

GRACE-FO Single-Satellite Ambiguity Resolution and Precise Orbit Determination (Post-print)

Authors: Jin Biao^{1,2,3}, Li Yuqiang¹, Zhou Wei⁴, Li Zhulian¹, Chen Shanshan⁵

Date: 2023-06-07T00:00:00+00:00

Abstract

Carrier phase bias products are utilized to correct satellite hardware biases, while inter-satellite single-differencing is employed to eliminate receiver biases. In conjunction with corresponding GPS precise orbit and clock products, wide-lane and narrow-lane ambiguities are sequentially fixed, followed by obtaining ionosphere-free combination ambiguities based on integer solutions. Virtual observations are then used to constrain undifferenced ionosphere-free ambiguities, ultimately yielding a fixed solution orbit. Simultaneously, carrier phase residuals are employed to conduct on-orbit estimation of on-board antenna phase center variation (PCV) to further enhance orbit determination precision. GPS precise orbit, clock, and phase bias products released by the Center for Orbit Determination in Europe (CODE), the French Space Agency (CNES), and Wuhan University (WHU) are respectively used to perform ambiguity fixing and precise orbit determination for GRACE-FO satellites, thereby evaluating the performance of products from different agencies. Results demonstrate that antenna PCV corrections can effectively reduce carrier phase residuals and improve orbit determination precision. The wide-lane ambiguity fixing rates for GRACE-FO satellites using products from different agencies are all superior to 99%, with narrow-lane ambiguity fixing rates superior to 95%. The precise orbit determination results for GRACE-FO satellites based on CODE, CNES, and WHU products are evaluated; compared with JPL precise orbits, the average 3D precision of fixed solution orbits is superior to 7.0 mm. The RMS values of SLR ranging residuals are superior to 9.6, 10.7, and 9.1 mm, respectively. Compared with KBR inter-satellite ranging values, the inter-satellite distance precision calculated using fixed solution orbits is superior to 1.8, 2.3, and 2.1 mm, respectively. The overall differences in GRACE-FO satellite orbits solved using products from different agencies are less than 2 mm.

Full Text

Preamble

ChinaXiv Partner Journal, Vol. 40, No. 3

September 2022

PROGRESS IN ASTRONOMY Vol. 40, No. 3, Sept. 2022 doi: 10.3969/j.issn.1000-8349.2022.03.07

GRACE-FO Single-Satellite Ambiguity Resolution and Precise Orbit Determination Research

JIN Biao^{1,2,3}, LI Yu-qiang¹, ZHOU Wei⁴, LI Zhu-lian¹, CHEN Shan-shan⁵

(1. Yunnan Observatories, Chinese Academy of Sciences, Kunming 650216, China; 2. University of Chinese Academy of Sciences, Beijing 100049, China; 3. Space Star Technology Co., Ltd., Beijing 100094, China; 4. Beijing Institute of Tracking and Telecommunications Technology, Beijing 100094, China; 5. Beijing Sixents Technology Co., Ltd., Beijing 100094, China)

Abstract

Carrier phase bias products are employed to calibrate satellite hardware delays, while inter-satellite single-difference observations eliminate receiver-side biases. Combined with corresponding GPS precise orbit and clock products, wide-lane and narrow-lane ambiguities are sequentially fixed to integer values, yielding integer-resolution ionosphere-free combination ambiguities. Virtual observations are then used to constrain the non-differenced ionosphere-free ambiguities, ultimately producing fixed-solution orbits. Simultaneously, carrier phase residuals are utilized to perform in-orbit estimation of satellite antenna phase center variation (PCV) to further enhance orbit determination accuracy. Using GPS precise orbit, clock, and phase bias products released by the Center for Orbit Determination in Europe (CODE), the French National Center for Space Studies (CNES), and Wuhan University (WHU), ambiguity resolution and precise orbit determination for GRACE-FO satellites are conducted to evaluate the performance of products from different agencies. Results demonstrate that antenna PCV correction effectively reduces carrier phase residuals and improves orbit determination accuracy. The wide-lane ambiguity fixing rate for GRACE-FO satellites exceeds 99% across all products, while the narrow-lane fixing rate surpasses 95%. Compared with JPL precise orbits, the three-axis average accuracy of fixed-solution orbits based on CODE, CNES, and WHU products is better than 7.0 mm. The RMS values of SLR ranging residuals are better than 9.6 mm, 10.7 mm, and 9.1 mm, respectively. Compared with KBR inter-satellite ranging values, the inter-satellite distance accuracy calculated using fixed-solution orbits is better than 1.8 mm, 2.3 mm, and 2.1 mm,

respectively. The overall difference between GRACE-FO satellite orbits calculated using different agency products is less than 2 mm.

