GRACE Gravity Model GGM02

The GGM02S gravity model was estimated with 363 days (spanning April 2002 through December 2003) of GRACE K-band range-rate, attitude, and accelerometer data. No 'Kaula' constraint, no other satellite information, no surface gravity information and no other *a priori* conditioning were applied in generating this solution. The GGM02S field was estimated to degree and order 160, and the solution appears to retain the correct signal power spectrum up to about degree 120 (see Figure 1). The parameters estimated along with coefficients of GGM02S were: i) initial conditions for daily arcs, ii) accelerometer biases (daily) and scale factors (monthly), and iii) KBR biases, GPS ambiguities and zenith delays.

GGM02C, a higher resolution global gravity model, combines GGM02S with terrestrial gravity information (surface gravity and mean sea surface) using the TEG4 covariance (complete to 200x200) to constrain the higher degrees to the harmonic coefficients of EGM96. Additionally, the (2,0) harmonic was constrained to its long-term (multi-decadal) mean value from EGM96. The GGM02C solution was created to degree and order 200, and retains correct signal power spectrum to this resolution (Figure 1). This solution can also be smoothly extended to 360x360 by using the EGM96 coefficients to fill in above degree and order 200.

The degree signal and error statistics of the GGM02 coefficients are shown in Figure 1, in units of geoid height. The root-mean-square predicted geoid height error, based on a calibrated error covariance matrix, is shown to degree 70 in Figure 2. As with GGM01 fields, there is no land-sea discrimination in the errors, but the errors are now consistently below 1 cm. Figure 3 is intended to show the relative information content of GGM02C in different degree regimes and that the GGM02C field is indistinguishable from GGM02S at the lower degrees. The transition between the GRACE-based information at lower degrees and terrestrial gravity information at higher degrees takes place near approximately degree 110 to 120. Finally, Figure 4 illustrates the extension of GGM02C to 360x360 using EGM96.

GGM02 is being provided as spherical harmonic coefficients and as gridded surfaces. The file contents and formats are provided below.

Please note:

GGM02S should not be used as is beyond approximately degree 110. Rapidly increasing errors make the coefficients unreliable at higher degrees. Over the polar region, it may be possible to use slightly higher degree coefficients. Depending on the application, the GGM02S field coefficients should be truncated or smoothed to an appropriate level. If a high-resolution gravity model is required, GGM02C should be used; no truncation or smoothing should be necessary.

The GRACE data used for GGM02S are an incomplete sampling of the seasonal cycle, and the later data, which are of higher quality, are weighted more heavily in the solution than the earlier data. As a result, the C20 estimate in GGM02S is significantly biased relative to the long-term (multi-decadal) mean value. **For precision orbit determination or other applications requiring an accurate long-term mean value for C20, the GGM02C field should be used.**

