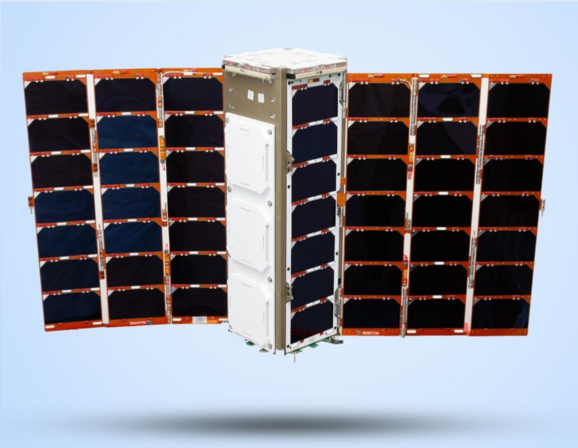

Comparison of Spire RO profiles processed by UCAR and Spire

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Introduction

Spire Global operates more than 100 3U CubeSats in various low Earth orbits. Each satellite is equipped with a GNSS receiver capable of collecting radio occultation (RO) profiles from all GNSS constellations. Currently Spire collects around 9000 quality-controlled profiles each day.

From December 2020 to January 2021, Spire participated in the first part of the NOAA Commercial Weather Data Operational Buy (CWDOB). During this 30-day period, Spire delivered 700 profiles per day from GPS and GLONASS. The Spire RO data delivered were characterized by the mean SNR of about 400 V/V at 1 s, bending angle noise of about 1.3 urad, mean latency of ~1.4 hours, and close to uniform global distribution. Each profile was processed from level 0 data by UCAR. GeoOptics, Inc. (GO) also provided RO data within the same program and these too were processed by UCAR..

We compared the statistics of QC-passed profiles provided by Spire, GO, and COSMIC-2 (C2) during two days in January 2021. In this comparison, we analyzed only data processed by UCAR and with UCAR-provided background evaluated from ECMWF gridded analysis. All data from Spire and Geooptics were part of those delivered to NOAA during Delivery Order 1 of the NOAA CWDOB and are available publicly from UCAR (https://data.cosmic.ucar.edu/gnss-ro/). **This removes any differences in processing and allows us to focus on the data quality among the satellite systems.**

We also used much larger datasets of RO profiles collected by C2 in 2020, to compare refractivity bias and standard deviation as produced by Spire-based processing and UCAR-based processing (we also include in this analysis RO profiles collected by Spire satellites as well). The comparison show only minor differences between Spire-processing and UCAR processing and between C2 and Spire collected RO.

Statistical comparison of Spire, GeoOptics, and COSMIC-2 RO profiles based on UCAR processing

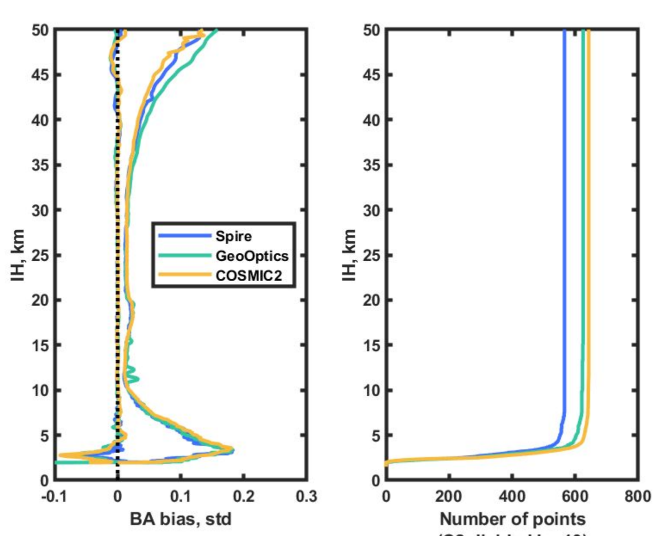

Figure 1: *Bias and STD of the bending angle of the profiles collected by the three RO systems. The number of C2 data is scaled by the factor of 1/10.*

