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New High-Resolution Model Developed for Earth's Gravitational Field

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After 3 years of intense work by some two dozen collaborating scientists at three institutions and after scores of evaluation tests, the Earth Gravitational Model 1996 (EGM96) was completed and released to the scientific community in September 1996. This model was developed jointly by the NASA Goddard Space Flight Center (GSFC), the National Imagery and Mapping Agency (NIMA, formerly the Defense Mapping Agency), and The Ohio State University.

EGM96 provides a more accurate reference surface for the topography, improves models of the ocean circulation, improves orbit determination for low-orbiting satellites, and contributes to global and regional studies in tectonics and geodynamics. The new spherical harmonic model, is complete to degree 360, corresponding to a global resolution of about 55 km. EGM96 incorporates newly released surface gravity data from around the globe, over three decades of precise satellite tracking data and altimeter measurements of the ocean surface from the TOPEX/POSEIDON, ERS-1 and GEOSAT missions. Figure 1a shows a global map of the geoid undulations implied by EGM96, while Figure 1b shows the corresponding gravity anomaly field.

Accurate modeling of the Earth's gravitational potential provides a reference surface, the geoid, for determination of the world's topography. For example, the conversion of ellipsoidal heights (heights above a reference ellipsoid) determined by the Global Positioning System (GPS) or by spaceborne laser altimeters to orthometric heights (heights above sea level), will be done more accurately than with previous models. The improved geopotential model will better model satellite orbital motion, thus contributing to accurate altimeter mapping of the world oceans by satellites such as TOPEX/POSEIDON, ERS-1, ERS-2, GEOSAT and the upcoming GFO and Jason. This and the high-resolution, accurate geoid model implied by EGM96 result in improved determination of the global ocean circulation from spacecraft altimeter measurements of the ocean surface. In turn, a more accurate definition of global ocean circulation ultimately improves the estimates of ocean mass transport and heat flux, parameters critical to better understand the role oceans play in global climate.

A robust solution of the static (i.e., time-averaged) gravitational field also provides the basis for monitoring temporal variations in gravity. These signals, albeit small, convey important information about geophysical fluid mass transports, such as atmospheric mass redistribution, continental water balance and deep ocean-current variations, all of which contribute in the formation of the global climate.

Prior to the dawn of the space age only limited solutions existed for the Earth's gravitational potential. For instance, *Zhongolovich* [1952] estimated a spherical harmonic representation from surface gravity data to degree eight (2500 km resolution).

The maximum degree, N_{max}, of a spherical harmonic model determines the field's resolution L, by the relation $L=20000\ km/N_{max}$. Tracking of Earth orbiting satellites stimulated the development and improvement of geopotential models, starting with the launch of the first artificial satellites in the late 1950's [see *King-Hele*, 1992]. As satellite tracking systems became more precise, and tracking data from additional spacecraft became available, the accuracy and resolution of gravitational models obtained from tracking data analysis has improved continuously. However, due to the attenuation of the gravitational signal with altitude, the presently available tracking data fail to resolve the finer structure of the field. With the exception of certain special terms, limited gravitational signal is contained in satellite-only geopotential models beyond harmonic degree 40 or so. Satellite tracking data such as Satellite Laser Ranging, Doppler, DORIS (Doppler Orbitography and Radio-positioning Integrated by Satellite), and GPS support the accurate determination of the broad (long wavelength) features of the gravity field.

Surface gravity data provide the regional and local information required for the determination of the finer structure of the gravitational field and they are therefore complementary to the satellite tracking information. Satellite radar altimeter measurements provide a detailed mapping of the ocean surface, from which a fundamental equipotential surface, the geoid, over the oceans can be deduced. Surface gravity information, satellite tracking, and altimeter data has been used to develop high-degree geopotential models, such as GEM-10C in 1978 to degree 180 (resolution of about 111 km), and OSU91A [*Rapp et al.*, 1991] to degree 360 (resolution of about 55 km).

