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The Joint Gravity Model 3

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Abstract. An improved Earth geopotential model, complete to spherical harmonic degree and order 70, has been determined by combining the Joint Gravity Model 1 (JGM 1) geopotential coefficients, and their associated error covariance, with new information from SLR, DORIS, and GPS tracking of TOPEX/Poseidon, laser tracking of LAGEOS 1, LAGEOS 2, and Stella, and additional DORIS tracking of SPOT 2. The resulting field, JGM 3, which has been adopted for the TOPEX/Poseidon altimeter data rerelease, yields improved orbit accuracies as demonstrated by better fits to withheld tracking data and substantially reduced geographically correlated orbit error. Methods for analyzing the performance of the gravity field using high-precision tracking station positioning were applied. Geodetic results, including station coordinates and Earth orientation parameters, are significantly improved with the JGM 3 model. Sea surface topography solutions from TOPEX/Poseidon altimetry indicate that the ocean geoid has been improved. Subset solutions performed by withholding either the GPS data or the SLR/DORIS data were computed to demonstrate the effect of these particular data sets on the gravity model used for TOPEX/Poseidon orbit determination.

Introduction

An Earth geopotential model, which has both high accuracy and spatial resolution, is a requirement for a number of contemporary studies in geophysics and oceanography. There has been significant recent improvement in the accuracy of the Earth's geopotential model, driven by oceanographic requirements for reduced errors both in the orbit of altimeter satellites and in the geoid over the ocean basins [*Tapley et al*., 1994a]. The TOPEX/Poseidon (T/P) mission, which was launched in August 1992 as a joint project of NASA and the French space agency Centre National d'Etudes Spatiales (CNES), contained the stringent requirement that the radial orbit accuracy must be less than 13 cm RMS [*Stewart et al*., 1986]. Although the T/P satellite was placed in an orbit at an altitude of 1335 km to minimize the effects of atmospheric drag and gravity model errors, the prelaunch radial orbit error budget was dominated by a 10-cm root-mean-square (RMS) contribution from gravity field uncertainty [*Tapley et al*., 1990], and a major effort to improve the existing gravity models was initiated in 1983 as a joint effort between the NASA Goddard Space Flight Center Space Geodesy Branch (GSFC) and the University of Texas Center for Space Research (CSR). This effort consisted of an iterative reprocessing of historical tracking data from a number of satellites covering a range of orbit configurations in combination with new data from the satellite laser ranging (SLR) and Doppler orbitography and radiopositioning integrated by satellite (DORIS) tracking networks. The results of this effort led to the Goddard Earth Model (GEM)-Tn and University of Texas Earth gravitational model (TEG)-n series of fields, detailed by *Marsh et al*. [1988, 1990], *Tapley et al*. [1989], *Shum et al*. [1990], and *Lerch et al*. [1994]. In addition, a group at the Ohio State University continued to expand and improve the surface gravity database as described in *Rapp and Pavlis* [1990], *Pavlis and Rapp* [1990], and *Rapp et al*. [1991]. CNES provided data from the DORIS tracking system carried on SPOT 2. The individual gravity model efforts were combined to develop the prelaunch gravity model for the T/P mission. The model, referred to as the Joint Gravity Model 1 (JGM 1) [*Nerem et al.*, 1994], and based upon an accurately calibrated covariance [*Lerch et al.*, 1981, 1991], predicted a radial orbit error of 6 cm RMS. This value is well below the mission budget allocation of 10 cm RMS and represents an order of magnitude improvement over gravity models available at the mission initiation, which predicted radial orbit errors exceeding 60 cm RMS. The JGM 1 model represents a major improvement in the model for the Earth's gravity field. The achievement was possible only after extensive improvements in both the software and the models and in the tracking and surface gravity data. The model's performance is evidence of the success of the efforts in these areas.

With JGM 1 as a starting point, information from the tracking of the T/P satellite itself was used to improve the estimates of the linear combinations of coefficients to which the T/P satellite is most sensitive. The complement of high precision tracking systems carried by T/P includes a retroreflector array for SLR [*Degnan*, 1985], a DORIS receiver [*Nouel et al.*, 1988], and an experimental Global Positioning System (GPS) receiver [*Yunck et al.*, 1994; *Melbourne et al.*, 1994], which provide both exceptional coverage and redundancy. This postlaunch model improvement, which led to the JGM 2 model, used only the SLR and DORIS data collected by T/P during a portion of the initial 6-month calibration/evaluation period [*Nerem et al.*, 1994].

The radial orbit accuracy obtained for operational T/P precision orbit determination, using the JGM 2 gravity model, is in the range of 3 to 4 cm [*Tapley et al.*, 1994a]. While this orbit accuracy is considerably better than the JGM 1 orbit accuracy, there is evidence of gravity model error in the JGM 2 orbits. This conclusion follows from comparisons with high-precision orbits determined with the GPS tracking of T/P [*Bertiger et al.*, 1994]. Thus incorporation of the GPS data can be expected to improve the gravity model further and reduce the T/P orbit errors, particularly those that are correlated geographically and are not reduced with temporal averaging [*Tapley and Rosborough*, 1985; *Schrama*, 1992].

Further evidence of error in the JGM 2 model is found by analyzing geodetic results from the LAGEOS-type satellites. The joint NASA/Italian Space Agency (ASI) LAGEOS 2 satellite, which is a replica of LAGEOS 1, was launched in October 1992 into a 52.6˚ inclination orbit. The force and measurement modeling errors for the two satellites should be very similar. However, when separate solutions for station position and geocenter (the absolute position of the SLR station network relative to the Earth's center of mass) are performed by using JGM 2, there are differences in the results which are an order of magnitude larger than the expected errors. Combined satellite solutions for polar motion also display biases relative to the series determined from each satellite alone. To achieve consistent results, it is necessary that selected geopotential coefficients be estimated as part of the multisatellite geodetic solutions, but the resulting solution is not consistent with the original JGM 2 geopotential model. Similar results were noted in the DORIS station solutions obtained from SPOT 2 tracking data [*Watkins et al.*, 1992; 1994]. Both of these results indicate that there is significant gravity model error remaining in the JGM 2 model.

New Satellite Tracking Data

The goal of this study was to combine several new data sets with the information in the JGM 1 solution to determine an improved model for the Earth's geopotential. This effort involved, first, the identification of tests accurate enough to distinguish improvements in the gravity field and, second, the use of these tests to define a strategy for combining the new data sets. JGM 1 was adopted as the starting field rather than JGM 2 since this investigation processed a more extensive set of SLR and DORIS data which was not available at the time JGM 2 was produced. The JGM 1 and JGM 2 models differ only by the inclusion of SLR and DORIS tracking of T/P. In addition, to investigate the specific contribution of the T/P GPS data described below, it was necessary to start with a gravity model that did not contain a contribution from T/P.

