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Effect of Higher-Order Ionospheric Delay on Precise Orbit Determination of GRACE-FO Based on Satellite-Borne GPS Technique

LINHU QI, JINYUN GUO, YAOWEI XIA, AND ZHOUMING YANG
College of Geodesy and Geomatics, Shandong University of Science and Technology, Qingdao 266590, China
Corresponding author: Jinyun Guo (guojy@sdust.edu.cn)

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ABSTRACT Ionospheric delay is one of the main errors in precise orbit determination (POD) of Gravity Recovery and Climate Experiment Follow-On (GRACE-FO) with satellite-borne GPS technique. Effective elimination or reduction of ionospheric delay can improve POD precision. For satellite-borne GPS dual-frequency data, the ionospheric-free linear combination is generally used to eliminate the first-order term, while igoring the influence of higher-order terms. To improve the POD precision of GRACE-FO, this paper presents an effective method to calculate higher-order ionospheric delay of GRACE-FO observation. Dual-frequency GPS receiver observation is used to calculate the total electron content on the signal propagation path. The magnetic field strength is calculated according to international geomagnetic reference field model, and the angle between the GPS signal propagation path and the geomagnetic field is calculated. Finally, the delays of second-order and third-order terms are calculated and introduced into GRACE-FO reduced-dynamic POD. The effect of higher-order ionospheric delay on POD of GRACE-FO is analyzed in detail. The results show that the influence of ionospheric higher-order term on satellite-borne GPS observation is in centimeter level. The orbit precision of GRACE-FO can be improved by adding higher-order ionospheric delay, with improvement order of sub-millimeter level.

INDEX TERMS GRACE-FO, higher-order ionospheric delay, low earth orbit satellites, precise orbit determination, satellite-borne GPS.

I. INTRODUCTION

Gravity Recovery and Climate Experiment Follow-On (GRACE-FO) is a joint mission launched by National Aeronautics and Space Administration (NASA) and German Research Centre for Geosciences (GFZ) on May 22, 2018. Its purpose is to replace the Gravity Recovery and Climate Experiment (GRACE) that was decommissioned in June 2017 after performed in orbit for 15 years, and to use twin satellites to accurately map the earth's gravity field [1], [2]. Like GRACE satellites, GRACE-FO satellites are also equipped with GPS receivers, K-Band Ranging System (KBR), laser retroreflectors and other scientific instruments [3]. Precise satellite orbits can ensure precise processing of gravity data, which is helpful for the estimation of gravity models and the acquisition of global gravity field products.

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Since the successful application of satellite-borne GPS receiver on low earth orbit (LEO) satellites, satellite-borne GPS precise orbit determination (POD) technology has gradually become the main means of LEO POD because of its large number of observations, high POD precision and orbit continuity [4], [5]. When using GRACE satellite-borne GPS and acceleration data combined with the dynamic model for dynamic POD, POD precision is better than 2 cm, and the radial, tangential and normal orbit precision can reach centimeter level only using satellite borne GPS observation data [6], [7]. The reduced-dynamic orbit and the kinematic orbit method are used to accurately determine the orbit of HY-2A satellite simulation data. The radial precision can reach the centimeter level, and the precision of kinematic POD is slightly lower than that of reduced-dynamic POD [8], [9].

Ionospheric delay is one of the main error terms in satellite-borne GPS POD technology. The variation of electron density distribution with time and space results in the complexity of ionospheric delay [10]–[12]. How to deal with ionospheric delay is an important factor to improve POD precision. When using satellite-borne GPS data to determine the orbit of GRACE-FO, ionospheric delay error is generally eliminated by ionospheric-free linear combination (LC) [13], but the LC combination cannot eliminate the influence of high-order ionospheric delay on GPS observation [14]–[17]. Higher-order ionospheric delay is the result of the interaction between ionosphere and earth's magnetic field, which depends on magnetic field, total electron content, angle between magnetic field direction and propagation path [18], [19]. The slant total electron content (STEC) can be calculated from dual-frequency observations [20], [21]. The magnetic field can be calculated by the model given by the International Geomagnetic Reference Field (IGRF) [22].

The effect of high-order ionospheric delay on Global Navigation Satellite System (GNSS) positioning and POD has been studied by many people. International GNSS Service (IGS) observation is used to analyze the impact of high-order ionospheric delay on GPS POD and static precise point positioning (PPP) [23]. The problem of high-order ionospheric delay is solved in different latitudes and different ionospheric environments, and its impact on PPP is studied [24]. Using the data from all IGS stations in Ethiopia from 2013 to 2015, the magnitude of the high-order ionospheric delay of the thin crust above the IGS station (60 km, 90 km, 150 km, 200 km and 450 km) is calculated [25]. The above studies believe that the impact of high-order ionospheric delay on the observation of ground stations is at the centimeter level, and the magnitude of the impact is different depending on solar activity and geographic location.

