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Performance Assessment of the Earth's Gravity Field Models in Precise Orbit Determination of LEO Satellites

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Abstract

Dynamic orbit determination is the conventional technique that has been commonly used for precise orbit determination (POD) of satellites at various orbital altitudes. The performance of this technique is mainly limited by inaccurate modelling of force perturbations acting on satellites. The perturbations include the Earth's gravity field, atmospheric drag, solar radiation pressure etc. Due to the fact that low Earth orbit (LEO) satellites are highly sensitive to the Earth's gravity field, the accuracy of the gravity field model used in the dynamic POD technique directly affects the accuracy of POD of LEO satellites. Therefore, selection of an accurate gravity field model for improving the POD accuracy plays a significant role in meeting the stringent requirements of space applications such as radio occultation, remote sensing and altimetry. Nowadays, with the successful launches of the CHAMP,GRACE and GOCE gravity missions, various high accuracy gravity field models have been developed and made publicly available at the International Centre for Global Earth Models (ICGEM).

In this study, the performance of13 selected gravity models applied in the dynamic POD was assessed using space-borne dual-frequency GPS measurements from the twin GRACE satellites during the period from 1st to 31st March 2008, and the effects of time-varying low-degree spherical-harmonic coefficients C_{20} , C_{30} and C_{40} on POD for the twin GRACE satellites were also analysed. The results of tracking data residuals, orbital overlap, external orbit comparison and independent satellite laser ranging (SLR) validation demonstrated that the highest POD accuracies of GRACE-A and -B are about 2.1 cm and 2.7 cm with respect to SLR measurements respectively and this is achieved using those combined models ,i.e. EIGEN-51C, GO_CONS_GCF _2_DIR_R3, andGOCO03S.In addition, a comparison of the orbits generated with and without the time-varying gravity field indicates that orbit variability caused by the time-varying component of EIGEN-GL04S1 was at a few mm level, suggesting that the time-varying low-degree spherical-harmonic coefficients do not lead to a notable variability in orbit quality

Keywords: gravity field model, LEO, dynamic orbit determination, GPS, GRACE

1. Introduction

In 1957, the first artificial Earth satellite, Sputnik 1, was successfully launched into space by the former Soviet Union. It not only marked the start of the Space Age, but also heralded new and rapid technological and scientific developments in space. So far, there are more than 3,000 satellites operating in the Earth's orbit, according to the US National Aeronautics and Space Administration (NASA), out of roughly 8,000 man-made objects in total for a variety of applications. Generally, the trajectory of these satellites, particularly those in LEO with high-accuracy scientific applications, such as radio occultation [*Hwang et al.*, 2009; *Zhang et al.*, 2011; *Zhang et al.*, 2013], remote sensing [*Montenbruck et al.*, 2006b], sea level monitoring [*HAINES et al.*, 2004], the Earth's gravity field recovery[*Visser et al.*, 2009],need to be determined at a certain accuracy. Taking satellite altimetry as an example, the satellite orbit error tends to be propagated into the measurements of radar altimeter, which in turn will contaminate their geophysical products such as the synoptic mapping of ocean topography, determination of global mean sea level and sea-level change, and solutions for ocean tides. Consequently, POD is the fundamental and critical prerequisite for many space applications.

To date, several tracking systems are capable of supporting satellite POD in a wide altitude range. This includes SLR, DORIS (Doppler Orbitography and Radio positioning Integrated by Satellite), and GPS (Global

Positioning System). Among these, GPS has the distinctive features of high-precision, all-weather, continuity, global coverage, and low cost. It has been considered as an emerging and indispensable technique for POD of LEO satellites since its first and extremely successful application on TOPEX/Poseidon satellite in 1992[*Schutz et al.*, 1994; *Tapley et al.*, 1994].During the last decade, numerous LEO satellites, including CHAMP(CHAllanging Minisatellite Payload), GRACE (Gravity Recovery And Climate Experiment), GOCE(Gravity field and steady-state Ocean Circulation Explorer mission), Jason-1/2, etc. at the altitude range from 400 km to 1300 km carried high-performance dual-frequency GPS receivers on-board to meet the increasingly stringent requirements of orbit accuracy imposed by the missions' scientific objectives[*Bock et al.*, 2007; *Kang et al.*, 2003; *Lemoine et al.*, 2010; *Reigber et al.*, 2002b].

Apart from the quality of satellite tracking data, the orbit determination technique is another critical factor for obtaining high-accuracy orbit. Generally, there are three POD techniques for LEO satellites based on GPS measurements, namely dynamic, reduced-dynamic and kinematic approaches. Among them, the dynamic orbit determination is the conventional and most widely used technique. Its quality depends on the availability, distribution and quality of tracking data, and the accuracy of force models such as the Earth's gravity field, atmospheric drag, and solar radiation pressure. Nowadays, with the advances in space technologies, the performance and capability of GPS has been significantly improved, thus the main limiting factor for LEO satellite POD is the modelling of the forces acting on satellites. The demand for accurate force models will continue to increase substantially with the rapid development in satellite navigation constellations of GLONASS (Russia), GALILEO (Europe), COMPASS (China) etc.Rim and Schutz[2002]demonstrated that the Earth's gravity filed is one of the dominant errors affecting orbit determination for satellites at an altitude under 600 km. Hence, the improvements of the Earth gravity field model will benefit orbit determination quality enormously.

