GOCE DATA ANALYSIS: THE SPACE-WISE APPROACH AND THE FIRST SPACE-WISE GRAVITY FIELD MODEL

F. Migliaccio[(1)], M. Reguzzoni[(1)], F. Sansò[(1)], C.C. Tscherning[(2)], M. Veicherts[(2)]

[(1)] DIIAR, Politecnico di Milano, Piazza Leonardo da Vinci 32, 20133 Milano, Italy,
Emails: federica.migliaccio@polimi.it, mirko.reguzzoni@polimi.it, fernando.sanso@polimi.it
[(2)] Niels Bohr Institute, University of Copenhagen, Juliane Maries Vej 30, 2100 Copenhagen, Denmark,
Emails: cct@gfy.ku.dk, mave@gfy.ku.dk

ABSTRACT

The space-wise approach is a multi-step collocation procedure, developed in the framework of the GOCE HPF data processing for the estimation of the spherical harmonic coefficients of the Earth gravitational field and their error covariance matrix. The final solution of this approach is based on both the satellite tracking data derived from the on board GPS receiver and the gravity gradients observed by the on board electrostatic gradiometer.

In this work the full processing chain of the space-wise approach is described in the framework of the analysis of the first two months of GOCE data. In particular the three main steps leading from the input data to the final space-wise gravity field solution are presented. These steps are: (i) data preprocessing to remove outliers and fill gaps, (ii) low frequency model estimation from satellite tracking data by exploiting the energy conservation approach and (iii) full model estimation up to higher degrees by introducing the information coming from the observed gravity gradients. The error covariance matrix of the estimated coefficients is derived by applying Monte Carlo techniques.

The result of this analysis is the computation of the first space-wise gravity field model that will be delivered by ESA to the users' community. Due to the short time span covered by the input data, the commission error at degree 200 is still beyond the final requirement, however this solution already gives a glimpse of the high potentialities of the GOCE mission to improve the global gravity field knowledge at low-medium degrees.

1. INTRODUCTION

The GOCE mission was successfully launched by ESA on 17 March 2009. After an initial period dedicated to orbital corrections, instrumental calibrations and so on, the mission entered in its operational phase on 30 September 2009 and from then on GOCE data have been continuously acquired, apart from some data gaps. The main goal of the processing of these data is certainly the determination of a global model of the Earth gravitation field at high accuracy and resolution. To this aim, three different strategies have been implemented in the framework of the High-level Processing Facility (HPF) [14]: the direct approach [1], the time-wise approach [10] and the space-wise approach [6].

In particular the main idea behind the space-wise approach is to estimate the spherical harmonic coefficients of the geo-potential model by exploiting the spatial correlation of the Earth gravity field. To this purpose a collocation solution [9] has been devised, modeling the signal covariance as a function of spatial distance and not of time distance, as it happens for the noise covariance. In this way, data which are close in space but far in time can be filtered together, thus overcoming the problems related to the strong time correlation of the observation noise.

At this point, it has to be reminded that a unique collocation solution, although theoretically clean and desirable, is computationally unfeasible due to the huge amount of data downloaded from the GOCE satellite. For this reason, the space-wise approach is actually implemented as a multi-step collocation procedure [13], basically consisting of a filter along the orbit to reduce the highly time correlated noise of the gradiometer, a spherical grid interpolation at mean satellite altitude and finally a harmonic analysis procedure by integration for the computation of the geo-potential coefficients. The whole procedure is iterated till convergence.

The resulting strategy is quite complicated, therefore an exact error covariance propagation is not feasible. As a consequence, the error covariance matrix of the estimated coefficients is derived by using Monte Carlo techniques [7].

In this paper the space-wise approach is applied to the first two months of GOCE data. The final gravity field solution, along with the intermediate results of the processing chain, is described. In particular, the input data are introduced in Section 2; the required preprocessing for data cleaning is described in Section 3; the estimation of a gravity field model based on GOCE Satellite-to-Satellite Tracking (SST) data is illustrated in Section 4; the application of the full space-wise approach, mainly based on GOCE Satellite Gravity Gradiometry (SGG) data, is presented in Section 5, analyzing the accuracy of the obtained geo-potential also in comparison with other existing models; finally some conclusions and future perspectives are outlined in Section 6.

