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GPS-Based Precise Orbit Determination of LEO Satellites Using Space-Based Double-Differenced Observations

Zhigui Kang[1] · Srinivas Bettadpur[1] · Himanshu Save[1] · Peter Nagel[1]

Abstract

One of the important GPS applications in space is precise orbit determination (POD) of Low-Earth Orbit (LEO) satellites. Thousands of LEO satellites are currently in orbit. One of the challenges is how to efficiently and precisely determine the orbits to satisfy the relative and absolute accuracy needs of missions. Currently, GPS-based POD of LEO satellites can be performed using either un-differenced (UD) or ground-based double-differenced (DD) observations. The UD POD needs both precise GPS satellite orbits and clocks; the DD POD needs not only the precise orbits, but also global ground reference receivers. Therefore, the GPS-based LEO POD is based on either global ground stations or precise GNSS clocks, which are not convenient for near real-time or real-time data processing. The GPS orbits can be precisely predicted in certain time; the clocks are not. For some formation flying satellite missions (two or more LEO satellites), the absolute orbit accuracy requirements are not as stringent as the relative requirements. The problem is how to perform LEO POD without global station data and precise GPS clocks in near real-time or real-time to achieve the mission orbit accuracy requirement. Based on this motivation, we investigated the GPS-based LEO POD using space-based DD observations without using global ground station GPS data and precise GPS clock products. For this study, we processed the real GPS observations from two LEO satellites. The absolute and relative orbit accuracy is assessed using several tests, including analysis of the orbit fits, external orbit comparisons, Satellite Laser Ranging (SLR) and K-band Ranging (KBR) residuals.

Keywords GPS · POD · GRACE-FO · LEO POD

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1 Introduction

With the successful use of GPS-based Precise Orbit Determination (POD) for Low-Earth Orbit (LEO) satellites, more and more satellites are expected to carry Global Navigation Satellite System (GNSS) receivers to support their orbit accuracy requirements. For efficient and precise orbit determination of LEO satellites using GPS data, many authors have investigated the related problems [1–6]. When the GPS-based POD is used for the satellite formation flying missions (two or more LEO satellites), it could satisfy different relative and absolute orbit accuracy requirements.

Generally, GPS-based POD of LEO satellites can be performed using either un-differenced (UD) or ground-based double-differenced (DD) observations, which are performed by two GPS satellites, one LEO satellites and one ground station. The main differences between DD and UD POD are clocks and reference receivers. The UD POD needs both precise GPS satellite orbits and clocks; the DD POD needs not only the precise orbits, but also global ground reference receivers. Therefore, the GPS-based LEO POD is based on either global ground stations or precise GNSS clocks, which are not convenient for near real-time or real-time data processing. As you know, the GPS orbits can be precisely predicted in certain time; the clocks cannot. In addition, for some formation flying satellite missions, the absolute orbit accuracy requirements are not as stringent as the relative requirements. The problem is how to perform LEO POD without global station data and precise GPS clocks in near real-time or real-time to achieve the mission orbit accuracy requirement. Based on this motivation, we investigated the GPS-based POD of LEO satellites without any ground reference station data and precise GPS clocks using space-based DD observations, which are performed by two GPS satellites and two LEO satellites.

In this paper, we describe our recent advances in GPS-based precise absolute and relative orbit determination for formation flying LEO satellites. The study was performed using the Center of Space Research Multi-Satellite Orbit Determination Program (MSODP), which is based on a dynamic orbit determination method utilizing the batch processing approach. The data used for this study are Gravity Recovery and Climate Experiment Follow-On (GRACE-FO) satellites level 1B products produced by the NASA JPL [7]. The two GRACE-FO satellites, which were launched into LEO in May of 2018, are equipped with geodetic quality GPS receivers for precise orbit determination and gravity recovery. The absolute and relative orbit accuracy is evaluated by analyzing GPS tracking observation residuals, by confirming the orbit solution with independent Satellite Laser Raining (SLR) tracking, by computing K-Band Ranging (KBR) residuals and comparing external orbits.

2 Methods and Observations

The use of GPS observations for LEO orbit determination is presently considered to be the most powerful method available. The main advantage of this system is that it allows continuous and multi-dimensional tracking of LEOs. There are mainly three orbit determination methods (kinematic, dynamic, and reduced-dynamic orbit determination) for GPS-based LEO POD [3, 5, 8]. Kinematic orbit determination requires only the geometric information contained in the GPS observations. Dynamic method relies on physically accurate force models. Reduced dynamic orbit determination technique balances the contributions from the force model and the geometric information.

