The gravity recovery and climate experiment: Mission overview and early results

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[1] The GRACE mission is designed to track changes in the Earth's gravity field for a period of five years. Launched in March 2002, the two GRACE satellites have collected nearly two years of data. A span of data available during the Commissioning Phase was used to obtain initial gravity models. The gravity models developed with this data are more than an order of magnitude better at the long and mid wavelengths than previous models. The error estimates indicate a 2-cm accuracy uniformly over the land and ocean regions, a consequence of the highly accurate, global and homogenous nature of the GRACE data. These early results are a strong affirmation of the GRACE mission concept. *INDEX TERMS:* 1214 Geodesy and Gravity: Geopotential theory and determination; 1243 Geodesy and Gravity: Space geodetic surveys; 1241 Geodesy and Gravity: Satellite orbits; 1294 Geodesy and Gravity: Instruments and techniques. **Citation:** Tapley, B. D., S. Bettadpur, M. Watkins, and C. Reigber (2004), The gravity recovery and climate experiment: Mission overview and early results, *Geophys. Res. Lett.*, *31*, L09607, doi:10.1029/2004GL019920.

1. Introduction

[2] The Gravity Recovery and Climate Experiment (GRACE) is a dedicated satellite mission whose objective is to map the global gravity field with a spatial resolution of 400 km to 40,000 km every thirty days. Jointly implemented by NASA and DLR under the NASA Earth System Science Pathfinder Program, GRACE was launched on March 17, 2002, with an intended lifetime of 5 years [*Watkins and Bettadpur*, 2000; *Tapley and Reigber*, 2001]. The GRACE mission consists of two identical satellites in near-circular orbits at ~500 km altitude and 89.5° inclination, separated from each other by approximately 220 km along-track, and linked by a highly accurate inter-satellite, K-Band microwave ranging system. Each satellite, in addition to the inter-satellite ranging system, also carries Global Positioning System (GPS) receivers and attitude sensors [*Dunn et al.*, 2003] and high precision accelerometers [*Touboul et al.*, 1999]. The satellite altitude decays naturally (~30 m/day) so that the ground track does not have a fixed repeat pattern. The satellites are nominally held in a 3-axis stabilized, nearly Earth-pointed orientation, such that the K-Band antennas are pointed precisely at each other. Except for the K-Band ranging system, there is considerable heritage in the satellite design from the CHAMP mission [*Reigber et al.*, 1999].

[3] In order to achieve the necessary precision, the dual-frequency one-way K-Band phase measurements transmitted and received by both spacecraft are combined during ground processing to produce an ionosphere-free 'dual one-way' measurement that largely removes the effects of oscillator instability [*Dunn et al.*, 2003]. The effects of the non-gravitational forces acting on the satellite are removed using the precise accelerometers that measure the surface force acceleration. The GPS receivers on each satellite enable precise time-tagging of the measurements used in extracting the inter-satellite range change and provide absolute positions of the satellites over the Earth. The attitude sensors provide high precision estimates of the inertial orientation of the spacecraft. The status of the payload and science data is summarized in Table 1. The contribution of the errors in each of these systems to the gravity field determination is discussed by *Kim and Tapley* [2002].

[4] The GRACE Science Data System uses this suite of measurements, along with ancillary data, to estimate a sequence of gravity estimates representing corrections to a well-defined background gravity model used in the GRACE data processing. Data collected during the Commissioning Phase were used to determine preliminary gravity field estimates. This paper describes the results from first improvements to the pre-launch Earth gravity models.

2. GRACE Gravity Models

[5] Initial GRACE gravity models, designated as GGM01S (UTCSR) and EIGEN_GRACE01S (GFZ), were determined using the GRACE measurements. The GGM01S model was derived using 111 selected days of early GRACE science data spanning the interval from April to November 2002, and using a conventional dynamic least-squares adjustment. The K-Band inter-satellite range-rate (5-sec sampling) and GPS phase data (30-sec high-low double-differenced phase) were processed in daily arcs. A nominal orbit was integrated numerically using best-known

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Table 1. GRACE Science Payload Status