The optimal determination of the Earth's gravitational potential to a high degree (360) requires the combination of the information supplied by all thre data sources discussed above. OSU91A [*Rapp et al.*, 1991] is a representative example of this approach. The new model, EGM96, represents yet another milestone in global gravity field modeling because of the addition of newly released surface gravity data provided by NIMA, the addition of 2 years of highly accurate altimeter data from the TOPEX/POSEIDON spacecraft, and the inclusion of new tracking data to satellites such as Stella, LAGEOS-2 and the low altitude Extreme Ultraviolet Explorer (EUVE).

General Methodology

A spherical harmonic geopotential solution to degree 360 requires the estimation of

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361^2 unknown coefficients. Even with today's high-speed supercomputers, a "brute force" approach to the problem is not feasible. The estimation of the complete model is therefore accomplished in a piece-wise fashion. We implement the most complete and rigorous modeling and estimation techniques for the lower degree (up to 70) part of the model, combining satellite tracking data, surface gravity data, and direct altimeter measurements. To estimate the potential coefficients beyond degree 70 (and up to degree 360), we exploit symmetry properties associated with the potential coefficient estimation from regularly gridded 30' x 30' mean gravity anomaly data. In this regard, the development of EGM96 was based on similar principles as in the case of OSU91A.

Satellite Tracking Data

Today, Satellite Laser Ranging (SLR) tracks up to eight "cannonball"-shaped satellites by measuring the range from a ground station to the satellite to better than a centimeter. In EGM96, SLR tracking of satellites such as LAGEOS, LAGEOS-2, Ajisai, Starlette, Stella and GFZ-1 were included. The SLR measurements, especially those to LAGEOS and LAGEOS-2, define the global reference frame of the EGM96 solution and control the determination of the low degree field.

For the first time, we have included a substantial amount of satellite-to-satellite tracking data, in the form of range and line-of-sight range rate (Doppler) measurements. Satellite-to-satellite tracking data from GPS (Global Positioning System) and TDRSS (NASA's Tracking and Data Relay Satellite System) were incorporated into EGM96. The model includes GPS and DORIS data from TOPEX/POSEIDON, GPS data from the GPS/MET and the Extreme Ultraviolet Explorer (EUVE) spacecraft, as well as TDRSS tracking of EUVE [*Marshall et al.*, 1996]. Data from EUVE contribute significantly to the solution by virtue of the satellite's low altitude (525 km) and low inclination (28.5°), which have been poorly represented in previous gravitational models.

As part of the collaborative work, the Naval Surface Warfare Center provided Tranet Doppler data to a number of satellites at altitudes and at inclinations where data from other satellites are either weak or unavailable (for instance HILAT at 800 km altitude and 82.0° inclination, and RADCAL at 825 km altitude and 89.5° inclination). Tranet is a one-way (satellite to ground), dual frequency Doppler measurement which has been operational since the 1960s. For HILAT and RADCAL, the data are obtained from modern Tranet systems whose noise is on the order of a few mm/s. DORIS data from the Spot-2 and TOPEX/POSEIDON spacecraft were included in EGM96. The tracking by the French space-borne system DORIS contributed significantly in EGM96 because of its high precision data and the global coverage provided by its ground beacons.

