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FINAL REPORT

NAGW-792

ANALYSIS OF HARMONIC SPLINE GRAVITY MODELS FOR VENUS AND MARS

May 15, 1985 through December 31, 1986

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(NASA-CR-180147) ANALYSIS OF HARMONIC SPLINE GRAVITY MODELS FOR VENUS AND MARS Final Report, 15 May 1985 - 31 Dec. 1986 (Woods Hole Oceanographic Institution) 12 p N87-17648

CSCL 03B G3/91 Unclas 43736

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INTRODUCTION

Gravity anomalies are important for exploring the interior structure and mass distribution within a planet, and the mechanical properties of its outer crust in supporting observed topography. The patterns of gravity anomalies were initially analyzed by using sets of spherical harmonic coefficients calculated from orbit perturbation data. Examples for Venus include Ananda et al. (1980); Bills (1982); Williams et al. (1983) and Mottinger et al. (1983). These solutions include information on the long wavelength portion of the gravity spectrum only.

More detailed information on planetary gravity fields is contained in the Doppler residual data from radio tracking of spacecraft. The acceleration (gravity) anomaly estimates determined from Doppler residuals are for components of the gravity field directed along the spacecraft-earth line, providing Line-of-sight (LOS) acceleration estimates. A method for estimating radial gravity anomalies from LOS acceleration data, their interpolation, and use of iteration for improved radial estimates was presented by Bowin (1983). A preliminary radial gravity anomaly map of Venus at spacecraft altitude was presented, and mass anomalies associated with topographic features were shown to be the most significant contributors to the gravity field of Venus. That study was supported by NASA Grant NAG 2-91.

In search of an appropriate means to invert the first radial gravity estimate to geoid anomalies for the proposed iteration method (Bowin, 1983), we encountered the technique of harmonic splines which allows direct estimation of the complete gravity field (geoid, gravity, and gravity gradients) everywhere over the planet's surface from the LOS vector data. A paper by Bowin, Abers, and Shure (1985) presented the harmonic spline results for Venus as a series of maps at spacecraft and constant altitudes. Global (except for polar regions) and local relations of gravity to topography were described. That study was supported by NASA Contract NASW-3770.

HISTORY OF EFFORT

At the end of the contract period for NASA Contract NASW-3770 we realized that corrections were possible for the errors in the zero reference level in the LOS values produced by the least squares filtering procedure. We submitted (September, 1984) a proposal to NASA to use the harmonic spline gravity models as input to the JPL ORBSIM program, to compute the expected distorted LOS vectors that would result if the harmonic spline model were the actual field. The ORBSIM program allows computed values along an orbit path to be integrated along that orbit path to produce distortion of the model's gravity field like that distorting the LOS vector values. This procedure is described by

Phillips et al. (1978) for previous analyses using point and disk mass models. The difference between the simulated LOS vectors and the observed LOS vectors would then be used to calculate modified LOS vectors. A harmonic spline model would then be computed again from the modified LOS vectors. The process is then repeated: use ORBSIM to compute distorted LOS vectors from the new harmonic spline and compare with the original LOS vectors. Using the difference, modify the observed LOS vectors and recompute another harmonic spline model from the modified LOS values. The original LOS vectors, of course, are retained unblemished for comparison with ORBSIM results of each new model. This would be iterated until satisfactory convergence is achieved; the resulting harmonic spline model should then represent a close approximation to the actual anomalous gravity field of the planet, and its distorted product should match the LOS vectors. A variant of this procedure, which presumably may permit a faster convergence, is to compute harmonic spline solutions for the difference vectors (between simulated and observed LOS vectors), and to use those models to estimate the distortion. New calculated distorted LOS vectors would then be computed from the combination of the distortion harmonic spline model and the original harmonic spline model. This process would then be iterated to satisfactory convergence.

