The Accuracy Assessment and Scientific Research Progress of Ionospheric Radio Occultation Products Observed by Fengyun-3 GNOS

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Abstract—Global navigation satellite system (GNSS) radio occultation (RO) is a novel detection technique that can provide global ionospheric products with high vertical resolution, high precision, and low cost. In recent years, China has launched the Fengyun-3 (FY3) series of meteorological satellites carrying the first RO payload to simultaneously receive global positioning system (GPS) and BeiDou navigation system (BDS) signals. In the accuracy assessment of RO products observed by GNSS occultation sounder (GNOS), the maximum F2-layer electron density (NmF2) of GPS occultation and BDS occultation has a standard deviation (std) of less than 20% in comparison with that of ionosondes. The std of F-layer worst case ionospheric scintillation index (S4:F) between Constellation Observing System for Meteorology, Ionosphere, and Climate and FY3/GNOS is less than 0.1. The above results prove the high precision of FY3 ionospheric RO products. The RO products have been applied to preliminary scientific research and applications, e.g., the process of main phase and recovery phase of magnetic storms revealed by the NmF2 observed by FY3C/GNOS, the pre-midnight dynamics of F-layer strong scintillation during magnetic storms revealed by GNOS scintillation data, the ionospheric perturbation driven by Tonga volcano eruption revealed by FY3/GNOS, applications of the RO data for the research of sporadic E layers, evaluation of International Reference Ionosphere model in statistics and ionospheric climatological characteristics, etc. With the successive network observation and continuous deployment of FY3 meteorological satellites, the continuous improvement of GNOS payload and the BDS system, massive high-precision ionospheric RO products will be developed and show more significant value.

Index Terms—Accuracy assessment, FY3, global navigation satellite system (GNSS) occultation sounder (GNOS), ionospheric radio occultation (RO), scientific application.

I. INTRODUCTION

A method of remote sensing detection, the global navigation satellite system (GNSS) radio occultation (RO) technique receives navigation signals refracted by the earth’s atmosphere and ionosphere through occultation receivers on LEO satellites, thus enabling limb sounding [1]. As a novel detection technique, GNSS RO can obtain the three-dimensional structure of the global atmosphere and ionosphere in a long-term, stable, and economical way. Also, it has the advantages of self-calibration, global coverage, high accuracy, and high vertical resolution [1], [2]. Based on the Abel integral transform inversion method of geometrical-optical approximation, the atmospheric refraction index can be inferred from the bending angle. The profiles of a series of ionospheric parameters can be obtained on a global scale such as electron density, total electron density content, and ionospheric scintillation index. GNSS RO products have shown significant research value and wide application prospects in many fields, such as ionospheric climatology study [3], space weather monitoring [4], [5], [6], [7], ionospheric data assimilation model [8], [9], [10], atmospheric ionospheric coupling studies [11], [12], [13], [14], etc.

In 1995, the United States launched the Global Positioning System/Meteorology (GPS/MET) project with a GPS receiver on its low-orbiting minisatellite. This project demonstrated the feasibility of the GNSS RO technology for detecting the atmosphere and ionosphere theoretically and technically for the first time and promoted the development and implementation of other RO projects [15], [16]. Subsequently, Germany launched the Challenging Mini-Satellite Payload (CHAMP) satellite for occultation sounding in 2001 [2], [17]. In 2002, The United States and Germany jointly launched the Gravity Recovery and Climate Experiment mission, which aims to enable simultaneous atmospheric and ionospheric occultation detection with CHAMP [18], [19]. In 2006, the United States and Taiwan implemented Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC). It is a RO constellation composed of six LEO satellites, and each satellite is equipped with a GPS occultation receiver [20]. The success of these projects has contributed to the continuous improvement of the ionospheric RO (IRO) detection system. Among them, the successful implementation of the COSMIC project is significant for accelerating the application of international RO technology, and
its ionospheric occultation products are widely used in scientific research, establishing a high standard in the global ionospheric observation [21], [22], [23]. Based on the high scientific significance and research value of the COSMIC-1 occultation constellation, COSMIC-2 was successfully implemented in 2019 [24].

