LEO Satellites Precise Orbit Determination Using Spaceborne Dual-frequency GPS

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Abstract

We study on reduced dynamic orbit determination using differenced phase in adjacent epochs for spaceborne dual-frequency GPS. This method not only overcomes the shortcomings that the epoch-difference kinematic method cannot be used when observation geometry is poor or observations are insufficient, but also avoids solving the ambiguity in the zero-difference reduced dynamic method. As the epoch-difference method is not sensitive to the impact of phase cycle slips, it can lower the difficulty of slip detection in phase observation preprocessing. In the solution strategies, we solve the high-dimensional matrix computation problems by decomposing the long observation arc into a number of short arcs. By GRACE satellite orbit determination and compared with GFZ post science orbit, for epoch-difference reduced dynamic method, the RMS of radial, transverse and normal components are 1.92cm, 3.83cm and 3.80cm, and the RMS in three dimensions is 5.76cm. The solution's accuracy is comparable to the zero-difference reduced dynamic method.

Limiting factors for the Precise Orbit Determination (POD) of Low-Earth Orbit (LEO) satellite using dual-frequency GPS are nowadays mainly encountered with the in-flight phase error modeling. The phase error is modeled as a compound error of systematic part and random part which both depend on the direction of GPS signal reception. The systematic part and standard deviation of random part in phase error model are respectively estimated by bin-wise mean and standard deviation values of phase post-fit residuals computed by direct orbit determination. By removing the systematic part and adjusting the weight of phase observation data according to standard deviation of random part, the orbit can be improved by POD approach again. For the 31-day GRACE data processed by precise orbit improvement, the Root Mean Square (RMS) values of phase post-fit residuals are reduced by about 3 mm, the 3-Dimensional (3D) magnitudes of orbit improvement for GRACE A and GRACE B are 0.0153 m and 0.0131 m respectively, the 3D RMS values of orbit comparison results with JPL precise science orbits are reduced from 0.0553 m to 0.0527 m for GRACE A and from 0.0515 m to 0.0502 m for GRACE B, and the relative positions obtained by zero-difference GRACE orbits are significantly improved by 0.38 cm K-band standard deviation.

The key technologies of 1mm level baseline determination for GRACE formation are presented, including spaceborne dual-frequency GPS data preprocessing, zero-difference (ZD) reduced dynamic orbit determination for single satellite, double-difference (DD) reduced dynamic relative orbit determination for two formation flying satellites, DD integer ambiguity resolution and so on. A precision orbit determination software is developed, with which GRACE two satellites orbits are estimated, and the results show that: compared to the K-Band Ranging (KBR) observations, the baseline determination precision for GRACE two satellites formation is 1.01mm, and the average success rate of integer DD integer ambiguities resolution is about 90%.

Keywords: dual-frequency GPS, phase epoch-difference, phase center variation estimation, relative positioning

1. Reduced Dynamic Orbit Determination Using Differenced Phase in Adjacent Epochs for Spaceborne Dual-frequency GPS

In reduced dynamic orbit determination with zero-difference phase observations, if a phase cycle slip occurs and the exact epoch has not been detected, the phase observation processing in the whole tracking arcs will be affected. But this impact can be easily avoided by epoch-difference method. Fig. 1 gives a numerical example to show the impact of a cycle slip in dynamic orbit determination of LEO satellite. At the epoch t = 2.5h, a size of 1 cycle slip is added to the phase observations. Compared to the situation without cycle slips, the orbit determination precision of phase zero-difference method in the entire arc is obviously deteriorated, and the maximum impact reaches 8cm near the epoch where the cycle slip occurs. But such big impact cannot be found in phase epoch-difference method, and the orbit determination precision of phase epoch-difference method is just the same as that with phase zero-difference method without cycle slip (see Fig. 1).

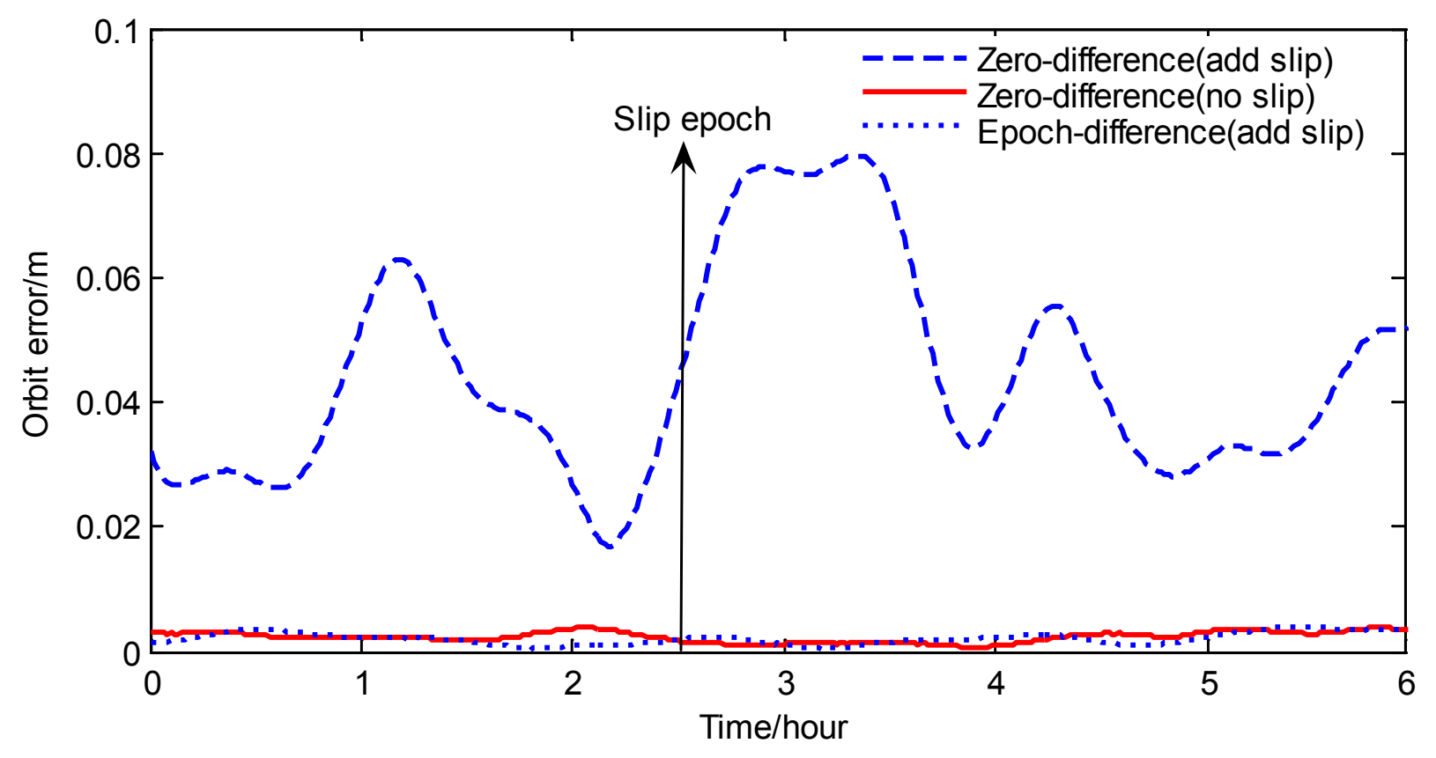


Figure 1 Cycle slip effect on reduced dynamic orbit determination.