2. DATA DESCRIPTION

Given the nature of this work, which is dedicated to the description of the first GOCE space-wise gravity field model, in this section a list of the used input data (with the corresponding product name) is provided in order to clarify the starting point of our solution. First of all, the considered time period has to be defined, which in this case goes from 30/10/2009, 00:57:57 to 11/01/2010, 07:38:15, corresponding to about 73 days of data.
The input data are:

- the common mode accelerations (EGG_CCD_2C) measured by the on board gradiometer and to be used in the energy conservation approach [16] to model the loss of energy due to non gravitational forces acting on the satellite;
- the satellite attitude quaternions (EGG_IAQ_2C) measured by the on board gradiometer;
- the uncalibrated gravity gradients (EGG_GGT_2C) measured by the on board gradiometer; calibrated data (EGG_NOM_2) are not used because they show jumps due to the calibration procedure which would introduce artificial high frequencies in the observations;
- kinematic satellite orbits (SST_PKI_2I) and the corresponding error estimates (SST_PCV_2I) are used for the determination of the SST-only solution; this was decided because reduced dynamic orbits, although more accurate, are strongly affected by the prior model used for their computation;
- reduced dynamic orbits (SST_PRD_2I) are mainly used for geo-locating gravity gradients, but also as a reference for data gap filling and outlier correction in the kinematic orbits;
- rotation quaternions between inertial and Earth-fixed reference frames (SST_PRM_2I);
- Earth rotation parameters (AUX_IERS), Sun, Moon and planetary ephemerides (AUX_EPH) and spherical harmonic coefficients from the ocean tide model FES2004 [2] (ANC_TID_2I) are used for modeling tides in the energy conservation approach;
- the GOCE quick-look model (EGM_QCO_2I) is used as prior model, meaning that its coefficients are the starting point for the space-wise solution;
- other gravity field models, in particular EGM2008 [12], EIGEN_5C [3] and ITG_GRACE2010 [4] (ANC_ICGEM) are used as reference models, for internal comparisons or to derive degree variances, meaning that their coefficients do not directly enter in the solution. This is the standard use of these models; however in this first solution, as it will be discussed in details below, EGM2008 affects the estimated low degrees because of the error calibration in the energy conservation approach, while EIGEN_5C is indirectly introduced into the solution via the quick-look model.

As for the output data, they are the set of estimated spherical harmonic coefficients of the geo-potential model (EGM_SPW_2I) and the corresponding full error covariance matrix (EGM_SVC_2I).

3. DATA PREPROCESSING

It is most evident that the quality of the final gravity field solution also depends on the capability to detect and correct outliers and data gaps. In this section, the philosophy behind the data pre-processing is outlined, also showing how it is applied to the different data types.
Remaining in the spirit of the space-wise approach, outliers and data gaps are replaced with values estimated by collocation after removing a certain reference signal (e.g. reduced dynamic orbits for repairing kinematic orbits) to make the residuals as much stationary as possible. In particular, available data before and after the data gap (or the outlier) are used to estimate an empirical covariance function that is then used to predict values in the gap by collocation (see [8] for details). However, residuals sometimes present a long period behaviour that cannot be predicted by a local collocation around the gap; for this reason, a cubic spline interpolation is used to remove these long period biases (see Fig.1 and Fig. 2 as an example).
Let us discuss now how the method is applied to each data type. In the case of the common mode accelerations, a further distinction is necessary because the stochastic characteristics of the accelerations in the along track direction are quite different from those in the other two directions (say, for simplicity, out-of-plane and radial directions, even if it is important to recall that the satellite and therefore the gradiometer are not perfectly aligned with the local orbital reference frame). The two different behaviours are displayed in Fig. 3 and Fig. 4, where the presence of outliers is also clearly visible. Note that the reference signal to be removed from the data is just a constant in the case of accelerations in the along track direction and that the data gap interpolation (or the outlier correction) depends on the local variability of the noise which is clearly non stationary.
Data gaps in the satellite attitude quaternions from Inertial Reference Frame (IRF) to Gradiometer Reference Frame (GRF) are recovered with the same method but now using the quaternions between IRF and Local Orbital Reference Frame (LORF) as the reference signal. Concerning the gravity gradients, simulated values from EGM2008 along the orbit positions are used as reference signal to be removed before applying collocation. Outliers can be easily detected looking at the trace of the tensor of the gravity gradients. It has to be noted that, after a data gap, the Kalman filter used for the production of the Level-1 gravity gradients could be reinitialized. This implies that there is a transient period before the data return to be acceptable, namely a data gap could be followed by a sequence of outliers.