Instrument	Measurement (Precision)	Collection Rate	Status
Ranging system	K- & Ka-Band phase (< 10 μm)	10 Hz	In-flight calibration precisely aligned K-Band antenna phase center relative to attitude sensors
Accelerometer	Linear accelerations (10^{-11} g)	10 Hz	In-flight calibration precisely aligned accelerometer with attitude sensors. The satellite CG is within ∼50 μm of the accelerometer proof-mass
Star cameras	Quaternions (80–200 μrad)	1 Hz	Routine dual-head/1-Hz operation since Feb 2003.
GPS receiver	L1 & L2 phase (7 mm) CA & P1 pseudo-range (20 cm)	1 Hz for L1 & L2 0.1 Hz for CA & P1	

a priori models for gravitational forces, and using the accelerometer and attitude data products from GRACE for non-gravitational forces. The difference between the GRACE observations of range-rate and the range-rate predicted by the nominal orbit were ingested into a large least-squares problem solving for updates to the spherical harmonic coefficients of the geopotential. A single set of harmonic coefficients was determined from 111 days of data. In addition, the satellite initial conditions and the accelerometer biases were estimated once for every arc, and a single set of accelerometer scales were estimated over the data span. Finally, empirical biases were also estimated for the GPS and K-Band tracking data. Details of the parameterization used for GGM01S are summarized in Table 2.

[6] It is emphasized that the model GGM01S was estimated from GRACE data only, without any use of *a priori* statistical constraints. In Figure 1, the degree statistics (in geoid height units) of the GRACE results are compared with the pre-GRACE model, EGM96 [*Lemoine et al.*, 1998]. EGM96 was developed by combining data from over a thirty-year period of tracking near-Earth satellites, satellite altimeter data over the oceans and an extensive set of land-based measurements. The square-root degree variances (in geoid height units) of GGM01S show good agreement with EGM96 to approximately degree 90 or so, indicating that GRACE by itself has recovered the spectrum of gravitational variations to this harmonic degree. Also, to this degree, the square-root degree difference variances relative to EGM96 are reasonably consistent with the EGM96 error estimate. Thereafter, the deviations between the two are indicative of increasing errors in GGM01S, pointing to the need for some form of statistical constraint or additional information.

[7] As an example of one method for constraining the gravity solution to extend it to higher degrees, the GGM01S information equations were combined with the TEG4 [*Tapley et al.*, 2001] information equations to produce the preliminary field GGM01C, complete to degree and order 200. The TEG-4 information equations contain marine and land gravity data similar to that used in EGM96. This model, while intended as an intermediate step in the iterative refinement of the GRACE data products, was also provided to the science community for assessment.

[8] Figure 1 also shows an estimate of the square-root degree error variances of the GGM01S spherical harmonic coefficients. This error estimate was obtained by an approximate calibration of the formal error covariance based on internal sub-set solution comparisons, a method commonly used for earlier gravity model covariance calibration [*Lerch et al.*, 1993]. In addition, the runoff at the higher degrees also aids the calibration of the error covariance. On comparison with EGM96, it is evident that with only 111 days of data, the accuracy of the long- and mid-wavelength components of the Earth gravity field model has improved by over an order of magnitude.

[9] Figure 2 shows the difference of the GGM01S geoid height relative to EGM96 at wavelengths of 200 km and greater. As expected, the largest differences are over land areas where previous gravity models had sparse or inaccurate data [*Lemoine et al.*, 1998]. Over the oceans, there are areas where the changes exceed 20 cm. It has been shown that these changes represent improvements, particularly in the equatorial region, the Antarctic circumpolar region and in the regions occupied by western boundary currents [*Tapley et al.*, 2003].

[10] Figure 3 shows the geographical distribution of the geoid height uncertainty (1-sigma) for various models, obtained by propagating the full covariance matrix of spherical harmonic coefficient errors into the geoid height map domain up to degree and order 70 (the maximum degree and order available for EGM96). Because of the varying coverage and quality of the data ingested into the EGM96 model, the land, ocean and polar regions have

Table 2. Estimated Parameters For GRACE Gravity Model GGM01S

Local Parameters (Arc Dependent)	Global Parameters (Common to All Days)
Orbit: initial position and velocity of 24-hour arc	Gravitational parameters: all spherical harmonic coefficients degree 2 and above complete to degree and order 120
GPS data: double-difference ambiguities for each pass and troposphere scale factors every 30 min.	Accelerometer: 3-D scale factors
Accelerometer: 3-D biases daily	
K-Band: bias and bias-rate every 1/2 orbital rev, periodic (1-cycle-per-rev) bias every rev	