China launched C (FY3C), D (FY3D), and E (FY3E) satellites of the Fengyun-3 (FY3) series in 2013, 2017, and 2021, respectively. In the next 10 years, three follow-up satellites (F, G, R) of the Fengyun-3 series will be deployed to establish a continuous observation network of at least four satellites, as shown in Fig. 1 [25]. FY3C is a sun-synchronous polar-orbiting satellite launched in September 2013. Its orbital altitude and inclination are 836 km and 98.8°, respectively. Compared with other international RO projects that can only receive GPS signals, FY3C carries the first occultation receiver capable of receiving both GPS and BeiDou navigation system (BDS) signals. The payload, named GNSS occultation sounder (GNOS), was developed by the National Space Science Center of the Chinese Academy of Sciences. It receives about 700 RO events per day on average (200 BDS + 500 GPS) [26]. It has now been in orbit for more than eight years, exceeding its scheduled five-year working life and is in extra-long service. The FY3D satellite was launched in November 2017, with orbital parameters similar to those of the FY3C. Its GNOS payload has been improved based on the FY3C in the antenna field of view and the number of occultation observation channels, and it can now receive about 250 BDS and about 600 GPS occultation events on average per day [27]. In addition, FY3C can only realize ionospheric scintillation observation of GPS signals, whereas FY3D adds the ionospheric scintillation monitoring of BDS so that it can detect ionospheric scintillation of BDS and GPS simultaneously [28]. Launched on July 5, 2021, the FY3E satellite is in a polar orbit with a local descent node time of about 6:00 P.M. The GNOS-II payload on FY3E adds observational support to the Galileo system. Moreover, GNOS-II can provide global ocean wind speed distribution based on the GNSS-Reflectometry technique, in addition to atmospheric and ionospheric observations [29].

Fig. 2 shows the global distribution of GPS/BDS electron density profiles (EDP) observed by FY3C and FY3D. The red dot and blue dot represent the BDS occultation event and the GPS occultation event, respectively. The above products can be obtained through National Satellite Meteorological Centre. As of March 5, 2022, the website provides L1-level and L2-level ionospheric products from June 1, 2014 to the present. This article focuses on the accuracy assessment and application progress of ionospheric data products observed by the FY3/GNOS RO technique. The rest of this article is organized as follows. Section II describes the accuracy assessment of the FY3 IRO products. Section III summarizes the application progress in FY3 RO products. Finally, Section IV concludes the article and gives an outlook.

II. ACCURACY ASSESSMENT OF FY3/GNOS RO PRODUCTS

A. Accuracy Assessment of EDP Data

Since the successful deployment of FY3C/GNOS in 2013, many EDP products have been released. The corresponding assessment of ionosonde and COSMIC has been carried out to verify the precision of its GPS/BDS EDP products. Yang et al. [30] statistically compared and analyzed FY3C/GNOS GPS EDP from October 1, 2013 to September 30, 2014 with ionosondes in the corresponding period. After quality control and spatial-temporal matching, 745 pairs of NmF2 data matching pairs between the GPS RO and the ionosondes were obtained. As shown in Fig. 3, the comparison results indicate that the correlation coefficient, bias, and standard deviation (std) of NmF2 differences between FY3C/GNOS and the ionosonde are 0.96, 6.71%, and 18.03%, respectively. Meanwhile, the statistical results in Fig. 4 show that the correlation coefficient, bias, and std of the height of the NmF2 (hmF2) between FY3C/GNOS and the ionosonde are 0.85, 4.68 km, and 25.96 km, respectively.

The above results illustrate the accuracy consistency of NmF2/hmF2 between GPS GNOS and ionosonde data, providing a support for its application in space weather monitoring,
model evaluation, and other ionospheric scientific research. Since GNOS is also compatible with BDS GNSS signals, the assessment of BDS EDP is conducted as follows. Yang et al. [31] compared the BDS NmF2 from October 1, 2013 to October 10, 2015, with that of the ionosonde data. The correlation coefficient, bias, and std of NmF2 between BDS and the ionosondes are 0.96, 10.21%, and 19.61%, respectively. The statistics results are presented in Fig. 5.

The statistical comparison of the EDP data between FY3C/GNOS and ionosondes has shown their accuracy consistency. The EDP data of FY3C/GNOS and the space-based COSMIC were exploited to explore the deviation between them. Bai et al. [32] matched the NmF2/hmF2 of FY3C/GNOS and COSMIC from February 4, 2016 to February 4, 2017. The results in Fig. 6 indicate that the correlation coefficient of NmF2 between FY3C/GNOS and COSMIC is 0.95, the std of NmF2 between them is 17.48%, and the two parameters of hmF2 are 0.91 and 18.01 km, respectively. The above results further confirm that the FY3C/GNOS RO product is comparable to other international RO products in terms of accuracy.

