IMPROVED CAL/VAL OF GOCE GRAVITY GRADIENTS USING TERRESTRIAL DATA

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ABSTRACT

One method for validating the calibration of the GOCE gravity gradients (GG) utilizes high quality gravity data measured on ground to predict GG in the GOCE data positions in order to compare the results between the GOCE GG and the predicted GG.
The calibration is performed in four regions distributed globally by estimating a scale factor between the data sets for each track crossing a calibration area. Each track contains approx. 150 points and each day 1-3 tracks pass a calibration area.
The GOCE GGs are affected by a 1/f characteristic noise and has the highest signal to noise ratio in the measurement band (MB) 5-100 mHz. Frequencies outside this band are removed.
The GG prediction is performed with least-squares collocation (LSC) and the resulting GG are merged into a time series of GG model data (EIGEN-5C) by substituting the data over the calibration areas with the predicted data before undergoing a similar filtering as the GG data to extract the data in the MB.

Having two comparable data sets requires significant pre-processing of the GOCE data and manual data quality check of the terrestrial data.

During the GOCE mission we have reevaluated our calibration data by adding more ground data and adjusted the LSC covariance functions for the data in the calibration areas. The results from both the initial calibration procedure and using the revised terrestrial data selection are presented.

Key-words: GOCE, gravity gradients, ground gravity, calibration.

1. INTRODUCTION

The ESA GOCE mission (Johannesen et al., 2003) was launched in March 2009. The satellite carries a gradiometer which produces gravity gradient data (GG) and GPS and star-tracker instruments which gives the position and the attitude, see (HPF, 2010). The gradients are derived from the gravity potential V (without centrifugal potential). The GG data are processed by the High Level Processing facility (HPF), and a part of the processing is the calibration of the data, for which several methods are applied (Bouman et al. 2004, 2008).
One method is the calibration with terrestrial data (Arabelos and Tscherning, 1998) which consist of the following steps:
Time series of GG data are created from a gravity potential model combined with predicted GG in the selected calibration areas. This data set is required because the comparison has to be done in the measurement-band (MB) 5-100 mHz, which requires a full time series to permit filtering. We describe the basic elements of the preprocessing in Section 3.
Calibration parameters are estimated track-wise for the tracks passing the calibration areas. Each track contains approx. 150 points and each day 1-3 tracks pass a calibration area.

During the GOCE mission we have reevaluated our calibration data by using EIGEN-5C instead of EGM96, adding more ground data and adjusted the LSC covariance functions for the data in the calibration areas. The results from both the initial calibration procedure and using the revised terrestrial data selection are presented.

2. CALIBRATION AREAS

The areas used for validation of the gradient calibration are selected on the basis of gravity smoothness, for the global geographical distribution, and naturally for the data availability. One area is from a more mountainous region (Norway), and the calibration in this area has shown to be a more challenging calibration process, because the results did not immediately indicate that a qualified calibration was possible. With various efforts such as e.g. increasing the number of ground data combined with a more careful

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selection process, where more representative data were selected, the results have improved as presented in the results below.

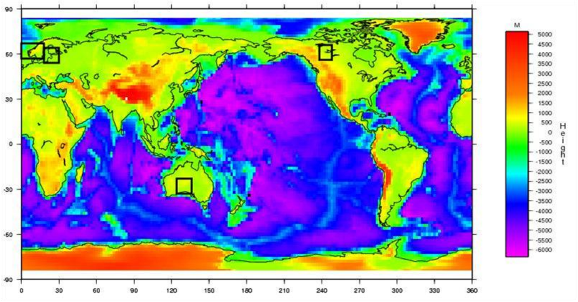

Figure 1. The calibration areas.

The calibration areas used in the GG validation are described in Table 1.

