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Low-degree gravity change from GPS data of COSMIC and GRACE satellite missions

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ABSTRACT

This paper demonstrates estimation of time-varying gravity harmonic coefficients from GPS data of COSMIC and GRACE satellite missions. The kinematic orbits of COSMIC and GRACE are determined to the cm-level accuracy. The NASA Goddard's GEODYN II software is used to model the orbit dynamics of COSMIC and GRACE, including the effect of a static gravity field. The surface forces are estimated per one orbital period. Residual orbits generated from kinematic and reference orbits serve as observables to determine the harmonic coefficients in the weighted-constraint least-squares. The monthly COSMIC and GRACE GPS data from September 2006 to December 2007 (16 months) are processed to estimate harmonic coefficients to degree 5. The geoid variations from the GPS and CSR RL04 (GRACE) solutions show consistent patterns over space and time, especially in regions of active hydrological changes. The monthly GPS-derived second zonal coefficient closely resembles the SLR-derived and CSR RL04 values, and third and fourth zonal coefficients resemble the CSR RL04 values.

1. Introduction

Low earth orbit satellites (LEOs) have become a basic and efficient tool for determining global gravity field and its time variation. A number of satellite missions were launched for that purpose, including the CHAllenging Minisatellite Payload (CHAMP; Reigber et al., 1996), the dual-satellite Gravity Recovery and Climate Experiment (GRACE; Tapley, 1997), and Gravity Field and Steady-State Ocean Circulation Explorer (GOCE; ESA, 1999). At the same time, the Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC) mission, also known as FORMOSAT-3 (Chao et al., 2000; Hwang et al., 2008) is also able to yield time-varying gravity signals.

Despite different measurement techniques, one common feature of the missions is to use GPS (Global Positioning System) observations for precise orbit determination. Compared to the satellite laser ranging (SLR) technique that can only obtain one-dimensional (scalar) distances, GPS coordinate measurements are fully 3-dimensional and also be used for gravity recovery (Hwang et al., 2008). GPS-determined precise kinematic orbits contain all information of orbital perturbation forces, including those due to time-varying gravity changes, which can be estimated if other perturbation forces are properly modeled. Before the launch of CHAMP and GRACE, time-varying gravity fields are mainly determined by SLR. Han (2003) used about 2 years of CHAMP orbit data to recover the temporal variation of the Earth gravity fields up to degree and order 3. Four releases of monthly GRACE gravity field solutions up to degree and order 60 or higher solely from GRACE K-band ranging (KBR) and GPS measurements have been published by CSR, GFZ and JPL (see http://www.csr.utexas.edu/grace; Bettadpur, 2007).

The release 4 (RL04) of GRACE solutions is based on the one-step approach to model the gravity field, i.e., to use the raw GPS measurements directly in the equations of motion for estimation of harmonic coefficients. The GGM and EIGEN series of static gravity field models (Tapley et al., 2004; Reigber et al., 2005; Förste et al., 2006) based on GRACE satellite-to-satellite KBR and GPS measurements are computed in this way. The two-step approach, i.e., computing the kinematic and reference (i.e., dynamic) orbits of LEOs first and estimating gravity fields using such orbits, is commonly used for gravity field modeling. In the second step of this approach where the gravity recovery is carried out, four methods may be employed by combining GPS-derived orbits of LEOs with different types of space measurements: (i) Kaula's linear perturbation theory (Kaula, 1966); (ii) direct numerical integration (Hwang, 2001; Visser et al., 2001; Rowlands et al., 2002); (iii) energy balance approach (Wolff, 1969; Wagner, 1983; Jekeli, 1999; Visser et al., 2003; Visser, 2005) (iv) acceleration approach (Ditmar et al., 2006).

In this paper, we will experiment with 16 months of COSMIC and GRACE GPS data, from September 2006 to December 2007, to demonstrate the feasibility of gravity recovery solely from GPS

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data from the six COSMIC satellites and two GRACE satellites. The solution will be based on the two-step approach described above. Gravity changes from GPS will be compared with those from the SLR technique (only for degree 2 zonal geopotential coefficient) and the latest GRACE solutions.

2. Data processing

2.1. COSMIC and GRACE kinematic orbit determination

In this paper, the kinematic orbits were treated as three-dimensional range observations and were used for gravity recovery. With zero-differenced, ionosphere-free GPS phase observables, the precise kinematic orbits of LEOs were determined by the Bernese Version 5.0 GPS software (Dach et al., 2007). The detail of GPS-determined orbits of GRACE and COSMIC satellites using the kinematic approaches by Bernese have been documented by Švehla and Rothacher (2004), Jäggi et al. (2007) and Hwang et al. (2009). In the kinematic approach, epoch-wise parameters such as coordinate components, GPS receiver clock errors and phase ambiguities were determined simultaneously in one orbit-arc solution. Both high-precision GPS satellite orbits and clock errors were used in kinematic orbit determinations, and were made available by the Center for Orbit Determination in Europe (CODE, http://www.aiub.unibe.ch/igs.html). The reduced (or simplified) dynamic orbit was also computed prior to kinematic orbit and it served as a priori orbit for kinematic orbit and for removing anomalous kinematic orbit values. In the reduced dynamic orbit determination, arc-dependent parameters such as the initial state vector (6 Keplerian elements), 9 solar radiation coefficients and 3 stochastic pulses in the radial, along-track and cross-track directions were estimated and numerical integrations were carried out subsequently to determine the reduced dynamic orbits.

