

Application of Accelerometer Data in Precise Orbit Determination of GRACE -A and -B *

Dong-Ju Peng^{1,2} and Bin Wu¹

¹ Shanghai Astronomical Observatory, CAS, Shanghai 200030, China; pdongju@shao.ac.cn

² Graduate University of Chinese Academy of Sciences, Beijing 100049, China

Received 2007 August 15; accepted 2007 September 17

Abstract We investigate how well the GRACE satellite orbits can be determined using the on-board GPS data combined with the accelerometer data. The preprocessing of the accelerometer data and the methods and models used in the orbit determination are presented. In order to assess the orbit accuracy, a number of tests are made, including external orbit comparison, and through Satellite Laser Ranging (SLR) residuals and K-band ranging (KBR) residuals. It is shown that the standard deviations of the position differences between the so-called precise science orbits (PSO) produced by GFZ, and the single-difference (SD) and zero-difference (ZD) dynamic orbits are about 7 cm and 6 cm, respectively. The independent SLR validation indicates that the overall root-mean-squared (RMS) errors of the SD solution for days 309 – 329 of 2002 are about 4.93 cm and 5.22 cm, for GRACE-A and B respectively; the overall RMS errors of the ZD solution are about 4.25 cm and 4.71 cm, respectively. The relative accuracy between the two GRACE satellites is validated by the KBR data to be on a level of 1.29 cm for the SD, and 1.03 cm for the ZD solution.

Key words: celestial mechanics — ephemerides — methods: numerical

1 INTRODUCTION

The GRACE (Gravity Recovery and Climate Experiment) mission, launched on 2002 March 17, is a joint partnership between the National Aeronautics and Space Administration (NASA) in the United States and Deutsches Zentrum für Luft- und Raumfahrt (DLR) in Germany. The twin GRACE satellites fly a polar orbit with an initial altitude of about 500 km. The key science instruments on-board both spacecraft include a BlackJack Global Positioning System (GPS) receiver, a SuperSTAR accelerometer, a star tracker, a K-band ranging (KBR) system and a Satellite Laser Ranging (SLR) retro-reflector. The BlackJack receivers on-board each GRACE satellite (GRACE-A and GRACE-B) used have 16 channels: 12 for precise orbit determination (POD) and 4 for occultation measurements (Wu et al. 2006). The primary objective of the GRACE mission is to obtain accurate global models for the mean and the time variable components of the Earth's gravity field. An additional goal of the mission is to enable advances in the atmospheric sciences by the recovery of the refractivity (and the derived quantities of the temperature and water vapor profiles) and fine ionospheric structure from the use of GPS radio occultation data. To satisfy this objective as well as other applications (e.g., atmospheric profiling), accurate orbits for GRACE are required. Since the launch many authors have investigated the GPS-based POD for GRACE using different approaches, including kinematic, dynamic, and reduced-dynamic POD, and have obtained satisfying results. All these results are based on the program of their own institutes such as GFZ, CSR and JPL (Kang et al. 2003, 2006; Jäggi et al. 2005, 2007).

* Supported by the National Natural Science Foundation of China.

Along with the rapid development of space technology and GPS, more and more Low Earth Orbiters (LEO) of new scientific missions are equipped with on-board GPS receivers, as primary instruments for precise orbit determination. On-board GPS has become one of the main POD approaches for LEO satellites. Shanghai Astronomical Observatory (SHAO) has developed a program named SHORDE-III for LEO satellite orbit determination using on-board GPS data. A number of tests indicated that SHORDE-III can achieve fairly high orbit accuracy (Peng et al. 2007). Based on the original functions of SHORDE-III, we further developed a function which uses the on-board GPS data combined with accelerometer data to determine the twin GRACE satellite orbits. The orbit accuracy was validated by external orbit comparison, independent SLR validation and KBR residuals.