GRACE-FO moves fast with no definite global ionospheric map (GIM), and there are few studies on the influence of high-order ionospheric delays on GRACE-FO dual-frequency observations. In order to solve the above problems, a model for calculating the high-order ionospheric delay of the GRACE-FO satellite is given, and the influence of the high-order ionospheric delay on the GRACE-FO satellite observation and POD precision is discussed.

In Section 2, a method to calculate GRACE-FO high-order ionospheric delay is given. In Section 3, the solution strategy is given, including way of acquiring data and the overall data processing as well as experimental flow chart. In Section 4, the influence of high-order ionospheric delay on the GRACE-FO observation and the changing law are analyzed. In Section 5, POD of satellite data with and without high-order ionospheric delay is carried out, and the influence of adding high-order ionospheric delay on the precision of GRACE-FO POD is analyzed by satellite laser ranging (SLR) verification and scientific orbit verification. Section 6 is analysis and summary.

II. METHOD FOR CALCULATING HIGHER-ORDER IONOSPHERIC DELAY

GRACE-FO is the follow-on mission of GRACE, consisting of satellites A and B with an interval of about 220 km, equipped with the latest generation of TriG receiver, with an orbit altitude of 500 km, and orbit inclination of 89° [1], [2]. For GRACE-FO, the signal transmitted by GPS satellite will be affected by the ionosphere in the process of transmission, and the signal propagation speed will change, the degree of change mainly depends on electron density of the ionosphere [26]. The propagation velocity V of electromagnetic wave signals in the ionosphere can be obtained through the refractive index n and the speed of light c in the ionosphere:

$$V = \frac{c}{\mathrm{n}} \tag{1}$$

According to the simplified Appleton-Hartree equation [16], [17], [27], [28], the expressions of group refractive index n_G and phase refractive index n_P are as follows [29]:

$$\begin{aligned} \mathrm{n}_G &= 1 + \frac{1}{2}X + XY\left|\cos^2\theta\right| \\ &\quad + \frac{3}{4}X\left[\frac{1}{2}X + Y^2(1+\cos^2\theta)\right] \end{aligned} \tag{2}$$

$$\begin{aligned} \mathrm{n}_P &= 1 - \frac{1}{2}X - \frac{1}{2}XY\left|\cos\theta\right| \\ &\quad - \frac{1}{4}X\left[\frac{1}{2}X + Y^2(1+\cos^2\theta)\right] \end{aligned} \tag{3}$$

where

$$X = \frac{1}{\mathrm{f}^2}\frac{e^2}{4\pi^2\varepsilon_0 m_e}N_e \tag{4}$$

$$Y = \frac{1}{\mathrm{f}}\frac{eB_0}{2\pi m_e} \tag{5}$$

in which $\mathrm{e} = 1.60218 \times 10^{-19}$ is the amount of charge carried by the electron, f is the carrier frequency (f_1 is 1575.42 MHz and f_2 is 1227.6 MHz), $m_e = 9.10939 \times 10^{-31}$ is the electron mass, $\varepsilon_0 = 8.8542 \times 10^{-12}$ is the vacuum dielectric coefficient, B_0 is the geomagnetic field strength along the propagation path, and θ is the angle between the propagation direction of the GRACE-FO carrier signal and the geomagnetic field.

In order to simplify the calculation, the influence of the ionosphere on propagation signal is usually compressed to the central ionosphere, and ionospheric pierce point (IPP) is used to replace the signal propagation path [30]. This method is also used for data processing in this paper

The group speed and phase speed of GRACE-FO satellite carrier signal propagation can be calculated by substituting n_G in Equation (2) and n_P in Equation (3) respectively, and then integrating the speed, the distance between GPS and GRACE-FO receiver can be obtained [18]:

$$P_{\mathrm{i}} = \rho + I^{(1)} + I^{(2)} + I^{(3)} + \varepsilon_P \tag{6}$$

$$L_i = \rho - I^{(1)} - \frac{1}{2}I^{(2)} - \frac{1}{3}I^{(3)} + \lambda_i N_i + \varepsilon_L \tag{7}$$

where P is the pseudo-range observation, ρ is the geometric distance from the receiver to GPS satellite, L is the phase observation, λ is wavelengths, N is Integer ambiguity, i represents different carriers, ε_P and ε_L are other unmodeled error terms, including observation noise, clock error, etc. $I^{(1)}$, $I^{(2)}$ and $I^{(3)}$ are the first-order, second-order and third-order effects of ionospheric delay, respectively. $I^{(1)}$ can be eliminated by LC combination, while the higher-order ionospheric delay should be calculated.