In an effort to improve the accuracy of satellite orbit determination by more accurately modelling of the Earth gravity field, extensive work has been conducted by many researchers. In 2000, the era of dedicated satellite gravity missions began with the launch of CHAMP, followed by the launches of GRACE in 2002, and GOCE in 2009.These missions have revolutionized our knowledge of the Earth's gravity field, and a significant number of improved gravity field models have been and will be developed, due to1) new and robust algorithms, 2) availability of new data (quality and quantity), and 3) technological advancement (new advanced satellite missions).This study aims at assessing the performance of currently available Earth's gravity field models generated using various data sources in dynamic POD of the GRACE satellites by making use of their highly precise dual-frequency GPS measurements.

This paper is organized as follows: section 2 presents a brief overview of the selected Earth's gravity field models and the space-borne GPS data used in this study; section 3 introduces the dynamic orbit determination strategy and the two components of gravity field models, namely static and time-varying gravity fields; section 4 assesses the performance of the static gravity field models in dynamic orbit determination for the GRACE satellites; section 5 analyses the effects of the time-varying component of low-degree spherical harmonics on the dynamic orbit solutions, and the conclusion of the paper is summarized in section 6.

2. Data Description

2.1 Earth gravity models

All the Earth's gravity field models used in this study are obtained from the International Center for Global Earth Models (ICGEM, http://icgem.gfz/potsdam.de/ICGEM /ICGEM.html), which is one of the six centres of the International Gravity Field Service (IGFS) and the International Association of Geodesy (IAG). The IGFS was established by the IGA-Executive Board at the 2003General Assembly and is an IAG "level-2" Service under IAG Commission 2[*Barthelmes and Köhler*, 2010].The main tasks of the ICGEM include: 1) collecting and archiving of all existing global gravity field models; 2) web interface for getting access to global gravity field models; 3) web-based visualization of the gravity field models for their differences and their temporal variation; 4) web-based service for calculating different functions of the gravity field models; and 5) web site for tutorials on spherical harmonics and the theory of the calculation service.

Currently, a total of 122 models with their references are listed at the ICGEM. Apart from 17 old models, all the other models are available in the form of spherical harmonic coefficients. In this study, we selected 13 representative models from different product series and the detailed information is summarized in Table 1. The criteria of the selection are based on the data sources used in deriving gravity field models. These selected models are further classified into the following five cases: case-1: Pre-CHAMP models, which are generated without satellite gravity mission data); cases 2-4: satellite-gravity-mission-only models, which are derived with data from a single satellite gravity mission (CHAMP-only, GRACE-only, GOCE-only); case 5: combined models, which are produced with data from at least two satellite gravity missions. In addition, it is worth noting that GRIM5C1 is the best gravity field model available before the CHAMP mission launched, and it is an upgraded version of GRIMS1 with addition of terrestrial gravity data.

Table 1: The details of the Earth's gravity field models used in this study

Model	**Description**	**Max degree**	**References**
Pre-CHAMP			
GRIMS1	Multi-satellite only	99	*Biancale et al.* [2000]
GRIMC1	Multi-satellite + terrestrial gravity data	180	*Gruber et al.* [2000]
CHAMP-only			
TEG4	Combined: 80 days CHAMP + Multi-satellite and terrestrial gravity data	180	*Tapley et al.* [2000]
EIGEN1S	CHAMP-only: 88 days	115	*Reigber et al.* [2002a]
EIGEN-CHAMP05S	CHAMP-only: 6 years	150	*Flechtner et al.* [2010]
GRACE-only			
GGM01S	GRACE-only: 111 days GRACE	120	Tapley et al. (2004)
GGM01C	Combined: GGM01S +Multi-satellite and terrestrial gravity data	200	*Tapley et al.* [2004]
GGM03S	GRACE-only: 4 years	180	*Tapley et al.* [2007]
EIGEN-GL04S1	Combined: 30 months GRACE + 24 months Lageos-1/2	150	*Förste et al.* [2006]
GOCE-only			
GO_CONS_GCF_2_TIM_R3	GOCE-only: 12 months	250	*Pail et al.* [2011]
Combination			
EIGEN-51C	Combined: 6 years CHAMP+ 6 years GRACE +terrestrial gravity data	350	*Bruinsma et al.* [2010]
GO_CONS_GCF_2_DIR_R3	Combined: 350 days GOCE+ 6.5 years GRACE + 6.5 years Lages-1/2	240	Pail et al. (2011)
GOCO03S	Combined:8 years CHAMP + 7 years GRACE + 18 months GOCE+ 5 years SLR data (multi-satellite)	250	*Mayer-Gürr et al.* [2012]

2.2 Space-borne GPS measurements

The GRACE mission, launched in March 2002 as a joint project between NASA and DLR, has two identical satellites flying about 220 km apart in a polar orbit approximately 485kmabove the Earth. The primary scientific objective of GRACE is to measure the Earth's gravity field and its temporal variability with an unprecedented accuracy [*Tapley et al.*, 2004]. In order to achieve this objective, a K-band ranging system, a SuperSTAR accelerometer, a SLR retro-reflector array and a BlackJack GPS receiver were carried onboard each of the twin satellites of GRACE-A and -B.