In general, the accuracy of a LEO's kinematic orbit is governed by the GPS-LEO geometry, the number of visible GPS satellites, the attitude of LEOs, antenna phase variation, GPS satellite orbit accuracy and GPS clock error (Byun and Schutz, 2001; Hwang et al., 2009). Tseng et al. (2011) show that the accuracies of COSMIC and GRACE kinematic orbits are 3 and 1 cm, respectively, based on an overlapping analysis.

The raw GPS kinematic orbits of COSMIC and GRACE satellites were computed at 5-s and 10-s intervals, respectively. Because the primary objective of this paper is to estimate low-degree gravity changes, such high sampling rates are not needed. Thus we compressed the raw kinematic orbits to one-minute normal-point orbits using the method of Hwang et al. (2008), and the one-minute normal-point kinematic orbits were actually used for gravity recovery. Also, outliers are present in the raw GPS data and must be removed by a proper filter. As defined in Ditmar et al. (2006), an outlier here is a kinematic orbit component whose difference with the reduced dynamic orbit exceeds 20 cm, which is about 2.5 times of the RMS orbit difference between the raw kinematic and reduced dynamic orbits. In most cases, raw kinematic orbits were rejected due to bad attitude data and poor receiver clock resolution.

Table 1
Standards for the orbit dynamics of COSMIC and GRACE satellites.

Model/parameter	Standard
N-body	JPL DE-405
Earth gravity model	GGM03S (70 × 70)
Ocean tides	GOT00.2
Solid earth tides	IERS standard 2000
Atmosphere density	Mass spectrometer incoherent scatter (MSIS) empirical drag model
Earth radiation pressure	Second-degree zonal spherical harmonic model
Solar radiation pressure	One coefficient per cycle
Atmosphere drag	One coefficient per cycle
General accelerations	9 parameters per cycle

2.2. Reference dynamic orbits for COSMIC and GRACE

The purpose of obtaining the dynamic orbits of COSMIC and GRACE is generating residual orbits (kinematic minus dynamic), which are then used for gravity recovery (Hwang et al., 2008). The reference orbit models the effects of a static gravity field and all other satellite perturbing forces, excluding the effect of temporal gravity. In this paper, the reference orbits of COSMIC and GRACE were determined by the NASA software GEODYN II (Pavlis et al., 1996); the standards for the orbit dynamics are given in Table 1. The static gravity field is described by the GGM03S model (Tapley et al., 2007) based on four years (January 2003 through December 2006) of GRACE KBR and GPS data. For the non-gravitational perturbing forces, we solved for coefficients of atmospheric drag, radiation and general accelerations (Pavlis et al., 1996) along the radial, along-track and cross-track directions per orbital period using the COSMIC and GRACE kinematic orbits. The reference dynamic orbit is critical to the determination of time-varying coefficients from the residual orbit. A good reference orbit depends on good model of the static gravity field and all other perturbing forces acting on COSMIC and GRACE satellites.

Table 2
Numbers of daily observation files and daily usable kinematic orbit files from September 2006 to December 2007.

Month	FM1	FM2	FM3	FM4	FM5	FM6	GRA	GRB
2006.9	26[a]/26[b]	15/14	26/26	27/27	29/29	23/23	30/30	30/30
2006.10	27/24	30/27	27/27	28/25	28/28	25/24	31/31	31/31
2006.11	28/28	16/16	30/29	29/29	28/27	29/25	30/30	30/30
2006.12	27/27	26/26	26/26	29/29	29/29	22/21	31/31	28/28
2007.1	29/29	30/29	27/27	29/29	29/28	20/20	31/31	31/31
2007.2	26/26	27/27	28/27	28/28	28/28	16/14	28/28	28/28
2007.3	29/29	6/6	31/31	28/23	30/30	30/30	31/31	31/31
2007.4	30/29	13/13	30/29	23/18	29/29	20/20	30/30	30/30
2007.5	31/30	12/10	30/28	23/21	30/29	31/31	31/31	31/31
2007.6	30/30	22/21	25/25	30/30	30/30	26/26	30/30	30/30
2007.7	30/30	29/29	16/14	30/30	31/27	31/31	31/31	30/30
2007.8	31/31	18/18	17/17	30/29	31/30	29/28	31/31	31/31
2007.9	28/27	8/8	7/7	30/30	29/28	7/7	30/30	30/30
2007.10	28/15	27/27	21/21	31/31	31/31	0/0	31/31	31/31
2007.11	29/28	13/13	7/4	30/30	28/26	12/12	30/30	30/30
2007.12	27/27	27/27	23/23	31/29	29/27	28/27	31/31	30/30

[a] Number of daily observation files.
[b] Number of daily usable kinematic orbit files.

Table 3
Monthly RMS differences between reference and kinematic orbits from September 2006 to December 2007 (unit: cm).

