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ORIGINAL ARTICLE

Zhigui Kang · Byron Tapley · Srinivas Bettadpur
John Ries · Peter Nagel · Rick Pastor

Precise orbit determination for the GRACE mission using only GPS data

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Abstract The GRACE (gravity recovery and climate experiment) satellites, launched in March 2002, are each equipped with a BlackJack GPS onboard receiver for precise orbit determination and gravity field recovery. Since launch, there have been significant improvements in the background force models used for satellite orbit determination, most notably the model for the geopotential. This has resulted in significant improvements to orbit accuracy for very low altitude satellites. The purpose of this paper is to investigate how well the orbits of the GRACE satellites (about 470 km in altitude) can currently be determined using only GPS data and based on the current models and methods. The orbit accuracy is assessed using a number of tests, which include analysis of orbit fits, orbit overlaps, orbit connecting points, satellite Laser ranging residuals and K-band ranging (KBR) residuals. We show that 1-cm radial orbit accuracy for the GRACE satellites has probably been achieved. These precise GRACE orbits can be used for such purposes as improving gravity recovery from the GRACE KBR data and for atmospheric profiling, and they demonstrate the quality of the background force models being used.

Keywords Precise orbit determination (POD) · GRACE · GPS · SLR

Z. Kang (✉) · B. Tapley · S. Bettadpur · J. Ries · P. Nagel · R. Pastor
Center for Space Research, University of Texas at Austin,
3925 W. Braker Lane, Suite 200, Austin, TX 78759-5321, USA
E-mail: kang@csr.utexas.edu
Tel.: +1-512-4710163
Fax: +1-512-4713570
E-mail: tapley@csr.utexas.edu
Tel.: +1-512-4715573
E-mail: srinivas@csr.utexas.edu
Tel.: +1-512-4717587
E-mail: ries@csr.utexas.edu
Tel.: +1-512-4717486
E-mail: nagel@csr.utexas.edu
Tel.: +1-512-2327521
E-mail: pastor@csr.utexas.edu
Tel.: +1-512-4717579

1 Introduction

The GRACE (gravity recovery and climate experiment) satellite mission is a joint project between the US National Aeronautics and Space Administration (NASA) and the Deutsches Zentrum für Luft- und Raumfahrt (DLR). The primary objective of the GRACE mission is to map, with unprecedented accuracy, the long- to medium-wavelength spherical harmonic coefficients of the Earth's gravitational field and to observe its temporal variations (Tapley et al. 2004). The twin GRACE satellites were launched on 17 March 2002 into near-polar orbits with an initial altitude of about 500 km.

For precise orbit determination (POD) and gravity field recovery, both GRACE satellites are equipped with several scientific instruments: a BlackJack GPS receiver, a SuperSTAR accelerometer, a star tracker, a K-band ranging (KBR) system and a satellite laser ranging (SLR) retroreflector. The BlackJack receiver (Dunn et al. 2003) is an advanced codeless, dual-frequency flight GPS receiver developed by the Jet Propulsion Laboratory (JPL). The BlackJack receivers onboard each GRACE satellite (GRACE-A and GRACE-B) use up to 16 channels: up to 12 for POD and the remaining 4 for occultation measurements. The average number of GPS satellites actually tracked is usually about 10. The sampling rate of the GPS P-code pseudorange and carrier-phase data is 10 s (0.1 Hz).

The SuperSTAR (super space tri-axis accelerometer for research missions) accelerometer, manufactured by ONERA, measures the non-gravitational accelerations such as atmospheric drag and solar radiation pressure. This information was deliberately not used in this analysis so that we could investigate the orbit accuracy that can be achieved from GPS only for satellites without such an instrument onboard. The star tracker measures the precise satellite attitude, required to translate the spacecraft reference frame to the inertial reference frame for the inclusion of accelerometer data. In addition, the attitude data is used for the precise center-of-mass offset corrections for the KBR and SLR data.

The SLR data provides an independent evaluation of the GRACE POD results. For the GPS-only-based GRACE POD, we use the GRACE attitude nominal model instead of the attitude data because the GRACE attitude control is very accurate (0.4°) and the GRACE GPS receiver antenna is just above (along the radial) the satellite's center of mass (0.450 m). The effect of incorrect attitude is only about 0.1 mm.

