THE OHIO STATE UNIVERSITY

Altimeter and Gravity Data Analysis

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1. Introduction

This report is the final technical report under NASA Grant No. NAG 5-781. This project started on June 30, 1986 in response to a proposal submitted to NASA, Goddard Space Flight Center. This project was terminated on February 29, 1992. This report summarizes the activities that took place under this project. More specific details may be found in the five status reports prepared for the project and several scientific reports that were prepared under grant sponsorship. Such reports will be specified in the Reference section of this report.

2. Research Activities

The studies carried out under this grant fell into two broad areas. The first area was the analysis of surface gravity data with the ultimate goal of providing normal equations that could be used in combination with normal equations from the analysis of satellite orbit perturbations to obtain an optimal estimate of the gravitational potential coefficients of the Earth. The second main research activity was the estimation of gravity anomalies in ocean areas from satellite altimeter data. Such anomalies could enable the improved calibration of potential coefficient models derived solely from the analysis of orbital perturbation information. The studies in these two areas will be discussed in the next sections.

2.1 Surface Gravity Normal Equations Studies

The Earth's gravitational potential can be expressed in terms of potential coefficients C_{nm} and S_{nm}. In the terminology, n is the degree and m is the order of the coefficient. A spherical harmonic expansion to degree N will contain $(N+1)^2$ coefficients. The potential coefficients can be related to gravity anomalies through a solution of the geodetic boundary value problem. Various approximations to this problem had been made prior to our research. However, our initial proposal indicated that a thorough analysis of the problem was needed as higher degree solutions were being developed or contemplated. The needed analysis was carried out by N. Pavlis with the results reported in Pavlis (1988). The Pavlis report developed several correction terms that needed to be applied to the terrestrial gravity data so that the corrected data could be used with a formulation of a simplified relationship between the corrected gravity anomaly and the potential coefficients. One of the key corrections was the removal of the high frequency effects from the surface gravity data. Unless this removal is made, the unadjusted high frequency information would alias the estimation of the potential coefficients being determined up to some lower degree. For example, if a solution to degree 50 was being sought, the contribution from degree 51 to ∞ needed to be estimated. In practice, this estimation was made through the degree 360 expansions that became available in 1986.

Another area that was identified as a problem related to the weighting of the surface gravity data. Such data for these applications is usually given as $1°\times1°$ average gravity anomaly values. Each value has a standard deviation which, if used as given, would lead to inappropriate weights for the anomalies. Procedures were implemented to obtain standard deviations that would yield surface gravity normal equations in a weighting system compatible with satellite derived normal equations as they were understood at Ohio State.

The work of Pavlis developed normal equations to degree 36 based on the June 1986 $1°\times1°$ mean free-air anomaly data set (Despotakis, 1986). These normal equations were supplied to the Goddard Space Flight Center and the University of Texas at Austin for use in their combination model development. The initial computations were carried out at the Pittsburgh Supercomputer Center (PSC).

In 1989 Kim and Rapp (1990) described the updating of the 1986 data file with a significant amount of new gravity data. In anticipation of new gravity material to be obtained in Asia, no new normal equations were formed. In 1990 Yi and Rapp (1991) described a minor updating of the 1989 file with the addition of 944 new or updated gravity anomalies. With this data set it was appropriate to develop a new normal equation data set. In doing this, a decision had to be made on the estimation of the anomalies in the areas where no data was available. We decided to calculate the anomalies from the GEM-T2 potential coefficient model from degree 2 to 9 plus the topographic-isostatic effect from degree 10 to 50 (Pavlis and Rapp, 1990). Such a procedure reduces the correlation between the satellite model and the "terrestrial" anomaly data. The "fill in" anomalies were calculated for 8116 blocks with terrestrial data in 45932 blocks. The high frequency part ($n = 51$ to 360) part of the spectrum was removed from the anomalies prior to the formation of the normal equations using a modified version of the OSU89B geopotential model that accounts for the incorporation of the China data. The surface normal equations were stored at the Ohio Supercomputer Center as file /a/OSU60/gnormal03/OSU90n50v01e. This file was transmitted to the Goddard Space Flight Center on November 9, 1990 and placed on the GSFC CRAY-Y-MS on Barbara Putney's account with the name OSU90n50v01e. On January 15, 1991 the file was transmitted to C.K. Shum at the University of Texas at Austin.

The model used to develop the above normal equations was based on that described in Pavlis (1988) where the observation was considered to be at the surface of the Earth. Testing of this normal equation set at Ohio State was carried out in combination with the GEM-T2 potential coefficients. The solutions made indicated a slight deterioration with respect to the OSU89B model in undulation difference accuracy in mountainous areas. We conjectured on the reason for this deterioration based on GPS/leveling comparisons. The normal equations used in the OSU89 models used a correction term that would downward continue the surface gravity anomaly to the geoid. We tested this procedure with the 1°x1° October 1990 data file by forming the 1°x1° mean value of the g_1 correction term (Rapp and Pavlis, 1990). New normal equations were formed with the anomalies reduced to the geoid. The test combination solutions yielded geoid undulation values more consistent with the GPS/leveling data than the previous normal equation set. Because of this apparent improvement the revised normal equations were transmitted to NASA/Goddard Space Flight Center on February 21, 1991 and to the University of Texas at Austin on February 19, 1991.