2 DATA PREPROCESSING

The SuperSTAR accelerometer, located at the center of mass of each GRACE satellite, measures all non-gravitational forces acting on the satellite to an accuracy of approximately $10^{-10} \text{ m s}^{-2}$. These forces include air drag, solar radiation pressure, and Albedo and infrared of the Earth. Registered users can acquire the high-rate Level 1B accelerometer data (ACC1B) at 1-second interval from the Information System and Data Center (ISDC) of GFZ. No doubt that any data set has measurement errors. In order to reduce the effects of these errors on the final results of analysis, it is necessary to smooth out first the spikes and outliers in the raw data. There are various smoothing techniques, such as curve fitting, the Gaussian method, and the Vondrak method, etc. In this paper, we use the Vondrak method to smooth the Level 1B accelerometer data. The Vondrak smoothing technique was developed by the Czech astronomer J. Vondrak, its main advantage is that it can smooth the measurement data reasonably even though the curve fitting function is unknown (Ye et al. 2000).

ACC1B provides the accelerations in the X , Y and Z directions in the Science Reference Frame (SRF). From a large volume of observed accelerometer data, it is found that the X component of the accelerometer data is regular, so we only need to smooth the Y and Z components of the accelerometer data. However, the 1-second data interval is unnecessary for the POD, so after the smoothing we use a polynomial of second degree to construct a normal point for every 10-second interval (Bock 2003), i.e., the accelerometer data are preprocessed in two steps: first, smoothing the raw data, second, constructing the normal points.

We used the above method to preprocess the real-time GRACE-B accelerometer data of 2002 Nov 22. Figure 1 shows the accelerometer data in the Y and Z directions before and after preprocessing. From Figure 1, we can see that the data become much smoother after the preprocessing.

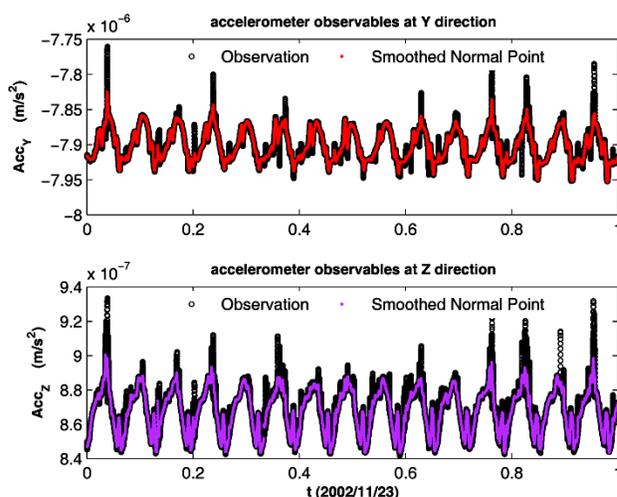


Fig. 1 GRACE-B Level 1 B accelerometer data before and after preprocessing in the Y (top) and Z (bottom) direction in SRF on 2002 Nov 22.

The satellite attitude data provided by the on-board Star Camera Assembly (SCA) are essential for POD using the GPS data combined with the accelerometer data. It is required to translate the accelerometer data from the spacecraft reference frame to the inertial frame. In fact, the original SCA data are occasionally interrupted, and the Level 1B SCA data (SCA1B) from ISDC are not uniform 5-second sampling either, so there are breaks, and we have to interpolate to obtain a continuous attitude data. We use cubic spline function to this end in this paper.

3 POD USING THE GPS AND ACCELEROMETER DATA

As is known, the orbit accuracy depends heavily both on the model of gravitational force and the model of non-gravitational force used, and the current models of such non-gravitational factors as air drag and solar radiation pressure acting on Low earth satellites, are not good enough. In order to reduce the effects of the errors in the force model on the POD, we usually take the empirical acceleration parameters, but the on-board accelerometer which measures the non-gravitational accelerations directly and precisely can provide a new way to solve the error problems. For the POD of GRACE, the GPS data could be processed with and without accelerometer data. Peng et al. (2007) have checked in detail the GPS data only and this study will focus on determining the GRACE orbit with the accelerometer data with the SHAO program. SHORDE-III.