The new data sets include the GPS data collected by the T/P GPS receiver, additional SLR and DORIS tracking of T/P, new SLR tracking of LAGEOS 2 and Stella, and additional SLR tracking of LAGEOS 1 and DORIS tracking of SPOT 2. Stella is a passive geodetic satellite designed to be tracked by SLR for studies of the solid Earth. The high-inclination, nearly circular orbit and the small area-to-mass ratio make the Stella data an important additional source of information for gravity model improvement. Additional details of these data sets are summarized in the following discussion.

TOPEX/Poseidon

The T/P satellite consists of a large bus and a 28 m^2 solar panel, with a total mass of 2500 kg. It occupies a nearly circular orbit with a 1330 km altitude and a 66˚ inclination. It carries two highly precise radar altimeters and a microwave radiometer, in addition to supporting three precise tracking types [*Fu et al., 1994*; *Tapley et al*., 1994a]. A laser retroreflector array supports SLR as the primary tracking system. The satellite is tracked by more than 30 sites around the world, with precisions ranging from 5 to 50 mm. A DORIS receiver provided by CNES allows the satellite to be tracked with Doppler range rate precisions that approach 0.5 mm/s from a well-distributed ground network of more than 50 beacons. An experimental GPS receiver provides carrier phase measurements with 5 mm precision and pseudorange measurements with approximately 500 mm precision, in the absence of antispoofing (AS). Because GPS tracking provides nearly continuous, high-precision, three-dimensional position information, it can be expected that the T/P GPS data will provide considerable information for improving the low orders of the gravity model. The ground tracking network for these systems is illustrated in Figure 1. These data provide the first opportunity for using the nearly continuous high-precision tracking provided by the constellation of 24 GPS satellites for precision orbit determination and gravity model improvement [*Bertiger et al*., 1994; Schutz et al., 1994; Tapley et al., 1995].

LAGEOS 2

LAGEOS 2 is a spherical spacecraft and a near-identical replica of the U.S.-launched LAGEOS 1 satellite, with a mass of 407 kg and a diameter of 0.60 m. As a part of the joint NASA-ASI LAGEOS 2 mission the satellite was launched in October 1992 into an orbit with a semimajor axis of 5900 km, an eccentricity of 0.02, and an inclination of 52.6˚. The spacecraft's high altitude and low area-to-mass ratio attenuate the effects of the short wavelengths of the gravity field and surface forces. LAGEOS 2 is tracked by a global network of laser ranging stations. The single-shot precision of the best stations is a few millimeters. These stations have been used to obtain centimeter-level orbit accuracies for geodetic and geodynamic studies.

The motivation for including LAGEOS 2 in the new gravity field solution includes the improvement of the estimates of the linear combinations of coefficients to which LAGEOS 2 is particularly sensitive. These are dominated by the low degree and order coefficients for this spacecraft. Furthermore, the geodetic parameters determined by analyses of LAGEOS 1 and 2 depend upon the gravity coefficients for both improved orbit modeling and reference frame definition. For polar motion solutions a linear combination of order 1 coefficients determines the means of the resulting series. Thus, if the data from both LAGEOS 1 and LAGEOS 2 can be used to produce a gravity field with order 1 terms that are consistent for both satellites, then the polar motion series determined by each of the individual satellites will have a consistent mean. In addition to the polar motion solutions, both the order one and resonance terms can also affect the determination of the tracking network origin with respect to the Earth's center of mass, or geocenter. Although the terms that define the mass center are actually of degree 1 and are not traditionally adjusted, we have found that because of nonuniform tracking station distribution, some aliasing from low-degree order 1 terms, as well as resonance terms, is possible. The computation of a gravity field model, which removes the problems described above, is a prerequisite for using LAGEOS 1 and 2 to determine accurate combined solutions for geodetic parameters.

Stella

The Stella satellite was launched by CNES on September 23, 1993. The satellite was constructed as a copy of the Starlette satellite launched by CNES in 1975, but since it was launched concurrently with the SPOT 3, it is in an orbit very similar to that of both SPOT 2 and SPOT 3. Stella's orbit has a semimajor axis of 7181 km, an eccentricity of 0.001, and an inclination of 98.7˚. The satellite has a depleted uranium core to decrease its area-to-mass ratio and, consequently, the effects of atmospheric perturbations at the 800 km altitude. Stella plays two roles in the gravity model solution. As a withheld data set, it provides an excellent external test of the performance of existing fields, measuring primarily the treatment of the SPOT 2 DORIS data, since it is in an almost identical orbit. As an easy-to-model spacecraft without maneuvers, attitude uncertainty, or solar panels, it provides unique information for additional gravity improvement. It is noted that, as with all Sun-synchronous orbits, errors in some of the solar tides, particularly S_2, will be aliased into the estimates of the zonal coefficients. Since the tide model employed is based on a determination from a number of satellites without this problem, the aliasing effect will be small relative to the errors in the current zonal coefficients, and the resulting gravity solution will be an improvement.

Evaluation of Existing Gravity Fields

As a necessary condition for any improved Earth's gravity field model, the orbit accuracy achieved for all satellites must be improved over the special models that have been developed for individual satellites. The objective of the JGM model development effort, while directed to the particular needs of the T/P mission, was to obtain a model that would yield the best accuracy on all satellites and, to the extent possible, improve the geoid. To a large measure, the long-wavelength components for the JGM 1 and 2 models [*Nerem et al*., 1994] represented the best model for the majority of the existing satellites. However, as noted in the previous discussion, there are areas where these models require improvement.

Several tests can be applied to evaluate the accuracy of a given gravity field model. One test for evaluating the model accuracy is the fit to tracking data on a specific satellite. The nature of the geographically correlated orbit error is another orbit performance test. A second test criterion is based on the stability and accuracy of the estimates of geodetic parameters, such as tracking station coordinates and Earth orientation parameters, with tracking data from different satellites using a given gravity model. Results obtained with data not included in the gravity model solution lead to a more rigid test using either of these criteria. Finally, the accuracy of the geoid represents a third test. The evaluation of JGM 1 and 2 by these tests is described in the subsequent discussion.

Tracking Data Residuals

To obtain an accurate evaluation of the performance of a specific gravity field model on a specific satellite, data spans of 3 to 5 days' length with robust tracking and modest surface force conditions were used. Generally, only the initial position and velocity, along with a drag coefficient or a constant along-track acceleration parameter to account for unmodeled along-track accelerations, are estimated to ensure that the mismodeled zonal gravitational signal is not absorbed. An exception to this philosophy was adopted for T/P. For this satellite, 10-day arc lengths were used, and in addition to the parameters used for the shorter arcs, the coefficients for daily once-per-revolution along-track and cross-track acceleration components were adjusted [*Tapley et al*., 1994a]. The data from these arcs have been processed by using the JGM 1 and JGM 2 gravity fields, and the results are presented in Table 1. This table is based on the SLR data from a number of satellites in orbits with varying inclinations and altitudes. Data from the

Stella satellite are not included in either field, but the Stella orbit is very similar to that of SPOT 2, which was included. With the exception of T/P and Stella, JGM 1 and JGM 2 yield the same results. The improved performance on T/P with JGM 2 is expected, since the T/P data used in the JGM 2 solution were not included in JGM 1. In Table 1, it can be seen that an additional test where one set of accelerations of 1 cycle per revolution (cpr) was included in the estimation process for Stella results in a significant reduction in the data fits. The 1-cpr parameters account for sinusoidal along-track and cross-track accelerations with a period equal to the orbital period (i.e., 1 cpr). These parameters effectively remove most of the secular and long-period orbit error due to the error in the even and odd zonal harmonic coefficients and allow an accurate evaluation of the remaining portion of the gravity model. It can be seen that the fits for Stella are considerably poorer than those for any other satellite and that a significant contribution to the overall RMS error can be attributed to errors in the zonal harmonics.

