

# SPACE WEATHER OBSERVATIONS FROM SPIRE'S GROWING CUBESAT CONSTELLATION

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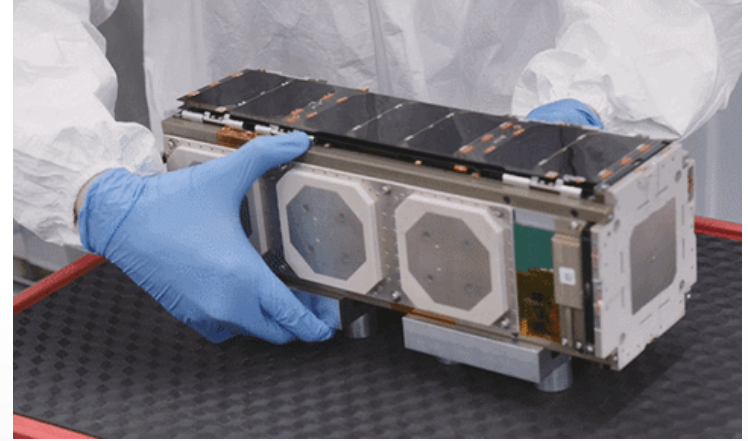
<sup>4</sup> Spire Global Luxembourg S.a.r.l.

<sup>5</sup> GPS Solutions, USA



# SPIRE CUBESAT CONSTELLATION

Spire is a satellite and data analytics company, collecting and analyzing a wide range of remote sensing observations from **a growing constellation of 80+ operating LEO 3U CubeSats:**



3U LEMUR CubeSat

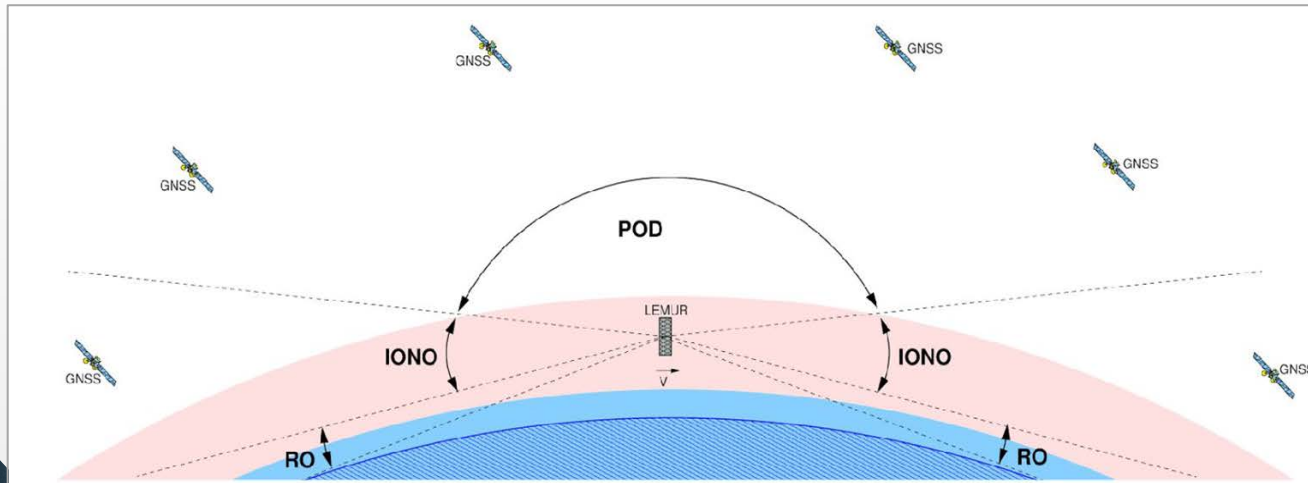
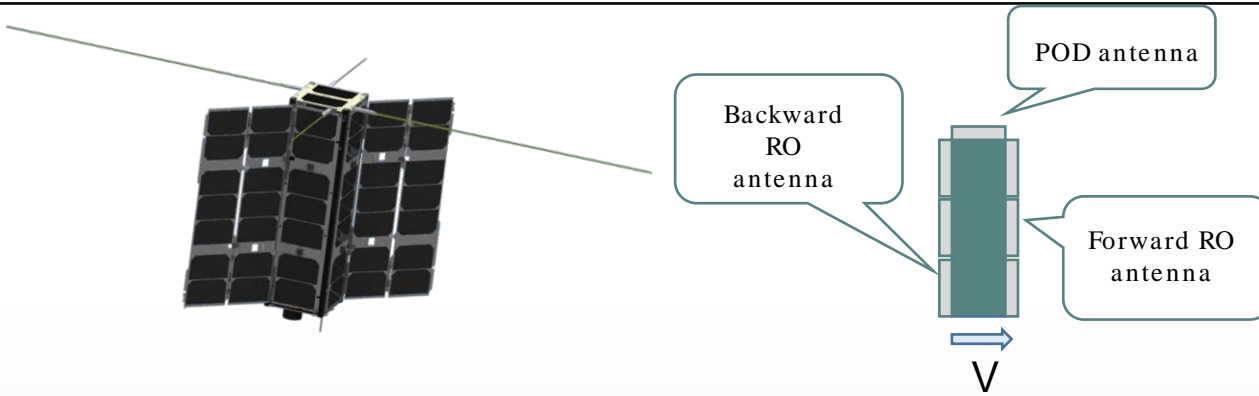
1. GNSS
  - a. Radio Occultation (RO)
  - b. Ionosphere (TEC, electron density)
  - c. Surface reflections (GNSS-R)
2. Hosted payloads / Orbital Services
3. AIS (ship tracking)
4. ADS-B (airline tracking)