By expanding $I^{(2)}$ in Equation (6) and Equation (7), the expression of the second-order effect of ionospheric delay can be obtained [18], [19], [31]:

$$I^{(2)} = \frac{1}{f^3} \frac{e^3}{8\pi^2 m_e^2 \varepsilon_0} \|B_0\| \, |\cos\theta| \, STEC \tag{8}$$

where B_0 can be calculated by the method of spherical harmonic analysis and using the spherical harmonic coefficient given by IGRF13 [22]. STEC can be inversely calculated from satellite dual-frequency observations [20], [21]:

$$STEC = \frac{1}{40.3} \frac{f_1^2 f_2^2}{f_2^2 - f_1^2} [[(P_1 - P_2) - c(DCB_r + DCB_s) + \varepsilon] \tag{9}$$

where DCB_s is the satellite hardware delay, and ε is the unmodeled error terms. DCB_r is the receiver hardware delay, which can be obtained by the assumption of spherical symmetry in the ionosphere [32], [33].

Equation (8) shows that when calculating the delay of the second-order term, it is necessary to use the coordinates of IPP to calculate the geomagnetic field information, so the most important thing is to find a central ionospheric height suitable for GRACE-FO in order to accurately calculate the coordinates of IPP. The Lear method, an empirical model for spacecraft proposed by Lear, is used to calculate the central ionospheric height [34]. The way to determine the central ionospheric height is:

$$h_{Lear} = 1.037 h_{Leo} + 236 \tag{10}$$

where h_{Lear} is the central ionospheric height, h_{Leo} is the orbital height of LEO satellites, with km as the unit in the equation.

By expanding $I^{(3)}$ in Equation (6) and Equation (7), the expression of the third-order term effect of ionospheric delay can be obtained [18], [29], [31]:

$$I^{(3)} \approx \frac{3e^4}{128 f^4 \pi^4 m e^2 \varepsilon_0^2} \eta N_{e,\max} STEC \tag{11}$$

where, factor $\eta = 0.66$ [27], and $N_{e,\max}$ is the maximum electron density.

It can be seen from Equation (11) that the third-order term of ionospheric delay is a function related to $N_{e,\max}$. $N_{e,\max}$ can be calculated using [35]:

$$N_{e,\max}(m^{-3}) = \frac{(20-6) \times 10^{12}}{(4.55 - 1.38) \times 10^{18}} STEC \tag{12}$$

III. SOLVING STRATEGY

A. EXPERIMENTAL DATA

In order to explore the influence of high-order ionospheric delay on observation and POD precision, satellite-borne GPS dual-frequency observation of GRACE-FO is used. GPS dual-frequency observation, provided by GFZ, is a processed Level-1B product [1], [2]. Its format is Receiver Independent Exchange (RINEX), sampling interval of 10s, and its acquisition address is: (https://isdc.gfz-potsdam.de/).

In order to verify the influence of adding high-order term on POD results, the scientific orbit published by Jet Propulsion Laboratory (JPL) is used to compare POD results with or without high-order term correction. The scientific orbit includes the coordinates and velocities in the earth-fixed coordinate system and inertial coordinate system of GRACE-FO. The Scientific Data System (SDS), which is composed of JPL, University of Texas (UTCSR) and GFZ, processes the satellite-borne GPS observation of GRACE-FO, and the orbit precision is better than 2 cm [1], [2]. The scientific orbit and satellite satellite-borne GPS observation are packaged and distributed together.

High-order ionospheric delay is closely related to STEC, so accurate differential code bias (DCB) data are needed in calculating STEC [36]. DCB data used in this paper are the hardware delay information of each GPS satellite calculated by the European Orbit Determination Center (CODE) based on the joint solution of more than 100 GPS stations distributed around the world [37]. The update interval is once a month, and the download address is: (ftp://ftp.aiub.unibe.ch/CODE).

When using Equation (8) to calculate the second-order effect of ionospheric delay, the relevant geomagnetic field information is obtained based on the latest generation of international geomagnetic reference field IGRF13 [22] issued by the International Association of Geomagnetism and Aeronautics (IAGA). IGRF13 is a mathematical model representing the global distribution of geomagnetic field and its annual rate of change. The coordinate system adopted is WGS84. The intensity and direction of the geomagnetic field at any point can be obtained by using the spherical harmonic analysis method and the spherical harmonic coefficient given by IAGA. IGRF13 can be downloaded from: (https://www.ngdc.noaa.gov/IAGA/vmod/igrf.html).

SLR is used to verify whether the addition of high-order ionospheric delay improves the precision of POD. At present, SLR verification is the most accurate means of orbit verification in the world, and its ranging precision can reach 1 cm. Its core idea is to use the orbit data calculated by satellite-borne GPS observation to calculate the station distance, and then to compare it with the station distance measured by laser [38], [39]. SLR verification uses normal point (NP) [40] data published by International Laser Ranging Service (ILRS), which is obtained at: (ftp://cddis.gsfc.nasa.gov/pub/slr/data/npt_crd/).