For our GRACE-FO POD, we selected the dynamic orbit determination method, but with an aggressive force model parameterization (such as estimation of many empirical parameters in precise orbit determination) to reduce the effects of the force model errors. Using this method, one of the advantages is that the orbits can be relatively precisely predicted. In addition, force model parameters (such as the atmosphere drag coefficient, one-cycle-per-revolution empirical acceleration parameters, and gravity coefficients) could be adjusted to obtain precise orbits. The orbit accuracy depends on the quality of the force models used in the dynamic solution and the POD strategies (such as selection of arc length and parameterization choice) as well as the accuracy of the GPS tracking data. The distinction between 'dynamic' and 'reduced-dynamic' is not clear-cut. As additional force model parameters are estimated in the dynamical orbit solution, it can start to approximate a 'reduced-dynamic' approach.

For dynamic orbit determination, important adjustable parameters are drag coefficients and empirical accelerations to reduce the effects of force model errors. The sub-arc length (the interval of time within the arc that a particular parameter spans) and a priori values must be chosen for those parameters. Usually, the sub-arc length is one orbit revolution; a priori values are 10.0 for drag coefficients, 10^8 to $10^9 m/s^2$ for empirical accelerations, which are dependent on the quality of dynamical models. If the models are good, a smaller a priori value is selected.

Currently, GPS UD or DD observations can be used for GPS-based POD of LEO satellites. The main difference is how to treat clock parameters. Processing UD observations needs to solve for GPS receiver clock parameters; there are no clock parameters in processing DD observations. There are two types of DD observations: ground-based DD observations, which are performed by two GPS satellites, one ground station and one LEO satellite; space-based DD observations, which are performed by two GNSS satellites and two LEO satellites. When the ground-based DD observations are used, the ground station coordinates are fixed, and the absolute orbit accuracy is very good. For this study, we use the space-based DD observations. Since there are no reference stations, the absolute orbit accuracy using space-based DD observations is not good as that using ground-based DD observation. Table 1 summarizes the POD standards adopted for the GRACE-FO data processing.

Table 1 Precise orbit determination standards for GRACE-FO

Force model	Description
Mean earth gravity	GGM05C (360 × 360)
Non-tide ocean and atmosphere	ECMWF atmosphere and barotropic ocean model
N-body	JPL DE 430 (Standish 1998)
Solid earth tides	IERS 2010 Conventions
Ocean tides	GOT4.8
Pole tide	IERS 2010 Conventions
Relativity	IERS 2010 Conventions
Earth radiation pressure	Box-wing model, Albedo and infrared
Atmospheric drag	Box-wing model, density
	Temperature Model (DTM)
Solar radiation	Box-wing model

Reference frame	
Conventional inertial reference frame	J2000.0
Precession and nutation	IAU2000A model
Earth orientation	IERS C-04
Station coordinates	ITRF2014

Input data and corrections	
GPS tracking data from GRACE-FO	Double-differenced, ionosphere-free combination of L1 and L2 carrier phase, 10-second sampling
GPS satellite PCV correction	IGS14.ATX
GRACE-FO GPS PCV correction	Applied (corrections provided by JPL)
GPS orbits and clocks	JPL IGS final GPS ephemerides and clocks

Estimated parameters	
GRACE-FO initial state	3D epoch position and velocity
GPS carrier phase ambiguity	One per combination per pass (float parameters for GPS DD)
Empirical 1-cpr along-track and cross-track accelerations	1-cpr accelerations per revolution ($10^{-8} m/s^2$ a priori)
Drag coefficient (Cd)	One per orbital revolution (10 a priori)
GRACE-FO GPS antenna correction	One per arc in nadir (Z) direction

3 Data Processing Strategies

The current approaches for precise orbit determination of formation flying satellites using GPS DD observations are: one-step and two-step methods. In the one-step method, the reference and second satellite orbits are determined using both ground-based and space-based GPS observations. In the two-step method, the reference satellite orbits are first determined using only ground-based GPS

observations; then the second satellite orbits are determined using only space-based GPS observations by fixing the reference satellite orbits which are estimated in the first step. Both methods need either reference stations or reference orbits. Both absolute and relative orbit accuracy can be achieved in this manner.