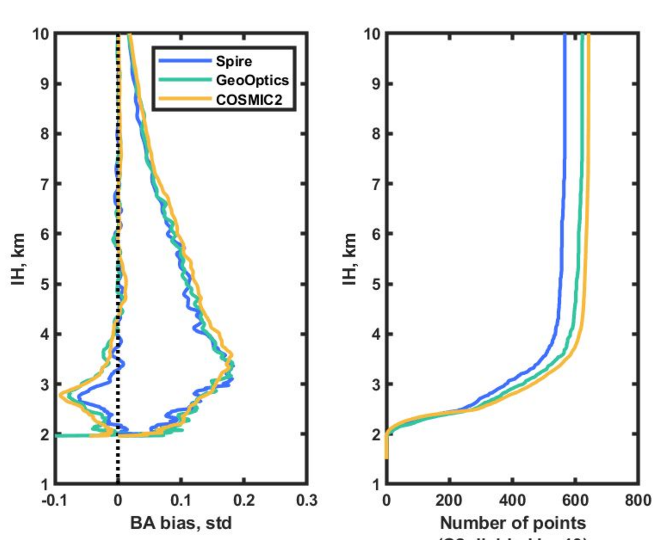

Figure 2: *Bias and STD of the bending angle of the profiles in the impact height range from 1 to 10 km.*

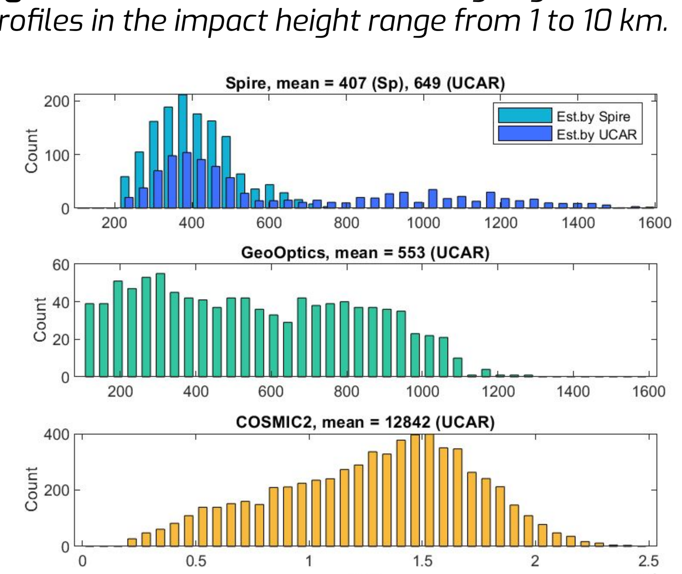

Figure 3: *Distribution of L1 SNR (note the different scale for C2 SNR).*

The presented statistical results are based on RO data collected and delivered on January 1st and 2nd 2021. The data were processed by UCAR processing center (UPC) from level 0 to level 2 and were accompanied by background profiles provided in *echPrf* files. In our statistical comparison, we are focused on bending angle and refractivity provided in *atmPrf* files.

Table 1 shows the number of profiles produced by Spire, GeoOptics (GO), and COSMIC-2 (C2), which passed UCAR quality control (QC) and were supplied with background profiles. **C2 profile geographic distribution is limited by about 44 degrees latitude, so we selected Spire and GO profiles located within this latitude range for adequate comparison.**

Table 1.

	Number of QC'ed profiles	Number of profiles within 44 deg. latitude
Spire	1002	566
GeoOptics	1019	625
COSMIC2	6451	6429

Figure 1 shows the bending angle (BA) bias and standard deviation (STD) estimated from (O-B)/B, where O is the observed RO BA and B is the background BA. **Both O and B were produced by UCAR.** The number of data points versus impact height (IH) is shown in the right panel. The number of C2 data points is reduced 10 times for better visibility.

Figure 2 shows the same bias and STD and number of points in IH range from 1 to 10 km.

Comparison of the three datasets shows very small difference between them in terms of the bias and STD. If we estimate IH where the number of the data points reaches 50% of the total number of the profiles, we also do not see a significant difference among the data sources.