In addition to the longer arcs evaluated above, 8-hour arcs have also been assessed for the T/P and SPOT 2 satellites by using the dense temporal coverage provided by the DORIS tracking system. The shorter arcs are less sensitive to the surface force effects and the long-period gravitational perturbations, such as resonances. Consequently, they provide a means of evaluating the short-period gravity model errors. GPS tracking is the only other data source that would support such short arcs. For T/P an orbit determined by using the dense DORIS tracking data is also evaluated by using SLR data for an estimate of the orbit error, while for SPOT 2, since there is only DORIS tracking, a measure of the error is computed by using the Guier plane analysis of *Guier and Newton* [1965]. In Table 2 it is shown that the short arcs for T/P are improved by using JGM 2 compared to JGM 1, while the same level of accuracy is retained for SPOT 2. Table 2 also demonstrates that geopotential errors at this low level can be difficult to quantify strictly on the basis of the data fits, since the changes in the RMS are in the second or third significant digit.

Geographically Correlated Orbit Error

The solution for the gravity field model contains both an estimate of the model parameters and a covariance matrix that describes the errors in the model. This error matrix can be used to map errors in the gravity field model, as characterized by the error covariance, into uncertainties in the spacecraft orbit as a function of geographical location [*Tapley and Rosborough*, 1985; *Schrama*, 1992]. The geographically correlated orbit error is a feature of all fields, although both the magnitude and the spatial structure will vary with the field. Furthermore, the structure will depend on the specific satellite of interest. For dynamically consistent orbit determination procedures it is a particularly insidious error source, since this class of orbit error goes directly into the long-wavelength components of the sea surface topography derived from satellite altimeter data and can be eliminated only by improving the gravity model. Plate 1 shows the geographically correlated errors for JGM 1 and JGM 2 for T/P. The 2.5 cm mean amplitude of the geographically correlated error for JGM 1 has been reduced to 1.6 cm for the JGM 2 model. This improvement is attributable largely to the excellent geographical coverage of the DORIS tracking system on the T/P satellite.

Geodetic Parameter Tests

One of the original requirements for accurate orbits resides in the need to determine accurate coordinates of a set of globally distributed tracking stations. The determination of such points on the Earth's surface is also a requirement for tectonic plate motion studies. The accuracy of tracking site coordinates determined from analyses of satellite data has reached the centimeter level in recent years [*Ray et al.*, 1991; *Watkins et al.*, 1994; *Himwich et al.*, 1993]. This accuracy allows the site coordinates to be used as sensitive diagnostics of parts of the gravity model. Specifically, the site coordinates are sensitive to the values of the terms of low degree and order, especially order 1, because of the dominant diurnal orbit signal associated with these terms. The method used to evaluate a specific gravity field solution is to adjust the entire tracking network in a minimally constrained solution (typically a single longitude is fixed) by using observations from a single satellite. The results from this solution can be compared with the solutions generated by long time series of SLR, very long baseline interferometry (VLBI), GPS, or the combination of these data sets. The approach is to fit a Helmert, or seven-parameter transformation, to the two network solutions to determine the relative translations, rotations, and scale differences. Since each satellite orbits the center of mass of the Earth, the translation parameters represent the consistency in the determination of the center of the tracking network. The mass center of the Earth is known with a centimeter-level accuracy from analysis of LAGEOS 1 data. The rotation terms are essentially arbitrary. The scale differences are generally negligible when an accurate value for the gravitational mass (GM) of the Earth is adopted and the same tropospheric mapping functions are used in all solutions [*Himwich et al*., 1993]. The residual differences after the removal of the common parameters are a measure of the relative positioning accuracy.

LAGEOS Station Comparisons

In this section the performance of the existing JGM 1 and JGM 2 fields is assessed by determining the effects on the relative station positioning and geocenter (i.e., translational errors in the terrestrial reference frame) from LAGEOS 1 and 2. All station positions were computed by using 3-day orbital arcs, 3-day Earth orientation parameter adjustments, and the adjustment of range or clock biases when necessary [*Tapley et al*., 1993]. The results demonstrate the inconsistency of the geocenters due to order 1 and resonance error in the JGM models.

Table 3 gives a comparison of LAGEOS 2 derived station positions to those obtained from LAGEOS 1, using the JGM 1 and JGM 2 fields. Note particularly the geocenter offsets, which at up to 36 mm in the X coordinate, for example, are about 10 times larger than the expected level of uncertainty. As mentioned earlier, this discrepancy is likely due to errors in the order 1 linear combination for LAGEOS 2, which was not included in either of these fields. Table 1 demonstrates that the performance of JGM 2 on the LAGEOS satellites is identical to that of JGM 1 in terms of data fit and that orbit fits alone are an incomplete test of the gravity model at this level of accuracy.

Table 3 also presents a comparison of the geocenter offsets obtained, for LAGEOS 1 only, by using the JGM 1 field and another gravity model, the University of Texas Earth Geopotential model (TEG) 2B [*Tapley et al*., 1991]. The primary difference is a 20 mm shift in the X component of the geocenter, which we interpret as being due to insufficient separation of geocenter and biases from the order 1 and resonance terms in the gravity model. This shift was first recognized in early 1993, and consequently, the CSR 1993 laser ranging station solution (CSR93L01) was performed simultaneously with a selected gravity field adjustment [*Eanes and Watkins*, 1993]. The resulting solution indicated that both JGM 1 and TEG 2B had differences in linear combinations of the geopotential coefficients that led to 10–15 mm errors in the X geocenter components. To remove the problem of geocenter error in the new field, additional LAGEOS 1 data were combined with new LAGEOS 2 data, and partial derivatives for the geocenter offsets and station-dependent biases were added to the estimated parameter array.

SPOT 2 Station Coordinates

Recent studies have shown that the positioning capability of the DORIS tracking system on the SPOT 2 spacecraft is at the few-centimeter level [*Watkins et al*., 1992, 1994a; *Cazenave et al*., 1992; *Soudarin and Cazenave*, 1995]. Thus the quality of the adjusted station coordinates can be used to discern the orbit errors due to the geopotential for this low-altitude satellite. In Table 4 we present a summary of the relative differences between the estimated DORIS beacon coordinates and a set of high-precision SLR and VLBI positions described by *Watkins et al*. [1994b]. The model, JGM 2*, in Table 4 is obtained by adjusting selected geopotential coefficients for each order between 0 and 29. This method gives a quick approximation of the performance of a tuned field. The positions estimated with the DORIS data are significantly improved when the gravity model is allowed to adjust, even though very short arcs (8 hours) were used in the station solution process in order to reduce the contribution of force modeling errors. On the basis of the results in Table 4 a reprocessing of the SPOT 2 data sets is warranted.