B. PROCESS TO VERIFY THE INFLUENCE OF HIGHER ORDER IONOSPHERIC DELAY ON GRACE-FO POD

GRACE-FO-borne GPS dual-frequency observation is used to calculate high-order ionospheric delay, the influence of high-order ionospheric delay satellite observation is studied and the observation is corrected. Orbit determination is

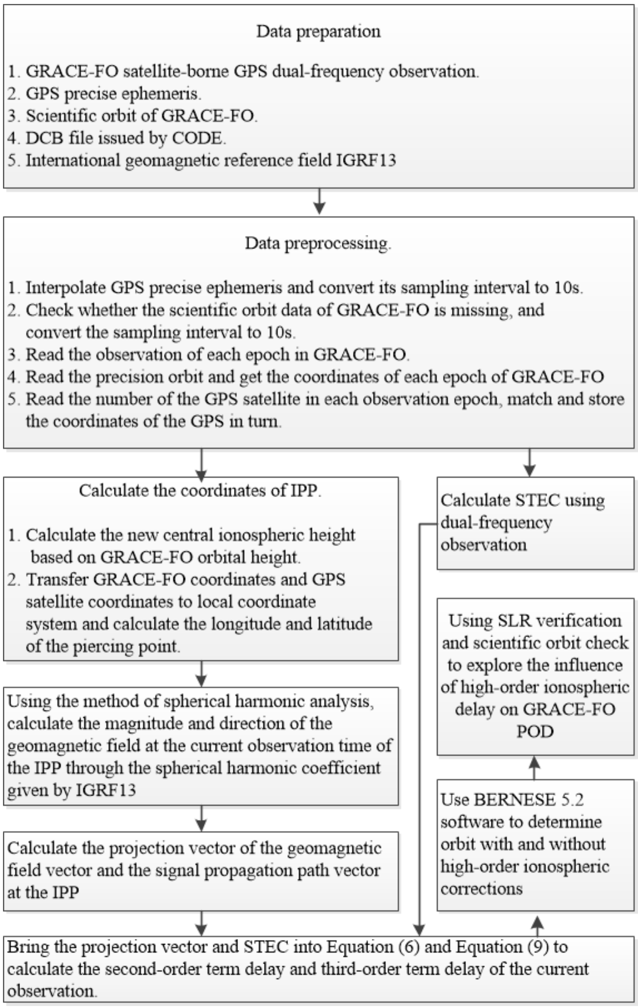

FIGURE 1. Technical Route of the influence of High-order Ionosphere on GRACE-FO POD.

carried out by using the data with and without high-order ionospheric delay correction, and the effect of high-order ionospheric delay correction on the precision of POD is studied by means of SLR verification and scientific orbit check. The specific flow chart is shown in Figure 1.

IV. THE EFFECT OF HIGHER-ORDER IONOSPHERIC DELAY

In order to explore the influence of high-order ionospheric delay on GRACE-FO observation, relevant calculations are carried out. In the process of calculation, Equation (9) is used to process and calculate STEC of the satellite-borne GPS dual-frequency observation of two GRCAE-FO satellites on DOY 71 in 2019, and Equation (12) is used to calculate the maximum electron density $N_{e,max}$ by STEC. According to the orbital height of GRACE-FO, the height of the new central ionosphere is 754.5 km, and the coordinates of IPP are calculated by Equation (10), and then the geomagnetic field intensity B and the angle θ between the geomagnetic field and the signal propagation direction are calculated according to the coordinates of IPP and IGRF13. Finally, Equation (8) is used to calculate the second-order term of ionospheric delay, and Equation (11) is used to calculate the third-order term.

TABLE 1. Mean and standard deviation of the influence of second-order terms on L1 and L2 observations of GRACE-FO satellites (mm).

	L1 band		L2 band	
	A	B	A	B
MEAN	6.55	6.57	13.86	13.91
Standard Deviation	4.80	4.82	10.15	10.21

TABLE 2. Mean and standard deviation of the influence of third-order terms on L1 and L2 observations of GRACE-FO satellites (mm).

	L1 band		L2 band	
	A	B	A	B
MEAN	0.08	0.08	0.21	0.22
Standard Deviation	0.04	0.04	0.10	0.11

Table 1 and Table 2 show the mean and standard deviation of the effects of ionospheric second-order and third-order delay on GRACE-FO L1 and L2 observations, from which it can be seen that the average value and standard deviation of high-order ionospheric delay correction of the two satellite observations are basically the same, with slight deviation resulting from the fact that GRACE-FO satellite B has less G06 observation than satellite A.

Figure 2 shows the effect of the second-order term delay on L1 and L2 observations of GRACE-FO GPS receiver. As is shown in Figure 2, Table 1 and Table 2, the second-order term of the ionosphere has an effect on satellite code pseudo-range observations in the order of centimeters. The maximum value of the influence of the second-order term on the L1-band observations of satellites A and B is 33.80 mm, with the average value of 6.56mm. The maximum influence of the second-order term on the L2-band observations of satellites A and B is 67.02 mm, with the average value of 13.86mm.