When the absolute orbit accuracy requirement for formation flying satellite missions is not as stringent as the relative requirements, GPS-based LEO POD can be performed using space-based DD observations in one step. Therefore, we investigated how well the relative orbits of the LEO satellites can be determined using only space-based GPS DD observations without any reference stations and orbits. At the same time, the absolute orbit accuracy obtained using this method is also provided for reference consideration.

To achieve the goals, the challenge was not only to generate the LEO satellite orbits, but also to assess both absolute and relative orbit accuracy. For our investigation, the data from twin GRACE-FO satellites are processed. The GRACE-FO mission consists of two identical formation flying spacecraft in a near-polar near-circular orbit with an initial altitude of approximately 500 km. The twin satellites have a nominal separation of 220 km. And they are equipped with several scientific instruments: such as BlackJack GPS onboard receiver, KBR system and SLR laser retroreflector [9]. Each instrument provides very important data for determining GRACE-FO orbits and/or evaluating the orbit quality. The space-based DD observations can be formed using data from GPS onboard receivers. The SLR data provides an independent evaluation of the GRACE-FO absolute orbit accuracy. The KBR system measures the range between the twin GRACE-FO satellites with a very high precision of about 10 µm, which can be used for evaluating the relative orbit accuracy of the GRACE-FO satellites.

4 Ambiguity Resolution

For this study, we use GPS carrier-phase data for POD and GPS pseudo-range data for ambiguity resolution. Resolving the integer carrier-phase ambiguities is one of the critical issues for precise GPS applications. Since the first demonstration of the use of the GPS carrier-phase observations for the precise GPS positioning, several ambiguity resolution methods have been developed and implemented [10]. As UD ambiguity is the mixture of the integer ambiguity and the uncalibrated phase delay for the receiver and GPS satellite, only the DD ambiguity between two GPS satellites and two receivers has a natural integer feature and can be fixed to an integer value. Therefore, the DD ambiguities can be fixed without external phase bias products, which UD ambiguity resolution needs.

The efficiencies of DD ambiguity resolution depend on many aspects, such as the distance of the two receivers, variances of the estimated real-valued ambiguities and the accuracy of GPS pseudo-range data. The space-based GPS DD ambiguity resolution is relatively easier than the ground-based GPS DD, when the two LEO satellites fly not so far, such as two GRACE-FO satellites (about 200 km). This is due to the longer passes of the two LEO satellites, the short distances between two receivers and no tropospheric errors.

The ambiguity resolution is a method to constrain the real-valued estimates to their nearest integer values. In many situations, the differences between the estimated real-valued ambiguity and resolved integer ambiguity can be as close as a few millimeters (observation fit level). Based on this fact, we have developed and implemented a modified approach quickly to fix the DD ambiguities. The main difference between our method and other methods is different decision criterion for ambiguity fixing: our criterion is the difference between the estimated and adjusted DD ionosphere free phase biases based on the resolved wide-lane and narrow-lane integers; the criterion of most current methods is the confidence test based the variances of the estimated real-valued DD bias.

The basic GPS pseudo-range and carrier-phase observations between a satellite (superscript i) and a space borne receiver (subscript k) are usually described by the following observation equations:

$$P^i_{k,m} = \rho^i_k + \mu_m I^i_k + c(dt_k - dt^i) + b_{k,m} - b^i_m \tag{1}$$

$$L^i_{k,m} = \rho^i_k - \mu_m I^i_k + c(dt_k - dt^i) + B_{k,m} - B^i_m + \lambda_m n^i_{k,m} \tag{2}$$

where $P^i_{k,m}$ is the pseudo-range measurement made at frequency m from receiver k to satellite i; ρ^i_k is the geometric distance; $\mu_m = (f^2_1)/(f^2_m)$; f_1 and f_m are the GPS frequency 1 and m; I^i_k is the first-order ionospheric delay on frequency f_1; c is the vacuum speed of light; dt_k is the clock error for receiver k; dt^i is the clock error for satellite i; $b_{k,m}$ is the receiver pseudo-range bias; b^i_m is the satellite pseudo-rang bias; $L^i_{k,m}$ is the carrier-phase observation; $B_{k,m}$ is the receiver carrier-phase bias; B^i_m is the satellite carrier-phase bias; λ_m is the wavelength; $n^i_{k,m}$ is the integer ambiguity.

