Accuracy Assessment of Gravity Field Models by Independent Satellite Crossover Altimetry

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Abstract. Continual progress in Earth gravity field modelling requires ever more precise data sets for their accuracy assessment as well as refinements in the assessment procedures. The method used here is based on Latitude Lumped Coefficients and makes use of single-satellite crossover altimetry data (independent of the tested model). The method effectively rationa-lizes the residuals in LLC measurements with the model's covariance matrix. It has been developed in years 1992 – 2000 and applied various gravity field models, from GEM T2 to the GRIM5's. We now apply it to EIGEN-1S & 2 which include highly precise continuous tracking data from the CHAMP mission. For the first time these CHAMP models recommend degree-dependent calibration fa-ctors for its covariance matrix. We find these factors are needed to explain the independent LLC measurements on the ERS and GEOSAT orbits.

Keywords: satellite crossover altimetry, accuracy assessment of gravity field models

1 Introduction

There are various methods to test Earth gravity field models for the accuracy of their harmonic geopotential coefficients. Some methods are sensitive to the lower degree portion of the gravity field, some to the higher harmonics. There is no universal test. Our method (see, e.g., Klokočník et al, 2000, Paper 1) enriches the range of methods of accuracy tests; we make use of independent Single Satellite Crossover (SSC) residuals from altimetry and their associated latitude lumped coefficients (LLC). By these we are able to test the order spectrum of a geopotential model uniquely for radial errors so important, for example, in satellite altimetry. The method is most sensitive to the low and resonant orders of the geopotential coefficients.

The progress towards greater accuracy in gravity modelling requires greater refinements in their accuracy assessments as well. Here, we present additional material to Paper 1. EIGEN-1S (European Improved Gravity models of the Earth by New techniques), includes CHAMP data (www.gfz-potsdam.de; Reigber et al., 2001), and is an extension of the GRIM5-S1 multi-satellite model (Biancale et al, 2000). The new CHAMP-included field was intensively tested at GFZ and CNES; here we add our test of accuracy. The procedure was also described in detail in Klokočník et al (2000, 2002). An outline is given here and numerical examples for EIGEN-1S are presented.

As EIGEN-1S is completely independent of satellite altimetry, we can test it by any available crossover data, provided that a sufficiently accurate and extensive data set is available. We make use of long-term averaged SSC (over more than one year) on the Geosat and ERS-1&2 orbits. Their original version was derived from the NASA Pathfinder data (Koblinsky et al., 1999) at NOAA, Silver Spring, by C. A. Wagner. The orbit-basis for Geosat was the

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JGM-3 geopotential model (Tapley et al., 1996) while for ERS 1&2 it was DGM-E04 (a field tuned to ERS orbit; Scharroo and Visser, 1998). These SSCs were linearly transferred to be EIGEN-1S based. A table of all altimetry corrections is given in Klokočník et al (2000) or in Wagner et al (2000).

The expected orbit radial accuracy, closely connected to the used satellites and tracking data, their accuracy and distribution, is shown in Fig.1, plotted as a function of orbit inclination for two selected altitudes (black, upper curve for CHAMP, gray for ERS 1&2, ENVISAT). It was derived from the variance-covariance matrix of the harmonic coefficients of the models (here GRIM5-S1, the dashed curves, and EIGEN-1S, the full curves). The variance-covariance matrix used was already scaled by a factor of 5^2 (compared to the covariance matrix just from the adjustment) for GRIM5-S1. For EIGEN-1S, the proposed scaling factor for its covariance matrix (P. Schwintzer, GFZ 2002, private commun.) depends (for the first time in gravity field modelling) on the degree of the harmonic geopotential coefficients: it is $k_1 = 45/2$ for l=0, $k_2 = 45/l$ for $0 \leq l \leq 36$, $k_3 = 45/36$ for $l > 36$ as factors for the formal standard deviations (retaining the original correlations).