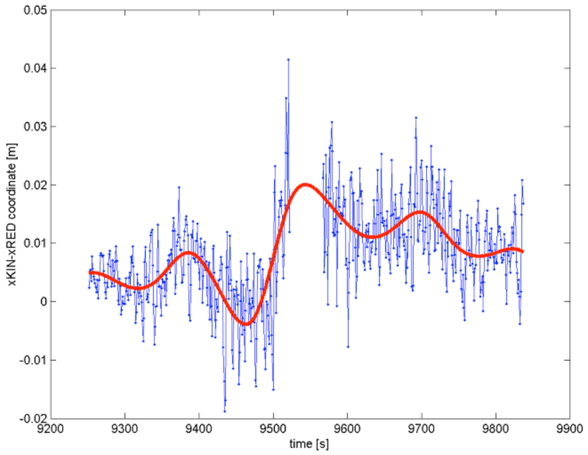

Figure 1. Cubic spline interpolation (in red) around the gap. Data (in blue) are differences between kinematic and reduced dynamic orbits.

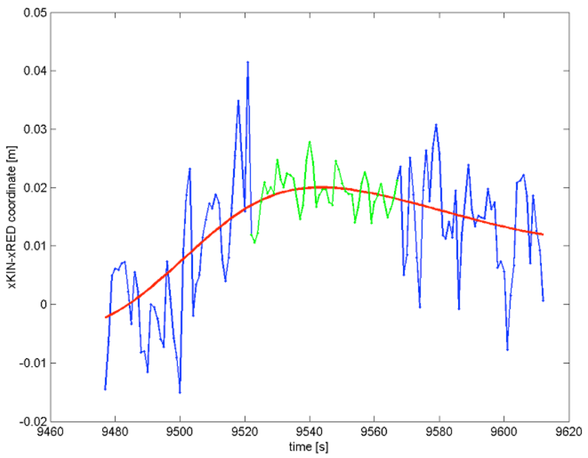

Figure 2. Collocation prediction (in green) inside the gap after removing spline interpolation (in red). Data (in blue) are differences between kinematic and reduced dynamic orbits.

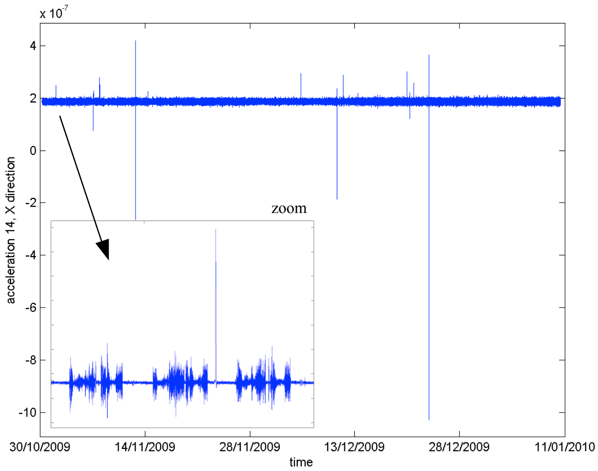

Figure 3. Outliers in the common mode accelerations measured in the along track direction (unit: m^2/s^2).

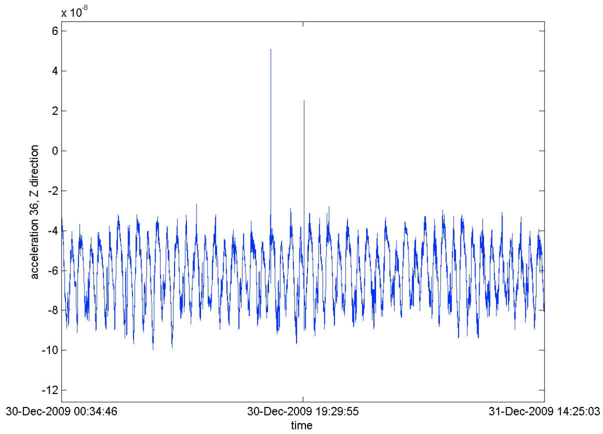

Figure 4. Outliers in the common mode accelerations measured in the almost-radial direction (unit: m^2/s^2).

Data gaps and outliers are not very frequent in the gradiometer data (namely, there are just five data gaps in the considered period), but are very common in the kinematic orbits, that, as already written, are "rougher" than the reduced dynamic orbits, but much better for the recovery of the pure gravitational signal (without any influence of other prior models used in the computation of the reduced dynamic orbits). Of course gaps in the orbital data are easily detected by checking the sampling rate that has to be close to 1 s in the case of kinematic orbits. Concerning the outliers, they are first detected by analysing the error estimates of the satellite positions: e.g. a too high value of the error variance is an indication of a too bad GPS satellite constellation geometry. After that, a comparison between kinematic and reduced dynamic orbits is performed: if the difference is too high, then the data are classified as outliers. Data gaps and outliers in the kinematic orbits are corrected by using the collocation method described before, with reduced dynamic orbits (interpolated in the kinematic position epochs) as reference signal.
Finally it has to be stressed that the replaced values are only used in the time-wise steps (e.g. the Wiener filter along the orbit) when it is useful to have a continuous flow of data. In the core of the space-wise approach, i.e. in the gridding procedure by collocation, the values interpolated in the data gaps or in correspondence to outliers are not used, because the gridding procedure does not require that the input data are regularly sampled in time. This is an advantage of the space-wise philosophy.

