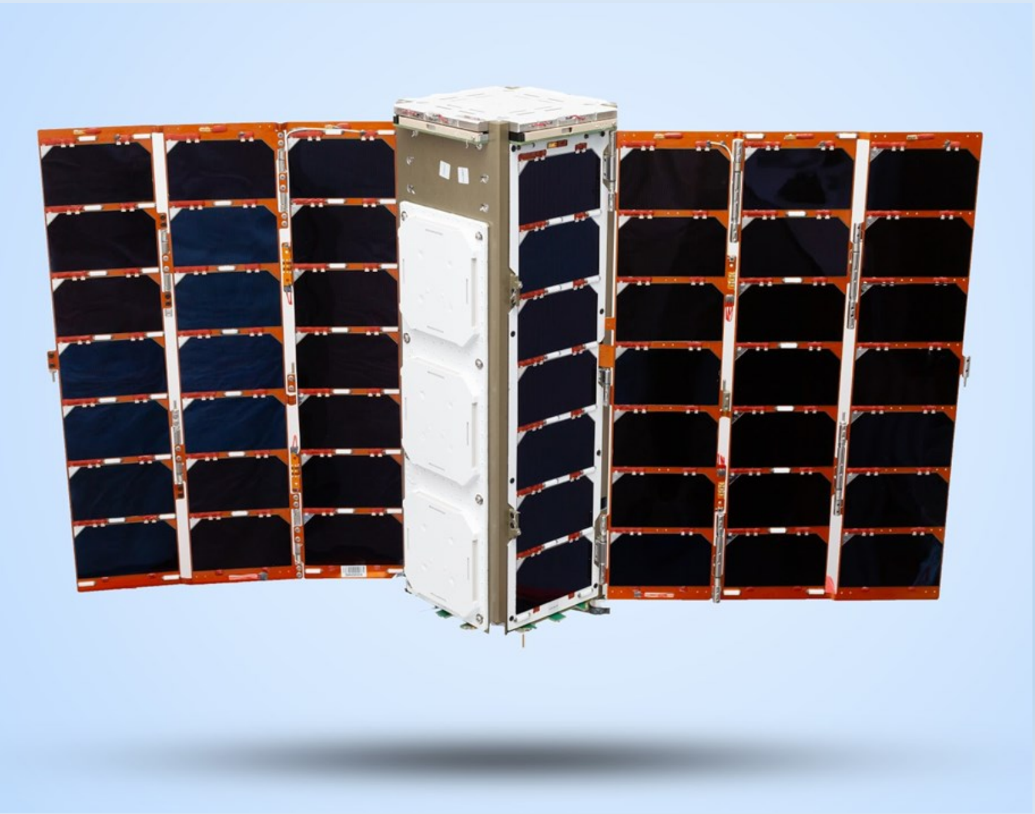

Radio Occultation Observations and Processing from Spire's CubeSat Constellation

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Introduction

Spire Global, Inc. is a leading player in the nanosatellite sector and the first to provide commercial GNSS radio occultation (RO) measurements for numerical weather prediction. Spire plans to provide over 100,000 radio occultation profiles per day, providing dense coverage of high-quality atmospheric measurements over the entire planet.

Currently Spire operates more than 80 3U CubeSats in various low Earth orbits (LEO). Each satellite is equipped with a state-of-the-art GNSS receiver. Three antennas collect dual-frequency L1 and L2 data for precise orbit determination (POD), ionospheric data (TEC and S4 and sigma-phi scintillation indices), and both setting and rising RO for atmosphere sounding. **Spire is the only RO producer collecting observations from four GNSS constellations: GPS, GLONASS, Galileo, and QZSS.** An extensive network of ground stations provides downlink for low latency data transfer and processing. Our current median latency time is about 90 minutes. Spire has developed state-of-the-art POD/RO processing software that accumulates the latest achievements in RO science and technology.