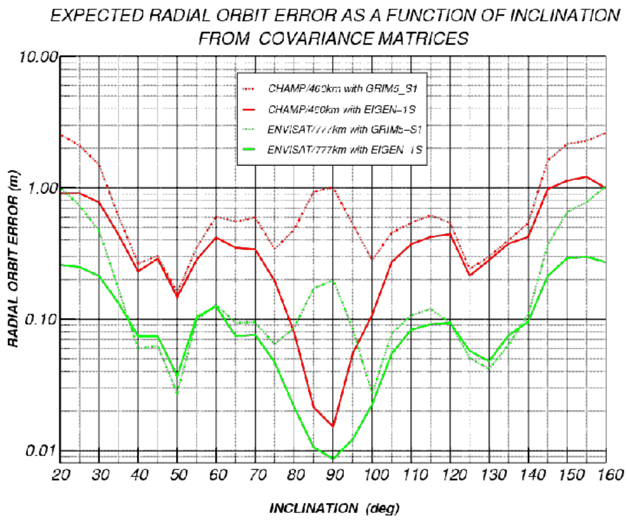

Fig. 1 Radial orbit error as a function of orbit inclination for two different altitudes (CHAMP and ERS/ENVISAT) and two gravity field models (GRIM5-1S and EIGEN-1S)

Fig. 1 shows a massive improvement of the radial orbit accuracy at the inclination of CHAMP and its vicinity, but because EIGEN-1S is an extension of the satellite solution GRIM5-S1, basically by the powerful CHAMP data only, one cannot expect better radial accuracy for orbits with arbitrary inclination and semimajor axis. For the orbits of ERS/ENVISAT, for example, there is an improvement, however, for TOPEX, EIGEN-1S is seen to perform slightly worse than GRIM5-S1.

Can we still test the new very precise gravity models, containing now the CHAMP data (like EIGEN-1S or 2) by means of altimetric SSC which are basically the same as used to test previous models without the CHAMP data (like GRIM5-S1, C1)? Is the test still reliable enough, i.e. is the signal to noise ratio (s/n) sufficiently large? [Here by s we mean the signal of projected SSC or LLC errors on an orbit with n being a "noise" of observed measurements of them.] From Fig.1, we see that the radial error for CHAMP has indeed decreased dramatically from about 100 cm in GRIM5-S1 to about 2-cm with EIGEN-1S. For ERS-1/2/ ENVISAT, the improvement is moderate, from about 3 to 2 cm. The formal standard deviations of the long-term averaged SSC residuals from the combination of ERS-1 & 2 was about 0.7 cm a few years ago and now is 0.6 cm or better. Thus, the s/n ratio was about 6:1 for GRIM5-S1/C1, and is now still about 5:1 (for the SSCs of ERS-1 and 2 together); similarly for Geosat. One has, therefore, a similar chance for the reliable accuracy testing of both pre and post-CHAMP recent gravity models with these precise crossover averages.

2 On the Method

The radial accuracy on Fig. 1 does not provide any insight into the geographical distribution of the radial error in latitude and longitude.

This is accomplished by using Rosborough's tranformation where the variance-covariance matrices of the tested gravity models is projected to yield expected errors of SSC geographically. But such information says nothing about the spectral quality of the errors. Following the natural formulation of spherical harmonics, this "Rosborough spectrum" is most readily displayed by order in terms of so-called latitude lumped coefficients (LLC). These LLC were defined in Klokočník et al (1992) and applied to test GEM-T2, JGM-2, JGM-3, EGM-96, TEG-4, GRIM5-S1, C1, POEM GS0.1, PGM-2000A, and now EIGEN-1S. (e.g., Wagner and Klokočník 1994; Wagner et al, 1997, with an extension to dual-satellite crossovers; Klokočník et al 1999, 2000, 2002). Following (Klokočník and Kobrle 1992, Klokočník et al 1992), for SSCs, we write

$$\Delta X(\phi,\Lambda)= \sum_{m=1}^{m=m_{\max}} \left[\, C_m(\phi,a,I)\sin m\lambda + \right.$$
$$\left. + S_m(\phi,a,I)\cos m\lambda \,\right]$$

where $C_m(\phi,a,I), S_m(\phi,a,I)$ are the LLC:

$$C_m = \sum_{l=m}^{l=l_{\max}} 2Q_{lm}^S \; C_{lm}, \quad S_m = -\sum_{l=m}^{l=l_{\max}} 2Q_{lm}^S \; S_{lm},$$

I is the inclination, a the semimajor axis of the satellite orbit, the Qs are the influence functions (Rosborough,1986) and ϕ is geocentric latitude. The harmonic geopotential coeffi-cients C_{lm}, S_{lm} (degree l, order m) and the influence functions $Q_{lm}(I,a,\phi)$ are fully normalized.