In the inertial frame (J2000.0), the forces acting on the satellite can be divided into three groups: central gravitation from Earth f_0 , gravitational forces f_{grav} , and non-gravitational forces $f_{\text{non-grav}}$:

$$f_{\text{total}} = f_0 + f_{\text{grav}} + f_{\text{non-grav}}. \quad (1)$$

In the orbit determination using GPS and accelerometer data (GPS+ACC), $f_{\text{non-grav}}$ is replaced by the accelerometer data. However, the SuperSTAR accelerometer output is not an absolute value. The measurement has to be corrected by applying a bias and scale factor for each axis. The accelerometer observation equation is :

$$f_{\text{SRF}_i} = a_{0i} + k_i \times a_i + \varepsilon_i, \quad (2)$$

where f_{SRF_i} is the non-gravitational acceleration, a_{0i} the acceleration bias, k_i the scale factor, a_i the acceleration measurement, and ε_i the acceleration measurement errors. GFZ has provided an array of scale and bias reference values for GRACE-A and B, but they are usually treated as unknown parameters and estimated together with the other parameters. The corrected accelerometer data are still in SRF. In the dynamic orbit determination, we must translate these into inertial frame. If the rotation matrix from SRF to J2000.0 is Q (more details see Wu et al. 2006), then we have

$$f_{\text{acc}_J2000} = Q \times f_{\text{SRF}}, \quad (3)$$

$$f_{\text{total}} = f_0 + f_{\text{grav}} + f_{\text{acc}_J2000}. \quad (4)$$

4 POD: TESTS AND ANALYSIS OF RESULT

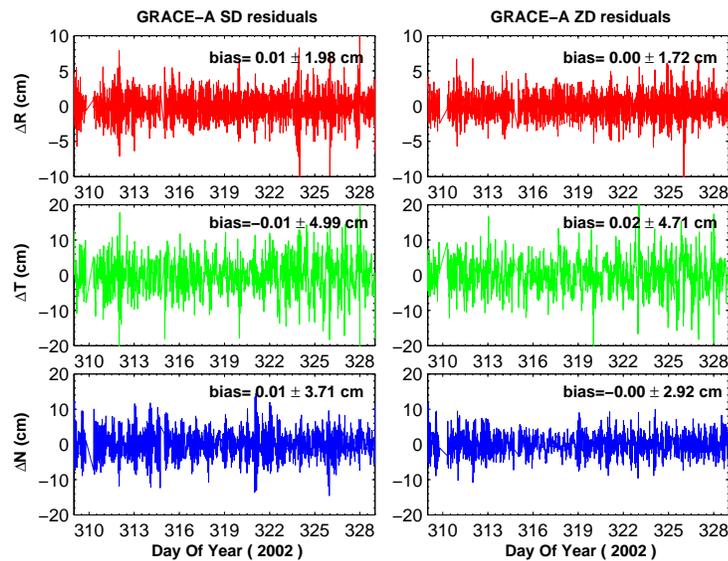
In a previous study (Peng et al. 2007), we used real GRACE data to test the approach with many empirical acceleration parameters to reduce the effects of the force model errors on the POD using only the GPS data. The results indicate that the single-difference (SD) method has an accuracy of about 14 cm, and the zero-difference (ZD) method has an accuracy of about 8 cm. In this paper, the real GRACE data for the same period (November 5–25, day 309–329, 2002) are chosen to test the orbit accuracy using GPS+ACC, so that we can easily compare the difference on orbit accuracy using the two different approaches. The ZD dynamic POD method and SD dynamic POD method are used in this study as well. Table 1 summarizes the model standards adopted for the GRACE orbit determination using GPS+ACC.

4.1 External Orbit Comparison

With the data processing strategy outlined in the previous section, we compute the GRACE-A and B orbits using both SD and ZD POD approaches over a period of 21 days with the GPS and accelerometer data, and compare these two orbit solutions with the so-called Precise Science Orbits (PSO) produced by GFZ. Figures 2 and 3 show the differences between PSO and the SD and ZD solutions in radial (R), tangent (T) and normal (N) directions, for GRACE-A and B, respectively. Shown are the residuals in cm. The