Radio occultation profiles collected during August 2018 — August 2019

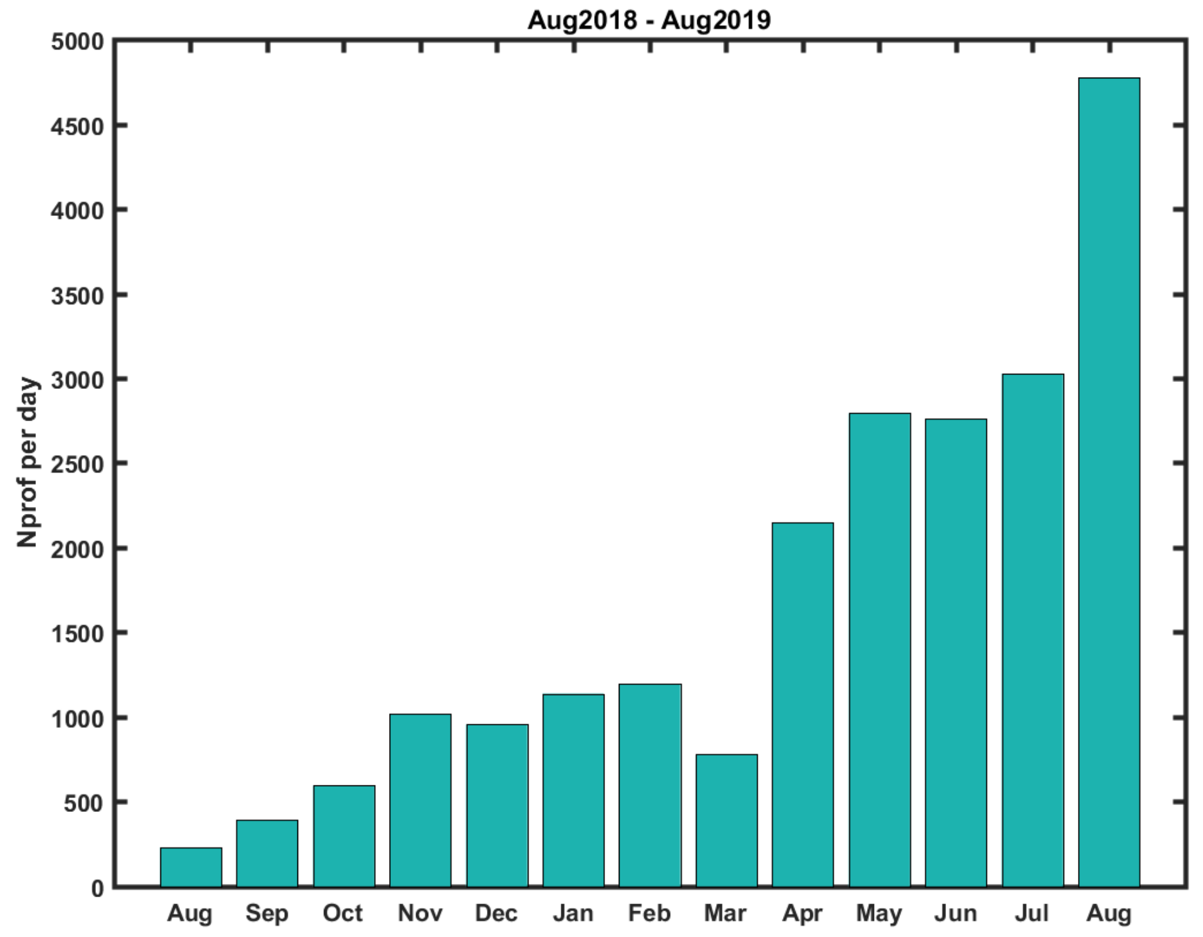

Figure 1: *Daily production of RO profiles during last 13 month.*

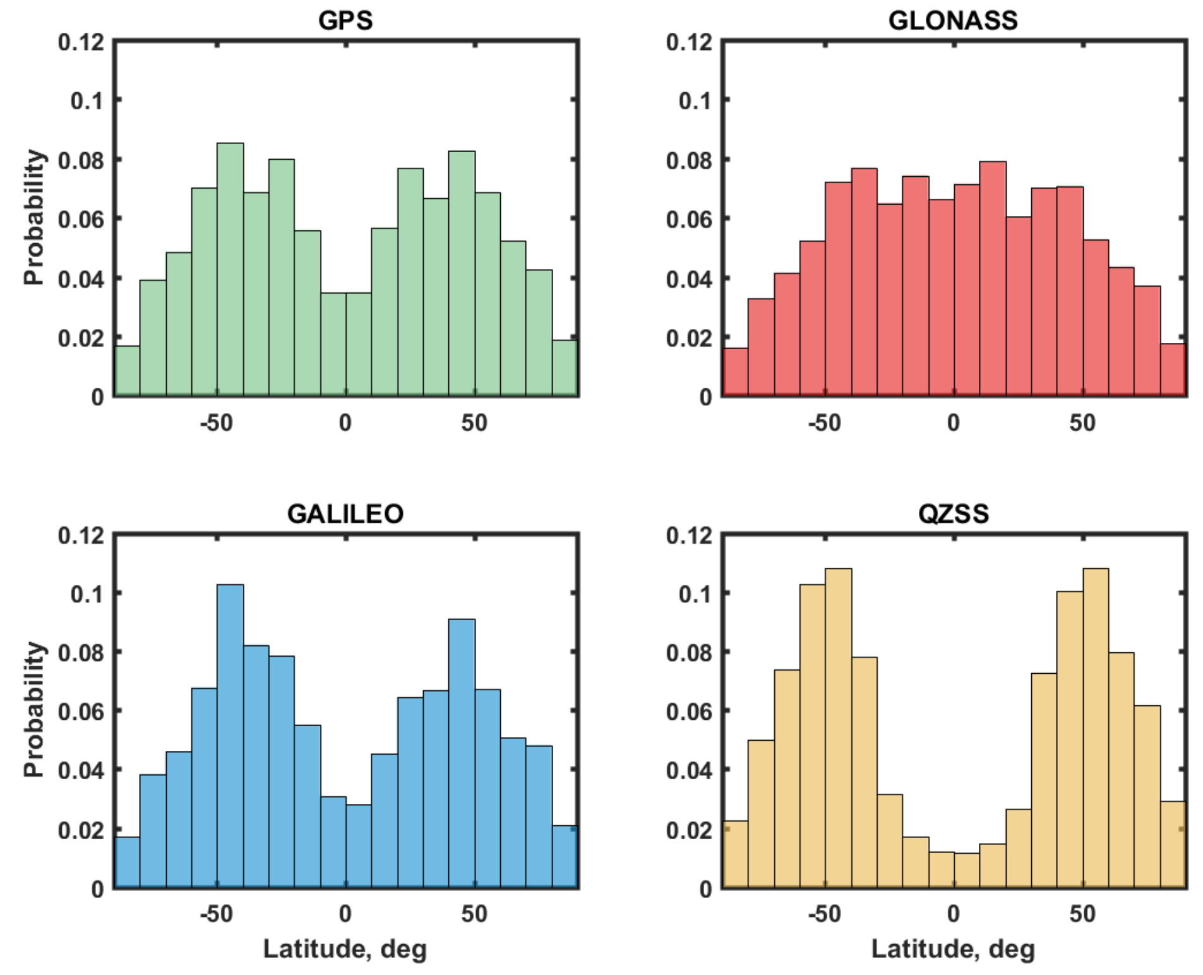

Figure 2: *Distribution of the profiles versus latitude.*

The presented statistical results are based on RO data collected during August 2018 – August 2019. **Figure 1** shows the monthly average number of the processed profiles for four different GNSS systems. Rapid growth in profile numbers is the result of:

- launching new satellites
- increased efficiency of each satellite coming from continuous improvements in design and technology.

