Monthly spherical harmonic gravity field solutions determined from GRACE inter-satellite range-rate data alone

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[1] New monthly estimates of the Earth's gravity field determined solely from GRACE inter-satellite range-rate measurements using an improved method of accelerometer calibration and the use of a baseline state parameterization are presented in this paper. Our methodology exploits the inherent power of the inter-satellite range-rate data at the expense of the GPS data, which are used solely for establishing an accurate orbital reference and for calibrating accelerometers. Resulting gravity solutions show significantly less error than previously published GRACE solutions, especially for spherical harmonic terms of degree 2 and terms of order 15,16. **Citation:** Luthcke, S. B., D. D. Rowlands, F. G. Lemoine, S. M. Klosko, D. Chinn, and J. J. McCarthy (2006), Monthly spherical harmonic gravity field solutions determined from GRACE inter-satellite range-rate data alone, *Geophys. Res. Lett.*, *33*, L02402, doi:10.1029/2005GL024846.

1. Introduction

[2] The GRACE satellites are equipped with two basic tracking systems. A K-band inter-satellite link provides information about the relative motion of the GRACE satellites while GPS receivers tie each GRACE satellite to the terrestrial reference frame. Most global fields derived from GRACE, as in *Tapley et al.* [2004a, 2004b], have been based on solutions that combine tracking data from both systems. However, the inter-satellite measurement is much easier to process than GPS data and its differential nature makes it much more desirable than GPS data for use in regional solutions [*Rowlands et al.*, 2005]. Although *Rowlands et al.* [2005] obtained realistic estimates of mass flux solely from GRACE inter-satellite range-rate data, it is natural to question the implications of gravity extraction from GRACE without the reduction of GPS data. This paper validates the processing used by *Rowlands et al.* [2005] by extending that processing to the estimation of monthly global gravity fields comprised of standard Stokes coefficients. These fields are then compared to the GRACE project monthly fields (level 2 product).

[3] In subsequent sections it will be shown that these new fields compare very closely with the GRACE project fields from degree 5 through 12. However, the new fields have two significant improvements: (1) more realistic recovery of information at the very lowest degrees and (2) fewer problems above degree 14 especially at order 15 and 16 (the source of North-South streaking seen in standard GRACE models). We relate these improvements to the two major differences in our processing: (1) a new parameterization of the accelerometer calibration and K-band inter-satellite range-rate (KBRR) reduction that does not require the estimation of KBRR measurement empirical parameters and (2) the exclusion of GPS data during gravity reductions.

2. GRACE Data Processing and Gravity Solution Methodology

[4] Fundamental to the extraction of gravity signal from the GRACE inter-satellite range-rate observations, whether in the form of traditional spherical harmonics or local mass anomalies, is the highly accurate knowledge of the GRACE satellites positions, velocities, orientations and calibrated accelerometer observations to account for surface forces. To address these needs the GRACE project provides level 1B data products that we have exploited for our gravity solutions. The following discussion summarizes our GRACE data processing methodology that is used for both our mass anomaly and spherical harmonic gravity solutions.

[5] Our processing begins with the calibration of the GRACE A and B level 1B accelerometer data to perform an initial reduction of the inter-satellite range-rate data in preparation for gravity recovery. The accelerometer calibration parameters are estimated from the simultaneous reduction of KBRR and precise orbit ephemeris data for the GRACE satellites. These precise orbits are computed by the GRACE team using a reduced dynamic strategy and are therefore relatively free from gravity and surface force error [*Bertiger*, 2002]. The two data types are used in the calibration process to help isolate true accelerometer error because any improvement in the accelerometry must improve the residual fit to both the KBRR and precise orbit ephemeris data. The Goddard Space Flight Center's GEODYN precision orbit determination and geodetic parameter estimation software is used to reduce these data in daily arcs using Bayesian least-squares differential correction. The level 1B accelerometer observations are used to account for surface forces, and GRACE level 1B quaternion data are used to model the orientation of the GRACE satellites. The force modeling includes the complete GGM02C GRACE gravity model through degree and order 120 [*Tapley et al.*, 2004b]. The ocean tides are modeled according to GOT00 [*Ray*, 1999; *Ray and Ponte*, 2003], where M2 is modeled to degree and order 70, and other major constituents are modeled to degree and order 50. The atmospheric gravity is forward modeled following *Chao*

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Table 1. GRACE Processing Estimated Parameters

Parameter	Description
	Accelerometer Calibration and KBRR Reduction in 24-hour Arcs
Orbit	Initial position and velocity per 24-hour arc
Accelerometer	X (∼along-track) and Z (∼radial) bias, and X 1CPR per 3-hours; Y (∼cross-track) and 3D scale per 24-hour arc
	Gravity Solution
Orbit	Pitch of GRACE A-B position baseline [*Rowlands et al.*, 2002]; magnitude of GRACE A-B velocity baseline; pitch of GRACE A-B velocity baseline
Gravity	Mass anomalies at various spatial and temporal resolution or monthly spherical harmonic coefficients complete to degree and order N

and Au [1991] using potential coefficients to degree and order 50 at six-hour intervals derived from NCEP pressure grids [*Petrov and Boy*, 2004] assuming inverted barometer for the ocean response. Table 1 summarizes the parameters that are estimated in these daily arc solutions.