Over a period of 31 days from January 1 to 31, 2006, GRACE A dual-frequency GPS observations are processed, and root of mean square (RMS) value of the O-C residuals obtained from reduced dynamic orbit determination using differenced phase is only 6.7mm (see Fig. 2), which reflects the consistency of the applied models with the GPS observation data. The differences between the orbit obtained from reduced dynamic orbit determination using differenced phase and the GFZ post science orbit are computed in the radial, along-track and cross-track directions at the discrete epoch (see Fig. 3). Over the 31-day period, compared with GFZ post science orbit, for phase epoch-difference reduced dynamic orbit determination method, the RMSs of R, T and N position components are 1.92cm, 3.83cm and 3.80cm, and the RMS in three dimensions is 5.76cm (see Fig. 4). The solution's accuracy is comparable to the zero-difference reduced dynamic method, for which, the RMSs in R, T and N position components is 1.96cm, 3.41cm and 3.85cm, and the RMS in three dimensions is 5.53cm (see Fig. 5).

The orbit determination accuracy of CHAMP and GRACE satellites with phase epoch-difference kinematic orbit determination method is about 30-40cm. Compared with kinematic orbit determination method, reduced dynamic orbit determination method can significantly improve orbit accuracy.

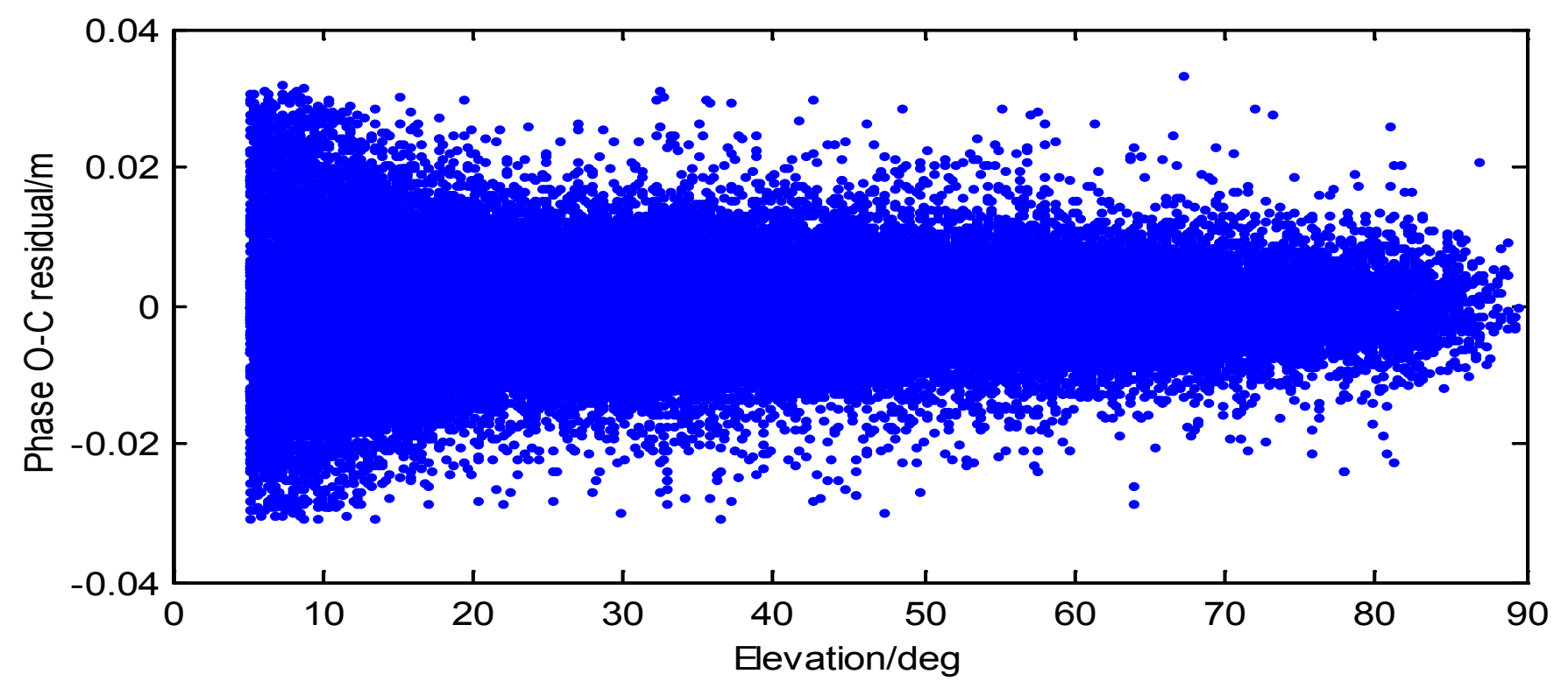


Figure 2 Phase O-C residual of reduced dynamic orbit determination using differenced phase for GRACE A on January 2, 2006 (RMS=6.7mm).