Linear GPS observation combinations are formed by linearly adding or subtracting GPS measurements on two or more frequencies. The most used combination is so-called ionosphere-free (IF) combination of observations at frequency f_1 and f_2 to remove the first order ionosphere effects, which are formulated as following:

$$P^i_{k,IF} = \frac{1}{f^2_1 - f^2_2}\left(f^2_1 P^i_{k,1} - f^2_2 P^i_{k,2}\right) = \rho^i_k + c(dt_k - dt^i) + b_{k,IF} - b^i_{IF} \tag{3}$$

$$L^i_{k,IF} = \frac{1}{f^2_1 - f^2_2}\left(f^2_1 L^i_{k,1} - f^2_2 L^i_{k,2}\right) = \rho^i_k + c(dt_k - dt^i) + B_{k,IF} - B^i_{IF} + \lambda_1 n^i_{k,IF} \tag{4}$$

where $b_{k,IF} = \left(f^2_1 b_{k,1} - f^2_2 b_{k,2}\right)/\left(f^2_1 - f^2_2\right)$

$b^i_{IF} = \left(f^2_1 b^i_1 - f^2_2 b^i_2\right)/\left(f^2_1 - f^2_2\right)$

$B_{k,IF} = \left(f^2_1 B_{k,1} - f^2_2 B_{k,2}\right)/\left(f^2_1 - f^2_2\right)$

$B^i_{IF} = \left(f^2_1 B^i_1 - f^2_2 B^i_2\right)/\left(f^2_1 - f^2_2\right)$

$n^i_{k,IF} = f_1\left(f_1 n^i_{k,1} - f_2 n^i_{k,2}\right)/\left(f^2_1 - f^2_2\right)$

Using the differencing techniques allows us to eliminate or reduce effects of some errors (such as clock errors and carrier-phase biases). For this study, double-differenced observations (between a pair of receivers and a pair of GPS satellites) are used. The DD IF equations for pseudo-range and carrier-phase are given as following:

$$P_{kl,IF}^{ij} = \rho_{kl}^{ij} \tag{5}$$

$$L_{kl,IF}^{ij} = \rho_{kl}^{ij} + B_{kl,IF}^{ij} \tag{6}$$

where $B_{kl,IF}^{ij} = \lambda_1 n_{kl,IF}^{ij} = \lambda_1 \left(n_{k,IF}^i - n_{k,IF}^j + n_{l,IF}^i - n_{l,IF}^j \right)$ is the DD phase bias.

The DD IF ambiguities $n_{kl,IF}^{ij}$ are usually decomposed into combinations of integer wide-lane (WL) and narrow-lane (NL) ambiguities to perform integer ambiguity resolution:

$$n_{kl,IF}^{ij} = \frac{f_1 f_2}{f_1^2 - f_2^2} n_{kl,WL}^{ij} + \frac{f_1}{f_1 + f_2} n_{kl,NL}^{ij} \tag{7}$$

where $n_{kl,WL}^{ij} = n_{kl,1}^{ij} - n_{kl,2}^{ij}$ is the integer WL ambiguity; $n_{kl,NL}^{ij}$ is the integer NL ambiguity.

Our ambiguity resolution procedure is as following. First, the real-valued DD ionosphere free phase biases $B_{kl,IF}^{ij}$ are estimated during POD. Then, the resolution of the wide-lane ambiguity is made with carrier-phase and pseudo-range observations directly using the Melboure–Wuebbena (MW) [11, 12] method. The DD MW combination is defined as:

$$\begin{aligned}
PL_{kl}^{ij} &= \left(\frac{f_1}{f_1 - f_2} L_{kl,1}^{ij} - \frac{f_2}{f_1 - f_2} L_{kl,2}^{ij} \right) \\
&\quad - \left(\frac{f_1}{f_1 + f_2} P_{kl,1}^{ij} + \frac{f_2}{f_1 + f_2} P_{kl,2}^{ij} \right) \\
&= \frac{c}{f_1 - f2} n_{kl,WL}^{ij} = \lambda_{WL} n_{kl,WL}^{ij}
\end{aligned} \tag{8}$$

where $\lambda_{WL} = \frac{c}{f_1 - f_2}$ is the WL wavelength.