Figure 3 shows the distributions of L1 band signal-to-noise ratio (SNR) for the three systems as estimated by UCAR. In the top panel, we also ass Spire's estimate of the SNR, which is different from that given by UCAR. Mean values of SNR are given in the titles of the figure. Here, we accounted for all global Spire and GO profiles (column 2 of the Table 1).

C2 SNR (Figure 3) is much higher than that of Spire and GO. Nevertheless, this does not appear to significantly improve bias and STD of RO profiles (Figures 1 and 2).

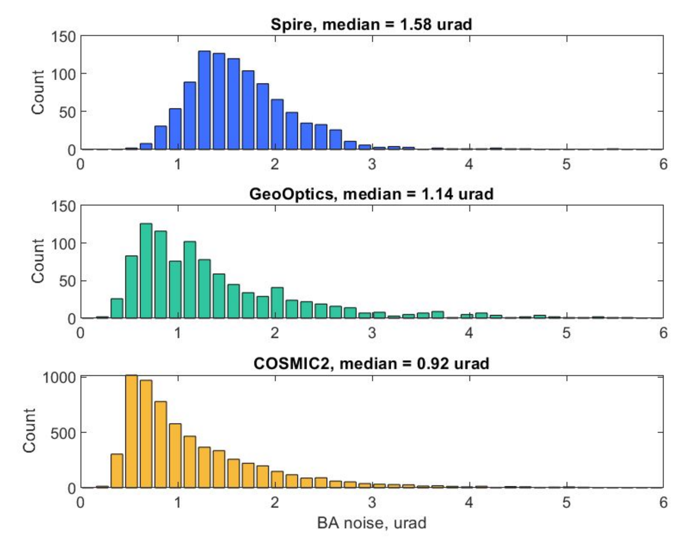

Figure 4: *Distributions of the BA noise estimated from ionosphere compensated BA at 70-80 km height.*

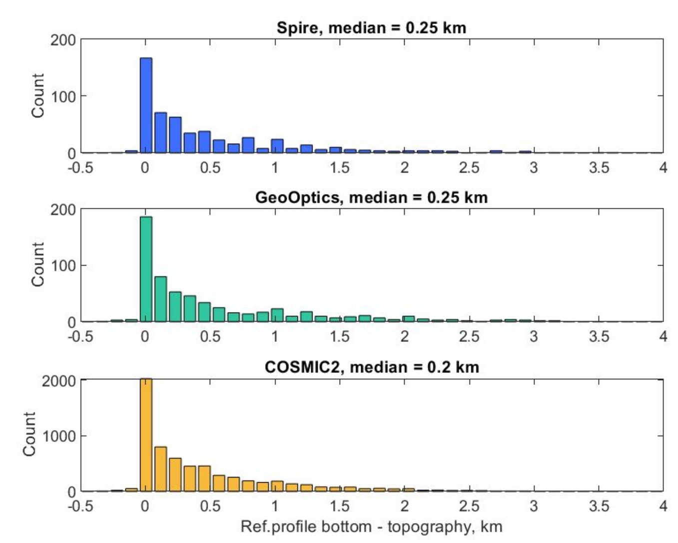

Figure 5: *Distributions and median values of profile penetration depths for all systems.*

Figure 4 shows the comparison of BA noise distributions estimated by UCAR from ionosphere compensated BA at 70-80 km height. Spire data shows higher noise (1.58 urad) compared with the noise in GO and C2 data. This is related primarily to the single differencing used by Spire for receiver clock correction versus zero differencing implemented by GO and C2. Still, the difference between median values of the noise is not critical for the quality of RO data (Figure 1 and 2). Here we use all global data from Spire and GO. The distributions of BA noise are strongly non-Gaussian, so we use the median as more stable and appropriate characteristic than mean value.

Finally, we compared the penetration depth of the refractivity profiles estimated as a difference between the height of the profile bottom point and the Earth topography. Due to dependence of the penetration depth on atmospheric moisture and temperature gradients, we use ±44-degree latitude-limited subsets of Spire and GO RO data to match C2. **Figure 5** shows the distributions of the penetration depth for the three sets of profiles. The minor deeper penetration depth median (50m) of C2 is related to the impact height grid rather than to the actual gain or loss in penetration.