Satellite	Radial	Alone-track	Cross-track
FM1	7.24	6.96	6.66
FM2	7.02	6.76	6.46
FM3	7.30	7.00	6.78
FM4	7.25	6.95	6.68
FM5	7.00	6.73	6.31
FM6	6.88	6.59	6.33
GRA	6.28	6.26	5.01
GRB	6.38	6.38	5.42

Several experiments have been made in several previous publications, e.g., Hwang (2001) and Hwang et al. (2008), based on simulated data with known time-varying coefficients. The current procedure used in this paper is optimized based on the results of these simulations.

Table 2 shows the number of GPS daily files for the six COSMIC satellites and the GRACE A and B satellites for each of the months from September 2006 to December 2007. The numbers of daily usable kinematic orbit files are also given in Table 2. In general, COSMIC cannot deliver full-month data and full-month usable kinematic orbits. By contrast, the monthly GRACE GPS data are almost complete. The unusable kinematic orbit data are mostly due to poor attitude control or GPS observation quality, or simply missing observations. Fig. 1 shows the monthly RMS differences between the reference and kinematic orbits of COSMIC and GRACE satellites in the radial, along-track and cross-track directions. The monthly RMS differences in these three directions for the COSMIC and GRACE satellites are listed in Table 3. Table 4 shows statistics of monthly standard errors of normal point orbits.

2.3. Recovering temporal gravity from residual orbit

The residual orbit is a functional of the temporal gravity and is regarded as observable to estimate the latter. Here we use the procedure and method described in Hwang et al. (2008) to estimate

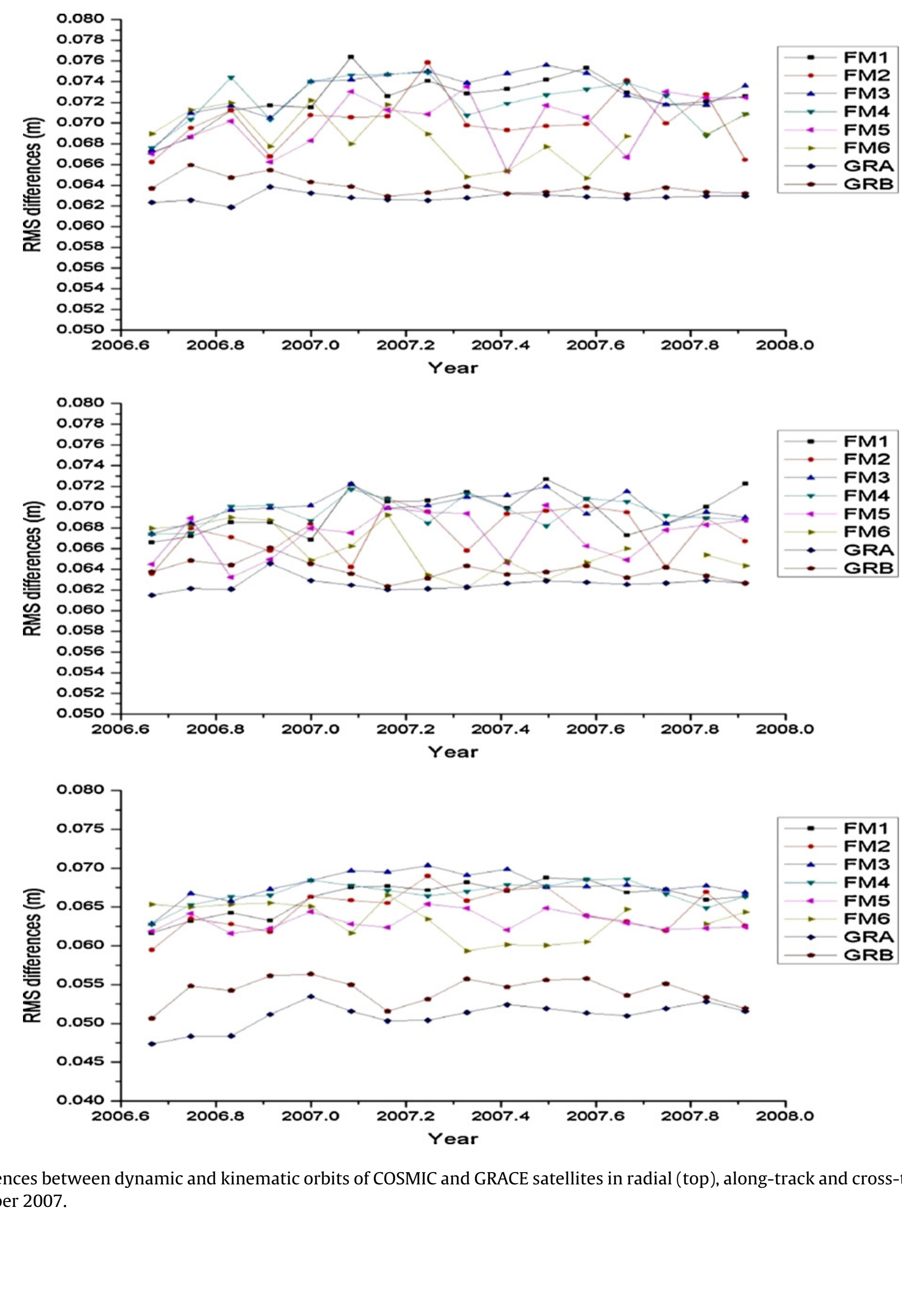

Fig. 1. Monthly RMS differences between dynamic and kinematic orbits of COSMIC and GRACE satellites in radial (top), along-track and cross-track (bottom) directions from September 2006 to December 2007.

