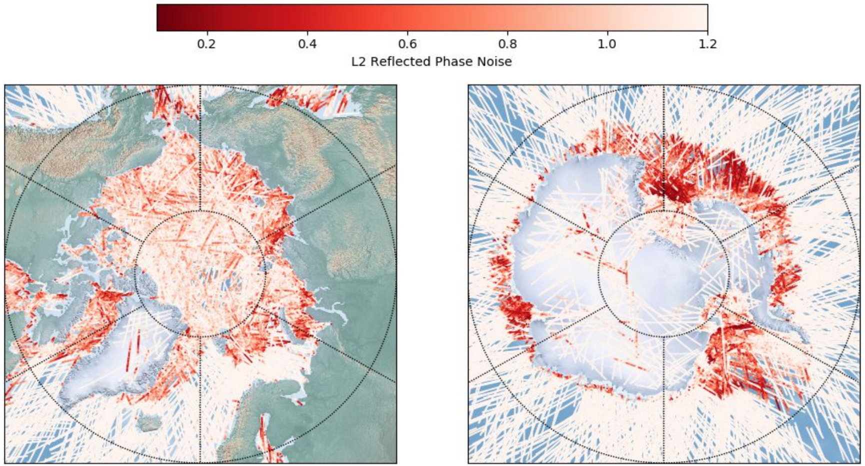
Abstract

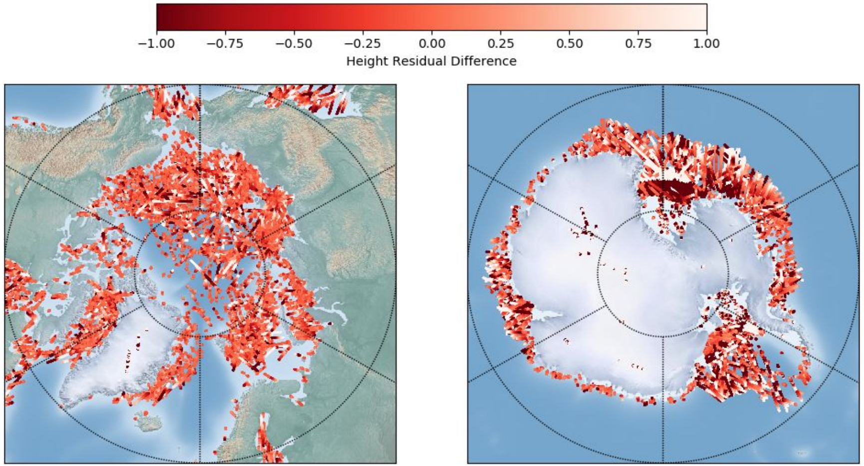
The collection of phase coherent Global Navigation Satellite System (GNSS) reflected signals from radio occultation receivers in low-Earth orbit potentially offers the capability of deriving precise altimetry measurements over open and sea-ice-covered water at unprecedented coverage and low cost. Although past studies have verified the possibility of deriving altimetric measurements from GNSS observations, there is still uncertainty regarding the precision of this technique and its application. This study highlights the extraction of altimetric information from initial grazing angle GNSS reflection events observed by Spire satellites. Results show that the majority of coherent events occur over sea-ice-covered regions. A smaller number of coherent events are observed over the open ocean due to rougher scattering conditions. Altimetric retrieval was performed using dual frequency phase measurements from several events and compared to