- **Collecting ~5,000 RO per day and growing each launch**
- Rising & setting occultations (**2 RO antennas**)

- GNSS constellations tracked:
- GPS
  - **GLONASS**
  - **Galileo** (first commercial producer)
  - **QZSS**



# SATELLITE GEOMETRY



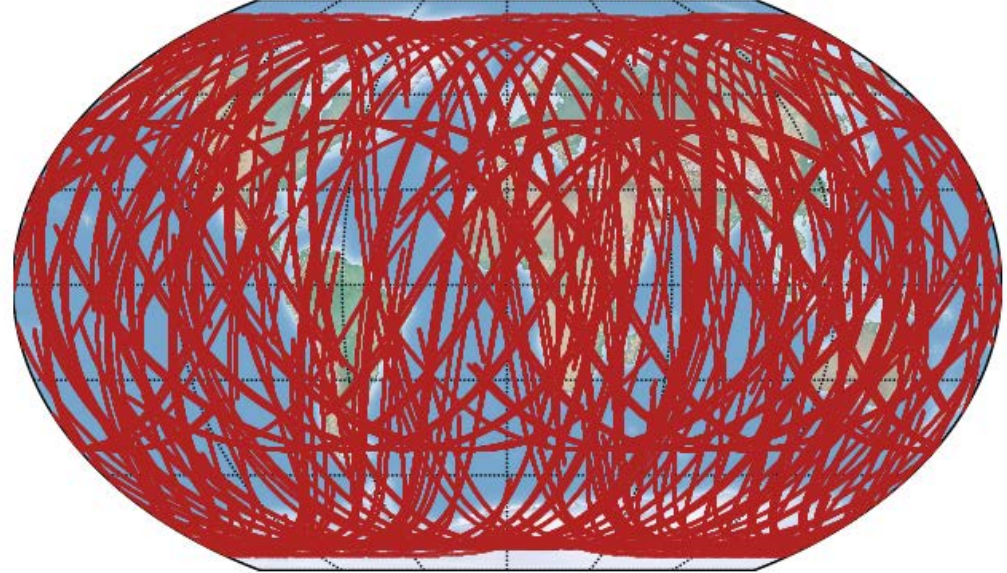
- Each satellite is equipped with a compact, low power, Spire-built GNSS radio occultation (RO) receiver
- Upward-facing antenna for precise orbit determination (POD)
- Dual-frequency observations also allow for derivation of ionospheric measurements



# SPACE WEATHER MEASUREMENTS

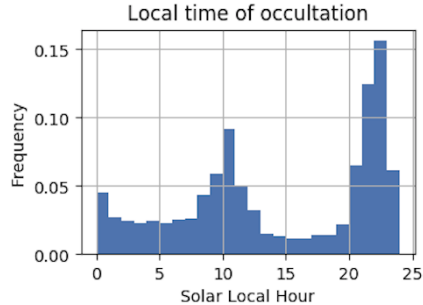
- Ionospheric information is derived from dual frequency GNSS signals
  - Slant total electron content (TEC)
  - Scintillation events
  - Electron density profiles
- Spire constellation provides these observations at unprecedented coverage
  - Data denied areas
  - Low latency
- Assimilation into upper atmospheric models for improved space weather forecasting predictions