That proposal, however, was declined. The proposal was resubmitted for the March 1985 Panel Review. Following discussions in January and February 1985 with the Discipline Scientist and a member of the former Panel it was implied that the prior panel's main criticism was that the ORBSIM procedure might not converge because of errors in dynamical parameters used in the original processing. I contended, however, that these errors would apparently mostly affect the long wavelength values. We discussed this possibility, and it seemed to me that, if this proves to be a real problem, spherical harmonic model solutions could help damp these errors and their effects. The panel member agreed that the panel's "axe" had swung too far in this case. He was also surprised to learn that this new methodology was only conceived about two weeks before submitting the proposal to meet the deadline. Therefore he could then understand why demonstration test cases were not presented in the original proposal, the lack of which apparently helped bring the panel to its position. Also, at that time, our NASA planetary funds were exhausted: payment of the page charges for publication of our paper (Bowin et al., 1985) on the gravity field of Venus published in the JGR Proceedings of the Fifteenth Lunar and Planetary Science Conference had to be covered by another unrelated grant. Because a three-year proposal without proof of the method might again be hard for a panel to concur with, I indicated my willingness to accept an initial amount that would allow me to test and demonstrate the method before NASA need commit to a three-year project.

On 1 July 1985, I received notification that within 60 days a negotiator would negotiate a contract at the $37,696 level for the period May 15, 1985, through November 30, 1985. These funds were awarded in late July 1985, and the investigation began. Appendix A reproduces an abstract prepared in November 1985 which further discusses the 'zero reference level' error and contains two illustrations to help the reader better understand the problem.

A status report of our efforts to October 21, 1985 is best summarized in the progress report reproduced on the following three pages. It outlines our reasons for obtaining a new minicomputer system to meet the computational needs of this and other investigations.

PROGRESS REPORT
NASA Research Grant No. NAGW-792 Entitled

ANALYSIS OF HARMONIC SPLINE GRAVITY MODELS FOR VENUS AND MARS

Carl Bowin, Principal Investigator

An initial amount of $37,969 was awarded in late July 1985 to aid a demonstration test of our proposed new methodology utilizing harmonic splines for determining the true gravity field from Line-Of-Sight (LOS) acceleration data from planetary spacecraft missions. As is well known, the LOS data incorporate errors in the zero reference level that appear to be inherent in the processing procedure used to obtain the LOS vectors. Our proposed method offers a solution to this problem.

Considerable progress has been made since the start of this grant, primarily in the conversion of programs and requisite data libraries from the Institution's VAX 11/780 to a Ridge computer system in our own laboratory. We obtained and installed the Ridge to overcome the computational dilemma we had experienced
for the previous two years (i.e., the Institution's VAX charges were rising at about 10% per year, the funding for our budgets had remained nearly constant, but our computing needs had risen exponentially). The high costs of the VAX were particularly traumatic one month when I learned that it cost $2,000 just to be logged onto the VAX 8 hours a day, 5 days a week, for one month. Because of these problems, I had been exploring the new generation of 32-bit super microcomputers and minicomputers. From that investigation we found that our needs, the modest equipment budget I had been able to accumulate from industry sources over the prior two years, and the design specifications for the Ridge computer were very compatible. Thus, in January 1985, we acquired a Ridge 32C personal mainframe computer with Reduced Instruction Set Computer (RISC) architecture. This computer provides us with a powerful computing resource as required for the proposed investigation.

Our conversion from VAX/VMS to the UNIX operating system, and from VAX-11 extended Fortran to ANSI Standard Fortran 77 has been a learning exercise but tractable. It has taken time and a willingness to work around problems, such as a lack of byte variables in standard Fortran 77. And then there are the rewards, such as finding that our optimum estimation runs, which took about 6 seconds per grid point on the VAX 11/780, now take about 4.0 seconds or less on the Ridge 32C, and of course, the delight in now being able to undertake 50 to 100 hour 'experimental' runs at no additional cost. However, we have needed to convert several hundred programs and subroutines which is not only time consuming, but salary consuming. Many of these routines are for general utilities such as graph, profile, and map plotting functions, and database manipulation routines needed by this investigation. Thus, this progress report is also a request for supplemental funding to aid the completion of our demonstration test of the new harmonic spline methodology. The VAX version of ORBSIM and LUNRES PROGRAMS provided by R. Wimberly of JPL remain on the Institutiton's VAX 11/780, however, as described later, ORBSIM and LUNRES are now known not to be appropriate.