With the successful use of GPS-only-based POD, more satellites are expected to carry onboard GPS receivers to support their orbit accuracy requirements (e.g. Kuang et al. 2001; Kang et al. 2003; Boomkamp and Koenig 2005; Zhu et al. 2005), which may range from hundreds of meters to a few centimeters. Usually, geodetic and oceanographic satellites (such as ICESat, JASON-1, CHAMP, GRACE and GOCE) have more stringent orbit accuracy requirements. The knowledge gained from the GRACE POD experiences can be applied to other similar satellite missions. The precise GRACE orbits can be used for such purposes as improving gravity recovery from the KBR data (e.g. Han 2004) and atmospheric profiling (e.g. Wickert et al. 2005), and they demonstrate the quality of the background force models being used. Based on those motivations, we investigate how well the GRACE orbits can be determined using only GPS data and force models, particularly with the use of a greatly improved geopotential model, GGM02C (Tapley et al. 2005).

Since the launch of the GRACE satellites, many authors have investigated the GPS-based POD for GRACE as well as it predecessor CHAMP (challenging minisatelltie payload) (Bertiger et al. 2002; Kang at al. 2003; Zhu et al. 2004; Švehla and Rothacher 2005). They use different methods (kinematic, dynamic and reduced-dynamic orbit determination), different observation types (undifferenced and double-differenced GPS measurements) and different data processing strategies. The main differences between our old and new GRACE POD investigations are the gravity models (GGM01C versus GGM02C), ocean tide models (CSR 4.0 versus FES2004), arc lengths (30 vs 24 h) and test data sets (5 days vs 4 months). In addition, we also used the de-aliasing products (Flechtner 2003) representing the non-tidal gravitational contributions from the atmosphere and the oceans in our GRACE POD for reducing the effects of the high (temporal) frequency gravity variations on the GRACE orbits.

This paper describes the POD methodology for the GRACE mission using only the high-accuracy GPS tracking data together with force models. The study was performed using the Center for Space Research (CSR) Multi-Satellite Orbit Determination Program (MSODP), which is based on a dynamic orbit determination method utilizing the batch processing approach (Rim 1992). The data used are GRACE level 1B products, produced by NASA JPL (Case et al. 2004). The suite of tests discussed in this paper indicate the GPS-based dynamic orbits have about 1-cm radial orbit accuracy and better than 2.5 cm accuracy in the along-track and cross-track directions. The orbit accuracy is evaluated by analyzing GPS tracking observation residuals and orbit overlaps, by confirmation of the orbit solution with independent SLR tracking (cf. Pearlman et al. 2002; Choi et al. 2004), and by computing KBR residuals.

2 Dynamic orbit determination

The use of GPS-SST (global positioning system satellite-to-satellite tracking) for low-Earth satellite orbit (LEO) determination is currently 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. However, there are a variety of orbit determination methods for LEOs using GPS-SST data. One is the traditional dynamic method (e.g. Kang el al. 2002; Zhu et al. 2005), which relies on physically accurate force models and adjusting a relatively small number of force model parameters as part of the orbit solution process.

The second method is kinematic orbit determination (e.g. Švehla and Rothacher 2005), which requires only the geometric information contained in the GPS observations. The third method is the 'reduced dynamic' orbit determination technique, which balances the contributions from the force model and the geometric information (e.g. Wu et al. 1991). However, 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 (Choi et al. 2004).

For our GRACE orbit determination, we have used the dynamic orbit determination method, but with an aggressive force model parameterization (such as estimation of many empirical parameters in POD) (Kang et al. 2003). Using this method, force model parameters, such as the atmosphere drag coefficient and 1-cycle-per-revolution (1-cpr) empirical acceleration parameters, could be adjusted in order to obtain more precise orbits. The 1-cpr empirical accelerations are particularly effective in accommodating dynamical modeling deficiencies to improve the orbit accuracy (Tapley et al. 1994). 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 lengths and parameterization choices), as well as the accuracy of the GPS tracking data.

3 Data processing

The GRACE GPS data are processed in the form of double-differenced (DD) carrier-phase converted range measurements using a network of 51 International Global Navigation Satellite System (GNSS) Service (IGS) (Beutler et al. 1999) ground stations. These sites were selected based on the IGS reported station performance and their good geographical distribution (Ferland 2001). Also, the 2000 realization of the International Terrestrial Reference Frame, ITRF2000 (Altamimi et al. 2002) includes these 51 stations. The IGS 'final' orbits of the GPS satellites are used in our GPS data processing, although corrections to selected orbital elements (eccentricity, inclination, argument of perigee and longitude of ascending node) are estimated to accommodate the remaining GPS satellite orbit errors (Rim et al. 1995). Three daily IGS-GPS final orbits are concatenated into one orbit file and the middle 30-h orbits are used for the 30-h arc GRACE data processing.