Spire Ionospheric Coverage 2019-06-01 to 2019-06-02

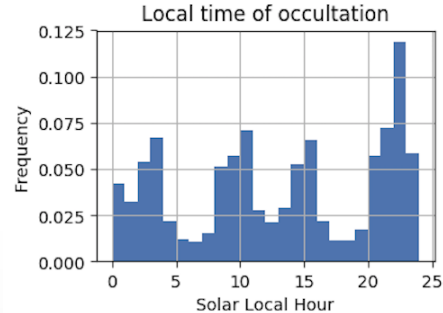


# GROWING DATA VOLUME

## Global Daily Coverage at All Local Times



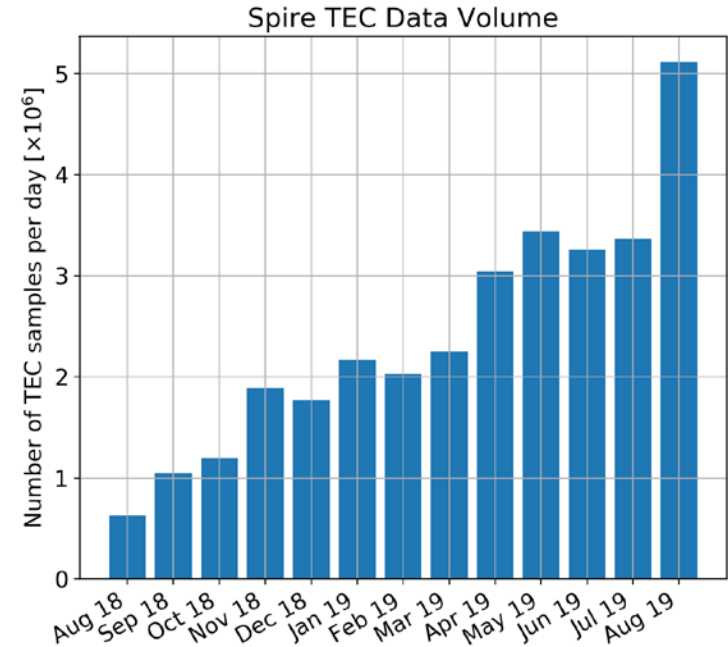
August 2018



August 2019

- **Ionospheric production has increased by 10x over the past year** due to launching of new satellites with enhanced capability
- New orbital planes result in better local time coverage

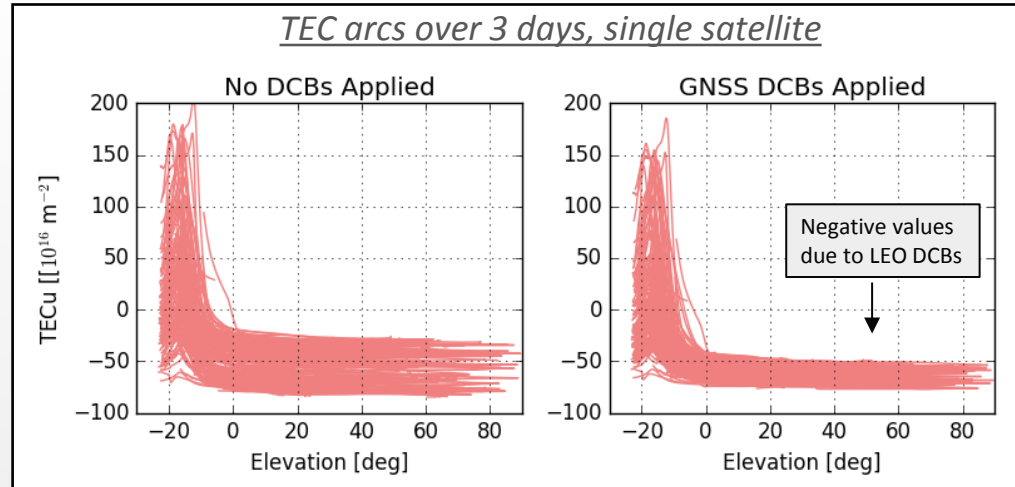
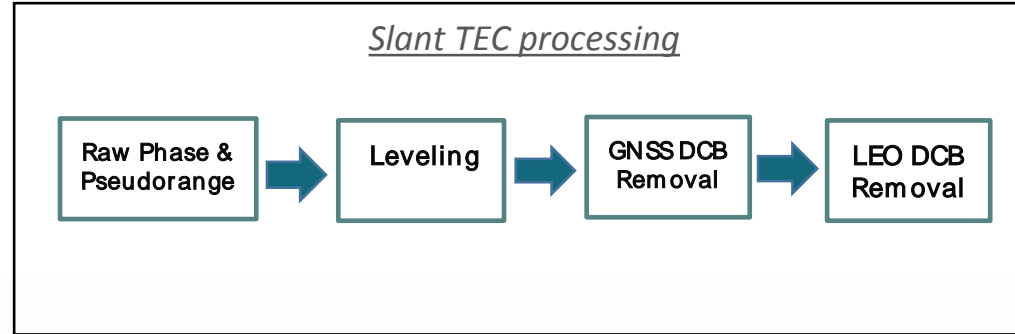
## Average Daily TEC Production Over Past Year





# TEC MEASUREMENTS

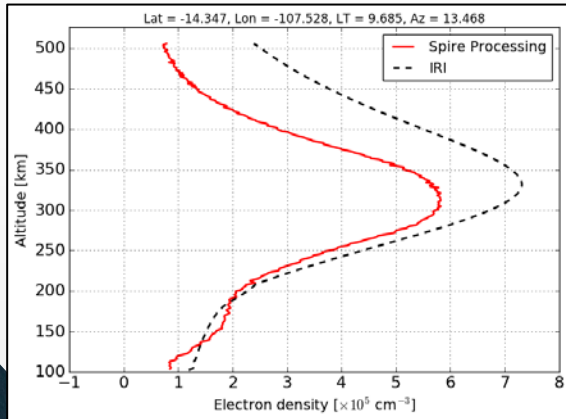
- Closed-loop dual-frequency observations are collected through the POD and RO antennas
  - 1-Hz pseudorange and phase
  - GPS-only
- Line-of-sight TEC data are processed by individual arcs
  - Leveling procedure minimizes the pseudorange-phase differences using a weighted scheme (*Pedatella, 2011*)
  - Cycle slip detection and correction algorithm applied
  - Stored in CDAAC *podTec* netcdf format