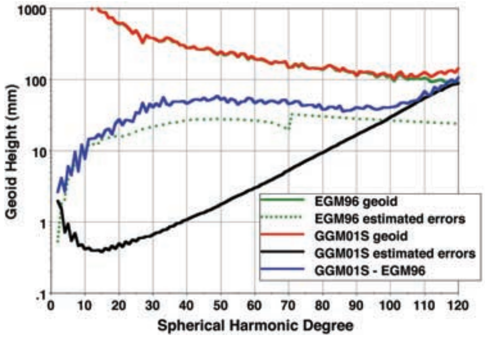

Figure 1. Statistics (in geoid height units) of the GGM01S gravity solution and its errors as a function of spherical harmonic degree. Units are mm.

distinctly different errors. The EGM96 error predictions can range from 6 to 10 cm over the oceans to a maximum of 50 cm over land [*Lemoine et al.*, 1998]. The global, homogeneous and highly accurate GRACE data, on the other hand, provides a uniform error estimate over both land and ocean regions, with a maximum error of ~2 cm. This indicates a realization of the geodetic community's goal of acquiring a global homogeneous, highly accurate data set.

3. GRACE Gravity Model Quality Validation

[11] Satellite orbit fits are one traditional measure of the gravity model accuracy. This is a particularly demanding test for the GRACE models because Earth gravity models have previously depended on the tracking to various geodetic satellites to determine the low degree part of the field, which led to these fields being noticeably tuned to their particular orbit inclinations. It is telling that GGM01S fits all tested satellites at the same level or better than models which incorporated data from these satellites, when tested with a level of parameterization typically used in the orbit fits. The RMS fit for the laser range data to Starlette was 3.7 cm using EGM96 and 2.8 cm using GGM01S. For Stella, a satellite similar to Starlette but at an inclination of 98.7°, the laser range fit was 6.4 cm with EGM96 but only 3.3 cm with GGM01S. For CHAMP, a satellite not in either model, the RMS of the GPS double-difference phase measurements was reduced from 6.3 cm using EGM96 to 1.2 cm with GGM01S; the laser range RMS was reduced from 38 cm to 8 cm (laser range data not used in the orbit fit).

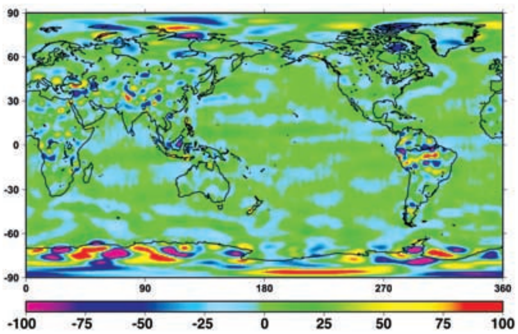

Figure 2. Geoid difference between GGM01S and EGM96 computed to degree and order 90 and smoothed with a 200 km averaging radius. Units are cm.

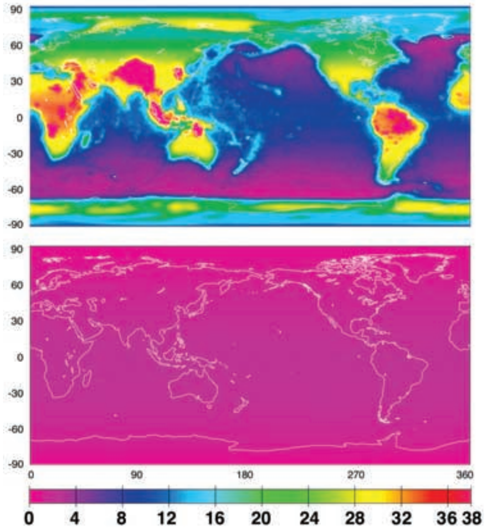

Figure 3. Geoid error predicted by the error covariance for EGM96 (top) and GGM01S (bottom) to degree and order 70. Units are cm.

[12] The GGM01S model contains no surface gravity data, and no conditioning or constraint was applied to make it agree better with the expected geoid signal. Consequently, comparisons with surface gravity data are another stringent test of the GRACE model. Limiting the test to degree and order 90, 1149 GPS/leveling points over Canada and 6418 points over the U.S. were compared to the EGM96 and GGM01S geoids. The RMS for EGM96 was 28.7 cm over Canada and 16.2 cm over the U.S.; for GGM01S, the RMS was 13.8 cm and 12.6 cm, respectively. The smaller difference over the U.S. is likely due to having removed a mean for each state in the U.S. results. Considerable variation in the mean from state to state was observed; a global geoid from GRACE accurate to the cm level at long wavelengths will help in identifying such biases in local geoid models.

