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The Development of the NASA GSFC and NIMA Joint Geopotential Model

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Abstract

The NASA Goddard Space Flight Center, the National Imagery and Mapping Agency (NIMA; formerly the Defense Mapping Agency or DMA) and The Ohio State University have collaborated to produce EGM96, an improved degree 360 spherical harmonic model representing the Earth's gravitational potential. This model was developed using: (1) satellite tracking data from more than 20 satellites, including new data from GPS and TDRSS, as well as altimeter data from TOPEX, GEOSAT and ERS-1. (2) 30' x 30' terrestrial gravity data from NIMA's comprehensive archives, including new measurements from areas such as the former Soviet Union, South America, Africa, Greenland, and elsewhere. (3) 30' x 30' gravity anomalies derived from the GEOSAT Geodetic Mission altimeter data, as well as altimeter derived anomalies derived from ERS-1 by KMS (Kort and Matrikelstyrelsen, Denmark) in regions outside the GEOSAT coverage. The high degree solutions were developed using two different model estimation techniques: quadrature, and block diagonal. The final model is a composite solution consisting a combination solution to degree 70, a block diagonal solution to degree 359, and the quadrature model at degree 360. This new model will be used to define an undulation model that will be the basis for an update of the WGS-84 geoid. In addition, the model will contribute to oceanographic studies by improving the modeling of the ocean geoid and to geodetic positioning using the Global Positioning System (GPS).

Introduction

NASA, NIMA, and The Ohio State University, with the aid of other organizations have participated in an unique collaboration lasting close to three years, to determine a significantly improved degree 360 spherical harmonic model of the Earth's gravitational potential. Accurate modeling of the Earth's gravitation field is required for: (1) precise orbit computations, especially for altimetric satellites such as TOPEX/POSEIDON, ERS-1 and 2, GEOSAT Follow-on, and GLAS; (2) accurate and high resolution modeling of the oceanic geoid and its slopes, which is of fundamental importance to oceanography for the determination of the ocean circulation; (3) accurate and efficient computation of orthometric height differences from GPS positioning and model derived geoid undulations; (4) to provide a reference surface (the geoid) that might be considered a simplified realization of a "world height system." NIMA provided the 30' x 30' surface gravity data, derived from new measurements and data in its archives. The U.S. Navy provided Doppler (Tranet) tracking to satellites located at critical inclinations. NASA was responsible for the analysis and processing of all the satellite tracking data, including the altimeter data, as well for the validation of the surface gravity provided by NIMA, the creation of normal equations from these data, and the combination of all the data into a single comprehensive solution. Preliminary solutions, were released to an international evaluation working group, chaired by Michael Sideris of the University of Calgary.

The final model, EGM96, is a composite solution. It consists of a combination solution to degree and order 70, a block diagonal solution from degree 71 to 359, and a quadrature solution at degree 360. The combination model is based on satellite tracking data to over 20 satellites, including those tracked by Satellite Laser Ranging (SLR), GPS, the Tracking Data Relay Satellite System (TDRSS) and Tranet Doppler, direct altimetry from TOPEX, ERS-1, and GEOSAT, as well as the normal equations of the 1˚x1˚ surface gravity data (excluding the altimeter derived anomalies) to degree and order 70. The quadrature solution is based on the satellite only counterpart of EGM96 (EGM96S), as well as the surface gravity data and altimeter derived anomalies described above. The block diagonal solution is also built on EGM96S, and uses the same 30'x30' data, and in addition uses the quadrature solution as a reference. The error covariance is complete to degree and order 70, and the coefficient standard deviations only are available from degree 71 to degree 360.

Surface gravity data

The joint project took advantage of new surface gravity data from many different regions of the globe, including data newly released from the NIMA archives. Major terrestrial gravity acquisitions by NIMA since 1990 include airborne gravity surveys over Greenland and parts of the Arctic and Antarctic, surveyed by the Naval Research Lab (NRL), and cooperative gravity collection projects, several of which were undertaken in conjunction with the University of Leeds. These collection efforts have improved the data holdings over many of the world's land areas, including Alaska, Canada, parts of South America and Africa, Southeast Asia, Eastern Europe and the former Soviet Union. In addition to the above surface gravity data acquisitions, there have been major efforts to improve NIMA's existing 30' mean anomaly database through mean anomaly contributions over various countries in Asia.