There are many issues to be considered in POD data processing. Two of the important issues are arc length and parameterization. The selection of the arc length depends on the force and measurement model errors. In general, the effects of the force model errors (geopotential, drag, solar pressure, etc.) on the orbit increase with increasing arc length. On the other hand, the effects of the measurement model errors (measurement noise, GPS ephemerides, etc.) can be reduced or smoothed by increasing the arc length. Based on our experiences from processing TOPEX (TOPography Experiment) and CHAMP GPS data (Rim 1992; Kang at al. 2002), 24-h and 30-h arc lengths were selected for comparison here.

For the force and measurement model parameterization, the first question is what type of parameters should be selected for estimation. Next, the sub-arc length (the interval of time within the arc that a particular parameter spans) and a priori values for estimated parameters must be chosen. For our POD, the estimated parameters are the GRACE satellite initial positions and velocities, DD ambiguity parameters, troposphere zenith delays, center of mass offset in the nadir direction, atmosphere drag parameters, 1-cpr transverse (along-track) and normal (cross-track) empirical accelerations, and the previously mentioned GPS orbit element corrections.

This heavy parameterization produces a very precise orbit and good fits to the GPS tracking data. Outputs from the POD process are the satellite ephemerides and the GPS DD carrier-phase observation residuals. These outputs are used to further understand the quality of the orbits and observation data. SLR data residuals computed relative to the fixed orbits obtained from POD provide an independent assessment of the orbit accuracy. Table 1 summarizes the model standards adopted for the GPS-only GRACE orbit determination.

Selecting the parameters to be estimated is one of the main questions for high-precision POD. The criteria we use are: (1) the estimated parameters should be effective in reducing or accommodating the errors in the dynamical or measurement models; and (2) the correlations between the estimated parameters should not be too high (<0.99) (Kang 1998). The first criterion means that the adjusted parameters have a sufficiently beneficial impact on the orbit accuracy. The second criterion ensures that the orbit fit is not over-parameterized, which can lead to unstable orbit solutions. Of course, the selection of parameters and arc lengths is also based on past experience and many tests (e.g. Kang et al. 2003).

4 Results and discussion

Approximately one hundred and twenty 24-h and 30-h arcs (1 July 2003–31 October 2003) were processed. The GPS data during the period appeared normal and there were not many data gaps. For our data processing, the GPS satellite antenna offsets provided by the IGS (Kouba 2003) were used. The initial antenna height (offset from the center of mass along the radial) for the GRACE onboard GPS receiver was 0.450 m based on our determination. The offset values for the SLR retroreflector provided in the current GRACE Level-1B products (Case et al. 2004) were used. The following sections summarize the POD results and the orbit accuracy evaluations.

4.1 Orbital fits and SLR residuals

The orbital fits to the GPS tracking data (observation residuals) permit the estimation of the quality of the force and observation models used in the dynamical orbit determination. If the forces and observations were modeled perfectly, the orbital fits would be at the level of the data precision. As an independent evaluation of the orbit quality, SLR data were processed to compute laser range residuals relative to the fixed GRACE orbits.

At first, the effects of the GPS orbital element corrections on the orbital fits and SLR residuals were investigated using 1-week of GPS data with a 30-h arc length to determine if we still need to estimate these corrections in the POD. Table 2 shows the effects. We can see that better GPS DD RMS, as well as better SLR RMS, can be obtained with the corrections. Therefore, the corrections should be estimated even though we have good IGS GPS final orbits. This also means that the GPS orbit errors are still one of the main error sources in the GPS-based POD.

Figures 1 and 2 show the GRACE-A and GRACE-B GPS DD RMS and RMS of the SLR residuals for the 24-h and 30-h arcs, respectively. The short-period variations in the fits are suspected to be residual gravity modeling errors (either in GGM02C or some other part of the background gravity model). The long-period variation may reflect variations in the surface forces, especially drag, but also solar radiation pressure as the angle of the orbit plane relative to the Sun slowly changes.

Table 3 summarizes the mean GPS DD RMS and RMS of the SLR residuals. According to these results, there are no significant differences between the different arcs, but there are some differences. The GPS DD RMS for the 30-h arc data processing is slightly smaller than that for the 24-h arc. As noted previously, the effects of the force model errors on the orbit tend to grow with the arc length, while the effects of the measurement model errors are reduced or smoothed by increasing the arc length.

In this case, the decrease of the effects of the measurement model errors (measurement noise, GPS orbit and antenna offset errors, etc.) on the GRACE POD appears to outweigh the increase of the effects of the force model errors (gravity, ocean tide, etc.) when going from 24-h to 30-h arcs. This may be because we have a very good mean gravity field model and other background models, and we used a heavy parameterization for the empirical accelerations. The other reason may be that the GPS orbit and antenna offset errors may be an important limitation of the GPS-based POD. We will investigate this problem in the future.