B. Accuracy Evaluation of Ionospheric Scintillation Index

Ionospheric scintillation refers to the phenomenon of random fluctuations in the amplitude/phase of the signal crossing the ionosphere [33], [34]. This phenomenon causes signal loss and cycle slips and makes it difficult for the receiver to lock onto the carrier phase, affecting the GNSS-based applications [35]. Therefore, monitoring and warning of ionospheric scintillation is important to ensure the stable operation of communication, navigation, and positioning systems.

Bai et al. [36] evaluated the detection accuracy of GPS ionospheric scintillation observed by FY3C/GNOS with COSMIC. First, the F-layer worst case scintillation index ($S_{4F}^{max}$) was extracted, and then the spatial-temporal matching $S_{4F}^{max}$ between FY3C/GNOS and COSMIC during the geomagnetic quiet period, i.e., from January 1, 2014 to January 9, 2015, was statistically analyzed. Fig. 7 shows the statistics of the deviations of $S_{4F}^{max}$ pairs for all day, nighttime, and daytime. The results indicate that during the whole day, the bias and std of $S_{4F}^{max}$ differences are 0.004 and 0.063, respectively. And the std at nighttime is larger than that at daytime. This may be due to irregularities in the electron density that vary over time after midnight and the disparity in the spatial-temporal matching criteria. The results prove that the GPS ionospheric scintillation detected by FY3C/GNOS has high precision, which provides support for constructing the BDS scintillation detection system on the FY3D satellite.

The FY3C/GNOS can only support the acquisition of the GPS scintillation, whereas the FY3D satellite launched in 2017 adds support for BDS scintillation detection and thus enables simultaneous observation of GPS and BDS ionospheric scintillations. Therefore, we conduct a statistical comparison of $S_{4F}^{max}$ between FY3D-BDS and FY3D-GPS/COSMIC-GPS to obtain the detection accuracy of ionospheric scintillation of FY3D-BDS. In Fig. 8, the upper graph shows the statistical distribution of $S_{4F}^{max}$ deviation between FY3D-GPS and FY3D-BDS, and
Fig. 7. Statistics of the numerical deviations of $S_{\text{max}}^4$ pairs between COSMIC and FY3C/GNOS for the whole day (top panel), daytime (bottom panel), and nighttime (middle panel) from January 10, 2014 to January 9, 2015. Modified from [36].

Fig. 8. Statistics of the numerical deviations of $S_{\text{max}}^4$ pair between FY3D-BDS and FY3D-GPS (top panels)/COSMIC-GPS (bottom panels) in whole day (left), daytime (middle), nighttime (right) from 2018 to March 23, 2019. The lower graph shows that between COSMIC and FY3D-BDS.

The results indicate that the std of $S_{\text{max}}^4$ differences between FY3D-GPS/COSMIC-GPS and FY3D-BDS are lower than 0.1, which proves the high precision of BDS scintillation observed by FY3D-GNOS. Similar to FY3C/GNOS, the $S_{\text{max}}^4$ deviation between FY3D-GPS/COSMIC-GPS and FY3D-BDS at daytime is lower than that at nighttime.

III. FY3 IRO PRODUCT APPLICATION STUDY

A. Space Weather Monitoring

The impact of magnetic storms on GNSS applications (e.g., navigation, positioning, and communications) is important. The St. Patrick’s Day super geomagnetic storm that occurred on March 17, 2015 was the strongest magnetic storm of the 24th solar cycle, and its impact on ionospheric morphology was studied based on the ionosonde or other observation methods [37], [38], [39], [40], [41].