Table 1
Statistics of the final EGM96 global 30' mean free-air anomaly merged file

Type	NIMA Terr. 30'	NIMA Altim. 30'	OSU Terr. 30'	NIMA Terr. 1°	Topo/Iso Fill-in 30'
Number	86740	146042	1064	6500	18854
% of Area	30.7	66.1	0.1	0.8	2.3
RMS Δg (mGal)	35.2	25.6	56.7	49.1	28.0
RMS σ (mGal)	5.4	1.7	16.9	35.7	36.0

NIMA computed and made available 30'x30' mean altimeter derived gravity anomalies from the GEOSAT Geodetic Mission. The distribution and extent of the surface gravity data is a major improvement on the data available for OSU91A [*Rapp et al*., 1991]. We have also included altimeter-derived anomalies derived from ERS-1 by KMS over portions of the Arctic and the coast of the Antarctic, as well as the altimeter-derived anomalies derived by *Schoene* [1996] over the Weddell Sea. The statistics of the final merged set of surface gravity data used in EGM96 are summarized in Table 1.

Satellite Tracking Data Used in EGM96

In addition to the data used in JGM2, we have added tracking data from satellites tracked by SLR, GPS, TDRSS, and Tranet/Doppler. Each set of data provides unique information and complements the other data incorporated into the solution.

The SLR data, especially the tracking of LAGEOS and LAGEOS-2, define the global reference frame of the solution, and control the determination of the low degree field. In addition, the errors in the nonconservative force modeling are minimized since the spacecraft are easily and correctly modeled as spheres studded with laser retroreflectors. We have added new SLR data to LAGEOS, LAGEOS-2, Ajisai, and Starlette. In addition

Stella and GFZ-1 were added to the solution. Stella is especially valuable since it is located in nearly the same orbit as Spot-2 and ERS-1. Stella controls the determination of the zonal terms for these satellites. Since both Spot-2 and ERS-1 have complicated shapes, including a spacecraft bus and solar arrays, they are more susceptible to nonconservative force mismodeling. To minimize this modeling error, empirical once per revolution acceleration terms are adjusted on Spot-2 and ERS-1 in the orbit determination process. These empirical terms successfully reduce the orbit modeling error on these satellites, but also negate their zonal gravity field contribution.

As part of the collaborative work, the Naval Surface Warfare Center (NSWC) provided Tranet Doppler data to BEC, D1C, D1D, Hilat, and Radcal. Tranet is a one-way (satellite to ground), dual frequency Doppler measurement [*Anderle*, 1986]. The Tranet data from these satellites provide coverage at altitudes and at inclinations where the existing data in EGM96 (Doppler or otherwise) are either weak or unavailable. The Doppler data from BEC, D1C, and D1D include tracking from the early generation of Tranet systems, whose accuracy was limited by the quality of the frequency standards carried on board the satellites. While these data were noisy (typically a few cm/s, RMS), they strengthen the contribution of the SLR data which we already have for these satellites by providing alternate gravity field information. The data from Hilat and Radcal are obtained from modern Tranet systems whose noise is on the order of a few mm/s, RMS.

For the first time, we have included a substantial amount of satellite-to-satellite tracking data from both GPS and TDRSS. The model includes GPS data from TOPEX, GPS/MET, and EUVE, as well as TDRSS tracking of EUVE. Both TOPEX and GPS/MET had dual frequency receivers, and their data were acquired when A/S (anti-spoofing) was not activated. The TOPEX/GPS data arcs are ten days in length and include data from cycles 10, 14, 15, 17, 18, 19 in 1992 and 1993. The GPS/MET data from the two A/S off periods in 1995 (April-May and October) were processed. EUVE carried a single frequency GPS antenna, and the pseudorange and the phase was used to derive an ionosphere correction. The processing of EUVE/GPS data is discussed in detail by *Olson* [1996], and we included data from late 1992. The EUVE data from TDRSS complements the GPS tracking. TDRSS provides both range and Doppler information [*Marshall et al.*, 1996]. We included data from TOPEX cycles 69 to 73 in 1994.