The presented statistical comparisons show that better SNR and lower BA noise do not necessarily lead to a statistically significant improvement of the RO profile parameters that are most important to numerical weather prediction models. The same software and QC applied to the three datasets (by UCAR) excludes any differences in processing. We see that the averaged BA bias, STD, and median penetration depth are practically the same for all three systems despite strong difference in SNR and minor to moderate difference in BA noise.

Comparison between Spire and UCAR Processing of RO data

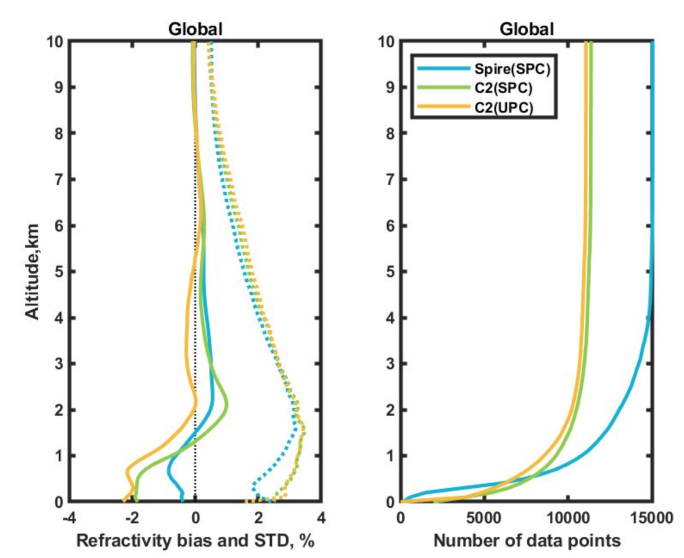

Figure 6: *Refractivity bias and STD (left) and number of data points (right) for the global data.*

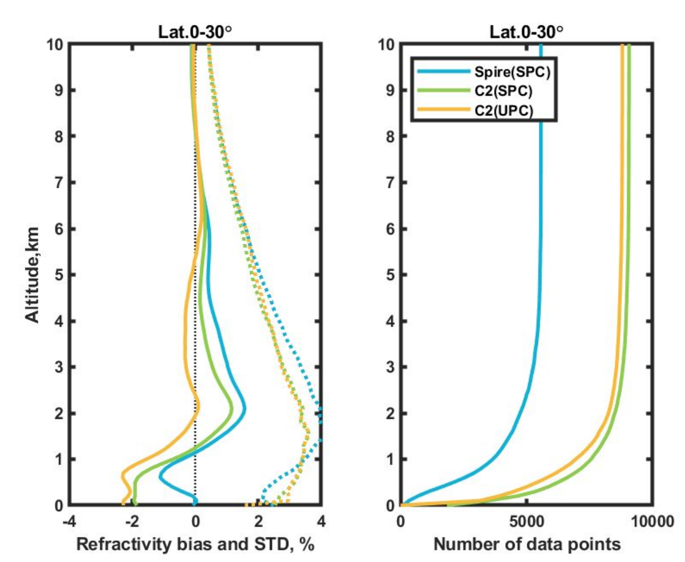

Figure 7: *The same as in Figure 6 but for the tropical region.*

In this section, we consider the statistics of the Spire refractivity profiles processed by the Spire Processing Center (SPC) and C2 refractivity profiles processed by both SPC and the UCAR Processing Center (UPC). We use the data collected in May 15, June 15, and July 15 of 2020, which contains many more profiles than the analysis in the previous section. The total number of the profiles is about 15000 for Spire and 11000 for C2. NCEP GFS analysis was used as a background refractivity for all three datasets.