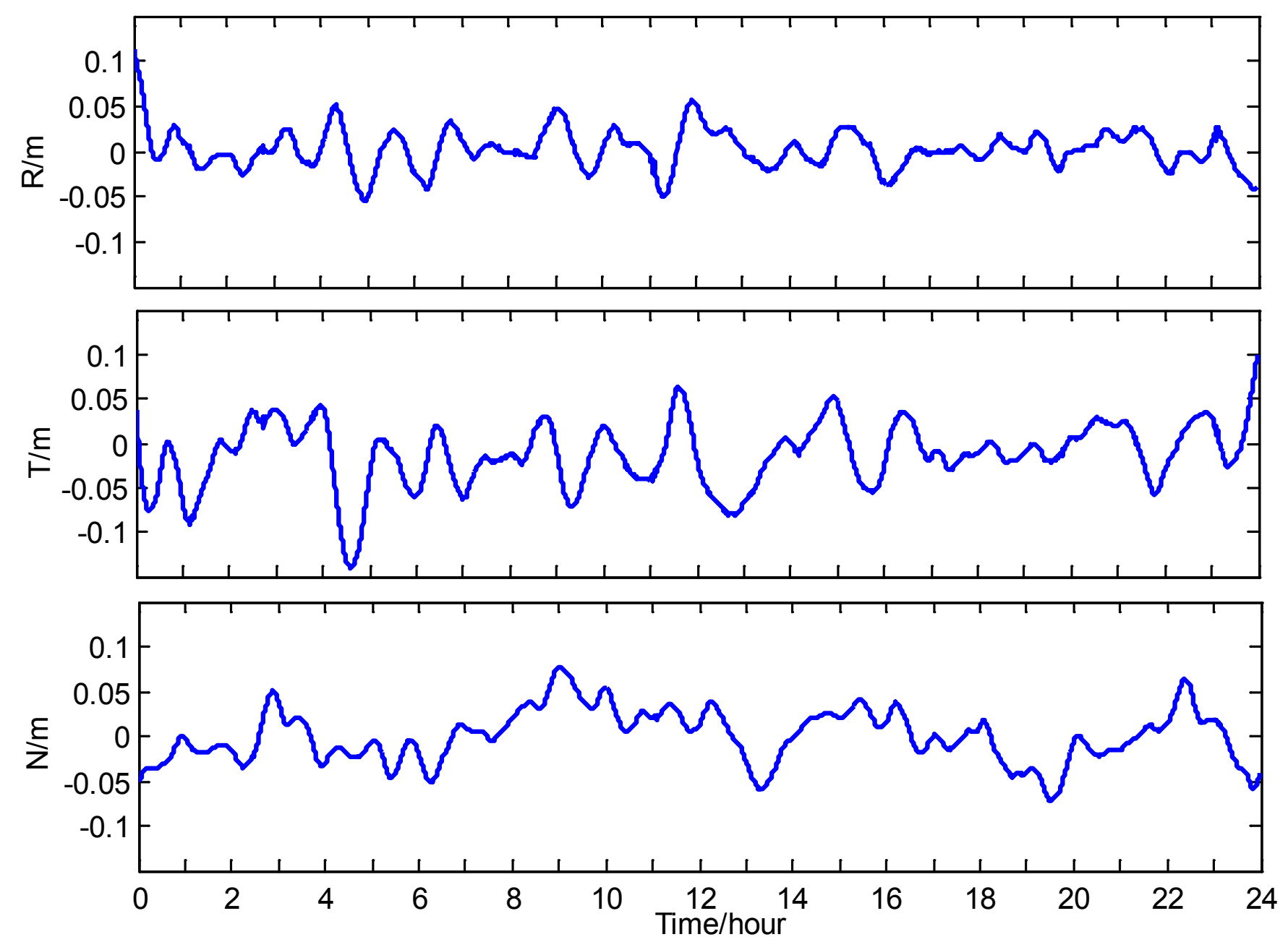


Figure 3 Comparison between GFZ science orbit and reduced dynamic orbit determination result using differenced phase for GRACE A on January 2, 2006. The RMSs of R, T and N components are 2.1cm, 3.8cm and 2.9cm.

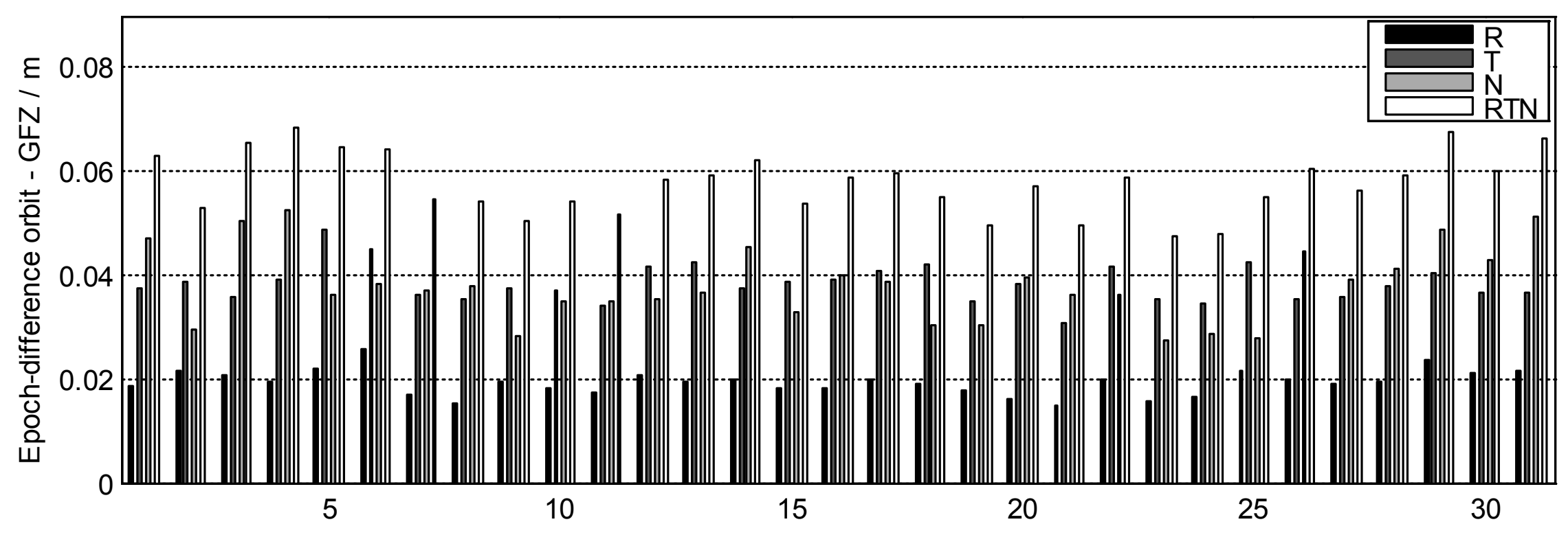


Figure 4 Comparison between GFZ science orbit and reduced dynamic orbit determination results using differenced phase for GRACE A in January, 2006 (Average RMS = 5.76cm).