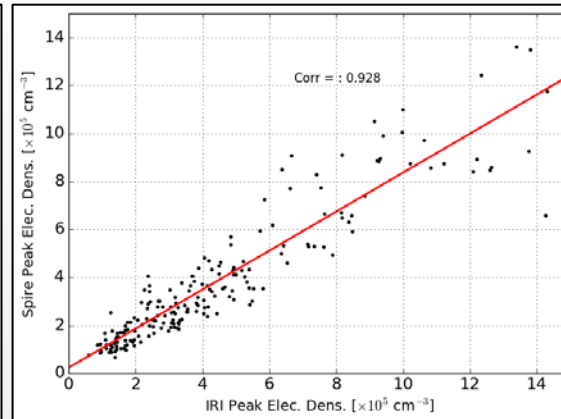
# ELECTRON DENSITY PROFILES

- Electron density profiles spanning up to orbit altitudes are derived from low elevation GNSS links
- A standard Abel inversion technique is currently applied. Model-aided approaches may be used in the future.

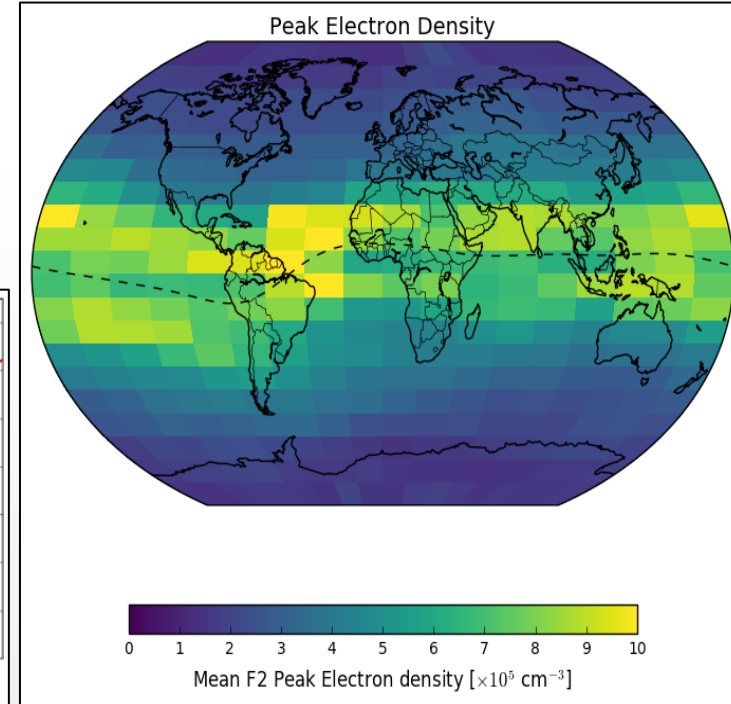
*Example of electron density profile*



*Nmf2 Spire-IRI comparison*

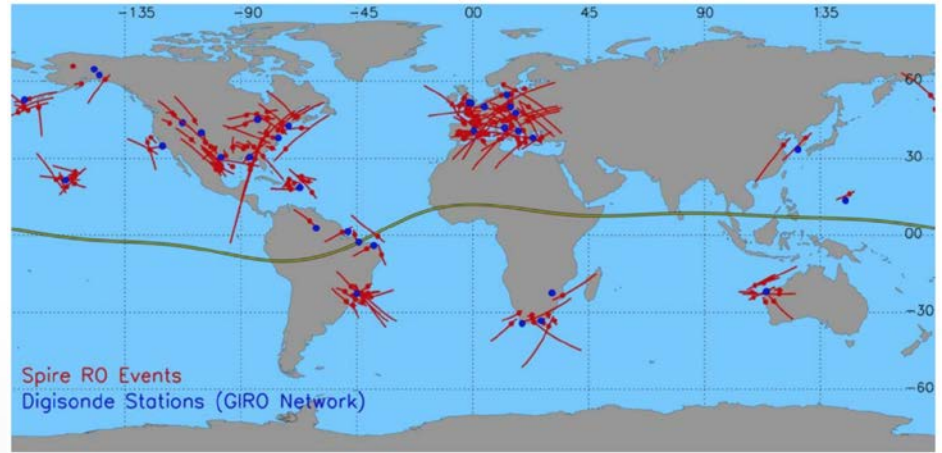


*Mean peak ionospheric electron density over 1 month*

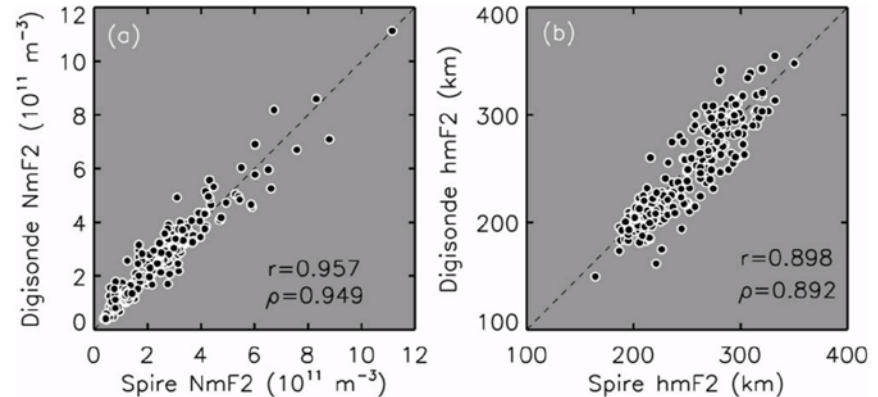


# ELECTRON DENSITY PROFILES

- V. Forsythe et al. retrieved electron density profiles from Spire TEC measurements
- Horizontal asymmetries were corrected by using the NeQuick model
