D-PAF Global Earth Gravity Models Based on ERS

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Abstract

In support of the ERS missions GFZ/D-PAF operationally is computing global satellite-only Earth gravity models, based on ERS tracking data (laser, altimetry, PRARE ranges and doppler) and tracking data from a large number of other satellites. Such models are the foundation for the ESA standard products, Earth gravity model, preliminary and precise orbits and implicitly also for the quick-look and precise altimeter products. Further on, by combination of these satellite-only models with terrestrial gravity information and geoid heights, derived from gravimetry and altimetry, so-called combined high resolution gravity models are computed. Such models are the basis for the ocean geoid ERS standard product with a global resolution of 50 km and below.
The paper summarizes the approaches, the most recent solutions and the quality of the satellite-only and the combined high resolution gravity models. Quality analysis of the models especially is focused on ERS applications, like orbit determination, altimeter data processing and others. The precise knowledge of the global Earth gravity field is one of the key parameters for remote sensing of the solid and liquid (inclusive ice) Earth. Therefore, in the near future big efforts will be started to further improve the accuracy of the gravity models, by a complete reprocessing of the historic and actual data, and by launching specific gravity field missions, like Champ.

Keywords: Gravity Field, Geoid, ERS, Orbit Determination, D-PAF

Content:

1. Introduction

Within the ERS project , GFZ/D-PAF is responsible for the operational orbit and high level geophysical altimeter products generation (D-PAF ERS products). Base of all of these products and of products from other PAF's is the ERS satellite-only gravity field model (EGM product .) This model has been updated from time to time, and consequently many of the related products have been reprocessed too. Each new gravity model resulted in a major quality improvement for all reprocessed products. This high quality enables new applications for ERS data, like sea level studies and SAR interferometry.

Laser tracking data of the passive GFZ-1 satellite, launched from the Mir station in April 1995, provides new information for gravity field modeling. Due to its initial orbital height of 390 km and the slow decay, the satellite moves through various resonance regimes of the Earth's gravity potential, which have not been measured from space before (König, et al, 1996). With the availability of the PRARE tracking system on ERS-2, additional globaly distributed microwave tracking data (range and doppler) are available for a further gravity field improvement. First results are promising and a further improvement of the gravity field especially for ERS-2 orbit determination is expected.

By inclusion of terrestrial gravity data and gravity field related information from the ERS altimeters (geoid heights, altimetric gravity anomalies), so-called combined gravity field models are generated. These models, which are complete to degree and order 360 of a spherical harmonic series, what corresponds to about 50 km spatial resolution at the equator, are the base of the ocean geoid ERS standard product (OGE product). The combination is performed by merging the satellite-only normal equation system with that of terrestrial and altimetric gravity anomalies or geoid heights. The solution of the complete series is done in one step by taking advantage of the structure of the combined normal equation system.

Figure 1 shows the different types of GFZ/D-PAF gravity fields and their relations. The complete gravity field work is an integrated and ongoing work, to which many people are contributing. In preparation of the Champ mission currently the gravity field work is reinforced, what means that new models are implemented and that all historic observations are reprocessed. It is expected that before launch of the Champ satellite in 1999, the quality of the gravity field is increased significantly with respect to the best current model. Major improvements are expected from the Champ mission, when a first set of observations will be available.