Figure 3 shows the effect of the third-order term delay on L1 and L2 observations of GRACE-FO GPS receiver. According to Figure 3, Table 1 and Table 2, the effect of the third-order term on the observations of the two GRACE-FO satellites is smaller than that of the second-order term. The maximum value of the influence of the third-order term delay on L1-band observations is 0.50 mm, with the average value of 0.06 mm; and the maximum effect of the third-order term delay on L2-band observations is 1.44 mm, with the average value of 0.22 mm.

It can be seen from Figures 2 and 3 that the delay of higher-order terms in the ionosphere varies periodically, with 15 peaks in a day, because the change of latitude is an important factor affecting the ionospheric delay, which is low in high latitudes and high in low latitudes. Because the orbital inclination of GRACE-FO is 89 °, the latitude of the satellite will constantly change when it is in orbit, making the delay of the higher-order terms of the satellite vary greatly. The orbital period of the satellite is 96 minutes, similar to the period of the variation of the higher-order terms of the

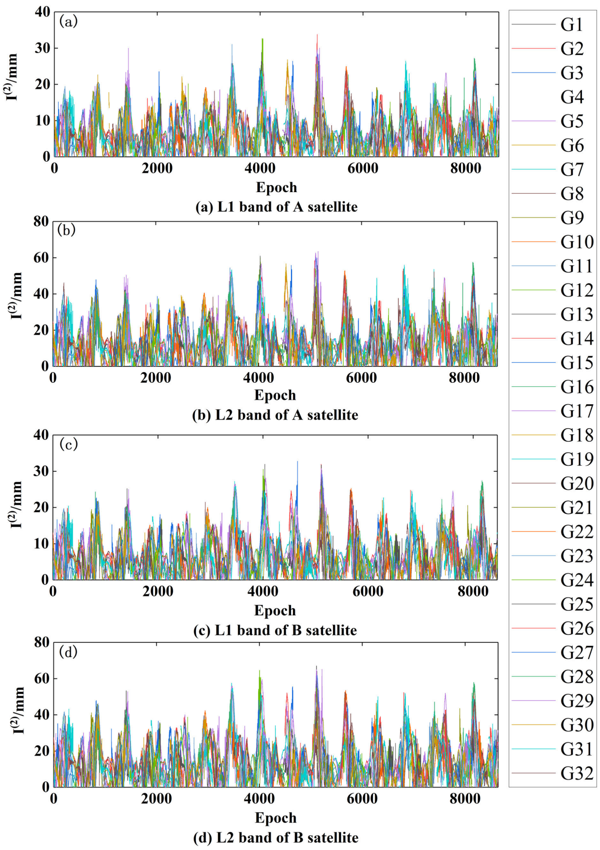

FIGURE 2. Influence of the L1/L2 observation of each GPS satellite on the ionospheric second-order, GRACE-FO-A(ab), GRACE-FO-B(cd).

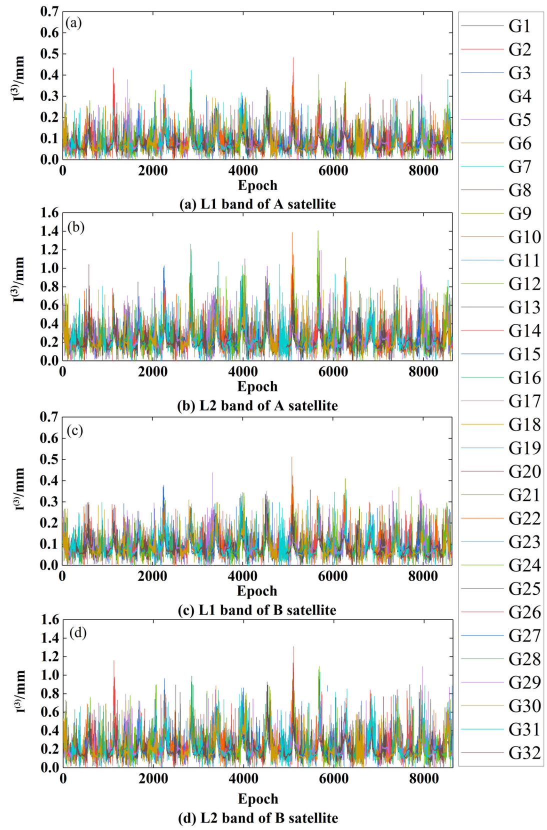

FIGURE 3. Influence of L1 and L2 observation of each GPS satellite on the ionospheric third-order, GRACE-FO-A(ab), GRACE-FO-B(cd).

ionosphere shown in Figure 2 and Figure 3. It can be concluded that the higher-order ionospheric delay of GRACE-FO satellite varies regularly according to the orbital period of the satellite.