Table 1 Geographical description of calibration areas

Area	Height 0-max [m]	Latitude min/max [degree]		Longitude min/max [degree]		Gravity anomaly min/max [mGal]	
Aust.	974	-32	-20	124	144	-112	123
Can.	1796	56	68	-124	-106	-79	68
Nor.	2469	54	66	3	18	-113	194
Scand	1717	60	72	19	30	-113	137

The areas extend of maximally 12^o in latitude and 18^o in longitude, corresponding to an approximate square with side lengths of approx. 1560km. This is partly in order to address the MB which corresponds to distances up to 1600km. The areas are shown in Figure 1.

The number of points used in both the initial processing and after reevaluationof the data is listed in table 2.

Table 2. Number of grounds data points used

Area	Points	
	Initial met.	Re-eval met.
Australia	12997	21776
Canada	4395	9501
Norway	5997	18733
Scandinavia	14851	14851

3. PRE-PROCESSING

The data pre-processing consists of a variety of problems and solutions including:

- data gap handling, - identification and fill-in procedures.
- overlap elimination, - synchronisation and weighting.
- outlier detection , - identification and fill-in procedures, including differentiation.
- data synchronisation, - Lagrange interpolation. Special problems with e.g. non-equidistant data and non contineous quaternion data.
- differentiation, - dynamic use of methods.

Furthermore it is required to utilise checks for continuity and data sampling equidistancy, because even very small deviations in these values may require the use of alternative methods as e.g. for the synchronisation procedure or when differentiating, where the Gregory-Newton forward differentiation method is replaced by a simple polynomial estimation of a data section which is then differentiated.

Below a short overview of the methods and a few results are found.

3.1. Data gap handling and outlier detection

The fill-in procedures when encountering a data gap or an outlier are similar However while data gaps are easily identified the detection of outliers is a combination of various methods – both statistical and the utilisation of the characteristics of the data itself.

The fill-in procedure depends on the length of the gap and of the data type. If the gap length exceeds a period of e.g. 500 s (= 3800 km) then a fill-in procedure is not meaningful, unless the data are only used for symbolic purposes (e.g. timestamps for synchronisation, or very regular attitude changes) and not for retrieving actual gravity field information.

In our procedure we use as baseline method different data fill-in methods. We use a simple least-squares collocation procedure for data types where model data or alternative data are available. For the kinematic positions the reduced dynamic positions are used to create residuals used in the LSC procedure. For GG data gravity model data generally are used for extrapolating (or rather predicting) data in the gaps. Finally also the inertial attitude quaternion (IAQ) can be handled similarly by using the Startracker camera data.

For stand-alone data such as common and differential mode accelerations (CCD), data gaps are filled with polynomial data created as a baseline with Forsythe polynomials.

The outlier detection is a more complicated process where data in general are examined in different regimes of outlier duration time, from small outliers of 5 s, over sections of 50 s, 200 s and up to long series of outliers extending up to 5500 s. The procedure is to use two neighbouring sections on each side of the examined piece of data. From these four datasets a polynomial is determined and used to find the residuals between data and polynomial values. The standard deviation (σ) of the residuals are calculated and compared to residuals between data and polynomial values in the examined section. If a residual exceeds a value of (e.g.) 5σ then the point is flagged as an outlier. For outliers exceeding the revolution length of 5500s, this naturally is not an effective solution and here a longer outlier duration must be considered.

Another method is to utilise the inherited characteristics of the data e.g. the Laplace condition when examining the GG ($V_{xx}+V_{yy}+V_{zz}= 0$).

The Kepler elements calculated from the positions should, - except from the true anomaly υ- be slowly varying and they have provide a good basis for a data quality check of the associated state vector.

For a rotation matrix check (and to some extent the positions also), it is beneficial to rotate the position and the velocity to the GRF (gradiometer ref. Frame, see HPF(2010)), using the inertial attitude quaternions (IAQ) which provide the rotation from inertial reference frame (IRF) to GRF and the Earth rotation (also provided as a GOCE data product: PRM), where the position will now be approximately ($0,0,|R_{sat}|$) and the velocity (a little less) approximately ($|V_{sat}|,0,0$), and as such less variable and better to use for outlier identification in either position or rotation data.