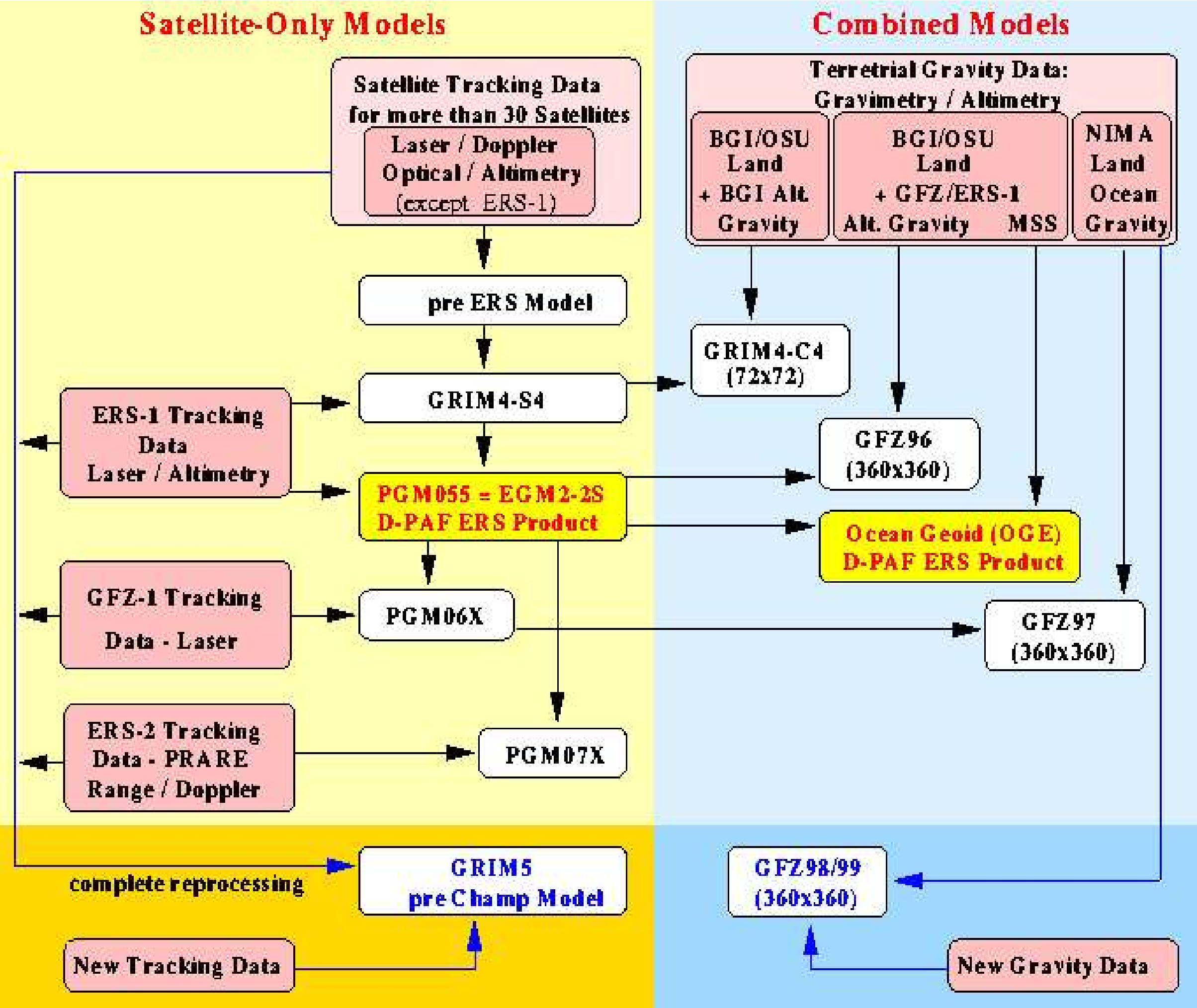


Figure 1:*Overview of GFZ/D-PAF Activities in Gravity Field Modeling*

2. Satellite-only Gravity Models

Starting from the pre-ERS satellite-only gravity fields GRIM4-S2 and -S3 (Schwintzer et al, 1993), which is computed from optical, laser and microwave tracking data of 30 satellites, ERS-1 laser tracking data and altimeter observations were used to improve the gravity field step by step for the operational product generation. By using the most recent model for the operational orbit determination, big quality improvements could be achieved during the last years for all the related standard products. Table 1 shortly summarizes the characteristics of the three satellite-only models used for ERS-1/2 product generation and shows the related product revisions for some D-PAF and F-PAF standard products. For indicating the overall quality improvement, the gravity field induced radial orbit error is given as additional parameter, which influences the quality of all ERS altimeter products.

Gravity Field Model				Related Product Revision Number					
Model Name	Degree	Base	Radial Accuracy [cm]	EGM	PRL	PRC	OPR	SSH OGE TOP	QLOPR
PGM009	63	GRIM4-S2	40-50	EGM-1	0	0	V1.X-V2.X	0	n/a
PGM035	66	GRIM4-S3	12-14	EGM-2-1S	1	1	V3.X	1	1-2
PGM055	69	GRIM4-S4	7-8	EGM-2-2S	2	2	V5.X-V6.X	2-3	3-6

PGM055 Model Description and Quality Assessment

The PGM055 model is given by a solution in spherical harmonics up to degree and order 60 and some resonant terms with maximal degree 69. It corresponds to a spatial resolution of 330 km at the Earth's surface. This dimension was chosen according to maximal orbit perturbations following from the orbit characteristics of the satellites which have contributions to the data processing. ERS-1 is the only satellite whose information was used to determine the resonant terms of degree over 60. The gravitational harmonic coefficients have been estimated by a rigorous least squares adjustment simultaneously with parameters of ocean tidal terms, tracking station coordinates and rates of motion. Therefore the gravity model is associated with a consistent ocean tide model and a terrestrial reference frame spanned by over 300 optical, laser and doppler tracking stations.

Gravity field recovery from satellite tracking data is based on satellite orbit perturbation methods. Observations given by the tracking data and crossovers are used to restitute a satellite orbit. For any observation partial derivatives are computed with respect to initial orbital elements, which are the parameters of the gravity model and ocean tides, station coordinates and rates of motion, drag and radiation pressure and empirical nuisance parameters. For ERS-1 data processing an empirical acceleration once per revolution was taken into account. To minimize the residuals between observed and computed quantities the system of normal equations is generated for any restituted orbit. The normal equation systems are accumulated according to a relative weighting scheme, which depends on the satellite and the data type. Constraints and stabilizing equations derived from Kaula's rule complete the accumulated system. The resulting system is solved for the parameters by inversion including the computation of the variance covariance matrix and the variance of the unit of weights according to the Gauss-Markoff model.

For the PGM055 model, data of 34 satellites have been processed. The orbit altitudes of the satellites used, range from about 800 km to 20000 km. Among the 34 satellites 15 have been tracked by cameras, 17 by laser and 9 by microwave instrumentation (Doppler, GPS), some of these by mixed optical/laser or laser/microwave systems at the same time. Some remarks to the ERS-1 tracking data, used for the GRIM4-S4 and PGM055 models are of special interest. One 35-day cycle of 1993 with ERS-1 laser tracking and crossover data and additionally with TOPEX laser tracking data, single TOPEX and double ERS-1/TOPEX crossovers were processed for both models. Two more 35-day cycles of 1993 and the first 168-day cycle of 1994 with ERS-1 laser tracking and crossover data were processed for the PGM055. All together a total sum of more than 2.7 million satellite tracking observations were processed for the model. The total number of observations is composed of 3% optical data, which were acquired in the 60's from 15 satellites, of 25% laser tracking data to 21 satellites starting in the 70's, of 70% microwave tracking data, mainly from Topex, Geosat and Nova-3, and finally only of 2% altimeter crossover observations.