Grazing Angle Measurement Coverage

Total Measurement Coverage over 1 Week



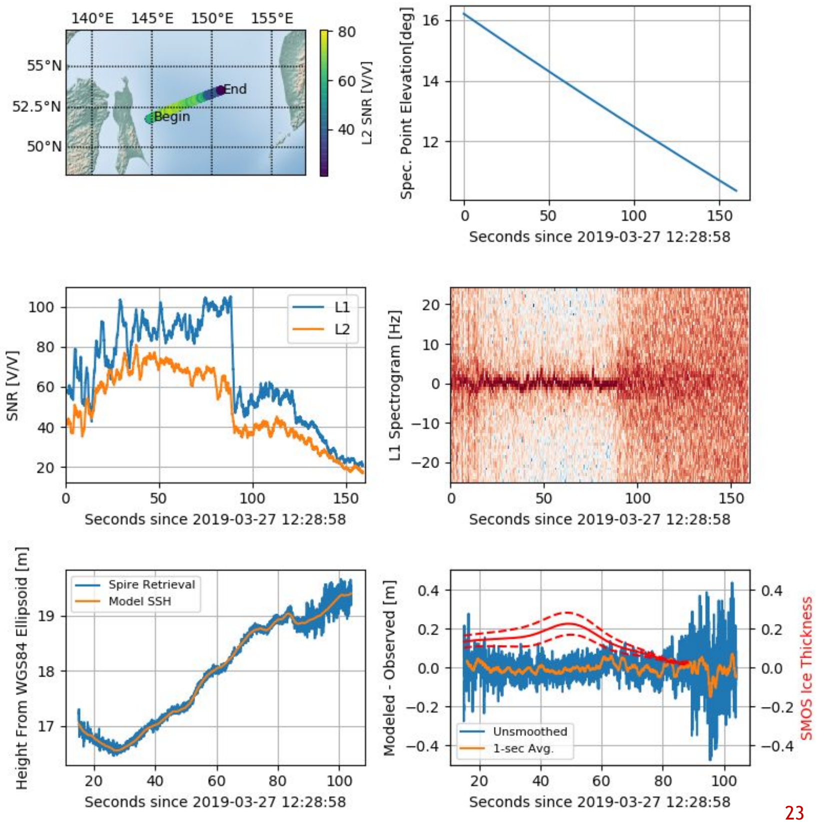
Altimetric Height Coverage over 1 Week



Grazing Angle Sea Ice Altimetry

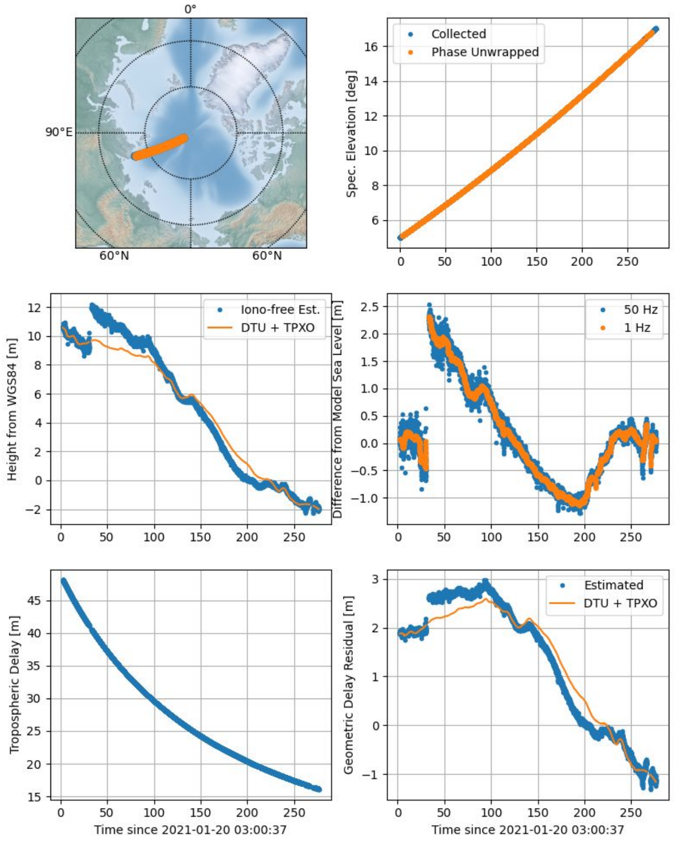
Reflection event over Sea of Okhotsk

- 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 or snow interface

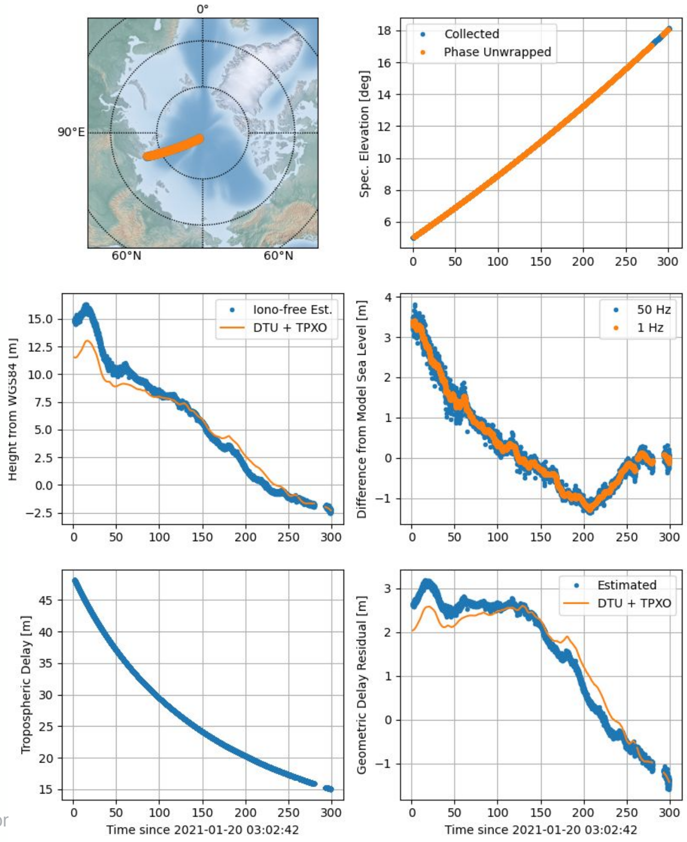


Two-Sat Validation of Sea Ice Altimetry

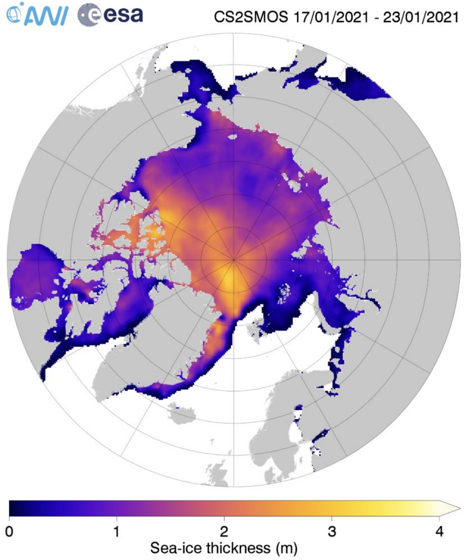
FM101 at T03:00



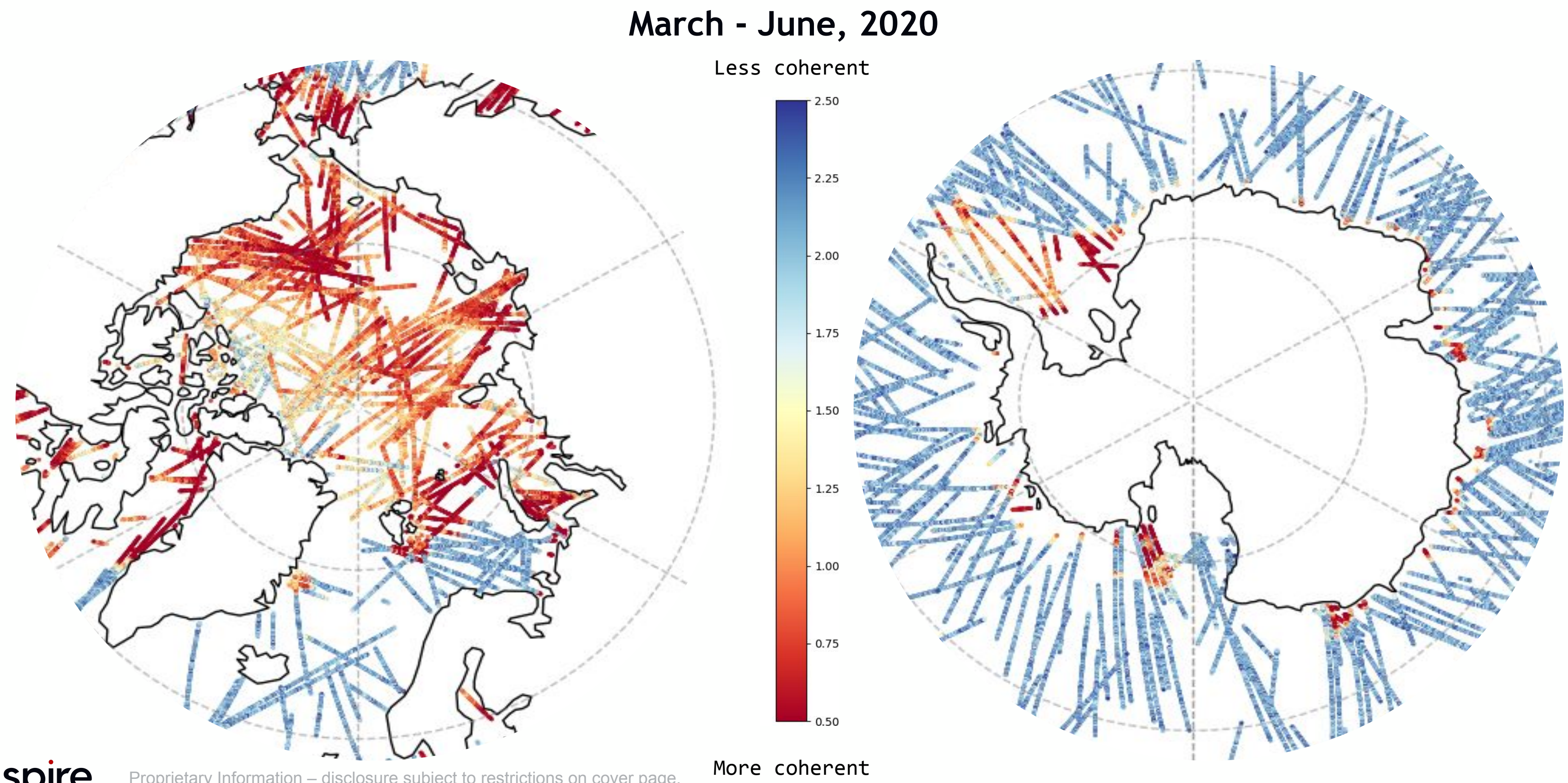
FM100 at T03:02



Sats in same orbit (2 min apart) measure similar profile gives **intrinsic method to validate data within the constellation (CS2SMOS below)**