The DD integer WL ambguity is resolved as following:

$$n_{kl,WL}^{ij} = \frac{PL_{kl}^{ij}}{\lambda_{WL}} \tag{9}$$

After fixing wide-lane ambiguities, the resolution for the narrow-lane ambiguity is made with following equation derived from Eqs. 6 and 7:

$$n_{kl,NL}^{ij} = \frac{f_1 + f_2}{c} \left(B_{kl,IF}^{ij} - c \frac{f_2}{f_1^2 - f_2^2} n_{kl,WL}^{ij} \right) \tag{10}$$

where $n_{kl,NL}^{ij}$ is the unknown NL integer number of DD carrier-phase.

Finally, the DD ionosphere free phase bias $\bar{B}_{kl,IF}^{ij}$ is adjusted based on the resolved wide-lane and narrow-lane integer phase biases using following equation:

$$\bar{B}_{kl,IF}^{ij} = c \frac{f_2}{f_1^2 - f_2^2} n_{kl,WL}^{ij} + \frac{c}{f_1 + f_2} n_{kl,NL}^{ij} \tag{11}$$

To decide whether the DD ambiguity can be fixed, the difference between the estimated $B_{kl,IF}^{ij}$ and adjusted $\bar{B}_{kl,IF}^{ij}$ DD ionosphere free phase bias is calculated. If the difference is less than 8 mm (about GPS DD RMS level), the ambiguity is fixed.

5 Results and Discussions

The precise orbit determination for the GRACE-FO satellites was carried out using the GRACE-FO data from January 1 to 31, 2019. The two different test cases were:

Case 1 (Float): space-based GPS DD observations for 24-h arc length without ambiguity resolution

Case 2 (Fixed): space-based GPS DD observations for 24-h arc length with ambiguity resolution

The relative and absolute orbit accuracy is assessed through orbit fits, SLR residuals, KBR residuals and external orbit comparison.

5.1 Orbit Fits

Orbit fits can be used to assess the orbit precision. The orbit fits to the GPS DD tracking data are the observation residuals, which are computed using the
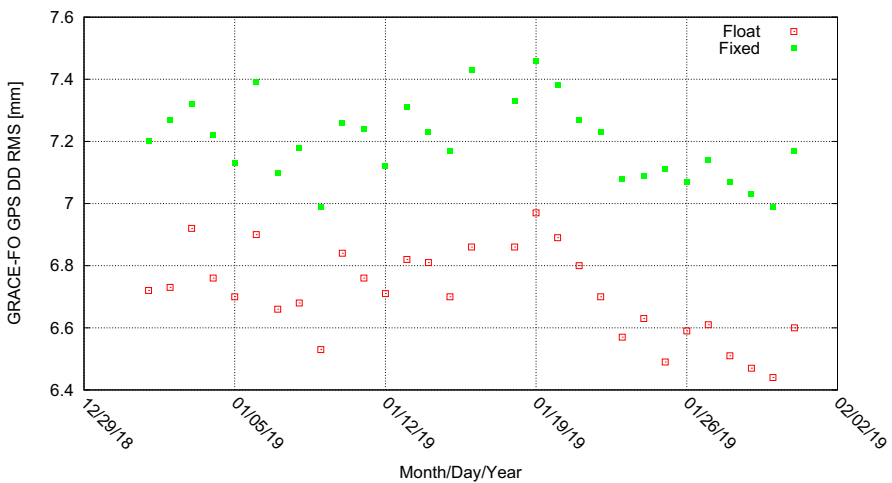
Fig. 1 GRACE-FO GPS DD RMS for different test cases

differences between the computed GPS DD and observed GPS DD. Figure 1 shows the GRACE-FO GPS DD RMS for the two different test cases (float and fixed ambiguity). The average RMS (about 6.7 mm) without ambiguity resolution is smaller than the value (about 7.7 mm) with ambiguity resolution. This is mainly because that fewer parameters are estimated by ambiguity resolution. Usually, the orbit fits are better when more parameters are estimated. When float ambiguity parameters are estimated, they include not only themselves but also correlated parts (such as constant parts of GPS orbit errors). Therefore, the estimated float ambiguity parameters can reduce the effects of GPS orbit errors to make the orbit fit RMS smaller. However, fixed ambiguities provide correct values and make the LEO orbits more accurate. Orbit fits can be used to evaluate the orbit precision, not orbit accuracy. Smaller orbit fits cannot directly indicate more accurate orbit. Orbit accuracy is evaluated in the following subsections.

5.2 SLR Residuals

As an independent evaluation of the absolute orbit quality, SLR data were processed to compute laser range residuals relative to the fixed GRACE-FO orbits. Figure 2 shows the GRACE-C (one of GRACE-FO satellites) SLR residuals for the two test cases. The residuals show no significant differences for float and fixed ambiguity. And the averaged value is about 8 cm.

