Recent ionosphere collection results from a 3U CubeSat GNSS-RO constellation

Timothy Duly, Vu Nguyen, Vladimir Irisov, Chris Rocken[1], Michael Gorbunov[2], and Dave Ector

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Spire Global, Inc.
1050 Walnut St., Suite 402
Boulder, CO 80302

[1]GPS Solutions Inc.
1320 Pearl St.,
Boulder, CO 80302

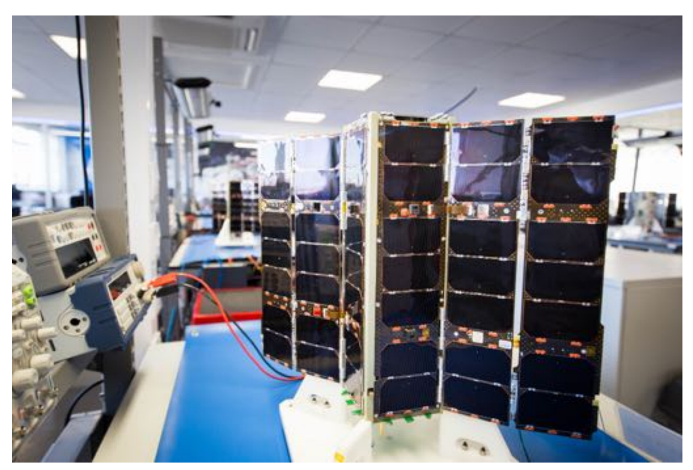
[2]A.M.Obukhov Institute of Atmospheric Physics
Russian Academy of Sciences,
Moscow, Russia

Spire Global, Inc.

Who are we?

- Leading player in nanosatellite sector building the most advanced, constantly refreshed 3U CubeSat constellation
- Each satellite is equipped with a state-of-the-art, open-loop tracking GNSS receiver that was built in-house and provides atmospheric and ionospheric data using GNSS radio occultation (RO) techniques

NOAA Commercial Weather Data Pilot



- Only company to participate in the first-ever NOAA Commercial Weather Data Pilot
- Provided 37+ days of radio occultation data, which included ionospheric products and radio occultation profiles of the lower atmosphere
- See presentation by V. Irisov, "Radio occultation profile results obtained from Spire's CubeSat GNSS-RO constellation"

Ionospheric products

- Receiver collects pseudorange and carrier phase data at 1 Hz which is used to compute total electron content (TEC) along the line of sight (LOS). This is referred to as **slant TEC**
- **Amplitude and phase scintillation indices (s4 and sigma-phi)** are computed in real-time on the receiver
- Future amount of ionospheric data provided by Spire in near real-time should greatly benefit space weather forecasters and researchers, as well as positively impacting ionospheric models

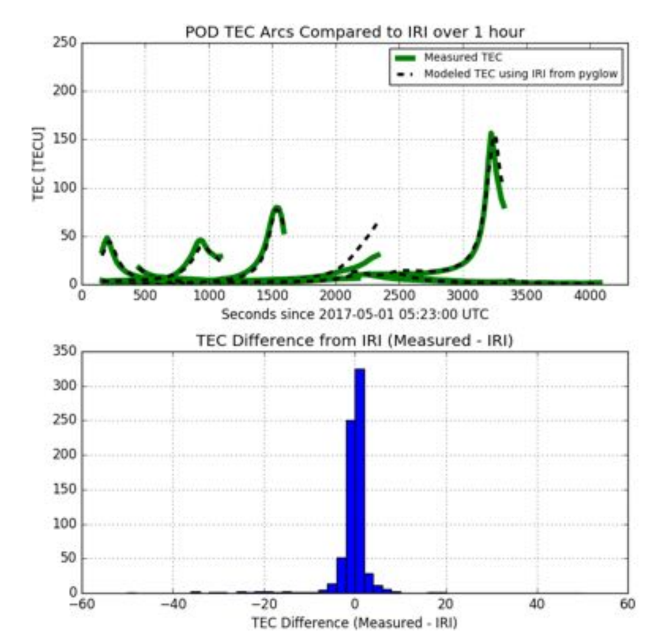
Comparison to International Reference Ionosphere (IRI) Model

- The IRI model is an empirical standard model of the ionosphere that provides climatologies of electron density, electron/ion temperature, and composition
- A comparison between the IRI model and Spire slant TEC data can be made by integrating the IRI model electron density along each Spire satellite measurement line of sight