Keywords: GRACE-FO satellites; ambiguity resolution; antenna PCV; precise orbit determination

1 Introduction

Low Earth orbit (LEO) satellites and their formations play indispensable roles in scientific research and engineering applications, including remote sensing, ocean environment monitoring, time-varying gravity field estimation, geomagnetic field research, occultation atmospheric observation, and positioning, navigation, and timing. Absolute precise orbit and relative position information of LEO satellites constitute the prerequisite and foundation for accomplishing these missions. Since the successful application of the Global Positioning System (GPS) to TOPEX/POSEIDON satellite precise orbit determination, reduced-dynamic orbit determination techniques based on spaceborne GPS observations have been widely applied to satellites such as the Gravity Recovery and Climate Experiment (GRACE), Challenging Minisatellite Payload (CHAMP), Ocean, Fengyun, and others. Using GPS precise orbit and clock products, LEO satellite ambiguity-float orbit determination accuracy can reach 1–3 cm. Fixing carrier phase ambiguities and performing in-orbit estimation of receiver antenna phase center variation (PCV) can further improve orbit determination accuracy.

Bertiger et al. and Tapley et al. utilized spaceborne GPS observations for TOPEX/POSEIDON orbit determination, achieving radial accuracy of 4 cm. Subsequently, numerous LEO satellites were equipped with GPS receivers for precise orbit determination. Van den IJssel et al. and Zhao Qile et al. employed GPS precise ephemerides released by the International Global Navigation Satellite System Service (IGS) and used ionosphere-free combination observations for CHAMP precise orbit determination, achieving radial accuracy better than 4 cm. Kang et al. evaluated GRACE orbit determination accuracy using Satellite Laser Ranging (SLR) data, obtaining three-dimensional orbit accuracy of 2–3 cm. Luthcke et al. comprehensively evaluated GPS reduced-dynamic orbit determination accuracy for JASON-1 using DORIS, SLR, and altimetry data, meeting the 1 cm radial accuracy requirement. Qin Jian et al. obtained centimeter-level JASON-2 satellite orbits using spaceborne observations. Similar results were achieved in other LEO missions such as GOCE, TerraSAR-X, Ocean, and Fengyun. In these orbit determinations, ambiguity parameters were float solutions. To achieve ambiguity fixing, Kroes et al. constructed relative dynamic models and fixed double-difference ambiguities for GRACE dual-satellite relative orbit determination, finding that K-band ranging (KBR) measurements achieved accuracy better than 1 mm. Jäggi et al. studied the impact of fixing inter-satellite and satellite-ground double-difference ambiguities on GRACE orbit determination accuracy, improving dual-satellite relative orbit determination accuracy from centimeter-level to 1 mm. Zhao and Hu achieved 2 mm relative orbit accuracy by fixing GRACE double-difference

ambiguities. However, for single LEO satellites, double-difference carrier observations cannot be formed, limiting the application of this method.

To enable single-receiver ambiguity resolution, scholars have proposed the fractional cycle bias method, integer phase clock method, and decoupled clock method. Bertiger et al. utilized carrier phase bias products from the Jet Propulsion Laboratory (JPL) to achieve single-satellite ambiguity resolution, improving GRACE relative orbit determination accuracy from 6 mm (float solution) to 2 mm, and achieving JASON-2 radial orbit determination accuracy better than 1 cm. Montenbruck et al. used wide-lane corrections and clock products released by CNES for ambiguity resolution in Sentinel-3A orbit determination, with significant improvements in fixed-solution orbit overlap accuracy and SLR residual precision. Zhang Xiaohong et al. achieved GRACE precise point positioning (PPP) ambiguity resolution using kinematic methods. Arnold et al. used phase bias products from CODE to fix ambiguity parameters in GRACE and Sentinel-3 precise orbit determination. Guo et al. compared the effects of double-difference ambiguity resolution, single-satellite ambiguity resolution, and double-difference ambiguity resolution based on single-satellite ambiguity resolution on GRACE orbit determination accuracy.

Another factor affecting LEO satellite orbit determination accuracy is the position of the spaceborne receiver antenna phase center. Pre-launch ground measurements of antenna phase center are conducted, but the actual in-orbit values differ from calibrated values due to environmental differences (such as multipath). Haines et al. calculated antenna PCV using JASON-1 spaceborne observations, reducing ionosphere-free combination carrier phase residuals from 8 mm to 5 mm after PCV correction, with SLR residual accuracy better than 11.9 mm. Jäggi et al. studied GRACE satellite antenna phase centers and described two estimation methods: direct estimation and residual methods. Montenbruck et al. performed in-orbit estimation of Sentinel-3A antenna PCV. Domestically, Ma Yang et al. estimated JASON-2 antenna PCV, reducing carrier residuals to 5.5 mm and achieving radial orbit determination accuracy better than 1 cm.