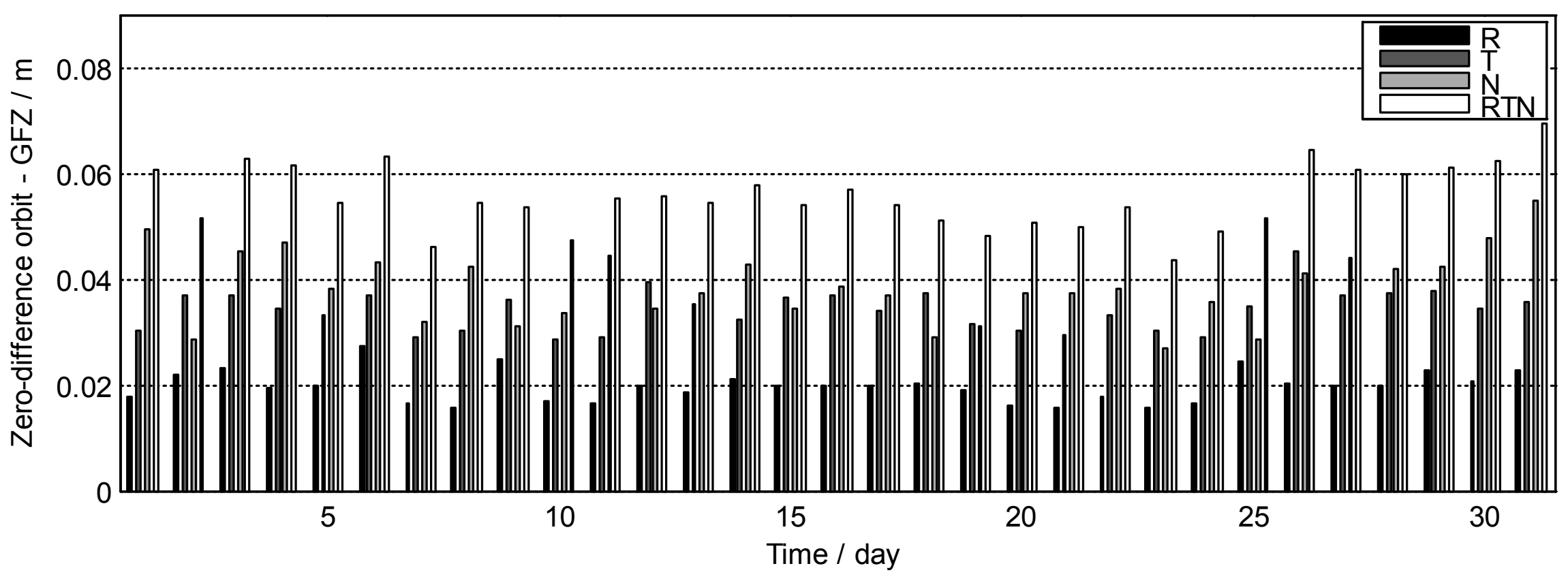
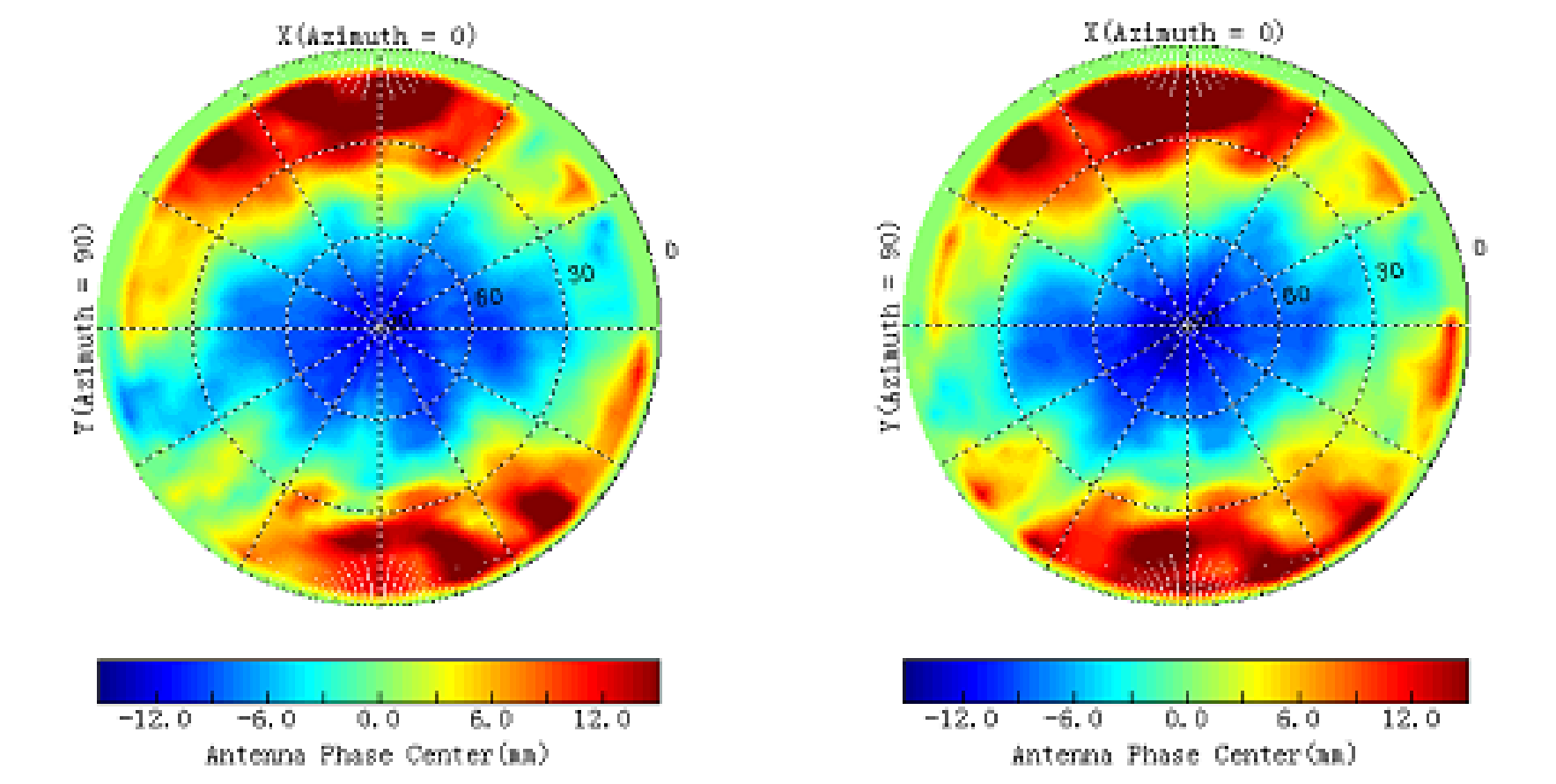


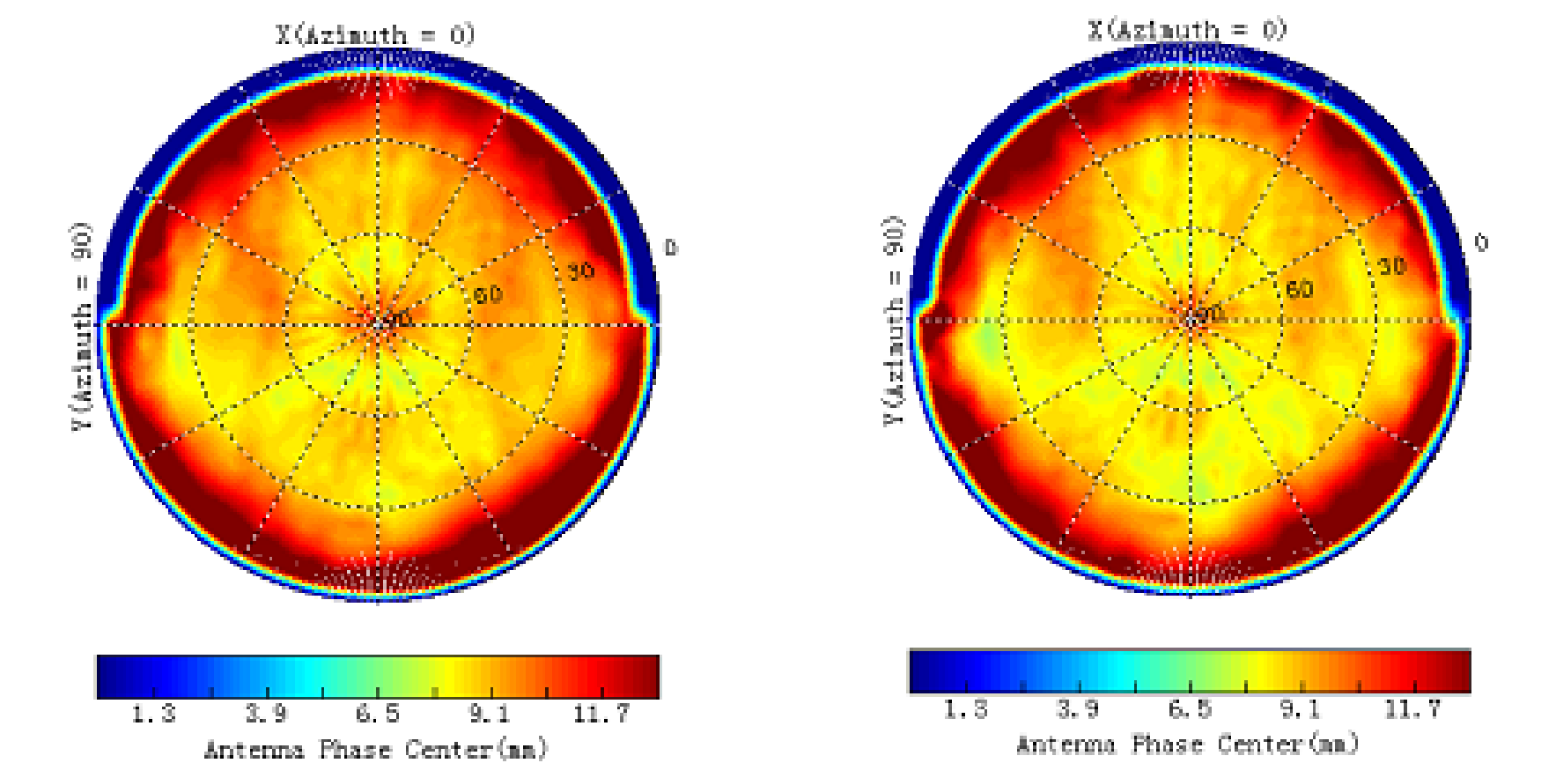
Figure 5 Comparison between GFZ science orbit and zero-difference reduced dynamic orbit determination results for GRACE A in January, 2006 (Average RMS = 5.53cm).