Figure 6 shows the global refractivity bias and STD (left) and the number of data points (right) in the lowest 10 km (as shown in the previous section, Spire and C2 profiles do not differ above this height). The bias is shown by solid lines, and STD by dotted lines. The three colored lines correspond to Spire data processed by SPC, C2 data processed by SPC, and C2 data processed by UPC. **Figures 7, 8, and 9** shows the same characteristics for the three latitude zones: 0-30 degrees, 30-60 degrees, and 60-90 degrees latitude (only Spire satellite data is shown for polar region since C2 does not sample there).

We note similar structure of the statistics of all three datasets: negligible bias above 7-8 km, change of the bias and STD dependence at 2 km, and larger errors in the tropics compared with mid-latitude. Maximal values of global STD is about 3% in all datasets. Spire data shows slightly higher STD in the tropical lower troposphere, which can be explained by the lower SNR of Spire data compared to that of C2. UCAR processing shows smaller positive bias compared with SPC (1% at 2 km). The reason for the difference between Spire and UCAR processing is not completely clear, and we continue to investigate the issue.

The results presented in this section show the statistical quality of Spire-processed and UCAR-processed RO data are comparable.

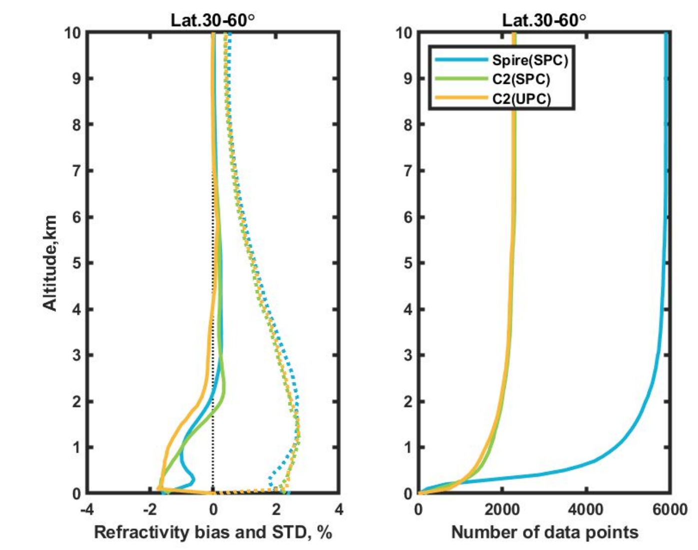

Figure 8: *The same as in Figure 6 for the mid-latitude region.*

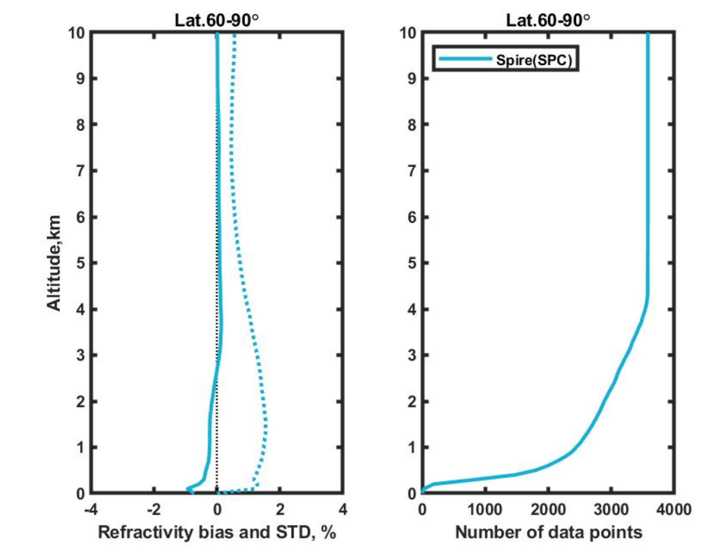

Figure 9: *Refractivity bias and STD for Spire data (SPC) in the polar region (where C2 does not sample).*