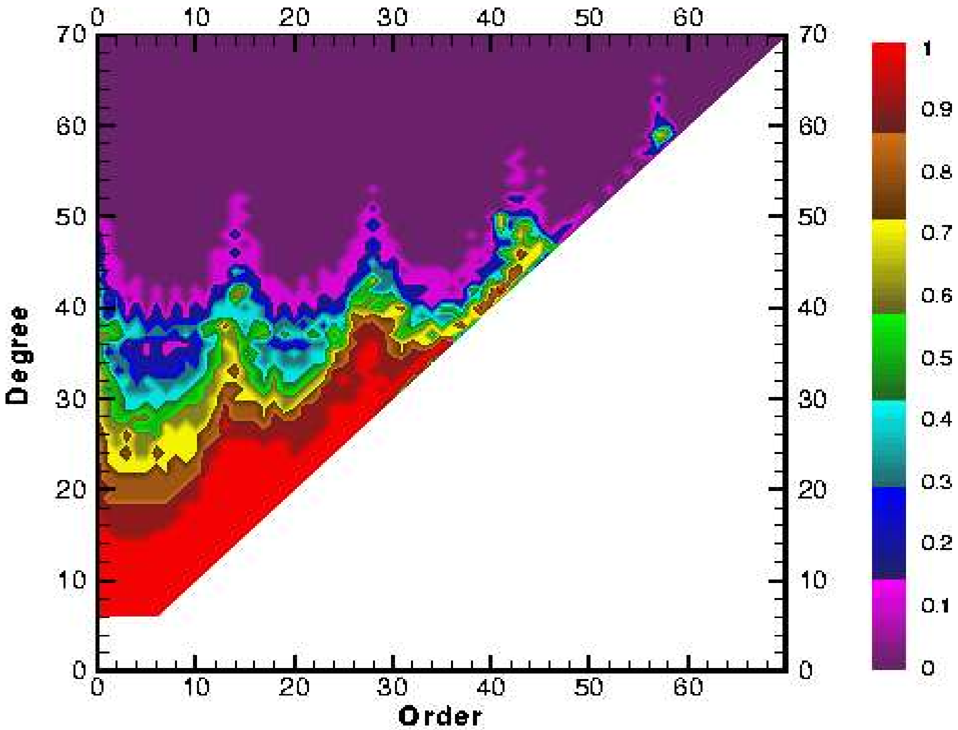


Figure 2: PGM055 Partial Redundancies

Figure 2 shows the partial redundancies, computed for each stochastic a priori observation (Kaula pseudo observation) for the related coefficients (C,S) of the spherical harmonic series. Partial redundancies are varying between 0 and 1, where 1 means that the coefficient of this degree and order is determined exclusively from tracking data, while 0 means, that the coefficient is determined only from the stochastic a priori information.The statistical method for computing the partial redundancies is described in detail in Schwintzer (1990). For coefficients up to degree and order 5 no a priori information was included, therefore the partial redundancies are not defined and meaningless. It can be deduced from figure 2 that there is a distinct and generally with higher degree descending sensitivity of the totality of the used tracking data to the resonant and weak resonant geopotential coefficients. The resonant zonals and the resonant orders about 14 and 28 can be stated up to degree 45, the resonant orders about 42 and 57 up to degree 52 and 64 respectively. ERS-1 contributes considerably to these resonant orders.

Of great importance for the quality assessment of a gravity field model is the complete calibrated variance - covariance matrix. To get realistic quality parameters, a single calibration factor of 5.5 has been estimated for the PGM055 model, by comparisons to external data sets. Figure 3a and 3b show the predicted geographically correlated (mean) and anti-correlated (variable) radial orbit errors for ERS-1/2 orbits, computed by error propagation of the full variance - covariance matrix of the PGM055 solution. While the variable or anti-correlated part, to a large extent could be estimated from single mission altimeter cross-over observations, the mean or correlated part could not be determined from this data type. It would be possible to determine it from double mission cross-overs, if perfect knowledge of the orbit and the altimeter ranges can be assumed. But there are problems. Take for example Topex data, the orbits also contain a geographical correlated orbit error, which is indeed due to its orbit characteristics approximately by a factor of 3 smaller than for ERS. Further the altimeter ranges are not perfect due to some calibration (e.g. oscillator drift) and other problems. This situation is insufficient for a precise determination of the geographically correlated error. Therefore the error propagation by the calibrated variance-covariance matrix is a welcome instrument to determine the geographically correlated orbit error. The sum of both radial orbit error components reflects the part of the orbital signal, which may go into the recovered sea surface heights from ERS-1/2 altimetric measurements. This error propagates completely into the estimation of the permanent part of the sea surface topography, which represents the deviation of the mean sea surface from the geoid and consequently is the fundamental parameter for determination of the water mass transport across the oceans.

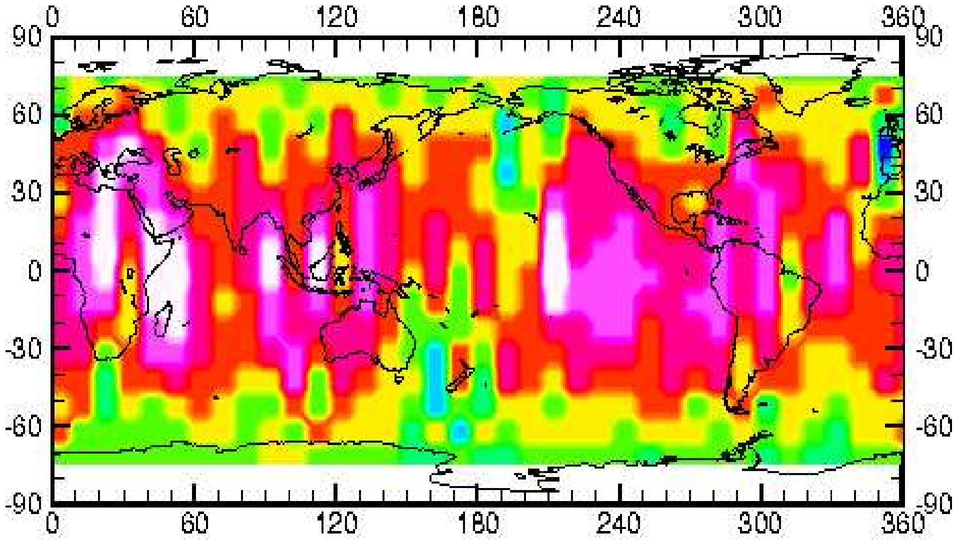
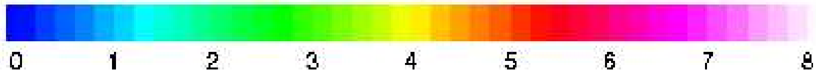


Figure 3a: PGM055: ERS-1/2 Mean Radial Orbit Error [cm]