The GRACE Follow-On (GRACE-FO) satellites were successfully launched in May 2018. Similar to GRACE, the GRACE-FO formation consists of two satellites (GRACE-C and GRACE-D), both equipped with GPS receivers, SLR retroreflectors, and KBR instruments. Kang et al. studied the impact of using GPS data alone versus combined GPS and KBR data on GRACE-FO orbit determination accuracy. Shao Kai et al. conducted research on GRACE-FO precise orbit determination based on ambiguity resolution. This paper utilizes actual spaceborne observations to develop GRACE-FO antenna PCV in-orbit models and performs single-satellite ambiguity resolution and precise orbit determination using GPS precise orbit, clock, and phase bias products from CODE, CNES, and Wuhan University (WHU), investigating the effects of ambiguity resolution and antenna PCV in-orbit calibration on LEO satellite absolute and relative orbit determination accuracy.

Section 2 presents the mathematical models for single-satellite ambiguity resolu-

tion and antenna PCV estimation based on GPS observation equations. Section 3 describes the GRACE-FO orbit determination strategy. Section 4 analyzes results, including antenna PCV calculation results, ambiguity resolution effects, single-satellite absolute orbit determination accuracy, and dual-satellite relative orbit determination accuracy. Section 5 presents conclusions.

2.1 GPS Observation Model

GPS pseudorange and carrier phase observations can be expressed as:

$$P_{r;j}^s = \rho_r^s + c(dt_r - dt^s) + I_{r;j}^s + b_{r;j} - b_j^s \quad (1)$$

$$L_{r;j}^s = \rho_r^s + c(dt_r - dt^s) - I_{r;j}^s + \lambda_j(N_{r;j}^s + \Delta\text{PCO} + \Delta\text{PCV}) + \lambda_j\omega_r^s + B_{r;j} - B_j^s \quad (2)$$

where $P_{r;j}^s$ and $L_{r;j}^s$ represent pseudorange and carrier phase observations, r and s denote the spaceborne receiver and satellite, j indicates signal frequency, ρ_r^s is the geometric distance between receiver and satellite, c is the speed of light, dt_r and dt^s are receiver and satellite clock errors, $I_{r;j}^s$ is ionospheric delay, $b_{r;j}$ and b_j^s are receiver and satellite pseudorange hardware delays, $B_{r;j}$ and B_j^s are carrier phase hardware delays, λ_j is the wavelength corresponding to frequency j , $N_{r;j}^s$ is the phase ambiguity in cycles, ΔPCO and ΔPCV represent the effects of spaceborne antenna phase center offset (PCO) and phase center variation (PCV) on observations (where ΔPCV varies with elevation and azimuth), and ω_r^s is carrier phase wind-up. Phase wind-up can be corrected using models and is ignored in subsequent derivations.

To eliminate the first-order ionospheric delay term, ionosphere-free combination observations must be constructed. In IGS data processing, pseudorange observations are typically used as the reference for solving navigation satellite clocks, causing receiver and satellite pseudorange hardware delays to be absorbed into the clock terms. Equation (1) can then be written as:

$$P_{r;\text{IF}}^s = \rho_r^s + c(\bar{d}t_r - \bar{d}t^s) + \Delta\text{PCO} + \Delta\text{PCV} \quad (3)$$

$$L_{r;\text{IF}}^s = \rho_r^s + c(\bar{d}t_r - \bar{d}t^s) + \lambda_l \bar{N}_{r;\text{IF}}^s + (B_{r;\text{IF}} - b_{r;\text{IF}}/\lambda_l) - (B_{\text{IF}}^s - b_{\text{IF}}^s/\lambda_l) + \Delta\text{PCO} + \Delta\text{PCV} \quad (4)$$

where $P_{r;\text{IF}}^s$ and $L_{r;\text{IF}}^s$ are ionosphere-free combination pseudorange and carrier phase observations, $\bar{d}t_r$ and $\bar{d}t^s$ are receiver and satellite clocks that have absorbed pseudorange hardware delays, $\bar{N}_{r;\text{IF}}^s$ is the ionosphere-free combination ambiguity, $b_{r;\text{IF}}$ and b_{IF}^s are receiver and satellite ionosphere-free combination pseudorange hardware delays, $B_{r;\text{IF}}$ and B_{IF}^s are ionosphere-free combination carrier phase biases, and λ_l is the L-band carrier wavelength. When using

pseudorange and carrier phase observations for positioning, the solved float ambiguities contain receiver and satellite pseudorange and carrier hardware delays.