Description of New Information Equations

The techniques for creating the JGM 1 information arrays are summarized by *Nerem et al*. [1994]. The approach for combining the new information with the JGM 1 information is described by *Tapley et al*. [1989] and *Yuan* [1991]. The standards and models used to process the new tracking data are described by *Tapley et al*. [1994a] and are in large part consistent with the International Earth Rotation Service (IERS) standards of *McCarthy* [1992]. Specific details pertinent to the individual data sets are given in the following.

LAGEOS 1 and LAGEOS 2

The information equations for the LAGEOS satellites were created by using arc lengths of 6 days. The 6-day arc length was used to capture the 2.2-day period of the primary resonance for LAGEOS 1 and most of the 8-day resonance for LAGEOS 2. The nominal site positions and velocities and Earth orientation series were from the CSR93L01 solutions. Within each 6-day arc, initial conditions and a constant tangential acceleration were adjusted. Partial derivatives for a single adjustment of the gravity coefficients and geocenter were written. Solar reflectivity coefficients were held fixed to values determined from previous long-arc solutions [*Tapley et al*., 1993]. The typical RMS for the reference orbits was 2.5 cm. The predicted RMS for this data set after the geopotential adjustment was 1.9 cm. The data span was November 1987 through August 1993 for LAGEOS 1 and October 1992 through August 1993 for LAGEOS 2.

Stella

All of the Stella data available at the time of the solution were used. They consisted of 30 days of SLR tracking data from approximately 20 ground sites. The data were processed by using three 10-day arcs in order to retain sensitivity to long-period resonance and secular zonal terms in the gravity field. Since such a limited data set was available and the primary goal was to improve the zonal harmonics, only a selected subset of the geopotential coefficients was adjusted with this data set. This set included all coefficients up to degree and order 36, plus the resonance at order 43. Daily drag coefficients was estimated along with the initial position and velocity. The empirical 1-cpr acceleration parameters was not estimated in order to avoid absorbing the secular and long-period signals from the errors in the zonal geopotential coefficients, since it was expected that the low area-to-mass ratio of Stella would prevent the surface force modeling errors from being a serious limitation. The solar reflectivity is poorly separated from gravity coefficients because of the short data span, and this parameter was fixed to the value determined from multiyear Starlette solutions. The site positions and velocities and Earth orientation series were fixed to the CSR93L01 values. The predicted RMS for this data set was 6 cm.

TOPEX/Poseidon GPS

The GPS data used for the gravity field adjustment consisted of cycles 10, 15, 17, and 19. For cycles 10, 17, and 19, double-differenced measurements were formed by using two GPS spacecraft, one ground site, and the T/P spacecraft. For cycle 15 only, double-differenced phase data between two GPS spacecraft and two ground sites were used in addition to the data formed for the other three cycles. A 14-site subset of the 21-site GPS tracking network was used. All data were preprocessed at CSR, including editing and formation of double differences. The dynamic and measurement models used are described by *Schutz et al*. [1994] and are generally consistent with the IERS standards for GPS. Selective availability (SA) was on during most of the data collection intervals, although AS was off. The information equations were created by using 3.3-day arcs for both T/P and the GPS spacecraft. Longer arcs produced degraded GPS spacecraft orbit accuracy, even with the adjustment of many dynamic parameters as well as the large parameter set resulting from the rigorous treatment of the ambiguities. The 3.3-day arcs, while short enough to allow good dynamic modeling, are long enough to capture the long-period resonance effects. Daily 1-cpr empirical accelerations in the along-track and cross-track directions were adjusted for both T/P and GPS.

The nominal T/P force and measurement models were derived from the T/P standards and included the macromodel of *Marshall et al*. [1994]. The measurement model used the dual-frequency GPS-derived ionosphere correction, and troposphere zenith delays were adjusted for each site every 2.5 hours. Double-difference phase ambiguities were adjusted. Antenna phase center variations in azimuth and elevation for both T/P and the Rogue and TurboRogue ground sites using the choke ring antenna were modeled. In addition, the phase windup due to antenna motion was included [*Wu et al*., 1993], as well as the Doppler phase bias described by *Bertiger et al*. [1994]. The nominal Earth orientation series was CSR93L01, and all but one of the station positions were estimated. Finally, since preliminary comparisons of GPS- and SLR-derived orbits for TOPEX/Poseidon indicated an error of approximately 6 cm in the measured spacecraft center of mass to GPS antenna offset in the spacecraft-centered Z coordinate (the radial component), partial derivatives for this parameter were also written. The typical predicted fit RMS for each 3.3-day arc was 1 cm. Further details on the GPS data and its processing are given by *Tapley et al*. [1996].

TOPEX/Poseidon SLR/DORIS

Twenty repeat cycles of 10 days each were processed by using SLR and DORIS tracking data. The cycles spanned the period from cycle 1 through cycle 23, with cycles 10 and 11 omitted because of weak tracking. Other than a few minor exceptions, the force and measurement models adhered to the T/P standards described by *Tapley et al*. [1994a]. Ten-day arc lengths were used for the long-arc information equations including SLR and DORIS tracking. Daily tangential accelerations and 1-cpr along-track and cross-track accelerations were adjusted. The nominal SLR positions and Earth orientation parameters were from the CSR93L01 solution, and the nominal DORIS site positions were based upon the SPOT 2 coordinates of *Watkins et al*. [1992]. The predicted SLR RMS was approximately 3.7 cm, while the predicted DORIS RMS was 0.51 mm/s.

SPOT 2

Two sets of SPOT 2 DORIS data have been processed at CSR for use in site positioning, orbit determination, and gravity field solutions. The first set consisted of 3 months of data covering the period from March 31, 1990, to July 5, 1990, and is characterized by numerous data gaps due to satellite maneuvers and receiver interrupts. Only the uninterrupted 26-day span from May 3 to May 29 was used for this solution. The data was processed in ten 2.6-day arcs, chosen to cover a significant resonance. The drag coefficient was adjusted every 6 hours, and a single solar radiation reflectivity for the spacecraft body was adjusted for each arc. The nominal surface force model assumed perfect yaw steering with main body areas of 6.5, 3.5, and 9.0 m^2 in the roll, pitch, and yaw axes, respectively. The panel area used was 18.5 m^2. Because of the reduced drag effects due to lower solar activity during this particular period, it appeared that estimating the empirical 1-cpr acceleration parameters could be avoided, and hence the zonal gravity information was retained.