Over the course of last year, Spire has increased RO production almost 20X, with about 89 percent of profiles passing our rigorous internal quality control (QC). **Currently, we are producing over 6000 profiles per day, with expectations to continue large increases in RO production.** Spire satellites share various payloads and missions, so not all satellites are dedicated to RO observations.

The ratio between setting and rising profiles is about 55/45. Newer versions of Spire satellites simultaneously collect both rising and setting occultations using separate forward and backward facing RO antennas.

Figure 2 shows the distribution of the number of the profiles versus latitude for the four GNSS constellations collected. GLONASS provides the best coverage of the equatorial latitudes. A decrease in counts for the equatorial region for QZSS is explained mostly by orbit phasing between the Spire and QZSS satellites. A combination of different GNSS constellations and various LEO orbits provides near uniform global coverage.

Improvements in Spire RO quality as a function of time

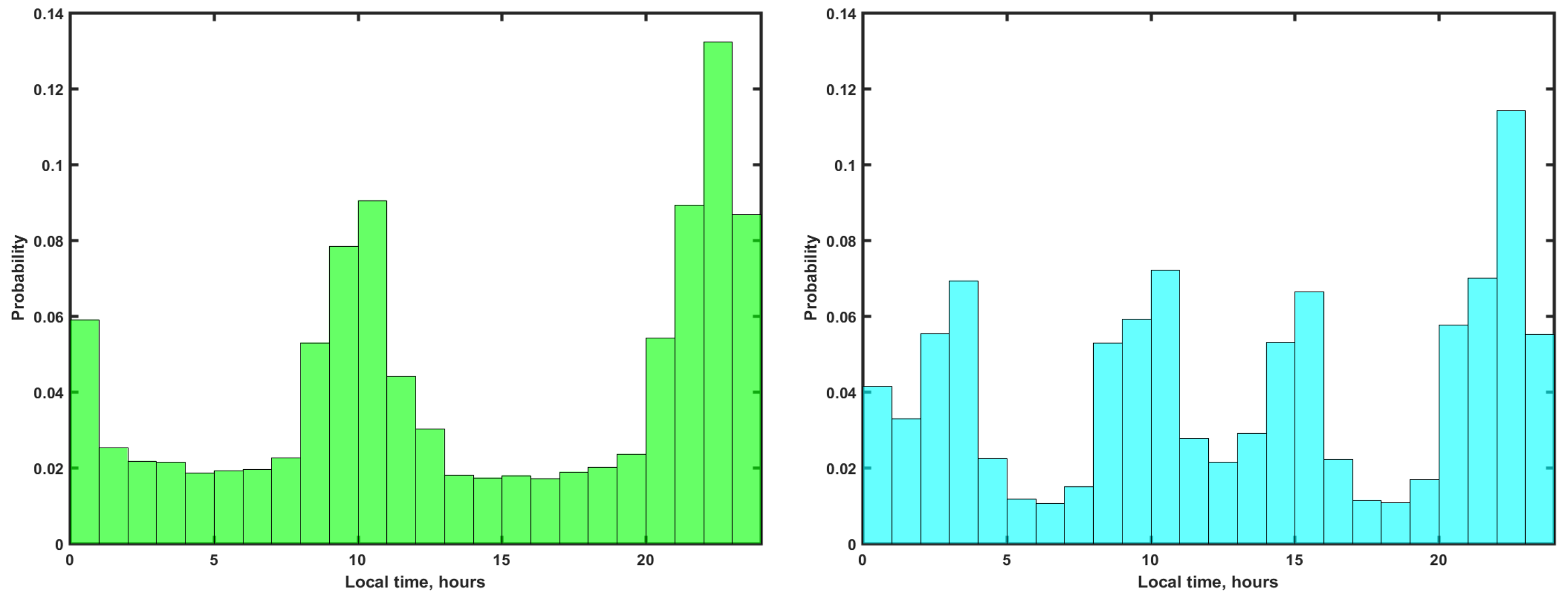

Figure 6: *Local time distribution before (left) and after (right) launching newer satellites.*

This section illustrates our ongoing efforts to improve data quality and quantity. Satellites with improved receiver characteristics were launched in April and July of 2019. The newer satellites have dual RO antennas, increased solar panel area, and an improved the power system. This has allowed us to extend the satellite duty cycle and number of profiles collected per day.

Figure 6 shows the distribution of the profile local time for the satellites before the April/July launches (left panel) and the same distribution for August 2019, when all satellites are operational. Introducing new satellites into new orbits provides us with more uniform local time distribution.