3.2 Ground data check

The ground data also requires a quality check. This is not so much to identify outliers even though off course very steep differences should not be present, but to examine whether the data is representative for the calibration area. In our case we had first selected three areas from smooth parts of the gravity field (Canada, Australia, and Scandinavia/Baltic sea) where an optimal calibration performance was anticipated (Arabelos and Tscherning, 1998). But in order to examine the behaviour and the performance of the calibration method also an area from a more mountainous region (Norway) was examined.

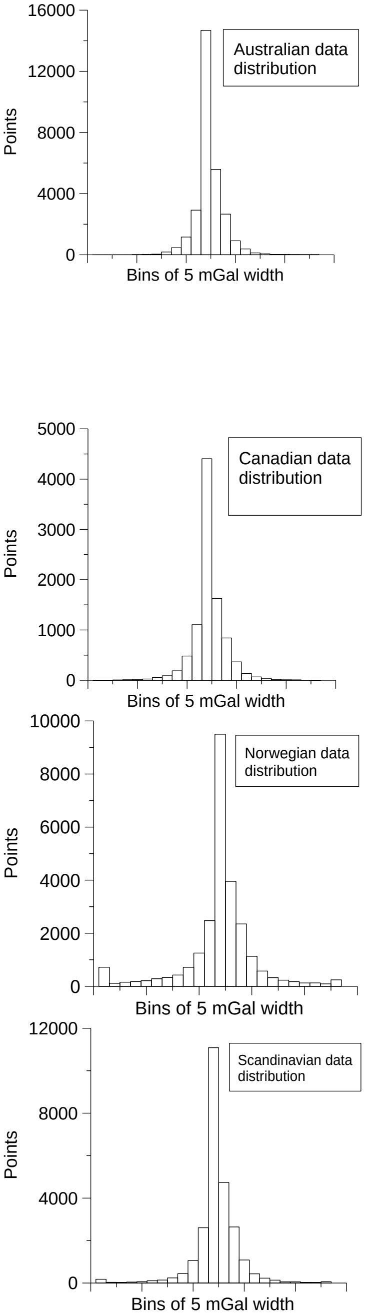

Figure 2. Histograms of ground data distribution

However the Norwegian region (actually both the Scandinavian areas) did not produce as good calibration parameters as the other areas (Fig. 5). The histograms in Figure 2 show that in both Scandinavian areas there are a significant number of points not following a normal distribution. The reason for this was found to be a high number of data measured in lowlands along heigways, which also was reflected in the difficulty to create a meaningful covariance function from the data, (the covariance function had highly extended correlation length). The data – mostly collected from the road in the lowlands - did not represent the topography of the area very well but when the 'roadmap' was expelled from the data set, the results improved as shown under results.

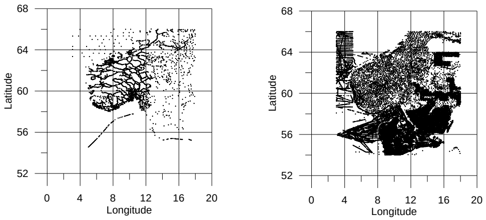

Figure 3. The expelled data from Norwegian roadnet (left) and resulting Norwegian (and Danish) data set (right).

4. TERRESTRIAL DATA SETS

The contribution from a spherical harmonic model are subtracted from the gravity anomalies in order to represent the data outside the calibration areas and to assure the consistent estimation of a local covariance function. The local covariance function is represented by an analytic function, (Knudsen, 1987). Tests of the use of different models have been performed and using different degree and order of the model. The reason has been to retain the maximum information in the data in the MB, which would imply to use a subtraction of model contributions of e.g. d/o to 120-150. Then the remaining part of the signal is available for the parameter estimation. In the present procedure it has been chosen to use the EIGEN-5C (Foerste et al., 2008) to d/o 360, which produce quite satisfying results. Earlier EGM96 (Lemoine et al., 1998) was used and the use of the new model made a new determination of the covariance model necessary.

From the reduced ground data points a covariance function is fitted as mentioned above. It is used in LSC to predict gravity gradients in the GOCE orbits. Note that the use of LSC requires the solution of a number of equations equal to the number of ground data points, see Table 1. However the reduced normal equations can be reused with each new calibration time period due to the so-called permanence property (Freeden, 1982).