- Strong agreement was obtained between the retrieved electron density profiles and nearby measurements from digisondes and incoherent scatter radars



Full results will be published at  
**V. Forsythe, T. Duly, D. Hampton and V. Nguyen (2019), Validation of Spire CubeSat constellation ionospheric electron density measurements, Radio Science (in-review)**

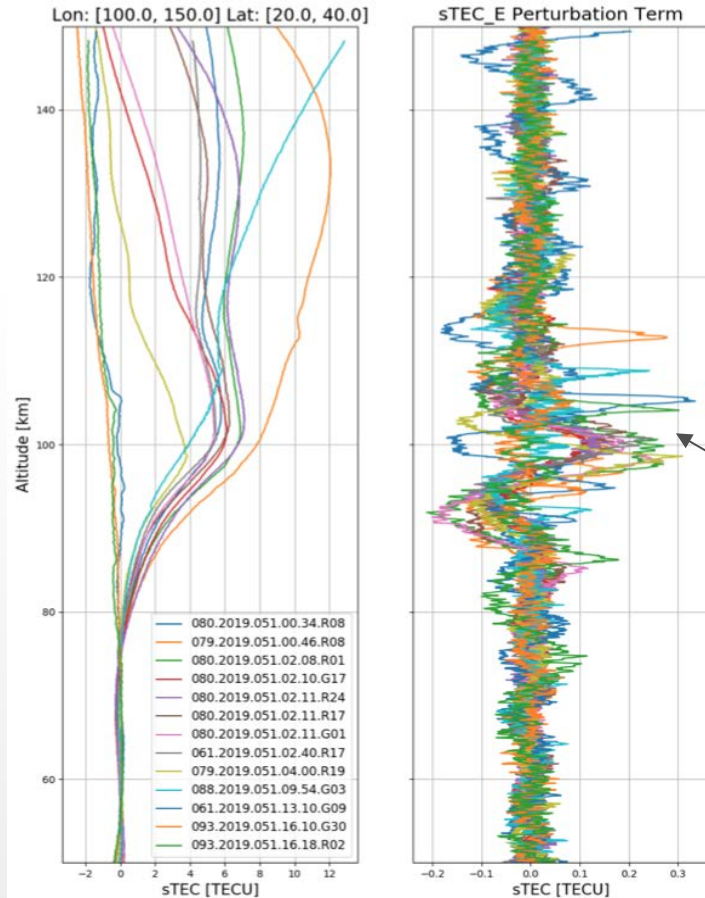




# HIGH-RATE IONOSPHERIC DATA

High rate (50 Hz) phase data are collected through the RO antennas

- Currently spans the lower E-region ionosphere (< 150 km)
- Considering increasing the altitude range to span the F-region
- High vertical resolution: < 100 m



E-region contributions to slant total electron content and electron density measurements can be derived from 50 Hz measurements (*Wu, 2018*)