2. Phase Error Modeling and its Impact on Precise Orbit Determination of GRACE Satellites

At first, all the GPS observation data of GRACE A and GRACE B are directly processed to obtain the precise orbits by reduced dynamic orbit determination approach. The mean values and standard deviations of phase post-fit residuals are stored with a resolution of 5º×5º. The mean value patterns and standard deviation patterns of GRACE satellites are shown in Figure 6. It is shown by Figure 6 that the mean value patterns and standard deviation patterns of both satellites exhibit the similar distributions. In addition, it is shown by mean value patterns and standard deviation patterns from different periods that the distributions of mean value patterns and standard deviation patterns keep relatively steady and can be assumed to keep constant as time varying.



(a) Mean value pattern of phase post-fit residuals of GRACE A
(b) Mean value pattern of phase post-fit residuals of GRACE B



(c) Standard deviation pattern of phase post-fit residuals of GRACE A
(d) Standard deviation pattern of phase post-fit residuals of GRACE B

Figure 6 Mean value patterns and standard deviation patterns of phase post-fit residuals of GRACE satellites.

In an effort to obtain some information on the magnitude of precise orbit improvement and the precision of GRACE orbits computed in this paper, internal mode and external mode are used for orbit comparison respectively. In internal mode, the orbits generated by direct orbit determination without phase center variation estimation(identifier "NDT+NOPCV.") are compared with the orbits obtained by precise orbit improvement (identifier "NDT+PCV."), which can be used to obtain the magnitude of precise orbit improvement. In external mode, the orbits computed in this paper are compared with the JPL precise science orbits (identifier "JPL"), which could analyze the impact of precise orbit improvement on POD precision. JPL precise science orbits are created by processing zero-difference ionosphere-free pseudo code and carrier phase data with the GIPSY-OASIS software package, which is distributed along with the GRACE GPS data and is a part of GRACE Level 1B product. The RMS values of orbit comparisons computed in R, T, N direction and 3D (see Figure 7) are listed in Table 1.

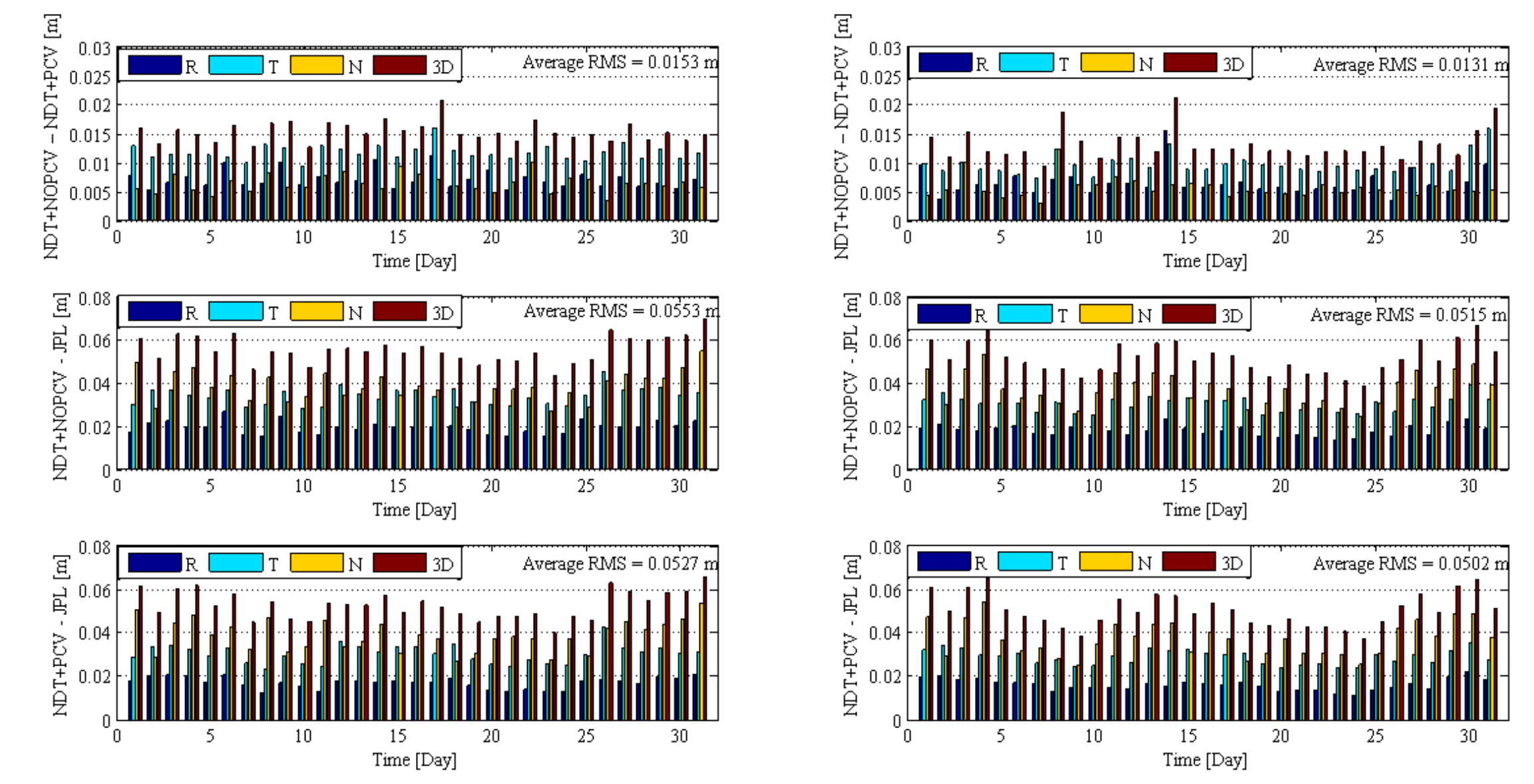


Figure 7 Orbit comparison results for GRACE A (right column) and GRACE B (left column).