Table 4
Statistics of monthly standard errors of normal point orbits (unit: cm).

Satellite	Max.	Mean	Min.
FM1	2.00	1.81	1.51
FM2	1.94	1.75	1.46
FM3	2.02	1.82	1.55
FM4	2.00	1.84	1.51
FM5	1.94	1.74	1.42
FM6	1.90	1.70	1.43
GRA	1.81	1.51	1.15
GRB	1.84	1.55	1.24

the time-variable gravity. First, the three components of a residual orbit Δx_i are expressed as (Hwang, 2001):

$$\Delta x_i = \sum_{k=1}^{6} c_k^i \Delta s_k(\Delta\bar{C}_{nm}, \Delta\bar{S}_{nm}) + \Delta r_i + \varepsilon_i, \quad i = 1, 2, 3 \tag{1}$$

where n, m: spherical harmonic degree and order. i: variations corresponding to the three components in the radial, along-track and cross-track (RTN) directions, respectively. Δs_k: Keplerian variations, or the perturbations in the six Keplerian elements as functionals of changes of harmonic coefficients $\Delta\bar{C}_{nm}$, $\Delta\bar{S}_{nm}$. c_k^i: coefficient for transforming Keplerian variations to RTN variations (Hwang, 2001). ε_i: noise of GPS-determined orbit. Δr_i: expression to compensate the deficiency of the Keplerian variations in modeling the temporal gravity.

In this paper, we used the following model for Δr_i (Colombo, 1984; Engelis, 1987):

$$\begin{aligned}\Delta r_i = {} & a_0 + a_1 \cos u + a_2 \sin u + a_3 \cos 2u + a_4 \sin 2u \\ & + a_5 t \cos u + a_6 t \sin u + a_7 t \sin 2u + a_8 t \cos 2u \\ & + a_9 t + a_{10} t^2 \end{aligned} \tag{2}$$

where u is argument of latitude, a_k the empirical coefficients, and t the time elapsed with respect to a reference epoch.

The coefficients $\Delta\bar{C}_{nm}$, $\Delta\bar{S}_{nm}$ are solved for by weighted least-squares with a priori constraints. The constraints are based on a model of degree variance of the temporal gravity computed using the GRACE monthly gravity solutions of CSR RL04 and GGM03S. Specifically, the harmonic coefficients of GGM03S were subtracted from the monthly coefficients of CSR RL04 from September 2006 to December 2007 to obtain monthly residual gravity coefficients. The following averaged degree variances of the monthly residual gravity coefficients were then computed:

$$\bar{\sigma}_n^2 = \frac{1}{2n+1} \sum_{m=0}^{n} (\Delta\bar{C}_{nm}^2 + \Delta\bar{S}_{nm}^2) \tag{3}$$

Fig. 2 shows averaged degree variances. Theses degree variances were then fitted by the Kaula rule $\alpha n^{-\beta}$, where α, β are two parameters describing the decay of temporal gravity field with respect to harmonic degree. The averaged degree variances were inversely weighted to the corresponding diagonal elements (see Eq. (4)) of the normal equations formed by the observation equations and the residual orbits in Eq. (1).

$$P_{c_{nm}} = P_{s_{nm}} = \frac{1}{\bar{\sigma}_n^2} \tag{4}$$

3. Results

We processed the COSMIC and GRACE GPS tracking data from September 2006 to December 2007 at one month interval. The result is the NCTU gravity solution containing monthly estimates of the temporal variation of the gravity field with respect to the

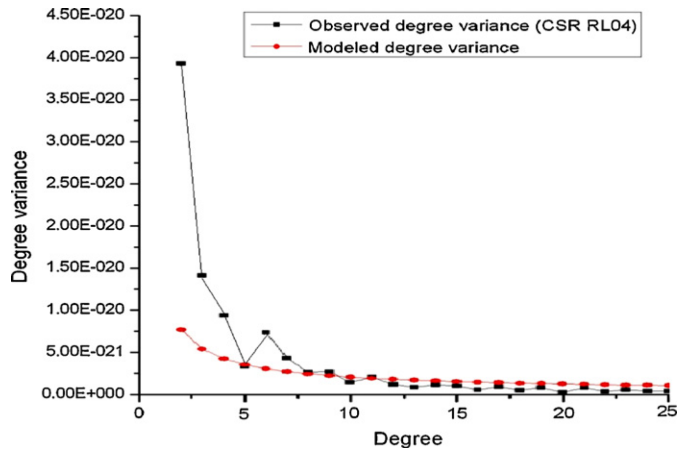

Fig. 2. Observed and modeled degree variances of CSR RL04 harmonic coefficients.

(static) GGM03S model. It is believed that, with GPS data only low-degree coefficients can be estimated with sufficient confidence (Xu et al., 2006; Hwang et al., 2008), and in general the signal-to-noise ratios of GPS-derived harmonic coefficients are larger than 1 only for degrees below 10. Therefore, in this paper we adopted degree 5 as the maximum degree of harmonic expansion in the gravity solution.