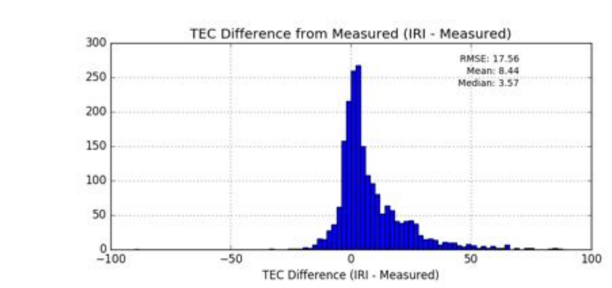
Comparison to IRI 2016 Model during April 25-31, 2017

- 234 slant TEC arcs from one Spire satellite were compared to the IRI 2016 model
- Mean (8.4 TECU) and RMSE (17.5 TECU) difference from IRI model for elevation below 0° are comparable to COSMIC differences from IRI 2007 (*Yue et al.,* 2012)
- Data supports previous observations that IRI model overestimates electron density during solar minimum

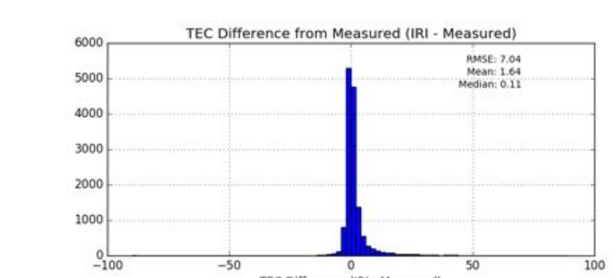
Example of TEC Arcs collected over 1 Hour



IRI Comparison over 1 Week (Elev. < 0)



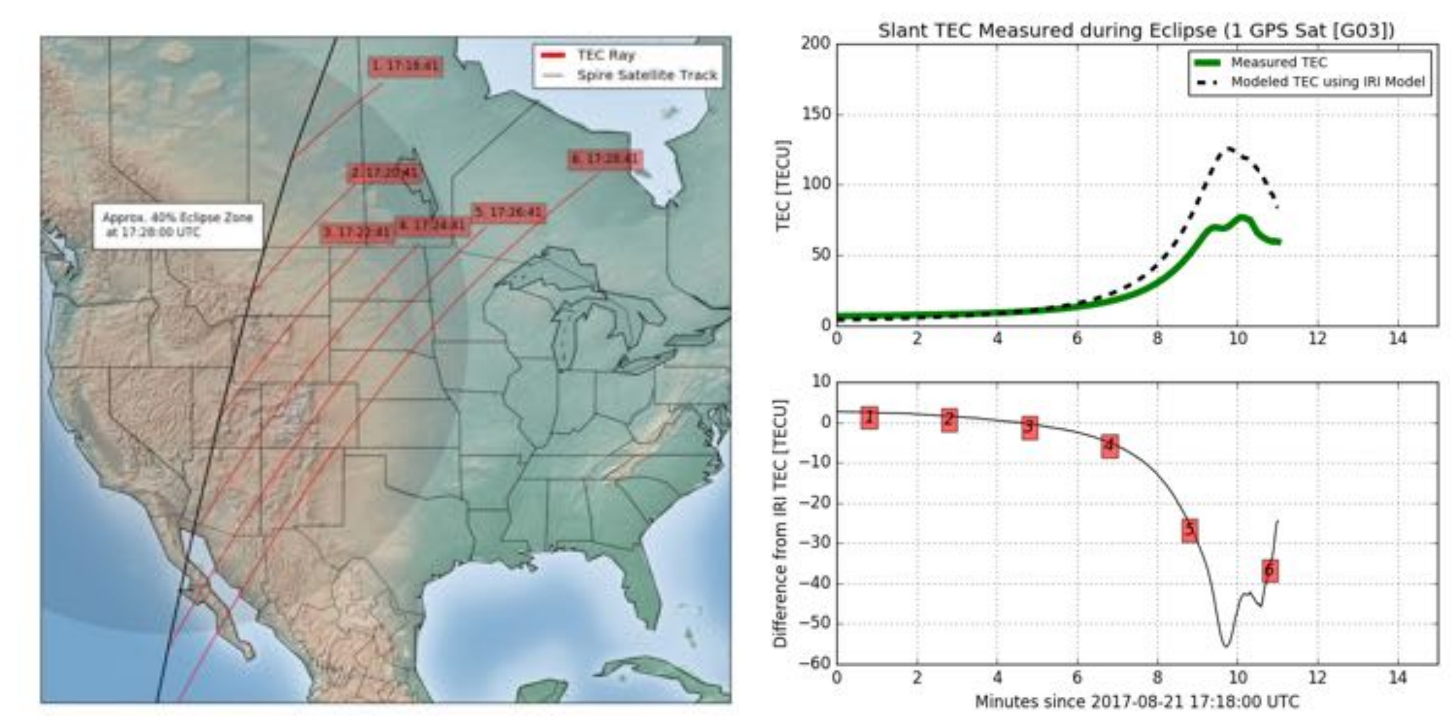
IRI Comparison over 1 Week (All Elev.)