2.2 Single-Satellite Ambiguity Resolution

The ionosphere-free combination ambiguity $\bar{N}_{r;\text{IF}}^s$ can be decomposed into wide-lane and narrow-lane ambiguities:

$$\bar{N}_{r;\text{IF}}^s = \frac{f_1}{f_1 - f_2} N_{r;\text{WL}}^s - \frac{f_2}{f_1 - f_2} N_{r;\text{NL}}^s$$

where f_1 and f_2 are the frequencies corresponding to carriers L1 and L2, $N_{r;\text{WL}}^s$ and $N_{r;\text{NL}}^s$ are integer wide-lane and narrow-lane ambiguities, and $N_{r;1}^s$ and $N_{r;2}^s$ are ambiguities for carriers L1 and L2. $d_{r;\text{NL}}$ and d_{NL}^s represent the narrow-lane combination of receiver and satellite pseudorange and carrier hardware delays.

Using the Melbourne-Wübbena combination to solve wide-lane ambiguities yields:

$$N_{r;\text{WL}}^s = \frac{f_{1L_{r;1}}^s - f_{2L_{r;2}}^s}{f_1 - f_2} - \frac{f_{1P_{r;1}}^s + f_{2P_{r;2}}^s}{f_1 + f_2} / \lambda_{\text{WL}} = N_{r;\text{WL}}^s + d_{r;\text{WL}} - d_{\text{WL}}^s$$

where $d_{r;\text{WL}}$ and d_{WL}^s are receiver and satellite wide-lane hardware delays, and λ_{WL} is the wide-lane wavelength. Correcting receiver and satellite wide-lane delays enables wide-lane ambiguity fixing. After wide-lane ambiguity fixing, the float narrow-lane ambiguity can be calculated by substituting into Equation (3):

$$\bar{N}_{r;\text{IF}}^s = N_{r;\text{NL}}^s + d_{r;\text{NL}} - d_{\text{NL}}^s$$

Similarly, correcting receiver and satellite narrow-lane delays enables narrow-lane ambiguity fixing. In practice, satellite wide-lane and narrow-lane phase biases can be solved using ground station network data and provided to users, while user-side wide-lane and narrow-lane hardware delays cannot be directly obtained. This paper employs inter-satellite single-difference to eliminate receiver-side delays. From Equations (4) and (5), we obtain:

$$\Delta \bar{N}_{r;\text{WL}}^{s_1, s_2} = \Delta N_{r;\text{WL}}^{s_1, s_2} + \Delta d_{r;\text{WL}} - \Delta d_{\text{WL}}^{s_1, s_2} \quad (5)$$

$$\Delta \bar{N}_{r;\text{NL}}^{s_1, s_2} = \Delta N_{r;\text{NL}}^{s_1, s_2} + \Delta d_{r;\text{NL}} - \Delta d_{\text{NL}}^{s_1, s_2} \quad (6)$$

where $\Delta \bar{N}_{r;\text{WL}}^{s_1, s_2}$ and $\Delta \bar{N}_{r;\text{NL}}^{s_1, s_2}$ are inter-satellite single-difference values of float wide-lane and narrow-lane ambiguities, $\Delta N_{r;\text{WL}}^{s_1, s_2}$ and $\Delta N_{r;\text{NL}}^{s_1, s_2}$ are differences of

integer wide-lane and narrow-lane ambiguities, and $\Delta d_{\text{WL}}^{s_1, s_2}$ and $\Delta d_{\text{NL}}^{s_1, s_2}$ are differences of inter-satellite wide-lane and narrow-lane hardware delays that can be corrected using correction products. After fixing inter-satellite single-difference wide-lane and narrow-lane ambiguities, the ionosphere-free combination ambiguity can be recovered according to:

$$\Delta N_{r;\text{IF}}^{s_1, s_2} = \frac{f_1}{f_1 - f_2} \Delta N_{r;\text{WL}}^{s_1, s_2} - \frac{f_2}{f_1 - f_2} (\Delta N_{r;\text{NL}}^{s_1, s_2} - \Delta d_{\text{NL}}^{s_1, s_2})$$

where $\Delta N_{r;\text{IF}}^{s_1, s_2}$ is the inter-satellite difference of ionosphere-free combination ambiguities. Using this to constrain non-differenced ionosphere-free combination ambiguities yields the fixed-solution orbit.