Table 1 POD Force Model and Data Standards for GRACE

Data type	Description
On board GPS data	GPS1B, real GRACE data with 10-second data interval
Accelerometer data	ACC1B, using a polynomial of second degree to construct a normal point for each 10-second interval
Attitude data	SCA1B, using cubic spline function to interpolate the discontinuity point, 5-second data interval
KBR data	KBR1B, 5-second data interval
'reference orbit' PSO	GNV1B, so-called precise science orbit produced by GFZ, 60-second data interval
GPS orbits and clock	GFZ final GPS orbit products, 30-second data interval
SLR data	normal point at 5-second data interval, from CDDIS
Earth orientation parameters	IERSBulletin B (IAU1980)
Force models	
Mean Earth gravity	GGM02C ,150 × 150
Solid earth tides	IERS96 conventionMcCarthy 1996
Ocean tides	CSR4.0Eanes 1994
General relativity perturbation	IERS2003 conventionMcCarthy and Petit 2002
N-body perturbation	JPL DE/LE 200
Estimated parameters	
GRACE initial state	3-Depoch position and velocityestimated per day
ambiguity	float ambiguity, one-cycle-per-revolution (1cpr)
Scale and bias	per day for each direction
GRACE clock bias	ZD parameters, estimated epoch-wise

**Fig. 2** Differences between PSO and ZD, ZD solutions using GPS+ACC for GRACE-A in the R, T and N directions for days 309–329 of 2002. Left three panels are for SD solution and right three for ZD solution.

comparison shows that there are no significant systematic offsets in all the three directions. The overall root-mean-squared (RMS) errors of SD and ZD solutions with respect to PSO in the R, T and N direction are, respectively, 1.98, 4.99, 3.71 cm and 1.71, 4.71, 2.92 cm for GRACE-A, the same for GRACE-B are, respectively 1.96, 5.28, 4.31 cm and 1.85, 4.88, 3.14 cm. Note that in Figures 2 and 3 the bias at the T direction is the largest among the three directions, in agreement with the result computed with only the GPS data (here, the overall RMS errors of the SD and ZD solutions with respect to PSO in the R, T and N directions are, respectively, 4.23, 9.39, 5.59 cm and 3.08, 6.95, 2.92 cm, for GRACE-A, and are, respectively,

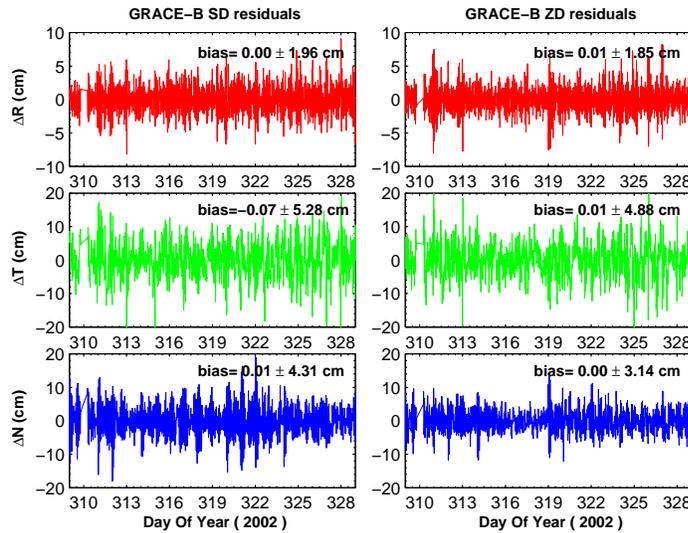


Fig. 3 Differences between PSO and ZD, ZD solutions using GPS+ACC, for GRACE-B in the R, T and N directions for days 309–329 of 2002. Left three panels are for SD solution and right three for ZD solution.

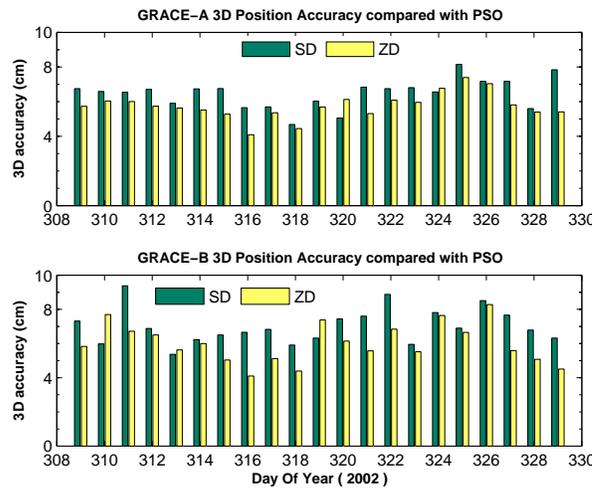


Fig. 4 Daily standard deviations (STD) of the position differences between the reference PSO and the SD, ZD solutions using GPS+ACC for GRACE-A (top) and GRACE-B (bottom), for days 309–329 of 2002.