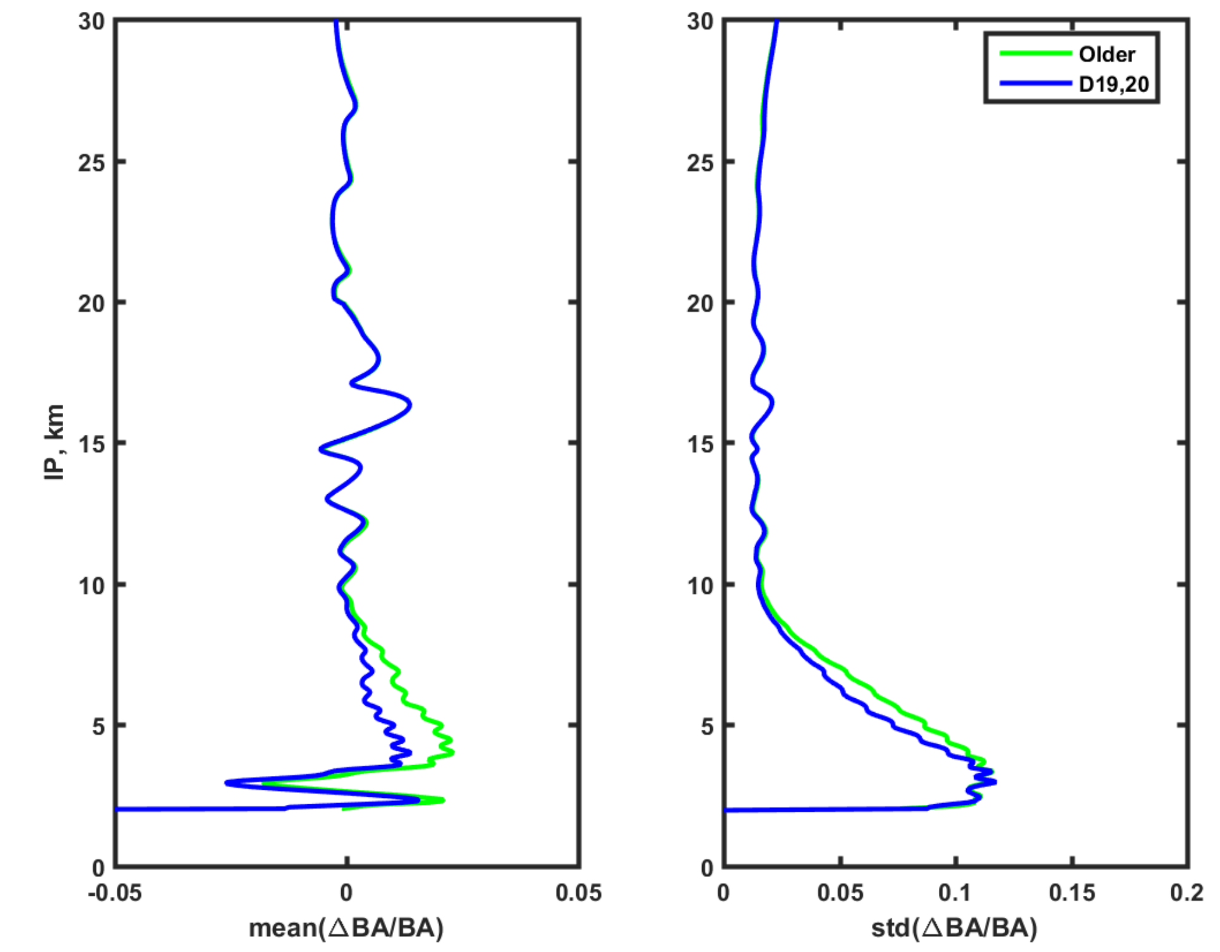

Figure 7: *BA bias (left) and STD (right) for newer (D19,20) (blue) and older satellites (green).*

Figure 7 show the comparison of BA bias and STD between older satellites and newer satellites. The bias and STD were calculated from global data obtained in August 2019. We see a reduced tropospheric bias and STD for newer satellites due to receiver improvements.

