GNSS-Based Earth Observations from Spire's Growing Nanosatellite Constellation

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THE SPIRE CONSTELLATION
THIRD LARGEST SATELLITE CONSTELLATION IN THE WORLD

- The Low Earth Multi-Use Receiver (LEMUR) is Spire’s 3U CubeSat platform used for Earth observations and tracking maritime and aviation activity.

- We operate the world’s largest EO sensing fleet and are the largest producer of radio occultation and space weather data.

- It’s a Spire product from start to finish (except for the rocket) and this allows us to innovate quickly (e.g., first commercial RO, first operational phase-delay altimetry, etc.).

- We are continuously launching improved sensors and upgrading them on-orbit.

- We go from idea to launch in as little as 6-12 months.

A new faster and more agile paradigm for EO.
Spire 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 RO CubeSat Technology

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design Lifetime</td>
<td>3 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, agile and precise</td>
</tr>
<tr>
<td>Power</td>
<td>Triple-deploy solar arrays with batteries</td>
</tr>
<tr>
<td>Communication</td>
<td>UHF, S-Band, X-band</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 observations to meet societal needs*
RO Production Advancement:
- First commercial provider of four constellations and the only provider of Galileo and QZSS data
- Quantity increase through launches and additional GNSS constellations tracked
- Continual receiver and bus performance improvements
- Continual data latency reduction

Unmatched Volume

Unmatched Coverage

~10K raw profiles per day and global coverage

High percentage of Spire data pass QC (exceeds COSMIC-2 req of 73%)
Galileo-based RO (faster chipping rate) is fully functional after open-loop tracking improvements (COSMIC-2 still struggling with Galileo rising profiles)

Spire RO difference statistics vs. ECMWF match current operational RO missions
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.

- Comparison between constellations or with other RO sensors must account for geographic sampling differences.

- Spire penetration depths exceed COSMIC-1 and are comparable to COSMIC-2 (NASA CSDAP report).

Note: geographic sampling bias by GNSS constellation.
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 forecast impact study.

UKMO forecast impact study deemed Spire RO is comparable to MetOp-C.

NASA study also found Spire RO comparable to operational missions.

[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.

NOAA has concluded that the commercial sector is capable of providing the quality of data needed to help support NOAA’s operational weather forecasting needs. As a result, NOAA is proceeding with plans to acquire commercial RO data for operational use. - NOAA CWDP Summary.
Spire RO Impact on ECMWF Forecasts

- Spire is provided RO to the ECMWF, UK Met Office, and US Air Force during the COVID-19 to compensate for the lack of aircraft measurements.

- ECMWF saw significant increase in relative forecast sensitivity to observation impact (FSOI) when COSMIC-2 RO was assimilated in March and again when Spire RO were assimilated in May.
GNSS Reflectometry (GNSS-R)
GNSS-R Observations

GNSS-R is a form of bistatic radar using GNSS signals of opportunity (e.g., GPS, Galileo, QZSS, GLONASS) to perform Earth surface scatterometry (reflectivity and roughness estimation, e.g., NASA CYGNSS mission).

Natural progression from successful Spire radio occultation (RO) satellites to add GNSS-R scatterometer satellites to Spire constellation
### New Spire GNSS-R Satellite Missions

**SPIRE GNSS-R “Batch-1” Satellites**
- Launched December 2019
- Novel calibration method
- Digital beamforming

<table>
<thead>
<tr>
<th>Parameter</th>
<th>NASA CYGNSS</th>
<th>Spire GNSS-R Batch-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simultaneous reflections observed</td>
<td>4</td>
<td>32</td>
</tr>
<tr>
<td>GNSS Constellations tracked</td>
<td>GPS</td>
<td>GPS, QZSS, Galileo, SBAS</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), <strong>beamforming</strong></td>
</tr>
<tr>
<td>Mass</td>
<td>25 kg</td>
<td>5 kg</td>
</tr>
<tr>
<td>Orbit</td>
<td>35 deg, 510 km</td>
<td>37 deg, 571 km</td>
</tr>
<tr>
<td>Expected lifetime</td>
<td>2 years</td>
<td>2 years</td>
</tr>
</tbody>
</table>
Spire GNSS-R: First to Beamform

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.
Spire GNSS-R Program Status

- Two GNSS-R Batch-1 satellites in operation producing onboard DDMs
- Two new GNSS-R Batch-2 satellites (new receiver and antennas) are scheduled to launch in December 2020
- Operational GNSS-R products (e.g., reflectivity and soil moisture) expected in late 2020
- Increased temporal and spatial sampling as GNSS-R constellation builds out
Ionospheric Observations
SpWx Measurements

- Ionospheric information is derived from GNSS signals
- Spire provides observations
  - in data denied areas
  - with low-latency
- Different scales
  - Global
    - Slant total electron content (TEC)
  - Mid-scale
    - Sporadic E, traveling ionospheric disturbances
  - Small scale
    - Scintillation events
High Rate Observations

- High rate (50 Hz) phase data are collected through the RO antennas
- Spans the E-region ionosphere (< 150 km)
- Data are valuable for studies investigating features of the MLT/E-region

If scintillation is detected, the high rate (50 Hz) data can then be downlinked for additional processing
  - S4 > 0.6 and persists for > 10s

Independent observations:
  - Different GNSS Tx
  - Different Spire’s Rx
Key Takeaways

1. GLOBAL CONSTELLATION
Spire has built an operational Earth observations constellation that is improving weather forecasting and enabling new Earth science and applications.

2. UNMATCHED VOLUME & COVERAGE
We cost-effectively harness CubeSats to collect large quantities of Earth observations to positively impact applications that benefit from high spatial and temporal sampling and low-latency.

3. EARTH OBSERVATIONS
Having proven the viability of commercial RO, Spire is now expanding into space weather monitoring and GNSS-R applications such as soil moisture, ocean winds, and sea ice.

4. CONTINUED IMPROVEMENT
Spire aims for continuous scaling, replenishment, and improvement for sustained, long-term Earth observations.
Contact Us

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