4.10, 9.51, 5.38 cm and 3.08, 7.01, 3.43 cm, for GRACE-B). Figure 4 shows the daily standard deviations (STD) of position differences between the SD, ZD solutions and the reference PSO for GRACE-A (top) and GRACE-B (bottom). Plotted are the 3D position STDs in cm. From Figure 4 we can see that: i) Compared with PSO the 3D position accuracy of both SD and ZD solutions are better than 10 cm, the mean STD values for GRACE-A are 6.47 cm and 5.75 cm, respectively. The SD daily value varies between 4.68 cm on day 318 and 8.15 cm on day 325, and the ZD daily value, between 4.09 cm on day 316 and 7.39 cm on day 325. The corresponding mean STD values of GRACE-B are 7.01 cm and 6.01 cm, while the SD daily value varies between 5.37 cm on day 313 and 9.38 cm on day 311, and the ZD daily value, between 4.39 cm on

day 318 and 8.28 cm on day 326. ii) The ZD solution is better than the SD solution, and the orbit accuracy of GRACE-A is a little better than GRACE-B, in agreement with the results of CSR (Kang et al. 2006) and the results using only the GPS data. iii) The SD and ZD solutions using GPS+ACC for both GRACE-A and B show a better agreement with respect to the PSO than using only the GPS data, the 3D position accuracy of the SD solution is now improved to the level of 3–6 cm, and the ZD solution, to the level of 2–4 cm.

4.2 Orbit Validation with SLR Data

LEO trajectories are usually validated with independent SLR measurements (Jäggi et al. 2005). The two GRACE satellites are equipped with laser retro-reflector arrays which allow for an independent validation of the orbit quality produced by SHORDE-III using GPS+ACC with the SLR observations. The SLR residuals are computed as the difference between the SLR measurements minus the distance between the SLR station and the orbit determined using the GPS and accelerometer data. Due to the low altitudes below 500 km of the twin GRACE satellites, tracking by the ground stations is difficult. For GRACE-A, a total of 1858 SLR residuals in 81 passes were obtained by 14 SLR stations of the tracking network of the International Laser Ranging Service on days 309–329 of 2002. For GRACE-B 1664 SLR residuals in 73 passes, by 13 SLR stations. Figure 5 shows the SLR residuals to the SD and ZD dynamic GRACE orbits, respectively, where the SLR residual in cm is plotted against the serial number of the SLR normal points. The tide correction, station offset, satellite center of mass correction, tropospheric delay, and relativistic correction have been applied to the SLR measurements.

The plots show no significant systematic offsets in the SLR residuals in both the SD and ZD solutions (e.g. in the GRACE-A ZD solution, the bias is -0.09 ± 4.25 cm), the SD solution for days 309–329 of 2002 yields an overall RMS error of 4.93 cm for GRACE-A and 5.22 cm for GRACE-B, while the ZD solution yields an overall RMS error of 4.25 cm for GRACE-A and 4.71 cm for GRACE-B. Compared to the solution derived from only GPS data (the overall RMS errors of GRACE-A and GRACE-B are 6.72 cm, 7.42 cm for SD and 4.64 cm, 5.40 cm for ZD), the overall RMS errors of the SLR residuals show a small improvement when using GPS+ACC to determine the GRACE orbits, the RMS errors of SD and ZD solutions were improved to an overall level of about 2 cm and 0.5 cm, respectively.

4.3 Orbit Validation with the KBR Data

One of the key scientific instruments onboard the GRACE satellites is the KBR system, which measures the one-way range change between the twin GRACE satellites with a precision of about $10 \mu\text{m}$ for KBR range at a 5-second data interval. The KBR data are used mainly for gravity field recovery, but due to its precise measurement of the range between GRACE-A and -B, it also provides a unique opportunity for a direct, continuous validation of the distance between the two satellites, hence the relative orbit accuracy of the GRACE satellites. Compared with the SLR measurements, the KBR measurements have the advantage that they are always continuous in space and time, and they are not sensitive to errors common to both satellites (Jäggi et al. 2007). On the other hand, the KBR measurements only observe a biased range between the two spacecraft, which is the true range plus an unknown bias. The bias is arbitrary for each piecewise continuous segment of phase change measurements and may change over day boundaries. Thus, one K-band bias parameter has to be estimated when using them for orbit validation, provided that no cycle slips occur in the K-band data for the time interval to be analyzed. The biased range also includes range changes (light time correction) as well as geometric range changes due to variations in the spacecraft's attitude. The biased ranges must be corrected for light time and geometric effects (i.e., antenna offsets). The corrected biased range is given by (Kroes 2006):