[6] It should be noted that our parameterization of the accelerometer calibration and KBRR reduction is quite different from previous investigations. Our approach results in KBRR residuals that do not require additional adjustment of empirical KBRR measurement model parameters such as those used by *Tapley et al.* [2004a] and *Reigber et al.* [2005]. For example, *Tapley et al.* [2004a] estimate the following empirical measurement model parameters: KBRR bias and bias drift every half orbital revolution and KBRR one-cycle-per-revolution (1CPR) parameters every orbital revolution. In total our calibration and KBRR reduction process uses nearly a factor of three times fewer parameters than those of *Tapley et al.* [2004a] and a factor of 1.5 times fewer than those of *Reigber et al.* [2005] for each gravity solution. Presumably, our processing strategy better preserves the low degree gravitational signal in the GRACE inter-satellite range-rate observations by not removing signal from the KBRR data through the estimation of empirical measurement parameters. It should be noted that KBRR residuals reflect mass concentrations directly below the GRACE system [*Rowlands et al.*, 2005]. Changes in $C_{(2,0)}$ result in a nearly exact twice per orbit revolution signal in the KBRR observations reflecting the change in the equatorial bulge sampled twice per revolution.

[7] The estimated calibration parameters are then used to generate normal equations for the recovery of time variable gravity as either mass anomalies or spherical harmonic coefficients. The GRACE inter-satellite range-rate data are orders of magnitude more sensitive to gravity signal than the GPS data. Furthermore, the reduction of GPS data requires the estimation of a host of measurement model parameters including ambiguity biases and troposphere scale factors that can mask gravity signal. Unless great care is taken, the gravitational signal contained within the GRACE inter-satellite range-rate observations can be weakened and corrupted by the inclusion of the GPS data within the GRACE derived gravity solutions. Therefore, our gravity solution normal equations contain KBRR data only and the GRACE A and B Cartesian position and velocity initial state parameters are transformed to a baseline parameterization [*Rowlands et al.*, 2002]. The baseline parameterization facilitates the estimation of the geopotential parameters from KBRR data alone, because only those components of the dual spacecraft state vectors that are sensitive to the inter-satellite data are estimated along with the geopotential parameters. Table 1 summarizes the parameters estimated for the geopotential solutions.

3. Monthly Gravity Solution Results: Analysis and Discussion

[8] Using the processing methodology presented above we have computed monthly spherical harmonic gravity solutions complete to degree and order 60 for the time period July 2003 through July 2004. The exception is January 2004 when there were significant GRACE level 1B data deficiencies. To assess the performance of these unconstrained monthly spherical harmonic gravity solutions based solely on KBRR data (GSFCmfs) we compare them to the GRACE project unconstrained monthly fields (CSRmfs) from July 2003 through July 2004 with the exception of January 2004. To directly compare the time variable gravity signal observed in the monthly solutions we have removed the mean gravity field for each solution type computed over our test time period. We also compare these monthly fields to a hydrology model [*Rodell*, 2004].

[9] Figure 1 compares the degree variance of all monthly solutions (with mean field removed) within our test period for each solution type. The GSFC and CSR fields are remarkably similar between degrees 5 through 12, which can be confirmed by examining the time series of individual Stokes coefficients. However, the CSRmfs show significant departure from our new monthly fields at specific wavelengths. It should be noted that these departures are not the result of one spurious GRACE project monthly solution, but are the result of significant monthly variability at degree 2, and degree 14 and above with particular problems through-

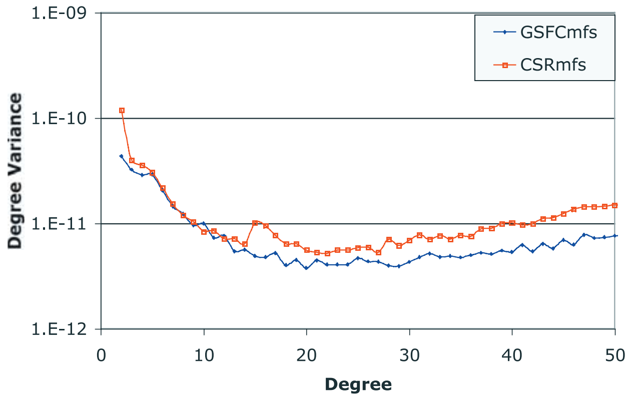

Figure 1. The degree variance over all monthly solutions (with mean field removed) within our July 2003–July 2004 test period for each solution type: CSRmfs (red) and GSFCmfs (blue).

