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The comparison of topmost radio occultation electron densities with *in-situ* ion densities from FORMOSAT-7/COSMIC-2

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ABSTRACT

The ionospheric radio occultation (RO) inversion is a powerful tool in retrieving the global electron density profiles (EDPs) remotely by using the time delay of the signals received by Low Earth Orbit (LEO) satellites from the GPS and other GNSS satellites based on the spherical symmetry assumptions and the coplanar approximation. However, these assumptions may cause the inaccuracy in the electron density retrieval. In this study, for the first time, we present an ionospheric electron density comparison between the estimated topmost electron density profiles from the FORMOSAT-7/COSMIC-2 (F7/C2) RO and the co-located *in-situ* ion densities obtained from the Ion Velocity Meter (IVM) onboard the F7/C2 satellites and then further quantitatively evaluate the impacts of the abovementioned Abel inversion assumptions on the topside ionospheric electron density. Results showed the RO topmost electron density is overall in good agreement with the IVM *in-situ* ion density but is slightly underestimation. Furthermore, the dihedral angle of the LEO and the occultation plane is also highlighted the importance of the coplanar approximation in the Abel inversion.

1. INTRODUCTION

The six-satellite FORMOSAT-3/Constellation Observing System for Meteorology, Ionosphere and Climate (FORMOSAT-3/COSMIC, or F3/C in short) launched in April 2006 and provided 1000 - 2500 ionospheric electron density vertical profiles per day through the Global Positioning System (GPS) radio occultation (RO) technique. These abounding observations are extensively employed in the global ionospheric research (e.g., Luan et al. 2008; Lin et al. 2010) and the ionospheric nowcast/forecast system (e.g., Lee et al. 2012; Lin et al. 2017).

The accuracy of the ionospheric peak density (NmF2) and the peak height (hmF2) from the GPS RO have been reported by comparing with the ground-based ionosonde and incoherent scatter (IS) radar (Lei et al. 2007; Kelley et al. 2009), and the space-based CHAllenging Minisatellite Payload (CHAMP) (Yue et al. 2011; Pedatella et al. 2015), showing the root-mean-square error is about 10 to 20%. This error is mainly caused from the assumptions of the Abel inversion when deriving the electron density profile (EDP), including the topmost electron density estimation and the coplanar approximation. Using the *in-situ* observations, around 400 to 800 km altitude, from the Communications/Navigation Outage Forecasting System (C/NOFS) satellites, the F3/C ionospheric topside electron densities have been validated (Lai et al. 2013; Pedatella et al. 2015). Results show the good agreement between the F3/C GPS RO and the C/NOFS *in-situ* observations. However, the C/NOFS satellite was placed into a low Earth orbit with a perigee height of ~400 km and an apogee of ~850 km, it is

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hard to directly compare its *in-situ* measurements with the topmost electron densities of the F3/C GPS RO, which is an important parameter for the Abel inversion (Lei et al. 2007).

Following on the F3/C mission, the six FORMOSAT-7/COSMIC-2 (F7/C2) satellites were launched on 25 June 2019 in a low earth orbit (LEO) with 24° inclination angle and ~550 km altitude. All six satellites have been receiving GPS and Global Navigation Satellite System (GLONASS) signals, which providing around 4000 ionospheric EDPs per day between 50° north and south latitudes. Another on board instrument, call as Ion Velocity Meter (IVM), can measures the *in-situ* temperature, velocity, and density of ions in the path of each F7/C2 satellite. These *in-situ* observations provide us a good opportunity to directly evaluate the system errors of the Abel inversion. By employing the *in-situ* ion densities measured by the IVM experiment on the F7/C2 satellite at the orbit altitude, the main objective of this study is to validate the topmost electron density of F7/C2 RO EDPs.