2.3 Antenna Phase Center Estimation

GPS phase observations are obtained by measuring the instantaneous phase centers of the navigation satellite signal transmitting antenna and receiving antenna. However, the instantaneous antenna phase center varies with elevation angle, azimuth angle, and signal frequency. The instantaneous antenna phase center can be described using the mean phase center (PCO) and variations relative to this mean (PCV), as shown in Equation (8):

$$\Delta \Phi(a, z, f_i) = \Delta \text{PCO} + \Delta \text{PCV}(a, z, f_i)$$

where a is the azimuth angle of the navigation satellite relative to the receiver, z is the elevation angle, f_i is the signal frequency ($i = 1, 2$ indicates the number of signal frequencies). This equation enables conversion from instantaneous phase center to antenna reference point. ΔPCO and ΔPCV are used in applications.

LEO satellite spaceborne antenna phase centers can be described using spherical harmonic functions or piecewise linear functions. This paper employs piecewise linear functions to model LEO satellite receiver antenna PCV. This model assumes antenna PCV consists of different grids, obtained by equally dividing azimuth and elevation angles. The azimuth range is 0° – 360° , and the elevation range is 0° – 90° . When an observation at a given moment falls within grid ABCD at point P , its PCV value is linearly interpolated as:

$$\Delta \text{PCV}_P = (1-\alpha)(1-\beta)\Delta \text{PCV}_A + \alpha(1-\beta)\Delta \text{PCV}_B + \alpha\beta\Delta \text{PCV}_C + (1-\alpha)\beta\Delta \text{PCV}_D$$

where $\alpha = (a - a_1)/(a_2 - a_1)$, $\beta = (z - z_1)/(z_2 - z_1)$, ΔPCV_P is the PCV value at point P , α and β are combination coefficients, a and z are the azimuth and elevation of point P , a_1 is the azimuth of points A and D, a_2 is the azimuth of points B and C, z_1 is the elevation of points A and B, z_2 is the elevation of points C and D, and ΔPCV_A , ΔPCV_B , ΔPCV_C , ΔPCV_D are the PCV values at

points A, B, C, and D, respectively, which are estimated parameters. This paper solves for PCV values at each grid point using carrier phase residuals, which are then interpolated during orbit determination to obtain PCV corrections for specific azimuth and elevation angles.

3 Orbit Determination Strategy

Reduced-dynamic methods are employed for GRACE-FO satellite precise orbit determination, with estimated parameters including satellite initial position and velocity vectors. Satellite attribute information is used to model solar radiation pressure and atmospheric drag, with atmospheric density calculated using the Drag Temperature Model 94 (DTM94). Atmospheric drag and solar radiation pressure coefficients are estimated during the orbit determination process. To compensate for model errors, periodic empirical accelerations in the along-track and cross-track directions are calculated once per revolution (one cycle per resolution, CPR). Additional estimated parameters include receiver clock errors and ambiguities. Spaceborne GPS antenna PCO is corrected according to published parameters, while PCV is estimated in-orbit using carrier phase residuals. GPS satellite orbits and clocks are adopted from post-processed precise products, and phase bias products are used to correct carrier phase observations. During orbit determination, float-solution orbits are first obtained based on ionosphere-free combination observations. Wide-lane and narrow-lane ambiguities are then sequentially fixed and used to recover ionosphere-free combination ambiguities according to the methods described in Section 2, ultimately yielding fixed-solution orbits. Specific orbit determination strategies are detailed in Table 1 .

4 Orbit Determination Results Analysis

The GRACE-FO satellites operate at an altitude of 500 km with an inter-satellite separation of approximately 200 km. This paper uses 2019 spaceborne GPS observations for GRACE-FO precise orbit determination. Observation data are obtained from the Level 1B RL04 data packages provided by the German Research Centre for Geosciences (GeoForschungsZentrum, GFZ). These packages contain satellite quaternion attitude information, maneuver data, JPL-provided precise orbits, and KBR inter-satellite ranging values. JPL precise orbits and KBR data are used to evaluate orbit determination accuracy. GPS satellite precise orbit, clock, and phase bias products released by CODE, CNES, and WHU are used for GRACE-FO single-satellite ambiguity resolution and precise orbit determination.

4.1 Antenna Phase Center Correction

Following the description in Section 2.3, GRACE-FO spaceborne GPS antenna PCV corrections are calculated using ionosphere-free combination carrier phase residuals. To reduce computational load, both azimuth and elevation resolu-

tions are set to 5° . Specifically, residuals from a single orbit determination arc are first used to estimate PCV corrections for that arc. All valid PCV corrections from 2019 are then averaged to obtain PCV estimates for the entire period. Carrier observations are corrected using these PCV values, and orbit determination is performed again. PCV improvements are estimated using new residual data, with four iterations performed to obtain final antenna PCV values. Figure 1 [Figure 1: see original paper] shows the GRACE-FO antenna PCV calculation results, with (a) showing PCV for GRACE-C and (b) for GRACE-D. For GRACE-C, 0° azimuth corresponds to the satellite flight direction; for GRACE-D, 180° azimuth corresponds to the flight direction. GRACE-C exhibits a maximum PCV of 13.28 mm at azimuth 10° and elevation 50° , and a minimum value of -12.57 mm at azimuth 185° and elevation 25° . GRACE-D shows a maximum PCV of 11.62 mm at azimuth 190° and elevation 50° , and a minimum value of -12.15 mm at azimuth 5° and elevation 25° .