$$L_{\text{KBR}}(t_i) = \rho_{\text{AB}}(t_i) + B_{\text{KBR}} + \Delta_{\text{ant}}(t_i) + \Delta_{\text{ct}}(t_i) + \varepsilon(t_i), \quad (5)$$

where $L_{\text{KBR}}(t_i)$ is the KBR measurement at time t_i , $\rho_{\text{AB}}(t_i)$ the distance between the center of mass of GRACE-A and B, $B_{\text{KBR}}(t_i)$ the KBR observation bias that is constant over time until a cycle slip occurs, $\Delta_{\text{ant}}(t_i)$ the antenna phase center correction, $\Delta_{\text{ct}}(t_i)$ the so called light time correction, and $\varepsilon(t_i)$ the observations errors. However, together with L_{KBR} , both Δ_{ant} and Δ_{ct} are also provided in the Level 1B KBR data files and can directly be used for the purpose of our research. If \mathbf{R}_A and \mathbf{R}_B are the precise position vector of GRACE-A and B produced by SHORDE-III using GPS+ACC, respectively, the relative position can be simply constructed as $\rho_{\text{AB}}(t_i) = |\mathbf{R}_A - \mathbf{R}_B|$, then we can obtain a KBR bias valid until

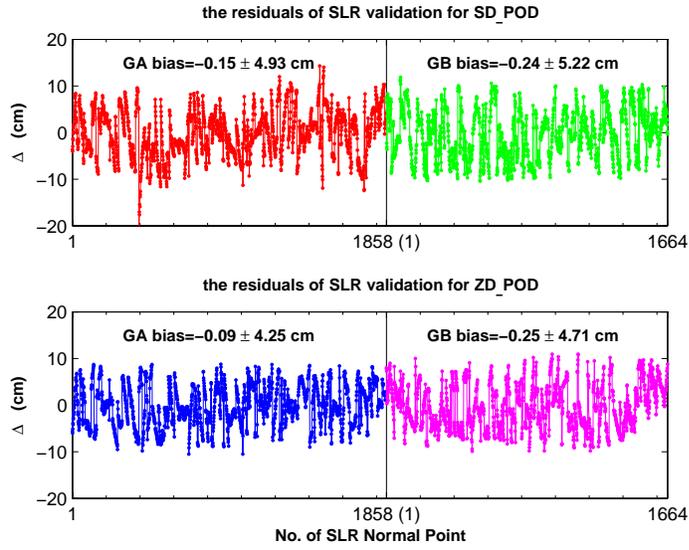


Fig. 5 SLR residuals (cm) of GRACE-A and GRACE-B for the SD (top) and ZD (bottom) solution for days 309–329 of 2002 plotted against the serial number of the SLR normal points. There are 1858 normal points in GRACE-A and 1664 in GRACE-B.

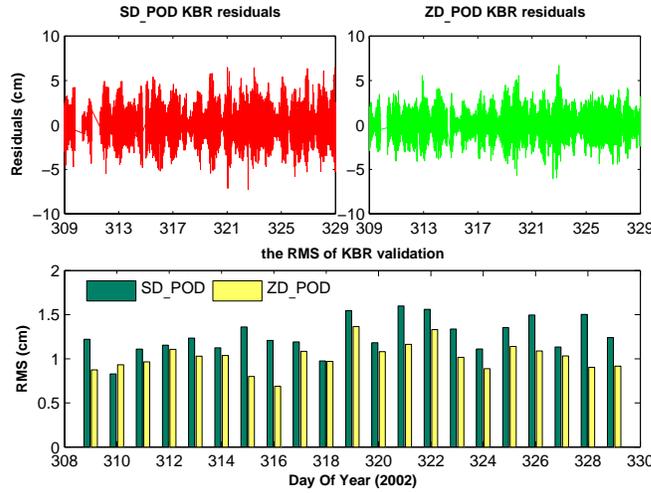


Fig. 6 KBR residuals (cm) of the SD (top left) and ZD (top right) solutions and the daily RMS errors (bottom) of the SD and ZD solutions.