2. RESULTS AND DISCUSSIONS

The topmost electron densities as well as the *in-situ* ion densities at the orbit altitude on 1 January 2021 have been examined in this study. At the beginning of January 2021, five LEO satellites had been transferred to the 550-km final mission orbits and only one satellite was still on its parking orbit of about 720 km altitude. Based on the first order estimation of orbit electron density in the Abel inversion (cf. Syndergaard et al. 2006), the different satellite orbits of 550 and 720 km altitude could significantly influence the retrieved electron density profiles. Furthermore, it is also found that the accuracy of IVM ion density is better at the low orbit (~540 km) than that at the high orbits (~710 km) (Wu et al. 2021). Therefore, we only choose both RO and IVM measurements when the satellite arrived to ~550 km altitude to exclude the orbit influence. Based on the above selection, there are 3965 EDPs obtained. Figure 1 shows the ground projected locations of one EDP (blue line) and the *in-situ* ion density (red line) during 12:00:48 UT to 12:07:36 UT on 1 January 2021 as an example. This is an ascending pass case, showing the LEO satellite flying from the north-west to the south-east direction. The topmost electron density occurred at 12:07:36 UT and its location is around latitude of -18.55°N, longitude of -42.79°E, and altitude of 540.22 km, which is very close to the LEO satellite location (-18.01°N, -43.52°E, 541.08 km) at 12:07:36 UT.

The 3058 topmost electron densities within 2° horizontal distance from the LEO satellite were selected for the comparison. Figure 2 presents the comparison between the GPS RO and the IVM ion density observations for the daytime (06 - 18 LT) and the nighttime (18 - 06 LT). It shows that the overall relationship between these two kinds of observations has a strong correlation since the value of correlation coefficient is greater than 0.9. This result is similar to the previous studies (Lai et al. 2013; Pedatella et al. 2015), which compared the F3/C GPS RO electron densities with the *in-situ* electron densities from the C/NOFS satellite at its orbital altitude, around 400 to 850 km. Figure 2 is also found that most of the scattered points are concentrated at the end of the line y = x during the daytime and concentrated at the beginning of the line y = x during the nighttime. The correlation coefficients for the daytime and the nighttime are 0.89 and 0.86 (not shown), respectively. This difference might come from the relatively small background electron densities during nighttime which has a relatively larger uncertainty of the calibrated TEC around the topside EDPs in the Abel inversion (Yue et al. 2011).

In order to know and evaluate the deviation of topmost electron density from the *in-situ* ion density, their differences as well as the root-mean-square-difference (RMSD) is computed. The RMSD is defined as

$$RMSD = \sqrt{\frac{\sum_{i=1}^{N}(D_{RO} - D_{IVM})^2}{N}} \quad (1)$$

in which N is the total number of observations (3058). D is either the topmost electron density (D_{RO} in the equation) or the *in-situ* ion density (D_{IVM} in the equation). Figure 3 presents the residual distribution histogram of their differences for all local times. It shows a mean of residual of -7.6×10^3 ele cm^{-3}, a standard deviation of 3.6×10^4 ele cm^{-3}, and a RMSD of 3.6×10^4 ele cm^{-3}, indicating that they match well but the topmost electron density is slightly lower than the *in-situ* ion density. This might be caused by the estimation of the electron density at the satellite orbit altitude (Lei et al. 2007; Yue et al. 2010, 2011). The orbit electron density is derived from the calibrated TEC below the orbit altitude by fitting a linear regression of square root function under the assumption of spherical symmetry for the electron density (cf. Syndergaard et al. 2006), which results in systematic biases in the standard Abel inversion processes (Schreiner et al. 1999; Lei et al. 2007; Wu et al. 2009). By compared F3/C GPS RO electron density in the topside ionosphere with *in-situ* electron density from C/NOFS, Pedatella et al. (2015) further suggested that the error introduced by the Abel inversion spherical symmetry assumption increases with decrease of altitude due to the higher and more structured electron densities at lower altitude. The mission orbit of F7/C2 satellite is around 550 km, which is lower than that of F3/C satellite (~800 km). It can be expected that the spherical symmetry assumption and the square root fitting might be sensitive to the estimation of topmost electron densities at F7/C2 orbit altitudes and the induced errors will be propagated to the bottom layer. If one can retrieve the electron density profiles by employing the *in-situ* orbit ion density from IVM, the accuracy of EDP approximates might be improved.

In the standard Abel inversion, there is another assumption that the LEOs and the occultation planes are coplanar. However, in the most situations, they are not exactly coplanar, which indicates that the coplanar assumption might cause the inversion error in the EDP. Lin et al. (2013) developed a technique based on the epoch difference inversion (EDI) to retrieve the EDPs without the coplanar assumption. Their results presented that the EDI has better performance than the standard Abel inversion, showing that the coplanar approximation is important to influence the accuracy of EDP retrieve. In order to quantitatively evaluate the impact of coplanar assumption to the topmost electron density, in this study, we further calculate the dihedral angle of the LEO and the occultation plane. Figure 4 illustrates the geometry of the LEO satellite and the GNSS (Global Navigation Satellite Systems) satellite not to scale. From the normal vectors of the LEO-LEO-Earth plane (blue vector) and the LEO-GNSS-Earth plane (red vector), we can calculate their dihedral angle by the dot product. In the case of Fig. 4, the LEO and the occultation plane is not coplanar with a dihedral angle of α. The dihedral angle is less than 90°. We, then, calculate the dihedral angles for each GPS RO and IVM comparison in Fig. 2 and further divide these angles into 6 equal sectors, 15° each. Figures 5a and b show