Using these antenna PCV results to correct carrier phase observations, orbit determination is performed again. Carrier phase residuals are statistically analyzed, with mean residual values shown in Figure 2 [Figure 2: see original paper] (plotting threshold: 5 mm). After antenna PCV correction, maximum phase residuals for GRACE-C and GRACE-D are reduced to 2.9 mm and 2.8 mm, respectively. Within the elevation range of 30° – 90° , carrier phase residuals are less than 1.5 mm. Carrier residuals reflect the consistency between error models and used data, indicating that antenna PCV correction will contribute to improved orbit determination accuracy.

4.2 Ambiguity Resolution Performance

The rounding method is used to fix float ambiguities, with wide-lane and narrow-lane ambiguity fixing thresholds of 0.25 and 0.15 cycles, respectively. Statistics of fractional parts for wide-lane and narrow-lane ambiguities solved using CODE products are shown in Figure 3 [Figure 3: see original paper]. The mean fractional part of wide-lane ambiguities is 0.01 cycles with a standard deviation of 0.11 cycles; narrow-lane ambiguities have a mean of 0 and standard deviation of 0.06 cycles. Small standard deviations facilitate ambiguity fixing and reflect high-quality phase bias products and correct models. Similar results are obtained for wide-lane and narrow-lane ambiguity fractional parts based on CNES and WHU products.

GRACE-FO satellite wide-lane and narrow-lane ambiguity fixing rates are shown in Figure 4 [Figure 4: see original paper], with (a) and (c) showing GRACE-C wide-lane and narrow-lane fixing rates, and (b) and (d) showing GRACE-D results. Red, green, and blue points represent results using CODE, CNES, and WHU products, respectively, with day of year on the horizontal axis. Results are not shown for days 33–51 due to missing data. Wide-lane ambiguity fixing rates exceed 99% for all products, while narrow-lane fixing rates surpass 95%. CODE products achieve the highest fixing rates, with wide-lane and narrow-lane fixing rates exceeding 99.4% and 96.8%, respectively.

4.3 Absolute Orbit Determination Results

GRACE-FO data packages include JPL precise orbit products, which are reduced-dynamic orbits based on single-satellite ambiguity resolution. Orbit determination accuracy is evaluated by comparing results with JPL precise orbits. To verify antenna PCV correction effects, differences between orbits with and without PCV correction and JPL precise orbits are analyzed. Figure 5 [Figure 5: see original paper] shows RMS values of along-track differences between CODE product-based fixed-solution orbits and JPL orbits before and after PCV correction, with (a) and (b) presenting GRACE-C and GRACE-D results, respectively. Blue points indicate differences without PCV correction, while red points show results with PCV correction. After antenna PCV correction, along-track differences are reduced from 7.2 mm to 6.0 mm for GRACE-C and from 6.4 mm to 5.9 mm for GRACE-D. Radial and cross-track results are shown in Table 2, demonstrating that antenna PCV correction most significantly improves along-track orbit accuracy.

Figure 6 [Figure 6: see original paper] shows along-track differences between fixed-solution orbits based on different products and JPL precise orbits, with (a) and (b) corresponding to GRACE-C and GRACE-D, respectively. Red, green, and blue points represent results using CODE, CNES, and WHU products. All orbit determinations apply antenna PCV corrections from Section 4.1. Normal and radial statistics are presented in Table 3. Differences between GRACE-FO fixed-solution orbits based on different products and JPL precise orbits are all less than 7.0 mm, with differences between different agency products less than 1.0 mm. Larger along-track errors occur at certain times (e.g., days 103, 134, and 270) due to fewer visible GPS satellites, resulting in degraded orbit determination accuracy.

