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ORIGINAL ARTICLE

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GGM02 – An improved Earth gravity field model from GRACE

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Abstract A new generation of Earth gravity field models called GGM02 are derived using approximately 14 months of data spanning from April 2002 to December 2003 from the Gravity Recovery And Climate Experiment (GRACE). Relative to the preceding generation, GGM01, there have been improvements to the data products, the gravity estimation methods and the background models. Based on the calibrated covariances, GGM02 (both the GRACE-only model GGM02S and the combination model GGM02C) represents an improvement greater than a factor of two over the previous GGM01 models. Error estimates indicate a cumulative error less than 1 cm geoid height to spherical harmonic degree 70, which can be said to have met the GRACE minimum mission goals.

Keywords GRACE · Geopotential · Geoid · Global gravity field modeling

1 Introduction

The Gravity Recovery And Climate Experiment (GRACE), a joint National Aeronautics and Space Administration/ Deutschen Zentrum für Luft- und Raumfahrt (NASA/DLR) mission to map the time-variable and mean gravity field of the Earth, was launched on March 17, 2002. The twin GRACE satellites carry a dual-frequency, K-band microwave ranging (KBR) system (Dunn et al. 2003) to continuously monitor the changing distance between the satellites, which in turn, reflects the changing gravity field of the Earth. The satellites also carry high precision accelerometers (ACC) to measure the non-gravitational accelerations (Touboul et al. 1999), geodetic quality BlackJack Global Positioning System (GPS) receiver (Dunn et al. (2003)) for absolute positioning and relative timing, as well star cameras for satellite attitude determination.

Based on approximately 100 days of early GRACE data spanning the interval from April to November 2002, a first generation of mean Earth gravity field models, GGM01, was made available in July 2003 (Tapley et al. 2004a). That field represented a factor of 10–50 improvement over pre-GRACE gravity models (for degrees ∼5–70), contributing to advancements in the study of dynamic ocean topography and ocean currents from satellite altimetry (Tapley et al. 2003) and in reducing geographically correlated errors and their effects on satellite geodesy (Willis and Heflin 2004; Haines et al. 2004).

A sequence of monthly Earth gravity models were produced in 2003, using GGM01C as the new starting gravity model, and using improved quality GRACE data products and processing methodologies. These were named Release 01 (RL01), and were made available in August 2004 to the user community (http://podaac.jpl.nasa.gov/grace/), along with the science measurements upon which the estimates were based. This sequence of monthly gravity models showed clear evidence of reasonable Earth gravity field variability to resolutions as small as 600 km, primarily due to hydrological variations (Tapley et al. 2004b; Wahr et al. 2004).

Fourteen of these RL01 monthly gravity models, with 363 days of data spanning from April 2002 to December 2003, were combined into the mean Earth gravity field model GGM02S. The GGM02S model is determined solely from GRACE data (KBR, GPS and ACC), and includes no constraints, regularization or other information. The GGM02S gravity field model was then combined with terrestrial gravity information to produce the model GGM02C. This paper presents a discussion of the generation of the GGM02 gravity field models (GGM02S and GGM02C) and their geodetic evaluation.

We note that other GRACE-based gravity models have also become available recently. These include EIGEN -GRACE02S (Reigber et al. 2005) and EIGEN-CG01C

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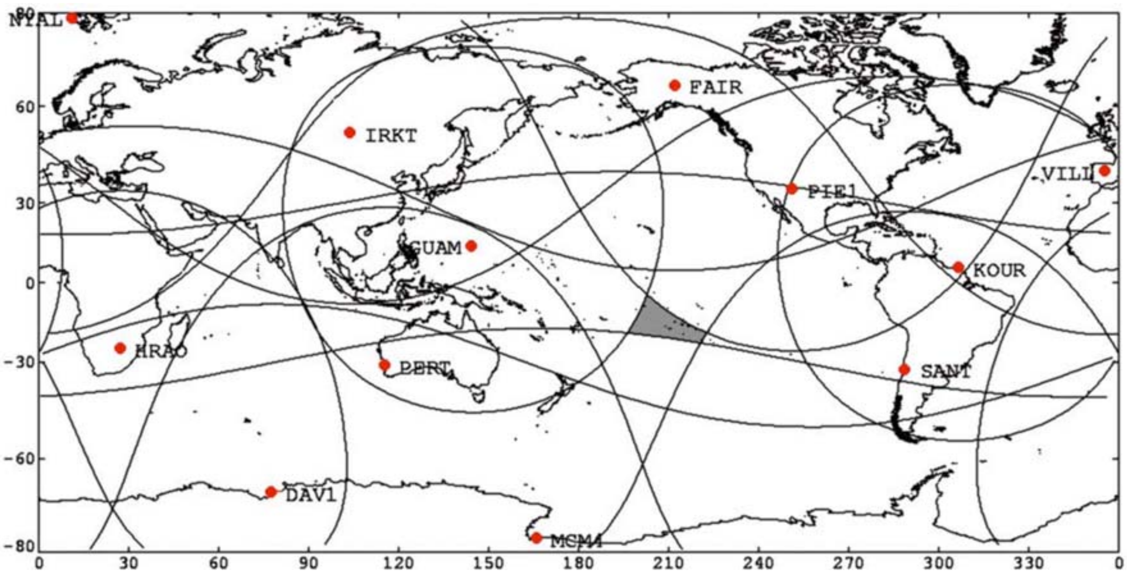

Fig. 1 Twelve station GPS ground receiver network with 15° visibility mask. The visibility mask shows the region of GRACE overflight where high-low double differences were formed. The *small gray area* is the only geographic region not covered by this network

(Reigber et al. 2004). EIGEN-GRACE02S is a GRACE-only model to degree/order 150, and was derived using 110 days of the same GRACE science data as used for GGM02S. EIGEN-CG01C combines 200 days of GRACE data (to degree/order 100) with surface information (gravimetry and altimetry) to extend the solution to degree/order 360.

2 Data processing

Continuing with the methodology described in Tapley et al. (2004a), the RL01 monthly gravity field models from GRACE were derived using a conventional, dynamic orbit and gravity adjustment process using least squares. The GRACE Level-1B data products used in this processing are described in (Case et al. 2004). The GRACE data were divided into approximately monthly spans, and one set of geopotential spherical harmonic (or Stokes) coefficients (Kaula 1966) was estimated for each month.