Table 1 Orbit comparison results of GRACE satellites

		RMS value (m)			
		R	T	N	3D
GRACE A	NDT+NOPCV – NDT+PCV	0.0071	0.0118	0.0064	0.0153
	NDT+NOPCV – JPL	0.0195	0.0341	0.0385	0.0553
	NDT+PCV – JPL	0.0174	0.0306	0.0388	0.0527
GRACE B	NDT+NOPCV –NDT+PCV	0.0065	0.0097	0.0057	0.0131
	NDT+NOPCV – JPL	0.0179	0.0303	0.0373	0.0515
	NDT+PCV – JPL	0.0165	0.0290	0.0372	0.0502

It is shown by the results of internal mode that the 3D magnitudes of precise orbit improvement for GRACE A and GRACE B are 0.0153 m and 0.0131 m respectively. The most improvements are all in T direction, 0.0118 m and 0.0097 m, which is because T direction corresponds to flight direction, the phase error perpendicular to the flight direction are to some extent absorbed by the carrier phase ambiguities and clock offset, but the phase error along the flight direction will almost be absorbed by orbit parameters in orbit determination. In external mode, the 3D RMS values of orbit comparison results are reduced from 0.0553 m to 0.0527 m for GRACE A and from 0.0515 m to 0.0502 m for GRACE B by precise orbit improvement, and the orbit accuracies of both satellites are improved. Compared to GRACE B, the orbit accuracy of GRACE A is improved obviously and increased by 0.26 cm.

KBR system is one of the key scientific instruments onboard the GRACE satellites, which measures the one-way range change between the twin GRACE satellites with a precision of about 10 μm for KBR range at a 5-second data interval. As the high precision of KBR data, the relative position accuracy of the GRACE satellites can be validated. The relative positions computed by direct orbit determination solutions, precise orbit improvement solutions and JPL precise scientific orbits are validated by KBR data respectively (see Figure 8), and the average standard deviations of KBR comparison residuals are shown in Table 2.

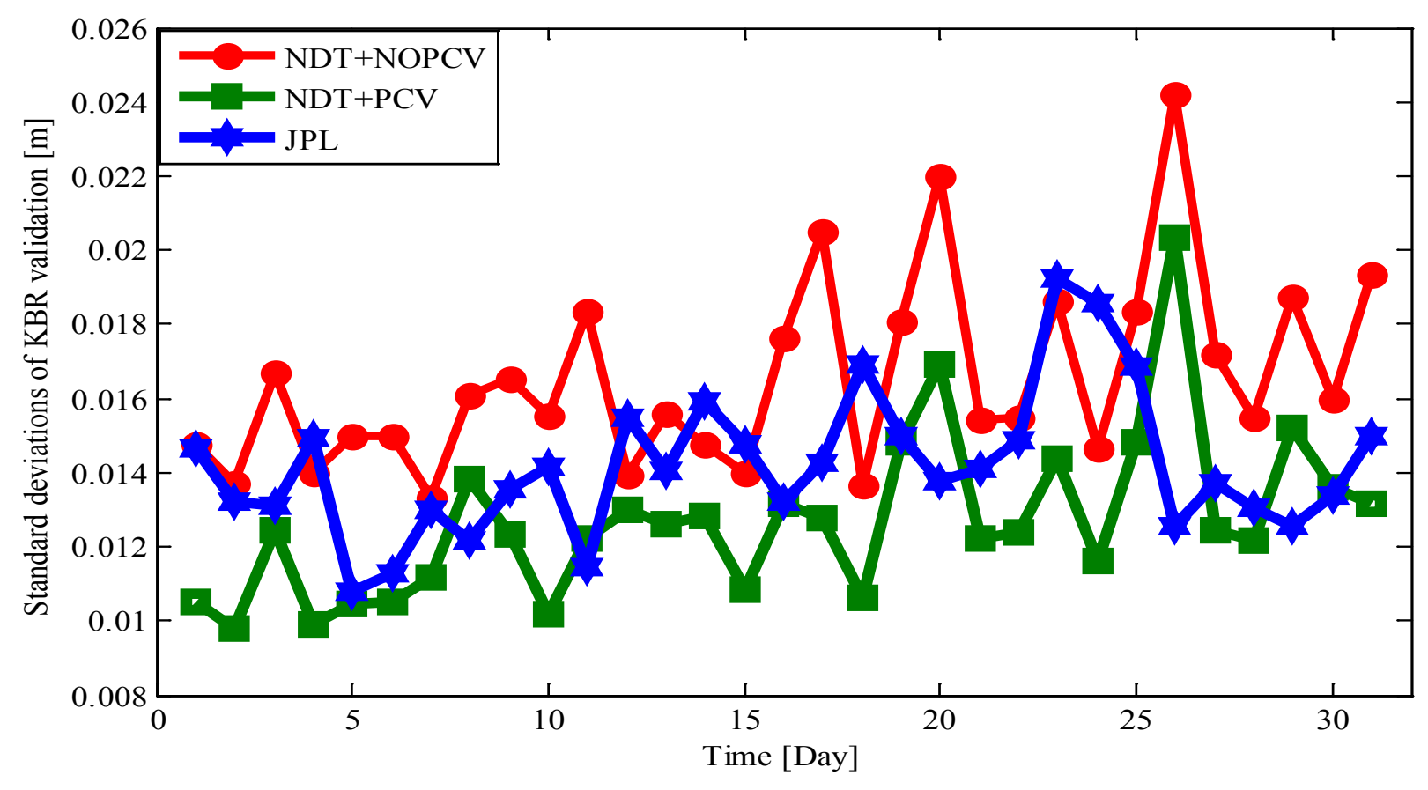


Figure 8 Daily standard deviations of KBR validation for GRACE satellites.

Table 2 Average standard deviations of KBR comparison residuals of GRACE relative position

Type of orbit solution	Average standard deviation (m)
NDT+NOPCV	0.0165
NDT+PCV	0.0127
JPL	0.0142

From Figure 8 and Table 2, we can see that the relative positions obtained by zero-difference GRACE orbits are significantly improved by 0.38 cm K-band standard deviation compared to direct orbit determination by precise orbit improvement, and they are also better than the K-band standard deviations computed by JPL precise science orbits. It shows that precise orbit improvement could remove the phase errors of both satellites and relative position accuracy could be obviously improved.

3. 1mm level baseline determination for GRACE two satellites formation

DD reduced dynamic relative orbit determination for two satellites programs were written, and over a period of 10 days from February 1 to February 10, 2006, both GRACE A and B dual-frequency GPS observations are processed. Firstly, Float ambiguity solution is obtained without estimating any integer ambiguities results in the so-called float solution for the relative position estimates, and the standard deviation of the KBR comparison of the float solution is 5.75mm (see Fig. 9).

