Analysis of GNSS radio occultation data from satellite ZH-01

Yan Cheng1, Jian Lin2*, XuHui Shen3, Xiang Wan1, XinXing Li2, and WenJun Wang1

1Space Star Technology Company Limited, Beijing 100194, China;
2Institute of Seismology, China Earthquake Administration, Wuhan 430071, China;
3Institute of Crustal Dynamics, China Earthquake Administration, Beijing 100085, China

Abstract: The electromagnetic satellite Zhangheng 01 (ZH-01) was successfully launched on February 2, 2018. The GNSS Radio Occultation (GRO) receiver on board the satellite is able to observe the occultation events of GPS and BeiDou navigation satellites. We analyzed the data acquired during the in-orbit testing period. We concludes that the GRO ionosphere inversion results are reasonable, the trend is correct, the satellite can observe about 600 ionosphere occultation events each day. The global coverage of more than 30000 consecutive GRO events in more than two months were analyzed and compared with COSMIC observations: both the GRO and COSMIC occultation can realize global coverage: the \( N_{mF_2} \) and \( H_{mF_2} \) global distributions are similar and change obviously with latitude. We used three digisondes at different latitudes to analyze and compare the spatio-temporally consistent GRO data: the RMSE of GRO \( N_{mF_2} \) relative to digisonde is better than 9.41%, the correlation coefficient is better than 0.8682: the relative RMSE of \( H_{mF_2} \) is better than 7.80% and the correlation coefficient is better than 0.7066.

Keywords: ZH-01; GRO occultation; ionosphere inversion; digisonde

Citation: Cheng, Y., Lin, J., Shen, X. H., Wan, X., Li, X. X., and Wang, W. J. (2018). Analysis of GNSS radio occultation data from satellite ZH-01. Earth Planet. Phys., 26(2), 499–504. http://doi.org/10.26464/epp2018048

1. Introduction

In conventional atmospheric research, the atmosphere parameters are measured primarily by means of meteorological satellites, radar, sounding balloons, etc., each of them with distinctive merits and drawbacks (Guo P, 2005). Radio sounding balloons have the advantages of high accuracy and resolution, but incur relatively high costs and are difficult to employ for routine observations in ocean, desert, and other special geographic environments (Yan HJ et al., 2006). The vertical resolution and inversion resolution of satellite remote sensing are relatively low, and remain at the level of quantitative analysis. Probing methods such as radar have the shortcomings of large spacing and single probing parameters (Yan HJ et al., 2007).

With the establishment and gradual improvement of global navigation and positioning systems (GNSS), radio technology is widely used for GNSS occultation observation (Xu XS, 2012). The GNSS/LEO (low earth orbit) radio occultation technology is possessed of the features of all weather and global coverage (Hocke, 1997). In addition, it has the advantageous characteristics of self-calibration and good stability, which are favorable to the studies of global climate change and long-term atmospheric changes (Leroy and North, 2000). At present the major occultation data processing and analysis centers include the ISDC of German GFZ, the JPL GENESIS and the UCAR CDAAC. China attaches much importance to ionosphere probing with GNSS. Based on the requirement of global meteorological observation, the China Meteorological Administration included GNSS/LEO occultation observation technology in its Fengyun Satellite project. Some Chinese scholars contributed to GNSS/LEO occultation inversion methods, occultation data assimilation operators and algorithms, and produced some preliminary results. At the same time important progress has been made on the research and development of probing payloads. These early contributions have provided technical reserves and accumulated engineering experiences for the development of GNSS/LEO occultation in China (Zhao, 2011).

The electromagnetic satellite ZH-01 is the first electromagnetic satellite launched by the China Earthquake Administration for space exploration; it carries 8 payloads, including a GNSS radio occultation (GRO) receiver that plays an important role in probing ionospheric electron densities. The GRO receiver can receive correctly and invert about 600 ionospheric occultation events each day. The occultation data processing system of the ZH-01 electromagnetic satellite provides an important platform for the routine processing of Chinese GNSS/LEO occultation data. Compared to some conventional observation means, GNSS ionosphere monitoring has the characteristics of low cost, high precision, near real time data provision, and all-weather operation, presenting great superiority in monitoring and research of ionospheric disturbances.

2. Principles of Ionosphere Occultation Inversion

The direct inversion of total electron content (TEC) data for electron density is based on the assumption that the signal is propag-
ated along a straight line. This method neglects the bending angle and assumes that the signal travels in straight lines; it uses the observed signal delay to calculate the total electron content, then uses an Abel integration inversion method to invert for the electron density profile; Chinese scholars have done a lot of work on the Abel inversion method (Xu XS et al., 2010; Zhao Y et al., 2010; Mo PH et al., 2015; Lin J et al., 2009; Hong ZJ et al., 2011).