The second set of DORIS data for SPOT 2 was 80 days of data collected during the so-called Asymptotic Campaign from January 2 through March 23, 1992. Although this data set had fewer data gaps than the 1990 set, it suffered from greater drag effects due to increased solar activity, despite its being temporally farther from the solar maximum. Consequently, it was necessary to adjust daily empirical 1-cpr accelerations in the transverse direction, in addition to the 6-hour drag coefficients for the 2.6-day arcs. This same data set was also processed in the short arcs described earlier, by using 8-hour arcs, with 4-hour drag coefficients, and a single 1-cpr along-track acceleration. In addition, the pass-dependent wet troposphere zenith corrections and frequency offsets for the Doppler tracking were adjusted for both data sets.

Combination of New Data

In developing the new model the question of determining the proper relative weight of the new data to the gravity field information arrays from the JGM 1 solution must be addressed. In the computation of JGM 2 a readjustment of all the relative weights for the information equations in the JGM 1 model along with the weights for new T/P data were required. These weights, however, changed little from their values in the JGM 1 model [*Nerem et al*., 1994]. Consequently, in our adjustment of JGM 1, the relative weights were fixed to the values assigned to the information arrays in the JGM 1 solution, and the relative weights of the new data sets were determined with respect to the JGM 1 solution. This procedure is equivalent to using the JGM 1 coefficients and their associated error covariance matrix. This procedure differs from that used in the computation of JGM 2 only when there are significant changes in the relative weights of the JGM 1 solution.

Effective Data Weight

In previous comprehensive gravity solutions performed at GSFC and CSR, relative satellite weighting was performed by using algorithms for selecting the optimal values for the weights as described by *Yuan* [1991] and *Lerch* [1991]. These approaches were not used in this investigation, because software and methodology differences prevented incorporating the full set of JGM 1 information equations. As an alternative, a parametric search for the optimal weights was performed by using a single data set. This weight was used for each new information equation. This parametric search was carried out by using information equations for SLR and DORIS tracking of T/P, and gravity solutions were created by using various weights relative to JGM 1. The resulting fields were evaluated by using withheld arcs of tracking data for T/P and other satellites as described in previous sections. The results of these tests indicate the need to weight the data well below the weight implied by either the data precision or the data fits.

To understand this conclusion, some background on satellite data weighting is appropriate. When the data weight used in the creation of the information equations is correctly chosen, and the residuals are purely Gaussian noise (with the data weight being equal to the inverse square of the standard deviation), the data set can be said to be correctly weighted, in the sense that the covariance for the adjusted parameters will be statistically consistent with their errors. However, in the typical satellite problem the residuals are not Gaussian but are dominated by systematic errors due primarily to gravity model errors, nongravitational surface force errors, and measurement model errors. Therefore the data noise variance is increased (the data weight is decreased), so that the computed covariance will provide a realistic error estimate. This scaling inflates the noise-only covariance to approximate the effect of the various unknown modeling errors. Although the magnitude of this increase depends to some extent on the satellite, for recent, well-tracked geodetic satellites the scaled data standard deviation is typically 10 to 50 times larger than the random noise in the tracking data. This is also roughly 5 to 25 times the fit RMS. For example, SLR tracking of LAGEOS 1 was assigned an effective standard deviation of 1.12 m in JGM 1, when the RMS SLR noise, averaged over 1980–1988 (the span used in JGM 1), is approximately 2–3 cm, and the RMS fit to the tracking data is better than 5 cm.

Returning to the description of our parametric search for appropriate weights, we note that, if the data noise used in the generation of the information equations reflects only the random component of the residuals, the optimal weighting scale factor should be between $(1/50)^2 = 0.0004$ and $(1/5)^2 = 0.04$. The upper bound of this range agrees with our observation that the solutions that used weighting scale factors of 0.01 and 0.04 performed best. An additional solution was also performed with a weight of 0.005, and the field was almost indistinguishable from fields with weights of 0.01 and 0.04. Therefore, while the optimal weights have not been determined in any rigorous sense, the optimal weight is in a fairly "flat" region in the weighting space, and the solution is not particularly sensitive to small changes in the weights. As a consequence of these observations an effective standard deviation approximately 30 times the data noise was used for each satellite. The effective standard deviations are summarized in Table 5. The only exceptions are the DORIS and GPS data, whose fits are much closer to the random noise because of the large number of measurement model parameters included in the solution. The standard deviations for these data sets are increased by a factor of 15. It is reiterated that the weight of the JGM 1 information array was fixed at 1.0; that is, the covariance of JGM 1 was assumed to be calibrated correctly. Comparisons of the differences between JGM 1 orbits and orbits computed with the improved gravity models have verified that the JGM 1 covariance was in fact well calibrated.

Arc Length Philosophy

The perturbations on a satellite due to the geopotential can be classified as one of four basic types: secular, long-period and resonance, m-daily or medium period, and short period [*Kaula*, 1966]. The perturbations with periods longer than 1 day are the secular, long-period, and resonance perturbations. The resonance perturbations can often have periods of several days to a few weeks. The secular and long-period terms are due to the zonal harmonics (of even and odd parity, respectively), while the resonances are satellite dependent and generally occur at the sectoral terms for orders equal to a small integer times the number of revolutions per day. These terms cause the largest amplitude perturbations; however, they are actually small in number when compared to the total number of geopotential perturbations. Most of the perturbations have periods that are less than 1 day, and the majority have periods less than 1 revolution. In contrast to the long-period perturbations, these short-period perturbations cannot be removed by adjustment of satellite initial conditions when the arc length exceeds a few revolutions.

The improvement in the RMS fit to the tracking data as the arc length is shortened has been demonstrated in Tables 1 and 2. The SLR range data for T/P using JGM 2 has an RMS residual of 4.7 cm for 10-day arcs, but a residual of 3.1 cm is obtained by using 8-hour arcs. In addition, as shown in Table 5, the determination of station positions on the Earth's surface using DORIS data collected by SPOT 2, a satellite sensitive to short-wavelength gravity perturbations, improved significantly when gravity coefficients were adjusted, even though an arc length of only 8 hours was being used.

To achieve maximum sensitivity to short-period gravity perturbations, arc lengths of only a few revolutions are a logical option. There is the additional advantage that the effects of mismodeling the nongravitational forces are substantially reduced by the frequent adjustment of the initial conditions, since surface force effects tend to build up secularly with time. However, short arcs of a few hours' length seriously degrade the observability of the large long-period, resonance, and m-daily terms for the lower orders. The accurate determination of these terms requires arcs of a few days' duration. To address these two conflicting requirements, we have chosen the approach of using two information equations for the satellites with tracking dense enough to allow short-arc solutions. One set of information equations is written by using arcs of a few days' length to determine the long-period terms, while another set with 8-hour arc lengths was used to increase the signal-to-noise ratio for the short-period terms. Only DORIS and GPS provide the dense tracking needed for the short-arc information arrays, and hence this approach could be used only for SPOT 2 and T/P. However, the relatively high altitude of the T/P satellite attenuates the short-period gravity signals, and hence short arcs were used only for the SPOT 2 spacecraft.