By comparison, it can be found that due to different frequencies of L1 and L2, the influence of the higher-order term of the ionosphere on L1 and L2 band signals is different. According to Equation (8) and Equation (11), the influence of the second-order term on L2 is about 2.11 times that on L1, and the influence of the third-order term on L2 is about 2.71 times that on L1 [41].

V. RESULTS AND ANALYSIS OF POD

In order to study the influence of high-order ionospheric delay on POD precision of GRACE-FO, the method of simplified dynamics is used for POD. Firstly, the precise orbit of GRACE-FO without high-order ionospheric delay correction is obtained by using the 15-day unprocessed observations of DOY 71-85 in 2019. Then the high-order ionospheric delay correction is calculated by Equations (8)-(12). The satellite-borne GPS pseudo-range and phase observations are corrected according to Equation (6) and Equation (7), and the corrected data are used for POD by way of simplified dynamics. Finally, SLR verification and scientific orbit check are used to check the precision of POD results of the two kinds of GRACE-FO observation.

The precision of the orbit is checked in the RTN coordinate system. The origin of the coordinate system is the satellite centroid; R is radial, which is the radial direction from the center of the earth to the center of mass of the satellite; T is tangential, which is perpendicular to the R axis in the orbital plane and points to the direction of satellite motion; and N is normal, which forms a right-handed system with R and T.

A. SLR VERIFICATION

In order to verify whether the method of calculating the high-order ionospheric delay used in this paper is correct, and explore the effect of GRACE-FO POD precision after adding high-order term delay correction, BERNESE 5.2 software is used to check the two POD results of GRACE-FO in 2019 DOY 71-85 (15 days).

There are 1732 NP data for GRACE-FO-A satellites and 1916 NP data for GRACE-FO-B satellites. The difference in the number of SLR observation is due to the fact that the two satellites are only flying on the same orbital plane with a distance of 220 ± 50 km, and the two satellites cannot be observed at the same time at the same SLR station in the instantaneous observation calendar; therefore, the SLR observation of the two satellites are obviously different in the same observation arc.

In the process of data calculation, the satellite height cutoff angle is set to 3°, and the tropospheric delay is corrected

TABLE 3. Statistics of RMS values for SLR verification of GRACE-FO satellites (mm).

	Satellite	Uncorrected	Corrected
MEAN	A	22.75	21.96
	B	18.93	18.27
Maximum	A	32.83	32.48
	B	32.61	31.77
Minimum	A	11.85	11.68
	B	10.27	10.03

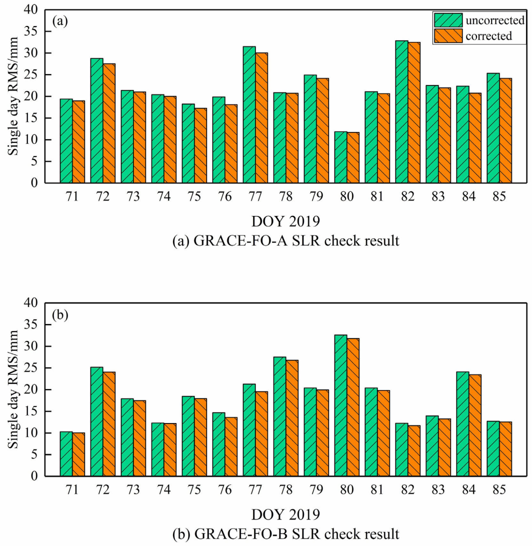

FIGURE 4. Results of single-day SLR verification, GRACE-FO-A(a), GRACE-FO-B(b).

by MENDES-PAVLIS empirical model [42]. To ensure the correctness of the check, the mean square error of checking data is calculated. If the number of points that can be used by a station during a day is less than 5 or the check result of the station is more than triple mean square error, the data of the station will be deleted. In the 15 days, 67 and 64 NP data are respectively removed from GRACE-FO-A and GRACE-FO-B, accounting for 3.87% and 3.34% of all NP data.

Table 3 shows the RMS values of the 15-day SLR verification of DOY 71-85 for two GRACE-FO satellites in 2019. As is shown in Table 3, the POD precision of the two satellites will be improved after adding higher-order ionospheric correction. The 15-day average improvements are 0.79 mm and 0.66 mm, and the maximum single-day improvements are 1.77 mm and 1.72 mm, respectively. This shows that high-order ionospheric delay has an impact on POD results of GRACE-FO, and the effects on the two satellites are basically the same.

Figure 4 shows the comparison of SLR verification, POD results with and without high-order ionospheric delay are checked (among which, the single-day RMS value is obtained, multiplying the RMS value of each SLR station by the amount of NP point data of the station, and then divided by the total amount of NP point data). As is shown in Figure 4, the POD precision of 15 days after adding high-order ionospheric delay correction is better than that without correction, which proves the reliability of the data POD results after adding high-order ionospheric correction. Combined with Table 3, the following conclusions can be drawn: adding high-order ionospheric delay can improve POD precision of GRACE-FO, and the order of magnitude is sub-millimeter level.