4. THE SST-ONLY MODEL

The low frequency part of the gravity field is estimated from satellite tracking data and then it will be used to reduce the long period signal when dealing with gravity gradients. The implemented procedure basically consists of three steps:

- estimation of the gravitational potential along the orbit by applying the energy conservation approach;

- gridding of the potential on a sphere at mean satellite altitude by applying collocation;
- recovery of the spherical harmonic coefficients from the gridded data by numerical integration.

Error estimation at each step is implemented by Monte Carlo methods.

Furthermore, the choice of computing the gravitational potential from kinematic orbits implies the need of estimating satellite velocities from satellite positions. This is done by a least-squares polynomial interpolation over a moving window, also taking into account position error estimates to weight the involved observations [8]. Note that this interpolation procedure produces positions and velocities at the observation epochs of the gradiometer which in general is not synchronized with the GPS receiver; this is useful when filtering together potential and gravity gradients.

The determination of the potential by the energy conservation approach requires to remove the effects of non-gravitational forces (atmospheric drag, solar pressure, etc.) and tides. The former can be computed by exploiting the common mode accelerations measured by the gradiometer, after calibrating biases. The latter have to be properly modelled by using external information such as Sun and Moon ephemerides, ocean tide models, etc.

The differences between the resulting potential and the one computed from EGM2008 (which can be taken as reference because it is superior to a GOCE-only solution at very low degrees) is shown in Fig. 5, together with the corresponding error estimates. These are derived by propagating the position errors first through the velocity interpolation procedure and then through the linearized energy conservation approach. As it can be seen, there is a good agreement between empirical and estimated errors.

However, comparing the empirical (with respect to EGM2008) and the estimated error spectrum (see Fig. 6), one easily realizes that there are two main differences. Firstly, there are spikes in the empirical spectrum indicating that some periodical behaviours (the highest with a period of half an orbit) are not properly modelled, probably in the tide description. Secondly, the predicted spectrum at very low frequencies is much lower than the empirical one; since the predicted spectrum is mainly computed by propagating the satellite velocity error, this discrepancy may be attributed to the use of unfiltered common mode accelerations in the computation of the non-gravitational force effects. In any case, independently from the causes of these differences, they are removed from the empirical error spectrum, thus introducing EGM2008 as prior information. This is the reason why the estimated spherical harmonic coefficients will be very good at low degrees, say below degree 20, much better than the expected accuracy of a GOCE-only solution from kinematic orbits. The final statistics of the estimated

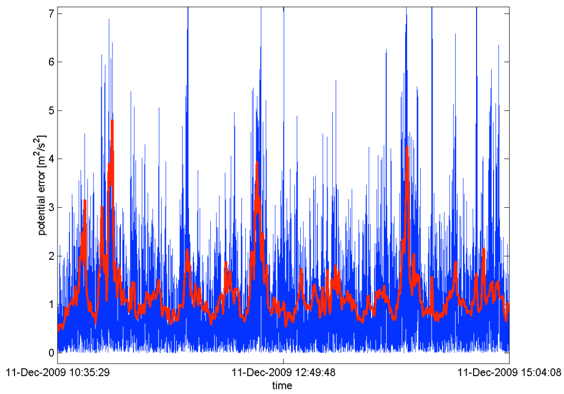

Figure 5. Absolute differences of the estimated potential with respect to EGM2008 (in blue) and error estimates (in red).

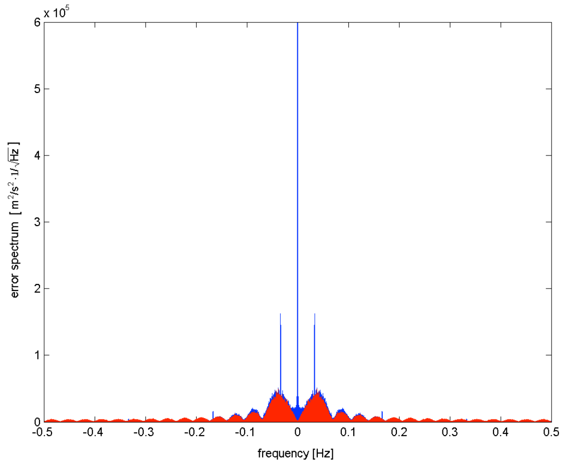

Figure 6. Empirical error spectrum of the estimated potential (in blue) and predicted error spectrum (in red).

potential are reported in Table 1.