These surface gravity normal equations were used in the development of the GEM-T3 potential coefficient model. A detailed description of the procedures and data used in the computation of the degree 50 normal equations was prepared by N.K. Pavlis and appears as Appendix A in the GEM-T3 report (Lerch et al., 1992).

In a letter dated January 4, 1991, Frank Lerch requested a set of surface gravity normal equations that would be complete to degree 70. Such a solution was to be based on the October 1990 1°x1° surface gravity data set and would contain 5037 harmonic coefficients. The development of this solution was started in June 1991 by N.K. Pavlis using the CRAY YMP 8/864. On August 6, 1991 Pavlis transmitted the file to the NASA/Goddard CRAY Y-MP (Putney account). Our file name was /tmp/OSU430/OSU060/OSU90u70v01e. The file stored on the Goddard computer was /tmp/nikos/OSU90n70v01e. On August 12, 1991 a letter was written to B. Putney describing the file with a one page write up describing the degree 70 normal equations sent on August 6, 1991.

The research in the area of rigorous surface gravity normal equations development has been quite useful. A rigorous mathematical model was developed, software developed, and large normal equations sets provided to several users. Improvement in the formation of the normal equations lies primarily with the acquisition of new and improved surface gravity data. This, however, was not a part of this contract. Excluding the collection of gravity material, two items merit additional study. One is in the analysis of methods to reduce the surface gravity anomaly to the geoid. We now use the g_1 term approach with an assumption on the correlation of the free-air anomaly with elevation. A second concern is the weighting procedures used for the surface gravity material. Certain ad hoc procedures are now used for the modification of original standard deviations. More rigorous procedures need to be developed.

A final area that should be studied relates to the improvement in the computational efficiency of forming the normal equations for degree 50, 70 or higher solutions. The formation of the degree 70 solution (5037 unknowns) took approximately 6 hours on the CRAY YMP. Recent studies by Hwang (1991, 1992) have shown how this time could be reduced by a factor of approximately 150 using a Fast Fourier Transform approach to the problem. The method proposed and tested by Hwang needs to be operationally implemented for the surface gravity normal equations. With the substantial reduction in computer time for the normal equations, it would be possible to generate several sets using different weighting and gravity reduction procedures. The development of multiple normal equations is difficult if each set takes approximately 6 hours on the CRAY YMP. Therefore, the implementation of the Hwang procedure would give us much greater flexibility than before.

2.2 Gravity Anomalies Derived from Satellite Altimeter Data

The accuracy calibration of potential coefficient models derived from satellite data has often been done, in part, through the comparison of gravity anomalies implied by the potential coefficients to the anomalies computed from satellite altimeter data. An example of such comparisons is given in Fig. 5.7 of the GEM-T3 report (Lerch et al., 1992). The advantage of such comparisons over the use of surface gravity data is the broader coverage in the ocean areas and the consistency in the estimation of the anomalies. The anomalies that have been used for almost 5 years were derived from Seasat data. The research carried out in this contract, for this item, was related to the estimation of an improved gravity anomaly data set using satellite altimeter data.

The procedures used in this work was least squares collocation. In such a case little additional computer time is needed for the computation of a gridded geoid undulation file and so this was considered part of this effort also.

The data to be used consisted of the Geos-3, Seasat, and Geosat (one year average track) altimeter data plus the ETOPO5U 5'x5' bathymetric data. The Geosat average track was based on the Ohio State 1991 orbits. The prediction process initially involved the computation of a $0.^\circ125 \times 0.^\circ125$ grid of gravity anomalies, geoid undulations, and their standard deviations. This data was then averaged to calculate the 30'x30', 1°x1°, and 5°x5° mean block values. Complete details are described in Bašić and Rapp (1992). The abstract of this report is as follows:

> "Satellite altimeter data (Geos-3, Seasat and Geosat) and bathymetric data have been used to calculate an ocean wide set of free-air gravity anomalies and geoid undulations. An averaged, over one year (1986/87),