TABLE 4. Statistical results of scientific orbit check, GRACE-FO-A (mm).

		R	T	N	3D
MEAN	Uncorrected	10.48	16.55	9.69	12.63
	Corrected	9.99	16.09	9.85	12.33
Maximum	Uncorrected	11.62	17.61	12.82	14.54
	Corrected	11.03	17.33	13.82	14.50
Minimum	Uncorrected	9.00	15.36	8.04	11.30
	Corrected	8.30	14.72	8.62	10.88

TABLE 5. Statistical results of scientific orbit check, GRACE-FO-B (mm).

		R	T	N	3D
MEAN	Uncorrected	10.28	16.74	17.76	15.34
	Corrected	9.74	16.35	18.05	15.20
Maximum	Uncorrected	10.52	17.44	22.27	17.20
	Corrected	9.92	17.03	22.91	17.16
Minimum	Uncorrected	7.85	12.12	13.00	11.12
	Corrected	7.41	11.44	13.18	10.70

B. SCIENTIFIC ORBIT CHECK

The POD results obtained by using the raw data of the two GRACE-FO satellites and the delayed correction data of higher-order terms from DOY 71-85 in 2019 are compared with the scientific orbits provided by JPL, respectively. In the process of checking, it is found that the scientific orbit check result of GRACE-FO-B satellite on the 78th day of DOY in 2019 suddenly becomes worse, and the 3D-RMS reaches up to 4 cm, but the SLR verification result on the 78th day is relatively normal. In order to avoid the influence of accidental factors on the experimental results, the scientific orbit check is not carried out on the POD result of the satellite on that day.

Table 4 and Table 5 shows the RMS values of the 15-day scientific orbit check for the two kinds of orbits, and Figure 5 and Figure 6 show the comparison of RMS values of the two kinds of orbits in radial(R), tangential(T), normal(N) and three-dimensional(3D) directions, respectively.

From Table 4, Table 5, Figure 5 and Figure 6, POD precision can be slightly improved by adding higher-order ionospheric delay. In the three-dimensional direction, the maximum daily improvement values of the two satellites are 0.70 mm and 0.40 mm, and the 15-day average improvement values of 0.30 mm and 0.14 mm, both lower than 0.79 mm and 0.66 mm obtained by SLR. This is because

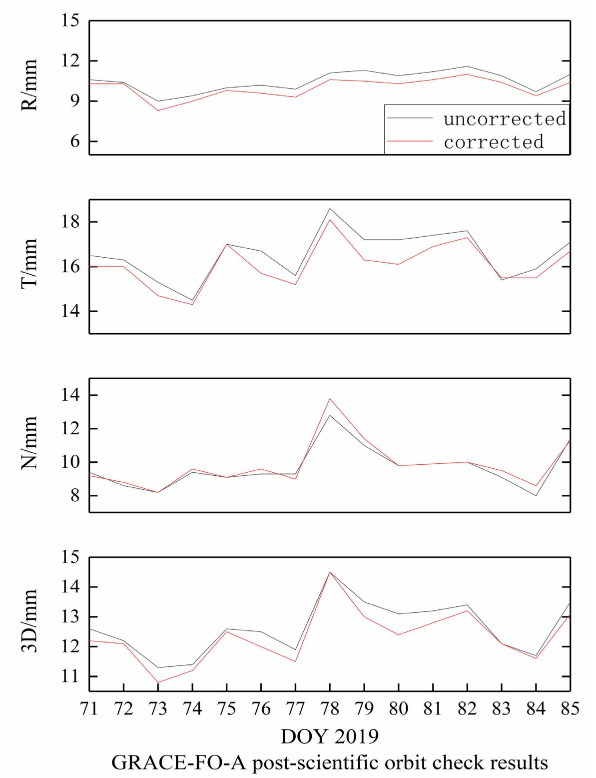

FIGURE 5. Results of single-day scientific orbit validation, GRACE-FO-A.