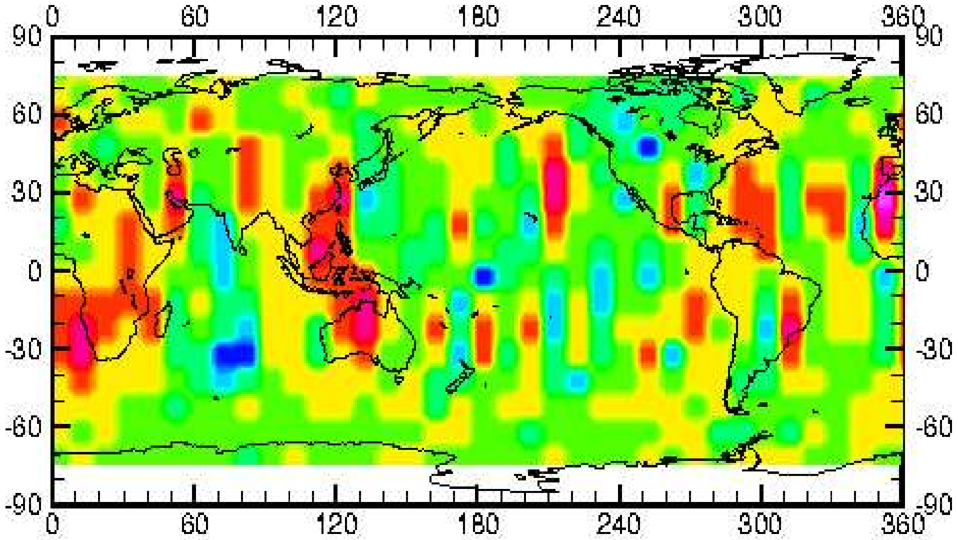


Figure 3b: PGM055: ERS-1/2 Variable Radial Orbit Error [cm]

The global geoid error for different models with respect to the degree of the spherical harmonic series is shown in figure 4. When interpreting this figure one has to have in mind, that for each of these models an individual calibration factor for the variance-covariances was determined by the model originator. Therefore it is difficult to compare different models. Here, two different types of models are shown. While satellite-only solutions like PGM055 and EGM96S (Lemoine, 1996) are suffering from the limited availability of spacecrafts, designed for gravity field determination, and are showing a strong increasing error when increasing the degree of the series, combined models like EGM96 (Lemoine, 1996) and TEG3 (University of Texas, Personal communication) are providing much more optimistic error estimates. But, for combined models terrestrial data (gravimetry, altimetry) were used, what could cause aliasing effects, when using such models for oceanographic purposes. Further on, due to unknown datums of terrestrial data, the very long wavelengths could be strongly influenced. To overcome such problems, only dedicated gravity field missions like GFZ-1, Champ and others can help. The long wavelenghts (up to degree and order 70 or even more) should be completely determined from satellite observations, which are the only data type providing global and consistent distributed data sets.

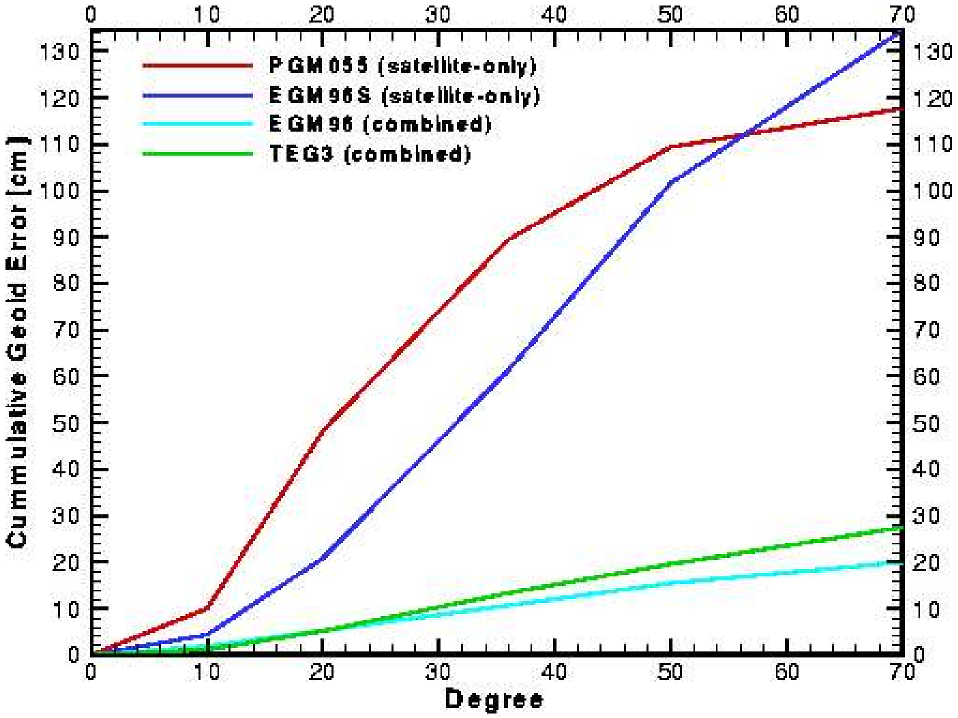


Figure 4: Cummulative Geoid Error wrt. Degree

For testing the long wavelenghts of a gravity field, usually orbital fits for different satellites provide the most valuable information. Because PGM055 currently is used as base for many ERS standard products, orbital tests are mainly focused on ERS-1/2. Orbital fits for the ERS satellites are a good parameter for the overall quality assessment, because, due to their relatively low orbit, they are much more sensitive to gravity than for example the Topex satellite. In summary using PGM055 for orbit determination, a mean fit of laser observations of about 7 cm and a crossover fit of about 8 cm for each arc is reached. Figure 5 compiles monthly crossover statistics (all possible crossovers within one month) over 3 years for the reprocessed precise orbits (rev. 3) based on PGM055 and the completely independent orbits from Delft University of Technology (DUT), based on the JGM-3 gravity field model. All together both orbits show very similar behaviour over the 3 years, with a mean crossover rms of about 14 cm. While the DUT orbits show some smaller values for the 168 day cycle, the PGM055 orbits fit better for the 35 day repeat cycles. More interesting is the mean of crossover differences, because it shows systematic differences between ascending and descending arcs.The PGM055 orbits are varying, except for two outliers, by some millimeters around the zero value, while the DUT orbits show significant positive values of up to 4 cm. Obviously there are some systematic effects in the DUT JGM-3 orbits, which cannot completely addressed to the geographicaly anti-correlated orbit error, which is assumed to be smaller for the JGM-3 combined gravity model (Tapley et al, 1996).

