Comparison of Ionospheric Electron Density Retrieved from Spire Global Radio Occultation Data with Arecibo Incoherent Scatter Radar and Digisonde Measurements

Victoriya V. Forsythe[1], Timothy Duly[2], Don Hampton[1], Vu Nguyen[2]

1. Geophysical Institute, Fairbanks, AK, USA

2. Spire Global, Inc, Boulder, CO, USA

Abstract: Radio occultation (RO) has been proven to be a powerful technique for ionospheric electron density profile (EDP) retrieval. Commercial GNSS-RO ionospheric measurements collected by the Spire 3U CubeSat constellation could significantly improve the determination of the global ionospheric state. In this work, the EDPs retrieved from Spire total electron content (TEC) measurements using Abel inversion corrected by horizontal asymmetry are compared to Arecibo density measurements. Good agreement is observed in case-by-case EDP comparison. The information about F2 layer peak and height obtained from Spire data is also compared to digisonde measurements at 34 stations around the globe from Global Ionospheric Radio Observatory (GIRO) network.

Introduction:

Spire Global, Inc. is an analytics company that utilizes proprietary satellite data and algorithms to provide maritime, aviation, and weather tracking. Spire designs, manufactures, and operates a constellation of low-Earth orbit (LEO) 3U CubeSats with high-gain antennas that perform GNSS RO for atmospheric and ionospheric remote sensing. The receivers onboard of LEO Spire satellites collect the GNSS dual-frequency signal phase data which corresponds to the slant TEC along the radio path. Further, the TEC measurements can be used to extract the EDPs along tangent points (TPs) (or ray perigee's locations) of ray paths between LEO and GNSS satellites. In the current work, the EDPs extracted from Spire TEC data are compared to digisonde and incoherent scatter radar measurements to examine the accuracy of Spire data.

Data:

The majority of Spire's TEC measurements are collected from each satellite's zenith-pointing precise orbit determination (POD) antenna, which provides good coverage of the ionospheric portion above the satellite orbit altitude. However, many of these TEC paths also traverse through the bottom-side of the ionosphere and thus provides the potential to convert to EDPs.

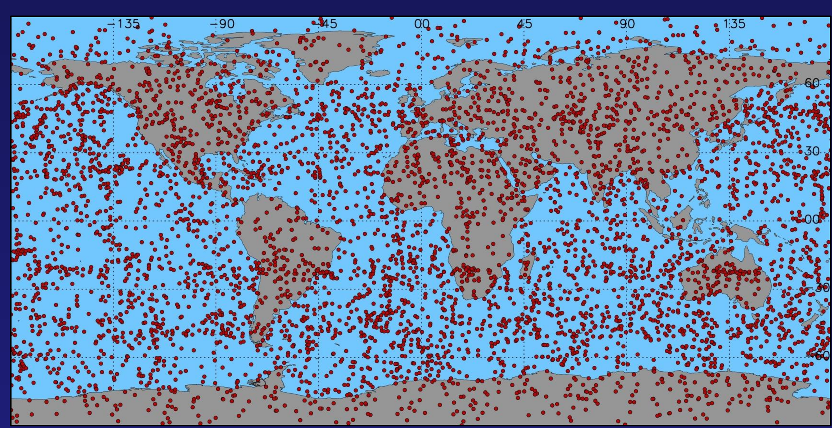


Figure 1: Spire RO data coverage on February 1–14, 2019.

The global distribution of Spire RO events during a quiet geomagnetic period (with F10.7 index ranging 6870 s.f.u.) between 2019-02-01 and 2019-02-14 is shown in Figure 1.