Geosat sea surface height track, based on improved, over GEM-T2, orbits was used as the master altimeter frame. The Geosat track was based on the averaging of 22 ERMs and taking into account geoid gradients (Wang and Rapp, 1992). In the computation, the altimeter sea surface heights were reduced to geoid undulations using an Ohio State long wavelength spherical harmonic representation of sea surface topography (dynamic heights). The altimeter data in a region, usually a 8°x8° area, was subjected to a bias alone crossover adjustment with a fitting to the geoid undulation implied by the OSU91 coefficient model. The average Geosat crossover discrepancies after this adjustment were ± 4 cm with poorer agreement with Seasat data (± 10 cm) and Geos-3 data (± 46 cm). The anomalies and undulations were predicted in a 0°.5 cell using a two component remove/restore technique. The first part was the use of the OSU91A potential coefficient model to degree 360 as a reference while the second part involved the computation of the residual terrain model (RTM) effect on both anomalies and geoid undulations using the 5'x5' ETOPO5U data set and a Fourier computation program from Forsberg. The incorporation of the bathymetric data introduces a strength to the solution, especially in areas where the altimeter coverage is sparse.

The initial predictions were subjected to several editing steps. Contour plots of the undulations were examined to identify obviously poor prediction. The predictions were also examined relative to magnitude and predicted standard deviations so that unacceptable predictions could be removed. A second edit was carried out by comparing predicted along track gradients along a Geosat track for comparison with observed values. Such comparison revealed significant discrepancies in some areas. The first edit predictions were then modified to correct most, but not all, of the problems. The final data set contained 2,312,964 geoid undulations and 2,325,669 gravity anomalies, on a 0°.125 grid, with standard deviations for each point. A mean sea surface can be created by applying a sea surface topography correction to the predicted geoid undulation, and taking into account a proper tide reference system.

The predicted point values were used to create the 30'x30', 1°x1°, and 5°x5° mean gravity anomalies and geoid undulations. The 1°x1° anomalies were compared to terrestrial anomaly data with an agreement of ± 9.2 mgals which is 14% less than with the previous (Hwang, 1989) prediction. A detailed description of a number of different data sets developed in this report are described in an appendix.

The number of mean anomaly values computed from the 0°.125 gridded values is as follows: 30'x30' (146,320), 1°x1° (36,955), 5°x5° (1,431). The values quoted represent the case when a minimum acceptable number of point values were available. Fewer mean values are available as the minimum number of acceptable points increases."

On February 26, 1992, magnetic tape OU060 was sent to B. Putney with the 1°x1° and 5°x5° mean gravity anomalies and their standard deviations. These values should be regarded as a significant improvement in our knowledge of the gravity anomaly field in the ocean areas.

The research described in this section was also supported, in part, by a contract from the Jet Propulsion Laboratory for studies supportive of the TOPEX mission. In this case, complimentary results were related to the development of a gridded mean sea surface.

3. Personnel

The principal investigator of the project was Richard H. Rapp, Professor. Mr. N.K. Pavlis carried out studies under this project as a Graduate Research Associate. Dr. T. Bašić carried out studies as a Research Associate. Ms. Melanie Hennell was a Student Intern Assistant under this project.

4. References

Bašić, T. and R.H. Rapp, Ocean wide Prediction of Gravity Anomalies and Sea Surface Heights Using Geos-3, Seasat and Geosat Altimeter Data and ETOPO5U Bathymetric Data, Report No. 416, Dept. of Geodetic Science and Surveying, The Ohio State University, Columbus, February 1992.

Despotakis, V., The Development of the June 1986 1°x1° and the August 30'x30' Terrestrial Mean Free-Air Anomaly Data, Internal Report, Dept. of Geodetic Science and Surveying, The Ohio State University, Columbus, September 1986.

Hwang, C., Orthogonal Functions Over the Oceans and Applications to the Determination of Orbit Error, Geoid and Sea Surface Topography from Satellite Altimetry, Report No. 414, Dept. of Geodetic Science and Surveying, The Ohio State University, Columbus, December, 1991.

Hwang, C., Fast Algorithm for the Formation of Normal Equations in a Least-Squares Spherical Harmonic Analysis by FFT, submitted to manuscripta geodaetica, April 1992.

Kim, Y-H, and R.H. Rapp, The Development of the July 1989 1°x1° and 30'x30' Terrestrial Mean Free Air Anomaly Data Bases, Report No. 403, Dept. of Geodetic Science and Surveying, The Ohio State University, Columbus, January 1990.

Lerch, F.J. et al., Geopotential Models of the Earth From Satellite Tracking, Altimeter and Surface Gravity Observations: GEM-T3 and GEM-T3S, NASA Technical Memorandum 104555, Goddard Space Flight Center, Greenbelt, MD, January 1992.

Pavlis, N.K., Modeling and Estimations of a Low Degree Geopotential Model from Terrestrial Gravity Data, Report No. 386, Dept. of Geodetic Science and Surveying, The Ohio State University, Columbus, 1988.

Rapp, R.H. and N.K. Pavlis, The Development and Analysis of Geopotential Coefficient Models to Spherical Harmonic Degree 360, J. Geophys. Res., 95, B13, 21,885 - 21,912, 1990.