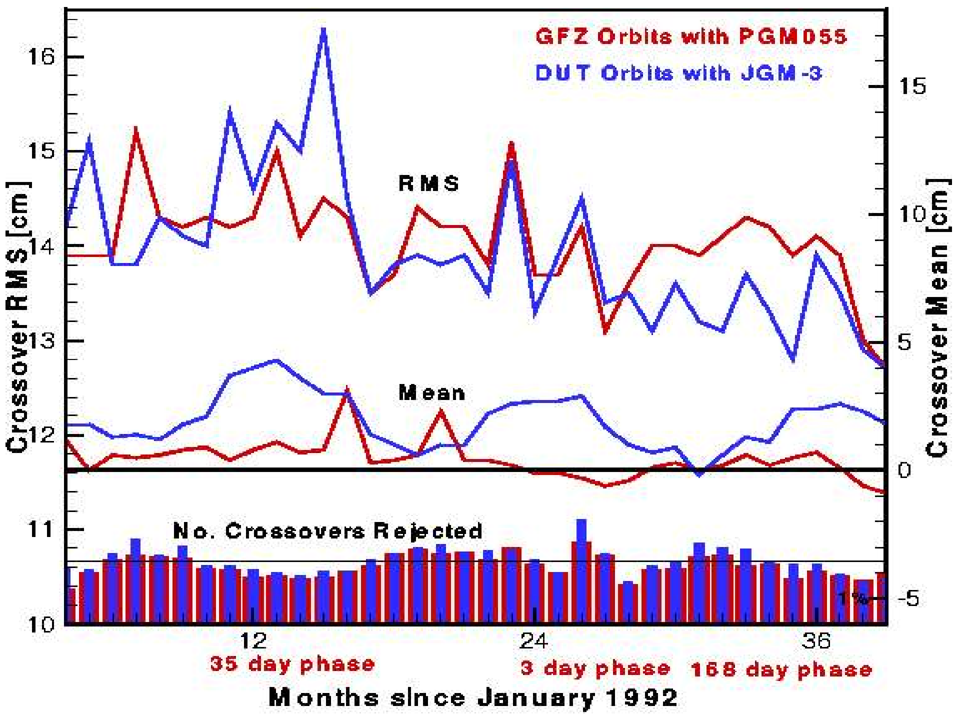


Figure 5: ERS-1 Crossover Statistics for Different Orbits

Regarding all internal and external tests, the PGM055 currently is one of the best available gravity field solutions for ERS applications. It is suitable for a highly precise ERS-1 and ERS-2 orbit computation and consequently for all related altimeter products. Even new ERS applications, as sea level studies (Anzenhofer, Gruber, 1997) and SAR interferometry, which require high precision and consistent orbits, are now possible.

GFZ-1 Gravity Field Solution

New laser tracking data to the low flying GFZ-1 satellite (390 km, 51.6 degree inclination) are now available and included in the satellite-only gravity field solutions. Due to its low altitude, gravity field induced orbit perturbations are observable up to degree and order 70 of the spherical harmonic series (and even more), what corresponds to a spatial resolution of about 250 km at the equator. GFZ-1 especially is sensitive around the resonant orders of 16, 31, 46, 62 and 78. The sensitivity will change with the decrease of the GFZ-1 altitude within its lifetime of about 5 years (König, et al, 1997). Therefore more new information is expected from this satellite in the next years.

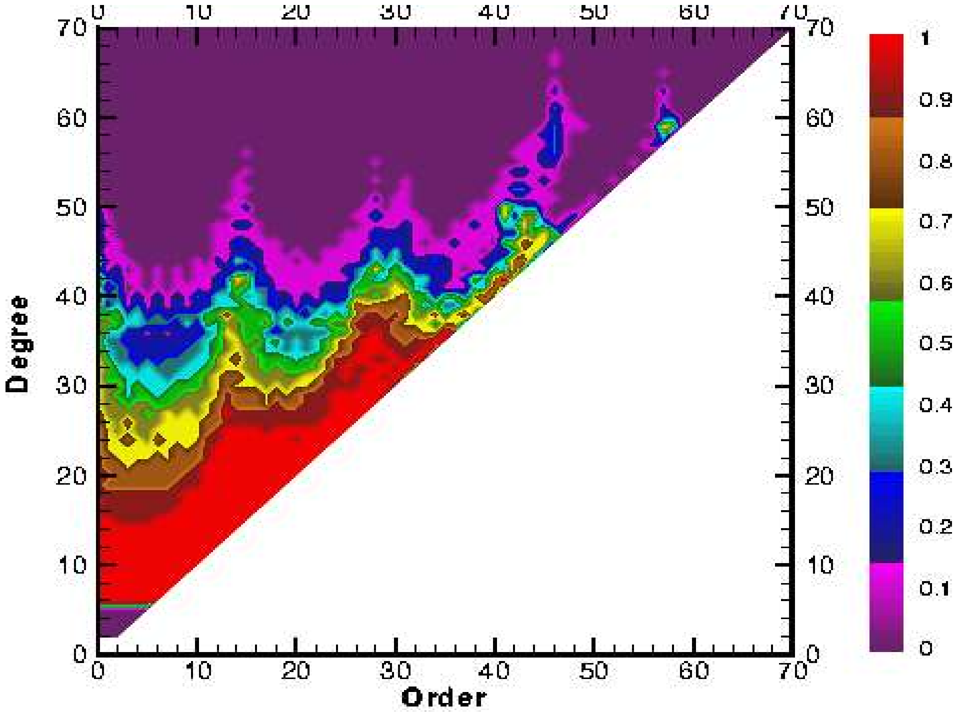


Figure 6: PGM062w Partial Redundancies

A series of GFZ-1 gravity field solutions based on the PGM055 model have been computed during the last months (PGM06X). The best available model currently is the PGM062w, which additionally contains 11580 laser ranging observations (690794 laser observations in PGM055).Figure 6 shows the partial redundancies of this model. Comparing it with figure 2 (PGM055 partial redundancies), we can clearly identify the additional resonances of GFZ-1. Orbital fits of GFZ-1 are reduced with this model from more than 2 m for PGM055 to the 40 cm level, while orbital fits for ERS-1 and other satellites do not change significantly. A clear improvement is already reached, but it is expected that with the decay of the satellite additional resonant terms even for higher degrees than 70 can be determined.