Table 1 POD model and data standards for GRACE

Force model	Description
Mean Earth gravity	GGM02C (120×120) (Tapley et al. 2005)
Non-tide ocean and atmosphere	ECMWF atmosphere and barotropic ocean model (Flechtner 2003)
N-body	JPL DE 405 (Standish 1998)
Solid earth tides	IERS 2003 conventions (McCarthy and Petit 2004)
Ocean tides	FES2004 (a recent update to FES2002; Le Provost 2002)
Pole tide	IERS 2003 conventions (McCarthy and Petit 2004)
Relativity	IERS 2003 conventions (McCarthy and Petit 2004)
Earth radiation pressure	Albedo and infrared (Knocke el al. 1988)
Atmospheric drag	Density temperature model (DTM) (Barlier et al. 1978)
Solar radiation	Box-wing model (Rim 1992)
Reference frame	
Conventional inertial reference frame	J2000.0 (McCarthy and Petit 2004)
Precession and nutation	IERS 1996 conventions (McCarthy 1996)
Earth orientation	IERS C-04 (Gambis 2004)
Station coordinates	ITRF2000 (Ferland 2001)
Tracking data	
GPS tracking data	Double-differenced, ionosphere-free combination of L1 and L2 carrier phase, 30 s sampling
GPS orbits	IGS final GPS ephemerides
Estimated parameters	
GRACE initial state	3D epoch position and velocity
GPS carrier phase ambiguity	One per combination per pass
Troposphere zenith delay	One per station in a 2.5-h arc
Empirical 1-cpr transverse and normal accelerations	1-cpr accelerations per revolution (10^{-4} mm/s^2 a priori)
Drag coefficient (C_d)	One per orbital revolution
GPS satellite orbit element corrections	One per arc for selected orbit elements
GRACE GPS antenna correction	One per arc in nadir (*Z*) direction

Table 2 Effects of GPS orbital element corrections on the GPS DD RMS and SLR RMS (cm) for 1–7 Sept. 2003

	GPS DD RMS		RMS of SLR residuals	
	With corrections	Without corrections	With corrections	Without corrections
GRACE-A	0.84	0.88	2.29	2.54
GRACE-B	0.85	0.91	2.39	2.43