The next step is the gridding at mean satellite altitude. A clarification is important at this point. When applying gridding in the space-wise approach, observables generated from a prior model are always removed from the data (at the beginning the prior model is an external information, in the following steps the prior model is the one computed at the previous step) and then added back to the solution. In principle, collocation is a linear operator, therefore adding or removing something to the observations should not change the solution. However, the resulting collocation operator depends on the signal covariance (which is a non linear statistics), therefore removing a known signal from the observations implies that residuals have a different covariance and the collocation operator is different. Generally, if the signal is lower, then also the estimation error is lower and this is the reason why some prior information is removed from the data. In principle the idea is to remove as much information as possible, provided that the covariance of the residual is estimable (which could be difficult when the noise is much larger than the residual signal).

Table 1. Statistics of the estimated potential.

Empirical error rms (differences from EGM2008)	Predicted error rms (using Monte Carlo)
1.704 m^2/s^2	1.523 m^2/s^2

On the other hand, when implementing this remove-restore procedure, one has to pay attention at not introducing too strong a priori information that data cannot correct. In other words, if the residual signal is too low with respect to the observation noise, the estimated corrections to the prior model will be close to zero and the final prediction will be the prior model itself and not the model implied by the data. Since the goal of the SST analysis is to produce a GOCE-only model, this consideration has to be seriously taken into account.

Here the idea is to remove from the estimated potential the one computed from a quick-look model [11], which is a prior information ingested by the space-wise approach, but still related to GOCE data. However the quick-look model delivered by HPF for the considered time period is not a GOCE-only model for two main reasons. Firstly, its SST part is based on reduced dynamic orbits which in turn make use of the satellite-only model EIGEN_5S derived by GRACE mission data. Secondly, spherical cap regularization [5] is implemented with the support of the model EIGEN_5C.

Since an SST-only model derived from reduced dynamic orbits will be definitely better than one derived from kinematic orbits (because GRACE is better than GOCE at low degrees), a preliminary step in the space-wise approach before gridding the potential observations is to degrade the quick look model in such a way that the degraded model is still useful to reduce the signal power but does not introduce prior information in the GOCE SST solution. Note that removing the original quick look model would have in any case the disadvantage to create an inhomogeneous field because of the higher residuals in the polar areas. The implemented degradation simply consists in rescaling the quick-look coefficients by a factor $k = 0.975$ in such a way that the error degree variances corresponding to this degradation are equal to the full-signal degree variances (that can be safely estimated by EGM2008) multiplied by a factor $(1-k)^2$. As it can be seen from Fig. 7, the degradation is dominant with respect to the intrinsic error of the quick look model at low degrees where it is expected that the contribution of the reduced dynamic orbits is present. On the other hand, at high degrees where the quick look model is mainly due to the GOCE gravity gradient information, the intrinsic error of the quick look is much higher than the degradation effect. All in all, the degree variances of the residual signal after removing the degraded quick look model from GOCE data will be a combination of the rescaled full-signal degree variances (at low degrees) and of the intrinsic estimation error of the quick look

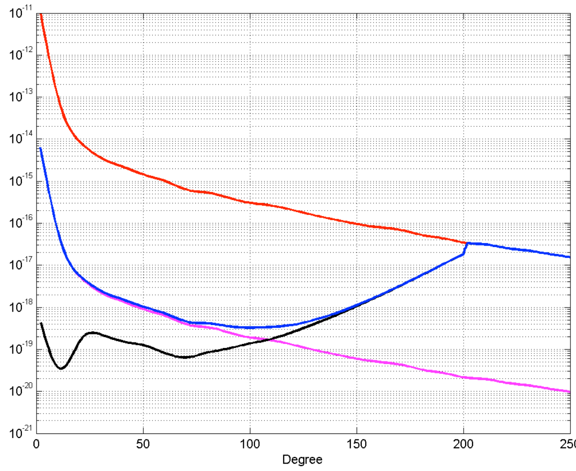

Figure 7. Full-signal (in red) and rescaled (in magenta) degree variances. Error degree variances of the quick-look (in black) and of the degraded quick-look (in blue).

model (at high degrees). The degree variances of the residual signal are used as input in the collocation procedure. Note that it cannot be excluded that some prior information used for regularizing the quick look model in the polar gaps could enter in the GOCE space-wise solution, because the implemented degradation is calibrated on error degree variances as shown before, while the spherical cap regularization acts on all low orders. In other words, the space-wise solution could inherit part of the quick look regularization at the poles.