EDP retrieval methodology:

Traditionally, the Abel transform (or onion-peeling method) is used to retrieve the EDP along the TPs from the calibrated TEC measurements. The approximation of the spherical symmetry in the ionospheric density distribution is the main source of errors in the Abel inversion method [Wu et al., 2009; Guo et al., 2015; Pedatella et al., 2015]. To take into account the expected horizontal asymmetry of the ionosphere, the Abel inverse assisted by the NeQuick model was developed and used in this study. As an example, the expected density along the radio path during one Spire RO event (20190205 18:21 – 18:27 UT), shown in Fig 2a, has strong asymmetry along the ray comparing to the TP locations. The asymmetry coefficient $a_{i,j}$ (shown in Fig 2b) assigned to each ray-shell (i, j) intersection point improves the classical Abel inversion. Fig 2c shows how the asymmetric Abel inversion method improves the reconstruction of the EDP during a test case using synthetic TEC data produced by NeQuick. Also shown a profile retrieved from Spire data (solid red line) which is very different from the model prediction.

$$n_e(\mathrm{TP}_i) = \frac{\mathrm{sTEC}^i_{\mathrm{cal}} - \sum_{j=0}^{i} n_e(\mathrm{TP}_j)\, l_{i,j}\,(a^1_{i,j} + a^2_{i,j})}{l_{i,i}}$$