Generally, the TEC is obtained by dual-frequency carrier wave phase combinations; the TEC is corrected utilizing non-occultation auxiliary observations to eliminate the TEC portion above the altitude of LEO orbit; under the assumptions of local ionospheric spherical symmetry and rectilinear propagation of signals, the electron density profile can be obtained through Abel integration transform. The details are described as follows.

The ionosphere is distributed above 100 km from the ground; the electron content reaches its maximum value between 250 and 500 km. Because the bending angle of GPS/BD occultation signals in the ionosphere is very small, generally smaller than 0.01 degrees, the GPS/BD signals can be approximately considered as propagating along straight lines. By linear combinations of the observation data of GPS/BD dual-frequency carrier wave delays, we obtain the oblique TEC (in unit of $10^{16} \text{m}^{-2}$):

$$\text{TEC} = \int n_e \, dl = \frac{1}{40.3} \frac{f_1^2 - f_2^2}{f_2} (L_1 - L_2) + N \lambda + \varepsilon, \quad (1)$$

where $l$ is the path of GPS/BD signal, and $n_e$ is the electron density ($\text{el} \cdot \text{m}^{-3}$), $f_1$ and $f_2$ are the two GPS/BD carrier frequencies, $N$ and $\lambda$ symbolize the ambiguity and wavelength of carrier phase, respectively, $\varepsilon$ is the observational noise in carrier phase. It should be pointed out that the dual-frequency combination inversion method requires that the propagation paths of dual-frequency carrier signals are identical, so we have made an assumption here that the path error caused by dispersion can be safely neglected. The schematic occultation geometrical relations are shown in Figure 1.

Under the assumption of ionospheric local sphericity, the oblique TEC and the electron density in between the LEO satellite and GPS/BD satellite satisfies the following formula:

$$\text{TEC}(r_0) = \int_{r_0}^{r_{\text{GPS/BD}}} n_e(r) \sqrt{r^2 - r_0^2} \, dr + \int_{r_0}^{r_{\text{LEO}}} n_e(r) \sqrt{r_2 - r_0^2} \, dr, \quad (2)$$

where $r_0$ is the distance from the occultation tangent point to Earth center, and $r_{\text{GPS/BD}}$ and $r_{\text{LEO}}$ are respectively the orbit radii of the GPS/BD and LEO satellites, as shown in Figure 1. Because the satellites are situated in the ionosphere and satisfy the spherical symmetry assumption, and the LEO satellite altitude is much lower than that of GPS/BD satellite, the ionosphere inversion contains errors. Assuming that the LEO satellite orbit is circular and the LEO satellite orbit plane is identical with the occultation plane, we can use the auxiliary observation data on the non-occultation side to correct TEC and eliminate TEC above the LEO satellite orbit, resulting in the calibrated TEC (TEC'):

$$\text{TEC}'(r_0) = \text{TEC} - \text{TEC}_0 = 2 \int_{r_0}^{r_{\text{LEO}}} \frac{n_e(r)}{\sqrt{r^2 - r_0^2}} \, dr. \quad (3)$$

Through the inverse Abel integration transform (Ding JC et al., 2009), the electron density is obtained from the TEC':

$$n_e(r_0) = -\frac{1}{\pi} \int_{r_0}^{r_{\text{LEO}}} \frac{dTEC'(r)}{\sqrt{r^2 - r_0^2}} \, dr. \quad (4)$$

The principles of space-based ionosphere inversion can be briefly summarized as follows. First, the TEC is calculated from the combinations of dual-frequency delay observations; the TEC is calibrated to obtain TEC; then, using the relation between TEC’ and electron density $n_e$, the electron density profile is obtained by inverse Abel integration transform.

3. Analysis and Application of GRO Data

In order to analyze the distribution of ionospheric occultation events from ZH-01 satellite and assess the accuracy of electron density derived from occultation inversion, we consider two aspects: the global coverage of occultation events, and comparison and verification of inversion results with digisonde observations. Because this satellite is a sun-synchronous satellite, flying globally at local time 2:00 and 14:00, we analyze the inversion results respectively for daytime and nighttime. Electron densities obtained from recent digisonde observations are commonly acknowledged to be relatively accurate, so we can reasonably assess the accuracy of densities obtained from occultation inversion by comparing them to corresponding digisonde results.