The use of GGM01C (Tapley et al. 2004a) as the background mean Earth gravity field model is the most significant change relative to the previous processing that led to the creation of the GGM01 models (which used a preliminary gravity model based on a limited span of very early GRACE data). The use of a de-aliasing product (Flechtner 2003) representing the non-tidal gravitational contributions from the atmosphere and the oceans is another significant upgrade relative to earlier processing. This product is used to remove the higher frequency (between 6 h and 1 month) mass variations in the atmosphere and oceans that, when sampled along the GRACE ground tracks, would be aliased into the monthly gravity model estimates (Thompson et al. 2004). Much of the more recent GRACE data products (i.e., the officially-released Level-1B inter-satellite K-band range-rate, GPS, accelerometer and satellite attitude data) used in this processing contained several improvements over the pre-release data used for GGM01. A particular improvement was the use of both star cameras, rather than just one, for attitude determination, but there were a number of other minor algorithm corrections incorporated into the data preprocessing. Another area of improvement was updates in knowledge of the relative alignment between the science instruments (KBR horn, accelerometer and star camera) through various calibration activities. Finally, the GGM01 models were based on approximately 111 days of GRACE data spanning April to November 2002 whereas the GGM02 model is derived from 363 days spanning April 2002 to December 2003.

The monthly gravity field estimation was carried out in two steps using the University of Texas Center for Space Research (UTCSR) software Multi-Satellite Orbit Determination Program (MSODP). In the first step, using a suite of background mean and time-variable Earth gravity field models, the orbits of the twin GRACE satellites were independently, numerically integrated. The accelerometer data, with estimates for the instrument bias and scale factor determined as part of the precision orbit determination, were used to represent the non-gravitational forces acting on the satellites. A detailed description of the background gravity field and other models is contained in Bettadpur (2004), and is summarized in Table 1.

The orbits in the first step were estimated using only the so-called high-low double-differenced phase tracking data between one GRACE satellite, one ground-station, and two GPS satellites. The orbits for the GPS spacecraft are provided by the International Global Navigation Satellite System (GNSS) Service (IGS) (Beutler et al. 1999). The twelve-station network of GPS ground receivers used for this purpose is illustrated in Fig. 1. Experiments have indicated that this network is more than adequate, and simulations showed that

Table 1 Summary of background force models used in GRACE data processing

Force model	Description	Parameters & remarks
Mean Earth gravity	GGM01C	Degree/order 200, epoch 2000.0
Solid tides	IERS96 Elastic Earth	Degree 2, 3 and 4
Ocean tides	CSR 4.0	Selection of harmonics based on magnitude of perturbation
Pole tide	Elastic Earth with IERSC04 polar motion series	Mean pole from IERS2003 standards
Secular changes	J2 only (IERS2003)	Epoch 2000.0
Non-tidal ocean and atmosphere	ECMWF atmosphere & barotropic ocean model	Degree/order 90
Luni-solar & planetary (3rd body) perturbations	DE-405	Including indirect J2 effect
Non-gravitational forces	From accelerometer data	
Earth orientation	IERSC04 (Gambis 2004)	IERS96 standards

Full model details are available in Bettadpur (2004)

Table 2 Summary of observations and parameter estimation for monthly gravity field solutions

Observations	Description	Parameters & remarks
GPS phase tracking	Double-differenced ionosphere-free L3 phase combination between two GPS satellites, one GRACE satellite and one ground station	The orbits were computed independently for both GRACE satellites. IGS final orbits used for GPS spacecraft.
K-Band range-rate	5-s sample rate from GRACE Level-1 data Release 00.	The range-rate is numerically derived from the inter-satellite microwave phase tracking.
Orbit parametrization – Step-1		
Orbit arc length	1-day	The arc-length is defined by the period over which single orbit initial condition is adjusted
Dynamical parameters	Accelerometer bias (three-components)	Estimated in accelerometer frame and rotated to inertial frame using attitude information and ACC orientation calibration
Observation parameters	Double difference bias	Adjusted as a real-valued parameter for each pass
	Troposphere zenith delay correction	Uncorrelated constant correction every 15 min
	GPS satellite orbit element corrections	Empirical corrections to selected orbit elements
Orbit & gravity parametrization – Step-2 (these are in addition to parameters already mentioned in Step-1 above)		
Gravity field	Degree 120 or 160	Choice of 120 or 160 was determined by ground-track coverage and data quality
K-Band empirical parameters	Bias	2,700 s piece-wise constant
	Slope	2,700 s piece-wise constant
	One cycle-per-orbital revolution	5,400 s piece-wise constant
Accelerometer scales	Three components	Estimated once over each monthly span

even six ground stations were sufficient (Kim and Tapley 2002). The KBR data were not used in this step since the GPS-based orbits are generally accurate to the few centimetre level, sufficient to support the required accuracy of the partial derivatives computed in next step. The Earth gravity field model parameters were not adjusted during this step, either, and the orbit was determined with iterative estimation of a limited set of parameters (to avoid using parameters that could significantly absorb the gravity signals). The observations used during this process, and the estimated parameters, are summarized in Table 2.

In Step-2, the observation residuals for the GPS double-difference phase and KBR data were computed based on the converged orbits from Step-1. At the same time, the partial derivatives (the regression equations) for all the estimated parameters relative to the measurement residuals were also computed. The additional parameters appearing in Step-2 are also summarized in Table 2.

At this stage, for each day (i.e., orbital arc), there were three sets of information files available (GPS for GRACE-A, GPS for GRACE-B and KBR involving both satellites), each comprising of a set of measurements residuals and their partial derivatives relative to the estimated parameters. A single set of gravity field parameters was estimated from a combination of the full set of (up to 63) information equations for each month, along with the simultaneous adjustment of the various other force and measurement model parameters. Briefly, the parameters estimated along with geopotential coefficients were: (1) initial conditions for daily arcs, (2) GPS orbit corrections, (3) accelerometer biases (daily) and scale factors (monthly), and (4) KBR biases, GPS ambiguities and zenith delays. The accelerometer scale factor appears to be relatively stable, and the choice was made to estimate a single scale factor for each axis once per month. The accelerometer biases, however, display some drift within a month, and this has been accommodated by estimating the bias for each axis for each daily batch of data. The KBR data and background model errors are expected to cause drifts in measurement residuals on time scales longer than the orbital period, and the estimated biases are designed to accommodate this (Kim 2000; Kim and Tapley 2002). The time interval for the piece-wise constant bias terms is chosen to be sufficiently