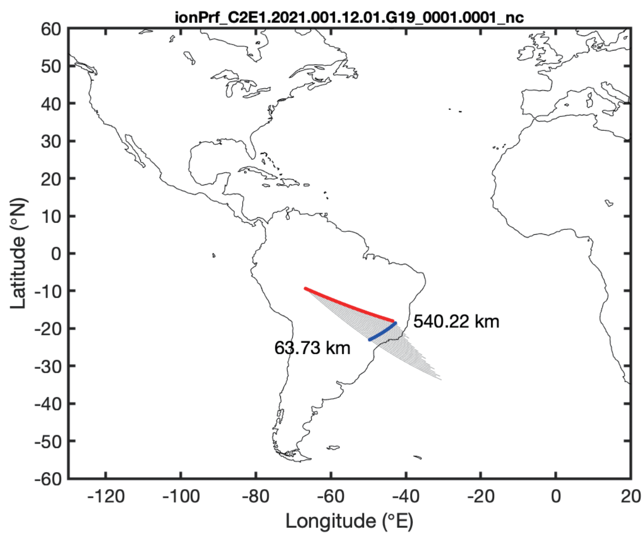

Fig. 1. The ground projected locations of one radio occultation event during 12:00:48 UT to 12:07:36 UT on 1 January 2021. The red and blue dots indicate the locations of IVM *in-situ* ion density and GPS RO electron density profile, respectively.

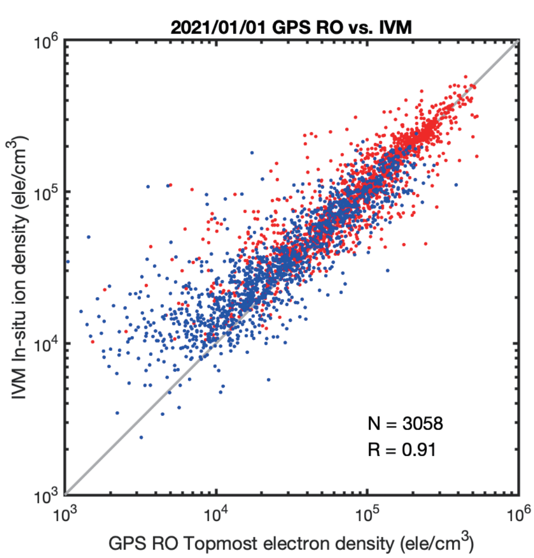

Fig. 2. The comparison between the topmost electron densities from GPS RO EDPs and the *in-situ* ion density from IVM. The red and blue dots indicate the daytime (06 - 18 LT) and nighttime (18 - 06 LT) observations. The gray line is the line that the IVM equals the GPS RO. The total observation number (N) is 3058 and the correlation coefficient (R) is 0.91.

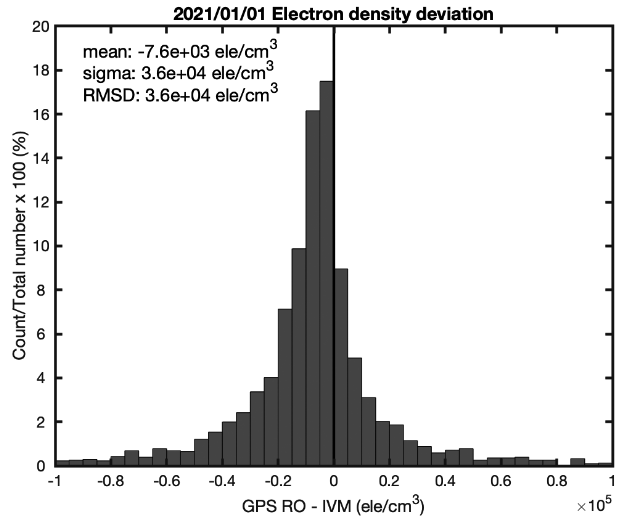

Fig. 3. The histogram of the residual distribution between GPS RO and IVM for all local times. The y-axes value is identified by the count in each residual interval divided by the total observation number (3058).