Tracking data to TOPEX is a major part of the EGM96 solution. We included two years of SLR and DORIS data, as well as the direct GPS tracking. It is true that in order to tune a gravity model to a given satellite orbit, a much smaller amount of data would be needed. However, since two years of direct TOPEX altimetry were included in the combination model, it was necessary to include the SLR and DORIS tracking for that same time period in EGM96, since we adjust simultaneously for the orbits, the geopotential and the sea surface topography.

Development of the Satellite Only Solution

We used the GEODYN orbit determination software to process our satellite tracking data and develop the normal equations [*Pavlis et al.*, 1996]. A companion program (SOLVE) was used to merge the normal equations and develop the least squares solution [*McCarthy et al.*, 1996]. The solution for EGM96S (and EGM96) to 70x70 involved the simultaneous adjustment of 56 tidal line pairs (out of a total of 395 modeled tidal line pairs), station coordinates, and polar motion (five-day pole position through 1992 and one-day pole position for 1993 and 1994).

As was the case with earlier satellite only solutions, such as JGM-2S [*Nerem et al.*, 1994], and GEM-T2 [*Marsh et al.*, 1990], a spectral constraint was applied to prevent the high degree terms from developing excessive power. These earlier solutions used the power law of $\text{Kaula}/\sqrt{2}$. However, this power law underestimates the power in the gravity field as observed by the surface gravity data, especially above degree 40, and would result in an overly optimistic satellite only error covariance. Since the satellite only solution is the foundation of the high degree solutions, it is important to avoid this anomaly. Thus, the spectral constraint applied in the derivation of the EGM96S solution came from a preliminary (quadrature) combination model.

After all the satellite tracking data had been assembled, the satellite only solution was calibrated with the subset solution method of *Lerch* [1991]. This technique, which was also applied in earlier solutions such as GEM-T2, and JGM-2S, adjusts the weights of the data by calculating the calibration factors between a master solution (containing all the data), and the subset solution (where the tested set of data has been removed). This calibration factor represents the aggregate differences of the coefficients divided by the aggregate differences in the coefficient standard deviations. A calibration factor greater than unity indicates the data are overweighted and that the covariance is overly optimistic. We calculated subset solutions, each to 70x70, for all the satellites contributing data to the solution. Since some satellites have similar orbits (for instance Spot-2 and Stella), these satellites had to be calibrated individually against a subset that held no data from these satellites and then again as a group against the master solution containing all the data. During the calibration process, we noticed that the data from the satellites that provided continuous tracking had a tendency to saturate the solution. To deal with this issue, and avoid an error covariance that was overly optimistic, we selected weights in the calibration process such that the calibration factors were in the vicinity of 0.8.

The satellite only solution was tested for fidelity by comparing with mean 5° x 5° altimeter derived gravity anomalies from the GEOSAT Geodetic mission computed from the 30'x30' values provided by NIMA. At degree 70, the residual comparison in the anomalies was 16.34 mGal^2 for JGM-2S, and 10.19 mGal^2 for EGM96. The fidelity of the satellite only model was also tested by performing tests with the RMS of fit to various satellite orbits, and by assessing the performance of the model on TOPEX using the second generation (JGM3 [*Tapley et al.*, 1996]) reduced dynamic orbits produced by JPL.

Development of the Combination Model

The combination model of EGM96 to 70x70 was developed using the satellite only model as a foundation. The combination solution includes the satellite tracking data used in EGM96S, as well as direct altimetry and the normal equations of the surface gravity data to 70x70. The altimeter data includes TOPEX altimetry from cycles 11 to 84 (no POSEIDON data), ERS-1 altimetry from the 35-day repeat phase of the mission (cycles 6, 8, 11, 14 and 17), and GEOSAT altimetry from 78 days of tracking of the GEOSAT Exact Repeat Mission in November 86 through January 87.