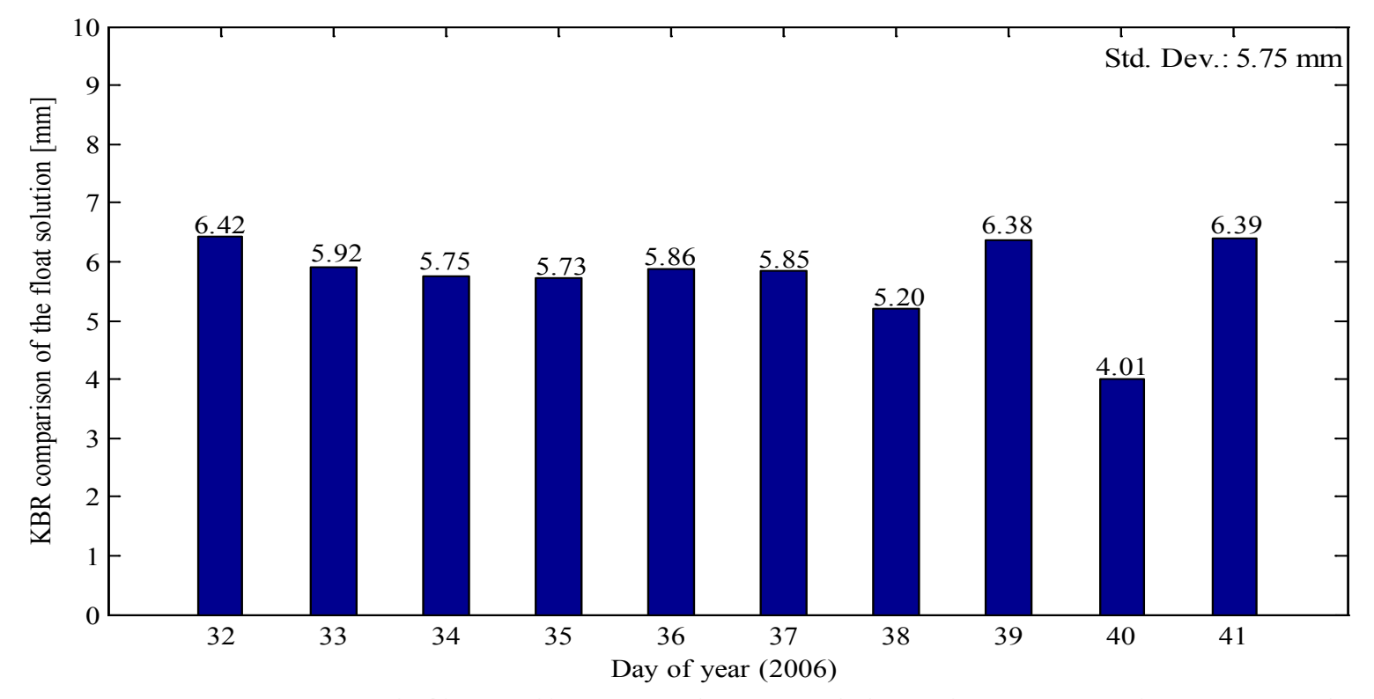


Figure 9 Daily mean square root of GRACE relative position from the float ambiguity solution when compared to the KBR measurements (Average RMS = 5.75mm).

Secondly, the highest achievable accuracy for the relative position solution is obtained when fixing the DD ambiguities to their resolved integer values, the average success rate of integer ambiguities resolution is about 90%(see Table 3), and the standard deviation of the KBR comparison of the fixed ambiguity solution is 1.01mm (see Fig. 9 and Fig. 10). Here it can be seen that the relative position precision of the fixed ambiguity solution is significantly higher than the float ambiguity solution. which shows the importance of Integer DD ambiguity resolution.

Table 3 Daily success rate of integer ambiguities resolution

Date	Count of total ambiguities	Count of fixed ambiguities	Success rate
2006-02-01	546	493	90.29%
2006-02-02	531	481	90.58%
2006-02-03	555	494	89.01%
2006-02-04	560	498	88.93%
2006-02-05	558	504	90.32%
2006-02-06	550	494	89.82%
2006-02-07	551	505	91.65%
2006-02-08	539	485	89.98%
2006-02-09	548	491	89.60%
2006-02-10	550	488	88.73%

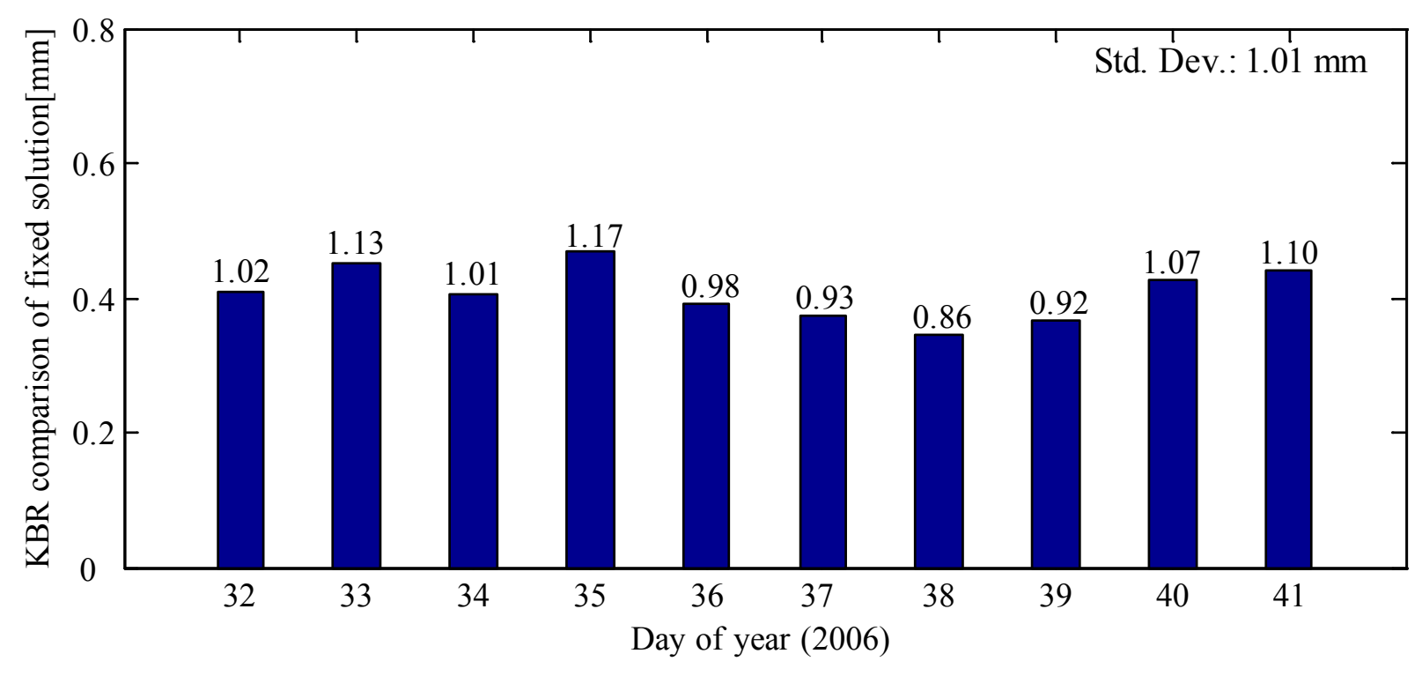


Figure 10 Daily mean square root of GRACE relative position from the fixed ambiguity solution when compared to the KBR measurements (Average RMS = 1.01mm).