Fig. 3 shows selected months of geoid variations constructed from CSR RL04 up to degree 5 (left column), as compared to those from the NCTU solution (right column). In general, the NCTU geoid variations show highs and lows similar to the CSR RL04 results. Both results show clear gravity variations over areas of large hydrological variations such as the Amazon, northern India, and central Africa. Here the maximum variations occur in spring (April) and autumn (September to October) and this pattern is consistent from one year to another.

However, there exist deviations between the two solutions in the geoid variations in certain months. For example, the NCTU monthly geoid variations in January, April and October of 2007 contain some artifacts at latitudes higher than 72°, which is the inclination angle of COSMIC, or the maximum latitude covered by COSMIC (see below). Otherwise, the magnitudes of geoid variation signals of NCTU solutions for February, April and May of 2007 disagree with CSR RL04 solutions due to large difference in the second zonal coefficients.

We make further evaluations particularly for the GPS-derived zonal harmonic coefficients. The conventional J_n and the fully normalized zonal harmonic coefficient $\bar{C}_{n0}$ are related by

$$J_n = -C_{n0} = -\sqrt{2n+1}\bar{C}_{n0}. \tag{5}$$

Ries et al. (2008) has shown that the GRACE data are not conducive to estimation of the second zonal temporal coefficient $\Delta\bar{C}_{20}$, mainly because of the polar orbit design and the presence of several long-period tidal aliases. The combination of satellite data of different inclinations such as COSMIC and GRACE will not only improve the accuracy of zonal harmonic coefficients, but also the tesseral coefficients (Zheng et al., 2008). Fig. 4 shows the monthly $\Delta\bar{C}_{20}$ values and their standard errors from the NCTU solution in comparison to the CSR RL04 and SLR results (the monthly SLR $\Delta\bar{C}_{20}$ are from the Jet Propulsion Laboratory GRACE ftp://podaac.jpl.nasa.gov/grace/doc/TN-05_C20_SLR.txt) (Cheng and Tapley, 2004), over the period from September 2006 to December 2007. We found relatively large differences of $\Delta\bar{C}_{20}$ in April, September and October of 2007. Fig. 5 shows the corresponding relative differences of $\Delta\bar{C}_{20}$ of the NCTU and the CSR RL04 coefficients with respect to the SLR-derived $\Delta\bar{C}_{20}$, showing the better agreement of the NCTU solution, than does the