Comments or Questions ? Please contact grace@csr.utexas.edu

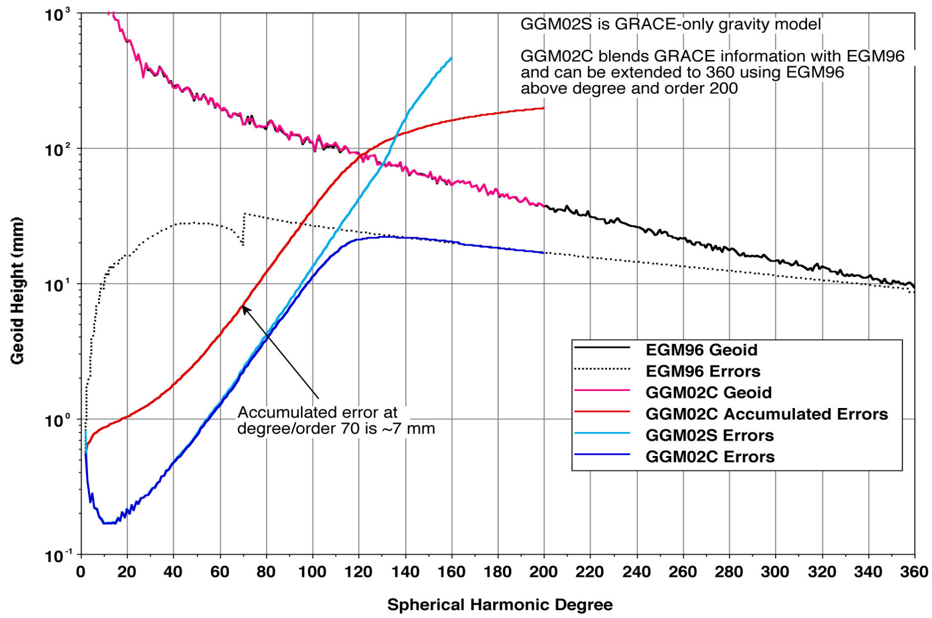

Figure 1. Estimated degree variances and degree error variances for GGM02S/C and EGM96 are shown in geoid height units. The calibration of the GGM02S errors is approximate, but it is consistent with comparisons of various subset and independent solutions.

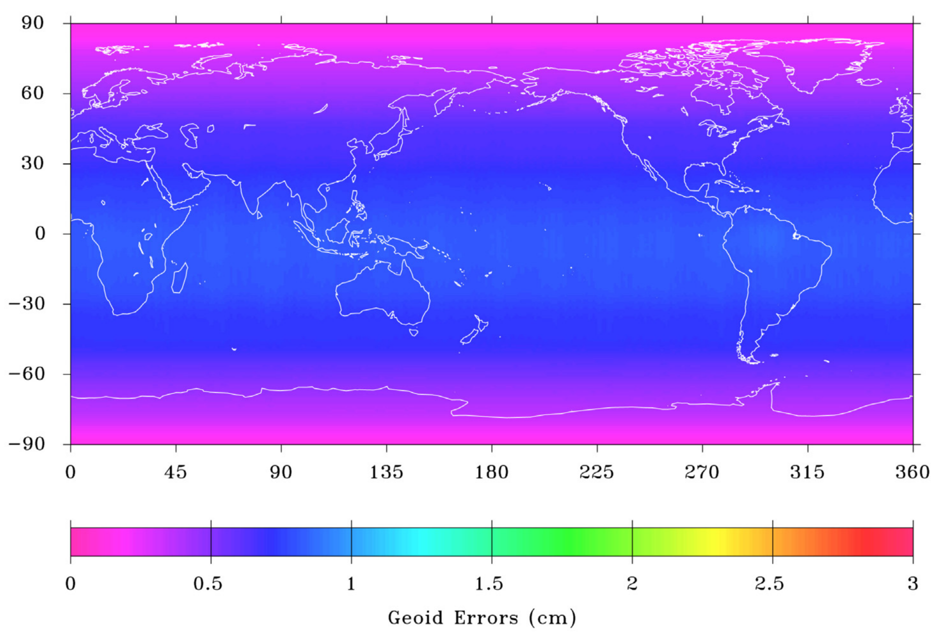

Figure 2. Geoid error predicted by the full covariance as a function of geographic location for GGM02S to degree and order 70. Due to the global, homogeneous nature of the GRACE data, the resulting geoid errors show no discrimination between land and sea. The global RMS of the GGM02S geoid height error is estimated to be ~7 mm, with a maximum error of ~9 mm.