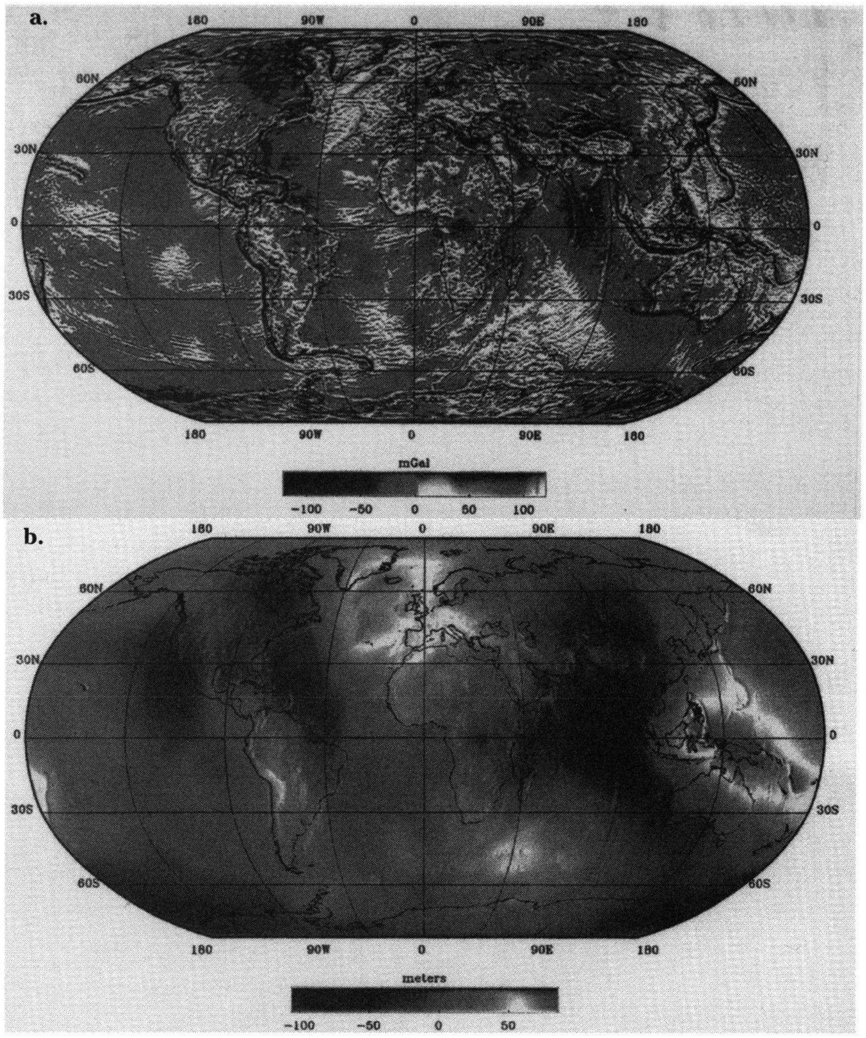

Fig. 1.a) 30' x 30' mean values of free-air gravity anomalies computed from EGM96 to degree and order 360. Values refer to the WGS84(G873) system of constants. Permanent tide system is "non-tidal". Units are mGal. b) 30' x 30' mean values of geoid undulations computed from EGM96 to degree and order 360. Values refer to the WGS84(G873) system of constants, which provide a realization of the geometry and the normal gravity potential of a mean-Earth ellipsoid. Permanent tide system is "non-tidal." Units are meters. Original color image appears at the back of this volume.

Surface Gravity Data

Complementary to the satellite tracking data, surface gravity data consist mostly of land measurements characterized by uneven geographical coverage, non-uniform quality, high resolution in certain areas, and a degree of availability that may depend on international politics and national security issues.

A previous model, OSU91A [*Rapp et al.*, 1991] used gravity data from the United States, western Europe, Africa, Japan, Australia, and marine ship track data. The surface gravity data base supporting EGM96 is substantially improved because it incorporates additional data, that only recently have become available, over many other regions of the globe. Major terrestrial gravity datasets acquired recently by NIMA include: the airborne gravity surveys over Greenland and parts of the Arctic and Antarctic by the Naval Research Laboratory, and cooperative gravity collection projects, several of which were undertaken in conjunction with the University of Leeds. These efforts have improved the data holdings over many of the world's land areas including Alaska, Canada, parts of South America and Africa, China, Southeast Asia, Eastern Europe and the former Soviet Union. NIMA computed and made available 30' x 30' mean gravity anomalies for all land areas for which sufficient data were available, as well as 1° x 1° mean anomalies covering both land and ocean areas.