The altimeter data was geometrically corrected using an updated version of the tide corrections from *Schrama and Ray* [1994]. The altimeter data were corrected for the high degree geoid using a quadrature solution, V058 (EGM-X04) to degree 460. This geoid correction is superior to those corrections previously available for instance, from JGM3/OSU91A. In the case of both GEOSAT and ERS-1, the IRI-95 ionosphere model [*Bilitza et al.*, 1994] was used to correct the altimeter range measurements.

EGM96 solves for a separate spherical harmonic expansion of the sea surface dynamic topography for both TOPEX/ERS-1 and GEOSAT to degree and order twenty. In addition a degree and order 10 time varying dynamic topography model using annual and semiannual terms is solved for using the TOPEX and ERS-1 data.

The TOPEX, GEOSAT and ERS-1 altimetry was weighted by a function that accounted for the sea surface variability and the value of the high degree geoid from V058 (l=71 to 460) on a point by point basis. Thus, for example, the altimeter data for the Kuroshio current or over the Aleutian trench are down weighted relative to data over other regions of the ocean. The sigmas on the altimeter data were scaled to yield values between 0.8 and 1.6 meters, and a global RMS of approximately one meter. The TOPEX altimetry was further downweighted in SOLVE to 1.769 m. In the case of ERS-1, an additional constraint applies. The ERS-1 altimetry must be added into the solution at a weight such that it does not alter the sea surface topography solution defined by TOPEX in the region from 66˚ S to 66˚ N by more than 2 cm RMS.

The surface gravity normals to 70x70 were prepared from the 1˚x1˚ surface gravity data that exclude any altimeter derived anomalies. The combination model was constructed form the surface gravity normals, the merged normals of the direct altimetry, and the normal equations of the satellite only model. As with JGM2, a separate fifth degree and order set of coefficients was solved for the surface gravity to minimize the impact of any long wavelength inconsistencies in these data. In JGM2, the surface gravity normal equations were down weighted by a factor of 0.25, since a degradation was observed in the satellite orbit fits when the surface data were added to the satellite only solution. With the incorporation of the new, high quality data, this degradation is no longer observed, so the surface gravity data were allowed to receive their full weight in EGM96.

The separation between the altimeter measurement of the sea surface, the sea surface topography and the geoid is accomplished primarily through the accuracy of the satellite only model, but is aided by two other factors: (1) the incorporation of 1˚x1˚ ocean gravity data used in OSU91A [*Rapp et al.*, 1991] and as well as other data provided by NIMA, (2) the application of an *a priori* power law constraint. The constraint takes the form described by equation (1),

$$\mathbf{y} = \frac{30.775}{\mathbf{L}^{1.4243}} \qquad (1)$$

where y represents the RMS power of the sea surface height per spherical harmonic degree (in cm), and L represents the spherical harmonic degree. This relation was derived empirically from a spherical harmonic fit to degree 24 provided by *Rapp* [1996a] of the output from the POCM_4B ocean circulation model of Semtner and Chervin, described in *Stammer et al.* [1996].

Geoid Undulation Evaluation

GPS/Leveling

The EGM96 model was evaluated using GPS/Leveling tests, comparisons with the dynamic ocean topography, orbit fits and orbit overlaps. In the tests with GPS/Leveling, the geoid derived from measurements of benchmarks using GPS and leveling are compared to the geoid heights derived from the geopotential models. In Table 2, the leveling results are showed for 1156 stations in the United States, derived from Milbert [1995], and calculated by *Rapp* [1996a]. These comparisons are shown with and without the height anomaly correction term as described by *Rapp* [1996b]. The 2497 stations from the original set of data were thinned so that stations closer than 25 km were eliminated from the evaluation set. The results illustrate the improvement in the new EGM96 geoid, compared to OSU91A, even for a region of the globe where the data available prior to the advent of this project were of reasonably high quality.