Observation during Total Solar Eclipse

- Spire satellite collected and processed slant TEC data during the August 2017 total solar eclipse
- Comparison of slant TEC with IRI model (which does not include eclipse effects) suggests a short-term decrease in TEC during the eclipse

TEC observations from one GPS satellite crossing eclipse

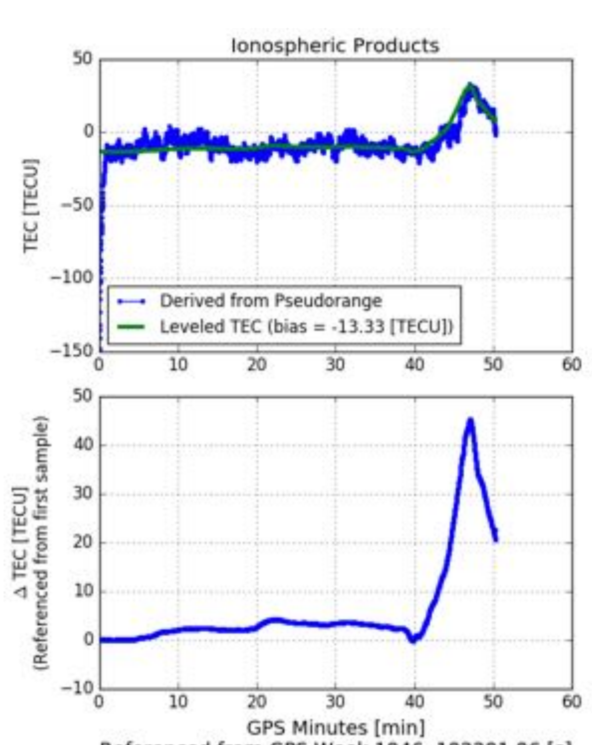


Estimating Slant TEC

Slant total electron measurement is computed by combining pseudorange and carrier phase observables through a process called *leveling* (*Mannucci et al.,* 1998)

Procedure

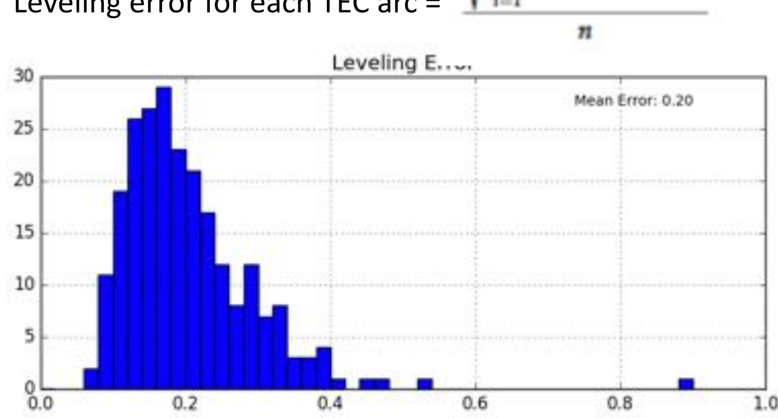
1. Split pseudorange and carrier phase data into near-continuous arcs while correcting for cycle slips
2. Carrier phase data are "leveled" to pseudorange observations through a data weighting scheme that minimizes multipath effects (*Pedatella,* 2011)
3. GPS Differential Code Biases (DCBs) are estimated externally and subtracted from the slant TEC measurements
4. LEO DCBs are roughly estimated and subtracted from the measurements (ongoing work is being conducted to provide more accurate LEO DCBs)