Evaluation of New Gravity Fields

On the basis of the previous discussion, new data from LAGEOS 1, LAGEOS 2, TOPEX/Poseidon, SPOT 2, and Stella have been combined with the JGM 1 information arrays, which were based on tracking data from 31 satellites, surface gravity data, and Geosat satellite altimetry. Each of the new data sets contributes to the improvement of the overall field, and the specific contributions of some of the data sets are illuminated by developing fields where the data set of interest is withheld. The performance of each of these models is compared with JGM 3, which included all the new data sets, and JGM 2, which was used for the initial release of the T/P altimeter data.

The four new fields considered are JGM 3A (without GPS data), JGM 3B (without T/P SLR/DORIS), JGM 3C (without Stella data), and JGM 3 (all data), using the same evaluation tests used earlier on the previously existing fields. Beginning with the long-arc evaluations, using the same arcs and parameterization as before, we find improved fits for every satellite when comparing JGM 3A, JGM 3B, and JGM 3 with JGM 2. JGM 3 fits the low satellites slightly better than JGM 3A. Note that the improvement on T/P from 4.7 cm to 3.9 cm implies a removal of 2.6 cm of radial orbit error in a root-sum-squared (RSS) sense. A similar improvement is obtained for Ajisai. In Table 6 only, we include the JGM 3C field, so that the improvement of the field over JGM 2 on a withheld satellite can be seen. It is interesting to note that the improvement over JGM 1 and 2 for Stella is not confined to the zonal harmonics, even when Stella is withheld from JGM 3. The Stella fits which included the adjustment of the 1-cpr acceleration (hence absorbing any zonal modeling error) show as dramatic an improvement as the fits where 1-cpr accelerations were not estimated.

The short-arc evaluations display similar improvements, as demonstrated in Table 7, although the residuals at this level tend to be limited by the data precision and other errors. The improvement in the Guier slant range RMS for the SPOT 2 satellite from 8.0 cm for JGM 2 to 7.4 cm for JGM 3 represents a removal of 3.0 cm in an RSS sense. The smaller improvement of 0.8 cm for T/P is likely due in part to the smaller short-period gravitational effects at the T/P altitude of 1335 km.

Plate 2 presents the mean, or constant, component of the geographically correlated errors for JGM 3A and JGM 3, based upon their respective covariances. The RMS of these errors has been reduced from 1.6 cm, with peak values of 2 cm, for the JGM 2 model to less than 0.6 cm, with peak values of less than 1 cm, for JGM 3. We attribute this reduction to the additional geographic coverage provided by the GPS tracking, as the RMS-correlated component for JGM 3A, which was determined without GPS data, is twice as large as JGM 3. As additional support for this conclusion the correlated error prediction for JGM 3B, with GPS but no SLR or DORIS data, is nearly identical to that of JGM 3. The geographically correlated orbit error for T/P orbits computed with the JGM 3 field is smaller, as indicated by closer agreement with orbits computed with data from the GPS receiver by using the reduced dynamic technique, which is less sensitive to gravity model errors. This agreement, presented for a typical cycle in Plate 3c, is currently at the 2.5-cm level in an RMS sense for the radial component, after removal of a bias along the Z axis of 1.5 to 3.0 cm. When other model improvements are employed by both the SLR/DORIS orbits and the GPS reduced-dynamic orbits, the differences are further reduced to 2 cm or better. Further, the spatially correlated structure of the orbit differences associated with JGM 2, as shown in Plate 3a, is essentially eliminated with JGM 3. Table 8 summarizes the agreement with the reduced dynamic trajectories for a number of cycles. Note that the agreement for cycles not included in the gravity solution is not degraded. The agreement of the reduced dynamic trajectories with dynamic orbits computed by using the JGM 3A or 3B field is slightly worse overall.

The Z shift between the orbits is not completely understood at this time. The offset did not change by more than a few millimeters with different gravity models, but it has been observed to change significantly when different data-weighting schemes are used. The offsets seen in these comparisons are small but deserve additional study.

As is demonstrated in Plate 3, the geographically correlated portion of the trajectory differences between orbits computed by using JGM 2 and JGM 3 are very similar to those between JGM 2 and the GPS-reduced dynamic trajectories computed at the Jet Propulsion Laboratory (JPL), an indication that both the reduced dynamic solution and the new gravity field model remove most of the gravity model error in JGM 2, although through substantially different approaches. This is a powerful argument supporting both the improvement of the gravity model and the capability of reduced dynamic filtering. Currently, since the errors from each technique are expected to be at the 2.0 to 3.0 cm level, it is unclear whether this agreement can be improved significantly [*Yunck et al.*, 1994; *Tapley et al.*, 1994a].

To test the consistency of the linear combinations for LAGEOS 1 and 2, we repeat the comparison for the independent site coordinate solutions from each satellite. Recall that the geocenter differences are determined as the mean of the coordinates of approximately 50 SLR tracking stations, whose coordinates are determined by using LAGEOS 1 and LAGEOS 2 tracking data to obtain two independent solutions. It is clear from Table 9 that the geocenter agreement is now at the few-millimeter level in all three components, and at the 1 standard deviation level. In addition, the relative positioning is substantially improved, from the 10 to 20 mm level to less than 10 mm in each coordinate. The performances of JGM 3A and JGM 3 are virtually identical.

Table 10 demonstrates the improved performance of the new geopotential model on the positioning for SPOT 2. By comparing Table 10 to Table 4 it can be seen that JGM 3 outperforms the tuned JGM 2, for which selected geopotential coefficients were adjusted by using SPOT 2 data. The performance of JGM 3A and JGM 3B was found to be nearly identical to that of JGM 3.

The JGM 3 Geoid

In addition to the accuracy of the gravity model at satellite altitudes, the accuracy at sea level, as manifested in the determination of the marine geoid, is a topic of crucial interest for the area of satellite oceanography. The differences of the JGM 3 and JGM 3A geoids with respect to the geoid of JGM 2 are presented in Table 11. The geoid difference between JGM 2 and JGM 3 is also presented graphically in Plate 4. This figure demonstrates that the differences are largely over land, particularly over eastern Eurasia and South America, where the surface gravity data are sparse. The predicted errors in JGM 3, presented in Plate 5, indicate that the uncertainties are also largest at these locations. Table 11 shows that the addition of the GPS data changes the geoid over land at the 13 cm level, although over the ocean the change is approximately half that value. The predicted commission errors in the JGM 2 oceanic geoid (through degree 70) are at the 25-cm level, so the differences found in this study are reasonable.