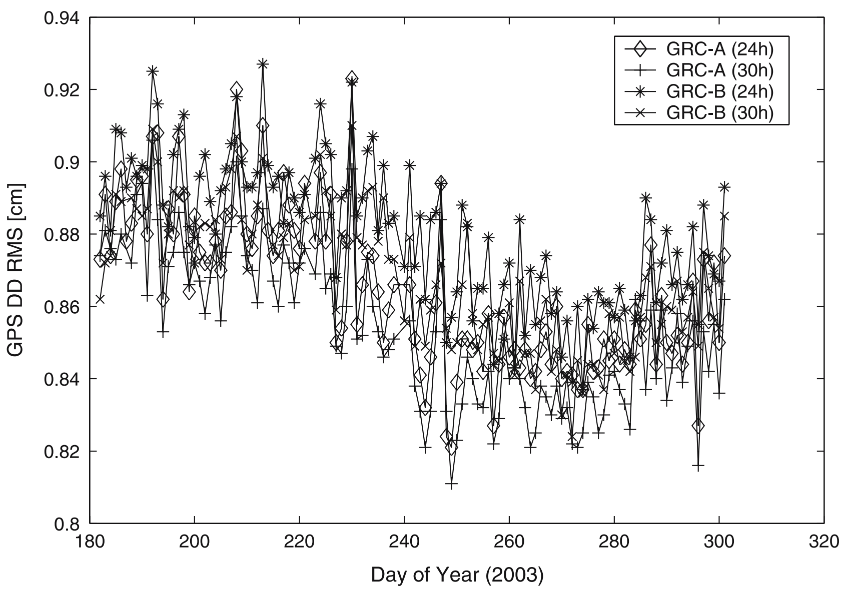

Fig. 1 GRACE-A and B GPS DD RMS for 24-h and 30-h orbit solutions

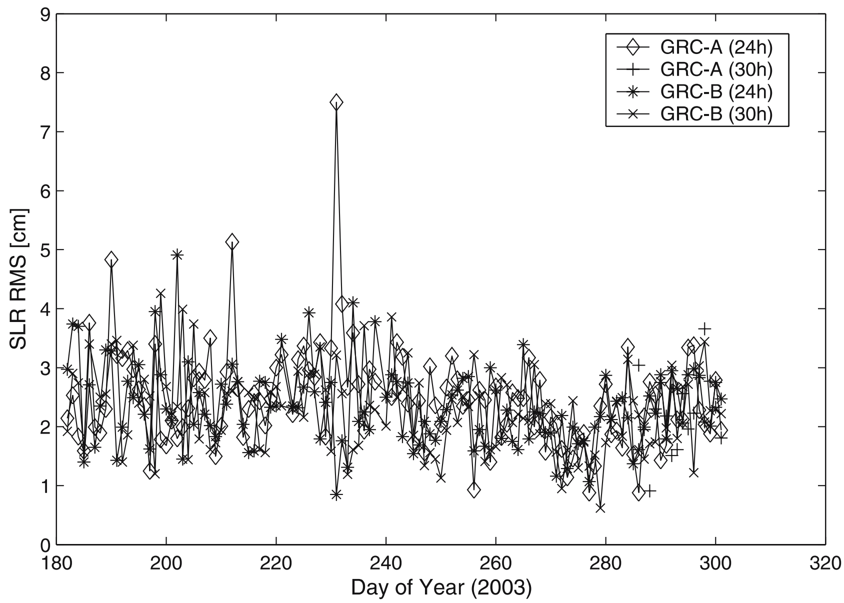

Fig. 2 GRACE-A and B SLR RMS for 24-h and 30-h orbit solutions

The GPS DD RMS should be less than 1 cm, according to the claimed noise level of BlackJack carrier-phase observations (less than or equal to 5 mm). The actual RMS for a 30-h arc length is 0.85 cm for GRACE-A and 0.87 cm for GRACE-B. Therefore, we have very good orbit fits for GRACE and a high-quality of force and observation models.

From Figs. 1 and 2, we can see that there are systematic changes for both GPS DD and SLR RMS. This is mainly because the GRACE satellites undergo different forces (such as air drag, attitude control) for different periods. Important is the relationship between the GPS DD RMS and SLR RMS: if the GPS DD RMS is small and stable, the SLR RMS is also small and stable.

Table 3 shows the RMS of the SLR residuals with a 10-degree elevation cutoff for four months of SLR data. For 30-h arcs, only the middle 24-h orbits were used for computing the SLR residuals. After the 10° elevation cutoff, there were about 13,000 SLR observations from 23 SLR stations for both GRACE satellites (about 110 data points and 6 passes per day). The resultant residuals can be analyzed on a pass-by-pass basis to assess the radial and along-track orbit accuracy (and to a limited extent, cross-track).

The orbit error analysis can be traced to the “Guier plane” navigation solution (Wells 1974). The adjustment of the station position in the plane formed by the line-of-sight and the velocity at the point of closest approach of the pass is equivalent to an adjustment of the orbit in the Guier plane, but in the opposite direction (Davis et al. 1997). In SLR parlance, this had been denoted as the range bias and the time bias, where the apparent time bias is equivalent to an along-track orbit error. If the station location errors are small and the SLR data have negligible biases and time biases, then the resulting navigation solution represents the orbit error along the line-of-sight and, perpendicular to that, the along-track error. The orbit error perpendicular to the Guier plane is poorly observed, so this analysis does not capture the entire orbit error.

When the maximum elevation of the pass is near zenith, the range bias becomes a strong measure of the radial orbit error (Tapley et al. 1994). For such passes, the separation between the range bias (radial orbit error) and the time bias (along-track orbit error) is the strongest, leading to a confident determination of the along-track orbit error as well. The cross-track orbit error is completely unobserved in high-elevation passes, but some part of its contribution is observed with the low-elevation passes.

Thus, by analyzing high-elevation passes for the range and time biases and the low-elevation passes for the overall variance of the SLR residuals, a reliable estimate of the radial and along-track orbit errors is obtained, as well as some measure of the level of cross-track orbit error. Since the latter is less well determined, we typically emphasize the radial and along-track error statistics, but it is not possible for the cross-track orbit errors to be very large while still maintaining few centimeter SLR residuals for all passes. It is our experience that, except in some especially peculiar situations, the cross-track orbit error tends to be comparable to the along-track error.

The outlier detection threshold of the SLR analysis is that both three-sigma editing (within each pass) and an allowed maximum (20 cm) were used. Looking at only the radial component of the SLR residuals in Table 3, we can see an RMS of 1.1 cm for GRACE-A for 30-h arcs and 0.9 cm for GRACE-B. For the SLR residuals, the bias was generally less than 1 cm.

