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.

Key word: Radio occultation inversion, topmost electron density, in-situ ion density, spherical symmetry

1. Introduction

The accuracy of the ionospheric peak density (NmF2) and the peak height (hmF2) from the Global Positioning System (GPS) radio occultation (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 hardly 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.

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 4,000 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 EDPs of F7/C2 RO.

2. Results and discussions

The topmost EDPs as well as the in-situ ion densities at the orbit altitude on 1 January 2021 have been examined in this study. The 3,058 topmost EDPs within 2° horizontal distance from the LEO satellite were selected for the comparison. Figure 1 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 km to 850 km.

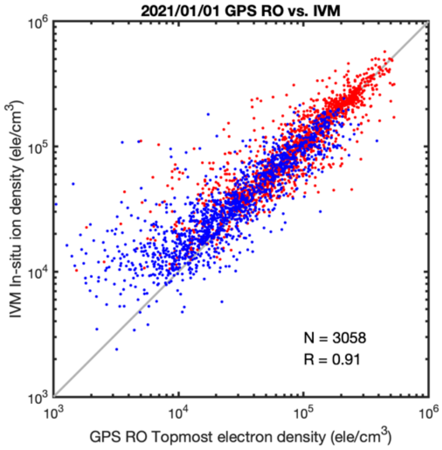

Figure 1. The comparison between the topmost EDPs from GPS RO and the in-situ ion density from IVM. The red and blue dots indicate the daytime (06-18 LT) and nighttime (18-06 LT) observations. The gray line is the line that the IVM equals the GPS RO.

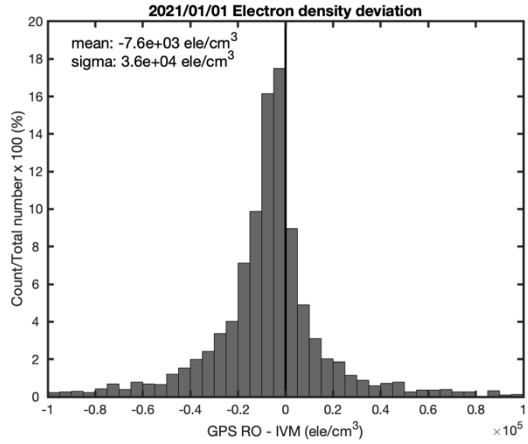

Figure 2. The histogram of the residual distribution between GPS RO and IVM for all local times.

In order to know and evaluate the deviation of topmost EDP from the in-situ ion density, Figure 3 presents the residual distribution histogram of their differences for all local times. It shows a mean of residual of -7.6x10^3 ele/cm^3 and a standard deviation of 3.6x10^4 ele/cm^3, indicating that they match well but the topmost EDP are 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]. 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 EDPs 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. We, then, calculate the dihedral angles for each GPS RO and IVM comparison in Figure 1 and further divide these angles into 6 equal sectors, 15° each. Figures 3a and 3b show the observation numbers and the correlation coefficients 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, indicating that the better agreements of topside electron density between the topmost EDP 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.

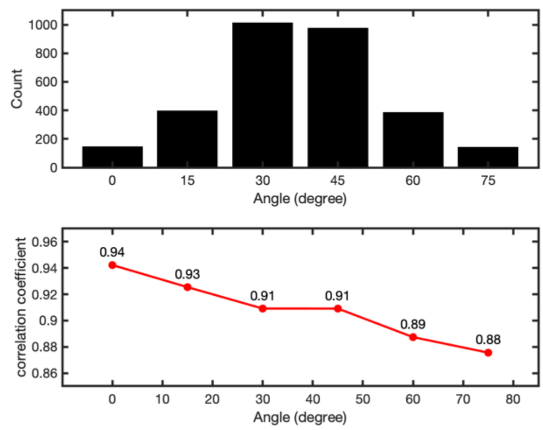

Figure 3. The observation numbers (a) and the correlation coefficients (b) at different dihedral angle sectors. The angles are divided into 6 equal sectors, 0°-15°, 15°-30°, 30°-45°, 45°-60°, 60°-75°, and 75°-90°.

3. Conclusions

This paper firstly evaluates the linear relationship between the estimated topmost EDPs from the F7/C2 GPS RO and the collocated in-situ ion density observations from the F7/C2 IVM instrument. The scatter and histogram plots between the topmost EDPs and the in-situ ion densities on 1 Jan. 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 EDPs. This discrepancy might be attributed to the assumption of spherical symmetry in the Abel inversion. The utility of in-situ orbit ion densities from F7/C2 IVM as the topmost EDPs in the Abel inversion is expected to have improvement on the accuracy of EDP estimation.
2. The electron density errors of topmost EDPs increase with increasing dihedral angle between the LEO and the RO planes.

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