While the changes in the geoid appear reasonable, it is difficult to assess whether they represent an actual improvement over other models. We currently have evidence from two sources that suggest geoid improvement. The first is comparison of the satellite altimeter determined quasi-stationary sea surface topography (SST), derived by using the JGM 3 geoid, with the SST determined from long-term in situ measurements such as those of *Levitus* [1982], which measures primarily the longer wavelength portion of the geoid. As described by *Tapley et al.* [1994b], SSTs from T/P referenced to the JGM 3 geoid are generally in better agreement with Levitus than those referenced to the JGM 1 or JGM 2 geoids. Table 12 demonstrates the results of a comparison for a 2-year mean SST determined with T/P altimeter measurements smoothed to degree and order 25. Data below -50° latitude are not compared because of errors in the Levitus surface due to lack of data. In addition to an overall reduction in RMS difference, specific features in the SST referenced to the JGM 3 geoid appear to more accurately represent known oceanographic features, such as the North Equatorial Countercurrent [*Wyrtki, 1974*; *Tapley et al.*, 1994b]. This finding is demonstrated in Plate 6, where the 2-year mean SST inferred from the T/P altimetry is shown in relation to the JGM 2 and JGM 3 geoids. The "trough" that should be apparent in the equatorial Pacific region, due to the equatorial currents, is more distinct when the JGM 3 geoid is used. In Figure 2, the difference between the JGM 3 geoid and the geoids calculated with JGM 3A and JGM 3B is presented. It can be seen that the GPS tracking data is the primary contributor to the better definition of the geoid features in the equatorial region.

The influence of the GPS data can also be examined by calculating the degree error variance, shown in Plate 7, for the various geopotential solutions. It can be seen that the contribution of all the data sets added to JGM 3, other than the GPS data, results in a decrease in the error power through approximately degree 60, with the greatest contribution occurring between degrees 20 and 45. The GPS data, in contrast, provide a significantly larger decrease in the error power through approximately degree 20. The contribution tapers off at approximately degree 38, presumably because of the higher altitude of T/P and the resulting decrease in the sensitivity to the higher degree perturbations. GPS tracking of a lower satellite would be expected to provide an improvement in the coefficients to a higher degree.

A second method of evaluating the JGM series of geoids is by comparisons with geoid undulations computed from surface gravimetry measurements determined with the aid of GPS leveling described by *Rapp and Pavlis* [1990]. These comparisons are provided in Table 13. Included in this comparison is the high-resolution geoid model, OSU91A [*Rapp et al*., 1991]. One traverse in each geographic region is included, and the RMS of the undulation differences is tabulated. These tests do not indicate changes that are inconsistent with the geoid uncertainty shown in Plate 5. The degraded performance for the European traverse is unexplained, although the higher noise for all fields on that test suggests that the leveling results in this region may be less accurate. For the remaining traverses, JGM 3 performs as well as or better than JGM 2 and OSU91A.

While the evidence presented here indicates an improvement in the marine geoid, the incorporation of all the new data has provided only an incremental advance toward the geoid accuracy required for oceanography. An accurate geoid is crucial to the study of the absolute and time-averaged circulation [*Wunsch and Gaposchkin*, 1980; *Tsaoussi and Koblinsky*, 1994; *Stammer and Wunsch*, 1994]. Plate 8 illustrates the error power computed for the JGM 2 and 3 models as a function of the degree of the spherical harmonics, calculated only over the oceans. This is compared to estimates of the long-term average of the ocean topography signal calculated by *Levitus* [1982], and to the topography inferred by the difference between a high-resolution mean sea surface based on Geosat, T/P, and ERS 1 altimeter data [*Kim*, 1993] and a geoid based on a combination of JGM 3 and OSU91A. It is clear that the long-wavelength components of the geoid have been improved with JGM 3, but the separation between the geoid errors and the SST becomes questionable for terms above degree 10 or for wavelengths 4000 km or less. The need for a dedicated gravity mission to improve the marine geoid at the shorter wavelengths is clearly evident.

Predicted Errors for Selected Geodetic Satellites

We close our evaluation of the performance of the JGM 3 field with a summary of the predicted contributions of the gravity model error to the radial orbit error for a number of satellites of geodetic interest. These include current and past altimetric satellites whose orbits may need recomputation with updated models. The predictions shown in Table 14 are based on the analytic theory described by *Rosborough and Tapley* [1987] and rely on the JGM 3 covariance. In Plate 9 the predicted radial orbit error is plotted as a function of order of the geopotential spherical harmonic for the T/P satellite. It can be seen that the primary contribution at the lower orders is from the GPS tracking data, particularly at order 1, which is responsible for the major portion of the geographically correlated errors. Plate 10 illustrates the radial orbit error predicted by the covariance for a satellite at roughly the altitude of Geosat, ERS 1, ERS 2, SPOT 2, SPOT 3, and Stella as a function of the orbit inclination. The increase in orbit error at the lower inclinations is an indication of the lack of satellite tracking for satellites at these inclinations. Even so, the JGM 3 model predicts significantly smaller errors at the lower inclinations than the other models, an indication of improvement in the overall gravity model, not just in the linear combinations associated with the new satellites.

It should be cautioned that, while there has been considerable effort over the last decade to develop reliable estimates of the error covariance for the geopotential solutions leading up to and including the JGM series, the errors cannot be assumed to be Gaussian, and the error estimate for any particular coefficient may not be correct. Past experience, however, has demonstrated that the covariance is quite accurate in predicting orbit errors for satellites not in the solution, such as the T/P error predictions using the JGM 1 covariance [*Nerem et al*., 1994].

Other Results

As was noted above, several parameters other than gravitational coefficients were adjusted globally in the JGM 3 solution. These included geocenter adjustments to the CSR93L01 values, GPS site coordinates, and the GPS antenna center-of-mass offset in the spacecraft centered Z axis for T/P.

The ground site coordinates for the GPS network were adjusted in a common fiducial free solution simultaneously with the JGM 3 solution. The relative positions disagree with the nominal IGN93C02 coordinates at the level of 19 mm RMS. This result is obtained after the removal of several sites whose coordinates indicate clear shifts from the nominal positions, primarily the site at Usuda, Japan, whose adjustment was near the meter level. Further, the translation parameters with respect to SLR-derived geocenter were at the centimeter level, a finding better than the agreement obtained by observing only the GPS satellites. Similar results are reported by *Malla et al*. [1993].

The JGM 3 solution for the T/P GPS antenna to center-of-mass offset correction was −5.3 cm with an uncertainty at the millimeter level. This uncertainty is determined in the presence of a fixed value for GM of the Earth of 398600.4415 [*Ries et al*., 1992]. The uncertainty in the value of GM of about 2 parts per billion limits the true uncertainty of the observed radial antenna to center-of-mass offset to about 1 cm. The value observed was remarkably stable under a wide variety of changes in weighting and site coordinate adjustment.