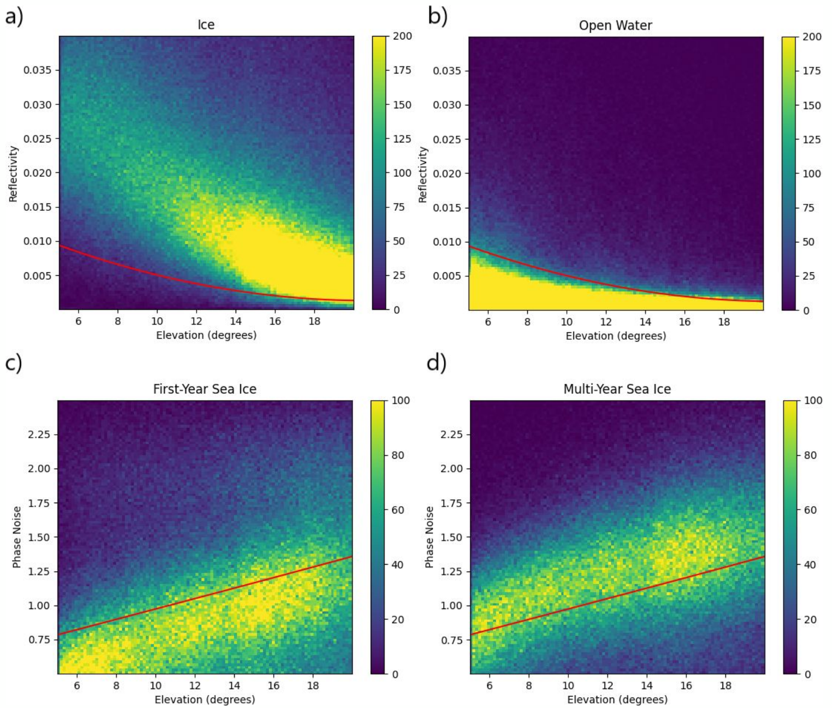
Grazing Angle GNSS-R Phase Noise

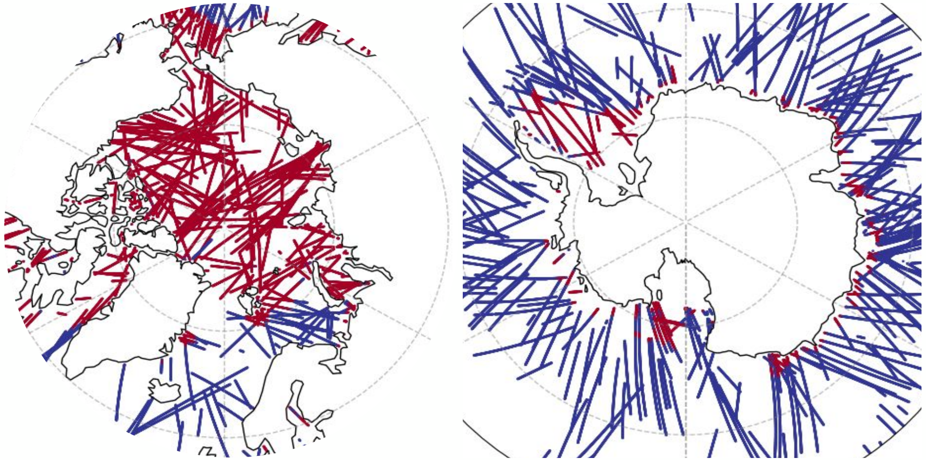


Application to Sea Ice Extent

Thresholds trained: 1st March - 7th March 2020

Data shown: 1st March - 30th June 2020

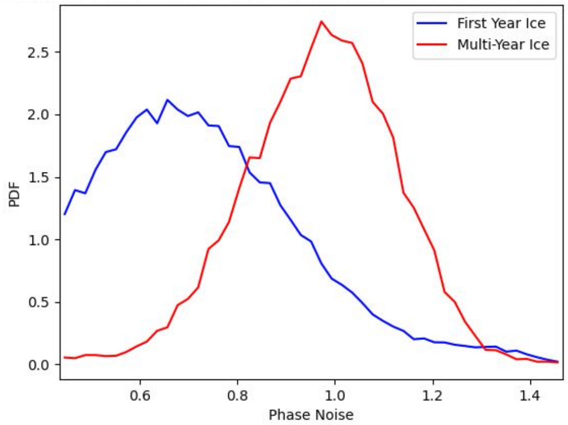




	Active	Passive	Operational
Arctic	94 %	93 %	95 %
Antarctic	98 %	96 %	-

Separate training and testing datasets

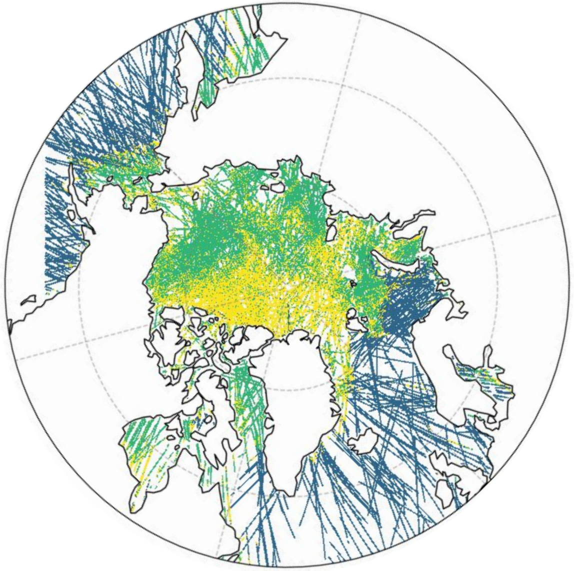
Application to Sea Ice Type

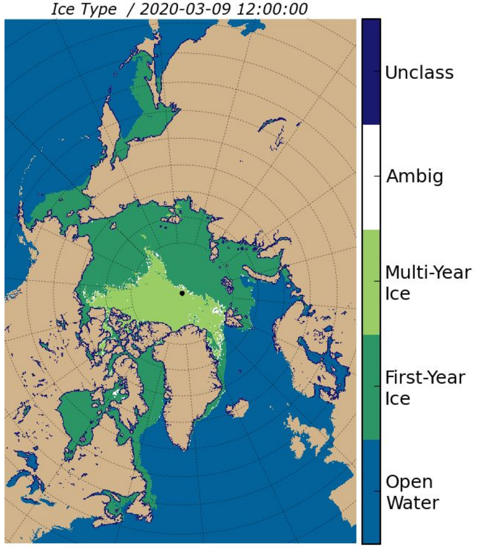


First-year Ice ← → Multi-year Ice

	Weekly Ice Chart	Active Product
Arctic	74 %	77 %

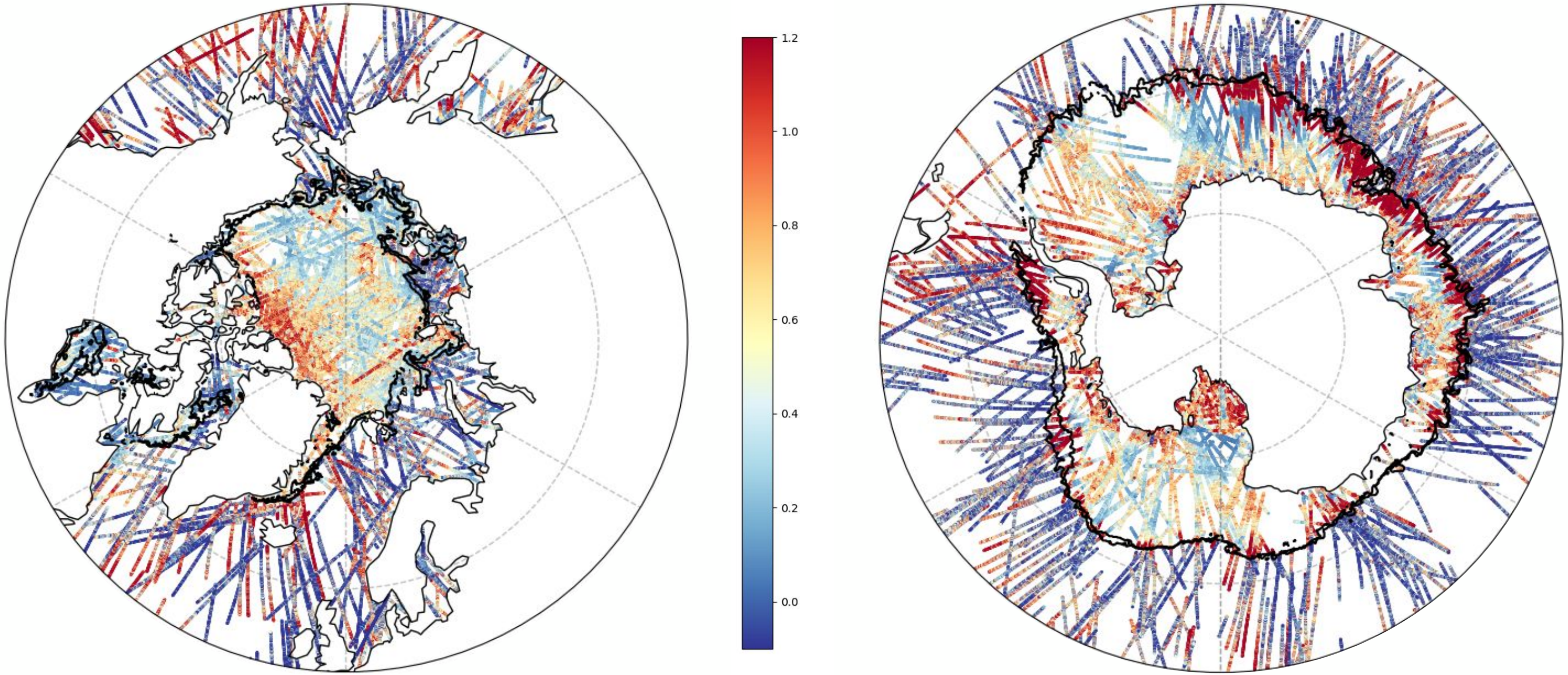
Separate training and testing datasets





“Excess Phase Noise” Variable

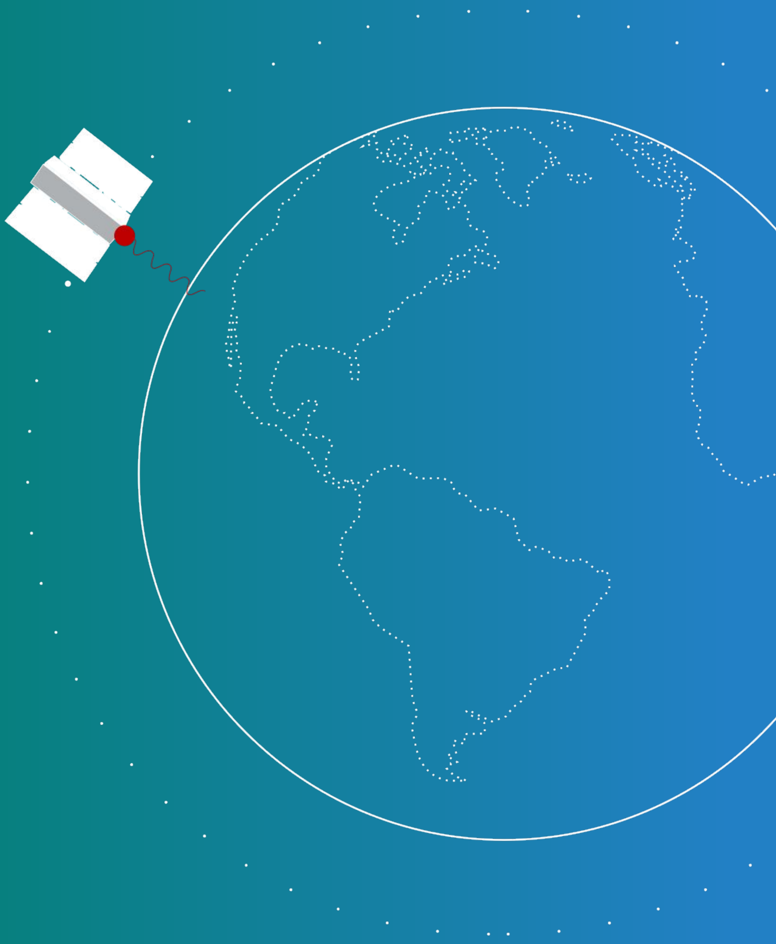
“Excess” phase noise of the reflected signal
(reflected minus amplitude-dependent)