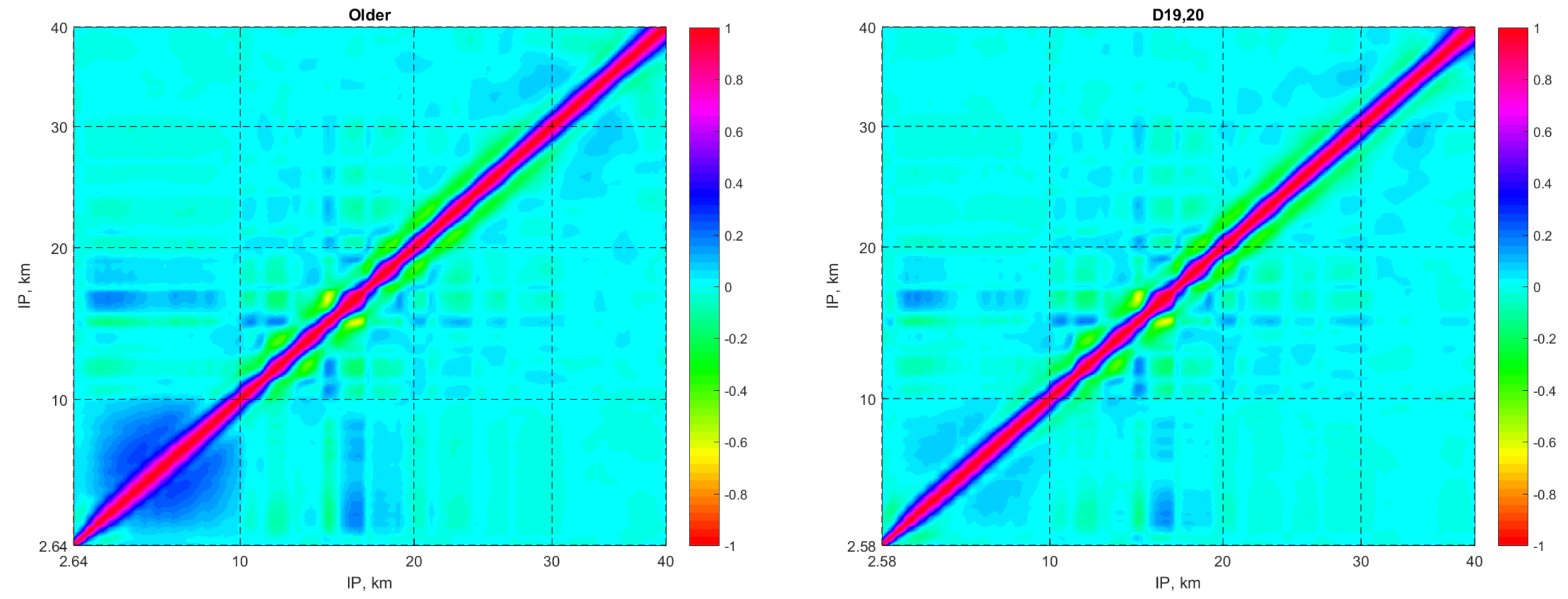

Figure 8: *Vertical correlations for older (left) and newer satellites (D19,20) (right).*

Figure 8 shows the comparison between vertical correlations for older satellites (left panel) and newer satellites (right panel). The vertical correlations were calculated from August 2019 data. One can see that receiver improvements result in significantly smaller off-diagonal vertical correlations in the lower troposphere — an important quality for data assimilation.

Statistics of bending angles (August 2019)