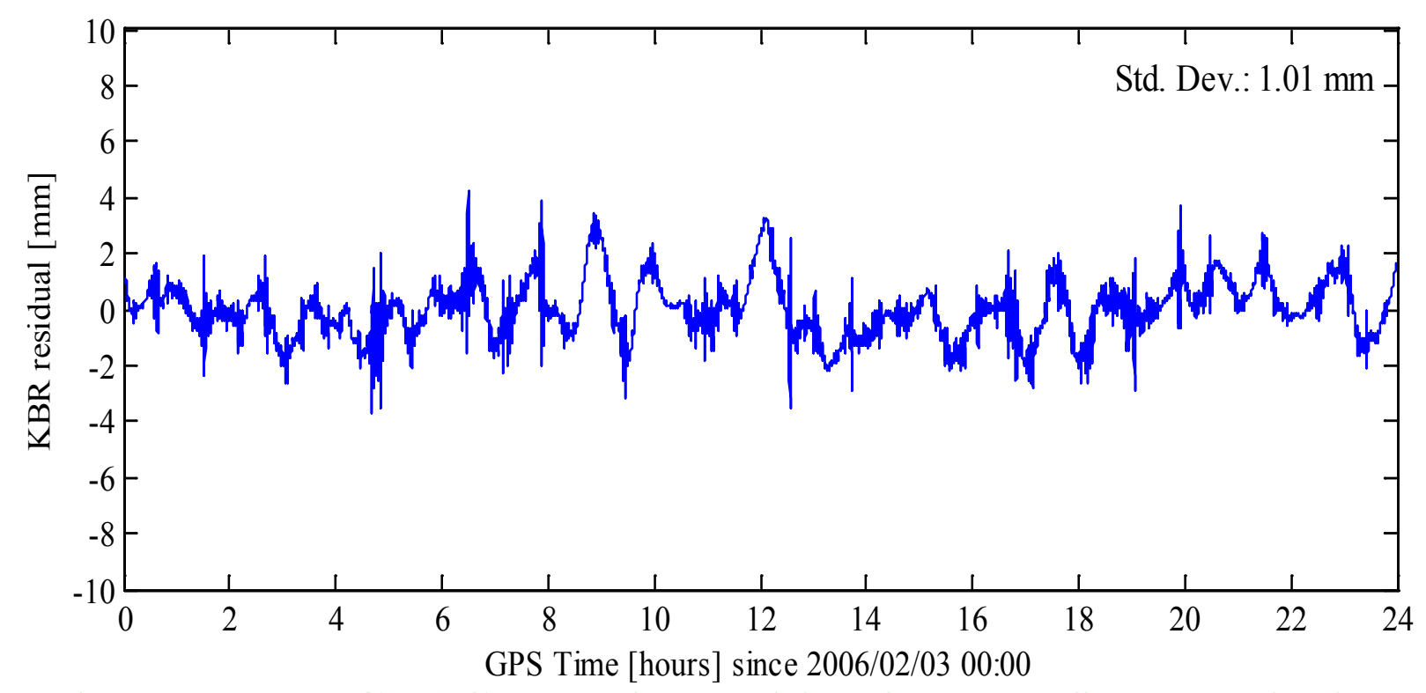


Figure 11 Comparison between GRACE relative position from the fixed ambiguity solution and the KBR measurements on Feb, 3rd, 2006 (RMS = 1.01mm).

The RMS of the phase O-C residuals obtained from DD reduced dynamic relative orbit determination is only 4.3mm (see Fig. 12), which reflects the consistency of the applied models with the GPS observation data.

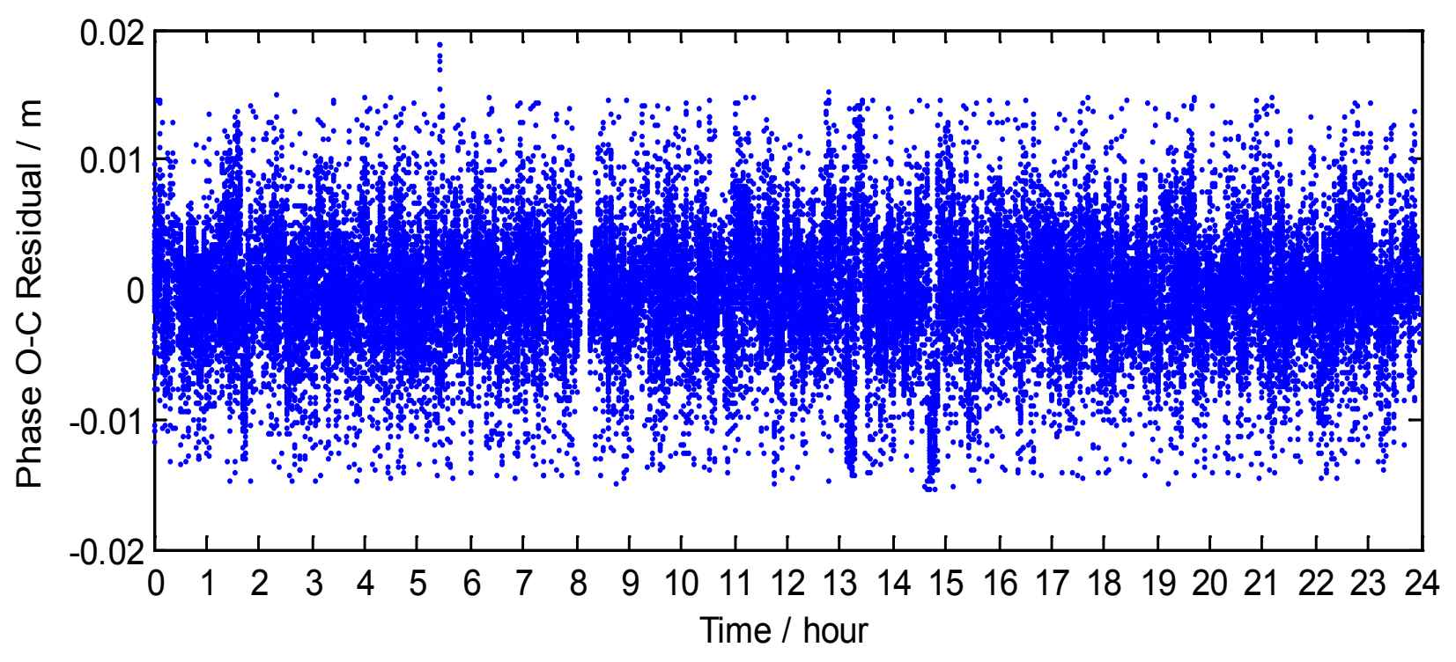


Figure 12 The phase O-C residual of GRACE relative position determination on Feb, 3rd, 2006 (RMS = 4.3mm).