Inclusion of Prare Tracking Data for Gravity Field Determination

The PGM055 model was updated by adding a set of 14 weeks of Prare range and doppler observations for ERS-2 (170000 observations) from 18 globaly distributed stations. Especially in the Southern hemisphere much more tracking data is now available. Such a globally distributed set of consistent satellite observations helps to improve the gravity field. An intermediate solution provides promising results for all tests. Orbital fits for different satellites as well as geoid differences show slightly better results than the PGM055 base model. When more Prare gravity field normal equations will be accumulated, a further improvement is expected, even, if the current model already performs very well for ERS applications..

3. Combined Gravity Models
Long Wavelength Solutions

By combination of satellite-only gravity field solutions, completely based on space observations, with observations on the geoid, like terrestrial gravimetry and altimetry, additional frequencies of the earth gravity field can be determined. During the last years several long wavelength combination models have been computed (JGM-3, TEG3, GRIM4-C4). In cooperation with the Groupe de Recherche de Geodesie Spatiale (GRGS) in Toulouse, a combination solution up to degree 72 based on the GRIM4-S4 model was computed by GFZ (Schwintzer et al, 1997). This model combines the GRIM4-S4 normal equation system with normals computed from 1 degree block mean values of gravity anomalies over land, and of altimetry derived geoid heights over the oceans. The missing 21%, where no observations are available (polar caps) were filled with mean gravity anomalies from the GRIM4-S4 base model.After a reduction of terrestrial normal equations for the very long wavelenghts up to degree and order 5, a one step solution of the combined normal equations is computed. Due to the additional and quasi global terrestrial information, the a priori observations from Kaula's rule for the coefficients can be eliminated. The GRIM4-C4 solution shows better performance for all applications on, or near the geoid. Also GFZ-1 orbital fits show a major improvement with respect to pre GFZ-1 models. This means, that due to the additional terrestrial information on the geoid all frequencies, which can not be determined from satellite observations are determined more or less good from these new observations. On the other hand a slight degradation of ERS-1 orbital fits can be found, when using GRIM4-C4 instead of the previous introduced satellite-only solutions. When computing combination models, the main problem is the proper relative weighting of the satellite-only and terrestrial information.

High Resolution Models

In addition to this long wavelength combined gravity field, also high resolution models complete to degree and order 360 of a spherical harmonic series, what corresponds to a spatial resolution of about 50 km at the equator are computed.For these high resolution models global half degree terrestrial information is necessary. Such information was gathered since many years by R. Rapp at Ohio State University (Rapp, Kim, 1990; Rapp, Yi, 1991). There, terrestrial and altimetry derived gravity anomalies were combined to half degree mean values. These data sets were used for the OSU91A (Rapp et al, 1991) and the GFZ95 (Gruber et al, 1996) and GFZ96 (Gruber et al, 1997) solutions. In the meantime a completely new data set, compiled by the U.S. National

Imagery and Mapping Agency (NIMA), is available (Trimmer et al, 1996; Kenyon et al, 1996). There, all terrestrial and altimetric derived gravity anomalies have been recomputed. In addition many new observations are available, so that nearly 90% of the earth's surface is now covered with observed half degree mean anomalies. This new data set was used for the EGM96 model (Lemoine et all, 1996) and is currently used for a new high resolution GFZ gravity field model.

The estimation technique for the new models (GFZ96/97, EGM96) has been improved significantly. While for the older solutions (GFZ95 and OSU91) only a reduced set of correlations between coefficients of the spherical harmonic series have been taken into consideration, now a complete long wavelength normal equation system, as described before, and a block diagonal system, which is automatically generated under certain conditions for the observations and their weighting is combined. This separation is necessary, because the number of unknown coefficients increases to more than 130000 for a series up to degree 360. For solving such a system, a symmetric matrix with more than 130000 rows and columns must be inverted, what is with current computer systems not possible. Figure 9 describes the solution technique of the GFZ96/97 models. There, a combined base model with a complete normal equation system up to degree and order 72 was computed (5329 coefficients). Then a block diagonal normal equation system is generated from a global half degree gravity anomalies data set with common weighting of observations. The combination of both systems then is performed by a reordering of the normals as shown in figure 9 on the right side.The 9 submatrices are treated separately for the solution. By this method also error estimates for all coefficients can be estimated by extracting the diagonal elements of the variance-covariance matrix, even if the full matrix cannot be computed.