In this study, the GRACE satellites were selected as our experimental satellites for two reasons 1) they are highly sensitive to the Earth's gravity field due to their low orbit altitudes and 2) the quality of their GPS measurements has been validated and demonstrated to be highly precise compared to other contemporary LEO missions equipped with high-performance dual-frequency GPS receivers [*Hwang et al.*, 2010; *Montenbruck et al.*, 2006a]. The GPS data for the period of 1−31March, 2008with 10-second sample intervals are obtained from the ISDC (Information System and Data Centre,http://isdc.gfz-potsdam.de/) of the GeoForschungsZentrum (GFZ) in Germany.

In addition, the orbit determination of LEO satellites is the focus of this study and GPS satellites' orbit and clock biases are held fixed in the estimation of LEO satellite orbits. As a result, the errors in GPS satellite orbit and clock products will affect our orbit solutions. In order to minimize these effects, the most accurate GPS orbit and clock products provided by the IGS (International GNSS Service, http://igscb.jpl.nasa.gov/)– the final GPS ephemeris products with 15-minute sample intervals and the high-frequency clock products with 30 seconds sample intervals are employed in this study.

3. Orbit Determination Strategy

3.1 Dynamic orbit determination

In the dynamic POD approach, all forces acting on a satellite are calculated from various models. Some of the force model parameters, such as the coefficients of the solar radiation pressure and atmospheric drag, are treated as dynamic variables and estimated with the initial state vector. These parameters are related to GPS measurements via variational partials. Once the numerical computation process converges, the final orbit, which is the best-fit solution, is obtained by using numerical integration with these newly estimated parameters and initial state vector.

The equation of motion of the satellite is generally expressed in the Earth centred inertial frame as:

$$\ddot{\vec{r}} = -\frac{kM}{r^3}\vec{r} + a(t,\vec{r},\dot{\vec{r}},\vec{p}) \qquad (1)$$

where,

- $\vec{r}$: the 3×1 satellite position vector in the inertial frame at time t;
- $\dot{\vec{r}}$: the velocity vector of the satellite at time t
- $\ddot{\vec{r}}$: total acceleration of the satellite at time t;
- kM: the product of the gravitational constant and the mass of the Earth;
- r : the magnitude of the position vector $\vec{r}$;
- a : the total perturbing force;
- t: time, at which the acceleration is calculated;
- $\vec{p}$: the dynamic parameter vector.

The sum of all perturbing forces can be categorized into gravitational and non-gravitational perturbations. The gravitational perturbations can be further decomposed into several different contributions: the effects of the non-sphericity of the Earth, the ocean tides, the Earth tides; and the effects due to the Earth's rotational deformation, the Third-body perturbations, and general relativity. The non-gravitational perturbations include the forces due to the solar radiation pressure, the Earth radiation pressure, the atmosphere drag, and/or some empirical force terms that normally account for all those unmodeled forces.

In this study, the dynamic orbit determination of GRACE-A and GRACE-B is performed on the platform of SHORDE which is a LEO POD software package developed by Shanghai Astronomical Observatory, the Chinese Academy of Sciences [*Peng and Wu*, 2007; 2008]. The strategies for dynamic orbit determination used in this study are summarized in Table 2.

The observations used in the POD are the ionosphere-free combination (L3) of the dual-frequency L1 and L2 phase data. Zero-differenced L3 is adopted to take full advantage of raw GPS observations. The detailed strategy of GPS data pre-processing and corrections for observation errors are referred to Peng and Wu [2012]. In addition, the same observations and POD strategy were used to avoid inconsistencies when assessing the performance of the selected gravity field models.

Additionally, both the arc length of orbit determination and the setting of unknown parameters could significantly affect the accuracy of dynamic orbits. The commonly accepted 30-h arc length is used as an optimal arc length for dynamic orbit determination for GRACE satellites using space-borne GPS data. The unknown parameters to be estimated include the initial state vector of GRACE-A and -B, one drag coefficient for each orbital revolution, once-per-revolution empirical coefficients in the transverse and normal directions, pass-by-pass float ambiguities of L3, and clock bias of GRACE-A and -Bin every 30 seconds.

Table 2: Summary of strategies for dynamic POD

Model	Standard
Earth gravity field	In Table1
Earth orientation parameter	IERS Bulletin B
Solid Earth tides	IERS Conventions (2003)
Ocean tides	CSR 3.0
Atmospheric density	DTM94
Third-body	Moon and Sun
Planetary ephemerides	JPL DE403
Relativistic correction	IERS conventions (2003)

3.2 Static and time-varying components in gravity fields

The Earth is not a rigid body, there exists mass transport between the atmosphere, ocean and solid Earth due to geophysical phenomenon (e.g. ocean circulation)and/or climate change (e.g. El Niño-Southern Oscillation, Antarctic ice melting).This mass redistribution results in time-variation of the Earth's gravity field with a spectrum ranging from hours to 18.6 years to secular. With the advancement of technology, the temporal variation in the Earth's gravity field is now detectable from the analysis of space geodetic measurements. For example, the GRACE mission is capable of mapping a gravity field model every 30 days and the monthly gravity field products are widely used in geophysical phenomenon and climate change studies. In the field of satellite orbit determination, a global-mean gravity field derived from a long period of measurements and/or all available data sources is usually used. Hence, all the 13 selected models introduced in section 2 are global-mean gravity field models.