After the gridding, harmonic analysis by numerical integration is implemented to estimate the spherical harmonic coefficients of the SST-only model. The empirical error degree variances up to degree 180 are shown in Fig. 8; they are computed with respect to the satellite-only model ITG_GRACE2010 that is not affected by problems connected to the use of ground gravity data (e.g. different height datum) and should be much better than GOCE at low degrees. These empirical degree variances are compared with the predicted ones by Monte Carlo and with the predicted ones for the ITG_GRACE2010 model.

5. THE SPACE-WISE MODEL

The final space-wise solution is computed according to the iterative scheme reported in Fig. 9. Basically the signal long wavelengths are removed by exploiting the low degrees of the estimated SST model, while the high variance and the long time correlation of the gradiometer noise are reduced by applying a Wiener filter along the orbit. In this way gridded values on a sphere at mean satellite altitude can be reasonably computed by applying collocation to local patches of data, making the solution feasible from the computational point of view. Starting from the gridded values, spherical harmonic coefficients are derived by numerical integration. The procedure is iterated by simulating observables along

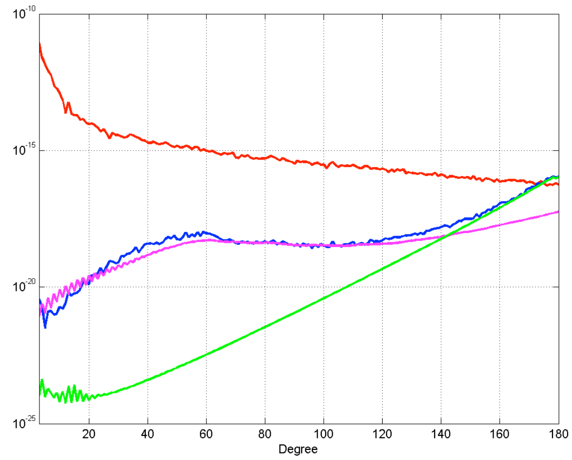

Figure 8. SST-model empirical error degree variances with respect to ITG_GRACE2010 in blue, SST-model predicted error in magenta, GRACE predicted error in green, reference signal in red.

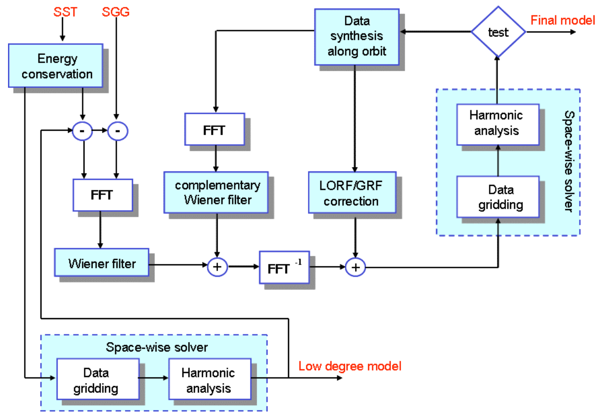

Figure 9. Space-wise iterative scheme

the orbit from the estimated coefficients in order to recover the signal cancelled out by the Wiener filter (by means of the so called complementary Wiener filter) and to correct the data rotation from GRF to LORF. It can be shown that the whole iterative procedure, apart from the numerical approximations due the local gridding, is equivalent to a unique and direct collocation from original data to spherical harmonic coefficients [13].

After this summary of the method, let us discuss the intermediate and final results obtained with the considered GOCE data. The error root mean square (rms) of the filtered data along the orbit is reported in Table 2, both as differences with respect to the corresponding EGM2008 signal and as predicted error by Monte Carlo. Empirical differences and predicted errors are in good agreement.

Table 2. Statistics of the time filtered data (anomalous potential T and its second derivatives, X=along track, Y=cross-track, Z=radial).

	T [m^2/s^2]	T_{XX} [mE]	T_{XZ} [mE]	T_{YY} [mE]	T_{ZZ} [mE]
Empirical	0.091	2.4	4.4	4.6	6.0
Predicted	0.089	2.5	4.2	4.6	5.9

The gravitational potential and the gravity gradients reported in Table 2 are jointly used as input in the gridding procedure. The output of this procedure is a spherical grid at mean satellite altitude of the gravitational potential and its second radial derivatives. The former functional is more suitable to describe the low degrees of the field (improving the previous estimate coming from SST-data only), while the latter is preferable for higher degrees (improving the quick-look model). Both functionals have an analytical expression that can be easily integrated to estimate the spherical harmonic coefficients from the gridded data.