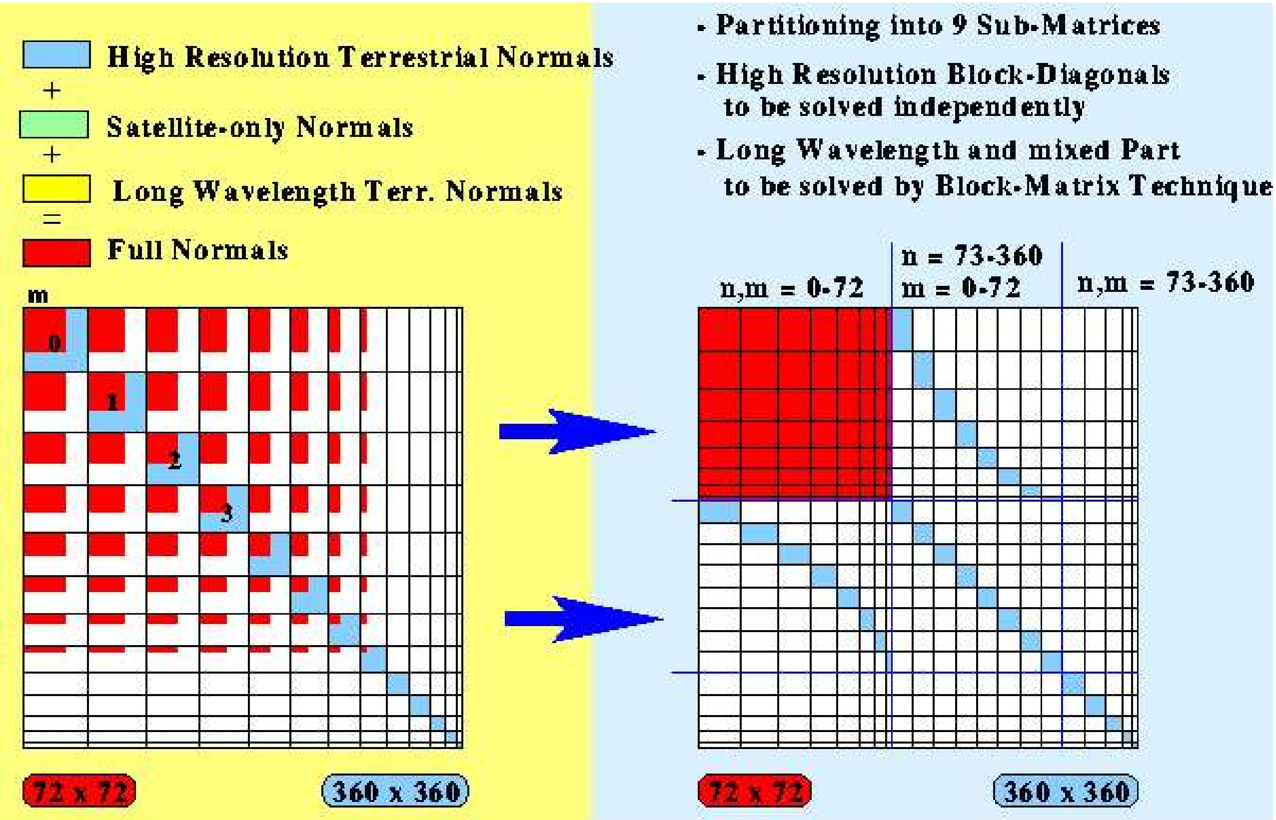


Figure 7: High Resolution Gravity Field Modeling

Before normals are generated, all terrestrial data have to be corrected for different effects. Figure 8 summarizes these correction terms and the reduction to gravity field related quantities. Geoid heights, derived from a ERS-1 mean sea surface are used as main information for the ocean geoid standard product (OGE), which is derived from a global high resolution gravity field model. For this product, terrestrial gravity, altimetric geoid heights and a satellite-only gravity field are merged to a high resolution gravity model, following the technique shown in figure 7. The OGE product finally is computed by solving the complete spherical harmonic series on a global half degree grid. For each half yearly updated ERS-1/2 mean sea surface also the ocean geoid model is updated and converges to a long term mean geoid.

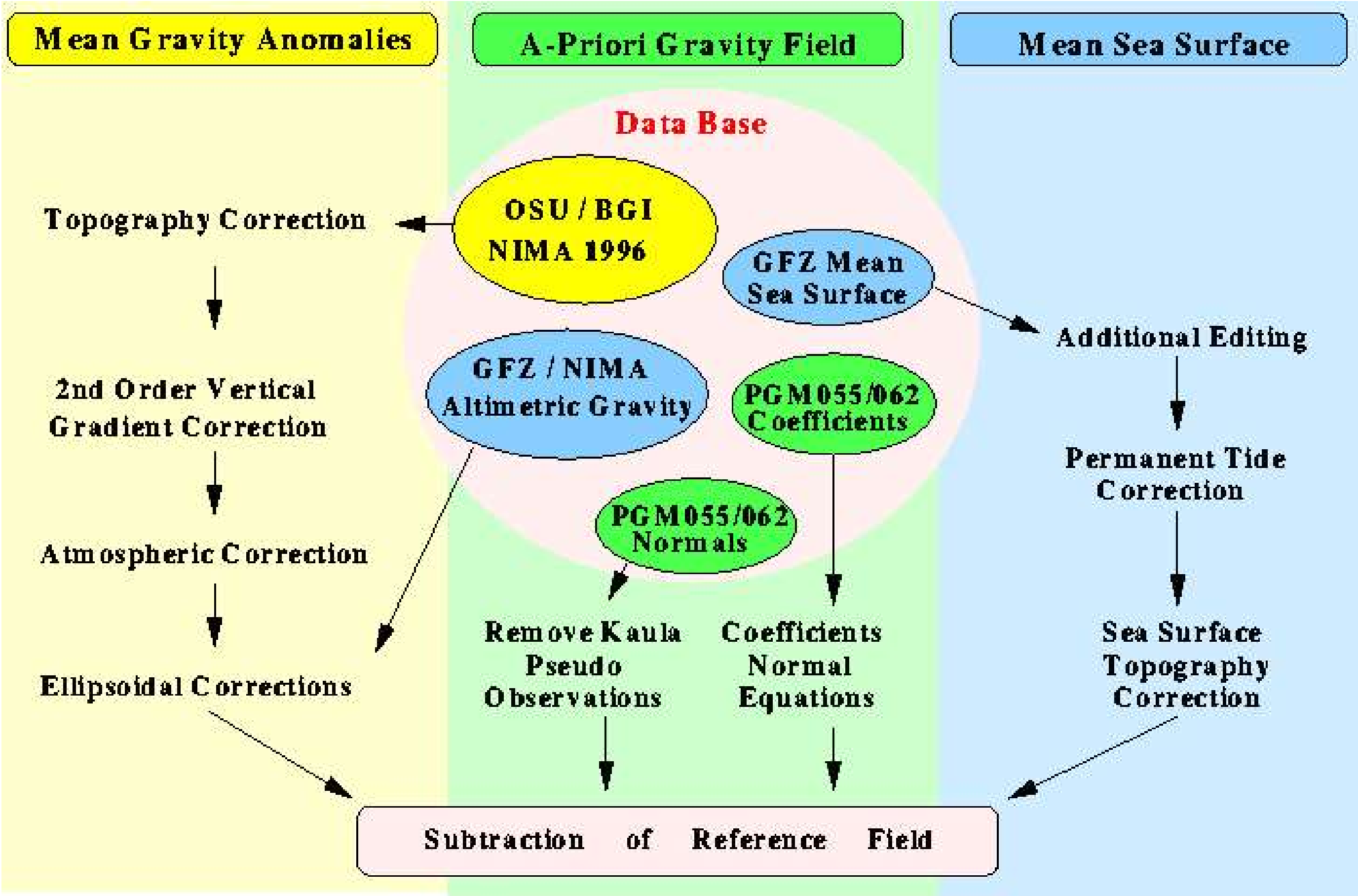


Figure 8: Data Preparation

Currently a new high resolution gravity field model based on a satellite-only solution, which is combined from the PGM055 system and additional GFZ-1 observations (PGM062w) is under development. First results are promising . Some results for a preliminary new GFZ97 solution are shown in the next paragraph. The main difference to the GFZ96 solution is the inclusion of GFZ-1 data, the usage of the new NIMA96 terrestrial and altimetric gravity, and the extension of the full normal equations system (red part in figure 7) to degree and order 100, what means a doubling of the number of parameters of the full system.