Other than the GRACE mission, the long history of SLR measurements provides a unique dataset of observations that can be used for the analysis of geophysical changes. SLR tracking data has been used for precise determination of the temporal variation in the low-degree spherical-harmonic components of the Earth's gravity field models successfully. This approach has been widely used to generate the time-varying spherical harmonic coefficients in high accuracy global mean gravity field models. Specifically, if the time-varying spherical harmonics are not provided in a gravity field product, then it is sometimes referred as the static gravity field model, otherwise the gravity field product contains both the static and time-varying components.

Theoretically, using the improved knowledge of the time-varying gravity component in dynamic POD will further improve the accuracy of the POD. However, although the time-varying component is provided in some gravity field products, it is usually considered to be negligible since it is insignificant, compared to the static component. In this study, the effect of the time-varying component in gravity field models on POD of GRACE-A and -B is investigated.

As for theEIGEN-GL04S1 model, in addition to the static spherical harmonics coefficients completed to degree 150, the time-varying$\frac{d\overline{C}_{20}}{dt}$, $\frac{d\overline{C}_{30}}{dt}$, $\frac{d\overline{C}_{40}}{dt}$of the low-degree spherical-harmonicscoefficientsC_{20}, C_{30} and C_{40} have also been given. If the time-varying component is taken into account in POD, then the low-degree spherical-harmonic coefficients of the gravity field can be written as:

$$\overline{C}_{n0}(t) = \overline{C}_{n0}(t_0) + \frac{d\overline{C}_{n0}}{dt}[t - t_0](n = 2,3,4); \qquad (2)$$

where,

t : the time at which the position of the satellite is calculated;

t_0 : January 1, 2004;

$\frac{d\overline{C}_{20}}{dt} = +1.1628 \times 10^{-11}/year$;

$\frac{d\overline{C}_{30}}{dt} = +4.9000 \times 10^{-12}/year$;and

$\frac{d\overline{C}_{40}}{dt} = +4.7000 \times 10^{-12}/year$;

4. Performance Assessment of Static Gravity Fields in POD

4.1 Residuals of tracking data

One measure for the quality of an orbit generated by dynamic POD is how well it fits the tracking data. The RMS (Root-Mean-Square) of the residuals of tracking data is a commonly used indicator for both accuracy of the POD model and the quality of the tracking data. Since the same tracking data and the same POD strategy are used in our performance assessment of the selected gravity field models applied to the dynamic POD, the residuals' RMSs resulting from using different gravity field models are compared because the differences between any two sets of POD RMSs reflect the relative variability of performance of the two gravity field models in POD.

Figure 1 shows the RMS values of GPS data residuals of the POD using the 13 gravity field models. All the values are the mean of RMS values of the total 31 orbit arcs. The results demonstrate, as anticipated, that those gravity field models derived from satellite gravity missions have better fits than those derived from previous generation gravity field models (GRIM5S1 and GRIM5C1). For example, the EGEIN1S with only 88 days CHAMP data makes remarkable contributions (~ 1 order) to the improvement in the orbit precision (RMS of tracking data residuals), compared to the earlier pre-CHAMP models. Specifically, the improvement in orbit precision fromGRIM5C1 to EIGEN1S is17.5 mm to 9.3 mm for GRACE-A, and correspondingly, 15.5 mm to 7.6 mm for GRACE-B.

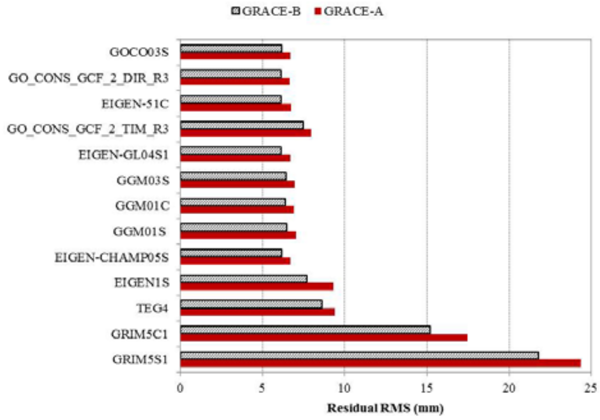

Figure 1: RMS of tracking data residuals

In addition, we can see from Figure 1 that both the CHAMP-only models (EIGEN1S and EIGEN-CHAMP05S) and the GRACE-only models (GGM01S and GGM03S) show an improvement in the orbit precision when a longer time period data is used in deriving the gravity field models .i.e., the RMSs of GRACE-A resulting from EIGEN-CHAMP05S with a 5-year period CHAMP data and EIGEN1Sbased on 88 days CHAMP data are about 6.7 mm and 9.3 mm respectively, while the corresponding values for GRACE-B are 6.1 mm and 7.7 mm.

The GRACE mission was designed to succeed the CHAMP mission in the era of the Earth's gravity field model determination, and the increase in the accuracy of gravity field models is anticipated to be achievable by utilizing two satellites following each other on the same orbital track. This anticipation has been validated and demonstrated in Figure 1. It shows that the GGM01S using only about 111 days GRACE data has an accuracy almost comparable with EIGEN-CHAMP05S that uses 5 years CHAMP data in dynamic POD for both GRACE-A and -B. However, the GOCE-only model, GO_CONS_ GCF_2_TIM_R3, with orbit precision about 8.0 mm and 7.5 mm for GRACE-A and -B respectively, is not as good as the GRACE-only models, but still remarkable, considering such a short span (12 months)of GOCE data used in deriving GO_CONS_GCF_2_TIM_R3.