[13] Another important test is the comparison of the ocean dynamic topography computed as the difference of an altimetry-derived mean sea surface and the marine geoid. In *Tapley et al.* [2003], the dynamic topographies from EGM96 and GGM01S were compared to the topography computed from data in the World Ocean Atlas 2001 (WOA01). The implied circulation was divided into zonal and meridional components and compared separately. The results, summarized in Table 3, indicate a dramatic improve-

Table 3. Global Statistics of Difference in Velocity Maps Computed With Geoid Models and That Computed With WOA01 to 4000 m Depth[a]

	Zonal Component		Meridional Component	
Model	RMS	Correlation	RMS	Correlation
EGM96	6.97	0.45	4.91	0.36
GGM01S	2.61	0.93	3.25	0.48

[a]RMS in cm/s. *Tapley et al.* [2003].

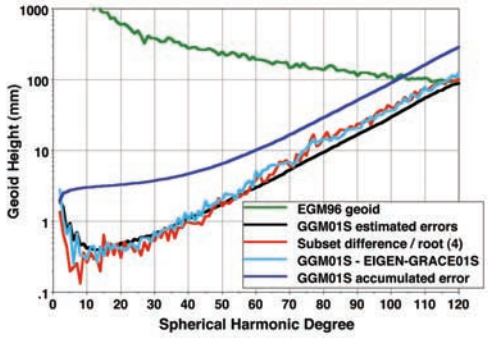

Figure 4. Comparison of subset and independent solution differences with calibrated error estimate for GGM01S. Units are mm.

ment in the correlation with the zonal circulation. At this point the zonal test is probably limited by the long-term hydrography, since other GRACE models such as EIGEN_-GRACE01S perform the same. There is also a significant improvement in the meridional correlation. This result is especially significant because the GRACE model has no altimetry data incorporated.

[14] One of the challenges anticipated for the GRACE mission was the difficulty of finding tests that could validate the expected geoid accuracies. The accumulated geoid error from the GGM01S calibrated error covariance to degree and order 40 is only 4 mm, for example (Figure 4). No external or independent test exists that can verify this error prediction. However, the internal consistency of subset solutions should be at this same level if the error prediction is valid. While a number of subset solutions were compared as part of the GGM01S calibration, one example is the comparison of a 25-day solution from October 2002 with a 26-day solution from November 2002, also shown in Figure 4. Since GGM01S has more than 4 times as much data as the individual solutions, it may be reasonable to reduce the differences by the square root of 4, leading to an error assessment that is consistent with the GGM01S error estimate. This error assessment method has been used to calibrate two earlier generations of GRACE models, and their error estimates agreed well when compared to their actual errors (as determined by comparison to a more precise subsequent gravity model), although it has tended to be conservative at the low degrees. Finally, based on comparing GGM01S with the independently derived EIGEN-GRACE01S from GFZ (based on 39 days of selected GRACE data), the difference statistics shown in Figure 4 are entirely consistent with the GGM01S error estimate (taking into consideration that GGM01S contains nearly 3 times as much data). These arguments give confidence in the prediction of 2-cm geoid accuracy (to degree and order 70) discussed earlier.

4. Conclusions

[15] A substantial improvement in the global Earth gravity models has been achieved using GRACE data. Calibrated errors indicate a global RMS error of 2 cm to degree and order 70, uniformly over land and ocean. At the low and middle degrees, this improvement is more than an order of magnitude over pre-GRACE models. These early results are a strong affirmation of the GRACE mission concept. Further improvements are anticipated when the data are re-analyzed with improved methods. Results based on these fields have been used elsewhere to demonstrate dramatically improved ocean surface current estimates and to reduce geographically correlated errors in the orbits of other geodetic satellites. Efforts continue to reduce the gravity model errors to a level closer to the mission objective.

[16] The spherical harmonic coefficients of the GGM01 models can be downloaded from the CSR web site: http://www.csr.utexas.edu/grace/gravity. The coefficients for EIGEN-GRACE01S are available at the GFZ web site: http://op.gfz-potsdam.de/grace/index_GRACE.html.

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