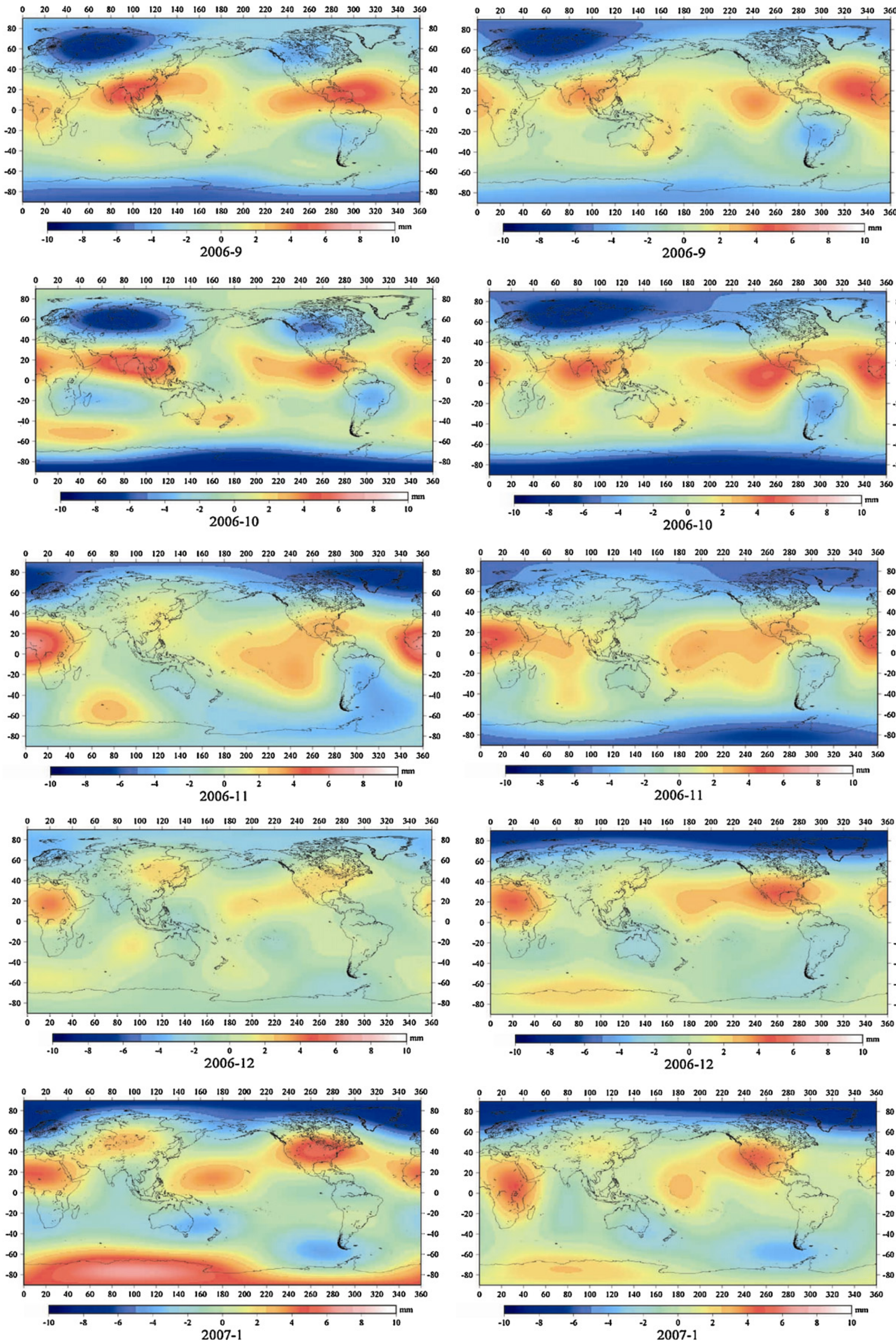

Fig. 3. Geoid variations up to degree 5 from CSR RL04 (left) and from NCTU.

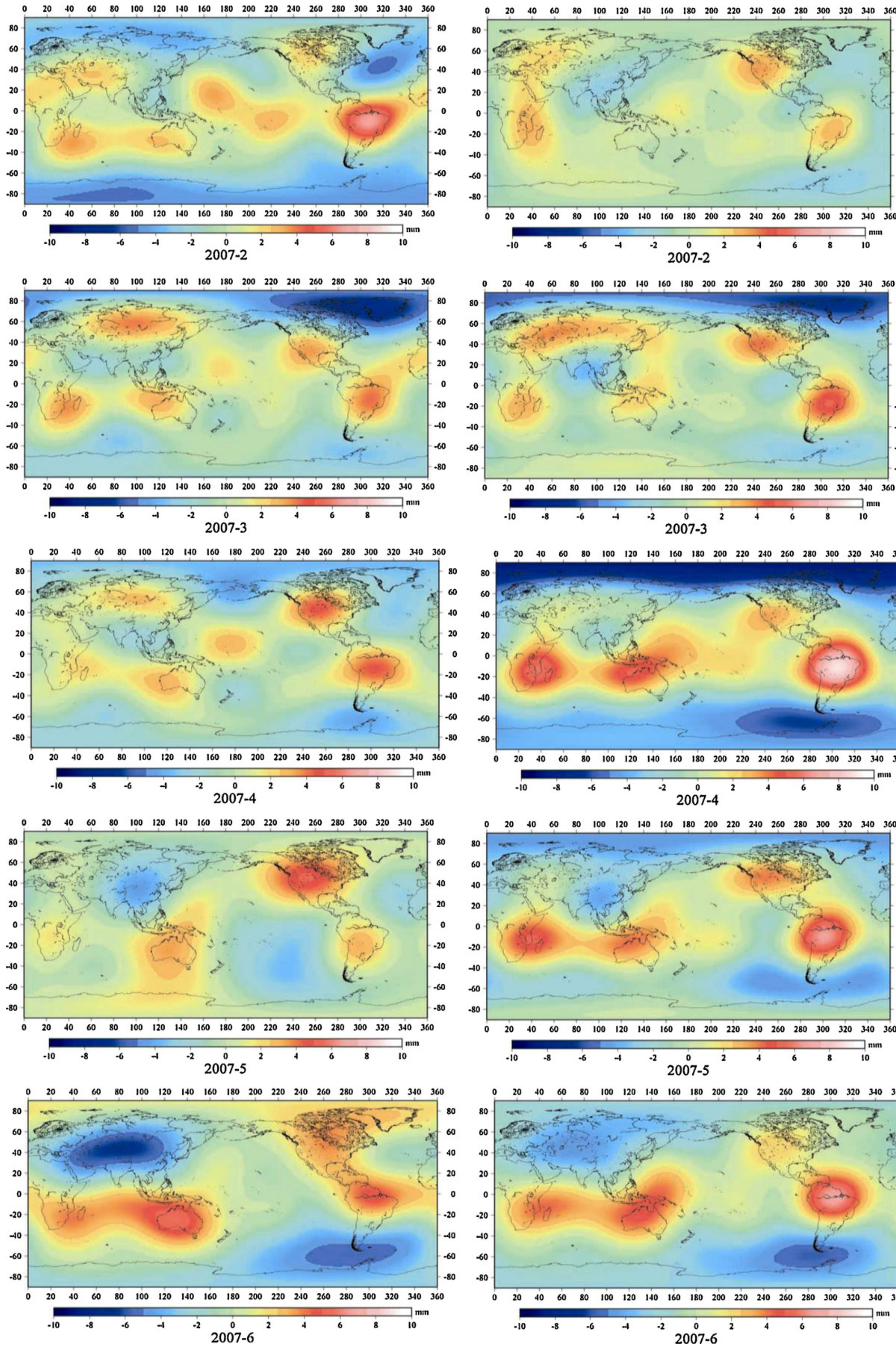

Fig. 3. (*continued*)