Comparing the results shown in Figure 1from each of the cases mentioned in section 2.1, we can see that: 1) for case-1,the Pre-CHAMP models, the orbit precisions of GRACE-A are about 24.4 mm and 17.5 mm from GRIM5S1 and GRIM5C1 respectively, and the corresponding orbit precisions of GRACE-B are 21.8 mm and 15.2 mm. As we know that GRIM5C1 is an upgraded version of the GRIM5S1 with inclusion of terrestrial gravity data, therefore, we can conclude that the orbit precision is remarkably improved when the upgraded gravity model with inclusion of terrestrial gravity data is used. 2) For cases 2-4, the satellite-gravity-mission-only models, the orbit precisions of GRACE-A using GGM01S and GGM01C models are about 7.0 mm and 6.9 mm respectively, and the corresponding orbit precisions of GRACE-B are about 6.5mm and 6.4 mm. This indicates that the GGM01S model and its upgraded version GGM01C lead to the similar orbit precision, further inclusion of terrestrial gravity data in deriving the gravity model does not make significant contribution to orbit precision in the era of satellite gravity. 3) For case 5, combined models, the orbit precisions resulting from EIGEN-51C, GO_CONS_GCF_2_DIR_R3, and GOCO03Sare at the same level with mean RMSs of the 31 orbit arcs of about 6.7 mm and 6.1 mm for GRACE-A and -B respectively. Compared with results using these satellite-gravity-mission-only models, using the models derived from multiple satellite gravity missions makes further improvement in orbit precision.

4.2 Orbital overlap

In this study, our orbit solutions are generated in an arc length of 30-hr, as mentioned in section 3, and the beginning of each arcis3 hours before midnight of the day and the ending is 3 hours after midnight of the next day, for producing a 6-hr overlap from two consecutive orbit arcs. Although part of the data used for the POD of two consecutive arcs are common, it is widely accepted that the two solutions in the overlapping period are uncorrelated since they are calculated independently. Hence, the consistency of the two solutions over the overlapping period is often used to assess the quality of POD. However, it only indicates the orbit precision like the residuals of tracking data, rather than the orbit accuracy which is by comparisons with external data sources.

The discrepancies between two orbit solutions over the overlapping period are calculated in the radial (R), tangent (T) and normal (N) directions on an epoch-by-epoch basis. A statistical value–RMS of all epoch sin each of the three directions and the 3D RSS (Root-Sum-Square) are calculated by:

$$RMS_d = \left(\frac{\sum \Delta d^2}{n}\right)^{\frac{1}{2}} \quad (d = R, T, N) \tag{3}$$

$$3D\ RSS = (RMS_R^2 + RMS_T^2 + RMS_N^2)^{\frac{1}{2}}$$

Where, ΔR, ΔT, and ΔN are the orbit differences in the three directions and n is the total number of epochs with an interval of 60s.

Figure 2 shows the mean 3D RSS values over the overlapping orbits of all the 30 arcs, from which the following results can be seen: 1) the improvement in orbit precision is remarkable when the data from satellite gravity missions were used in deriving gravity field models; 2) the orbit precision tends to be at the same level from EIGEN-CHAMP05S to GOCO03S except forGO_CONS_GCF_2_TIM_R3. Among them, the highest precisions of GRACE-A and -B, which are about 3.3cm and 3.0cm respectively, are achieved by EIGEN-CHAMP05S, GO_CONS_GCF_2_DIR_R3,EIGEN_GL04S1, EGEIN-51C,and GOCO03S, matching with the conclusion of section 4.1.

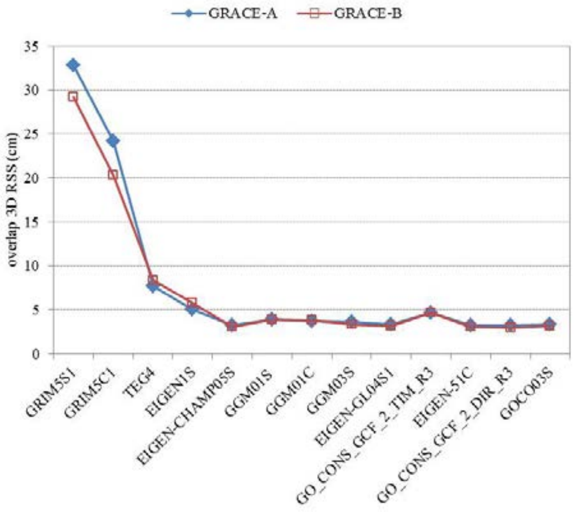

Figure 2: Mean 3D RSS of orbit differences over all overlapping periods of 30 arcs

Table 3 lists the precision of the overlapping orbits in the R, T, and N directions for the investigation over which orbital direction the orbit precision benefits the most from the improvement in the gravity field models. This table shows the following results 1) the orbit precisions in all the three directions benefit from the improvement in gravity models, and the benefit in the T direction is slightly larger than that in the other two directions; 2) among all the four GRACE-only models, EIGEN-GL04S has the best orbit precision, and the improvements in all the three directions are noticeable. It has been revealed that the harmonics of very-low degrees, e.g. degrees 2 and 3in particular cannot be estimated accurately with only GRACE data. However, the inclusion of SLR data from LAGEOS-1 and -2over the same time period as that of GRACE in deriving gravity field models can make contribution to the improvement in the gravity models and eventually benefit the precision of POD. This explains why the orbit precision of EIGEN-GL04S is better than that of GGM03S associated with the fact that GRACE data used to derive GGM03S is more than that of EIGEN-GL04S.