Data: 2020-07-01 - 2020-07-07
Contours: OSISAF Ice edge 2020-07-01 and 2020-07-07

Conventional GNSS-R

NASA CSDA Program



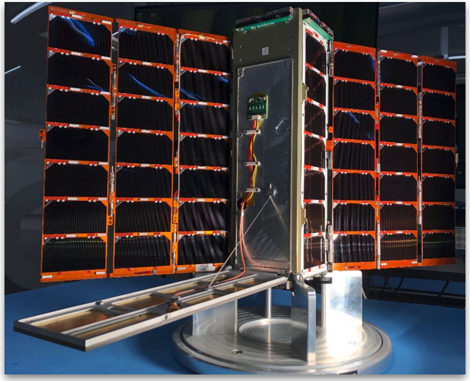
Spire GNSS-R Missions

Spire GNSS-R Satellite Constellation (four and growing)

- Two "Batch-1" satellites launched in Dec. 2019 (operational phase)
- Two "Batch-2" satellites launched in Jan. 2021 (cal/val phase)
- Prototype sats for long-term, high-res (3 km) soil moisture (SM) observations
- Level 2 along-track SM preview product under evaluation by GSFC (Kumar)
- Further GNSS-R constellation build out in 2022 (KAUST-sponsored mission)

Parameters	NASA CYGNSS	Spire GNSS-R Batch-1	Spire GNSS-R Batch-2
Simultaneous reflections observed	4	**30**	**27 (larger bandwidth)**
GNSS Constellations tracked	GPS	**GPS, QZSS, Galileo, SBAS (soon)**	**GPS, QZSS, Galileo, SBAS (soon)**
Direct antenna	L1 Single patch	**L1/L2 single patch**	**L1/L2 single patch**
Reflection antenna	2, 3x2 L1 LHCP array (off-nadir) 14 dB peak gain	**2, 3x1 L1 LHCP array (nadir), beamforming**	**3, 3x1 L1 LHCP array (nadir, 35 deg off-nadir, and beamforming**
GNSS receiver	SGR-Resi	**STRATOS v1**	**STRATOS v2 (direct sampling, onboard calibration, larger FPGA)**
Mass	25 kg	**5 kg**	**5 kg**
Orbit	35 deg	**37 deg**	**SSO: 9:30 LTDN (global)**

Spire "Batch-1 GNSS-R satellite



Spire "Batch-2" GNSS-R satellite

GNSS-R Data Under Evaluation

- Spire grazing angle GNSS-R products are collected operationally by GNSS-R Batch-1 satellites (Batch-2 data in late 2021)
- The product types are Spire-defined and include:

Level 1A
GNSS-R Surface Reflectivity
(along-track, netCDF)

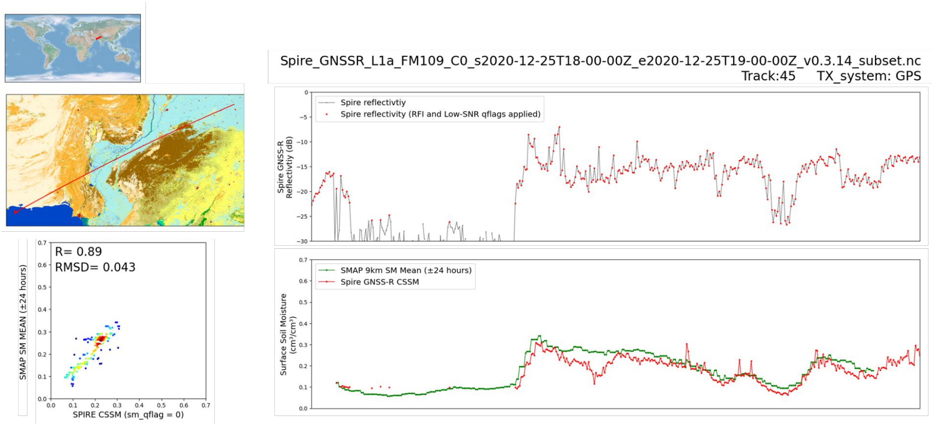
L2
Soil Moisture
(along-track, netCDF)

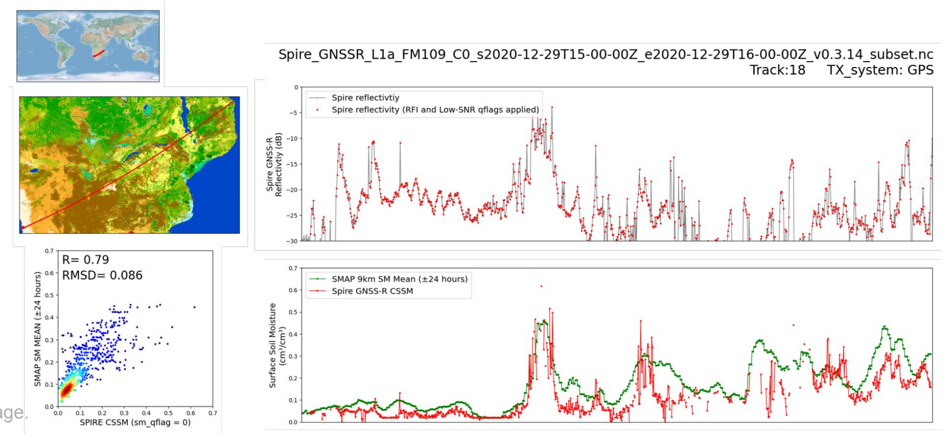
Level1B
GNSS-R Ocean Normalized Bistatic Cross-sections
(along-track, netCDF)

L2
Ocean Wind Speed and MSS
(along-track, netCDF)

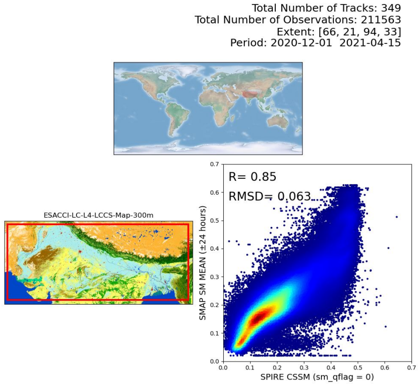
Spire L2 GNSS-R Soil Moisture

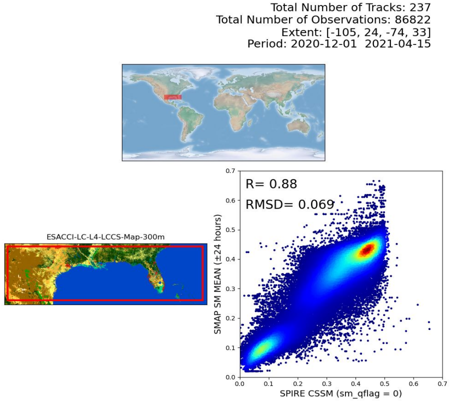
- Track-wise Comparison of Spire & SMAP SM
- GNSS-R soil moisture shows comparable quality to SMAP but has inherently smaller footprint