There is no fundamental change of the method since Paper 1. We correct the SSCs for all available corrections, convert them into "observed" LLC discrepancies along constant latitude bands (constraining for land areas). Against these we compute "projected" (estimated) LLC errors for the gienv orbit with the given field's variance-covariance matrix, using an appropriate filter to account for the absorption of long-period geopotential terms in the orbit determination process giving rise to the "observations" (see Paper 1). Then we compare rms of powers of the LLC discrepancies and the LLC errors over all latitudes with crossover data for all orders appropriate to the longitude gridding of the data, generally most sensitive to the lowest orders (excluding zero).

The long-term (multi-year) averaging of data minimizes seasonal and interanual signals in the SSCs as much as possible.

The test with LLC is always stronger for the southern hemisphere (less land areas). This fact is described by a larger scatter of the "observed" LLC discrepancies in the northern hemisphere (see Figs. 27 and 29 of Paper 1). For a more objective accuracy assessment, we rejected the majority of northern latitudes (and the most southern bands, too), and used the LLC in the latitudinal range from +20° to –60°.The linear transfer from one gravity model to another was extensively tested (Klokočník et al., 2000, 2002) to prove that it works well even for models which are not too close each other (say JGM-3 and EIGEN-1S).

3 Data

Given are the variance-covariance matrices formal or tentatively scaled. Then we have the SSC residuals, corrected. The ERS-2 SSC (Koblinsky et al, 1999) cover 58 cycles in the interval 1995 - 1999 (while ERS-1 covers only 18 such cycles in 1992 - 1993). We combined both in 2x3 deg bins (latitude *vs* longitude) averaging over 1 800 000 SSC residuals. The ERS-1 and ERS-2 crossovers originally were DGM-E04 based, and thus they were linearly transformed to EIGEN-1S by the difference of the two geopotential models, using a 1.3 day cut for orbit perturbations. But there are other SSC data sets available: 13 months averaged point values for ERS 1&2 tandem mission (1995-6), related to EIGEN-1S, among others (Scharroo, 2002, private commun.)

4 Examples of Results

For some models, like GEM T2 or EIGEN-2, and for a few lowest orders (m < 4), anomalously large LLC discrepancies have been discovered which could not be absorbed even by rescaled covariance matrices. In the majority of cases, however, the given scaling factors were confirmed. Traditionally, the scaling factor was a number (k) by which the formal covariance matrix was multiplied to estimate the accuracy of the model. It was true for all models with the exception of the newest EIGEN-1S. It was for the first time suggested (by P. Schwintzer, GFZ, private commun. 2002, see above) that the scaling factor might depend on the degree of the harmonic geopotential coefficients. (The correlation of the original covariance matrix being was preserved in this scaling proposal). The tests presented below confirm that this scaling is compatible with our LLC results for both satellites. The data, the SSC residuals of ERS 1&2 (47 and 18 cycles), in 2x3 deg bins in latitude and longitude, with Pathfinder corrections, are EIGEN-1S linearly transferred from DGM-E04. Fig. 2a shows the LLC discrepancies corresponding to those SSC. Fig. 2b shows the LLC errors, projected from the tested scaled covariance matrix of EIGEN-1S, for the ERS/ENVISAT orbit.

The RMS of power of LLC discrepancies/ errors over latitudes are in Fig. 2c. We see a fair agreement between the data and the covariance projections, which means that the EIGEN-1S scaled covariance matrix is, in general, correctly calibrated. We also confirm that the difference between the data and projections is not statistically important (see the belt of standard errors around one of the results, Fig. 2c). Nevertheless, the data curves are above the curve for the LLC projected errors for a majority of orders, namely for the higher orders; thus, we recommend a small increase of the overall scaling factor of EIGEN-1S.