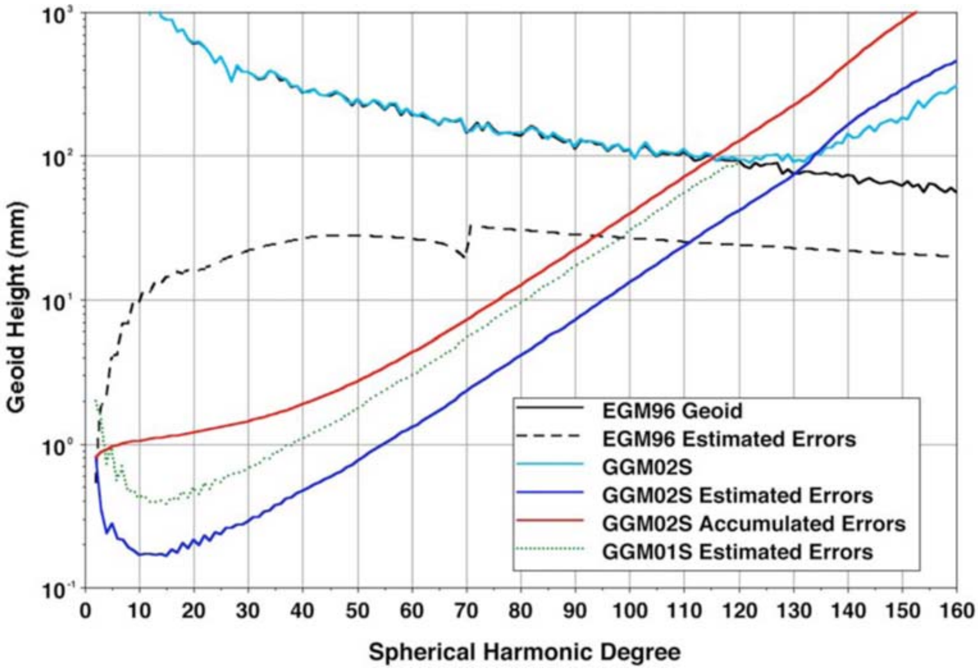

Fig. 2 The estimated square-root degree variances and degree error variances for GGM02S, contrasted with GGM01S and EGM96, are shown as a function of degree in terms of geoid height (mm). For a given degree N, the root-sum-square of the coefficients (or their 1-sigma error estimates) for all orders (0 through N) is calculated. The lower degrees can be associated with longer wavelengths and the higher degrees with shorter wavelengths. For geopotential models, this provides useful statistical information about the nature of the gravity model and its errors as a function of wavelength

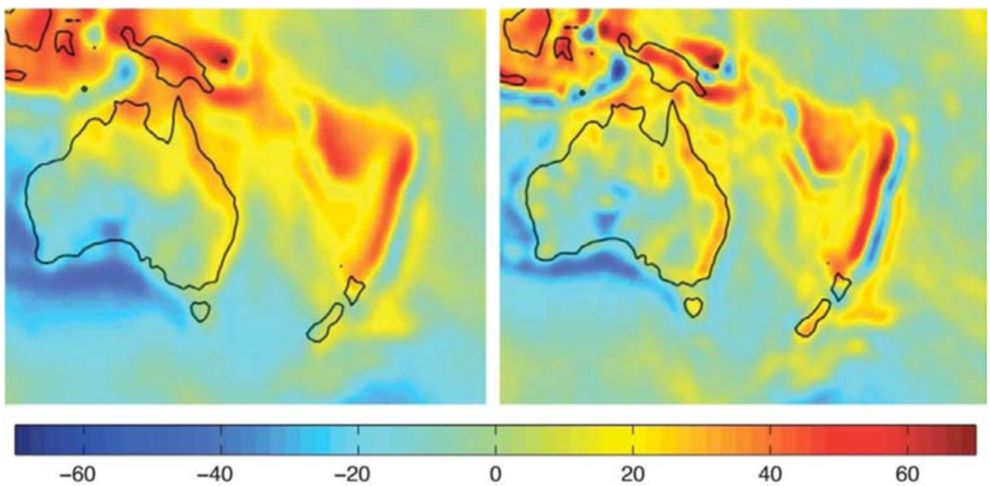

Fig. 3 Improvement in resolution in gravity anomalies computed from GGM02S (*right*) compared to GGM01S (*left*) in the Tonga-Kermadec region. With the increased accuracy of the GGM02S model, less smoothing is required to remove artifacts and more detail is revealed. Units are milligals

long so that the higher frequencies associated with the geopotential harmonics are not absorbed. As the GRACE instruments are understood better over the course of the mission, the various parameterization choices will be refined.

Along with the geopotential coefficients and the previously mentioned parameters, the weights of the individual information equations were also adjusted using an optimal weighting procedure (Yuan 1991). This is an iterative procedure, and leads to each dataset being weighted in an inverse proportion to the postfit residuals of that dataset (this is consistent with assuming that the noise in the data is white). Therefore, three relative weights were allowed to adjust each day, one each for the two GPS information equations, and one for the KBR range-rate information equations. The K-Band range-rate data were thus weighted between 0.4 μ/s for the earlier data in the mission to 0.2 μ/s for the data in late

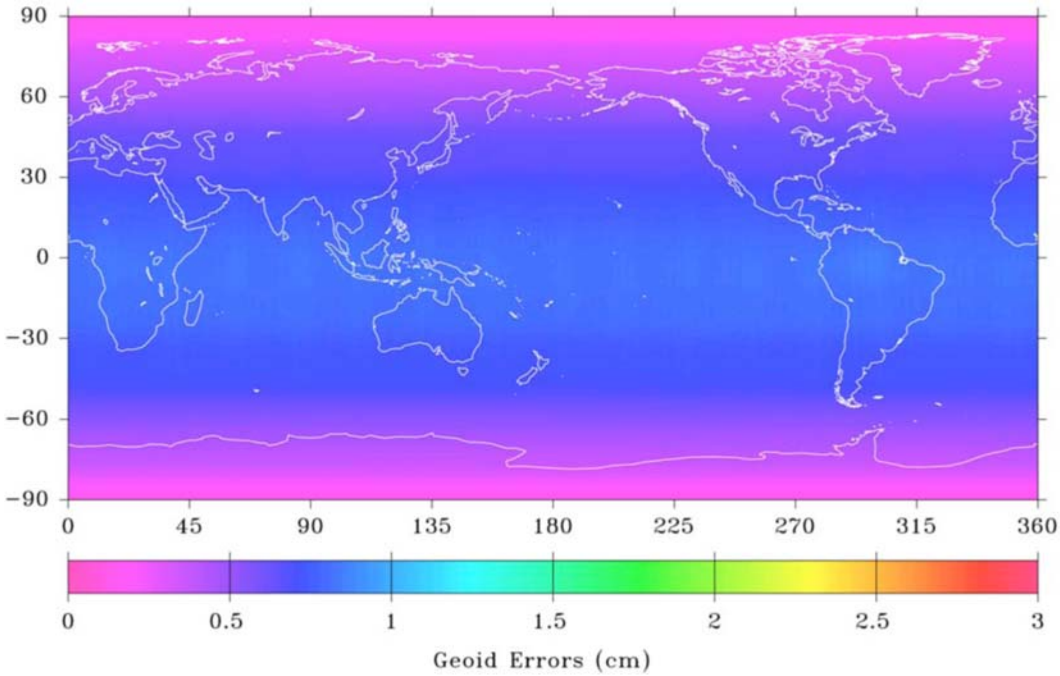

Fig. 4 Geoid height error predicted by the full covariance as a function of geographic location for GGM02S to degree/order 70. Due to the global, homogeneous nature of the GRACE data, the resulting geoid errors show no discrimination between land and sea. The global RMS of the GGM02S geoid height error is estimated to be ∼7 mm, with a maximum error of ∼9 mm. Units are centimetre

Table 3 Summary of monthly fields contributing towards the determination of GGM02 gravity field

Month	Number of days	Maximum degree estimated
April/May 2002	29	120
August 2002	28	120
November 2002	26	160
February 2003	22	120
March 2003	31	160
April 2003	30	160
April/May 2003	27	120
July 2003	30	160
August 2003	30	160
September 2003	27	160
October 2003	31	160
November 2003	30	160
December 2003	29	160

Months with poorer quality or insufficient data were limited to degree/order 120. Note that the improved star tracking data was available after March 2003

2003; the GPS data weights ranged between 1 and 2 cm, depending on the quality of the fits each day.