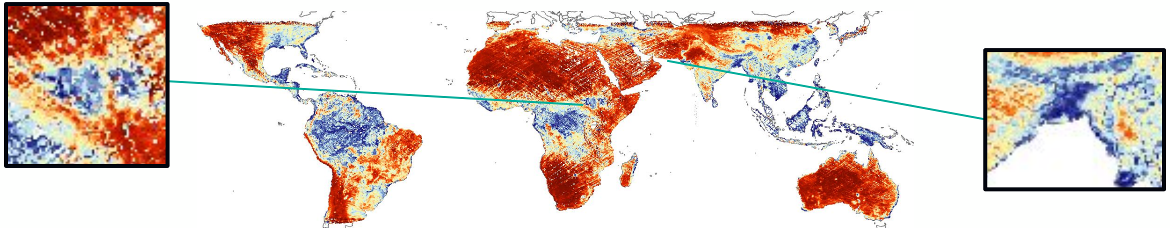
Spire L2 GNSS-R Soil Moisture



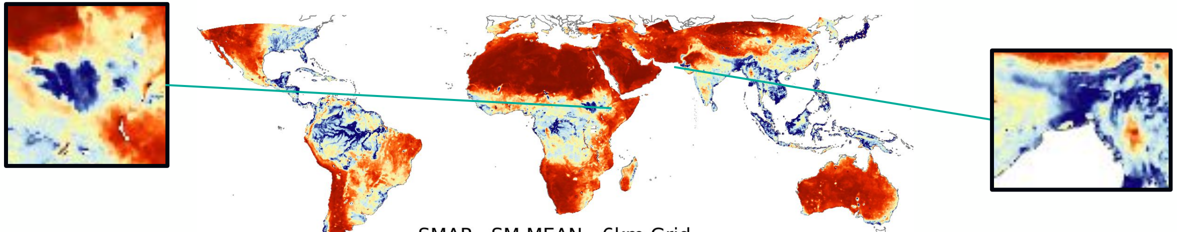


Regional and Spatial Comparison of Spire & SMAP SM

Averaging period
(**2021: Jan, Feb, Mar, Apr**)



Spire GNSS-R - CSSM MEAN - 24km Grid

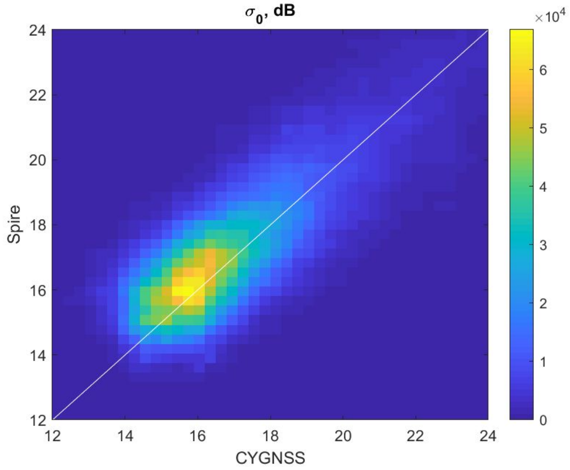


SMAP - SM MEAN - 6km Grid

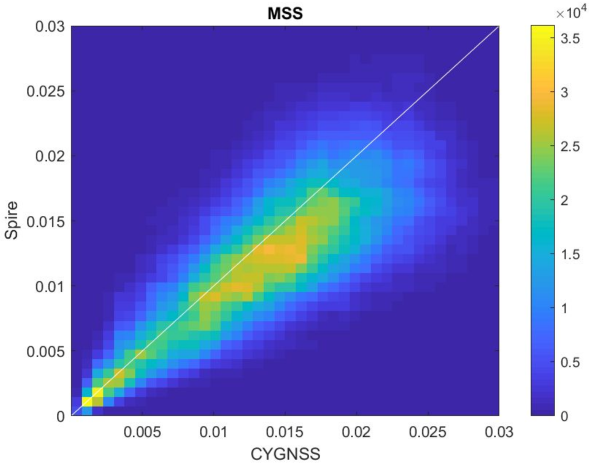
Spire L2 GNSS-R Ocean Products

Spire vs. CYGNSS ocean products

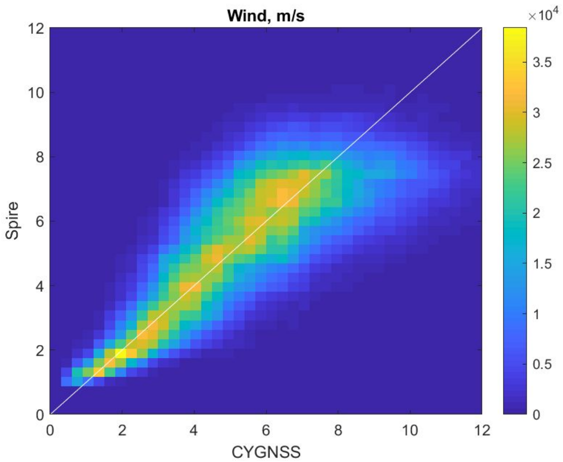
(8.6*10^6 point pairs)



NBRCS
corr = 0.83
std(diff) = 1.53 dB



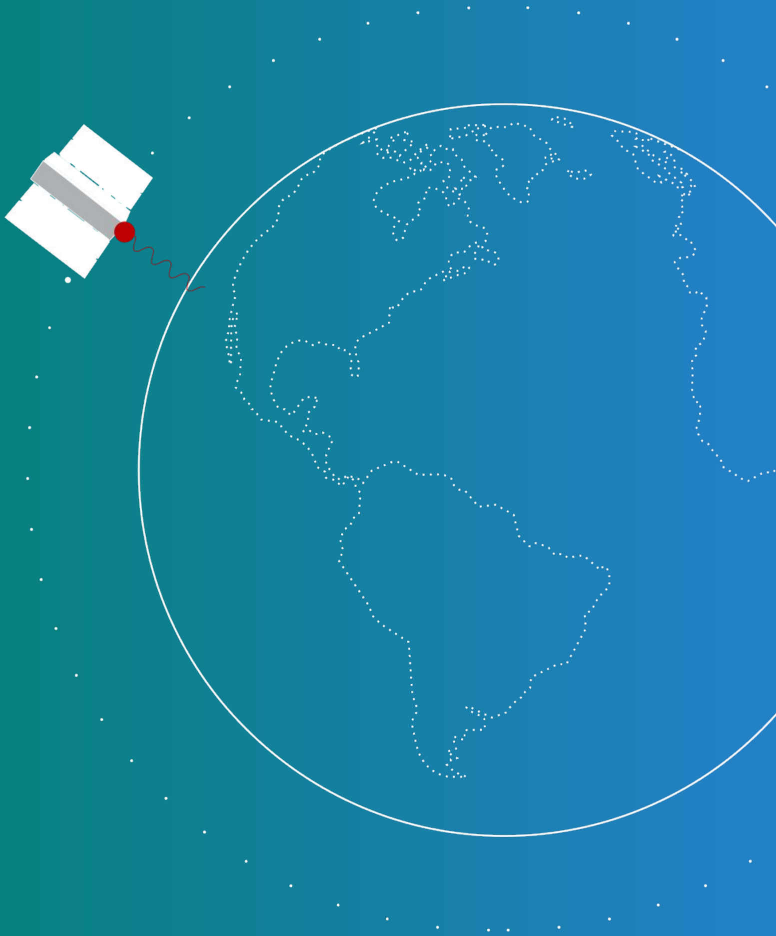
Mean Square Slope
corr = 0.75
std(diff) = 0.004