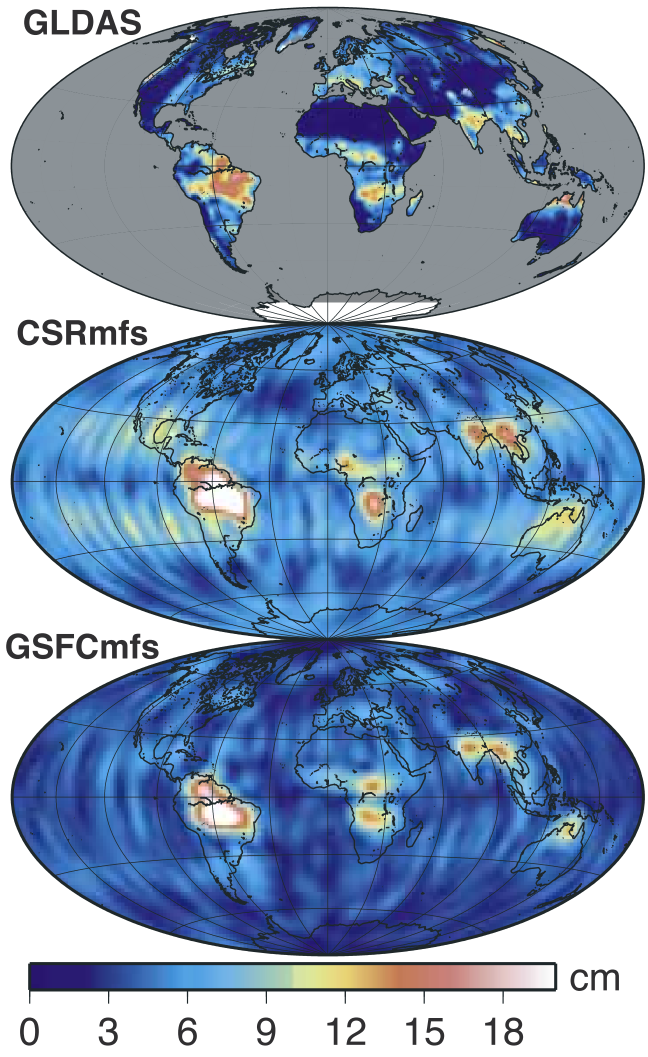

Figure 2. The RMS in equivalent water height taken over the July 2003–July 2004 test time period computed from (top) GLDAS hydrology model, and the monthly gravity solutions out to degree and order 20: (middle) CSRmfs and (bottom) GSFCmfs.

out orders 15 and 16, but especially at degrees 15 and 16 (the result of the GRACE ~15.3 orbit per day ground track sampling).

[10] By far, the largest difference between the two sets of monthly fields occurs at degree 2 driven by the differences in C(2,0). The CSRmfs degree 2 variance is 235% larger than that predicted by the sum of the CPC hydrology model and the ECCO ocean model [*Fan and van den Dool*, 2004; *Stammer et al.*, 2002], whereas the GSFCmfs degree two variance is 22% larger than the model prediction. Additionally the CSRmfs degree 2 annual amplitude variance is 165% larger than that predicted by the model, whereas the GSFCmfs degree 2 annual amplitude variance is 5% less than that predicted by the model.

[11] The next largest difference shown in Figure 1 is the hump peaking at degrees 15 and 16 observed in the CSRmfs and then the larger power in the CSRmfs out through the high degrees. The CSRmfs show particularly significant variability throughout orders 15 and 16 that are especially large at degrees 15 and 16. Figures 2 and 3 demonstrate the impact of these differences in the CSRmfs. For each monthly gravity solution in our test period we have computed the equivalent mass in height water out to degree and order 20. Figure 2 presents the RMS of these monthly equivalent height water fields for both the CSRmfs and GSFCmfs. For comparison, Figure 2 includes the RMS of height water over our test time period as predicted by the Global Land Data Assimilation System (GLDAS) hydrological model [*Rodell*, 2004]. Figure 2 suggests the CSRmfs suffer from spurious signal that does not appear to be geophysically reasonable and appears less pronounced in the GSFCmfs. For example, in the CSRmfs, Australia, south western USA and South America all suffer from significant north south streaking.