GRACE-FO satellites are equipped with SLR laser retroreflectors, enabling independent orbit determination evaluation through SLR measurements. Nine high-quality SLR stations (Yarragadee, Greenbelt, Haleakala, Zimmerwald, Mount Stromlo, Wettzell, Graz, Herstmonceux, Potsdam) are selected for analysis. Distances between stations and satellites are calculated using GRACE-FO orbits and SLR station coordinates, then differenced with SLR observations. These residuals reflect orbit determination accuracy. Figure 7 [Figure 7: see original paper] shows SLR ranging residuals (values >20 cm are removed as outliers). Figures (a) and (b) present GRACE-C and GRACE-D results, respectively, with red, green, and blue points indicating CODE, CNES, and WHU product-based results. Orbit determination results using CODE and WHU products show good agreement with SLR, with validation accuracy better than 9.6 mm and 9.1 mm, respectively. CNES product-based validation accuracy is better than 10.7 mm, with overall SLR validation differences less than 2 mm.

4.4 Inter-Satellite Baseline Results

GRACE-FO satellites are equipped with K-band laser ranging instruments with micrometer-level ranging accuracy. Inter-satellite distances calculated from single-satellite precise orbit determination results are compared with KBR observations to accurately reflect along-track orbit accuracy. Figure 8 [Figure 8: see original paper] shows the standard deviation (STD) of differences between inter-satellite distances calculated from precise orbits and KBR ranging values for day 180 of 2019. Red points represent float-solution results with PCV correction, green points show fixed-solution results without PCV correction, and blue points indicate fixed-solution results with PCV correction. Ambiguity fixing reduces ranging residuals from 5.4 mm to 1.7 mm, while antenna PCV correction reduces residuals from 3.0 mm to 1.7 mm. Float-solution results show larger errors around 12 hours due to fewer visible GPS satellites; correctly fixing ambiguities effectively improves orbit determination accuracy during such periods. Figure 9 [Figure 9: see original paper] presents annual KBR ranging residual STD values for 2019. STD values of GRACE-FO precise orbit inter-satellite KBR residuals using CODE, CNES, and WHU products are better than 1.8 mm, 2.3 mm, and 2.1 mm, respectively, similar to results assessed in reference [26].

5 Conclusion

This paper employs wide-lane and narrow-lane phase bias products to correct carrier phase observations, achieving ambiguity parameter fixing in single-satellite precise orbit determination. Simultaneously, antenna PCV corrections are estimated based on ionosphere-free combination carrier phase residuals, enabling in-orbit calibration of spaceborne receiver antennas. Using 2019 GRACE-FO spaceborne observation data, GPS precise orbit, clock, and phase bias products from CODE, CNES, and WHU are used for GRACE-FO ambiguity resolution and precise orbit determination. Results demonstrate that in-orbit antenna PCV calibration effectively reduces carrier phase residuals and further improves orbit determination accuracy, with the most significant improvement in the along-track direction. GRACE-FO wide-lane ambiguity fixing rates exceed 99% and narrow-lane fixing rates surpass 95% across different products, with CODE products achieving the highest fixing rates (wide-lane >99.4%, narrow-lane >96.8%). Using JPL precise orbits as reference, three-axis average accuracy of GRACE-FO precise orbits using different products is better than 7.0 mm. SLR ranging validation shows RMS residuals less than 10.0 mm for CODE and WHU products and better than 11.0 mm for CNES products. Inter-satellite KBR ranging evaluation demonstrates relative orbit accuracies better than 1.8 mm, 2.3 mm, and 2.1 mm for CODE, CNES, and WHU products, respectively. Overall differences between GRACE-FO precise orbits using different agency products are less than 2 mm. Additionally, during some observation periods, reduced-dynamic GPS-based orbit determination accuracy degrades due to insufficient visible satellites. With the continued application of

multi-GNSS spaceborne receivers and multi-system phase bias products, single-satellite ambiguity-fixed orbit determination accuracy will further improve.