Before discussing the results, two considerations are in order. First of all, as already stated before, the gridding is not applied to the full signal, but observables from a prior model are removed from the data. At the beginning the prior model is the SST-model. After iterating and reaching convergence with the same prior model (the operators involved in the iterations do not have to be changed), a new solution is obtained which is used as prior model for the next sequence of iterations and so on. In other words there are two levels of iterations, the more internal one based on a fixed prior model and the external one when the prior model is changed. Note that the update of the prior model also implies an improvement in the error spectra estimation and not only a stronger reduction of the signal power (see [13] for details).

The second consideration is about the modelling of the signal covariance in the collocation gridding. Making the usual hypothesis of homogeneous and isotropic (i.e. invariant by rotations) field [15], the signal covariance function can be expressed in terms of degree variances. However, when removing the prior model contribution, this hypothesis is not satisfied by the residual field because the remaining signal is generally much higher at the poles. In other words, the assumption that the variance of spherical harmonic coefficients only depends on the degree is not realistic, because the variance of the low order coefficients is much higher. This means that the collocation gridding based on degree variances (even if they are estimated using more robust statistics like square degree medians, as it is done here) is not anymore the optimal linear estimator minimizing the mean square error, because the original hypotheses are not fully satisfied. Note that, even if the collocation operator is not optimal, the corresponding error estimates are reliable because they are computed by Monte Carlo, generating signal samples that are consistent with the single coefficient variances (and not with the degree variances used for computing the collocation operator). Moreover, in this way the effect of polar gaps is preserved in the error estimates.

Coming back to results, some statistics on the accuracy of the estimated grids (both with respect to EGM2008 and predicted by Monte Carlo) are reported in Table 3. The error degree variances of the final model are shown in Fig. 10; they are computed with respect to both EGM2008 and ITG_GRACE2010. Predicted error degree variances by Monte Carlo are displayed too. The differences of the GOCE space-wise model up to degree 70 with respect to EGM2008 and to ITG_GRACE2010 are practically the same and are both representative of the true error, because both reference models are based on GRACE which is superior to GOCE at low degrees. Above degree 70, the differences from EGM2008 are much higher than the ones from ITG_GRACE2010 and should not be used as representative of the GOCE model error; this is because EGM2008 is a combined model based on ground data, so errors due e.g. to different height datums in the observed ground gravity anomalies could enter in the solution. On the other hand, above degree 120 GRACE information is not anymore superior to the present GOCE solution, therefore the differences with respect to ITG_GRACE20010 are dominated by the GRACE errors. At the highest degrees (say above 180), the quality of the EGM2008 model returns to be superior, therefore the differences between the GOCE model and EGM2008 are representative of the true error. The predicted error degree variances are consistent with the reasoning above, confirming that a GOCE solution based only on two months of data is superior to GRACE above degree 120 and could contribute to detect errors due to ground gravity data in combined models such as EGM2008. This is also confirmed by the geoid differences of the GOCE solution up to degree 150 with respect to EGM2008 and ITG_GRACE2010, that are shown in Fig. 11 and Fig. 12, respectively. In the case of EGM2008, clear topographic features are visible, probably depending on the quality of the used ground data. In the case of ITG_GRACE2010, the comparison is between two satellite-only models and therefore the differences are mainly latitude dependent, with an indication that GOCE can correct typical GRACE strips.

Table 3. Statistics of the gridded data for $|\varphi| < 83°$ (potential T and its second radial derivative T_{rr}).

	T [m^2/s^2]	T_{rr} [mE]
Empirical	0.020	2.64
Predicted	0.016	1.44

According to Fig. 10, the maximum degree of the GOCE space-wise solution is chosen equal to 210, where the error degree variances reach the signal degree variances, before being strongly regularized. The geoid error up to degree 200 predicted from the full covariance matrix of the estimated coefficients, based on 400 Monte Carlo samples, is shown in Fig. 13; note that the error structure is essentially latitude dependent.

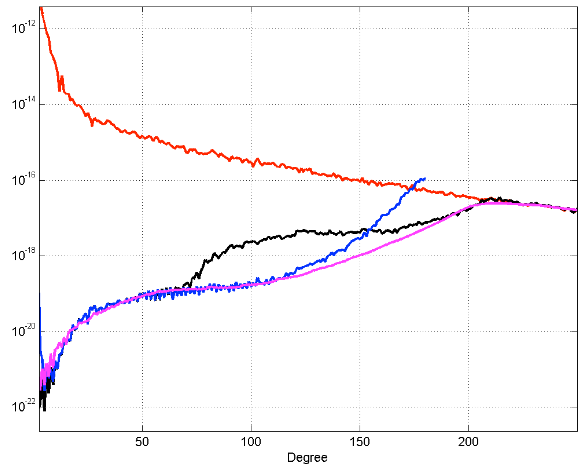

Figure 10. Empirical error degree variances with respect to ITG_GRACE2010 in blue and EGM2008 in black; predicted error in magenta, reference signal in red.