The Ridge computer system came without output display devices, so we have had to add them in order to have analysis capabilities. One particularly useful display device is a 36" wide digital plotter which we are leasing. This plotting capability is important for testing and evaluating the results of the proposed harmonic spline modeling methodology for the correction of LOS vector data.

We presently have created on the Ridge system a library of Pioneer Venus LOS vectors now organized by revolution number (rev) and by time within each rev. This library was made by resorting the LOS library organized by latitude and longitude cells used by our prior harmonic spline analysis (Bowin, Abers, and Shure, Gravity Field of Venus at Constant Altitude and Comparison with Earth, JGR, vol. 90, Supplement, p. C757-C770, 1985). This procedure took advantage of the editing already accomplished for that study. We have also created a library of basis points for the intended rev-by-rev processing. The basis points will be the nodes used in the harmonic spline solutions for each rev. Another file identifies the sets of revs to be used for the harmonic spline processing. We have started the conversion of harmonic spline coding from the VAX-11 extended Fortran to ANSI Standard Fortran 77. The VAX version utilized keyed-access data storage, which is not available in standard Fortran.

We also have examined the functionality of the programs ORBSIM and LUNRES and find that neither is appropriate as they now stand for our proposed methodology. Basically, ORBSIM calculates LOS accelerations along given trajectories over an input configuration of point or disk masses for comparison with the observed LOS accelerations. LUNRES calculates Doppler residuals from the raw observed Doppler signal, and then LOS accelerations by diferentiating a smoothed cubic spline fit to the Doppler residuals along individual revs. LUNRES is not prepared to reproccess a product of LUNRES, ie. LOS accelerations, nor even their integral as Doppler residuals. Thus, we find we must now prepare two programs. One program will calculate Doppler residuals by integrating a Rev time series of LOS accelerations, for the line-of-sight vector, calculated from harmonic spline coefficients. The other program will fit a smoothed cubic spline to those Doppler residuals, and calculate LOS accelerations from them as originally done by LUNRES. We plan to adopt the appropriate subroutines and functions from LUNRES for the second program. We also find that the Pioneer Venus LOS data we received from S. Ritke of JPL in 1981 has only time tags to minute resolution. Hence, time in seconds must be added to our PVO data in order to accomplish the integration to Doppler residuals. For the demonstration test we expect to hand edit them into the data for the few test revs over Beta Regio, and these values will be read from the microfilm that accompanied the LOS data tape received from JPL. In a recent telcon, Bill Sjogren of JPL has offered to provide a new magnetic tape with LOS time tags to second resolution to avoid transcription errors and the enormous effort such hand editing would take. This will surely be warranted for further processing following the demonstration test success, but to speed our testing we may edit in labels for time tags to seconds by referencing the microfilm information.