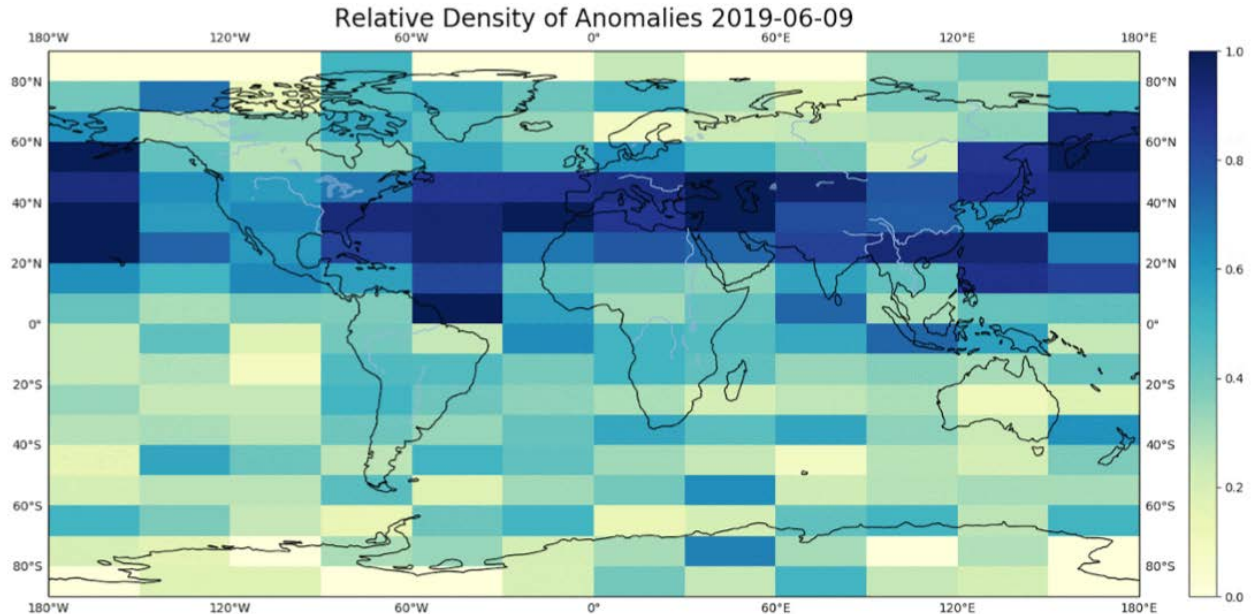
Data are valuable for studies investigating features of the MLT/E-region

- Gravity waves
- Atmospheric tides
- Sporadic E-layers



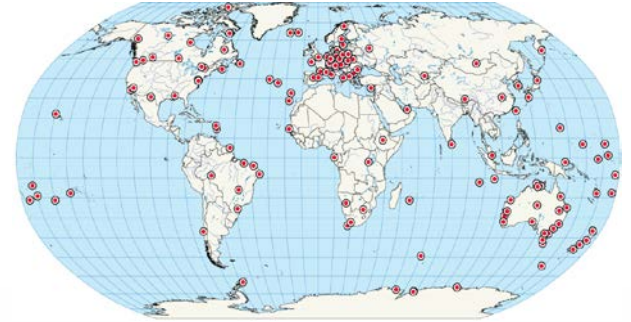
# E-REGION ANOMALY DETECTION

- Spire E-region profiles were processed to detect anomalies using Hilbert-Huang transform likely caused by TIDs and sporadic-E layer events
- Enhancement of anomalies detected at summer-time mid-latitudes, which agrees with past phenomenology



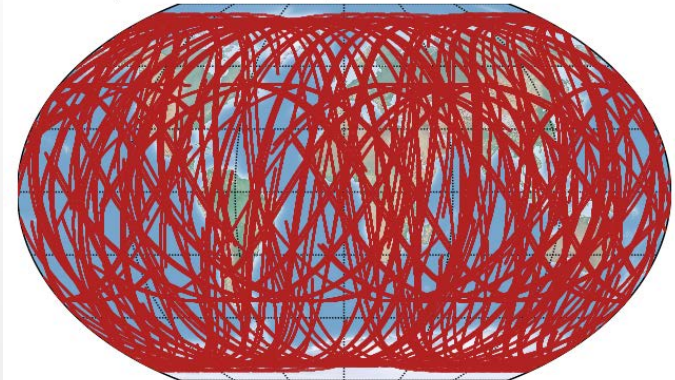
# DEVELOPMENT OF IONOSPHERIC MODEL

- **Spire TEC Assimilative Model (STEAM):**
  - Combines NeQuick ionospheric model with an local ensemble transform Kalman Filter (LETKF) data assimilation scheme
  - TEC data is derived from Spire LEO constellation and GNSS ground networks
  - Extendable to use in-situ data, ionosondes, etc.
  - 15 minute assimilation window
- Spire LEO data provides valuable information on the vertical structure of the ionosphere and helps compensate for data-poor regions such as **oceans**