5.3 KBR Range Residuals

One of the key science instruments onboard the GRACE-FO satellites is the KBR system, which measures the dual one-way range change between the twin
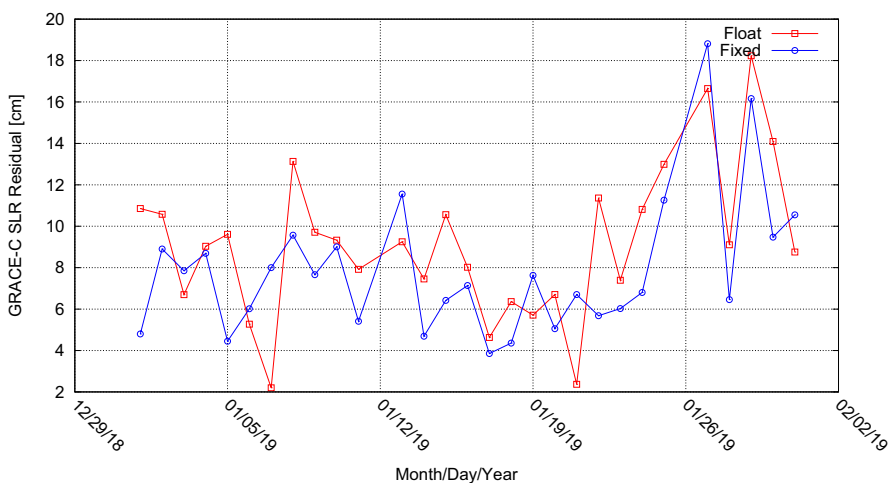
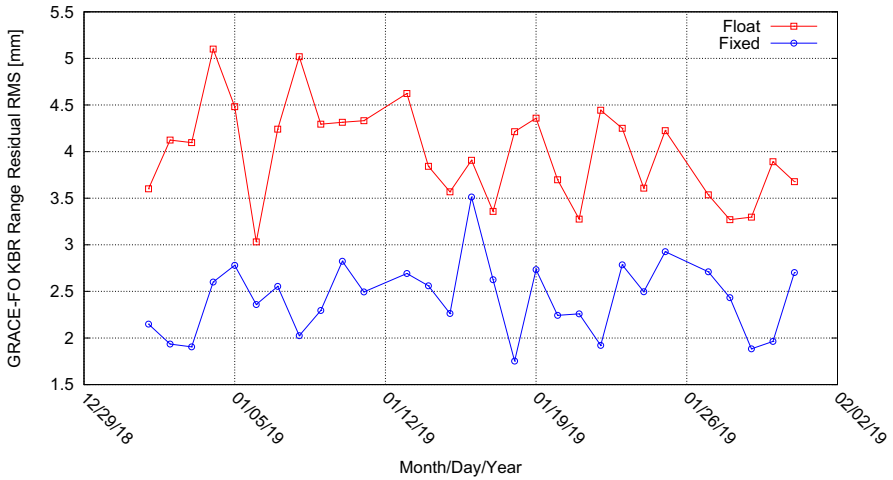

Fig. 2 GRACE-C SLR residuals for different test cases

Fig. 3 GRACE-FO KBR range residuals for different test cases

Table 2 GRACE-C orbit comparison [cm]

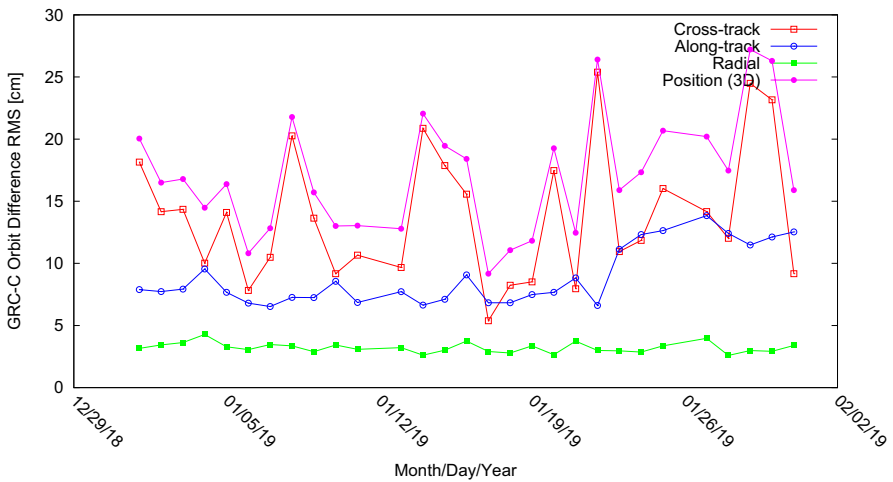| Test case	Cross-track	Along-track	Radial	Position (3D)
Float ambiguity	13.8	8.9	3.2	17.1
Fixed ambiguity	7.8	9.9	3.4	13.2