Bai et al. [42] presented the variation process of different phases of this magnetic storm with the $N_{\text{mF2}}$ data of FY3C/GNOS in Fig. 9. It can be seen in Fig. 9(a) that in the prestorm period, the high values of $N_{\text{mF2}}$ during the daytime are mainly concentrated in the magnetic equatorial region, and the $N_{\text{mF2}}$ is relatively low in the high magnetic latitudes. In the main phase of the storm, there are significant $N_{\text{mF2}}$ disturbances in some areas, such as the South Atlantic area and the South Pacific area, but all return to the prestorm level during the recovery phase by March 22. At nighttime in Fig. 9(b), the $N_{\text{mF2}}$ exhibits a suppressed trend in East Asia in the main phase. Also, during the magnetic storm, the mean $N_{\text{mF2}}$ observed by FY3C/GNOS exhibits a nearly consistent trend with that of the ionosonde in two zones in Fig. 10, and the $N_{\text{mF2}}$ error bars are shown in Fig. 11. The $N_{\text{mF2}}$ of FY3C/GNOS and ionosonde decreases during the magnetic storm and increases in the recovery phase, i.e., the negative magnetic storm characteristics, which shows the decent response capability of FY3C/GNOS $N_{\text{mF2}}$ to global magnetic storm events.

Wang et al. [43] then exploited the GPS ionospheric scintillation data observed by FY3C/GNOS to reveal the dynamics...
Fig. 10. Distribution of the ionosondes in two zones. The red stars and black squares represent the ionosondes of the Meridian Project and Space Weather Prediction Center, respectively. Figure from [42].

Fig. 11. Error bar of GNOS NmF2 and ionosonde NmF2 at nighttime (21:00–24:00 LT) and daytime (09:00–12:00 LT) from March 14, 2015 to March 22, 2015 in (a) zone 1 and (b) zone 2. Figure from [42].

Fig. 12. Global scintillation ($S_{\text{max}} \geq 0.3$) observed by FY3C/GNOS and FY3C orbit track (red solid line) at nighttime on March 17–18. The upward red arrows with ST MP and ST RP indicate the position of FY3C at the beginning of the main phase and the recovery phase, respectively. LT and UT correspond to the moment when the FY3C satellite crosses the equator. Figure from [43].

Fig. 13. Global distribution of mid-strong ionospheric scintillation at night from March 12 to March 23 observed by FY3C/GNOS. Figure from [43].

Fig. 14. Longitude-time distribution of irregularities (red stars) detected by C/NOFS before midnight on March 17, 2015. The circle and cross represent 6:00 and 18:00 local time, respectively. The red arrows correspond to the beginning of the main phase and the recovery phase, respectively. Figure from [43].
B. Statistical and Climatological Evaluation of the International Reference Ionosphere (IRI) 2016 Model

Obtaining accurate ionospheric parameters is essential for studying morphology and dynamic changes of the ionosphere and providing support for navigation, communications, and space environment monitoring. The IRI model absorbs a variety of space-based and ground-based global ionospheric data, and it has been recognized by the International Organization for Standardization as the standard ionospheric model [44], [45]. FY3/GNOS IRO data can be used as a third-party data source for comparative analysis of the IRI-2016 model in terms of data accuracy and climatological characteristics.

Bai et al. [46] compared URSI NmF2, BSE hmF2, and newly added AMTB hmF2 and SHU hmF2 generated by the IRI-2016 model with IRO data including FY3C/GNOS and COSMIC from 2017 to 2019 in statistics and ionospheric climatology. The comparison results in Fig. 15 indicate that the NmF2 predicted by IRI-2016 URSI is almost consistent with that of IRO, with a systematic bias of less than 10%. Compared to the BSE/AMTB option, the SHU option estimates hmF2 more closely to IRO data, as shown in Fig. 16.

The study also divided NmF2 and hmF2 into 3° × 6° grids in four seasons to evaluate seasonal variations of IRI-2016 ionospheric climatological features. For example, in the NmF2 climatological comparison, Fig. 17 shows the seasonal average of NmF2 of IRI-2016 and IRO at daytime and nighttime in DS month (±45 days of the December Solstice). It can be seen that in the summer hemisphere at nighttime, the NmF2 of IRO and IRI-2016 exhibit southern mid-latitude summer nighttime anomaly features. In hmF2 climatological comparison, Fig. 18 shows the seasonal average of hmF2 of IRO and IRI-2016 (BSE, AMTB, SHU) in JS month (±45 days of the June Solstice), and the hemispheric asymmetry of hmF2 at daytime and nighttime can be observed. The comparison results of climatological features show that IRI-2016 URSI NmF2 is consistent with IRO NmF2 on typical ionospheric climatological features. The globally distributed IRO observations may provide a scientific reference for IRI-2016 prediction in the ocean region. Besides, the BSE/AMTB/SHU hmF2 of IRI-2016 exhibits typical hemispheric asymmetry like IRO hmF2. The SHU option proves the
validity of its data fusion because it is also consistent with the
IRO data in minor hmF2 features such as day-night reversal.