Table 3 GRACE-A and B GPS DD RMS and SLR RMS (cm). SLR range and time biases statistics limited to passes with high maximum elevation (>70°)

	24-h arc		30-h arc	
	GRACE-A	GRACE-B	GRACE-A	GRACE-B
GPS DD RMS	0.86	0.88	0.85	0.87
SLR RMS (total)	2.5	2.4	2.5	2.4
Number of SLR data points	13,024	12,929	13,024	12,929
SLR range bias RMS (radial component)	1.1	1.0	1.1	0.9
SLR time bias RMS (transverse component)	2.1	1.8	2.2	1.6

(Note: time bias converted to units of distance)

4.2 Orbit overlaps

The orbit differences during the overlapping time period can be used as a test of orbit precision and an indicator of orbit accuracy. The precise orbits for GRACE satellites are produced with 30-h data arcs on 24-h centers, providing a 6-h overlap. Figures 3 and 4 show histograms of the overlap RMS over full 6-h overlaps for GRACE-A and GRACE-B, respectively. The statistics peak around the median values and are not normally (Gaussian) distributed. The median RMS values in radial, along-track and cross-track directions are 0.8, 1.7 and 1.0 cm, respectively, for GRACE-A and 0.9, 1.9 and 1.1 cm for GRACE-B.

In order to see the edge effects on the overlap statistics, two different overlap periods (central 5 h and full 6 h) were used. Tables 4 and 5 summarize the orbit overlap statistics. The overall RMS values for GRACE-A are 1.0 cm in radial direction, 1.9 cm in along-track and 1.2 cm in cross-track, and 1.1, 2.0 and 1.2 cm for GRACE-B, respectively. The mean values are relatively small compared to the RMS values. This means that there are no large biases for the overlap orbits.

From Tables 4 and 5, we can see that there are large RMS differences between the central 5-h and full 6-h overlaps, particularly in the radial direction (e.g. the RMS changes from 1.0 to 0.6 cm for GRACE-A). This is due to the edge effects. Because the overlap statistics using the full 6-h overlap period is closer to the independent test (SLR residuals), these orbit test results are probably more realistic.

4.3 Orbit connecting points

When providing orbit products, the quality of orbit connecting points (arc end points) can be a useful indicator of the overall orbit quality. Usually, if one produces the orbit products with the same time period as the data processing arc length, one cannot have a smooth connection among orbits due to the edge effects. To solve this problem, we can use the overlap method.

Figures 5 and 6 show the orbit differences at the connecting points of the 24-h arcs (solar day boundary) of the 24-h processing and the 30-h processing, respectively. There are larger orbit differences for some points of the 24-h data processing (Fig. 5). Tables 6 and 7 summarize the orbit connecting point statistics for both GRACE-A and GRACE-B. Because of the edge effects, the analysis of orbit connecting points at day boundaries yields a pessimistic estimate of the orbit accuracy for 24-h arcs.

The RMS values for the connecting points in radial, along-track and cross-track directions are respectively 4.0, 4.2 and 1.8 cm GRACE-A for the 24-h processing. However, the RMS values are only 0.6, 1.5 and 1.1 cm for the 30-h processing (Fig. 6). The mean values are relatively small compared to the RMS values. This means that there are no large biases for the orbit connecting points.

The RMS values for the orbit connecting points of the 30-h data processing are nearly the same as those of the orbit overlaps (Table 4). This is because the connecting points are within the overlaps. Therefore, the ends of the orbit solutions are not well constrained by the tracking data, and it is typical to use the 24-h span within a 30-h orbit solution to avoid this.

4.4 KBR residuals

One of the key science 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 μm for KBR range and 1 μm/s for KBR range rate with a 5 s data interval. The KBR data are used mainly for gravity field recovery. However, the KBR data residuals computed by fixing the GRACE POD orbits can be used for evaluating the relative orbit accuracy of the GRACE satellites.

For comparison, two different 24-h GRACE orbits were used for computing KBR residuals. One is from the 24-h arc data processing; the other is the middle 24-h from the 30-h arc. Table 8 summarizes the RMS of the KBR residuals for the 24 and 30-h data processing. The KBR residuals indicate the relative orbit accuracy. The 30-h arcs appear to be slightly better than the 24-h arcs for KBR residuals. The relative accuracy between the two GRACE satellites is about 1.0 cm in position, 10 μm/s in velocity and 90 nm/s^2 in acceleration.

5 Conclusion

The main goal of this paper was to investigate how well the GRACE satellite orbits can be determined using only GPS data and based on the current models and methods at CSR. To

