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

Chia-Hung Chen¹, *, Ho-Fang Tsai¹, Li-Yuan Wang¹, Chien-Hung Charles Lin¹, Jann-Yenq Liu²,³, and Wen-Hao Yeh⁴

¹Department of Earth Sciences, National Cheng Kung University, Tainan City, Taiwan
²Institute of Space Science, National Central University, Taoyuan City, Taiwan
³Center for Space and Remote Sensing Research, National Central University, Taoyuan City, Taiwan
⁴National Space Organization, Hsinchu City, Taiwan

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.

Article history:
Received 17 April 2021
Revised 10 June 2021
Accepted 26 July 2021

Keywords:
Radio occultation, Spherical symmetry assumption, Coplanar approximation, Ion Velocity Meter, FORMOSAT-7/COSMIC-2

Citation:

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
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 pro-
vide us a good opportunity to directly evaluate the system
ersors of the Abel inversion. By employing the in-situ ion
densities measured by the IVM experiment on the F7/C2 sat-
ellert 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 park-
ing 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 ascend-
ping 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° hori-
zontal 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 day-
time (06 - 18 LT) and the nighttime (18 - 06 LT). It shows
that the overall relationship between these two kinds of ob-
servations has a strong correlation since the value of corre-
lation 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 concentration
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 un-
certainty 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 differ-
ences as well as the root-mean-square-difference (RMSD)
is computed. The RMSD is defined as

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

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 differ-
ences for all local times. It shows a mean of residual of
-7.6 x 10^4 ele cm^-3, a standard deviation of 3.6 x 10^4 ele
cm^-3, and a RMSD of 3.6 x 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 er-
ror introduced by the Abel inversion spherical symmetry
assumption increases with decrease of altitude due to the
higher and more structured electron densities at lower alti-
itude. 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 $\alpha$. 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.](image1)

![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.](image2)
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.

Acknowledgements The study is supported by National Space Organization (NSPO) and Ministry of Science and Technology (MOST) of Taiwan to National Cheng Kung University under NSPO-S-108002, NSPO-S-109059, and MOST-109-2121-M-006-014. The authors would like to thank the Taiwan Analysis Center for COSMIC (TACC) team for providing the RO-derived electron density profiles as well as the in-situ ion densities of FORMOSAT-7/COSMIC-2 mission at the database (https://tacc.cwb.gov.tw/v2/download.html).

REFERENCE