The 14 months that contributed towards the GGM02 solution, and the maximum estimated geopotential degree/ order for each span, are summarized in Table 3. Some months had fewer usable days or were of lesser quality, and the maximum degree/order that could be confidently estimated was lower. These fourteen monthly gravity field estimates are part of the RL01 gravity field products from the GRACE mission (http://podaac.jpl.nasa.gov/grace/). The routine availability of dual-star camera data past March 2003 provided improved alignment of the instruments, and the quality of the data and the accuracy of the gravity models is generally superior past that point. The quality of these models, as well as the geophysical variability they represent, is discussed in detail in Tapley et al. (2004b).

3 The GGM02S gravity field model

The GGM02S model coefficients were estimated to degree/ order 160 with no constraints or regularization. The fourteen monthly gravity field solutions (mentioned in the previous section) were regarded as fourteen observations of the gravity field, and their respective information equations were combined together to determine the GGM02S field coefficients. The data weights for each month were not re-adjusted in this combination solution. The data for each day were therefore weighted in inverse proportion to its postfit residual RMS from that month's solution. To account for systematic errors, as well as to provide an absolute calibration of the resulting errors of the combined solution, a post-solution calibration of the formal (or 'noise-only') covariance is determined as discussed later.

Figure 2 shows the degree square-root variance statistics of GGM02S, as well as that of GGM01S and EGM96 (Lemoine et al. 1998) for contrast. All statistics are shown in units of mm of geoid height and are derived from simply multiplying the degree-accumulated statistics of the geopotential harmonic coefficients by the equatorial Earth radius of 6378136.3 m. Figure 2 indicates that GGM02S reproduces

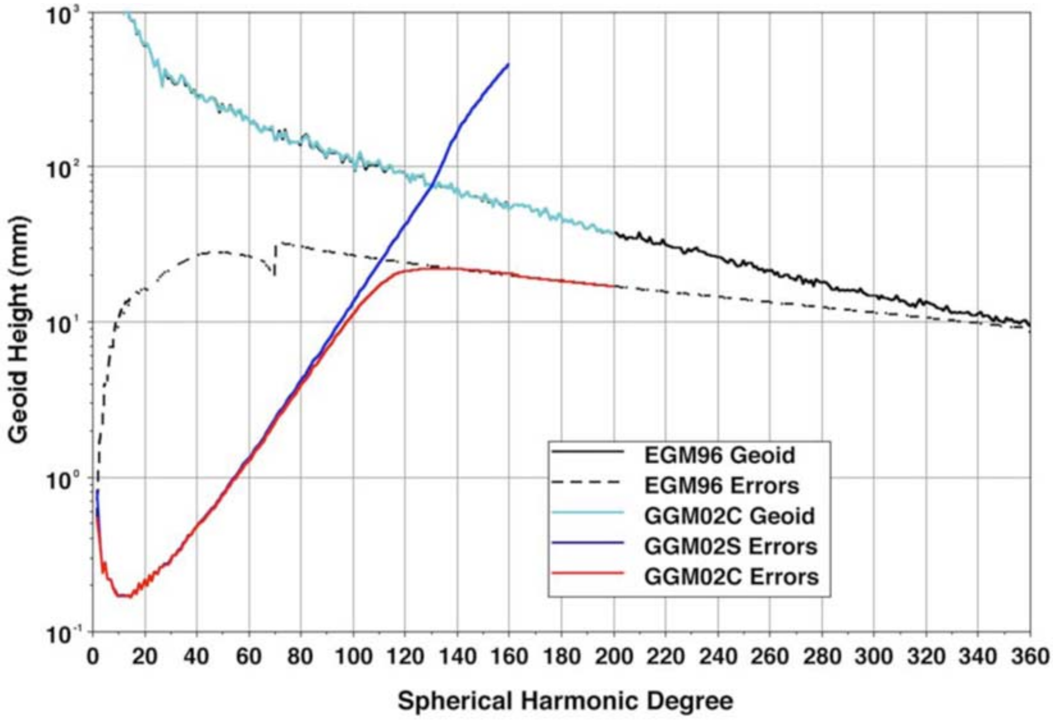

Fig. 5 Estimated square-root degree variances and degree error variances for GGM02S and GGM02C are shown in terms geoid height (mm). By rigorously combining the information equations from GRACE with the TEG4 covariance to degree/order 200, a smooth transition to the surface information is achieved

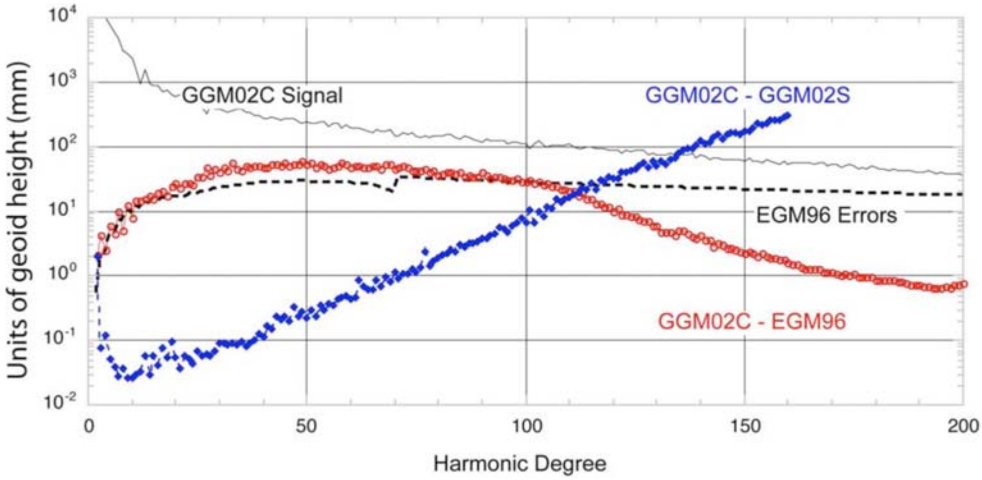

Fig. 6 The spectral differences of GGM02C relative to GGM02S and EGM96. The GRACE information dominates the combination solution below approximately degree 100 and smoothly blends into EGM96 above that. This allows GGM02C to be extended to degree/order 360 by appending the EGM96 coefficients above 200

the correct spectral power of the Earth gravity field to approximately degree 120, assuming that EGM96 is correct. There is little reason to believe that GRACE gravity estimates above degree 120 are more precise than the gravity information from the terrestrial gravity data. Therefore, the runoff in the degree variance above degree 120 is indicative of growing errors in GGM02S, as the solution had no additional constraints or conditioning applied to control the solution at the higher degrees. By contrast, for GGM01S, the coefficients were reliable in this sense only to approximately degree 90.