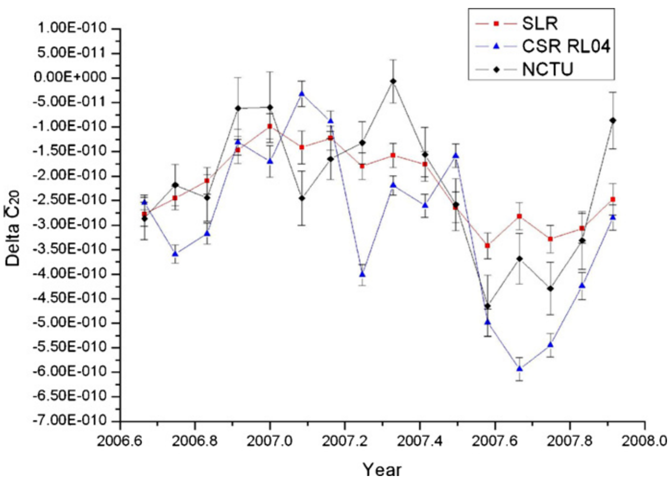

Fig. 4. Time series of $\Delta\bar{C}_{20}$ (change of second zonal coefficient) from NCTU, SLR, and CSR RL04 from September 2006 to December 2007.

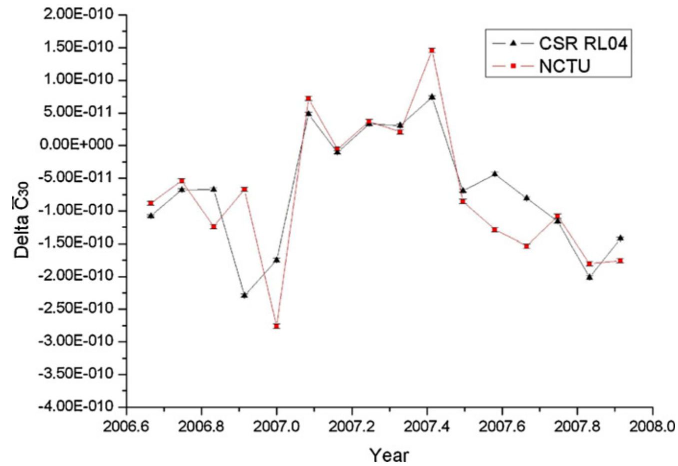

Fig. 6. Time series of $\Delta\bar{C}_{30}$ (change of third zonal coefficient) from NCTU and CSR RL04 from September 2006 to December 2007.

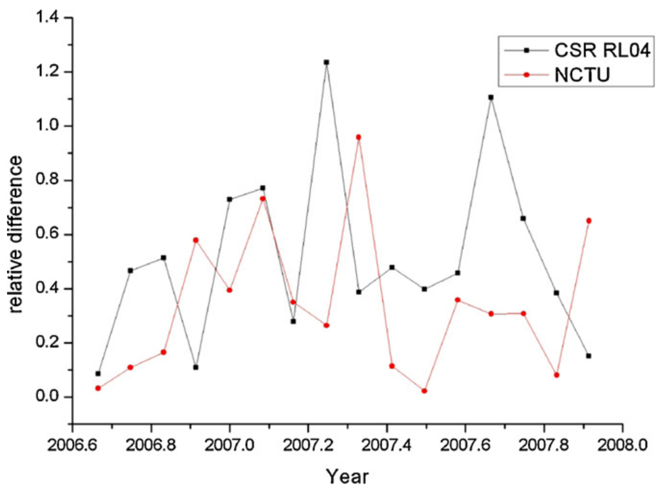

Fig. 5. Relative differences of $\Delta\bar{C}_{20}$ of the NCTU and CSR RL04 coefficients with respect to the SLR-derived coefficients from September 2006 to December 2007.

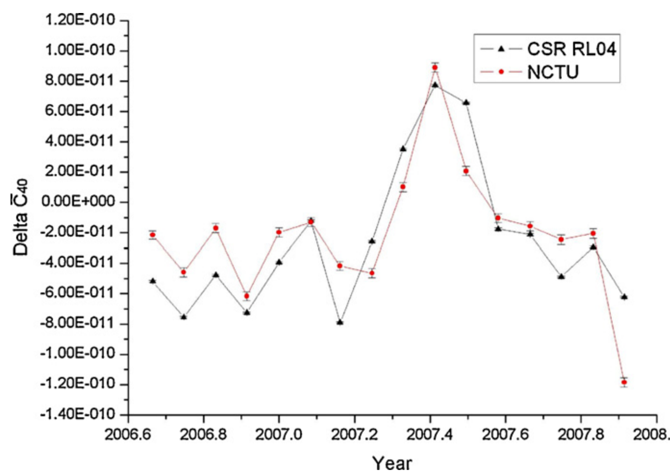

Fig. 7. Time series of $\Delta\bar{C}_{40}$ (change of fourth zonal coefficient) from NCTU and CSR RL04 from September 2006 to December 2007.

CSR RL04 solution, to the SLR solution agree. For the $\Delta\bar{C}_{30}$ and $\Delta\bar{C}_{40}$ values, the NCTU and CSR RL04 solutions show similar magnitudes of variation and almost the same phases (see Figs. 6 and 7).