The harmonic spline model objectively provides the smoothest model that matches input vector LOS data. From these model coefficients we can calculate vector data at any selected location in space. It serves a similar role to the point and disk masses used in ORBSIM analyses, but is not dependent upon a person for selection of the location and magnitude of point and disk masses, a very significant advantage. Our plan therefore is to use harmonic spline model coefficients as a memory. In the first iteration, that memory matches the LOS accelerations along the orbit trajectory, but upon a lower trajectory (ie., downward continuation, errors in the LOS acceleration values become strikingly evident. For example see Figure 6 in our paper cited above. Thus the calculated LOS accelerations along such a lower and constant altitude can be integrated to Doppler residuals, and those residuals least-squares fit by a smooth cubic spline, which when differentiated will yield calculated LOS accelerations with a new zero mean refernce level. These new LOS accelerations will be used to determine another harmonic spline model which can then be used to calculate it's LOS accelerations along the spacecraft orbit. Those accelerations would be integrated to Doppler residuals which would again be smooth spline fit and differentiated to calculated LOS accelerations. This process can be repeated as desired. Alternately, LOS differences can be used in the computation of harmonic spline model coefficients and those coefficients added or subtracted to the original set to achieve faster convergence. The object being to obtain a harmonic spline model whose LOS accelerations along the rev trajectory when integrated to Doppler residuals and then cubic spline fit and differentiated and zero meaned by least squares match the original LUNRES determined LOS accelerations. At that stage the harmonic spline model provides an estimate of the true planetary gravity field beneath that rev path to the data resolution. Such rev harmonic spline models then can be used to construct grids of gravity values at constant altitudes over the planet surface. Such grids are vital for admittance studies of planetary structures by gravity/ topography transfer function methods, and offer the strongest means by which to examine the internal structure of another planet.

HISTORY OF EFFORT CONTINUED

The preceding PROGRESS REPORT was also a SUPPLEMENTAL FUNDING REQUEST UNDER NASA Grant Award No. NAGW-792 (for $27,275) for one month's funding support. The Lunar and Planetary Review Panel met in early November 1985 and recommended that no additional funding should be considered until the pilot project is completed. My letter to the Discipline Scientist of November 22, 1985 indicated that I could understand the reasons for such a decision, and I could also understand (and feel) the reasons for our needing funding. To have adequate computing resources for the Venus and Mars gravity task, and other projects, I had to obtain our own high-performance computing resource. The conversion of software to it has taken more time that originally thought (a common ailment). We also had to develop our own routines, for example for matrix inversion, which formerly were provided as commercial IMSL routines on the Institution's VAX. IMSL was willing to allow us to port the matrix inversion routine to the Ridge computer but at a cost of about $3,000. Our efforts were also required to add time in seconds to the LOS vector data for the PV data from JPL so that it can be integrated back to Doppler data. Thus, that letter requested a no-cost extension to 30 June 1986 for our grant which was to have terminated November 30, 1985.

Following conversion of our PV LOS library to rev-by-rev with time tags, and conversion of our harmonic spline programs from the VAX 11/780 to the Ridge 32C computer and its modification for the processing of individual and adjacent revs, development of a node database for such processing, testing began. Unfortunately, we could not get the ensuing matrix to invert without error. On January 7, 1986 I requested a no-cost extension to 31 December 1986 for Research Grant No. NAGW-792, for which approximately $6,000 remained.

We solved a problem with our matrix inversion routine that improved inversion of the data matrices used in our Optimum Estimation program for global earth studies. We hopefully thought that change would also benefit the harmonic spline processing of PV revs, but it did not. None of our experiments through 31 December 1986 obtained a successful matrix inversion for a single rev supplemented by data for the two adjacent revs. Without this important inversion, testing could not proceed, and our funds were exhausted.

We tried to the best of our ability and resources to prove our new suggested methodology for determining the true detailed gravity field of Venus and Mars from LOS data. I have additional ideas in mind that may help to resolve this dilemma and thereby obtain an inversion for the needed harmonic spline model. I will try them if we have the opportunity to self-fund the effort in the future. The recent increased difficulty in obtaining federal research support, the soft-money status of research at W.H.O.I., and the lack of encouragement from NASA, however, makes this prospect dim.

