SPIRE EARTH OBSERVATIONS FOR NASA'S CSDAP

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

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
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
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 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:
    ■ 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
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 Available in the CSDAP

<table>
<thead>
<tr>
<th>Data Type</th>
<th>Date Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw IF GNSS-R</td>
<td>2020 (various captures)</td>
</tr>
<tr>
<td>(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.)</td>
<td></td>
</tr>
<tr>
<td>Space Weather (TEC, EDP, scintillation)</td>
<td>11/1/2019 - onward</td>
</tr>
<tr>
<td>Magnetometer (simple sensor data)</td>
<td>11/1/2019 - onward</td>
</tr>
</tbody>
</table>
RADIO OCCULTATION DATA
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

RO production advancement:
- Quantity increase through launches and additional GNSS constellations tracked
- Receiver performance improvements
- Satellite bus performance improvements
- Continual data latency reduction

Feb 15, 2020: ~10K profiles per day
WORLD’S ONLY GPS, GLO, GAL, QZSS RO

- 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

Bending angle bias & STD vs. ECMWF

Distribution of the bending angle noise (median)

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

Slightly higher GLONASS bending angle noise due to transmitter clock

GLONASS
(1.75 urad)

GPS
(1.56 urad)

QZSS
(1.59 urad)

GLONASS

GALILEO

QZSS

GPS

BA noise, urad

BA noise, urad

Probability

Probability

Mean(ΔBA/BA)

std(ΔBA/BA)
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**

- 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)?
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
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 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 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
SPRIE 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 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)
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
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.
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” 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
### BUILDING ON THE CYGNSS PATHFINDER

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