Table 5 shows the correlation coefficients among various harmonic coefficients. For $\Delta\bar{C}_{20}$, the SLR and NCTU solutions show a stronger correlation than that between the SLR and CSR RL04

Table 5
Correlation coefficients between zonal harmonic coefficients from two solutions.

Coefficient	NCTU-GRACE	NCTU-SLR	SLR-GRACE
$\Delta\bar{C}_{20}$	0.64	0.82	0.76
$\Delta\bar{C}_{30}$	0.81	N/A	N/A
$\Delta\bar{C}_{40}$	0.82	N/A	N/A

solutions. For $\Delta\bar{C}_{30}$ and $\Delta\bar{C}_{40}$, the CSR RL04 and NCTU solutions again show strong correlations with SLR. The linear rates of $\Delta\bar{C}_{20}$, $\Delta\bar{C}_{30}$ and $\Delta\bar{C}_{40}$ from NCTU, SLR and CSR RL04 are listed in Table 6. Again, the rate of $\Delta\bar{C}_{20}$ from NCTU matches the SLR result better than the rate from GRACE. For $\Delta\bar{C}_{30}$ and $\Delta\bar{C}_{40}$, the amplitudes of the annual variations from the NCTU and CSR RL04 solutions are (1.196×10^{-10}, 1.162×10^{-10}) and (4.549×10^{-11}, 5.594×10^{-11}), respectively. The phase of the annual variations of NCTU and CSR RL04 solutions are (113.41°, 120.22°) and (152.61°, 144.09°) for $\Delta\bar{C}_{30}$ and $\Delta\bar{C}_{40}$, respectively. The magnitudes from GPS appear to be larger than the ones from KBR, and the phase differences can be up to 8° (for $\Delta\bar{C}_{40}$). Fig. 8 shows the correlation coefficients between harmonic coefficients from NCTU and CSR RL04 solutions. This deviation is partly caused by the short data records we used in this paper.

Table 6
Linear rates of zonal coefficients from NCTU, GRACE and SLR solutions.

Coefficient	NCTU	GRACE	SLR
$\Delta\bar{C}_{20}$	$(-1.06\pm0.86)\times10^{-10}$	$(-1.98\pm0.86)\times10^{-10}$	$(-0.94\pm0.45)\times10^{-10}$
$\Delta\bar{C}_{30}$	$(-5.13\pm7.09)\times10^{-11}$	$(-1.58\pm6.07)\times10^{-11}$	N/A
$\Delta\bar{C}_{40}$	$(-0.20\pm2.91)\times10^{-11}$	$(3.46\pm3.06)\times10^{-11}$	N/A

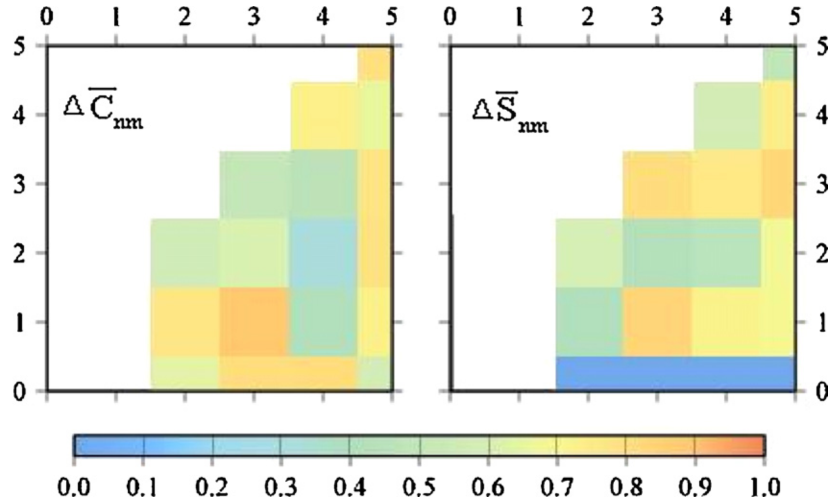

Fig. 8. Correlation coefficients between harmonic coefficients to degree 5 from NCTU and CSR RL04 solutions.

4. Conclusions

This paper demonstrates experimental monthly gravity solutions produced on the basis of GPS tracking data from COSMIC and GRACE. Due to combining data from satellites of different orbital inclinations, the NCTU solutions show a higher accuracy of low-degree zonal coefficients than the GRACE solutions. Due to mainly missing GPS data, deviations between GPS (NCTU) and GRACE-derived monthly geoid changes exist, and in most cases they are largely due to the differences in the zonal terms, especially the second zonal coefficient. The GPS-derived second, third and fourth zonal harmonic coefficients are consistent with the CSR results, and their correlation coefficients with GRACE results are 0.64, 0.81 and 0.82, respectively. For the second zonal coefficient, the GPS (NCTU) solution shows a high correlation coefficient of 0.82 with the SLR solution, and this correlation is stronger than that between the GRACE and SLR's second zonal coefficients. This study highlights the importance of using GPS data in recovering the low-degree harmonic coefficients, especially the second zonal coefficient. Future work will be to extend the monthly solutions from GPS to a longer period to improve the accuracy of the COSMIC kinematic orbit and to increase the percentage of usable GPS data from COSMIC.

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