Figure 3 illustrates the improved resolution in GGM02S over GGM01S by mapping the gravity anomalies in the Tonga/Kermadec region, smoothing each solution to the appropriate level (where the higher degree errors are no longer apparent). The increased resolution supported by GGM02S reveals more details than before in the structure of the crust in this area. As a usage guideline, it is recommended that the GGM02S harmonic coefficients should not be used, in general, past degree 120 without smoothing. Over the polar regions, it may be possible to use coefficients of higher degree. The convergence of the ground tracks of the polar-orbiting GRACE satellites provides a denser areal coverage at the poles, supporting a higher resolution in the gravity model estimation.

Figure 2 also shows an estimate of the square-root degree error variance of the GGM02S spherical harmonic coefficients, again contrasted with GGM01S and EGM96. This error estimate was obtained by an approximate calibration of the formal error covariance based on internal sub-set solutions (Lerch et al. 1993) and external independent comparisons with gravity solutions most notably from GeoForschungs Zentrum (GFZ). In addition, the runoff at the higher degrees, illustrated in Fig. 2, can be directly attributed to the errors in the GRACE solution, which also aids the calibration of the error covariance. The formal error curve can be scaled up to match the apparent runoff at the higher degrees.

The calibrated error covariance predicts that the global cumulative error to degree/order 70 in the GGM02S model is less than 1 cm, which is more than a factor of two improvement over GGM01S. Figure 4 shows the geographical distribution of the geoid height uncertainty (1-sigma) for GGM02S obtained by propagating the full approximately-calibrated covariance matrix of the spherical harmonic coefficient errors into the geoid height map domain up to degree/order 70. The global, homogeneous and highly accurate GRACE data provides an error estimate that does not distinguish between land and ocean regions with a maximum error of $\sim$9 mm and a global RMS of $\sim$7 mm. The latitudinal dependence of the error simply reflects the convergence of the ground tracks at the poles. Whether the true geoid error is really so much smaller over the poles is an issue that remains to be explored. Calibration of geoid error models at the sub-mm level was expected to be a challenge for the GRACE mission.

4 The combination solution GGM02C

Creation of a complete mean Earth geopotential model, whose spectral power does not run off at higher degrees, required the combination of the GGM02S model information with terrestrial gravity information. For creating this combination model GGM02C, terrestrial gravity information (land surface gravity and mean sea surface) was incorporated as distilled in the form of the spherical harmonic coefficients of EGM96. A weighted combination of GGM02S and EGM96 spherical harmonic coefficients was computed to degree and order 200. The coefficients of GGM02S to degree and order 160 were weighted by the calibrated error covariance matrix described in the previous section. The coefficients of EGM96 to degree and order 200 were weighted by a tuned, full degree and order 200 error covariance matrix of the Texas Earth Gravity Model 4 (TEG4 – Tapley et al. 2001). The TEG4 error estimates were used as weights for EGM96 coefficients because for the TEG-4 model – which used much the same terrestrial gravity data as EGM96 – the error covariance matrix is available to degree and order 200. The EGM96 error covariance, on the other hand, is a full matrix only to degree and order 70 (Lemoine et al. 1998). It is recognized that this is a somewhat ad hoc procedure, and future combination models will be based on full degree/order 360 normal equations directly from the surface information.

An important consideration when combining the GRACE and surface information is the relative weighting. This is a challenging problem with the GRACE data due to its extraordinary accuracy and its unique error characteristics. At the low degrees, it is essential to prevent the surface gravity information from having any significant influence, since the GRACE data is orders of magnitude more accurate. In addition, the EGM96 coefficients or the TEG-4 error covariances at long wavelengths also contained information from years of tracking to various geodetic satellites, and their contribution also needed to be minimized. Consequently, for the combination, the lower degrees in the TEG4 error covariance were artificially (but smoothly) downweighted by several orders of magnitude. Starting at approximately degree 110, the downweighting was increased as the degree decreased.

As part of its calibration, the high degree GGM02S information was downweighted starting at approximately degree 130 (see Fig. 2), so that the higher degree estimates derive from the EGM96 coefficients. The inflation of the error estimates for the higher degrees in GGM02S reflects the fact that the ‘near-sectorial’ coefficients (where the order and degree are closer) tend to have larger errors (a consequence of being more susceptible to longer wavelength dynamical modeling errors), leading to significant large-scale north-south striations in the geoid whose magnitude are underestimated in the covariance. Unfortunately, inflating the error estimates for all coefficients of the higher degrees also downweights the important contribution from GRACE to the zonal and ‘near-zonal’ coefficients (where the order is small relative to the degree), and a hint of this can be seen in the discussion of the oceanographic validation. Finally, because the data span used for GGM02 is still relatively short, the J_2 harmonic was constrained to its long-term (multi-decadal) mean value from EGM96 (using the original EGM96 sigma for J_2), which is largely determined from satellite laser ranging (SLR) data.

This rigorous combination allowed for a smooth transition from GRACE gravity information in GGM02S to the surface gravity information in EGM96, as illustrated in Figs. 5 and 6. The GGM02C solution retains correct spectral power at all estimated degrees up to the solution limit of 200 (Fig. 5). Because the higher degrees were constrained to EGM96, this solution can (when an even higher degree model is required) be smoothly extended to degree/order 360 by using the EGM96 coefficients to fill in above degree/order 200, which is well above any sensible contribution from the GRACE data. Figure 6, where the square-root degree variance of the GGM02C coefficient differences with GGM02S and EGM96 is shown, illustrates that the GGM02C combination strategy was effective. The GRACE information dominates the solution below $\sim$degree 100 and smoothly blends into EGM96 above that.