Table 3: Overlapping orbit precision (cm) in three directions

Model	GRACE-A			GRACE-B		
	R	T	N	R	T	N
Pre-CHAMP						
GRIMS1	14.7	18.6	20.6	12.5	19.0	16.8
GRIMC1	10.6	13.8	15.2	8.6	12.6	13.3
CHAMP						
TEG4	3.3	6.3	2.7	3.5	6.8	2.9
EIGEN1S	2.2	4.1	1.7	2.6	4.6	2.1
EIGEN-CHAMP05S	1.4	2.6	1.2	1.3	2.4	1.2
GRACE						
GGM01S	1.8	3.1	1.3	1.7	3.2	1.3
GGM01C	1.6	3.0	1.3	1.6	3.4	1.2
GGM03S	1.7	3.0	1.2	1.4	2.7	1.3
EIGEN-GL04S1	1.5	2.7	1.2	1.4	2.5	1.2
GOCE						
GO_CONS_GCF_2_TIM_R3	1.9	3.7	1.9	2.0	3.6	1.9
Combination						
EIGEN-51C	1.4	2.6	1.2	1.3	2.5	1.2
GO_CONS_GCF_2_DIR_R3	1.4	2.5	1.3	1.2	2.3	1.1
GOCO03S	1.5	2.7	1.2	1.3	2.5	1.2

4.3 Comparison with external orbits

Comparison with orbits determined by other analysis centres or by different POD techniques is one of the commonly used methods to validate the quality and accuracy of orbit solutions. In this section, comparison between our orbit solutions and external orbits – the precise science orbits (PSO) generated by the Jet Propulsion Laboratory (JPL) using the reduced-dynamic POD technique are performed. The PSO product is regarded as the best orbits available to the public.

The mean 3D RSS of the differences between our orbit and the PSO for 1–31 March, 2008 is displayed in Figure 3. It is found that from both GRACE-A and -B results, the level of consistency between PSO and our orbit solutions using the gravity field models derived with data from at least one single satellite gravity mission (cases 2-5: satellite-gravity-mission-only and combined models) is of the order of a few cm. In addition, the highest orbit accuracy with respect to PSO is about 3.8 cm for GRACE-A and 4.0 cm for GRACE-B, which are achieved using EIGEN-CHAMP05S, EIGEN_GL04S, EGEIN-51C, GO_CONS_GCF_2_DIR_R3, and GOCO 03S.

Comparing Figure 2 with Figure 3, we can see that they have a similar trend in the variation of orbit precision/accuracy from GRIMS1 to GOCO03S, except that the quantities on the vertical axis of these two figures are different as they are supposed to be. This further consolidates the results of orbital overlaps in previous section and makes the results from both orbital overlap and external orbit comparisons more convincing.

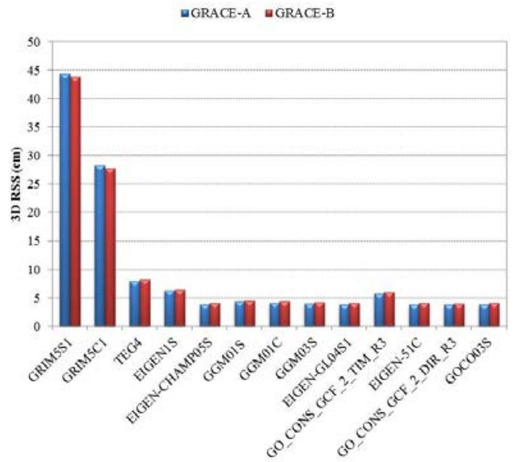

Figure 3: Mean 3D RSS (cm) of the differences between the orbit solutions resulted from the 13 selected gravity field models and the reference orbits PSO for March 1 – 31, 2008

4.4 SLR validation

SLR is a proven space geodetic technique with accurate and unambiguous range measurements for satellite tracking. A few mm precision for the SLR normal point data is claimed. It is therefore commonly used to validate GPS/DORIS-based orbit solutions. In this study, we also use SLR measurements for the validation of our POD solutions using the 13 selected gravity field models for both GRACE-A and -B. More details about SLR validation can be referred to Peng and Wu[2009].In addition, the SLR measurements of GRACE-A and -B are obtained from the CDDIS (Crustal Dynamics Data Information System, ftp://cddis.gsfc.nasa.gov/slr/), which archives and provides SLR data for all SLR satellites [*Pearlman et al.*, 2005; *Pearlman et al.*, 2002].

During the testing period from 1 to 31 March, 2008, 17 SLR stations tracked GRACE-A and 18 stations tracked GRACE-B. Due to the fact that atmospheric refraction in SLR measurements at low elevation angles can hardly be corrected by models, we set the elevation cut-off angle of 15^{o}for the selection of SLR observations. As a result, a total of 3109 and 2544 normal points for GRACE-A and -B respectively are selected for the validation of our orbit solutions. The SLR residuals, which are the differences between SLR measurements and the ranges calculated from our orbit solutions and coordinates of ground stations, of GRACE-A orbit solutions using the CHAMP-only gravity field models, i.e. TEG4, EIGEN1S and EIGEN-CHAMP05S, are displayed in Figure 4.It clearly shows a decrease in SLR residuals (meaning an increase in orbit quality) from TEG4 to EIGEN1S, and further to EIGEN-CHAMP05S. This result is consistent with the results from the residuals of tracking data, orbit overlaps and comparison with external orbits, discussed in previous sections.