The gravity anomaly data and one of the predicted components of the GG in the GOCE positions are shown in Figure 4.

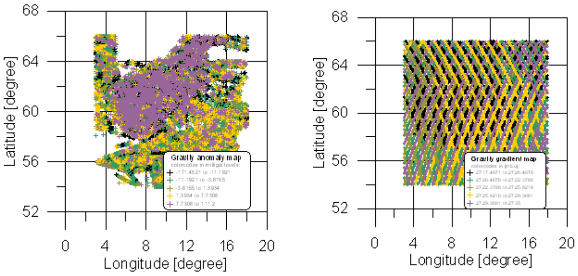

Figure 4. Reevaluated Norwegian data set (left) and corresponding predicted GG (right).

5. DATA EXTRACTION AND SCALE FACTOR ESTIMATION

The filtering is performed by first subtracting the remaining long-wavelength information of the GOCE GG in subsections per revolution using a spline function. Subsequently a simple Fourier transformation is performed where coefficients outside the MB are cut off. This square filter induces Gibbs effects and other edge effects in the filtered data but only in the order of 1 to 2 % of the data. Several other filters have been tested, but the choice of filtering characteristics has been only of minor importance.

With the filtered data sets it is possible to estimate scale factors (SF). They are calculated using a least squares solution using the a priori error derived from the GOCE GG product (EGG_NOM_2i, cf. (HPF, 2010, section 5.2)). Since this product has been calibrated (Bouman et al., 2004) we expect the calibrated SF to be close to 1.0. We consider a calibration to be succesful if a value close to 1.0 is obtained which generally was the case. The least-squares adjustment also produces error-estimates of the scale-factors which very much reflect the number of points on the track.

6. RESULTS

The Scandinavian areas are not performing as well as the Australian and the Canadian areas and the reason is currently under investigation despite the new data selection, see section 3.2. Below is a figure with all V_{xx} scale factors from the first part of the GOCE mission calibration (including preliminary results) to May 2010. The results are divided area-wise so each vertical red line indicates a shift to next area. Scandinavian areas are the first and the third.

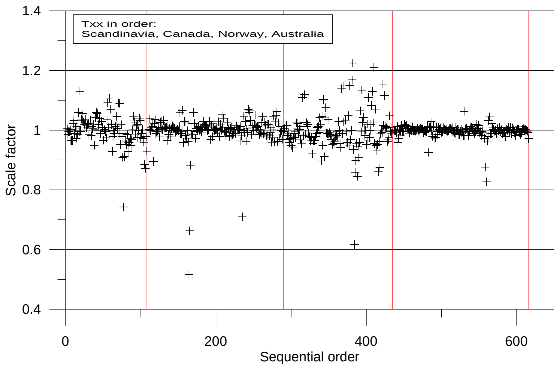

Figure 5. Scale factor results for V_{xx} for each calibration area.

The results of the gravity gradient validation in the calibration areas are divided in two periods from September 2009 – May 2010 and from May 2010 to ultimo 2010 marked with respectively red and green in the following figures. The periods are different with respect to the global gravity field model used, the covariance functions and the amount of ground data used.

The results show that the scale factors generally are close to 1 as expected and that the scale factor determination method and the ground data handling has improved from the start of the launch of GOCE.

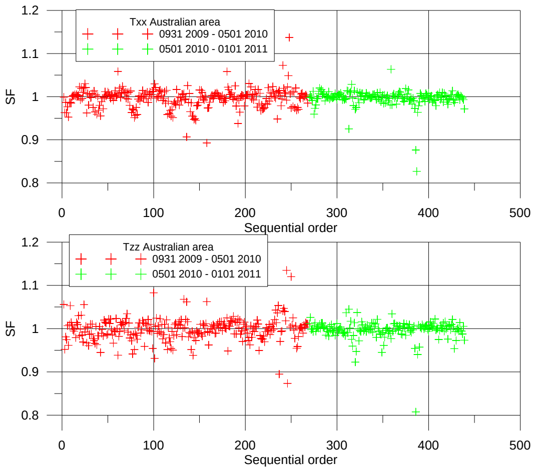

Figure 6. SF V_{xx} and V_{zz} for Australian area before (in red) and after (in green) reevaluating the calibration area data.