Satellite Altimetry

Satellite altimeter measurements of the sea surface height are an important part of the EGM96 solution. Based on these measurements and on the gravitational information provided primarily by the tracking data, one can estimate simultaneously with the potential coefficients, spherical harmonic coefficients representing the long wavelength component of Dynamic Ocean Topography (DOT). DOT is the separation between the sea surface and the geoid, and its long wavelength component reflects primarily the (quasi) permanent ocean circulation. DOT has a Root Mean Square value of about ±62 cm, and ranges between +1 m and -2 m (approximately).

In EGM96, altimeter data enter in two ways: as direct tracking observations, in the low-degree (70) combination model and as 30' x 30' altimeter-derived gravity anomalies in the high-degree (360) models. Direct altimeter data from TOPEX/POSEIDON, ERS-1, and from the Exact Repeat Mission of GEOSAT were included in the low-degree combination solution. From these data, as well as satellite tracking and surface gravity data, in EGM96 we estimate the potential coefficients to degree 70, as well as two separate spherical harmonic models of DOT, both complete to degree 20: one applicable to the time period of the TOPEX and ERS-1 data used (1993-1995), and a separate one for GEOSAT's data time span. The direct altimeter data were prefiltered to remove the high-degree (beyond degree 70) geoid contribution to avoid aliasing in the low-degree (to degree 70) combination solution. The high-degree (360) solution used in the ocean regions 30' x 30' mean gravity anomalies estimated from altimetric sea surface heights, after removal of DOT effects. Over the ocean areas between latitudes ±72°, EGM96 uses 30' x 30' mean gravity anomalies computed by NIMA from GEOSAT's Geodetic Mission altimeter data. Outside this latitude band, 30' x 30' mean gravity anomalies derived from ERS-1 altimeter data, by P. Knudsen and O.B. Anderson (Kort-og Matrikelyrelsen, Denmark), and by T. Schoene (Alfred Wegner Institute, Bremerhaven, Germany) were used.

Model Testing and Future Prospects

For over 10 years the primary metric of comparison in evaluating gravitational models at NASA GSFC was their performance on satellite orbits. For example, orbit performance on TOPEX/POSEIDON was the main design consideration for the JGM-2 [*Nerem et al.*, 1994] and the JGM-3 [*Tapley et al.*, 1996] gravity models. For EGM96, we weighed the improvement of the land and marine geoid equally with the orbit performance. Furthermore, the selection of the final model was heavily influenced by the unbiased evaluation results of preliminary solutions by an international working group chaired by M. Sideris.

In the ocean regions, the EGM96-implied geoid and satellite altimeter data, yield estimates of DOT which are in the closest agreement with independent estimates of DOT from Ocean Circulation Models, than for any other contemporary geopotential model. EGM96 was also evaluated using comparisons of its geoid undulations with geoid undulation estimates derived from GPS-derived ellipsoidal heights and orthometric heights from spirit leveling. Over the U.S. (a region where the gravity data were already of high quality prior to the development of EGM96) the standard deviation of the differences between the GPS/leveling and the model geoid undulations (to degree 360) improves from 48 cm with JGM3/OSU91A to 43 cm with EGM96. An even more significant improvement is observed in British Columbia, Canada, a region where new surface gravity data was included in EGM96. There, the standard deviation of the undulation differences improves from 95 cm with JGM3/OSU91A to 52 cm with EGM96. Numerous other tests were conducted by many different individuals and institutions, and are reported by *Sansò* [1997].

EGM96 has been widely and freely distributed to the international geodetic, geophysical, and oceanographic communities. It has already been used as a reference geoid model for the recent high-resolution geoid surface GEOID96 developed by the National Geodetic Survey for the U.S., and the corresponding detailed European Gravimetric Geoid 1997 (EGG97). At present, the efforts of our modeling team are concentrating on further improving the model by improved relative weighting between the heterogeneous data types and paying even closer attention to time varying gravitational effects. Our short-term goal is to acquire additional independent data: low altitude satellite data in polar orbits; improved marine gravimetric data, particularly in southern oceans; and independent estimates of DOT to enhance the separability of geoid and dynamic topography signals from altimetric observations. In the long term, high-precision and homogeneous global data will soon become available from dedicated satellite gravity missions such as CHAMP, GRACE, and GOCE. CHAMP will be launched in mid-1999, GRACE in 2001, while the GOCE mission is a candidate for a 2003 launch pending final approval by the European Space Agency. We look forward to challenging activities in gravitational field modeling for many years to come.