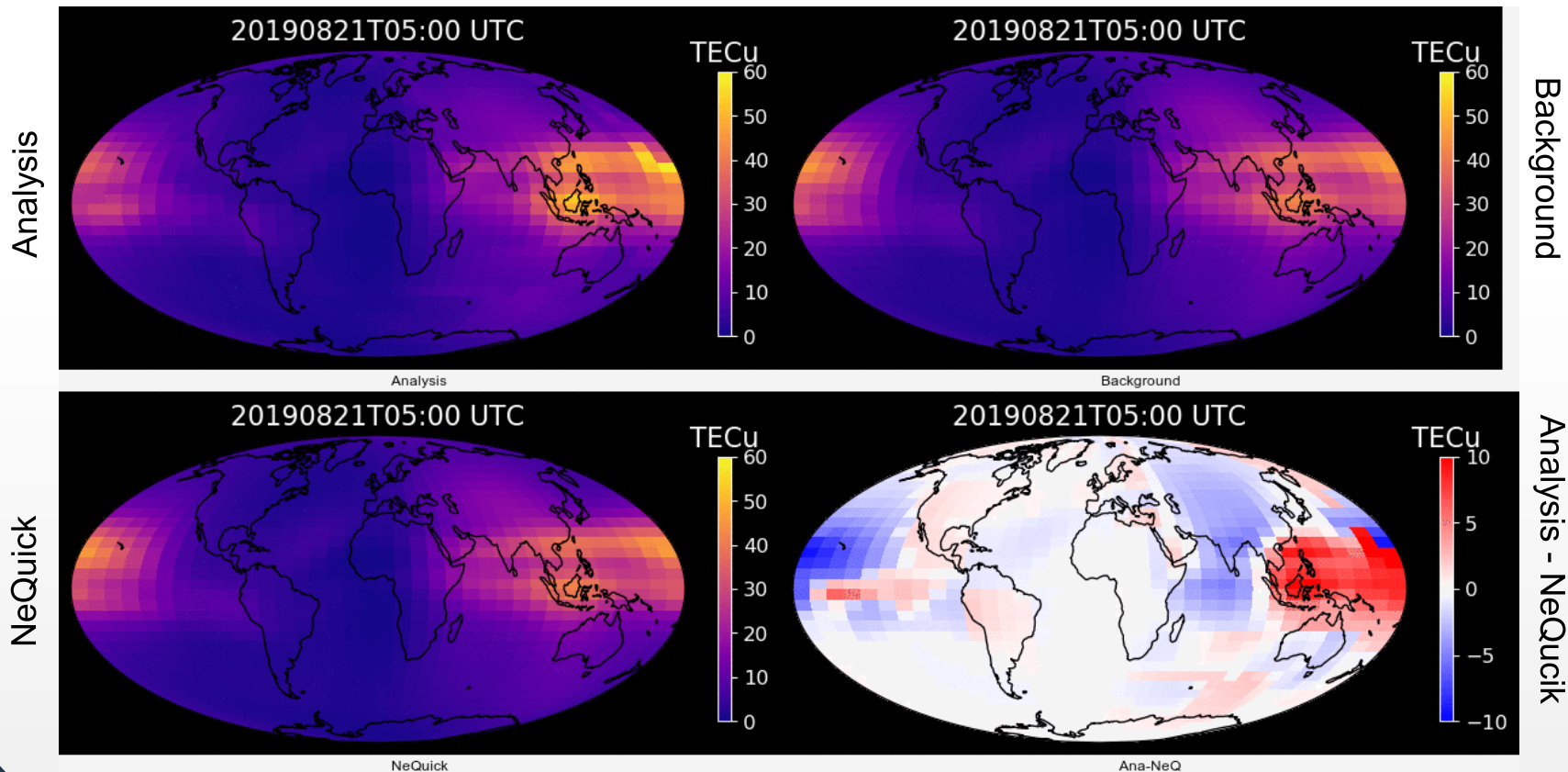


Map of the location of ground stations forming part of the IGS network.

Spire Ionospheric Coverage 2019-06-01 to 2019-06-02



# IONOSPHERIC DA MODEL - STEAM TEC



Example STEAM TEC maps for 2019-08-21

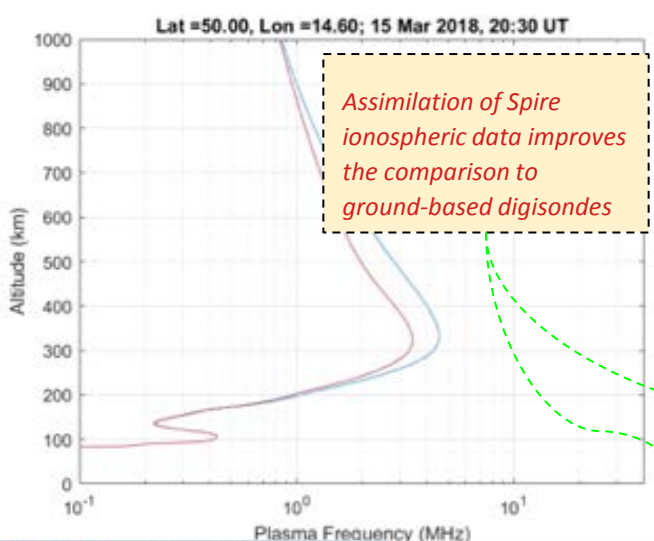


# IMPACT ON EXTERNAL SPWX MODELING

External users have also utilized Spire data to improve SPWX modeling and understanding