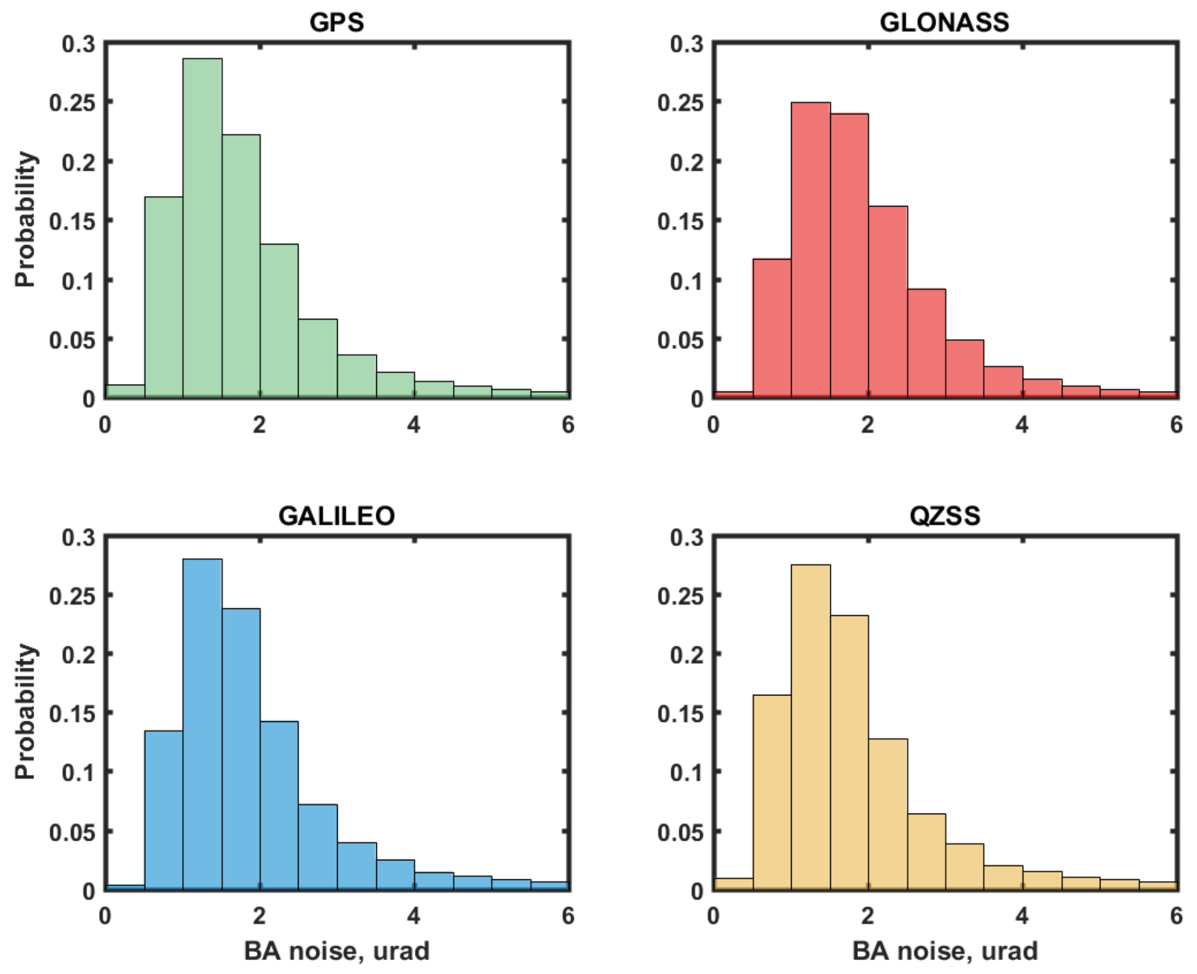

Figure 3: *Distribution of the bending angle noise.*

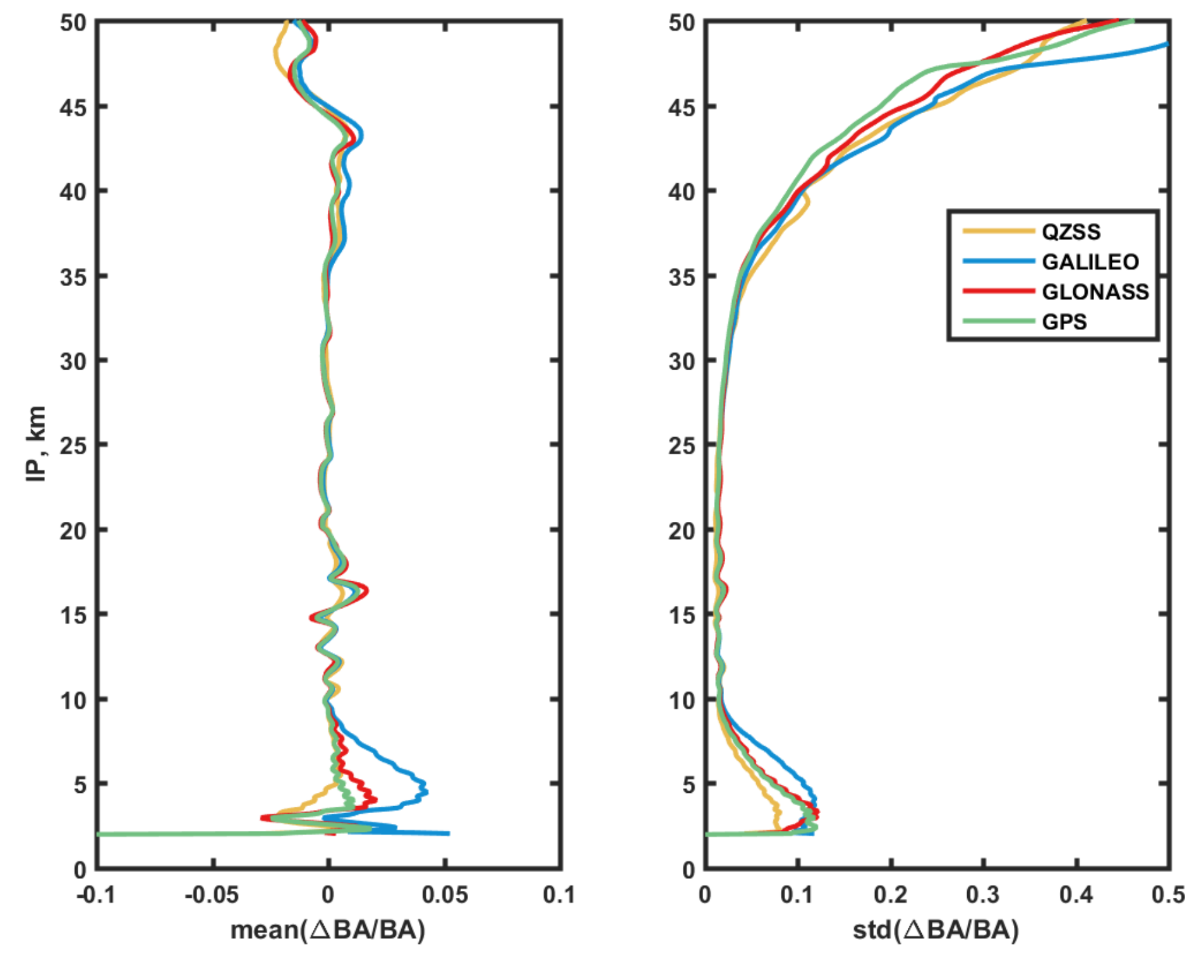

Figure 4: *Vertical profiles of (O-B)/B [BA] bias (left) and standard deviation (right) for four GNS systems. Background 'B' is estimated from GFS analysis.*