the next cycle slip:

$$B_{KBR} = \frac{1}{n} \sum L_{KBR}(t_i) - \rho_{AB}(t_i) - \Delta_{ant}(t_i) - \Delta_{ct}(t_i), \quad (6)$$

where n is the number of KBR data over the time period free of cycle slips. Combined with Equation (5), we can obtain the KBR residuals between KBR observation and the distance computed between GRACE-A and -B orbit positions.

We use the KBR data to validate the relative position of the twin GRACE satellites as well, their orbits are individually computed using GPS+ACC. Validation of the relative position solution is done for each 24-hour segment. Figure 6 shows the KBR residuals of the SD solution (top left), ZD solution (top right), and the daily K-band range RMS errors (bottom) obtained from the distance computed every 5 second between the dynamic GRACE-A and -B orbit positions obtained from the SD and ZD solutions. The corresponding overall K-band range RMS errors are 1.29 cm and 1.03 cm, while the daily values vary only between 0.83 cm on day 310 and 1.60 cm on day 321 for the SD solution, and only between 0.80 cm on day 316 and 1.33 cm on day 319 for the ZD solution.

5 CONCLUSIONS

We have studied the POD methods, models for GRACE satellites orbit determination, and how well the GRACE satellite orbits can be determined using the GPS and accelerometer data. To assess the orbit accuracy, a number of tests were made, including external orbit comparison, independent SLR validation, using the KBR residuals. Based on the results of analyzing real GRACE data, we obtain following conclusions:

- (1) Compared with the PSO, the 3D position accuracy of the SD solution is about 7 cm, and that of the ZD is about 6 cm;
- (2) Compared with the GPS-ONLY solution, using the GPS data combined with accelerometer data can improve the orbit accuracy, the 3D position accuracy of the SD solution was improved to some 3–6 cm, and that of the ZD, to some 2–4 cm;
- (3) Both of the SD and ZD dynamic orbits were validated by independent SLR observations at an overall level of 4.93 cm, 5.22 cm for GRACE-A, and 4.25 cm, 4.71 cm for GRACE-B;
- (4) For the 21-day GRACE data arc processed, the overall relative position precision of the SD and ZD solutions with the KBR data are 1.29 cm and 1.03 cm, respectively, so we deem that a 1-cm relative position accuracy of the twin GRACE satellites, derived by using the GPS and accelerometer data, has been probably achieved.

Acknowledgements The authors extend special thanks to the information system and data center (ISDC) of GeoForschungszentrum (GFZ), for providing the GPS satellites orbit and GRACE Level 1B data. This study is supported by the National Natural Science Foundation of China (Grant 40274006), the National High-tech Program (863 program) of China (2006AA12A107) and the Science & Technology Commission of Shanghai Municipality(06DZ22101).

References

- Bock H., 2003, Efficient Methods for Determining Precise Orbits of Low Earth Orbiters Using the Global Positioning System, Switzerland: Schweizerische Geodätische Kommission
- Jäggi A., Beutler G., Hugentobler U., 2005, *Adv. Space Res.*, 36, 438
- Jäggi A., Hugentobler U., Bock H. et al., *dv. Space Res.*, 2007, 39, 1612
- Kang Z., Nagel P., Pastor R., 2003, *Adv. Space Res.*, 31, 1875
- Kang Z., Tapley B., Bettadpur S. et al., *Adv. Space Res.*, 2006, 38, 2131
- Kang Z., Tapley B., Bettadpur S. et al., *J Geod.*, 2006, 80, 322
- Kroes R., 2006, Precise Relative Positioning of Formation Flying Spacecraft using GPS, Delft: Geodesy 61
- Peng D. J., Wu B., *Chin Sci Bull.*, 2007, 52, 2024
- Wu S. C., Kruizinga Z., Bertiger W., 2006, Algorithm Theoretical Basis Document for GRACE Level-1B Data Processing V1.2
- Ye S. H., Huang C., 2000, Astro-geodynamics research, Jinan: Shandong science and technology (in Chinese)