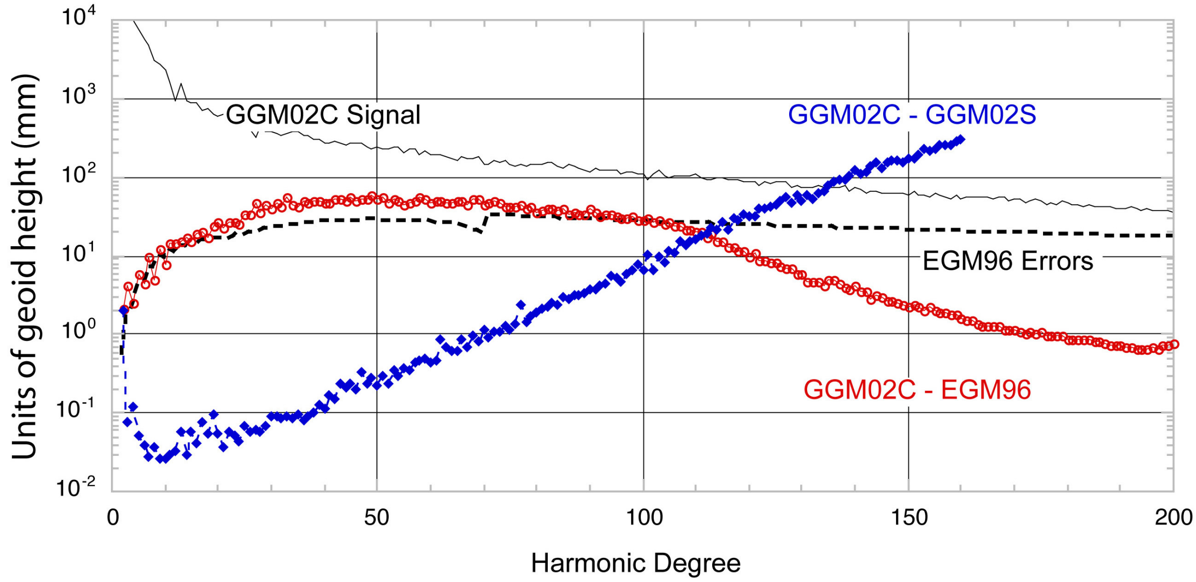

Figure 3. The spectral differences of GGM02C relative to GGM02S and EGM96 are shown. The GRACE information dominates the combination solution below ~degree 110 and smoothly blends into EGM96 above that, allowing GGM02C to be extended to 360x360 by appending the EGM96 coefficients above 200x200.