[12] In an attempt to isolate the geophysically unreasonable signal, or presumably noise in these solutions, we have removed a trend, annual and semi-annual signal from the monthly equivalent water fields computed from the monthly gravity fields out to degree and order 20. This model should account for most signal variance, thus leaving mostly noise and stochastic variability. Figure 3 presents the RMS of these residual monthly fields over our test time period and shows the CSRmfs have significantly more noise variance than the GSFCmfs. The CSRmfs have a global residual

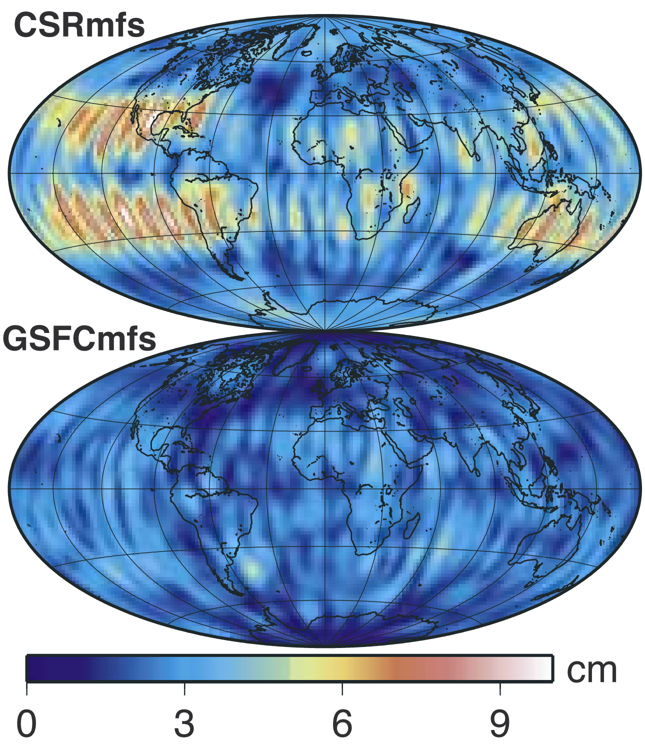

Figure 3. The residual RMS in equivalent water height (out to degree and order 20) taken over the July 2003–July 2004 test time period after a trend, annual and semi-annual signal has been removed: (top) computed from the CSR monthly gravity solutions (global RMS of 3.7 cm and maximum of 12.0 cm), and (bottom) computed from the GSFC monthly gravity solutions (global RMS of 2.2 cm and maximum of 5.6 cm).

RMS of 3.7 cm and a maximum of 12.0 cm, while the GSFCmfs have a global residual RMS of 2.2 cm and a maximum of 5.6 cm. The variance in the CSRmfs is dominated by north south streaking corresponding to the problems throughout orders 15 and 16 and particularly at degrees 15 and 16 as observed in the CSRmfs power spectrum shown in Figure 1.

[13] To further quantify the error in the GRACE derived solutions, we have computed the RMS of the equivalent height water signal (to degree and order 20) over our test time period and only at those arid locations where the GLDAS hydrological model predicts less than 2 cm RMS variability. For regions within 60° latitude, and with variability less than 2 cm RMS as predicted by GLDAS, the CSRmfs have an RMS of 6.2 cm while the GSFCmfs have an RMS of 4.3 cm.

4. Conclusion

[14] Our processing methodology follows a strategy of fundamentally preserving the gravity information contained within the GRACE inter-satellite range-rate observations. We have accomplished this in two ways: (1) through our accelerometer calibration method that eliminates the need to estimate empirical inter-satellite range-rate measurement parameters (bias, drift and 1CPR as noted above), and (2) through the use of a baseline state parameterization that allows us to estimate gravity from the inter-satellite range-rate data alone while still simultaneously refining the GRACE A and B initial states. Additionally when the complexity of the GPS data, both number of observations and parameters, is removed from the gravity solution process, significant savings in both computer processing and storage resources are realized such that the GRACE level 1B processing and monthly gravity solutions can easily be performed on a small workstation. Our resultant unconstrained monthly gravity solutions determined from inter-satellite range-rate data alone appear to have significantly less error than previous unconstrained monthly solutions particularly at spherical harmonic coefficients of degree 2 and throughout orders 15 and 16 but especially at degrees 15 and 16. While further analysis will detail the errors remaining in these GRACE solutions, the initial analyses presented here indicate the precision in the GRACE monthly spherical harmonic gravity solutions can be improved by more than a factor of two using the methods outlined in this paper.

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