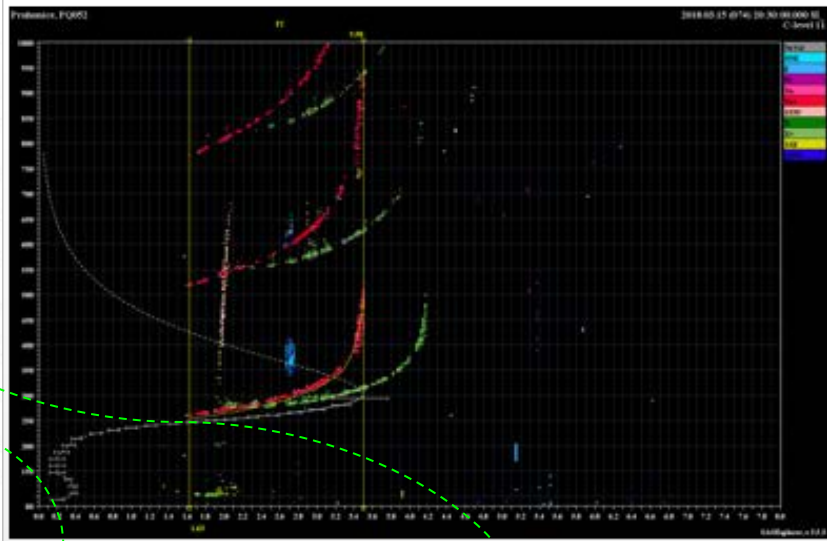
K. Kramer et al. (NWRA) conducted a study that highlights the promise of using Spire ionospheric data in an assimilative system (GPSII)

GPSII Profiles with and without Spire Data



**NWRA** NORTHWEST RESEARCH ASSOCIATES  
Excellence in Basic & Applied Research

Nearby Digisonde Measurements



Figures courtesy of K. Kramer

Max frequency of background profile (blue): 4.535 MHz  
Max frequency of GPSII solution profile (red): 3.435 MHz



F2 layer critical frequency: 3.500 MHz





# DATA & PAYLOAD OPPORTUNITIES

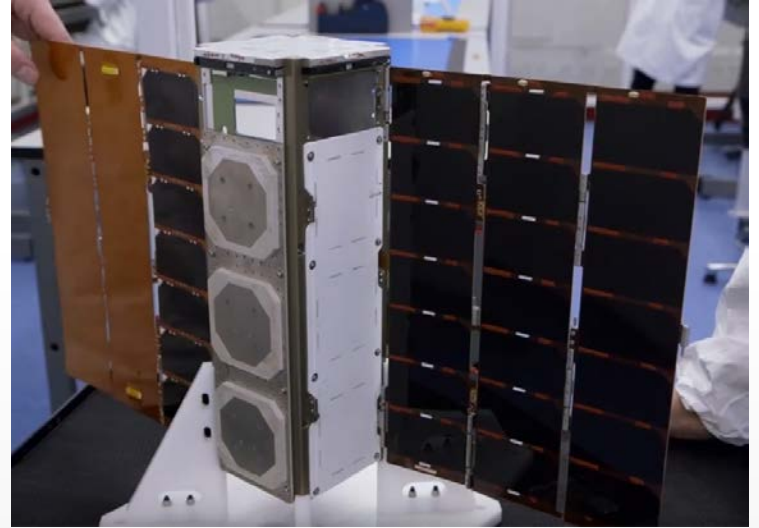
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Data available to researchers and operations via:

- **Current NASA Bulk Purchase Agreement (BPA):**
  - NASA PIs can request Spire RO/SpWx data
- **ESA Earthdatanet in trial phase**
- Data samples available upon direct request
- Near real-time access via cloud-based API

**Spire is offering “Space-as-a-Service” for rapid, cost-effective hosted Earth observation payloads**

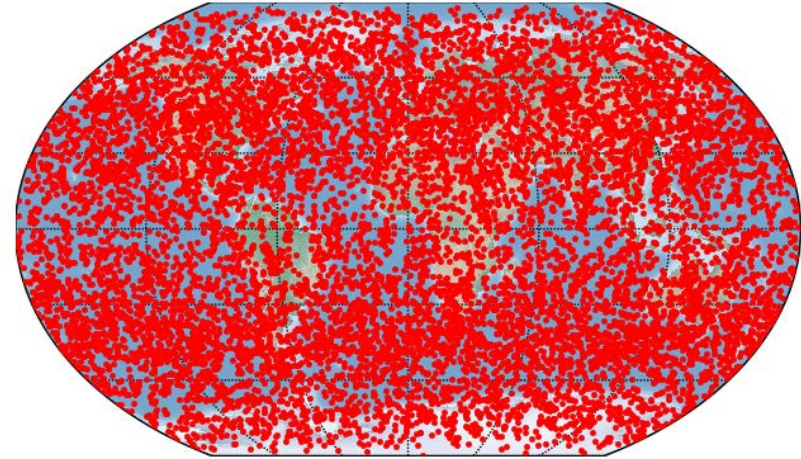
- 1U or more available
- 6-12 months from idea to launch
- Launches every 6 weeks on average



# KEY TAKEAWAYS

- Spire's current constellation is one of the largest producers of RO and SpWx measurements ever
  - Currently producing 5M+ TEC measurements per day and **increasing**
- Internal and external analyses have highlighted the **positive impact of Spire ionospheric data**
- Ionospheric data available now to researchers and operations via NASA BPA
- **Spire will provide consistent, long-term SpWx data as a service**

*Expected Daily Spire RO Coverage in 2020*



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