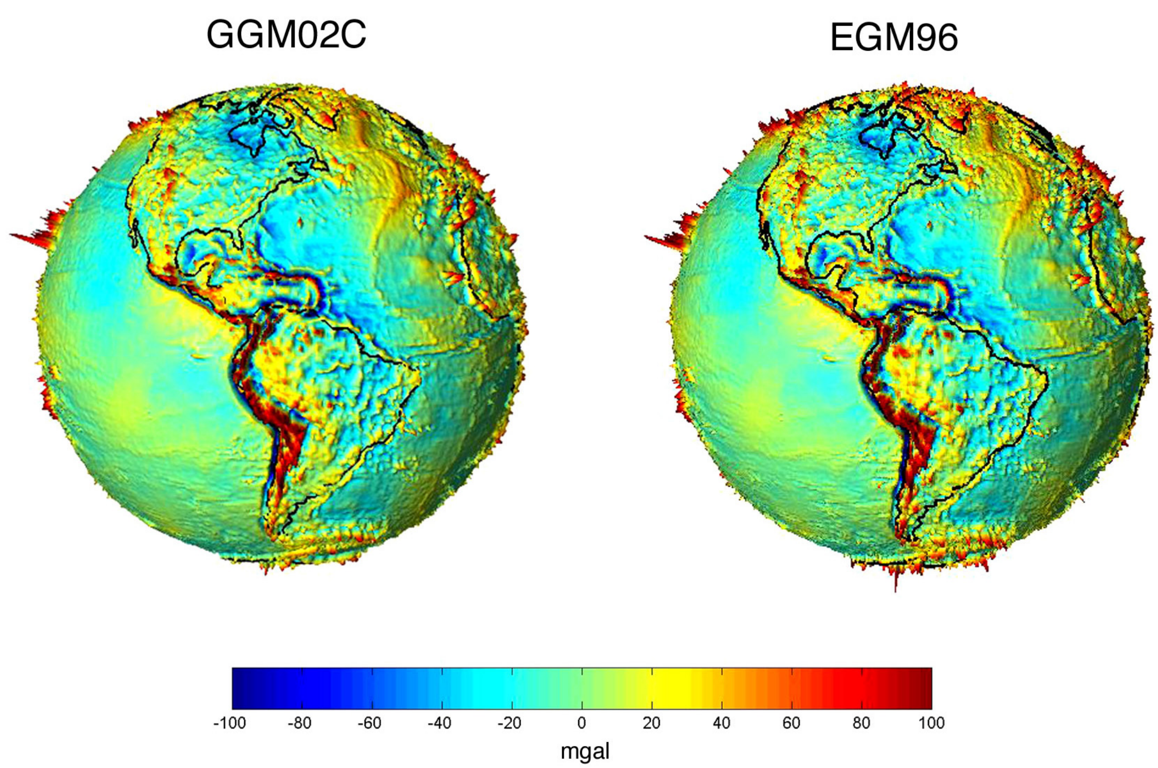

Figure 4. Global gravity anomalies computed to degree/order 360 using GGM02C extended to 360x360 by appending the EGM96 coefficients above 200x200.

<u>Additional Notes</u> on the GGM02 gravity field solution and background modeling:

C20, C00, C10, C11, S11

C20 is a zero-tide value, *i.e.* it includes the zero-frequency (permanent) tide contribution; in order to convert to a tide-free system, add 4.173×10^{-9}. Its epoch is 2000.0, and a rate of C20_dot = $+1.162755 \times 10^{-11}$/year (J2_dot = -26×10^{-12}/year) was employed.

C00 is defined to be exactly 1, and the degree one terms are defined to be exactly 0. These coefficients are not explicitly included in the geopotential file.

Rotational deformation was modeled using IERS2003 conventions:

Based on the new mean pole series, we have for the mean pole and rates:

Xp_mean = 0.054 arcsec at epoch 2000.0
Yp_mean = 0.357 arcsec at epoch 2000.0
Xp_mean_dot = 0.00083 arcsec / year
Yp_mean_dot = 0.00395 arcsec / year

C21/S21:

C21 and S21 were estimated; they were not fixed to the IERS2003 standard values. They are epoch 2000 values. The following rates were employed, which are based on the above mean pole rates (from the IERS2003 standards):

C21_dot = -0.337×10^{-11} / year
S21_dot = $+1.606 \times 10^{-11}$ / year

Coefficient file description:

The coefficients for GGM02S and GGM02C are normalized according to the so-called "fully-normalized" convention, where the squared norm of a spherical harmonic over a unit sphere is 4π (see below). The standard deviations or 'sigmas' (approximately calibrated, not the formal values) are included with the coefficients. The Earth radius and GM to be used for scaling in the expression for the geopotential are included in the coefficient file (they are the same as the standard used for JGM-3 and EGM96).

Format specification:

line 1: Format for next line
line 2: 20 character description, GM (km^3/s^2), Ae (m), Epoch (for those terms with rates)
line 3: Format for following lines
line 4+: 6-character string, degree, order, C, S, C-sigma, S-sigma, normalization flag (-1 = normalized)

Gridded surface file description:

In addition to the geopotential coefficients, gridded surfaces are provided as geodetic latitude, longitude, and value(s) at the latitude and longitude.

1) **GGM02_DOT.GRID** is a text file with a 1 degree resolution grid of the dynamic ocean topography (computed as CSRMSS98-GGM02S). The GRACE-only field is used to degree 120, and the combination field is used to degree 180. For this calculation, the GGM02S geoid is converted to the mean-tide system, via a change to C20 (to be consistent with the mean sea surface). Values are provided only over the ocean between latitudes of ± 65°. Because smoothing over a radius of ~400 km is suggested; a set of filtered values is also provided on the same file.