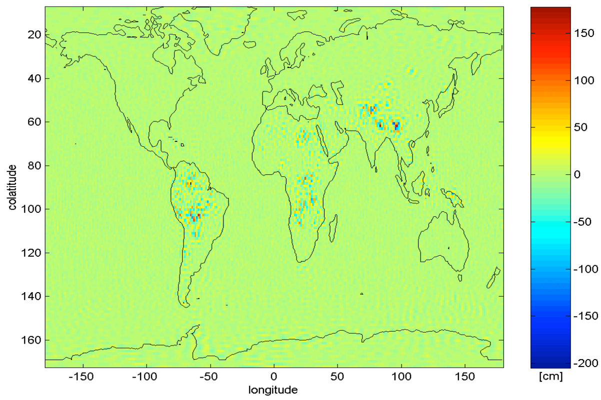

Figure 11. Geoid differences of the GOCE solution with respect to EGM2008 up to degree 150.

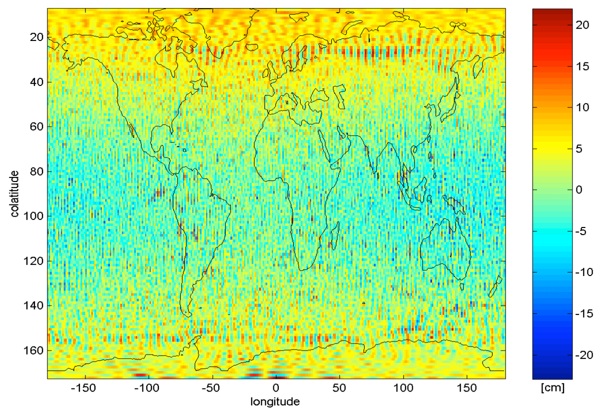

Figure 12. Geoid differences of the GOCE solution with respect to ITG_GRACE2010 up to degree 150.

Finally the error rms of geoid undulations and gravity anomalies, for the latitude interval covered by GOCE data and up to degree 200, is reported in Table 4, confirming that the mission requirement in terms of gravity anomalies is less critical.

Table 4. Statistics of the final model up to degree 200 and for $|\varphi| < 83°$

Predicted geoid error	10.86 cm
Predicted gravity anomaly error	3.03 mgal

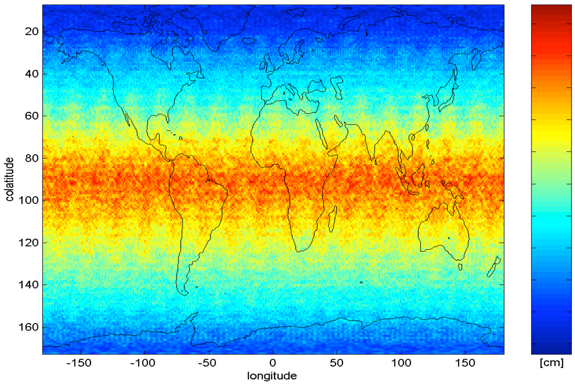

Figure 13. Predicted geoid error up to degree 200.

6. CONCLUSIONS AND FUTURE WORK

The analysis of the first two months of GOCE data has proven that the space-wise approach is able to provide good results. Data preprocessing, such as outlier rejection and data gap filling, is fundamental to improve the quality of the final solution. The SST-model should be computed from kinematic orbits in order not to include GRACE information; however the use of prior models for the error calibration and for the data gridding can indirectly affect the solution and has to be carefully evaluated. The iterative scheme exploiting the gravity gradient information leads to a solution up to degree 210 with a commission error of the order of 10 cm. An accuracy improvement can be achieved with a larger data set, while the signature of the error structure should remain more or less the same, considering that the orbits have a repeat cycle of two months.

Concerning the future activities, the remaining dependence from prior models in the SST solution will be eliminated to produce a pure GOCE-only model. Of course, a new solution will be computed for a longer data period. However since the iterative scheme cannot be applied to the full data set for computational reasons, a combination of grids at mean satellite altitude based on different data subsets will be necessary; the error covariance of the estimated grids will be taken into account in this combination.

ACKNOWLEDGEMENTS

This work has been performed under ESA contract 18308/04/NL/NM (GOCE HPF).

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