$l_{i,j}$ is distance of ray i in shell j

$a^1_{i,j}$, $a^2_{i,j}$ are expected asymmetry on both sides of TP

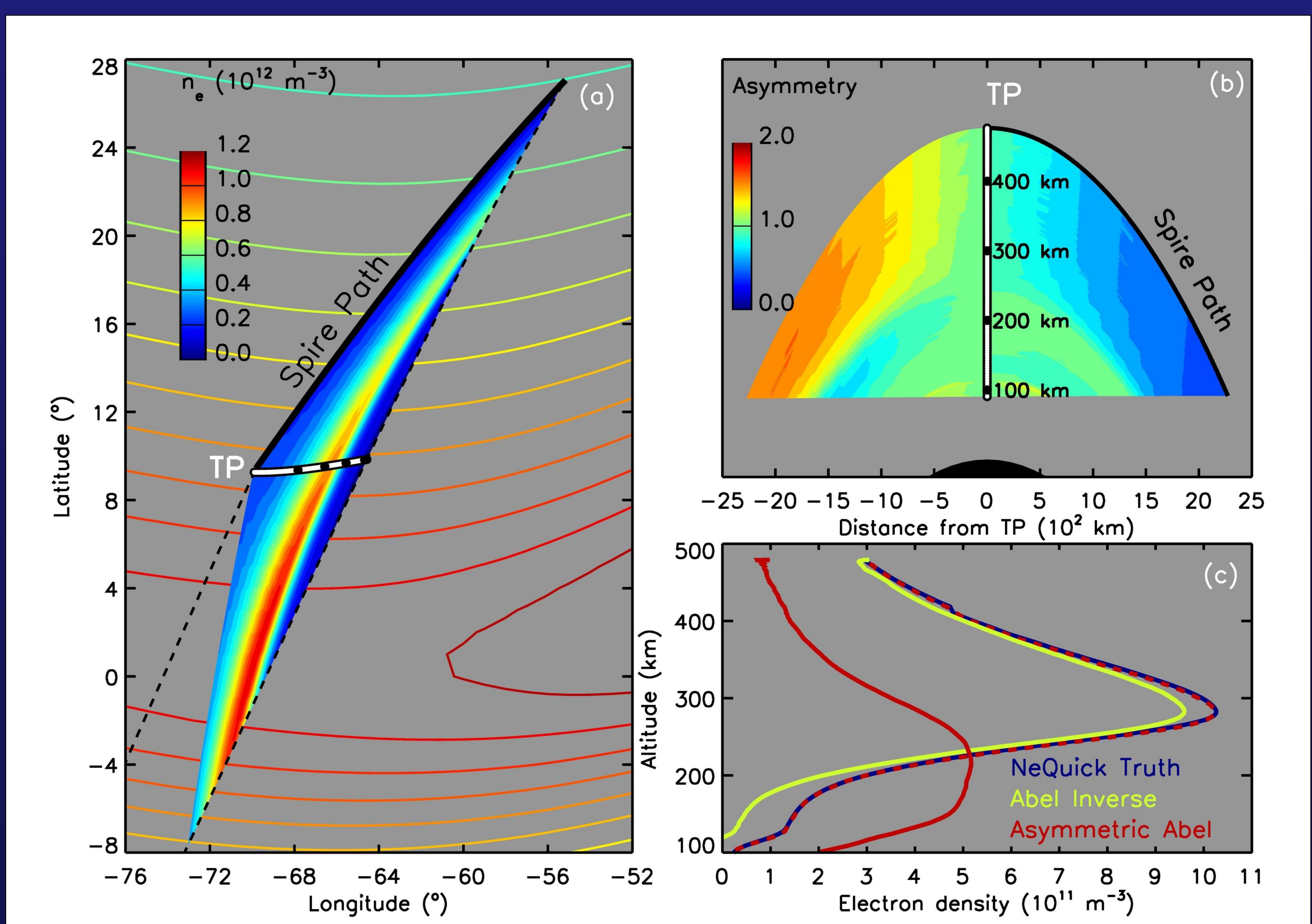


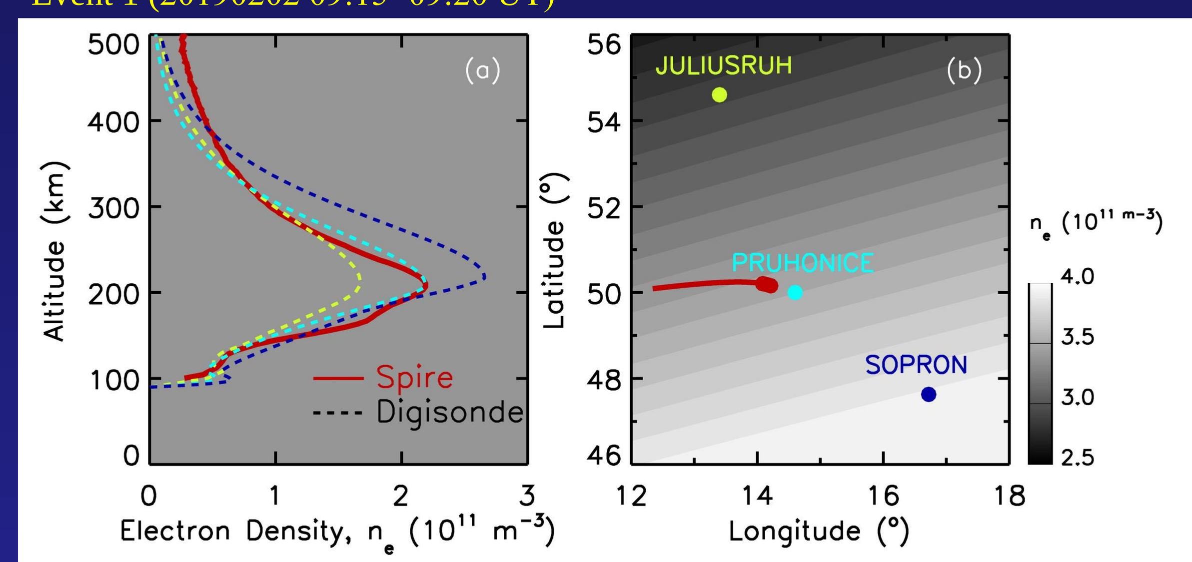
Figure 2: (a) Projection of the radio path on the Earth's surface during one RO event. Color indicates expected electron density from NeQuick model along the radio path. (b) Asymmetry of the expected electron density is defined as a ratio of the electron density along each shell and the density at the TPs and used to improve the Abel inversion method. (c) During the test case, the Abel inversion without approximation of spherical symmetry (red dashed) reconstructs the truth (blue) better than a regular Abel transform (yellow). The EDP reconstructed from Spire data is also shown with solid red line.

Results:

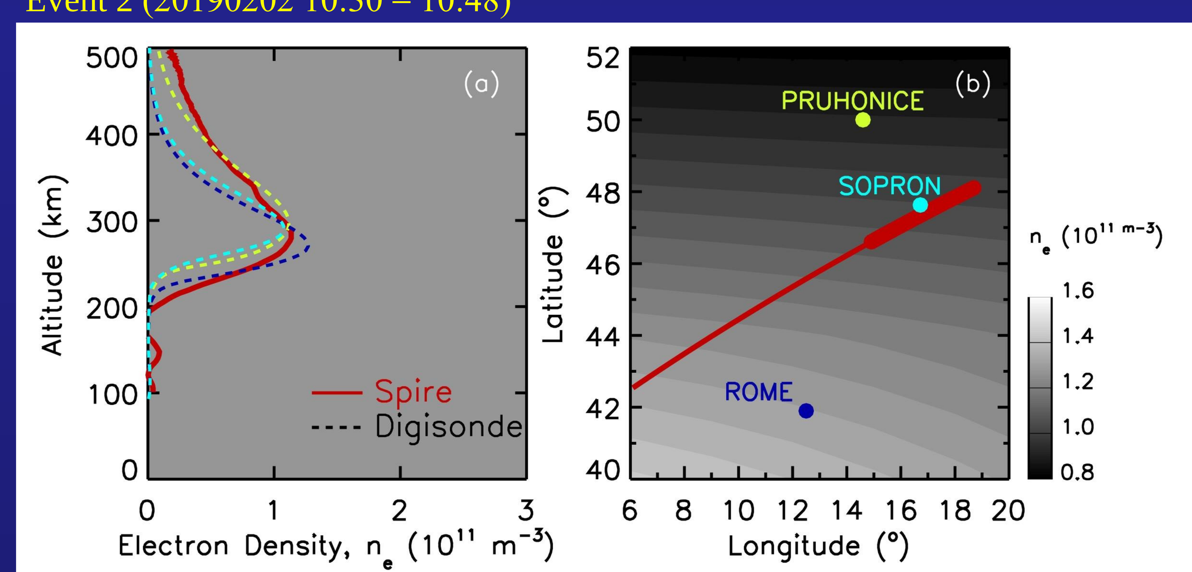
4 events were found when Spire RO occurred within 600 km from 3 digisonde stations. For the comparison with the ground measurements it is important to keep in mind that RO retrieved EDP is not a vertical profile, but a profile along the TP trace, therefore it is critical how far the part of trace that corresponds to the bottom side of the profile (thick red line in Fig 3b) is located from the digisonde station and how spatially extended the occultation trace is. In addition, the topside of digisonde profiles is constructed by fitting a model to the peak density value and should not be considered as a ground truth.

1. Good agreement between Spire retrieved EDP with the closest digisonde at Pruhonice. As expected by NeQuick model (gray contours), the digisonde at Juliusruh observes lower F2 peak and digisonde at Sopron observes higher F2 peak.
2. Longer RO trace probably smears the shape of bottom side, however still a good agreement is observed for F2 peak values.
3. Two simultaneous Spire RO events occurred close to 3 digisonde stations. 1st RO has lower F2 peak than the second one, as expected by NeQuick model. Good agreement between 1st RO and Fairford and Chilton digisondes and 2nd RO with digisonde at Dourbes. Vertical orientation of F2 peak density contours is consistent with the observation.
4. Disagreement between NeQuick prediction and digisonde observations. Geographic location of RO trace suggested that NmF2 values lays between Sopron and San observations, which is consistent with Spire EDP.

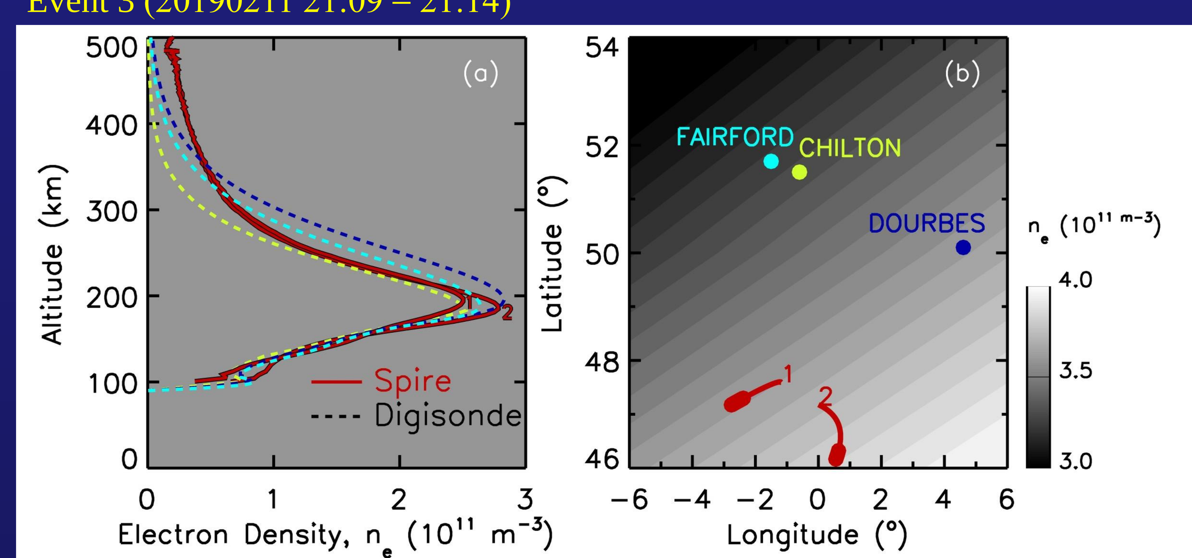
Event 1 (20190202 09:15–09:20 UT)