SNR effect on RO profile statistical quality

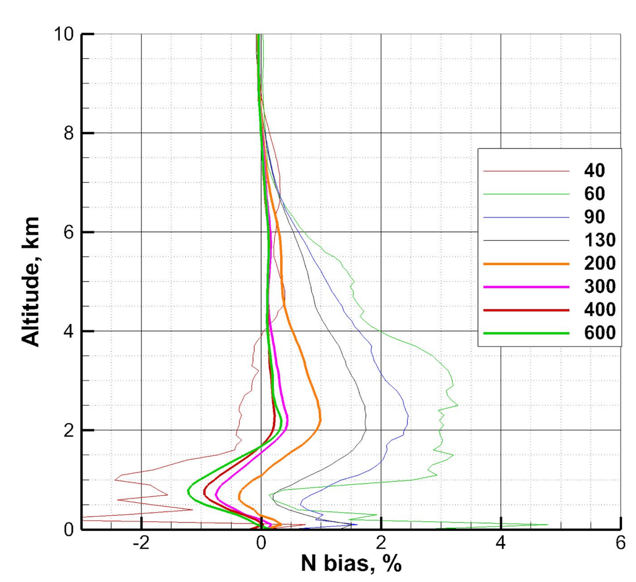

Figure 10: *Refractivity bias versus altitude and SNR.*

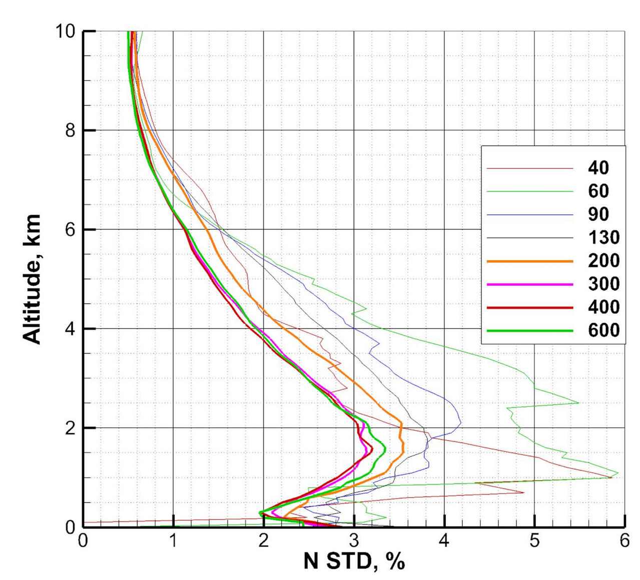

Figure 11: *Refractivity STD versus altitude and SNR.*

We use Spire satellite RO data considered in the previous section to study dependence on SNR. For that purpose, we divided the whole dataset into groups according to SNR value and estimated the refractivity bias and STD for each set separately. Table 2 shows the limits of the SNR bins, number of profiles, and the labels as they are referred in the figures.

Table 2.

SNR label	SNR range	Number of profiles
"40"	< 40	143
"60"	40 -- 60	107
"90"	60 -- 90	433
"130"	90 -- 130	1141
"200"	130 -- 200	3697
"300"	200 -- 300	7342
"400"	300 -- 400	5645
"600"	> 400	3120

Figure 10 shows the refractivity bias for the SNR bins, and **Figure 11** shows the refractivity STD for the same bins of profiles. Strong fluctuations of the bias and STD for "40" and "60" datasets are explained by fewer data points used in the statistics.

We see that increasing SNR above very low levels does result in reduction of the bias and STD, but increasing SNR above 200 V/V does not significantly improve the statistical quality of the RO profiles (as noted in the previous sections comparing Spire and C2 profiles as processed by UCAR). Instead of pruning profiles below a certain SNR cutoff (e.g., 200 V/V), we suggest that profiles with lower SNR should be cut off or deweighted at the lower altitudes. We are working on adapting our processing software to the signals with various noise levels.

Conclusions

- **The quality of raw RO profiles collected by Spire, GeoOptics, and COSMIC-2 satellites and processed by UCAR is statistically comparable.**
- **Spire and UCAR processing centers produce similar results for the same COSMIC-2 data, but small differences in the processing are still under investigation.**
- **Increasing the SNR level above 200 V/V does not significantly improve the statistical quality of RO profiles for NWP applications, and profiles with lower SNR could still be used but deweighted below about 8 km.**

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