Figure 7 illustrates this important aspect of the model improvement since GGM01C. The size of North-South striations, most visible in differences relative to EGM96, is

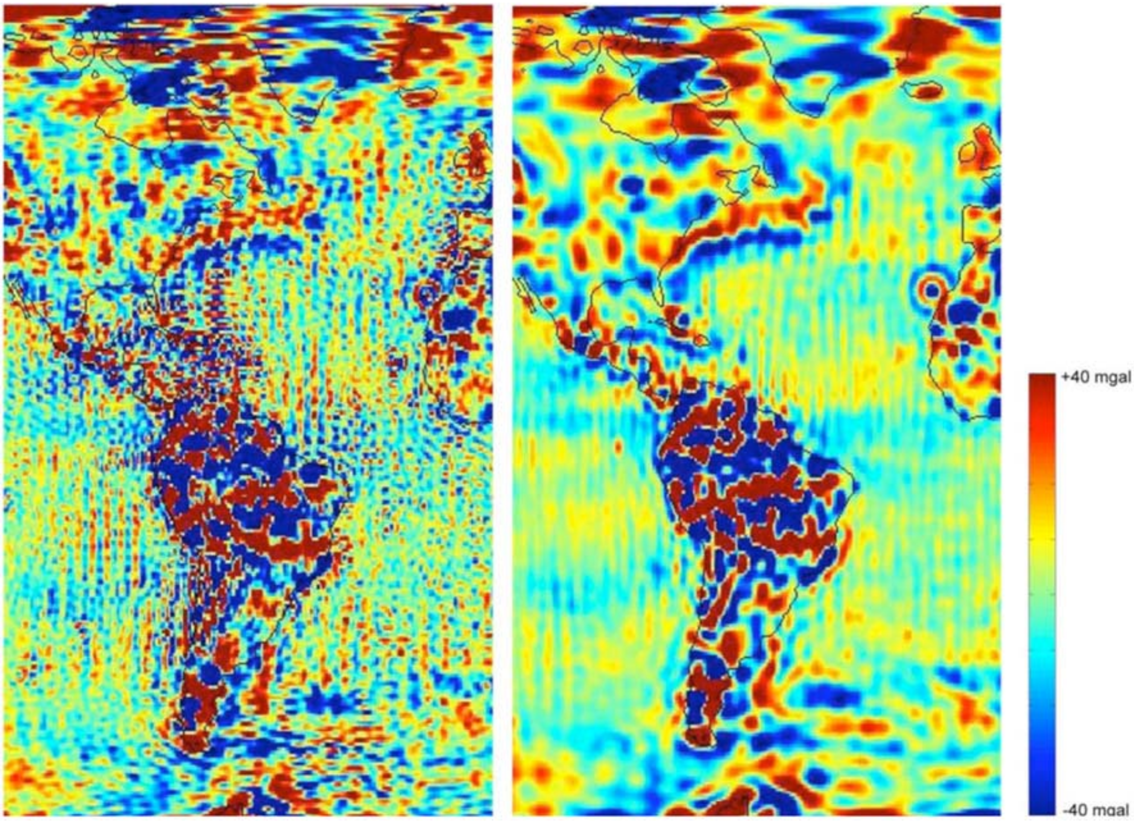

Fig. 7 Close-up view of differences in the gravity anomalies between EGM96 and GGM01C (*left*) and GGM02C (*right*), to degree/order 200. Improvements relative to the EGM96 model are more cleanly delineated, but some broad-scale North–South artifacts are still visible in the marine geoid differences

considerably reduced in GGM02C. The residual striations indicate that the downweighting of the GRACE information at the higher degrees may still be insufficient. Future solutions will address this better in three ways: (1) taking into account the different error characteristics as a function of both the coefficient degree and order, (2) reducing the causative errors by improvements in the input data products and processing methods, and (3) continuing to fill in gaps in the longitude coverage.

5 GGM02 model quality validation

5.1 Geodetic validation

Satellite orbit fit quality is one traditional measure of the gravity model accuracy (Lemoine et al. 1998; Tapley et al. 2001; Reigber et al. 2005). 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 tailored to the particular orbits of these satellites (Tapley et al. 1996). Of the various geodetic satellites tested, Starlette and Stella provided the best discrimination between the various gravity models. They are low enough to be sensitive to a large portion of the geopotential and high enough for sufficient SLR tracking. With their ‘cannonball’ design, the low area-to-mass ratio (i.e. ballistic coefficient) reduces the susceptibility to surface forces (particularly atmospheric drag) and enables a well-determined center-of-mass offset model for the SLR data.

It is telling that, when tested with a level of parameterization typically used in the orbit fits, the GRACE models yield better orbit fits for these satellites than models that incorporate data from these same satellites. The RMS fit for the laser range data to Starlette, for example, using 5-day arcs, was 3.7 cm using EGM96, 2.8 cm using GGM01S, and 2.7 cm for GGM02S. For Stella, a satellite similar to Starlette but at a different inclination, the laser range fit was 6.4 cm with EGM96, 3.3 cm with GGM01S and 3.1 cm for GGM02S. Because GGM02S and GGM02C are very close to each other at the lower degrees, which is the part of the gravity model that dominates the satellite orbits, the orbit fit statistics for GGM02C were the same as GGM02S to within a mm. Further improvement is likely to be difficult to detect in these tests, since the covariance predictions indicate that the contribution to the orbit error from the static gravity field model has been nearly eliminated. Only in the case where there is a particularly strong resonant perturbation in a satellite orbit would the gravity model error be visible; and in such cases, some

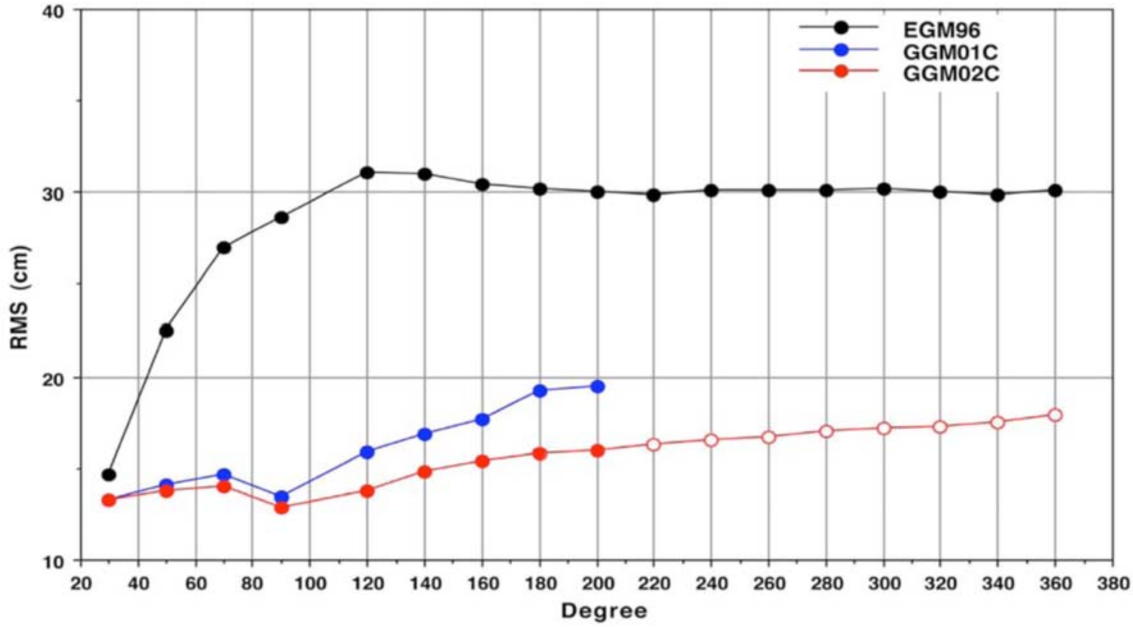

Fig. 8 Degree-banded GPS leveling residual RMS over Canada as a function of degree. GGM01C was limited to degree/order 200, but GGM02C can be seamlessly extended beyond degree/order 200–360 using the EGM96 coefficients

specific tuning of selected harmonics might be warranted for improved orbit determination.