Ocean wind
corr = 0.74
std(diff) = 1.60 m/s

Space Weather

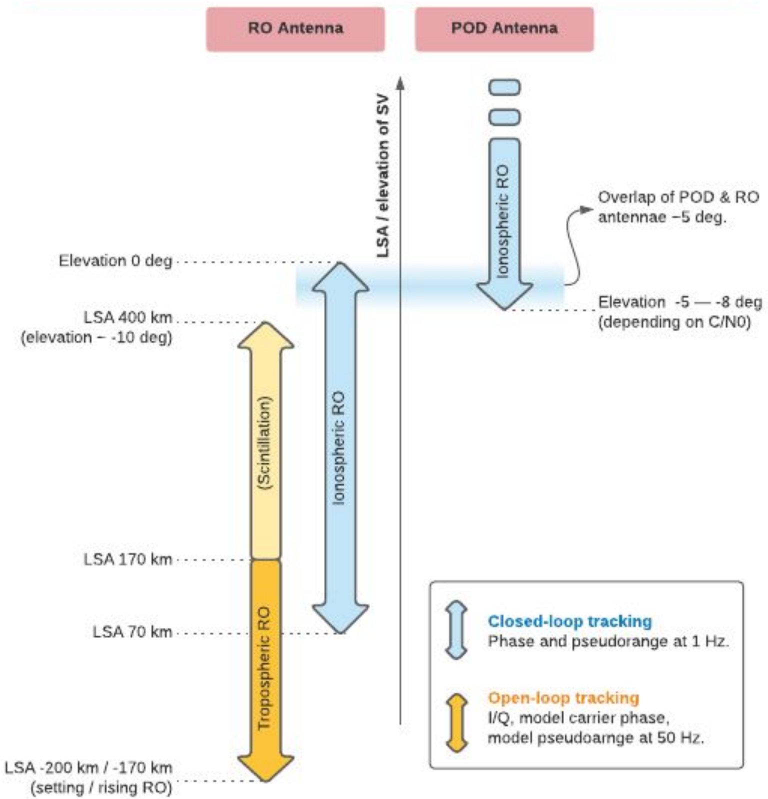
NASA CSDA Program



spire

SpWx Data in CSDA Program

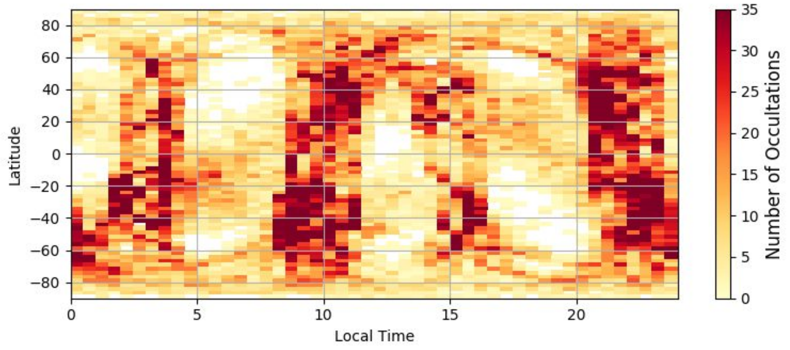
- SpWx relevant data collected from both POD and RO antennas
- POD antenna
  - 1 Hz, closed loop tracking
- RO antenna
  - 1 Hz, closed loop tracking
  - 50 Hz open loop tracking
- Slant TEC (podTEC, RINEX)
- Ionospheric density profile (ionPrf)
- Navigation data (leoOrb precise orbits in SP3 format, RINEX data)
- Scintillation (indices and 50 Hz raw)



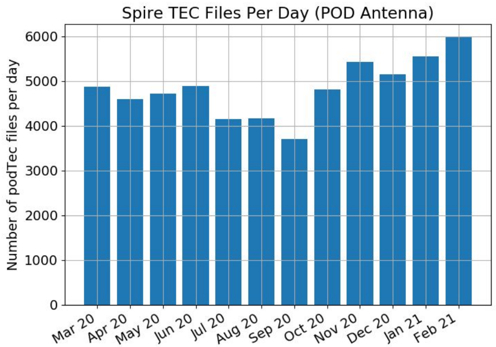
SpWx Data in CSDA Program

- Spire satellites mostly located in a mixture of sun-synchronous and mid-latitude orbits
- 5000+ continuous, closed-loop GPS links are processed into TEC measurements per day through the POD antenna
    - 8 million TEC points per day
- Increasing number of ionospheric events collected through the RO antennas
    - ~4000 events per day

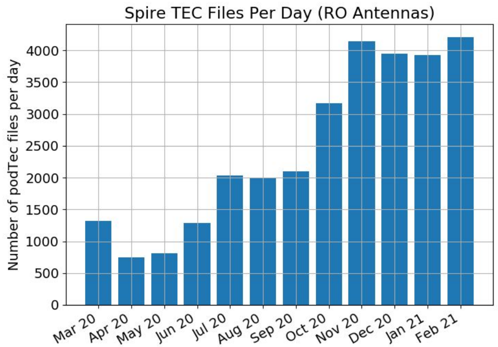
Global RO profile collection density



Number of TEC Files (POD antenna)

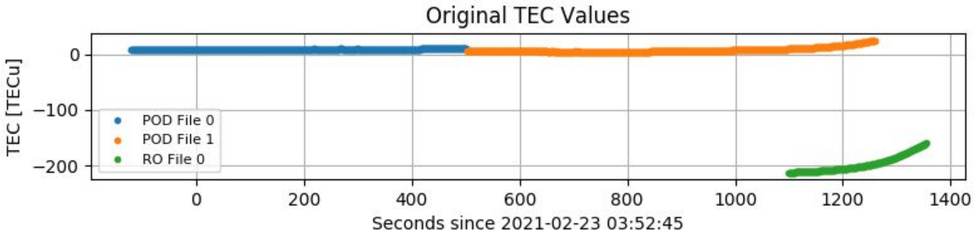


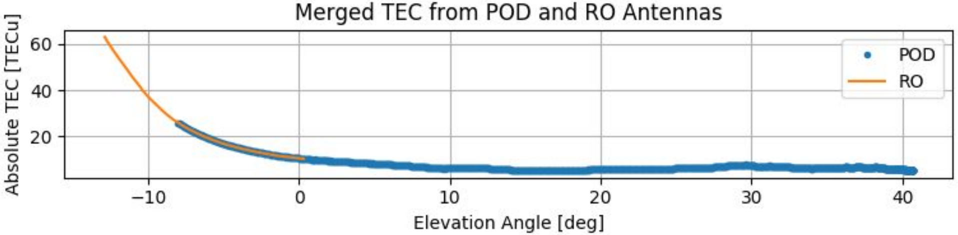
Number of TEC Files (RO antenna)

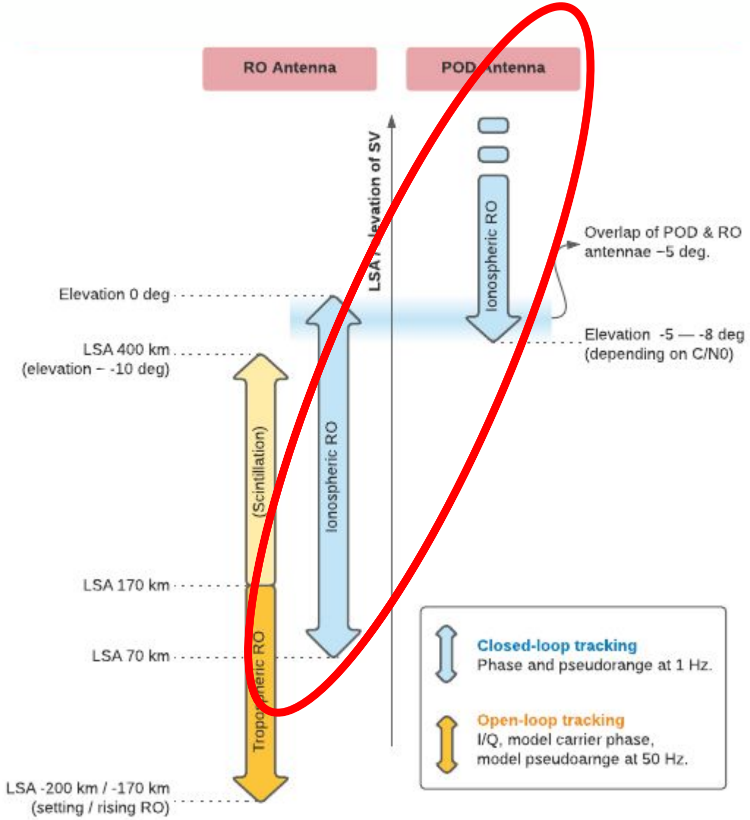


New Merged TEC Product

- Combined ionospheric TEC from both POD and RO antennas
- Level RO antenna TEC to POD antenna TEC
  - Calibrated data across extended height range
- Allows for more reliable retrieval of electron density