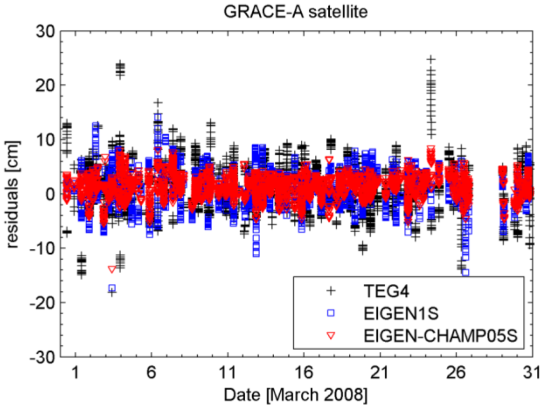

Figure 4: SLR residuals of GRACE-A orbit solutions resulted from TEG4, EIGEN1S, and EIGEN-CHAMP05S.

Since the quality of SLR measurements varies with station, the proven quality station YARRAGADEE (station number 7090) located in Western Australia is chosen to assess our orbit solutions resulted from different gravity field models. Owing to its advantageous location and nearly perfect climate conditions, both quality and quantity at this station are better than most of the remaining stations in the whole SLR network. During the testing period, there are 1020 and 954 normal points of GRACE-A and -B respectively from this station 7090.

Table 4: Statistical results (RMS) of SLR residuals (cm) of GRACE-A and -B orbit solutions resulting from the 13 selected gravity field models

Model	**Total**		**Station 7090**	
	GRACE-A	GRACE-B	GRACE-A	GRACE-B
Pre-CHAMP				
GRIMS1	24.9	27.1	26.0	23.9
GRIMC1	16.1	14.9	17.1	15.3
CHAMP				
TEG4	4.6	4.9	5.6	4.8
EIGEN1S	3.3	3.5	3.0	3.4
EIGEN-CHAMP05S	2.1	2.7	1.7	2.4
GRACE				
GGM01S	2.3	2.9	2.0	2.4
GGM01C	2.3	2.8	2.27	2.5
GGM03S	2.1	2.7	2.0	2.3
EIGEN-GL04S1	2.1	2.7	1.7	2.3
GOCE				
GO_CONS_GCF_2_TIM_R3	3.0	3.8	2.7	4.3
Combination				
EIGEN-51C	2.1	2.7	1.6	2.3
GO_CONS_GCF_2_DIR_R3	2.1	2.7	1.6	2.3
GOCO03S	2.1	2.7	1.7	2.3

The statistic results of SLR residuals of GRACE-A and -B orbit solutions are summarized in Table 4. Generally, the result of using measurements from the single 7090 station is better than that of using measurements from all the SLR stations tracked the GRACE satellites, except the Pre-CHAMP and TEG4 models. However, the results of using all the stations and using the single 7090 station show the improvement in orbit quality from the Pre-CHAMP models (GRIM5S1, GRIM5C1) to the CHAMP-only models (TEG4, EIGEN1S, and EIGEN-CHAMP05S), to the GRACE-only models(GGM01S, GGM01C, GGM03C, and EIGEN-GL04S1), and finally to the combined models (EIGEN-51C, GO_CONS_GCF_2_DIR_R3, and GOCO03S). In addition, the SLR validation results also demonstrate that the accuracy of orbits of GRACE-A and -B usingEIGEN-CHAMP05S, EIGEN-GL04S, EIGEN-51C, GO_CONS_GCF_2_DIR_R3, and GOCO03S reaches about 2.1 cm and 2.7 cm respectively.

5. Effects of the Time-varying Component on Orbit Quality

Among the 13 selected gravity models, GRIM5S1, GRIM5C1, EIGEN1S, EIGEN-CHAMP05S, EIGEN-GL04S1, and EIGEN-51C provide the time-varying low-degree spherical harmonics. Based on the performance analyses in section 4, the static version of GRIM5S1 has the worst performance in GRACE POD, while EIGEN-CHAMP05S, EIGEN-GL04S1 and EIGEN-51C are approximately at the same accuracy level. In this section, both GRIM5S1 andEIGEN-GL04S1are tested to investigate the effects of the time-varying component on the dynamic orbit accuracy of GRACE-A and -B employing the same POD strategy as the one used in section for performance assessment of the static gravity fields.

The 3D RSS of orbit differences derived from both with and without the time-varying components of EIGEN-GL04S1 and GRIM5S1are shown in Figures 5 and 6, respectively. The one-month comparison results indicate that the effects of the time-varying components of EIGEN-GL04S1 are at a level of a few mm, ranging from 1 mm to 7 mm (Figure 5). The mean 3D RSSs of GRACE-A and -B are 1.6 mm and 2.3 mm respectively, suggesting that the inclusion of the time-varying low-degree spherical-harmonic coefficients has not led to significant variability in the orbit solutions. As for GRIM5S1, the variability caused by the time-varying spherical-harmonic coefficients is at a level of a few cm, ranging from 2 cm to 10 cm (Figure 6), and the average 3D RSSs of GRACE-A and -Bare about 4.0 cm and 4.3 cm respectively. However, the effects of the time-varying component in both EIGEN-GL04S1 and GRIM5S1 on orbit accuracy are substantially at the same level in terms of ratio when comparing the orbit variability caused by the time-varying gravity fields with the orbit accuracy obtained by external orbit comparisons and independent SLR validation. This indicates that the time-varying of the low-degree spherical-harmonics of GRIM5S1 does not make notable contribution to the improvement in the orbit quality.