References

- [1] Bertiger W, Bar-Server Y E, Christensen E J, et al. *Journal of Geophysical Research*, 1994, 99(12): 24449 [2] Tapley B D, Ries J C, Davis G W, et al. *Journal of Geophysical Research*, 1994, 99(12): 24383 [3] Wu S C, Yunck T P, Thornton C L. *Journal of Guidance Control and Dynamics*, 1991, 14(1): 24 [4] Kang Z, Tapley B D, Bettadpur S, et al. *Journal of Geodesy*, 2006, 80: 322 [5] Van den IJssel J, Visser P, Rodriguez E P. *Advances in Space Research*, 2003, 31(8): 1889 [6] Zhao Qile, Liu Jingnan, Ge Maorong, et al. *Geomatics and Information Science of Wuhan University*, 2006, 31(10): 879 [7] Guo Jing, Zhao Qile, Li Min, et al. *Geomatics and Information Science of Wuhan University*, 2013, 38(1): 52 [8] Li M, Li W, Shi C, et al. *Journal of Geodesy*, 2017, 91: 1313 [9] Li X, Zhang K, Meng X, et al. *Engineering*, 2020, 6(8): 904 [10] Jäggi A, Hugentobler U, Bock H, et al. *Advances in Space Research*, 2007, 39(10): 1612 [11] Hackel S, Montenbruck O, Steigenberger P, et al. *Journal of Geodesy*, 2017, 91: 547 [12] Shao Kai, Yi Bin, Zhang Houzhe, et al. *Acta Geodaetica et Cartographica Sinica*, 2021, 50(4): 487 [13] Luthcke S B, Zelensky N P, Rowlands D D, et al. *Marine Geodesy*, 2003, 26: 399 [14] Qin Jian, Guo Jinyun, Kong Qiaoli, et al. *Geomatics and Information Science of Wuhan University*, 2014, 39(2): 137 [15] Bock H, Jäggi A, Meyer U, et al. *Journal of Geodesy*, 2011, 85: 807 [16] Bock H, Jäggi A, Beutler G, et al. *Journal of Geodesy*, 2014, 88: 1047 [17] Kroes R, Montenbruck O, Bertiger W, et al. *GPS Solutions*, 2005, 9: 21 [18] Zhao Q, Hu Z. *Geo-spatial Information Science*, 2010, 13(3): 221 [19] Ge M, Gendt G, Rothacher M, et al. *Journal of Geodesy*, 2008, 82(7): 389 [20] Laurichesse D, Mercier F, Berthias J P, et al. *Navigation*, 2009, 56(2): 135 [21] Collins P, Bianath S, Lahaye F, et al. *Navigation*, 2010, 57(2): 123 [22] Bertiger W, Desai S D, Haines B, et al. *Journal of Geodesy*, 2010, 84: 327 [23] Montenbruck O, Hackel S, Jäggi A. *Journal of Geodesy*, 2018, 92: 711 [24] Loyer S, Perosanz F, Mercier F, et al. *Journal of Geodesy*, 2012, 86: 991 [25] Zhang Xiaohong, Li Pan, Zuo Xiang. *Geomatics and Information Science of Wuhan University*, 2013, 38(9): 1009 [26] Arnold D, Schaer S, Villiger A, et al. *Undifference Ambiguity Resolution for GPS Based Precise Orbit Determination of Low Earth Orbiters Using the New CODE Clock and Phase Bias Products*. http://www.bernese.unibe.ch/publist/2018/post/IGSWS2018_{LEOAR}.pdf, 2018 [27] Guo X, Geng J, Chen X, et al. *GPS Solutions*, 2020, 24: 14 [28] Haines B, Bar-Sever Y, Bertiger W, et al. *Marine Geodesy*, 2004, 27(1-2): 299 [29] Jäggi A, Dach R, Montenbruck O, et al. *Journal of Geodesy*, 2009, 83(12): 1145 [30] Ma Yang, Ou Jikun, Yuan Yunbin. *Journal of Geodesy and Geodynamics*, 2015, 35(2): 186 [31] Wen H, Kruizinga G, Paik M, et al. *Grace-Fo Level-1 Data Product User Handbook*, JPL D-56935. Pasadena: JPL, 2019: 20 [32] Kang Z, Bettadpur S, Nagel P, et al. *Journal of Geodesy*, 2020, 94: 85 [33] Blewitt G. *Journal of Geophysical Research*, 1989, 94(B8): 10187 [34] Wu J T, Wu S C, Hajj G, et al. *Manuscripta Geodaetica*, 1993, 18(2):

91 [35] Melbourne W G. Bulletin Géodésique, 1985, 58(4): 373 [36] Wübbena G. Bulletin Géodésique, 1985, 58(4): 403 [37] Hu Zhigang, Zhao Qile, Guo Jing, et al. Acta Geodaetica et Cartographica Sinica, 2011, 40: 34 [38] Berger C, Biancale R, Ill M, et al. Journal of Geodesy, 1998, 72(3): 161 [39] Gu D, Lai Y, Liu J, et al. Chinese Journal of Aeronautics, 2016, 29(5): 1335 [40] Xia Y, Liu X, Guo J, et al. Acta Geod Geophys, 2021, 56(1): 93 [41] Schaer S, Villiger A, Arnold D, et al. Journal of Geodesy, 2021, 95: 81 [42] Villiger A, Schaer S, Dach R, et al. Journal of Geodesy, 2019, 93: 1487 [43] Geng J, Chen X, Pan Y, et al. Journal of Geodesy, 2019, 93: 2053 [44] Dong D, Bock Y. Journal of Geophysical Research, 1989, 94 (B4): 3949

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv — Machine translation. Verify with original.