To confirm the importance of the variable scaling factors we also worked with the original unscaled matrix and repeated the accuracy test on the ERS 1&2 crossovers. In Fig. 2c, the dashed curve for the LLC errors with the descaled matrix is added. While the descaled covariance matrix yields slightly smaller RMS of power of LLC errors for the higher orders, the difference "scaled minus descaled" is dramatic for the lowest orders (Fig. 2c). Although the LLC themselves are order-dependent, we confirm that some degree/order dependent scaling factors for EIGEN-1S is necessary and this particular degree-dependent one is consistent with our observations. A simple overall factor could not produce the match of data with projections at low orders. The values of the scaling factors themselves (Sect. 1) are in general confirmed.

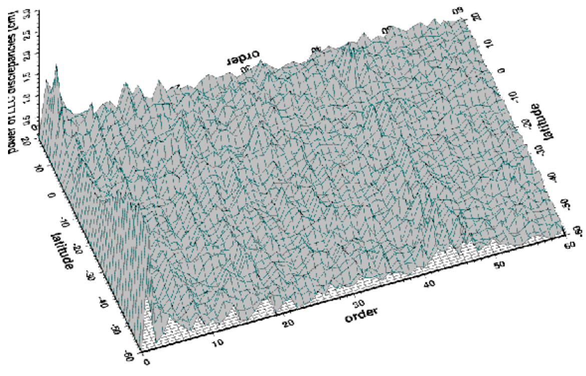

Fig. 2a LLC discrepancies over latitudes +20° to –60° from SSC residuals of ERS 1&2, 2x3 bins in latitude and longitude, Pathfinder data, EIGEN-1S linearly transferred from DGM E04.

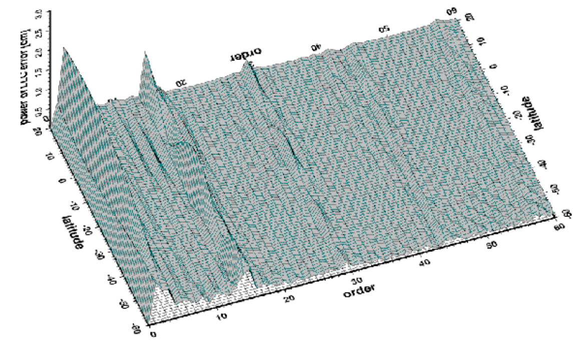

Fig. 2b LLC errors over latitudes +20° to –60° for ERS 1&2, ENVISAT projected from tentatively scaled covariance matrix of EIGEN-1S (to degree and order 70), with 1.3 day cut of orbit perturbations

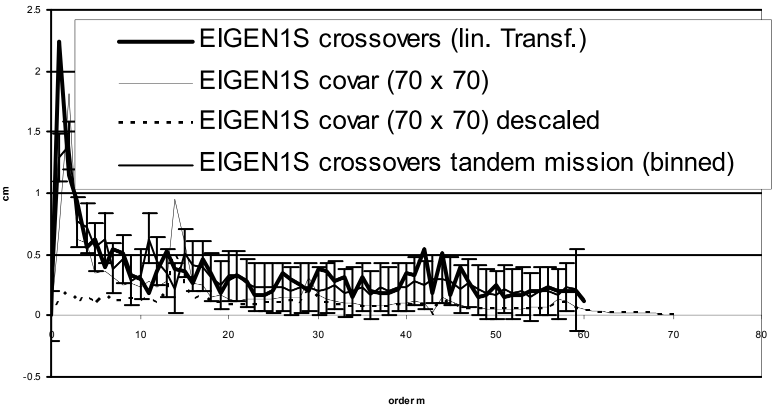

Fig. 2c RMS of power of LLC discrepancies/errors for ERS 1&2 with scaled and descaled covariance matrix of EIGEN-1S

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