There are 6 columns:
column 1 = geodetic latitude (°N)
column 2 = longitude (°E)
column 3 = CSRMSS98 - GGM02S to 120x120 (cm)
column 4 = CSRMSS98 - GGM02S to 120x120, with additional 400 km radius Gaussian filter (cm)
column 5 = CSRMSS98 - GGM02C to 180x180 (cm)
column 6 = CSRMSS98 - GGM02C to 180x180, with additional 400 km radius Gaussian filter (cm)

2) **GGM02_GHT_GRAV_2.GRID** is a 30 minute resolution grid of geoid heights & gravity anomalies calculated from GGM02C to both degree/order 200 and to degree/order 360 (augmented with EGM96 past degree 200). The geoid height is computed as the ellipsoidal normal distance between a reference ellipsoid (defined by Ae = 6378136.3 m, 1/f = 298.257) and the equipotential surface with the same value of W_0 as that specified for the ellipsoid (where W_0 = 62636858.57 m^2/s^2, GM = 398600.4415 km^3/s^2 and Ω = 0.7292115x10^{-4} rad/sec). Some applications, such as determining dynamic topography from altimetry, have the sea surface data defined in a mean tide system and require the geoid to be in the same system – hence geoid heights are provided in both systems. The gravity anomaly is computed as the difference between gravity on the geoid (as defined above - to degree 200 or 360) and normal gravity on the ellipsoid.

There are 9 columns:
column 1 = geodetic latitude (°N)
column 2 = longitude (°E)
column 3 = geoid height in the zero-tide system (m) – to degree 200
column 4 = geoid height in the mean-tide system (m) – to degree 200
column 5 = geoid height in the zero-tide system (m) – to degree 360 (EGM96 past deg 200)
column 6 = geoid height in the mean-tide system (m) – to degree 360 (EGM96 past deg 200)
column 7 = gravity anomaly to degree/order 200 (mGal)
column 8 = gravity anomaly to degree/order 360 (mGal)
column 9 = normal gravity (mGal) (Note: total gravity = normal gravity + gravity anomaly)

Normalization Convention:

If φ denotes the geographical latitude of a field point (0° at equator, 90° at the North pole, and –90° at the South pole), and if $u = \sin\varphi$, then the un-normalized Legendre Polynomial of degree l is defined by

$$P_l(u) = \frac{1}{2^l \times l!} \times \frac{d^l}{du^l}\left(u^2 - 1\right)^l$$

The definition of the un-normalized Associated Legendre Polynomial is then

$$P_{lm}(u) = \left(1 - u^2\right)^{\frac{m}{2}} \frac{d^m}{du^m} P_l(u)$$

If the normalization factor is defined such that

$$N_{lm}^2 = \frac{(2 - \delta_{0m})(2l+1)(l-m)!}{(l+m)!}$$

and the Associated Legendre Polynomials are normalized by

$$\overline{P}_{lm} = N_{lm} P_{lm}$$

then, over a unit sphere S

$$\int_S \left[\overline{P}_{lm}(\sin\varphi) \begin{Bmatrix} \cos m\lambda \\ \sin m\lambda \end{Bmatrix} \right]^2 dS = 4\pi$$

In this convention, the relationship of the spherical harmonic coefficients to the mass distribution becomes

$$\begin{Bmatrix} \overline{C}_{lm} \\ \overline{S}_{lm} \end{Bmatrix} = \frac{1}{(2l+1)M_e} \times \iiint_{Global} \left(\frac{r'}{a_e} \right)^l \overline{P}_{lm}(\sin\varphi') \begin{Bmatrix} \cos m\lambda' \\ \sin m\lambda' \end{Bmatrix} dM$$

where r', φ' and λ' are the coordinates of the mass element dM in the integrand. The integration is carried out over the entire mass envelope of the Earth system, including its solid and fluid components.

This convention is consistent with the definition of fully-normalized harmonics in NRC (1997), and textbooks such as Heiskanen and Moritz (1966), Torge (1980); as well as in earlier gravity field models such as EGM96.