GGM02S contains no surface gravity data, and no conditioning, regularization or other 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-only models. Limiting the test to degree/order 90 using a degree-banded approach that restricts the comparison to a specified upper limit for the satellite-based gravity model (Huang and Véronneau 2005), 1149 GPS/leveling points over Canada were compared to the EGM96, GGM01S and GGM02S geoids. The RMS was 28.6 cm for EGM96, 14.4 cm for GGM01S and 13.8 cm for GGM02S. Extending the test to degree/order 120, the RMS is 31.1, 32.7 and 18.1 cm for EGM96, GGM01S and GGM02S, respectively. GGM01S does not perform well beyond degree/order 90 or so, which is reflected in these results. The combination models GGM01C and GGM02C are compared in Fig. 8, using the degree-banded approach to restrict the comparison to selected degrees. It is apparent that GGM02C is an improvement over GGM01C, but the test is probably dominated by the errors in the leveling data rather than the geoid errors, at least up to degree 90 or so. The predicted error for GGM01C at degree/order 70 is less than 1 cm, whereas the RMS of the residuals is at the 12–13 cm level and does not change much over the entire range of degrees.

5.2 Oceanographic validation

Tapley et al. (2003) illustrated the improvements in the models for the dynamic ocean topography and geostrophic currents based on altimetry and the GGM01S geoid compared to earlier geoids based on decades of satellites and surface data. The same comparison is performed here with the GGM02 geoids, and the results are compared with those obtained with the GGM01 and EGM96 geoids, as well as with two other recent GRACE-based models. Some modifications have been made in these tests in order to highlight improvement in the GGM02 geoids for shorter wavelengths.

For previous testing of the GGM01 models, only the coefficients to degree/order 90 were used to compute a 1° gridded map of geoid height, because of noticeable errors in some higher degree/order coefficients. Here, however, the coefficients to degree/order 120 are included. Using this geoid height map, the dynamic topography is computed using the same gridded mean sea surface (MSS) model as before (Tapley and Kim 2000), decomposed into spherical harmonics to degree/order 120. The dynamic ocean topography (DOT) is the departure from the level geopotential surface (i.e., the geoid) due to the currents. The resulting topography maps are smoothed as before [Tapley et al. 2003, Eq. (1)] with a radius of influence equal to 500 km.

The zonal and meridional circulation are again computed from all the topography maps using forward-backward differences between adjacent grids and compare values to a circulation map derived from the World Ocean Atlas 2001 (WOA01) (Stephens et al. 2002) relative to 4,000 m depth. Circulation maps are especially useful for evaluating improvement in the geoid models over shorter wavelengths, since small changes in the geoid can lead to significant changes in the circulation (because currents are inferred from the gradient of the dynamic topography). The circulation map is a multidecade average, and there will be some differences between

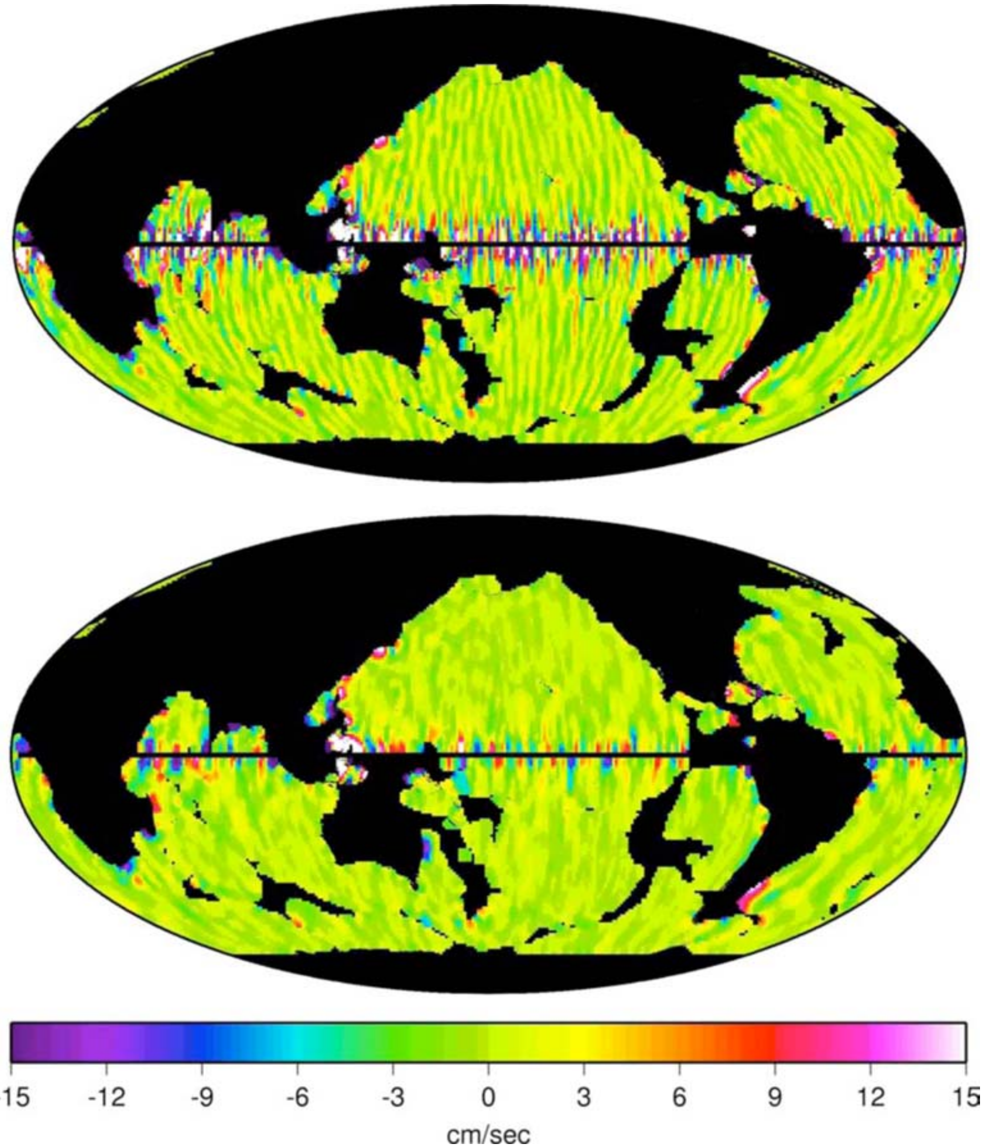

Fig. 9 Improvement in comparison of implied meridional geostrophic currents from GGM01S (*top*) to GGM02S (*bottom*), when compared to the World Ocean Atlas 2001 (WOA01) data (relative to 4,000 m, courtesy of V. Zlotnicki). A smoothing of 500 km was used for this figure. Missing data over the ocean is caused by missing values from WOA01 due to the 4,000 m reference level. Units are centimetres per second

the averaging period of the altimeter-based mean sea surface model and the circulation map. This will be one reason that the comparisons do not match perfectly, setting a limit to the test results.