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ANALYSIS OF HARMONIC SPLINE GRAVITY MODELS FOR VENUS AND MARS

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The use of harmonic spline methodology to resolve planetary gravity fields from the randomly oriented residual line-of-sight (LOS) vectors that result from processing Doppler tracking data was first demonstrated in our work published earlier this year (Bowin et al., 1985). The LOS vectors are components of the planetary gravity field along that direction that happened to point toward the earth at the time of measurement. The LOS acceleration vectors are computed by differentiating the residual Doppler signal that remains after the Doppler contribution from the central body attraction, along the computed orbit trajectory is subtracted from the observed Doppler data. Least-squares filtering procedures, applied to the Doppler data to obtain the LOS results reduce the true absolute amplitudes of the acceleration vectors (Gottlieb, 1970), perhaps by as much as 40 percent. Apparently that reduction of a maximum of a positive anomaly is accompanied by the pumping of energy into lows that flank a gravity high.

I view the reduction of the positive amplitude as most likely, indicating an uncertain location of the zero reference level. For example, imagine a volcano or ridge upon a planet with a very strong crust. In this case the topographic load would be completely uncompensated, and the free-air gravity anomalies across the structure would be entirely positive, as shown by the solid curve, in reference to the dotted zero line in Figure 1. An integral of the gravity acceleration curve would yield anomalous Doppler frequency variations. Upon a least-squares fitting of a smooth curve through such Doppler data, and its subsequent differentiation, an anomalous gravity curve shown by deviations from the dashed line (which represents an inferred erroneous zero reference level) might result. The resulting gravity profile might then have a reduced positive anomaly with flanking lows. In such a situation, the integral of the positive and negative gravity anomalies along the orbit path would tend to approach closer to zero than in the true condition.

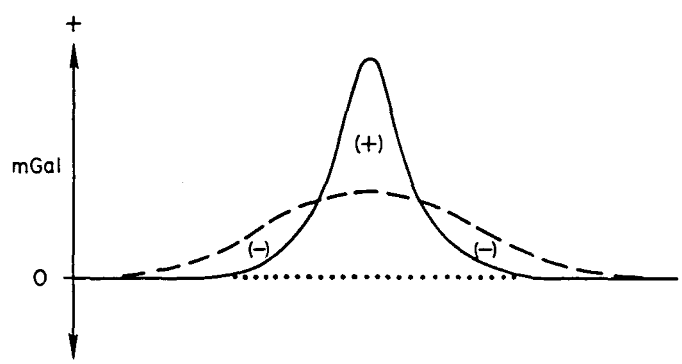

Figure 1. Hypothetical gravity anomaly. See text for discussion.

The above hypothesis is supported by the occurrence of gravity lows flanking positive gravity anomalies associated with topographic highs on Venus and Mars. Where the topographic high is a nearly circular feature, the lows symetrically straddle the positive along the orbit tracks. This is true even though the spacecraft altitude at the two symmetric lows may be quite different. See Figure 2 for the example of this relationship in the orbit passing above the Crest of Beta Regio on Venus. This observation is seen also to be true in maps of LOS accelerations at spacecraft altitude for Venus published by Sjogren et al. (1980,1981), Bowin (1983) and Bowin et al. (1985) for example. In fact it was these relations that led to the above hypothesis.

Tracking data and spacecraft ephermeris have been used to compute the coefficients for spherical harmonic expansions of the potential field of planets. For example, see Bills (1982) and Mottinger et al. (1983) for Venus. These global solutions only have low resolution, however. Point masses and disk models over a grid have been used to compute Doppler residuals along orbit trajectories by the program ORBSIM and results compared with the observed LOS residual accelerations. This process has allowed the construction of radial gravity anomaly maps from the point mass or disk models. Depending on where or how the zero reference errors arise during processing, they may remain in the point and disk mass models since they match to the LOS data.