Fig. 4 GRACE-C orbit differences between CSR and JPL (float ambiguity)
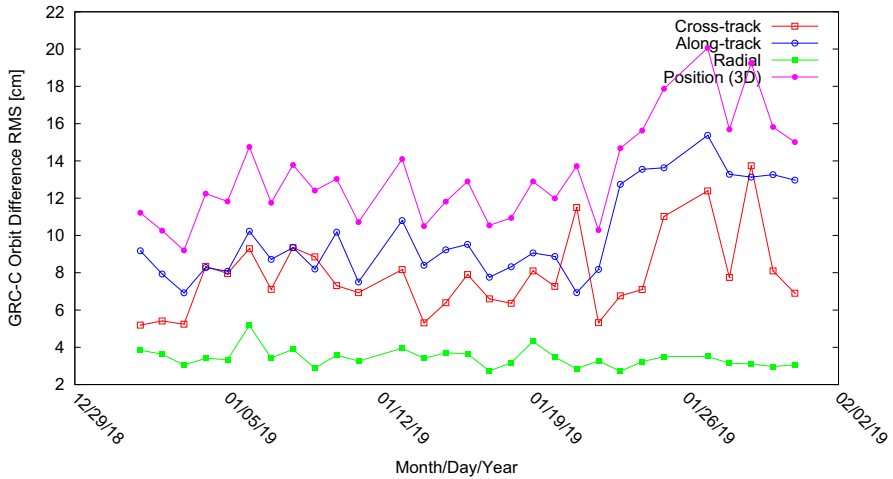
Fig. 5 GRACE-C orbit differences between CSR and JPL(fixed ambiguity)

GRACE-FO satellites with micron level accuracy. The KBR data are used mainly for gravity field recovery. However, the KBR data residuals computed by fixing the GRACE-FO orbits can be used for evaluating the relative orbit accuracy of the GRACE-FO satellites. Figure 3 displays the RMS of the KBR range residuals. The results show that improved relative orbit accuracy from about 4 to 2.5 mm for the GRACE-FO satellites is achieved through the ambiguity resolution.

5.4 External Orbit Comparison

The GRACE-FO orbits determined using GPS DD observations were directly compared with GRACE-FO orbits of JPL. The absolute accuracy of JPL GRACE-FO orbits is about 2–3 cm in position (3D) [3]. The comparison results can be used to evaluate the absolute orbit accuracy. Figures 4 and 5 show the orbit difference RMS for GRACE-C for different test cases (float and fixed ambiguity, respectively). Table 2 summarizes the orbit difference statistics for GRACE-C. The results show that improved absolute orbit accuracy from about 17 to 13 cm for the GRACE-FO satellites is achieved through the ambiguity resolution.

6 Conclusion

The GRACE-FO twin satellite orbits were precisely and relatively determined using only space-based GPS DD observations without any reference station data or reference orbits as well as GPS clocks. Based on the various tests and assessments (Orbit fits, SLR residuals, KBR residuals and external orbit comparison), the absolute and relative accuracy is provided. Both SLR residuals and external orbit comparison can be used to indicate the absolute orbit accuracy. The results show a

very good agreement: 8 cm for SLR residual RMS and 13 cm for 3D orbit difference RMS. According to the GRACE-FO KBR range residuals, the relative accuracy between two GRACE-FO satellites is about 2.5 mm in position. In short, the LEO orbits can be determined with reasonably good absolute accuracy and very good relative accuracy based on our approach (GPS-Based Precise Orbit Determination of LEO Satellites Using Space-based Double-Differenced Observations).

Data availability The GNSS datasets used for this study are available at https://cddis.nasa.gov/archive. The GRACE-FO data can be found at https://podaac.jpl.nasa.gov/dataset/GRACEFO_L1B_ASCII_GRAV_JPL_RL04.

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