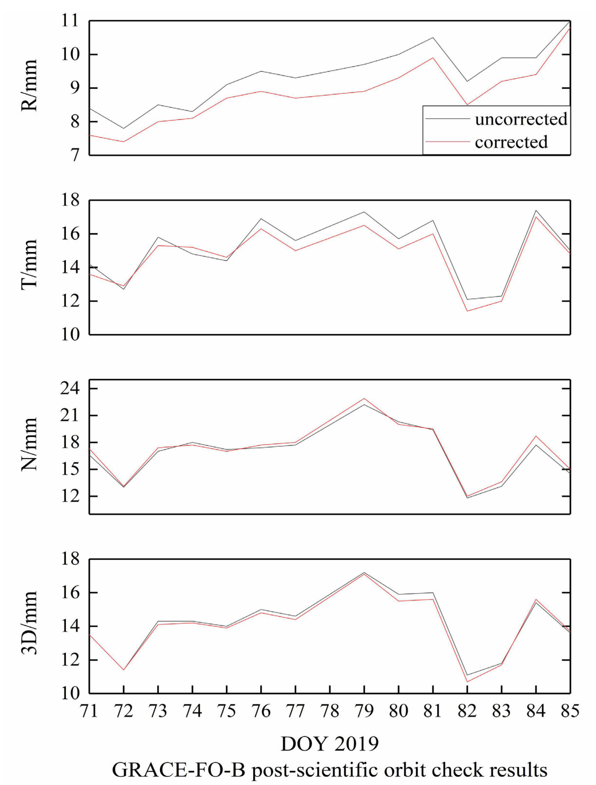

FIGURE 6. Results of single-day scientific orbit validation, GRACE-FO-B.

the precision of SLR verification is different from scientific orbit check. Compared with scientific orbit, the precision of SLR verification is higher and more reliable. On the other hand, with the addition of higher-order ionospheric delay, the radial and tangential precision will be improved, while the normal precision will be reduced. According to Figure 5 and Figure 6, the radial precision improvement is more stable than that in the tangential direction, and the RMS values after adding correction are smaller than those without correction in 15 days. This is because the high-order ionospheric delay corrects the distance between GRACE-FO satellite and GPS satellite, and the correction will certainly improve the radial precision of the satellite.

VI. CONCLUSION

The influence of high-order ionospheric delay on the observation and POD precision of GRCAE-FO satellite-borne GPS is studied. Based on the observation of dual-frequency satellite-borne GPS receiver and the 13th generation geomagnetic field model IGRF13, the high-order ionospheric delay correction is estimated, and its influence on L1 and L2 observations is analyzed. GPS observations with and without high-order term correction are imported into BERNESE 5.2 software for POD, and the POD results are analyzed by various means. It is found that the result of POD will be improved after adding high-order term delay.

Through analysis of the delay of higher-order terms, it can be seen that the effects of the higher-order terms of the ionosphere on the two GRACE-FO satellites are basically the same. Because of the high orbit and fast motion of GRACE-FO, the correction of the higher-order terms of the ionosphere has an influence on the observed values of L1 and L2 in the order of centimeters, and will change regularly with the orbital period of GRACE-FO. For L1 band observations of two GRACE-FO satellites, the maximum value of the second order term is 33.80 mm, with the average of 6.56 mm, and the maximum value of the third order term is 0.50 mm, with the average of 0.06 mm. For L2 band observations, the maximum value of the second order term is 67.02 mm, with the average of 13.86 mm, and the maximum value of the third order term is 1.44 mm, with the average of 0.22 mm.

SLR verification results show that the impact of high-order term delay on the precision of GRACE-FO POD is in the sub-millimeter level. After adding high-order term delay, the precision of POD results will be improved, and the maximum precision improvement amount can reach 1.77 mm, and the 15-day average is 0.73 mm. After the scientific orbit check, it can be concluded that compared with the reference orbit released by JPL, the addition of high-order term delay will slightly improve POD result. The maximum amount of improvement is 0.70 mm, and the 15-day average value is 0.22 mm.

The improvement is mainly in the radial direction, but not obvious in the tangential and normal directions, because the ionospheric delay is mainly corrected by the distance between GRACE-FO and GPS. So after adding high-order ionospheric delay, POD precision in the radial direction will be improved.

By effectively correcting the delay of higher-order terms in the ionosphere, a higher-precision POD orbit can be obtained, so high-resolution earth gravitational field models and global gravitational field products can be obtained, and it is helpful to accurately detect magnetic fields, it also contribute to study the interaction between geomagnetic field, solar activity and ionosphere, and further understand the interference of space environment and ionosphere activity on communication and navigation satellites.

The use of GRACE-FO satellite-borne GPS dual-frequency observation can directly correct high-order ionospheric delays, and real-time and quasi-real-time positioning can be performed without obtaining external GIM data. However, due to the low precision of pseudo-range observations, precise calculation of STEC needs further study. For different solar and ionospheric activities, the impact of higher-order ionospheric delays on GRACE-FO observation and POD needs to be further studied.

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LINHU QI is currently pursuing the master's degree with the Shandong University of Science and Technology. His research interests include low-orbit satellite and orbit determination.

JINYUN GUO received the Ph.D. degree from the Shandong University of Science and Technology, in 2004. He is currently a Professor with the College of Geodesy and Geomatics, Shandong University of Science and Technology. His research interest includes space geodesy.

YAOWEI XIA is currently pursuing the master's degree with the Shandong University of Science and Technology. His research interests include PPP and regional atmospheric modeling.

ZHOUMING YANG is currently pursuing the master's degree with the Shandong University of Science and Technology. His research interest includes GNSS algorithm.