Conclusions

A new model for the Earth’s geopotential, JGM 3, has been computed by combining the information from the JGM 1 solution with new and robust tracking of T/P, LAGEOS 2, and Stella. In addition, some weaknesses of the JGM 1 and 2 models have been removed by the addition of more data for LAGEOS 1 and SPOT 2. The new field provides significant improvements in orbit accuracy as evaluated by tracking data fits and geodetic parameter recovery. In addition, the GPS tracking of T/P has significantly reduced the geographically correlated errors in the gravity model. The JGM 3 model has been adopted for the rerelease of the TOPEX/Poseidon altimeter data, and the radial orbit error for the typical 10-day repeat period is reduced to approximately 2.8 cm RMS, with the geographically correlated orbit error reduced to 6 mm RMS. We find that the T/P GPS data efficiently sense the gravity signal, with only four 10-day repeat cycles used to obtain gravity model improvement, comparable to 20 repeat cycles of SLR and DORIS tracking. The geoid differences between the JGM 2 and JGM 3 models are within the expected uncertainties and are due primarily to the introduction of the GPS data. The improved geoid associated with the JGM 3 model yields more realistic ocean surface topography solutions from T/P satellite altimeter data. Further, the continuous coverage provided by the GPS tracking data improves the observability of nonresonant short-period gravity terms, which affect the geoid but have little effect on the fit to tracking data and are thus difficult to assess. While we believe that the geoid differences represent significant improvement, further study of this issue is required.

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Table 1. Gravity Field Evaluation Fits Using the Residual RMS in Long-Arc Fits to SLR Data

Field	Ajisai	Starlette	LAGEOS 1	LAGEOS 2	T/P	Stella	Stella*
JGM 1	5.3	4.8	1.8	2.2	6.1	30.8	16.2
JGM 2	5.3	4.8	1.8	2.2	4.7	32.8	14.5

All units are in centimeters. See text for definition of terms.
* Includes adjustment of 1-cpr empirical accelerations.

Table 2. Gravity Field Evaluation Using the Residual RMS in Short-Arc Fits

Field	T/P DORIS	T/P SLR	SPOT 2 DORIS	SPOT 2 Guier Range RMS
JGM 1	0.544	3.5	0.524	7.9
JGM 2	0.541	3.1	0.523	8.0

Units are SLR data and Guier Range, cm; and DORIS, mm/s.
See text for definition of terms.

Table 3. Comparison of Station Positions From LAGEOS 1 and LAGEOS 2

	Geocenter			Relative positioning RMS		
Field	ΔX	ΔY	ΔZ	ΔE	ΔN	ΔU
Lageos 1 versus Lageos 2 with JGM 1	36 ± 4	−1 ± 4	−1 ± 4	9	15	14
Lageos 1 versus Lageos 2 with JGM 2	36 ± 4	−1 ± 4	−1 ± 4	9	15	14
Lageos 1 only, TEG 2B versus JGM 1	19 ± 4	11 ± 4	1 ± 4	4	3	4

All units are in millimeters; E, east; N, north; U, up.

Table 4. Comparison of Station Positions for SPOT 2 versus SLR/VLBI

Field	Relative Positioning RMS		
	ΔE	ΔN	ΔU
JGM 1	72	36	40
JGM 2	53	35	41
JGM 2*	33	22	25

All units are in millimeters. See text for definition of terms..
*Included estimating selected gravity coefficients.

Table 5. Effective Data Standard Deviations in JGM 3 Solution

Data Set	Effective Standard Deviation
T/P (DORIS)	6 mm/s
T/P (GPS)	13 cm
LAGEOS 2 (SLR)	30 cm
LAGEOS 1 (SLR)	30 cm
Stella (SLR)	30 cm
SPOT 2 (DORIS)	6 mm/s

See text for definition of terms..

Table 6. Gravity Field Evaluation Fits Using the Residual RMS in Long-Arc Fits

Field	Ajisai	Starlette	LAGEOS 1	LAGEOS 2	T/P (SLR)	T/P (DORIS)	Stella	Stella*
JGM 1	5.3	4.8	1.8	2.2	6.1	0.60	30.8	16.2
JGM 2	5.3	4.8	1.8	2.2	4.7	0.54	32.8	14.5
JGM 3A	5.1	4.8	1.7	1.9	4.0	0.53	7.0	4.2
JGM 3B	5.0	4.8	1.7	1.9	4.2	0.53	7.3	4.6
JGM 3C	5.2	4.8	1.7	1.9	3.9	0.53	10.9	8.5
JGM 3	5.0	4.8	1.7	1.9	3.9	0.53	6.7	4.1

All units are centimeters or millimeters per second.
* Include adjustment of 1-cpr acceleration parameters.

Table 7. Gravity Field Evaluation Using the Residual RMS in Short-Arc Fits

Field	T/P DORIS	T/P SLR	SPOT 2 DORIS	SPOT 2 Guier Range RMS
JGM 1	0.544	3.5	0.524	7.9
JGM 2	0.541	3.1	0.523	8.0
JGM 3A	0.539	3.0	0.516	7.4
JGM 3B	0.538	3.0	0.516	7.4
JGM 3	0.539	3.0	0.516	7.4

Units are SLR data and Guier Range, cm; DORIS, mm/s.

Table 8. SLR/DORIS Orbit Comparisons With GPS Reduced Dynamic Trajectories for TOPEX/Poseidon

	Radial RMS				
Cycle	JGM 2	JGM 3	JGM 3A	JGM 3B	*Z* shift
14	30	21	23	24	–16
15*	31	23	23	27	–26
17*	30	26	25	28	–23
18	27	24	24	24	–23
19*	29	26	28	26	–32
20	30	22	24	24	–30
21	27	21	23	22	–27
32	29	20	23	22	–22
Average	29	23	24	25	-25

All units are millimeters.
*Indicates GPS tracking from this cycle used in gravity solution.

Table 9. Comparison of Station Positions for LAGEOS 1 versus LAGEOS 2

	Geocenter			Relative positioning RMS		
Field	ΔX	ΔY	ΔZ	ΔE	ΔN	ΔU
JGM 2	36 ± 4	–1 ± 4	–1 ± 4	9	15	14
JGM 3	4 ± 4	3 ± 4	6 ± 4	6	8	9

All units are millimeters.

Table 10. Comparison of Station Positions for SPOT 2 versus SLR/VLBI

Field	Relative Positioning RMS ΔE	ΔN	ΔU
JGM 2	53	35	41
JGM 3	33	22	25

All units are millimeters.

Table 11. Geoid Undulation Differences

Fields	Total RMS	Land RMS	Ocean RMS
JGM 2 JGM 3	20	30	14
JGM 2 JGM 3A	17	25	12
JGM 3 JGM 3A	9	13	6

All units are centimeters.

Table 12. Three-Year Mean SST Derived From T/P Compared With Levitus Topography

Geoid	RMS of Difference
OSU91A	18
JGM 2	16
JGM 3	15

All units are centimeters.

Table 13. Geoid Comparison to GPS/Leveling

Field	Europe	Canada	Australia	United States
OSU91A	33	31	35	21
JGM 2	38	28	27	19
JGM 3A	47	29	27	20
JGM 3	47	28	26	19

All units are centimeters.

Table 14. Predicted Radial Orbit Errors Due to Gravity Modeling Errors

Satellite	JGM 1	JGM 2	JGM 3
TOPEX/Poseidon	3.4	2.2	0.9
Geosat	7.4	6.7	5.1
ERS 1/ERS 2	7.8	7.2	3.7

All units are centimeters.