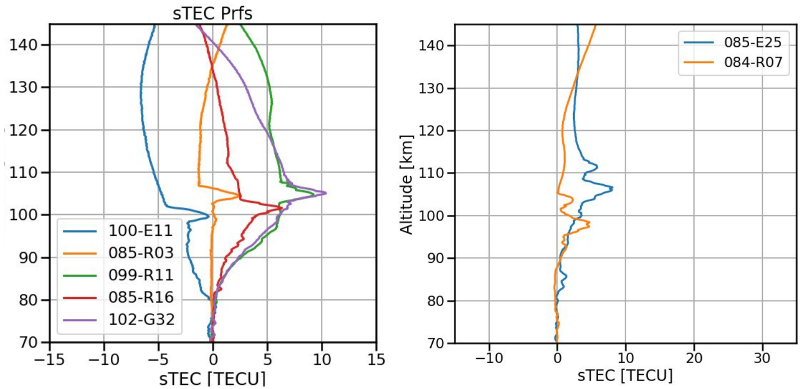




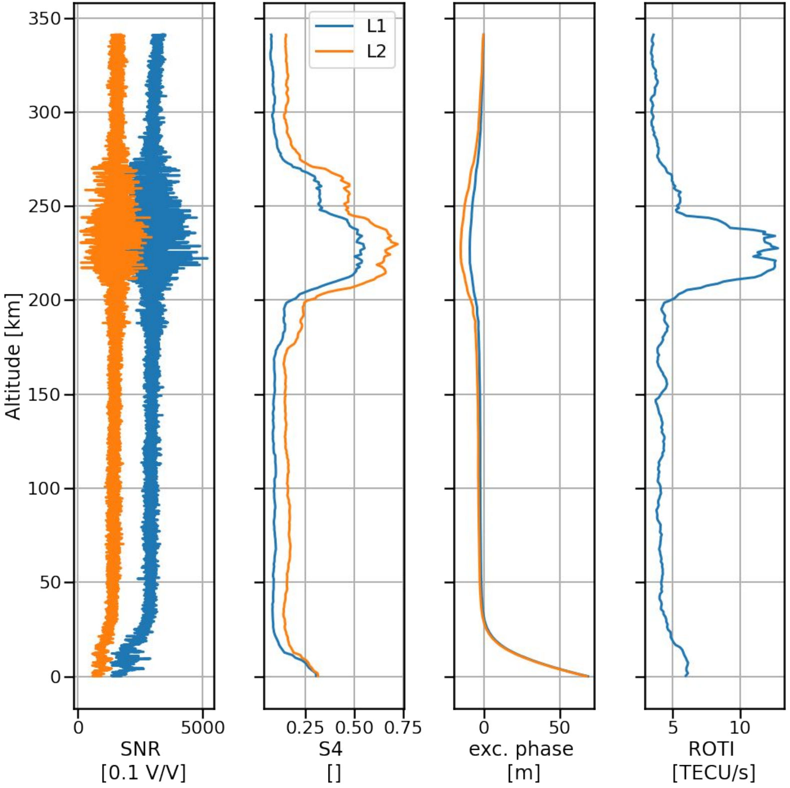
High-Rate Data and Scintillation

- High-rate (50 Hz) open-loop phase data are collected through RO Antennas
  - Spans at least from 150 km and downward
  - Multi-constellation
- On-board estimation of S4
  - **50 Hz data from orbit altitude downward is downlinked if S4 exceeds threshold (like COSMIC-2)**

Relative TEC Profiles in E-region

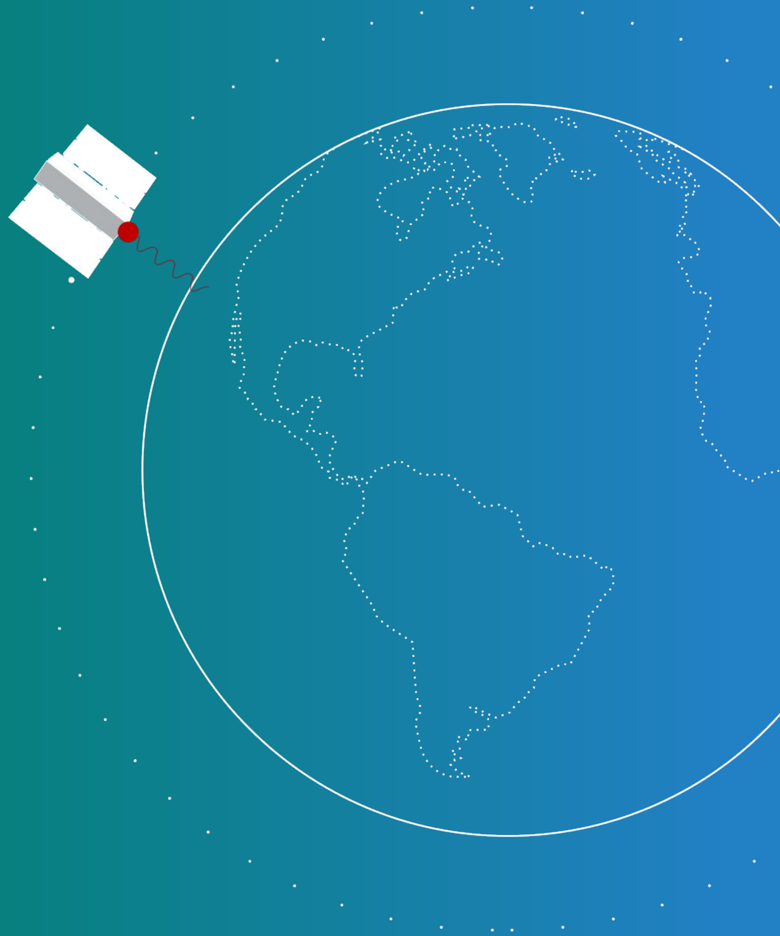


F-region 50 Hz Data and Scintillation Indices



Precise Orbit Data

NASA CSDA Program



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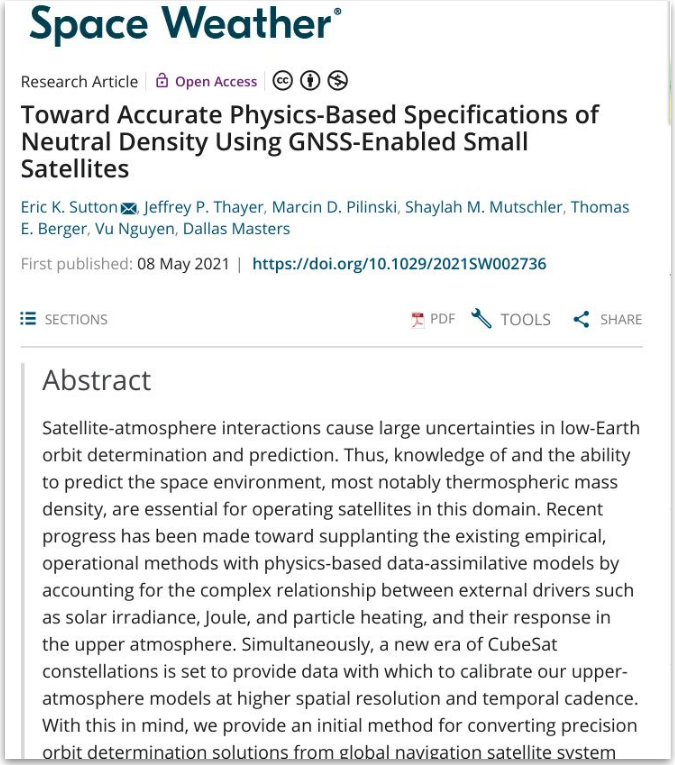
Precise Orbit Data in CSDA Program

- 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
  - Mass change trend signals and annual signals for different recovered by GPS receivers in LEO using POD techniques (e.g., da Encarnação et al, 2019)



Space Weather®

Research Article | Open Access

Toward Accurate Physics-Based Specifications of Neutral Density Using GNSS-Enabled Small Satellites

Eric K. Sutton, Jeffrey P. Thayer, Marcin D. Pilinski, Shaylah M. Mutschler, Thomas E. Berger, Vu Nguyen, Dallas Masters

First published: 08 May 2021 | https://doi.org/10.1029/2021SW002736

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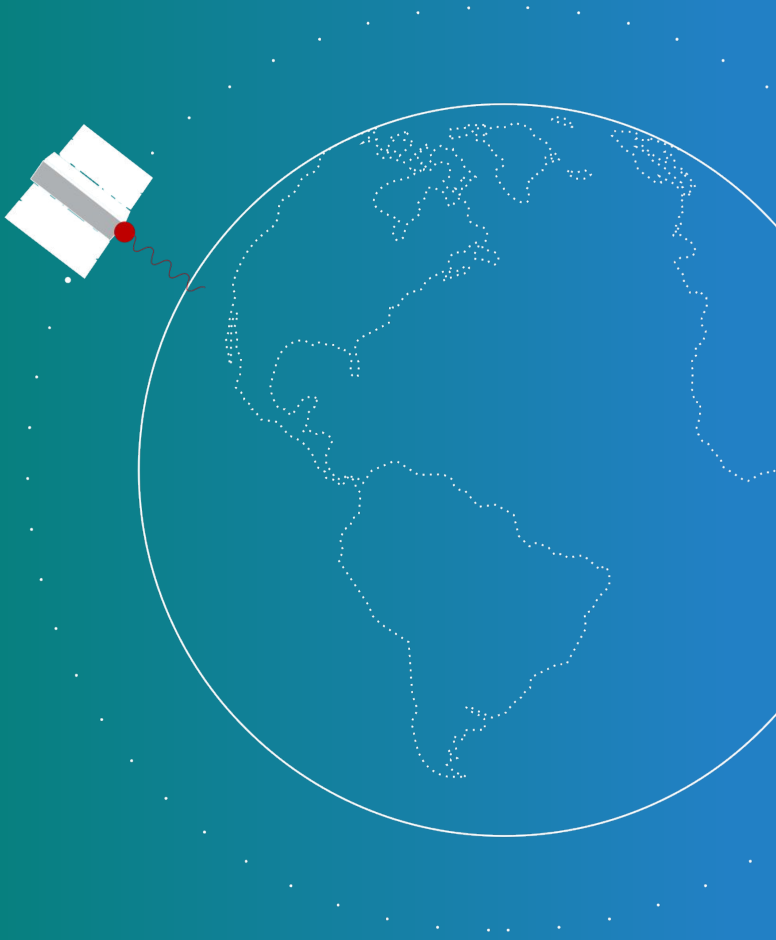
Abstract