Note: A web site has been established at the URL http://cddisa.gsfc.nasa.gov/926/egm96/egm96.html. The geopotential coefficients and standard deviations, the geopotential error covariance matrix to degree and order 70, the surface gravity data used in EGM96, including the new 30'x30' data set released by NIMA, and a variety of ancillary products may be downloaded directly from this site. A NASA Technical Memorandum on EGM96 is expected to be released in the Spring of 1998. A special publication prepared by the International Geoid Service, International Geoid Service Bulletin No. 6 contains the detailed reports from the international scientific evaluation team on EGM96 (available through Fernando Sansò, Politecnico di Milano, Milano, Italy; fsanso@ipmtf4.topo.polimi.it).

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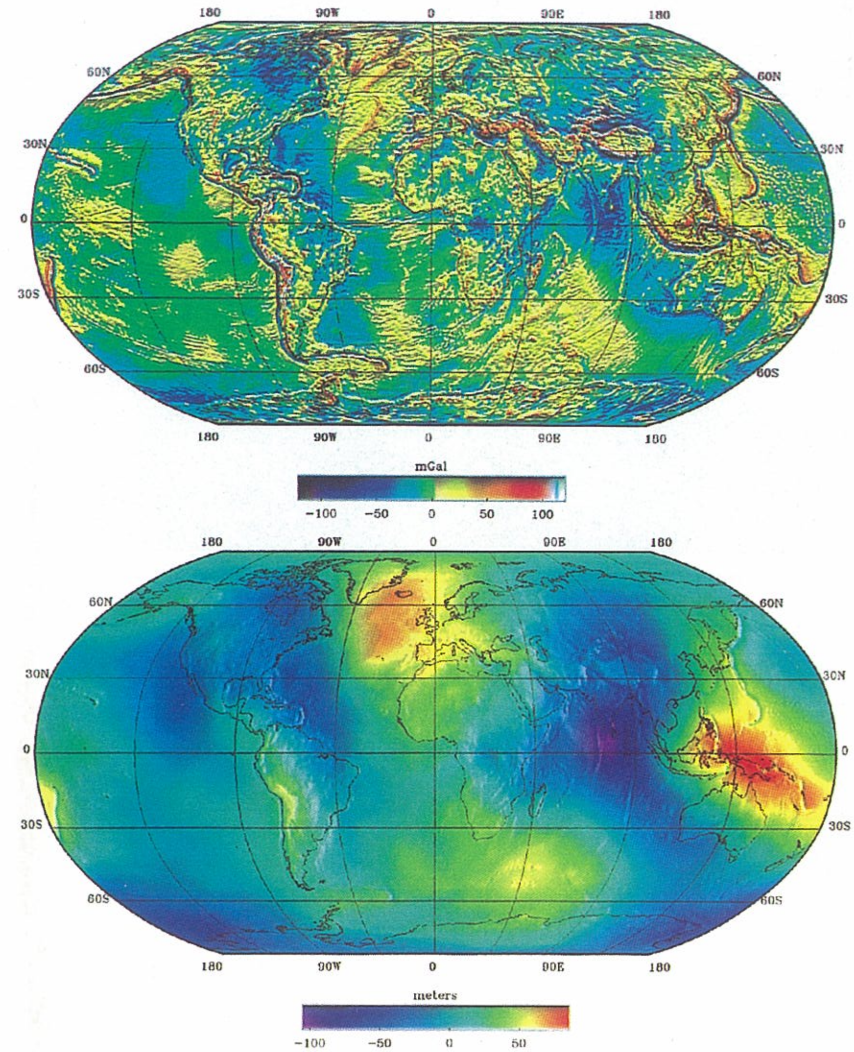

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