Quality Assessment

For testing gravity field models different procedures can be applied. For the long wavelenghts, usually orbital fits to a number of satellites are tested. Long and short wavelengths were tested by comparisons with independent geoid heights on Doppler/GPS stations, and by comparisons of altimeter observations and their gradients, with sea surface heights and their gradients, derived from the gravity field model. The following table summarizes these tests for some up to date high resolution gravity field models. Additionally orbital fits for the PGM055 and the GFZ-1 solution (PGM062w) are shown.

	Orbital Fits Fields truncated at degree 70 ERS-1: 9 arcs 11/92, 8/94 GFZ-1: 5 arcs 10/95 rms [cm]			**Doppler/GPS (degree 360) Geoid Differences GPS: Euro Traverse (105 Stations) Doppler: Global Set (N of 1261 Stations)**		**Altimeter Data Comparisons (degree 360) Adding POCM Topography to Geoid from Gravity Model SSH: Alt .- Model, rms [cm] Gradient: Alt. - Model, rms [cm/km]**	
	ERS-1		**GFZ-1**	**Doppler**	**GPS**	**ERS-1 35 days cycle**	
Model	**Laser**	**X-Over**	**Laser**	**rms (N)**	**rms**	**SSH**	**Gradient**
PGM055	7.4	10.77	247.6	n/a	n/a	n/a	n/a
PGM062w	7.4	10.77	43.8	n/a	n/a	n/a	n/a
GFZ96	7.7	10.14	132.2	185 (1210)	46.6	57.8	1.67
GFZ97	7.9	9.89	35.8	183 (1212)	48.8	46.5	1.64
EGM96	8.5	10.32	36.2	175 (1203)	27.9	40.7	1.63

The numbers above show a significant improvement from the GFZ96 solution (Gruber et al, 1997) based on PGM055 to the most recent 1997 solution, which is based on PGM062w. This improvement can be addressed partly to the improved satellite-only solution, partly to the new NIMA gravity anomaly data sets and partly to the relative weighting of all information. Orbital fits for ERS-1 show a large reduction of nearly 1 cm in the crossover rms and a slight increase in the laser rms, which heavily depends on the station coordinates of the corresponding laser stations. In contrast to the GFZ96/97 and EGM96 solutions, for the satellite-only models these station coordinates were solved simultaneously with the gravity field. Together with the further decrease of the GFZ-1 laser rms of nearly 20% from the PGM062w satellite-only to the GFZ97 solution, this new solution shows better results for the low-flying satellites than the completely reprocessed EGM96 model. Regarding the geoid tests (geoid height differences on Doppler/GPS stations and with altimetry), a major improvement with respect to the GFZ96 solution can be seen. Comparing it with the EGM96 model, the GPS stations test on the European traverse and especially the altimetry test show better results for the EGM96 model. Results from the GFZ96 solutions (Gruber et al, 1997) indicate, that if direct altimetry in terms of geoid heights is used instead of altimetric gravity anomalies, all geoid height tests are significantly better. This can explain the differences to the EGM96 model, where for the long wavelenghts up to degree and order 72 direct altimetry was introduced. Further investigations on the combination of different functionals of the gravity potential, as geoid heights and gravity anomalies have to be performed, to understand this situation.

4. Conclusions and Outlook

The paper summarizes the current gravity field work at GFZ/D-PAF , and the relations to some ERS ESA standard products. Satellite-only gravity field solutions, which are the base for many other products are described and the quality of the current EGM2 (=PGM055) solution is shown in some details. From all the results it can be seen that the operational ERS orbits based on this model are competitive with orbits from any other group. By inclusion of GFZ-1 tracking data a further improvement of orbital fits could be reached. Even the completely reprocessed satellite-only base of the EGM96 model doesn't show better performance for a number of satellites. With the processing of a large data set of Prare observations for the gravity field, soon, a further increase of quality is expected, especially for ERS applications. On the basis of this satellite-only solutions, low and high resolution combined gravity field models are computed. Satellite-only normal equations are combined with normals from terrestrial gravity data and altimetric geoid heights or gravity anomalies. High resolution models are computed by a new approach, which combines different types of normal equation systems. All tests for the new high resolution models show significant improvements and indicate a similar quality as the EGM96 model. Further investigations are necessary on the combination of heterogeneous data sets of different gravity field functionals.

In near future a reprocessing of all historic and actual satellite tracking data will be initiated, to take into account many improvements in the modelling and data editing. From this first GRIM5 model (pre Champ model) a significant improvement for all applications is expected. But a major quality increase is expected from the new Champ mission, which is designed for gravity field determination (Reigber et al, 1996)and will be launched in mid 1999. Thanks to its dedicated orbit design, an unpreceded low altitude in a near polar orbit, and its continuous GPS satellite-to-satellite tracking capability, together with a direct on-board measurement of the non-gravitational orbit perturbations, improvement of one order of magnitude in accuracy for the coarse structures of the gravity field is expected. With Champ the resolution of a 10 cm geoid will be increased from presently degree and order 10 to 36.

It was shown that gravity field determination is an integrated approach with many different processing steps, and that GFZ/D-PAF is covering all these aspects. In context with the Champ mission these experiences will be bundled , to provide step by step a completely new quality class of multi purpose gravity fields.

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