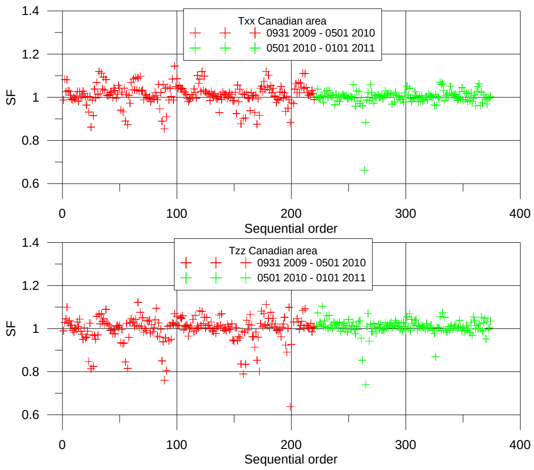

Figure 7. SF from Canadian area for V_{xx} and V_{zz} before and after reevaluating the calibration area data.

The Norwegian and Scandinavian areas are less affected by the re-evaluation of the calibration area data as the Canadian and Australian areas but still a positive effect can be traced in the tables listing the results for all SF in all areas listed below.

Table 3. V_{xx} SF – all areas

SF V_{xx}	0931 2009 - 0501 2010			0501 2010 – 0101 2011		
Area	N (SF)	Mean	RMS	N (SF)	Mean	RMS
Australia	267	0.996	0.023	170	0.996	0.021
Canada	220	1.015	0.057	153	1.000	0.054
Norway	197	1.039	0.0685	154	0.989	0.0456
Scandinavia	146	1.010	0.0273	85	1.007	0.0480

Table 4. V_{yy} SF – all areas

SF V_{yy}	0931 2009 - 0501 2010			0501 2010 - 0101 2011		
Area	N (SF)	Mean	RMS	N (SF)	Mean	RMS
Australia	267	0.989	0.142	170	0.993	0.056
Canada	220	1.004	0.330	153	1.003	0.109
Norway	197	1.014	0.171	154	0.928	0.184
Scandinavia	146	1.004	0.060	85	0.999	0.103

Table 5. V_{zz} SF – all areas

SF V_{zz}	0931 2009 - 0501 2010			0501 2010 - 0101 2011		
Area	N (SF)	Mean	RMS	N (SF)	Mean	RMS
Australia	267	0.994	0.055	170	0.996	0.028
Canada	220	1.001	0.099	153	0.999	0.095
Norway	197	1.033	0.088	154	0.985	0.065
Scandinavia	146	1.007	0.037	85	1.013	0.056

Table 6 V_{xz} SF – all areas

SF V_{xz}	0931 2009 - 0501 2010			0501 2010 - 0101 2011		
Area	N	Mean	RMS	N	Mean	RMS
Australia	267	0.995	0.030	170	0.998	0.025
Canada	220	1.006	0.056	153	1.007	0.031
Norway	197	1.035	0.072	154	0.989	0.036
Scandinavia	146	1.016	0.030	85	1.005	0.032

7. CONCLUSION

The method of calibration of scale factors with terrestrial data has shown to give satisfactory results. The validation can be made very fast – actually in the matter of hours – if required. It potentially makes the method a fast alarm bell and response to irregularities.

The method has potential to be improved – maybe significantly? – by improved targeting of both the MB when reducing the ground data with model data, and when targeting the MB width itself in the filtering process.

It must be noted that the data sets from Australia and Canada seem to produce much more homogenous and more stable calibration parameters than the ground data from the Scandinavian areas. These data consists of a variety of sources, and which probably should be investigated further in order to eliminate other ground data-”disturbances”.

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