That the lows flanking the gravity highs are in large part artifacts from the LOS processing is clearly documented by the harmonic spline results (Bowin et al., 1985). The power of the harmonic spline methodology is that it objectively solves for the smoothest field that will match the observed data, and that the data may be of random components of the field, and at random altitudes. Then from the harmonic spline coefficients at the basis points used for the computation, any component of the gravity

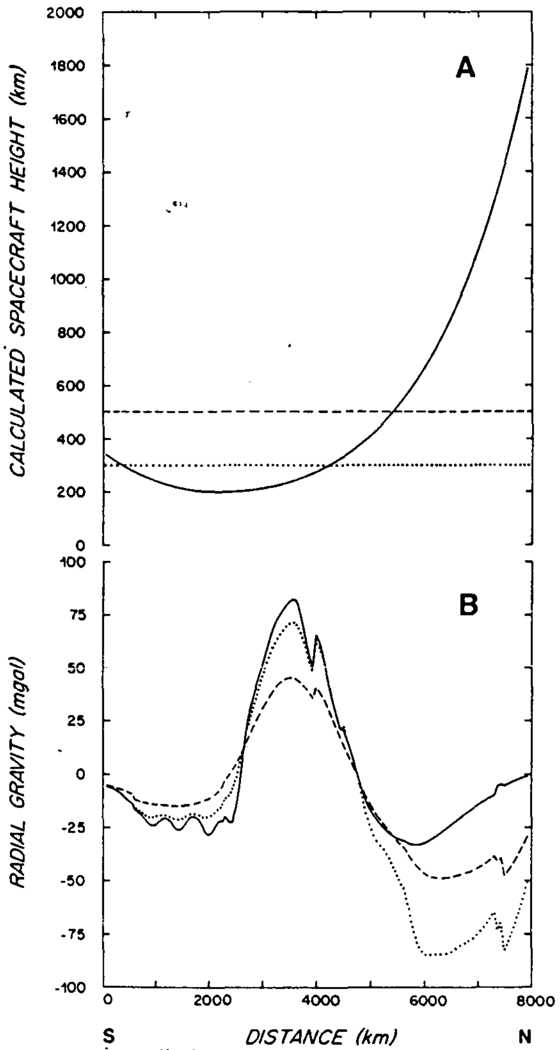

Fig. 6. Comparison of profiles of radial gravity anomaly at spacecraft, 500 km, & 300km altitudes across Beta Regio in a direction parallel to the orbit paths. The line types in the height plot (A) provide identifications for the lines describing the gravity profiles (B) (Bowin et al, 1985, Fig. 6).

field at any location and altitude may be determined. In addition to the gravity profile at spacecraft altitude in Fig. 2, we show the curves at constant altitudes of 300 and 500 km. Note how the low north of Beta Regio becomes greatly exaggerated upon increasing downward continuation. In the 300 km map (Bowin et al., 1985, Fig. 5) that low is seen to greatly exceed the absolute magnitude of all other anomalies on Venus, and thus it is obviously in error. Because downward continuation is a rigorous procedure, that error signifies that its value at spacecraft altitude is too negative. Note, also, that the low south of Beta Regio is upward continued to 300 and 500 km and thus is attenuated at those constant altitudes. Through the use of harmonic spline models, in an iterative manner, we are now attempting a procedure by which a harmonic spline model can be obtained that when appropriately filtered will match the observed LOS data along the spacecraft trajectories, and when unfiltered, will represent the true anomalous gravity field of the planet. At that stage, we can construct grids of gravity values at constant altitudes over the planet surface. Such grids are vital for admittance studies of planetary structures by gravity/topography transfer function methods, and offer the strongest means by which to examine the internal structure of another planet.

For this computer intensive study, as well as for other computing needs, we have acquired a Ridge personal mainframe computer with RISC architecture. This system provides us with an essentially unlimited computer resource. The 'noise' in the harmonic spline results of Fig. 2 along the spacecraft trajectory result from differences in solutions at boundaries of latitude and longitude cells previously used to divide the large LOS data set into manageable sizes. For the present study we have created on the Ridge system a library of Pioneer Venus LOS vectors organized by revolution number (rev) and by time within each rev. Harmonic spline models will be computed for entire revs, thus eliminating the noise described above.

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