3.1 Coverage and Daytime-Nighttime Analysis

From the statistics of ionospheric electron peak density and height observed by the ZH-01 satellite during its in-orbit testing period (May 22 to August 2, 2018), their global distributions and the electron density distributions of COSMIC in the corresponding time period are shown in the following Figures (2, 3, 4, 5), where the abscissa is longitude and ordinate is latitude, and color indicates the value, with blue being the smallest and red the largest. The peak densities are divided into daytime and nighttime according to the local time; since the ZH-01 satellite is sun-synchronous, the daytime is about 14:00 and nighttime is about 2:00 of local time (the same below).

The peak densities from GRO and COSMIC during daytime are shown in Figures 2 and 3, respectively; the unit of peak density is $\text{el} \cdot \text{m}^{-3}$ (the same below). It can be seen from Figures 2 and 3 that the peak densities of global ionosphere $F_2$ layer of GRO...
and COSMIC are of the same order of magnitude and have similar distributions. The equatorial anomalies are distributed along the two sides of Earth’s magnetic equator.

The peak heights of GRO and COSMIC during daytime are shown in Figures 4 and Figure 5, respectively. It can be clearly seen from the figures that the peak heights of layer $F_2$ of the GRO and COSMIC occultation all display an obvious equatorial anomaly phenomenon; the peak $F_2$ layer heights near the equator are 300–340 km, greater than in middle and high latitude areas, and the equatorial anomalies are distributed along both sides of the geomagnetic equator. The peak $F_2$ layer heights in middle and high latitude areas are mostly below 250 km, with only a few points reaching above 300 km.

3.2 Accuracy Assessment Utilizing Digisonde

The digisonde is ground-based equipment for routinely probing the ionosphere; it can attain a relatively high accuracy in ionospheric electron density measurement. We chose the stations Fuke of Hainan Province at latitude 19.4°, Zuoling of Wuhan at 30.5°, and Mohe of Heilongjiang Province at latitude 52° to assess the accuracy of ionosphere electron density obtained by ZH-01 satellite occultation.

We carried out event and space matching between the ZH-01 satellite occultation events and digisonde results, and made comparison and verification. The data sources are the GRO in-orbit data from February to July of 2018 and the corresponding digisonde data. The matching conditions are as follows: the time difference of the ionosphere electron density peaks of occultation events is within one hour, the longitude difference is within 10°, and the latitude difference is within 5°; the impacts of solar activities and magnetic storms are eliminated, the data quality is mainly controlled by checking weather conditions, sunspot numbers, and geomagnetic parameters. The digisonde measures the critical frequency $f_0F_2$ of layer $F_2$ at the station; the critical frequency and the peak density $N_{mF_2}$ of layer $F_2$ satisfy $N_{mF_2}=1.24\times10^{11}\times(f_0F_2)^2$. The relative RMSE of GRO occultation in-orbit data with respect to the digisonde data is calculated by the following formula:
RMSE = \sqrt{\frac{\sum_{i=1}^{n}[(a_i - b_i)/b_i]^2}{n}}, \quad (5)

where $a$ is the peak density or peak height of layer $F_2$ of GRO occultation, $b$ is that of digisondes, $n$ is the number of matched occultation events, and RMSE is the relative RMSE of ionosphere.
electron density of GRO occultation with respect to digisonde. In the following we assess the quality of ionosphere electron density from GRO occultation at three stations at different latitudes: Fuke, Zuoling, and Mohe. In order to further assess the accuracies of electron density in different time segments, we set three scenarios of whole day, daytime, and nighttime for evaluation. The results are listed in Table 1, where $N_{mF_2}$ is $F_2$ layer peak electron density, $H_{mF_2}$ is the peak height.

It can be seen from Table 1 that the number of spatio-temporally matched events of GRO and digisonde increases with increasing

Figure 6. Scatter diagram of whole-day peak density (a, c, e) and height (b, d, f) measurements of GRO and digisonde at station Fuke (a, b), Zuoling (c, d), and Mohe (e, f).
latitude. The relative RMSE of $F_2$ layer peak density $N_{m}F_2$ of GRO occultation with respect to digisonde is better than 9.41%, and that of peak height $H_{m}F_2$ is better than 7.8%. The correlation of $F_2$ layer peak density $N_{m}F_2$ between GRO and digisonde is better than 0.8682, and that of peak height $H_{m}F_2$ is better than 0.7066. At stations Fuke and Mohe the RMSE of daytime peak density $N_{m}F_2$ is better than that of nighttime, while at station Zuoling the nighttime peak density RMSE is better than that of daytime. Figures 6 (a, b, c, d, e, f) show respectively the peak density and peak height resulting from GRO and digisonde at stations Fuke, Zuoling, and Mohe; the accuracy of SRO with respect to digisonde can be evaluated from the scattering of data.