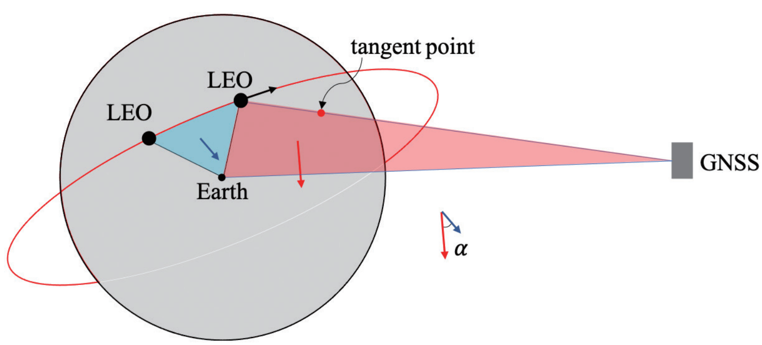

Fig. 4. The sketch of the geometry of the LEO and GNSS satellites. The term of 'Earth' in the sketch indicates the earth's center. The blue and red lines indicate the normal vectors of the LEO-LEO-Earth plane and the LEO-GNSS-Earth plane, respectively.

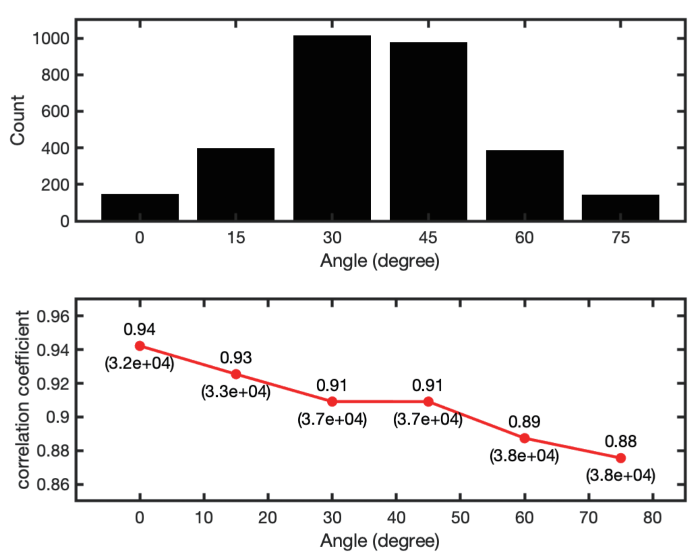

Fig. 5. The observation numbers (a) and the correlation coefficients and RMSDs (b) at different dihedral angle sectors. The angles are divided into 6 equal sectors, 0 - 15°, 15 - 30°, 30 - 45°, 45 - 60°, 60 - 75°, and 75 - 90°. The RMSD value is shown by the parentheses in (b). The unit of RMSD is ele cm^{-3}.

the observation numbers and the correlation coefficients and RMSDs in each sector, respectively. The observation number shows that the most observations are concentrated in the angle of 30 to 60°. It is also clearly seen that the correlation coefficient decreases from 0.94 to 0.88 with the increase of dihedral angle. The RMSDs also show the similar tendency, indicating that the better agreements of topside electron density between the topmost electron density and the *in-situ* ion density occur at the situation of small dihedral angles. This result is in line with our expected that larger angles lead to more sensitivity to the horizontal density gradient, resulting in the electron density errors on the topside EDP estimation.

3. CONCLUSION

This paper firstly evaluates the linear relationship between the estimated topmost electron densities from the F7/C2 GPS RO EDPs and the collocated *in-situ* ion density observations from the F7/C2 IVM instrument. The scatter and histogram plots between the topmost electron densities and the *in-situ* ion densities on 1 January 2021 are employed in this study. The obtained results can be summarized as follows:

(1) The correlation coefficient results reveal the overall good agreement between these two kinds of observations but has a slightly underestimation in the retrieved topmost electron densities. This discrepancy might be attributed to the estimation/assumption of topside electron density at satellite altitudes in the Abel inversion. Applying the *in-situ* orbit ion densities from F7/C2 IVM to the topmost electron densities with the Abel inversion is expected to improve the accuracy of EDP estimation.

(2) The electron density errors of topmost electron densities increase with increasing dihedral angle between the LEO and the RO planes.

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