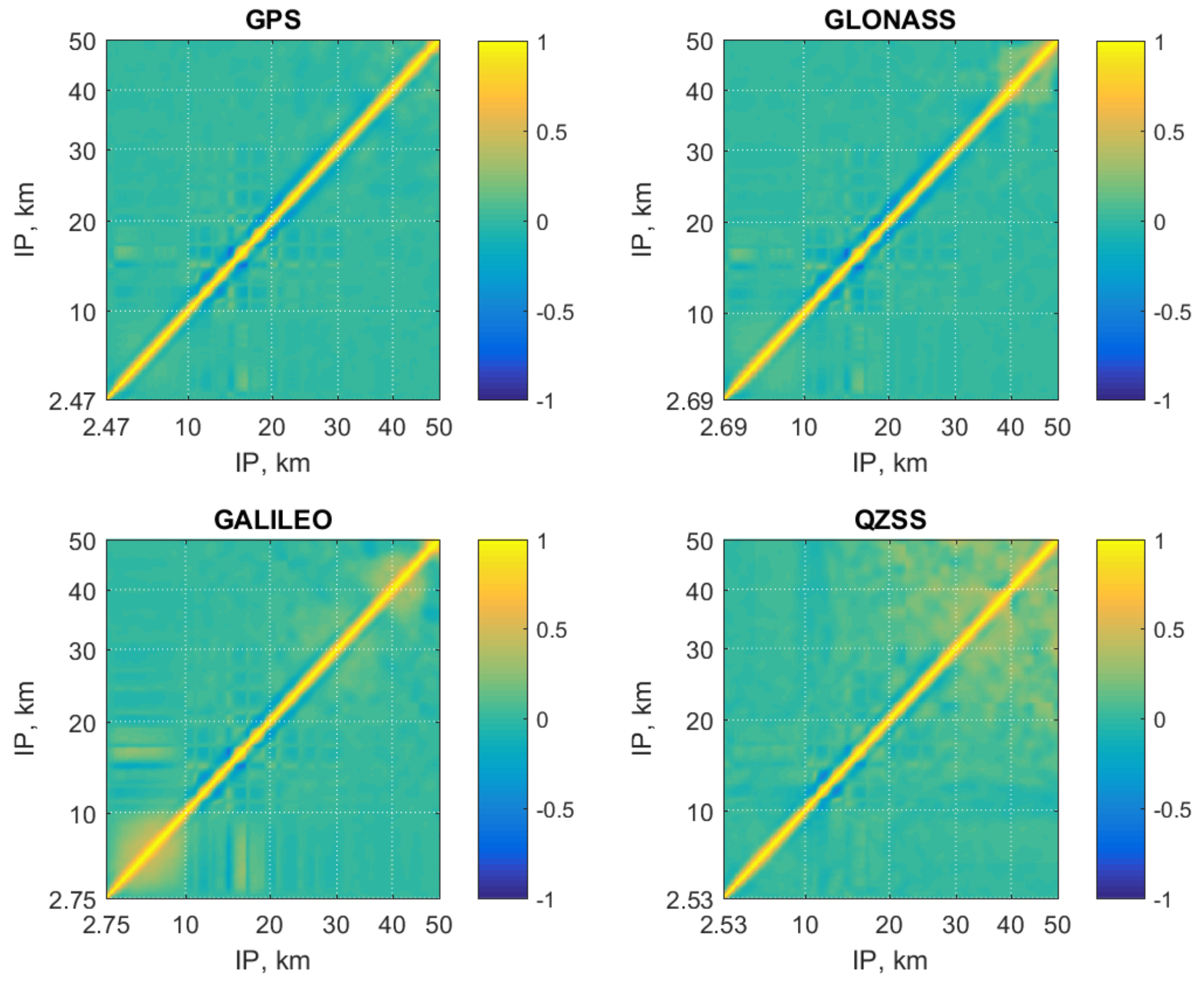

Figure 5: *Bending angle vertical correlations of (O-B)/B for four GNS systems.*

Continuous monitoring of RO data quality is a high priority task. Our QC is based on the following metrics:

- bending angle (BA) noise
- "badness score"
- BA bias and standard deviation
- vertical correlations
- other characteristics: SNR, upper transition height, penetration depth, etc.

"Badness score" is an empirical dimensionless parameter introduced by M. Gorbunov. It characterizes self-consistency and quality of L1 and L2 raw data. The results presented in this section are derived from the profiles with

Figure 3 shows the distributions of BA noise estimated after ionospheric correction at impact heights of 70-80 km and local time between 20:00 and 4:00. Median values of std(BA) are given as:

GPS	1.56 urad
GLONASS	1.75 urad
Galileo	1.65 urad
QZSS	1.59 urad

BA noise meets Metop requirements (2 urad) for all constellations.

We associate stronger GLONASS BA noise with relatively higher signal phase fluctuations at time intervals of one second and shorter due to GLONASS transmitter clock quality.

Figure 4 shows the profiles of BA bias (left panel) and standard deviation (right panel) for the four GNSS constellations. Bias and STD are calculated as (O-B)/B, where O is the RO observation of BA, and B is the background BA derived from GFS analysis.

The increased bias for Galileo is explained by higher noise level in the I and Q signals associated with the shorter chip duration and, consequently, tougher requirements to the accuracy of the open-loop tracking model. **Ongoing work has improved the open-loop tracking performance, and future Galileo profiles should have quality similar to GPS.**

The change of positive/negative sign for the tropospheric QZSS bias is related to the skewed latitude statistics (see Figure 2).

The statistics shown in this section was obtained from August 2019 data set (147969 profiles).

Vertical correlation of (O-B)/B characterizes the vertical resolution of RO profiles and is an important characteristic for data assimilation. **Figure 5** shows the vertical correlations for the four GNSS constellations estimated from August 2019 data. Higher correlations in the lower atmosphere in Galileo data are due to the stricter open-loop tracking requirements of the faster chipping rate signals used in the Galileo observations, and this has been recently improved.

The vertical correlation depends equally on both observation 'O' and background 'B'; using a different background may result in a different vertical correlation.

Independent comparison between Spire and other RO data (COSMIC-1, MetOp, Kompsat-5) shows that our data demonstrate comparable bias, standard deviation, and vertical correlations.