Event 2 (20190202 10:30 – 10:48)



Event 3 (20190211 21:09 – 21:14)



Event 4 (20190211 13:57 – 14:03)

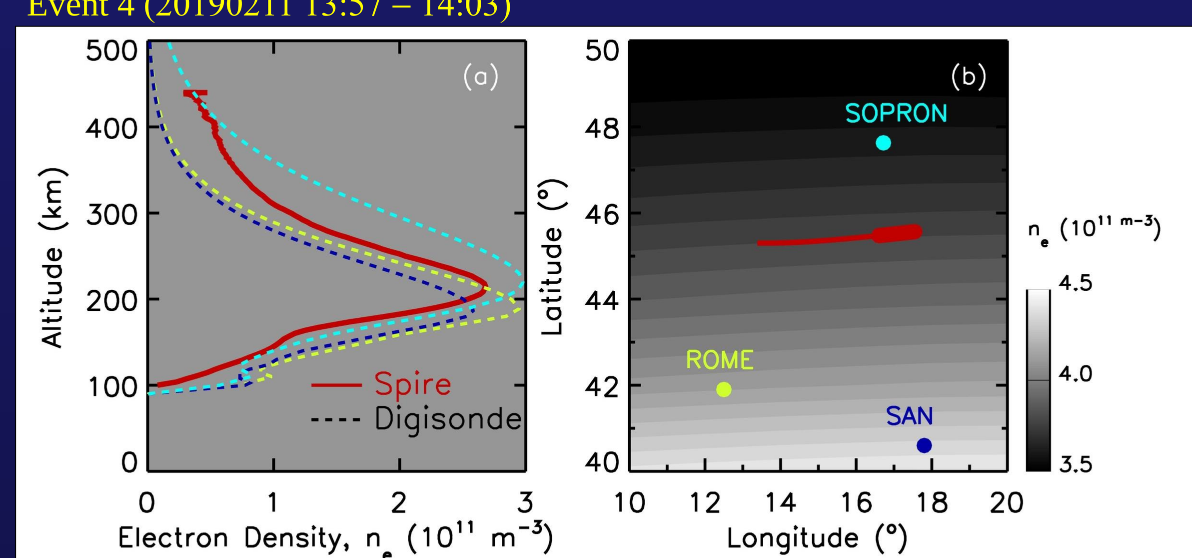


Figure 3: (a) Comparison of EDP reconstructed from Spire TEC data using asymmetric Abel transform added by NeQuick model with digisonde data from Global Ionospheric Radio Observatory (GIRO) [*Reinishch and Galkin*, 2011] network at 3 different stations. (b) Location of the Spire TP in relation to 3 digisonde stations. Contours show the expected F2 density peak from NeQuick model during the time of the events.