C. Study of Ionospheric Sporadic E Layer

Sporadic E-layer (Es) is a nonstable inhomogeneous structure
with exceptionally high and randomly varying electron density.
It can easily cause miscoding and distortion of signals and
thus have a serious impact on communication and navigation
systems [47], [48]. Since the GNSS RO technique can achieve
global detection, the study of the Es layer is not limited to the
area where the ground-based observatory is located, and a more
comprehensive understanding of the variability of the Es layer
can be obtained.

Yang et al. [49] utilized the GPS RO data detected by
FY3C/GNOS from June 2014 to May 2015 to statistically ana-
lyze the SNR disturbance at a sampling frequency of 50 Hz and
then studied the morphology of the Es-layer. The perturbations
of the Es-layer in the mid-latitudes in the summer hemisphere are
higher than those in the winter hemisphere, and the perturbation
is significantly stronger near the latitude of 40°.

As shown in Fig. 19, near the height of 100 km, Es perturbation
reaches its peak at 10:00 LT and 22:00 LT. The occurrence rate
of Es-layer in the summer hemisphere is higher than that in the
winter hemisphere, as shown in Fig. 20. This work also proves
that the RO observations of FY3C are consistent with those of
the COSMIC system, suggesting the potential of FY3C/GNOS
in detecting morphology of Es-layer.

D. Tonga Volcanic Eruption Observation

The Tonga submarine volcano (20.5 °S, 175.4 °S) erupted on
January 15, 2022 at around 4:15 UTC. Unlike volcanoes on land,
shock waves from submarine eruptions are more unique and
rare. The ionospheric TEC perturbation generated by the Tonga
eruption has been studied based on ground-based observa-
tional data [50], [51], [52], [53], and this work investigates the iono-
spheric perturbation with space-based NmF2 data observed by
FY3D/GNOS. Fig. 21 shows the distribution of daytime NmF2
(1200-1600LT) within a 30° area around the epicenter before and
after the eruption of Tonga volcano, and the average NmF2 near
the epicenter is indicated in the upper right corner of each graph.

As shown in Fig. 22, under the influence of volcanic eruptions
and acoustic pulses, the strong expansion of the thermosphere
leads to a large outflow of the ionosphere [53], which causes
a sharp drop in NmF2 around epicenter, followed by signs of
recovery to the pre-eruption level. This work demonstrates the effective response of space-based RO data to natural hazards like volcanic eruptions (earthquakes), and thus expands the effective application of FY3 RO data.

IV. CONCLUSION

The FY3/GNOS realized the world’s first GPS and BDS compatible IRO observation, which provides a foundation for the development of further multi-GNSS RO missions such as subsequent FY3 series. This work first presents a review of the accuracy assessment for the EDP and scintillation products of FY3C/FY3D, where these products achieve a precision comparable to other similar products. Then, the review of a series of scientific application studies of FY3C/FY3D ionospheric products is presented, including magnetic storm studies, ionospheric model evaluation, Es-layer research, etc. The above studies can provide scientific references for the data validity and offer effective support for improving the quality of the subsequent RO data. Furthermore, they can provide a guidance to improve future occultation sounding payloads, thus contributing to the commercial application of the GNOS IRO products. However, the scientific research and application value of ionospheric occultation products of FY3 series still need to be further explored.

The FY3E satellite launched in 2021 will be grouped with the FY3C and FY3D in a three-satellite network with an orbital layout of dawn, dusk, morning, and afternoon, forming the coverage of an all-day observation period. With the continued deployment of subsequent satellites in the Fengyun-3 series and the continuous improvement of GNOS payload, a large number of high-precision IRO products will be available, offering data support for international ionospheric research, such as space weather monitoring, the mechanism of Es layer formation, ionospheric climatological research, etc. Besides, with the official opening of the BDS-3 system, the coverage and spatial-temporal resolution of IRO events will be significantly improved. The fusion of RO data between different GNSS payloads will be beneficial to real-time space weather monitoring and the construction of ionospheric climate models.

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