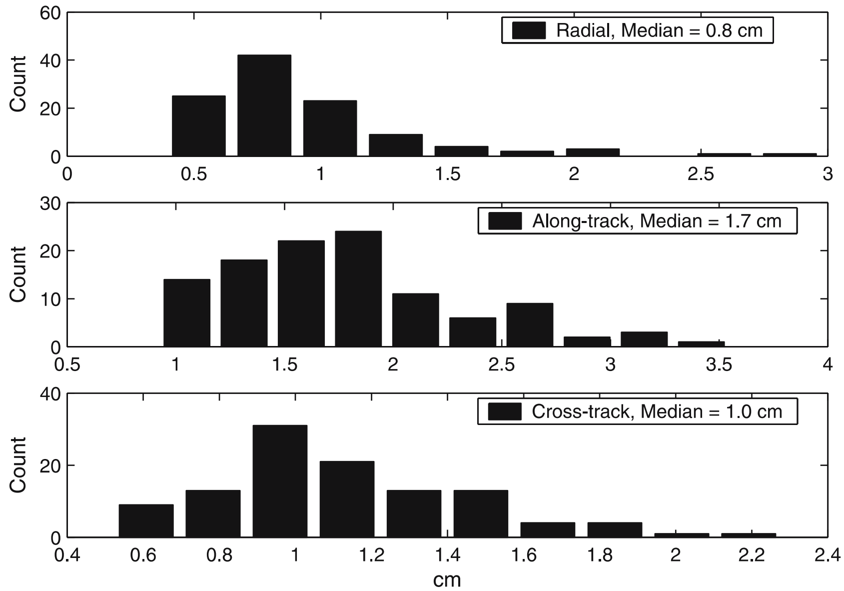

Fig. 3 Histogram of GRACE-A orbit overlap RMS for 30-h data processing

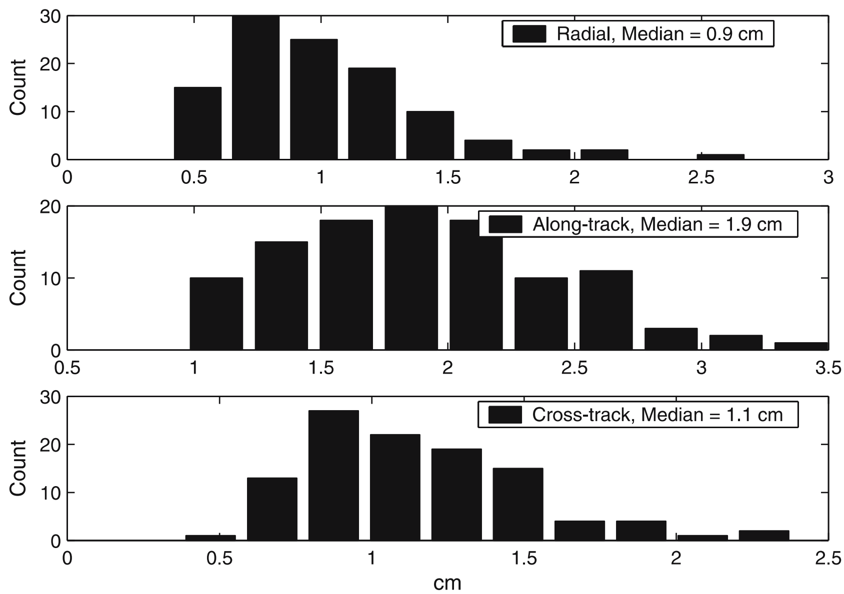

Fig. 4 GRACE-B orbit overlap RMS for 30-h data processing

Table 4 GRACE-A orbit overlap (cm)

	Full 6-h overlap			Central 5-h overlap		
	Radial	Along-track	Cross-track	Radial	Along-track	Cross-track
Mean	0.1	0.9	0.1	0.1	0.8	0.1
RMS	1.0	1.9	1.2	0.6	1.6	1.0

Table 5 GRACE-B orbit overlap (cm)

	Full 6-h overlap			Central 5-h overlap		
	Radial	Along-track	Cross-track	Radial	Along-track	Cross-track
Mean	0.1	0.9	0.1	0.1	0.9	0.1
RMS	1.1	2.0	1.2	0.6	1.7	1.1