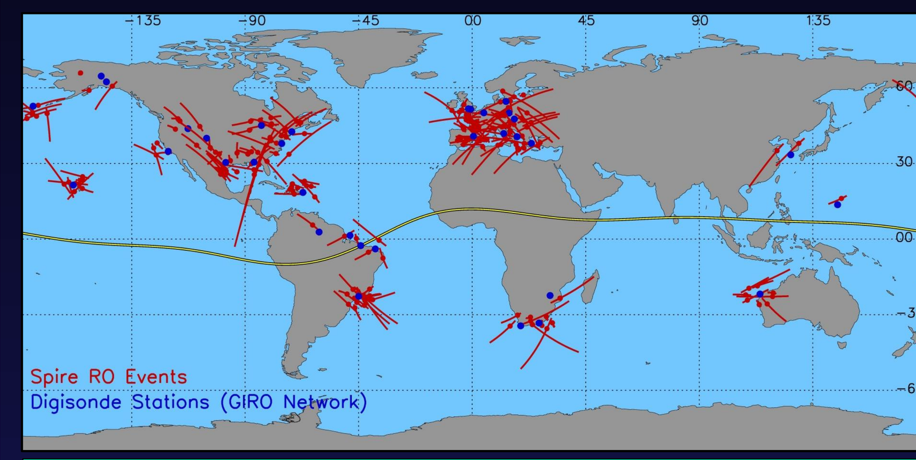


Figure 4: Locations of Spire RO events (red) and digisonde stations from GIRO Network.

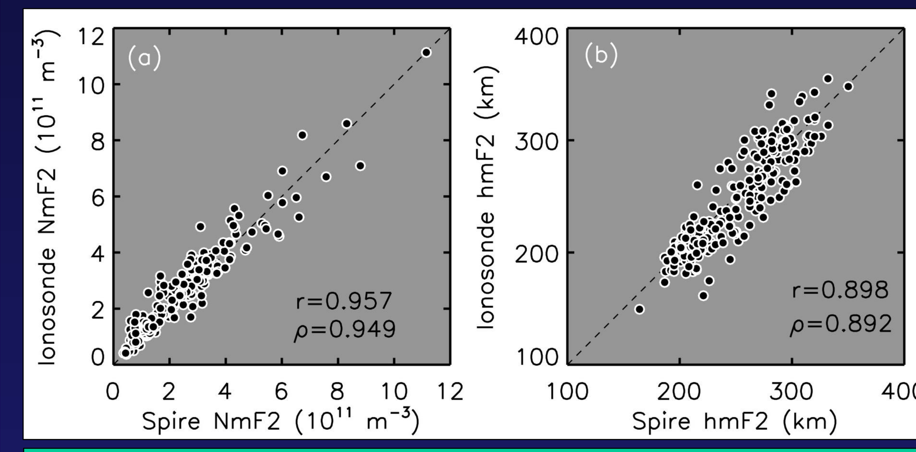


Figure 5: The scatter plots of Spire and digisonde (a) NmF2 and (b) hmF2 values.

237 events when the Spire RO was located within 600 km from digisonde station were selected. Only NmF2 and hmF2 digisonde parameters automatically scaled by Automated Real Time Ionogram Scaler with True height (ARTIST) software [*Reinisch et al*., 2005] with confidence level higher than 75% were considered. A high degree of correlation is observed between Spire and digisonde independent estimates of NmF2. The results have high linear and Pierson correlation coefficients of 0.957 and 0.949. A good agreement is visible for the heights of the peak electron density as well, with linear and Pierson correlation coefficients of 0.898 and 0.892.

The NmF2 correlation coefficient is higher in comparison with one validation study for COSMIC satellites (r = 0.85 with 276 points) [*Lei et al*., 2007], and slightly lower than in other COSMIC validation study (r = 0.986 with 750 points) [*Krankowski et al*., 2011] focused on European region.

10 Spire RO events located close to Arecibo ISR were selected for EDP comparison. Gregorian coded long pulse Arecibo data was used for this analysis.

Good agreement with linear correlation coefficient of 0.912 was observed in comparison of the profiles, taking into consideration that several RO events (number 3, 5, 6, 7, 8, 9, 10) happened further than 600 km from the Arecibo radar and that several RO events (number 5, 6, 8, and 9) had long traces. Poor agreement was observed among low-altitude points (blue points in Fig 6c) most likely due to the well-known increasing errors with decreasing height in the Abel inversion.