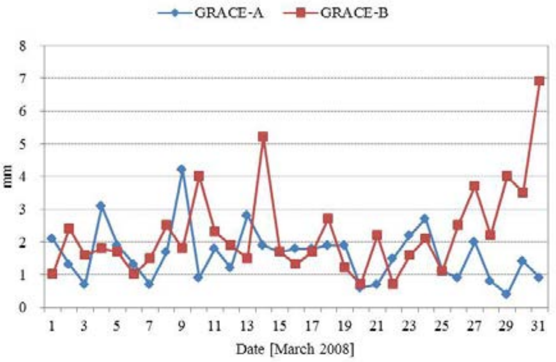

Figure 5: Comparison of orbits derived from with and without the time-varying component of EIGEN-GL04S1.

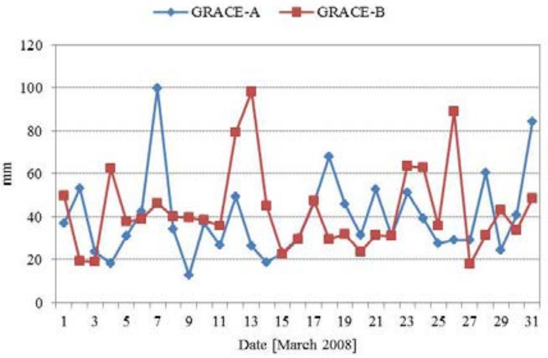

Figure 6: Comparison of orbits derived from with and without the time-varying component of GRIM5S1

6. Conclusion

A number of Earth's gravity field models were selected to investigate their performance and effects on the orbit quality of LEO satellites in the dynamic POD method using the twin GRACE satellites. Both internal precision (residuals of tracking data and consistency of orbital overlaps) and external accuracy (comparison with reference orbits derived by JPL and independent SLR validation) were analysed for the orbit solutions using the 13 global mean gravity field models without considering the time-varying components. Based on these results, the following conclusions can be drawn: 1) the gravity field models derived using data from satellite gravity missions can largely improve both precision and accuracy of dynamic orbits; 2) the performance of the combined models is generally better than the ones from a single satellite gravity mission, although the use of data from extra one or two satellite gravity missions do not necessarily lead to a significant change in orbit quality; 3) the inclusion of SLR data from Lageos-1/2 in the derivation of the gravity field model from GRACE data has substantially improved its performance in dynamic POD: the orbit accuracy resulting from EIGEN-GL04S1 is slightly better than that of GGM03S model associated with the fact that less GRACE data were used in the derivation of EIGEN-GL04S1, compared to GGM03S;4) among the 13 models and for GRACE-A and -B results, GRIM5S1 has the worst orbit precision and accuracy, the mean RMS of tracking data residuals is about 24.4 mm and 21.8 mm, the 3D RSSs with respect to PSO are about 44.4 cm and 44.0 cm, while the RMSs of SLR residuals are about 25.0 cm and 27.1 cm respectively. Although the addition of territorial gravity data in deriving GRIMS1 improves the orbit accuracy, it still hardly meets the orbit accuracy requirement imposed by the GRACE mission objective; and 5) the highest precision and accuracy of our orbit solutions were achieved by EIGEN-CHAMP05S, EIGEN-GL04S, EIGEN-51C, GO_CONS_GCF_2_DIR_R3, and GOCO03S, and their corresponding RMSs of tracking data residuals are about 6.7 mm and 6.1 mm, 3D RSSs with respect to the reference orbit are about 3.8 cm and 4.0 cm, while the RMSs of SLR residuals are about 2.1 cm and 2.7 cm, for GRACE-A and B, respectively.

The variability in orbit solutions of GRACE-A and –B caused by the time-varying components of EIGEN_GL04S1 is about 1.6 mm and 2.3 mm respectively, and the corresponding results of the time-varying components of GRIM5S1 are about 4.0 cm and 4.3 cm. Since orbit accuracy achieved by the static component of EIGEN_GL04S1 and GRIM5S1 is not at the same level, for example, the 3D RSSs of GRACE-A orbit solutions resulted from EIGEN_GL04S1 and GRIM5S1 with respected to the external reference orbits are about 44.4 cm and 3.8 cm respectively. Therefore, the effects of the time-varying component of both EIGEN-GL04S1 and GRIM5S1 on the orbit quality are at the same ratio level, suggesting the inclusion of the time-varying low-degree spherical-harmonic coefficients does not lead to significant variability in dynamic orbit solutions.

Since the sensitivity of orbit accuracy to gravity fields depends on the altitude of LEO satellites, more satellites at various altitudes will be further investigated in future for performance assessment of currently available gravity field models in dynamic POD. In addition, with the availability of a longer time period of GOCE data in future, the accuracy of both satellite-gravity-mission-only and combined models is expected to be better, this will benefit the accuracy of dynamic orbit solutions. Accordingly, the effects of their performance on dynamic POD for LEO satellites will be assessed once these high-accuracy gravity field models are publicly available.

Acknowledgments

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