Table 4 lists statistics of the comparison of the GGM01 and GGM02 derived circulation maps relative to the WOA01 maps, separated into zonal (East–West) and meridional (North –South) components. Included in the comparison is EGM96 as well as two other recent GRACE gravity models, EIGEN-GRACE02S and EIGEN-CG01C. For the zonal (or East–West) circulation, the difference in statistics between the GGM01 models and the other more recent geoid models is very small (approximately 0.1%). The GRACE satellite-to-satellite tracking is nearly north-south, and the geoid variations in this direction are well determined even with the smaller number of days of data in the GGM01 models. Maps of the zonal circulation residuals (not shown) were indistinguishable between GGM01S and GGM02S. It is likely that the zonal circulation comparisons are now limited by accuracy of the model for the long-term hydrography, and further improvements in the marine geoid will be difficult to detect with this test.

The limited quantity and quality of data used for GGM01S, as compared to GGM02S, did cause errors in the higher degree 'near-sectorial' coefficients. This resulted in north-south striations in the geoid maps, which would affect the meridional circulation determination. Compared to the GGM01 models, the statistics in Table 4 indicate a significant improvement in the meridional circulation with the GGM02 models, as well as the other more recent GRACE gravity models. This is also demonstrated in maps of the meridional current residuals, shown in Fig. 9 with 500 km smoothing

Table 4 Residuals of the geostrophic currents implied by the mean surface (CSRMSS98) minus various marine geoid models compared to the World Ocean Atlas 2001 (WOA01) data (relative to 4000 m, courtesy of V. Zlotnicki)

Model	Standard deviation (cm/s)		Correlation	
	Zonal	Meridional	Zonal	Meridional
EGM96	7.0	5.0	0.43	0.37
GGM01S	2.5	3.3	0.93	0.44
GGM01C	2.6	2.9	0.93	0.55
GGM02S	2.5	2.8	0.94	0.57
GGM02C	2.6	2.8	0.93	0.57
EIGEN-GRACE02S	2.5	2.8	0.93	0.57
EIGEN-CG01C	2.6	2.9	0.93	0.56

Comparison is to degree/order 120, and 500 km smoothing has been applied

Table 5 Global RMS of residual geoid (MSS – WOA01 DOT – geoid model) along the new interleaved T/P ground track for different wavelength filtering

Model	>300 km	<300 km
EGM96	10.2	13.5
GGM01C	15.5	26.4
EIGEN-CG01C	10.6	14.4
GGM02C	8.5	13.6

Means have been removed along each pass before computing the RMS. All models complete to degree/order 360 (GGM01C and GGM02C extended to 360 using EGM96 coefficients above degree/order 200). Units in centimetre

applied, where the North–South striations are much more obvious for GGM01S than GGM02S. When surface information was added to GGM01S to form GGM01C, the meridional errors were reduced, but Table 4 shows that GGM01C still does not perform as well as GGM02S, which includes only GRACE data. This is probably a consequence of the greater number of days of better quality data used to generate GGM02S.

Table 4 also shows that there was little change in the statistics from GGM02S to GGM02C, to degree/order 120 used here. The weighting in the combination, discussed earlier, appears to have been effective in preventing distortions in the geoid at the lower degrees (below 120). There is evidence of a barely significant degradation in the circulation statistics with GGM02C relative to GGM02S, alluded to earlier.

The improvement of GGM02C over GGM01C over the ocean for the shorter wavelengths is demonstrated by comparing it to mean sea surface (MSS) profiles determined from TOPEX/POSEIDON (T/P) data from September 20, 2002 to December 31, 2003, after the T/P satellite was maneuvered into a new ground track halfway between its old ground track. These data are used because the ground track is different from any of those from previous altimeter missions used to create either GGM02C, EGM96 or the EIGEN solutions, and thus they represent new and independent observations of the marine geoid. The residuals along each satellite pass are calculated from ((MSS – WOA01 DOT) – geoid). The World Ocean Atlas 2001 dynamic ocean topography (WOA01 DOT) is computed to a reference level of 4,000 m, and the geoid is evaluated using coefficients to spherical harmonic degree/order 360. Because GGM01C and GGM02C are only complete to degree 200, they were extended using the EGM96 coefficients for degrees 201–360. As noted earlier, GGM02C was designed to be seamlessly extendable to degree 360 using EGM96, and EIGEN-CG01C is available as a full degree/order 360 solution. The mean along each pass was removed because the DOT is biased relative to the geoid. Because the MSS has significant power at wavelengths shorter than degree 360, statistics of the residuals without smoothing will tend to be dominated by these very-short wavelength variations. To better determine the influence of the GRACE geoids, the residuals along each pass are smoothed using a Gaussian filter with a radius of influence equal to 300 km. This radius was chosen as the approximate wavelength of transition between GRACE and surface data. The RMS statistics are calculated for the 300 km smoothed residuals, as well as for the unsmoothed residuals with the 300 km smoothed residual subtracted. The former will represent the signal where the GRACE contribution to the geoid is large, while the latter represents the signal where the GRACE contribution is going to be small, although problems at the transition from GRACE to the surface information will be apparent in these statistics. Smaller RMS values, shown in Table 5, indicate that the particular geoid model fits the observed marine geoid (MSS – WOA01 DOT) better.

At the wavelengths tested, GGM01C did not perform as well as EGM96. Whereas GGM02C, performs significantly better than EGM96 for wavelengths greater than 300 km and comparably for wavelengths less than 300 km, even though it is only complete to degree 200 and patched for higher degrees with EGM96. The short-wavelength statistics should improve with future combination models, where more accurate GRACE models will extend the resolution to higher degrees and where full degree/order 360 surface information equations will be rigorously combined with the GRACE information.

6 Conclusions

A substantial further improvement in global mean Earth gravity models has been achieved using the latest available GRACE science data. The satellite-only model GGM02S (to degree/ order 160) has been successfully combined with terrestrial gravity information to obtain GGM02C (to degree/order 200), preserving the strength of the GRACE information at longer wavelengths and the surface information contained in EGM96 at shorter wavelengths. Calibrated error estimates for the GGM02 generation of models (either GGM02S or GGM02C) indicate a global geoid height RMS error of approximately 7 mm to degree/order 70, with no discrimination between land and ocean. At the low and middle degrees (approximately degree 5–70), this improvement is nearly two orders of magnitude over pre-GRACE models, and more than a factor of two improvement over the earlier GGM01 generation. Results shown here demonstrate further improvements in ocean surface current estimates, and efforts continue to reduce the gravity model errors further.

7 Remark

The spherical harmonic coefficients of GGM02S and GGM02C, along with a description of the format and related constants, are provided in the Electronic Supplementary Materials (ESM).

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