Leveling Error

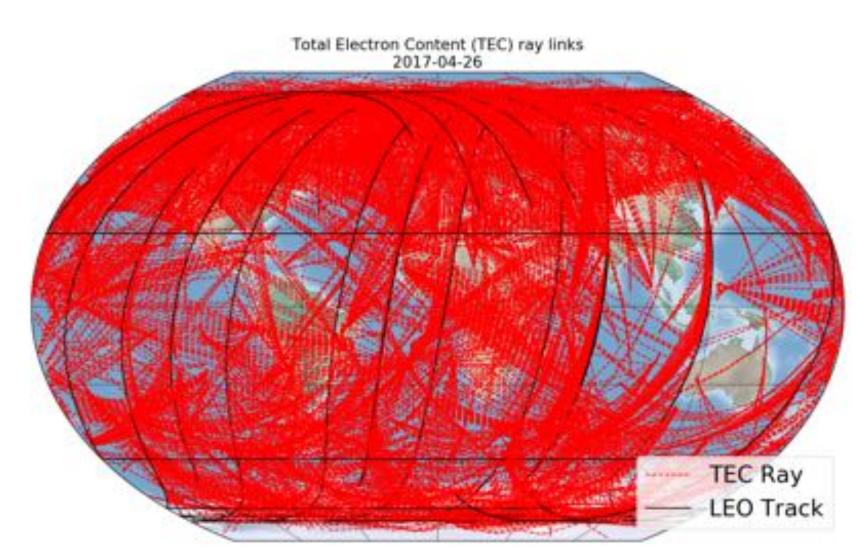
- Leveling error (see *Yue et al.,* 2012) provides an estimate of the difference between the "phase derived" and the "pseudorange derived" TEC data
- Mean leveling error of slant TEC arcs over one week is ~0.2 TECU

Leveling error for each TEC arc = $\frac{\sqrt{\sum_{i=1}^{n}(TEC_L - TEC_P)^2}}{n}$



Current & Future Capabilities

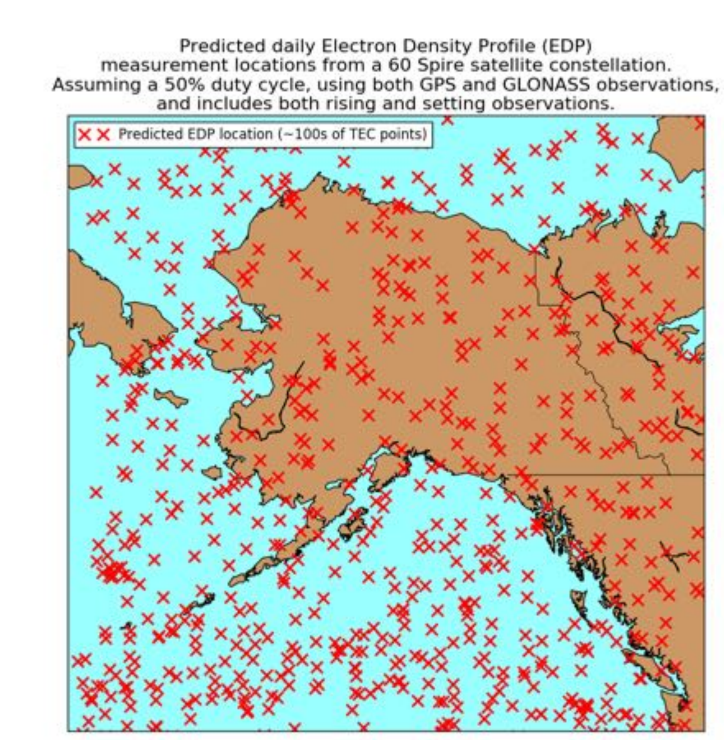
LOS TEC Track Collects over 24 hours



- With just a few CubeSats operating over one day at ~25% duty cycle, we achieve near global coverage of TEC ray links

Future Constellation Capability

- Additional ionospheric products will also soon be available, including electron density profiles (EDPs)
- Coverage simulation of a 60 satellite constellation with both GPS and GLONASS observations (rising & setting)
- Combined with 20+ ground stations, there will be unprecedented latency and coverage of near real-time ionospheric state



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Conclusions

- RO observations from Spire's CubeSat constellation also provide a wealth of information about the ionosphere, including TEC and scintillation measurements
- Spire has incorporated leveled LOS TEC data as part of their standard ground processing
- Additional CubeSats to Spire's growing fleet will provide unprecedented coverage for ionospheric observations in near real-time

References

- Mannucci, A. J. et al. (1998), A global mapping technique for GPS-derived ionospheric total electron content measurements, *Radio Sci.,* 33(3), 565-582.
- Pedatella, N. M. (2011), Response of the Ionosphere-Plasmasphere System to Periodic Forcing, PhD Dissertation, University of Colorado.
- Yue, X. et al. (2012), Validate the IRI2007 model by the COSMIC slant TEC data during the extremely solar minimum of 2008, *J. Adv. Space Res.,* doi:10.1016/j.asr.2011.08.011.