Satellite-atmosphere interactions cause large uncertainties in low-Earth orbit determination and prediction. Thus, knowledge of and the ability to predict the space environment, most notably thermospheric mass density, are essential for operating satellites in this domain. Recent progress has been made toward supplanting the existing empirical, operational methods with physics-based data-assimilative models by accounting for the complex relationship between external drivers such as solar irradiance, Joule, and particle heating, and their response in the upper atmosphere. Simultaneously, a new era of CubeSat constellations is set to provide data with which to calibrate our upper-atmosphere models at higher spatial resolution and temporal cadence. With this in mind, we provide an initial method for converting precision orbit determination solutions from global navigation satellite system

Future Products

NASA CSDA Program



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Possible Future CSDA Program Products

- Spire is developing new EO products that will be made available for consideration for future task orders possible next year
- Time frame is dependent on Spire development

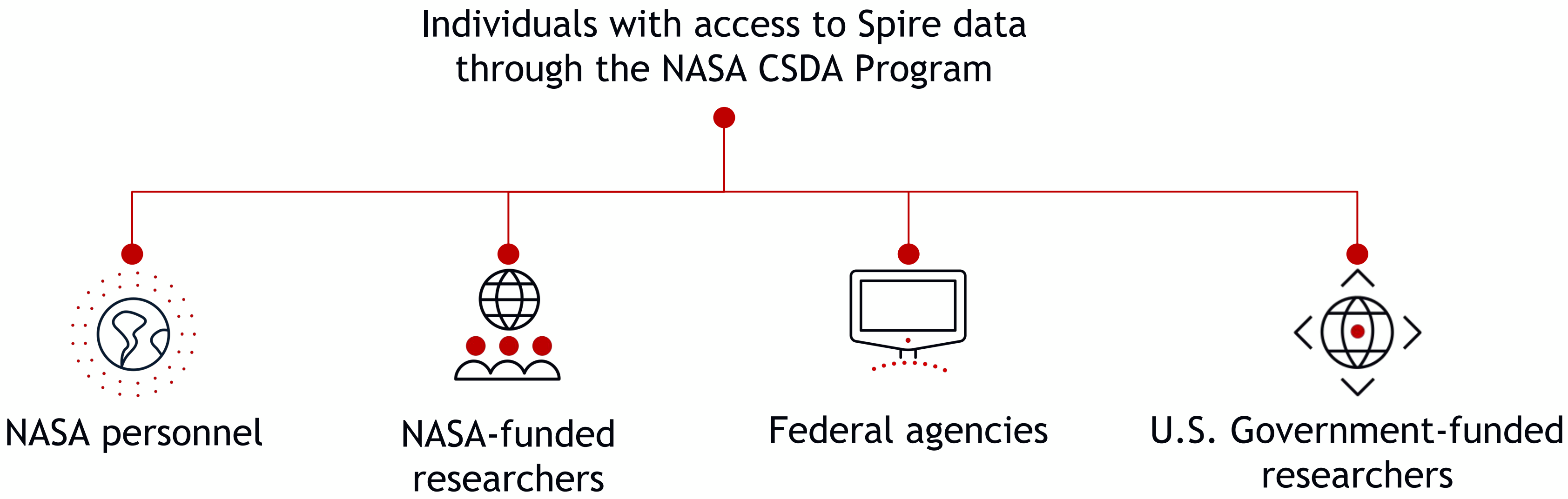
Product	Description
L2 GNSS-R Surface Water Mapping (L3 gridded product to follow)	Along-track GNSS-R surface water mapping state estimates from Spire GNSS-R satellites
L2 GNSS-R Soil Freeze/Thaw State (L3 gridded product to follow)	Along-track GNSS-R surface soil moisture freeze/thaw state estimates from Spire GNSS-R satellites
L2 GNSS-R Sea Ice (L3 gridded product to follow)	Along-track GNSS-R seas ice properties from Spire GNSS-R satellites (e.g. GNSS-R Batch-2 satellites to be launched in JAN 2021)
L2 GNSS-R River Width Estimates	River width estimates derived from Spire GNSS-R satellites

AGENDA

- Spire Overview
- EO Satellite Constellation
- CSDA Program Data Products
- **EULA and T&Cs**
- Accessing the Data & Support

End User License Agreement

This latest version* of the EULA is effective as of 9 NOV 2020 and applies to Spire data accessible through the NASA CSDA Program



* The EULA document is available on the CSDA Program website: https://cdn.earthdata.nasa.gov/conduit/upload/16879/CSDA_Program_USG_EULA-11-09-20_Rev3.pdf

Terms and Conditions

Pertaining to the use of Spire Data under the NASA CSDA Program

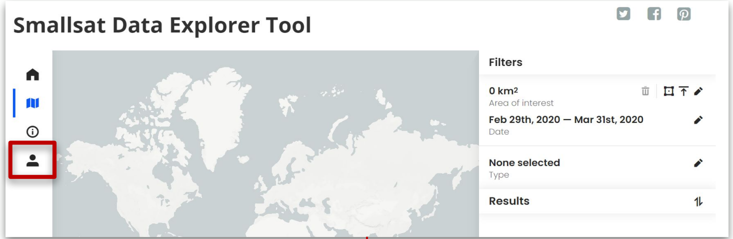
- Commercial Data is the exclusive property of Spire
- Commercial Data is provided only for scientific use
- Commercial Data is **not for commercial use**
- Derivative publications must include a **copyright notice:**
  - “Includes copyrighted material of Spire Global, Inc. All rights reserved”
- Courtesy 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

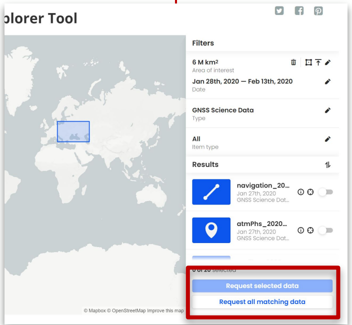
AGENDA

Accessing the data

Spire data is accessible through the NASA Smallsat Data Explorer (SDX) using Earthdata login credentials

- Create an Earthdata login: https://urs.earthdata.nasa.gov/
- Navigate to the CSDA Program Smallsat Data Explorer (SDX): https://earthdata.nasa.gov/esds/csdap/sdx
- On the left side of the screen, login to your Earthdata account.
- Selected your filter parameters and click “Request data”
- A NASA reviewer will validate the request and, if approved, send a URL with access to the data





User Support

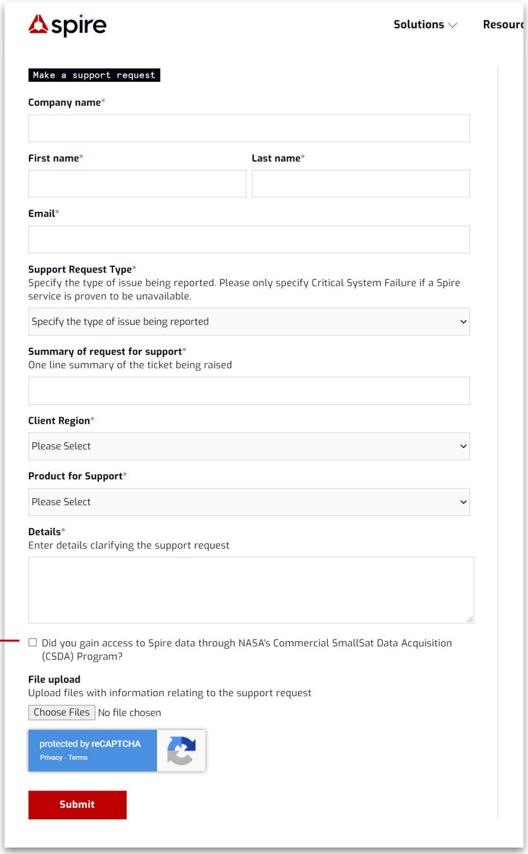
NASA can provide SDX and data access support, Spire is available for questions on the data itself

Accessing the data through SDX:

- Click the *Contact Us* link at the bottom of the SDX page

Submit a Spire Support Request:

- Navigate to https://spire.com/developers/support/
- Fill out the requested information
- Indicate on the form that you are asking about NASA CSDA Program data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First name* Last name*
Email*
Support Request Type*
Specify the type of issue being reported. Please only specify Critical System Failure if a Spire service is proven to be unavailable.
Specify the type of issue being reported
Summary of request for support*
One line summary of the ticket being raised
Client Region*
Please Select
Product for Support*
Please Select
Details*
Enter details clarifying the support request
Did you gain access to Spire data through NASA's Commercial SmallSat Data Acquisition (CSDA) Program?
File upload
Upload files with information relating to the support request
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Thank you

From our team, to yours.

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