Wet profile retrieval using neural network

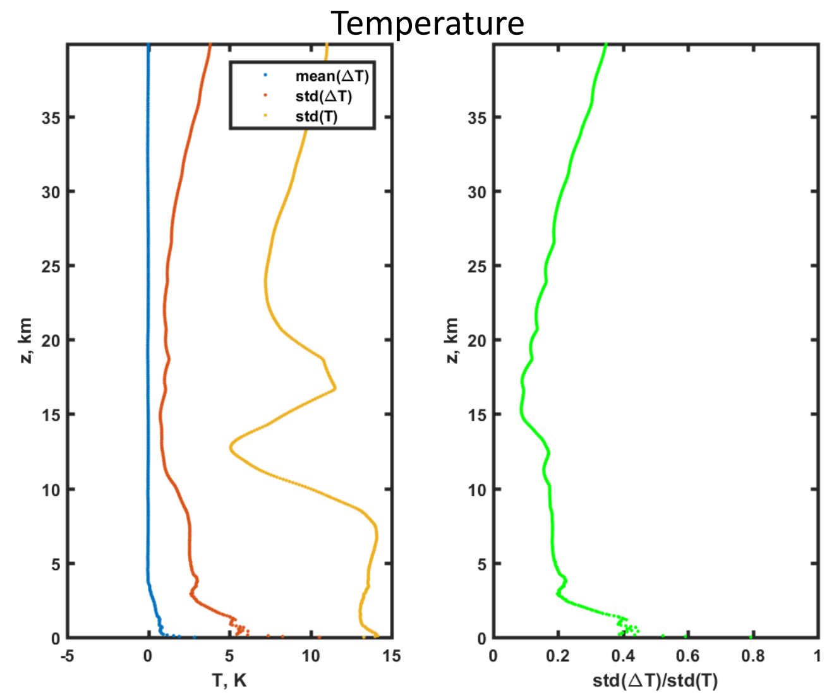

Figure 9: *NN performance of temperature retrieval: left — bias, STD of the retrieval-test difference, and STD of the test profiles; right — the ratio of two standard deviations.*

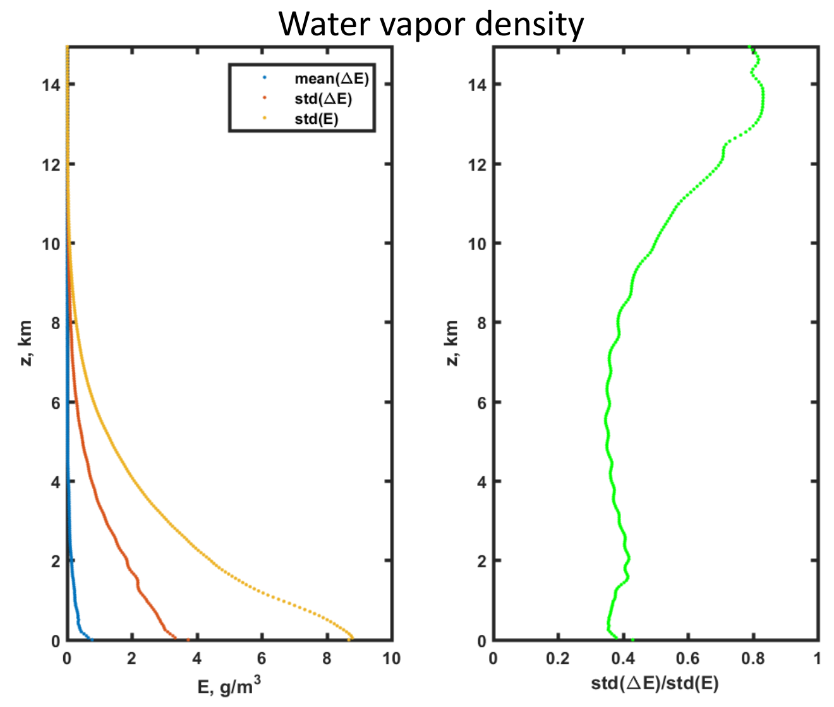

Figure 10: *NN performance of water vapor retrieval (same as in Figure 9).*

The final section is devoted to our efforts on deriving wet temperature and water vapor profiles from RO refractivity profiles by using neural network (NN). The decision to use NN for wet profile retrieval is motivated by the following reasons:

- statistical inversion requires an estimate of the measurement and model error covariances, which is hard to do;
- NN can handle non-linear relation between observables and targets;
- NN can naturally absorb ancillary information.

We choose refractivity profile in favor of BA because it removes Abel inversion from the retrieval process and simplifies the task. Training dataset includes large amount of RO profiles distributed globally and covering all seasons and local times. Each refractivity profile is accompanied with GFS analysis profiles of T(K) and E(g/m^3) interpolated in space and time to the occultation time-location. Profile location, season, and time are added to the observables.

We use empirical orthogonal function (EOF) decomposition to reduce the dataset size for both observables and targets. We consider a simple NN with one hidden layer and limit the number of T, E, and N EOFs by 40. The size of the hidden layer is chosen to get an optimal NN performance.

Figures 9 and 10 shows the results of the NN trained for wet temperature (left two panels) and water vapor (right two panels) retrieval from refractivity profiles. The first and third panels show the mean bias (blue), the standard deviation of the difference between retrieved and GFS profiles (red), and the standard deviation of the target GFS profiles. The second and fourth panels show the ratio of the standard deviation of the difference to the standard deviation of the profile itself. We can see that the ratio is less than 0.2 for T between 3 and 25 km and less than 0.4 for E below 8 km. That characterizes NN skill in wet temperature and water vapor retrieval.

Conclusion

- **Spire demonstrates a remarkable growth in maturity and RO profile production.**
- **The latest generation of the satellites shows significant progress in RO profile quantity and quality.**
- **Spire has developed modern software for POD/RO processing and data distribution.**
- **Validation of the Spire data shows quality is comparable with other production systems like COSMIC-1 and Met-Op satellites.**
- **Spire will continue to significantly increase daily production of RO profiles while also reducing latency and improving data quality.**
- **Spire is working closely with customers to meet their needs and requirements and attain valuable feedback.**

References

[1] Gorbunov, M. E., "Ionospheric correction and statistical optimization of radio occultation data," Radio Sci., v.37, N. 5, 1084, doi:10.1029/2000RS002370, 2002.

[2] Gorbunov, M. E., K. B. Lauritsen, A. Rhodin, M. Tomassini, and L. Kornblueh, "Radio holographic filtering, error estimation, and quality control of radio occultation data," J. Geophys. Res., v. 111, D10105, doi: 10.1029/2005JD006427, 2006.

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