Earth Surface Monitoring with Spire’s New GNSS Reflectometry (GNSS-R) CubeSats

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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 save lives and billions of dollars... TODAY.
Established company with ~220 people (and growing) across six offices
• Full nanosatellite manufacturing facilities and supply chain
• 88 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 coverage in multiple orbit inclinations
• World’s largest GNSS-based, Earth observation (EO) constellation for weather, space weather, and GNSS-R
• World’s largest ship tracking constellation
• ADS-B aircraft tracking product
• Various weather forecast products
• Over $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 leverages the ultra-stable, dual-frequency L-band signals broadcast by GNSS satellites to measure Earth properties that perturb these signals (e.g., refraction, reflection, etc.). These observations have various applications, such as NWP (radio occultation), space weather (TEC), bistatic radar, altimetry.
GNSS-REFLECTOMETRY (GNSS-R)

GNSS-R is a form of bistatic radar using GNSS signals of opportunity (e.g., GPS) to perform Earth surface scatterometry (reflectivity and roughness estimation, e.g., NASA CYGNSS mission) or grazing angle phase delay altimetry (performed on Spire RO satellites).

Natural progression from RO to add GNSS-R scatterometer satellites to Spire constellation

GNSS-R observables include the power of the reflected signal normalized by the measured direct signal power, either as a peak power, delay-Doppler map (DDM), or as a stare-processed “pixel.”
The NASA’s Cyclone Global Navigation Satellite System (CYGNSS)

- Constellation of 8 Satellites
- Launched in December 2016 (science data take starting March 2017)
- L-band reflectometer
- Coverage: approximately 38° N and 38° S latitude.
- Spatial resolution:
  - Incoherent observations (ocean): < 15 km
  - Coherent measurements: ∼ 3.5x0.5 km
- Mean temporal resolution: 7.5 hr at 25km
Spire is developing its first GNSS-R missions in two batches

- Batch-1: 2 sats launched in 2019 Q4
- Batch-2: 2 sats to be launched in 2020

**GNSS-R Applications** (EO constellation)

- Soil moisture
- Ocean wind/waves
- Phase-Delay Altimetry
- Sea ice
- Wetlands/flood inundation
<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>16-24 (possibly more)</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>
BISTATIC RADAR CONCEPT

- The scattered power at the receiver is composed of a reflected, coherent component and a scattered incoherent component
  \[ P_{pq}^r = P_{pq}^c + P_{pq}^i \]

- Flat surface (coherent reflection, soil)
  \[ P_{lr}^c = \frac{p_t^t G_t^t}{4\pi(R_{ts} + R_{sr})^2} \frac{G_r \lambda^2}{4\pi} \Gamma_{lr} \]

- Rough surface (Incoherent scattering, ocean)
  \[ P_{rl}^i = \frac{p_t^t G_t^t}{4\pi R_{ts}^2} \frac{G_r \lambda^2}{4\pi} \int_A \frac{\sigma^0}{4\pi R_{sr}^2} \, ds \]
SPIRE’S SM RETRIEVAL METHOD

- The reflectivity over land varies according to soil moisture, surface roughness and vegetation. For a given location, the surface roughness can be considered nearly constant. Short-term fluctuations in reflectivity (dB scale) have a linear relationship to the changes in soil moisture. Seasonal changes in vegetation may still affect the reflection, but in a much longer time scale than of soil moisture.

- A relative measure of reflectivity is calculated which corresponds to soil moisture variations. The obtained product is ranging between 0 and 100 and is called Relative Surface Soil Moisture (RSSM).

- The RSSM can be calibrated if the soil porosity is known. The RSSM could be also calibrated using other soil moisture observations (e.g. SMAP) by simple scaling or using a more sophisticated technique like CDF-matching.
SPIRE’S SM RETRIEVAL METHOD

- $\Gamma^{40}$ is the normalized reflectivity at 40° incidence angle:

- $\Gamma_{dry}$ and $\Gamma_{wet}$ are the normalized reflectivity corresponding to driest and wettest soil conditions:

- The obtained product is ranging between 0 and 100 and is called Relative Surface Soil Moisture (RSSM). The RSSM can be calibrated if the soil porosity is known:

$$CSSM(m^3m^{-3}) = RSSM(\%) \frac{Soil\ Porosity(m^3m^{-3})}{100}$$

- RSSM could be also calibrated using other soil moisture observations (e.g. SMAP) by simple scaling or using a more sophisticated technique like CDF-matching.
CYGNSS coverage is limited to ~ +/- 37 deg latitude band due its orbit selection targeting hurricanes.
Spire has produced a soil moisture product from CYGNSS data and is operationalizing it to prepare for processing data from Spire GNSS-R satellites.
GNSS-R RSSM TIME SERIES EXAMPLE
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SPACE PROGRAM, GNSS-R R&D

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