Table 2
Comparison of Geoid Undulations from Geopotential Models
to Undulations from 1156 Milbert Stations (Apr. 1996) in the United States
With and Without Height Anomaly Correction Term

Model	No Correction (cm)		With Correction (cm)	
	Mean	σ	Mean	σ
OSU91A	-97.5	61.5	-84.9	54.7
JGM3/OSU91A	-106.0	57.5	-93.3	47.4
EGM-X02	-112.8	52.0	-100.6	42.3
EGM96	-111.8	52.1	-99.1	42.4

EGM-X02 represents a preliminary version of EGM96 (a blended combination and quadrature solution) that was released to the scientific evaluation committee led by Professor Michael Sideris of the University of Calgary in April 1996. GPS and leveling tests for other regions are summarized in Table 3. The dramatic improvement in the results for British Columbia is due to the addition of the new surface gravity data for that area used in the EGM models. The mean difference in both Tables 2 and 3 correspond to vertical datum offsets with the orthometric heights, nongeocentricity in the ellipsoidal heights, as well as errors in the geopotential model. So it does not follow that improvements in the geopotential model alone will lead to a reduction in the mean difference.

Table 3
Comparison of Geoid Undulations from Geopotential Models

Area	British Columbia		Europe		Canada		Australia		Scandinavia	
No. of pts.	298		60		63		38		46	
Model	Mean (cm)	σ (cm)	Mean (cm)	σ (cm)	Mean (cm)	σ (cm)	Mean (cm)	σ (cm)	Mean (cm)	σ (cm)
OSU91A	-39.3	93.9	39.5	32.7	-9.3	31.4	-48.8	34.6	32.4	31.8
JGM3/ OSU91A	-23.6	94.7	13.4	46.6	23.6	27.8	-55.4	25.5	21.6	47.6
EGM-X02	-25.2	54.0	12.1	33.3	20.8	23.4	-72.4	33.4	21.8	23.1
EGM96	-21.9	51.7	7.8	31.6	30.8	27.4	-79.5	28.0	18.9	19.1

Tests with dynamic ocean topography

The marine geoid was evaluated using tests with the dynamic ocean topography, as described by *Rapp et al.* [1996]. A two year TOPEX mean sea surface, and the output from the POCM_4B ocean circulation model [*Stammer et al.*, 1996] was differenced with the geoid undulations from various geopotential models in an orthonormal domain. The cumulative differences through degree 18 and 24 are shown in Table 4. The comparisons suggest that EGM96 has made a substantial improvement in the modeling of the ocean geoid. The most striking improvements can be seen in the region of the Banda Sea, between Australia, Papua New Guinea, and Indonesia, where differences reach peak values of 62 cm with JGM3/OSU91A. While the GPS/Leveling tests show only modest differences between the preliminary models (i.e. EGM-X02) and EGM96, the significant improvement observed in the dynamic ocean topography comparisons between EGM96 and EGM-X02 can be attributed to the reprocessing of the altimetry that was undertaken between April and July 1996.

Table 4
Cumulative RMS Difference between Ocean Dynamic Topography Comparisons Using Two Years of TOPEX data with Geopotential Models and that from the POCM_4B Ocean Circulation Model (in cm)

Model	To Deg. 18	To Deg. 24
JGM3/OSU91A	13.4	13.8
EGM-X02	13.2	13.8
EGM96	10.5	11.2

Conclusions

New surface gravity data, direct GEOSAT, TOPEX and ERS-1 altimetry, and satellite tracking data to over 20 satellites have been used to develop a new spherical harmonic solution of the Earth's geopotential to degree and order 360. This model, EGM96, is a composite solution, consisting of a combination model to degree 70, a block-diagonal model to degree 359, and the corresponding quadrature model at degree 360. This model represents a major advance in the modeling of the Earth's geoid in both land and ocean areas.

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The EGM96 coefficients and ancillary information can be obtained by anonymous FTP to cddis.gsfc.nasa.gov. Change directory (cd) to
ANON_DIR:[EGM96] and enter the relevant sub directories. A web site containing general information has been established at the URL:

http://cddis.gsfc.nasa.gov/926/egm96/egm96.html.

Send questions to flemoine@olympus.gsfc.nasa.gov (Frank Lemoine), npavlis@geodesy2.gsfc.nasa.gov (Nikos Pavlis), or kenyons@nima.mil (Steve Kenyon).

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