4. Conclusion
The observation data of the GRO payload of ZH-01 satellite during its in-orbit testing period were used to study the coverage of occultation events and the daytime and nighttime electron density distribution; the quality of occultation data was assessed by comparison with corresponding digisonde data, and the following conclusions were obtained.

(1) The global distributions of layer $F_2$ peak density and peak height derived from GRO and COSMIC occultation are generally consistent; the peak density and peak height of ionospheric layer $F_2$ around the equator all exhibit obvious equatorial anomaly phenomena, and the equatorial anomalies are distributed along both sides of the geomagnetic equator.

(2) The quality of GRO data was evaluated using digisonde data; the relative RMSE of $N_{m}F_2$ of GRO with respect to digisonde is better than 9.41%, with correlation coefficient exceeding 0.8682; the relative RMSE of $H_{m}F_2$ is better than 7.80% and the correlation coefficient is better than 0.7066. Spatio-temporal matching errors, as well as solar activity and magnetic storms, all may cause relatively large errors in the electron density; the evaluation result is obtained after eliminating the impact of the above mentioned sources of error.

Acknowledgments
The authors thank the Institute of Crustal Dynamics, China Earthquake Administration, and the Resources Satellite Application Center of China for providing the occultation observation data of ZH-01 satellite, the state key science and technology infrastructure Meridian Project Data Center for providing relevant scientific data, the COSMIC website for providing COSMIC occultation data, and the Space Physics Data Facility of NASA for solar and geomagnetic data. We are also grateful to Dr. Qing Yun of Hubei Seismological Bureau and Chu Wei of Institute of Crustal Dynamics for their help in the work.

References
Ding, J. C. (2009). GPS Meteorology and Its Application (in Chinese). Beijing: Meteorological Publishing House.
Guo, P. (2005). GPS Radio Occultation Technique and CHAMP Occultation Data Retrieval (in Chinese). Shanghai: Chinese Academy of Sciences.
Hocke, K. (1997). Inversion of GPS meteorology data. Ann. Geophys., 15(4), 443–450. https://doi.org/10.1007/s00585-97-0443-1
Hong, Z. J., Liu, R. J., Guo, P., and Dong, N. M. (2011). Non-spherical symmetric inversion of ionospheric occultation data. Acta Phys. Sin. (in Chinese), 60(12), 129401. https://doi.org/10.7498/aps.60.129401
Leroy, S. S., and North, G. R. (2000). The application of COSMIC data to global change research. Terr. Atmos. Ocean. Sci., 11(1), 187–210. https://doi.org/10.3319/TAO.2000.11.1.187(COSMIC)
Lin, J., Wu, Y., and Liu, J. N. (2009). Research on ionospheric inversion of GPS occultation. Chinese J. Geophys. (in Chinese), 52(8), 1947–1953. https://doi.org/10.3969/j.issn.0001-5733.2009.08.001
Mo, P. H., Ou, M., and Zhang, F. G. (2015). Simulation of GNSS/LEO based ionospheric radio occultation monitoring. Global Posit. Syst. (in Chinese), 40(3), 6–10. https://doi.org/10.13442/j.gnss.1008-9268.2015.03.002
Xu, X. S., Hong, Z. J., Guo, P., and Liu, R. J. (2010). Retrieval and validation of ionospheric measurements from COSMIC radio occultation. Acta Phys. Sin., (in Chinese), 59(3), 2163–2168. https://doi.org/http://wulixb.iphy.ac.cn/CN/10.7498/aps.59.2163
Xu, X. S. (2012). Radioholographic Technique for GPS/LEO Radio Occultation (in Chinese). Shanghai: Shanghai University.
Yan, J. H., Fu, Y., and Hong, Z. J. (2006). Introduction to Modern Atmospheric Refraction (in Chinese). Shanghai: Shanghai Science and Technology Education Press.
Yan, J. H., Fu, Y., Hong, Z. J., and, Guo P. (2007). Space-based GPS Meteorology and Inversion Techniques (in Chinese). Beijing: China Science and Technology Press.
Zhao, Y., and Zhang, X. H. (2010). Inversion of ionospheric electron density profiles with COSMIC occultation data. Wuhan Univ. Inf. J. (in Chinese), 35(6), 644–648.
Zhao, Y. (2011). GNSS Ionospheric Occultation Inversion and Its Application (in Chinese). Wuhan: Wuhan University.