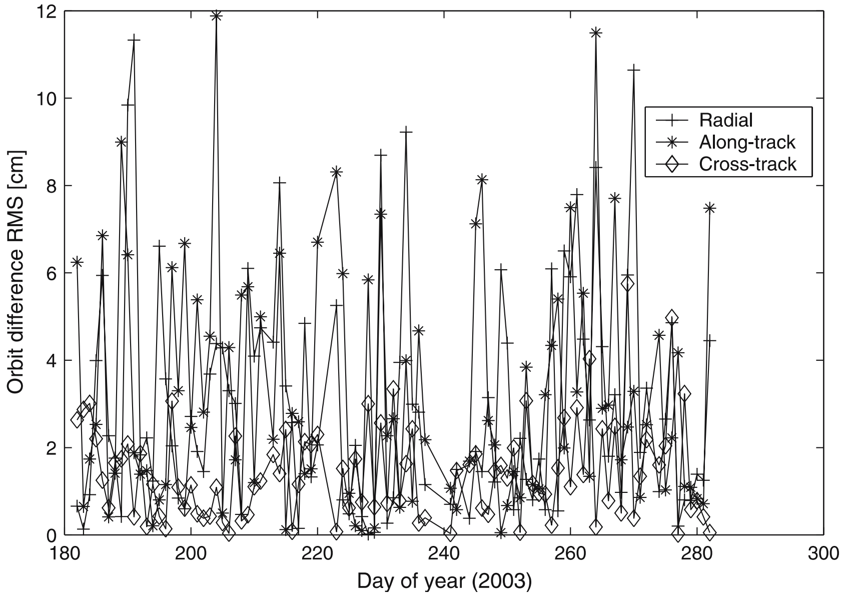

Fig. 5 GRACE-A connecting point orbit difference for 24-h data processing

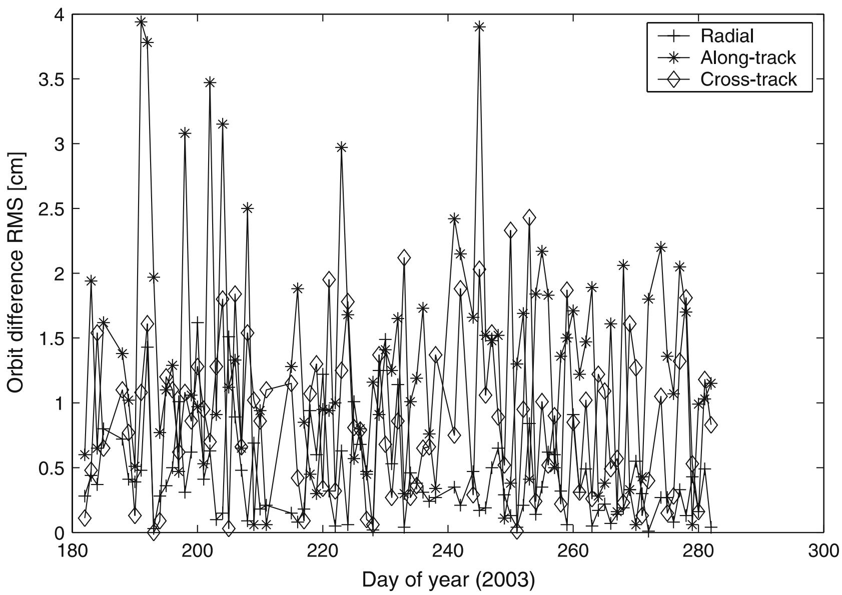

Fig. 6 GRACE-A connecting point orbit difference for 30-h data processing

Table 6 GRACE-A orbit connecting points (cm)

	24-h data processing			30-h data processing		
	Radial	Along-track	Cross-track	Radial	Along-track	Cross-track
Mean	0.3	0.2	0.3	0.1	0.2	0.3
RMS	4.0	4.2	1.8	0.6	1.5	1.1

Table 7 GRACE-B orbit connecting points (cm)

	24-h data processing			30-h data processing		
	Radial	Along-track	Cross-track	Radial	Along-track	Cross-track
Mean	0.8	0.2	0.1	0.0	0.2	0.3
RMS	4.2	4.2	2.1	0.6	1.6	1.3

Table 8 GRACE KBR residuals

Arc length (h)	KBR range (cm)	KBR range rate (μm/s)	KBR range acceleration (nm/s^2)
24	1.05	9.96	93.10
30	0.98	8.90	81.59

achieve this goal, the challenge was not only how to produce the orbits, but also how to assess the orbit accuracy. Therefore, proper assessment of orbit accuracy, development of the best strategies for POD, and characterization of the orbit errors were the main tasks of the article.

Based on the various tests (orbit fits, SLR residuals and orbit overlap), an accuracy of about 1.0 cm in the radial direction and better than 2.5 cm in the along-track and cross-track directions has probably been achieved for our GRACE orbits. According to the KBR residuals, the relative accuracy between the two GRACE satellites is about 1.0 cm in position, 10 μm/s in velocity and 90 nm/s^2 in acceleration. There are only small differences between the 24 and 30-h arc lengths, but the 30-h arcs provided a smoother connection between the individual GRACE satellite orbits. Note however that all these values apply to our limited test period from 1 July 2003 to 31 October 2003 (approximately 120 arcs).

The orbit accuracy achieved for GRACE using only GPS data is a direct result of many improvements made in the data quality, mean gravity model and background models. Further orbit accuracy improvement can be realized by improvements in force models, GPS orbits and GPS satellite antenna offsets, by fixing ambiguity parameters and by using improved antenna phase center correction maps.

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