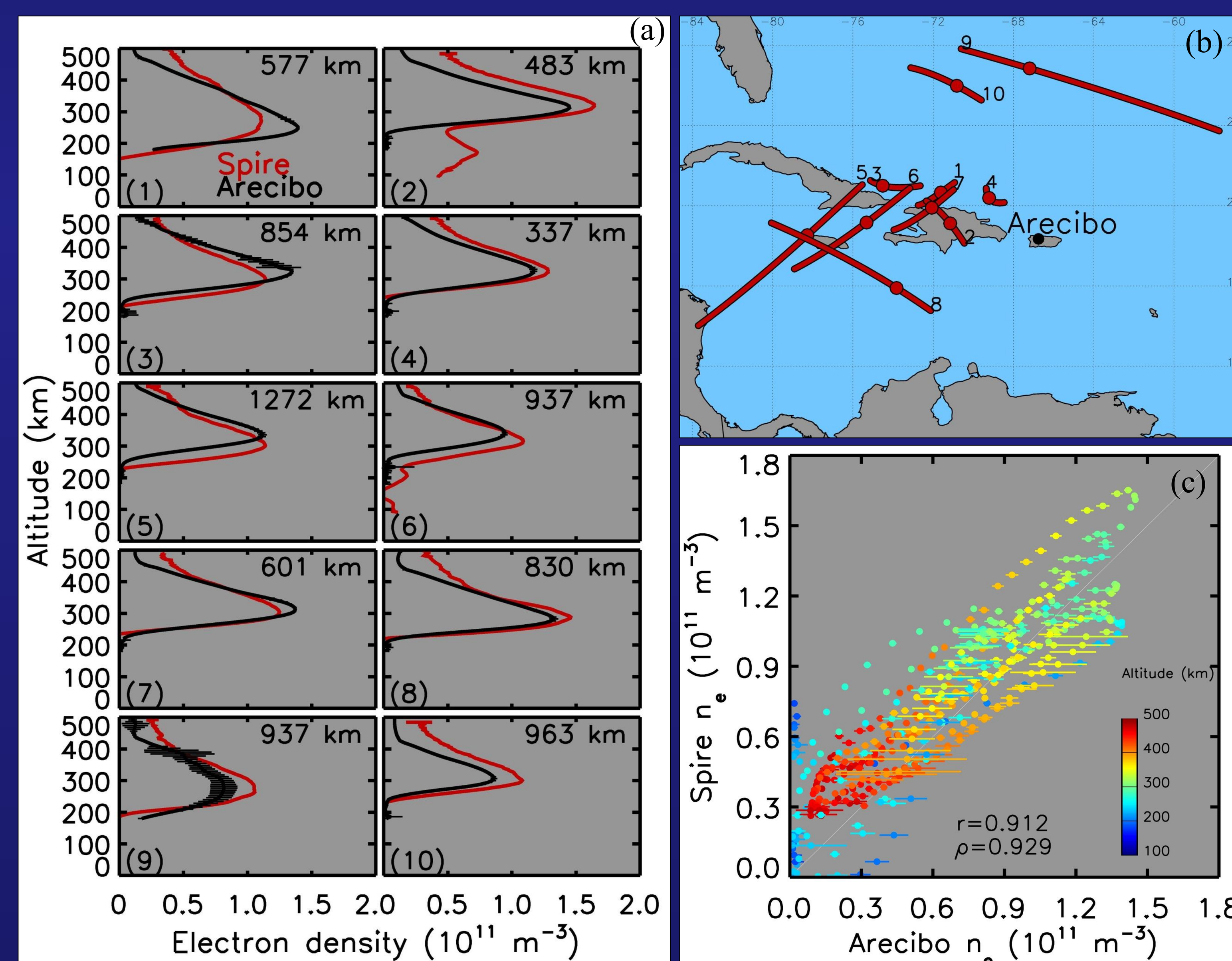


Figure 6: (a) Comparison of EDP reconstructed from Spire data with Arecibo Incoherent Scatter Radar (ISR) data during 10 RO events. (b) Geographic location of the Spire TPs in relation to Arecibo. (c) The scatter plot of Spire-derived and Arecibo-observed electron density with color indicating the altitude of the points.

Conclusion:

Statistical analysis of Spire and digisonde data carried out for 14 geomagnetically quiet days shows that Spire profiles are in generally good agreement with digisonde profiles. Case-by-case comparison of Spire profiles with Arecibo ISR data also showed a good agreement. This indicates that EDPs retrieved from Spire RO measurements are reliable and can be used for ionospheric physics studies. Spire Global is constantly increasing the number of LEO satellites and has a high potential of making significant contribution to the studies of ionospheric structure and dynamics on the global scale.

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