UPWARD CONTINUATION OF DOME-C AIRBORNE GRAVITY AND COMPARISON TO GOCE GRADIENTS AT ORBIT ALTITUDE IN EAST ANTARCTICA

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An airborne gravity campaign was carried out at the Dome-C survey area in East Antarctica between the 17th and 22nd of January 2013, in order to provide data for an experiment to validate GOCE satellite gravity gradients. After typical filtering for airborne gravity data, the cross-over error statistics for the few crossing points are 11.3 mGal r.m.s., corresponding to an r.m.s. line error of 8.0 mGal. This number is relatively large due to the rough flight conditions, short lines and field handling procedures used. Comparison of the airborne gravity data with GOCE RL4 spherical harmonic models, confirmed the quality of the airborne data and that they contain more high frequency signal than the global models. First, the airborne gravity data were upward continued to GOCE altitude to predict gravity gradients in the local North-East-Up reference frame applying least squares collocation using the ITG-GRACE2010S field to degree and order 90 as reference field, which is subtracted from both the airborne gravity and GOCE gravity gradients. Then, the predicted gradients are rotated to the gradiometer reference frame using level 1 attitude quaternion

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data. The validation with the airborne gravity data is limited to the accurate gradient anomalies (T_{XX}, T_{YY}, T_{ZZ} and T_{XZ}) where the long-wavelength information of the GOCE gradients has been replaced with GOCO03s signal to avoid contamination with GOCE gradient errors at these wavelengths. The comparison shows standard deviations between the predicted and GOCE gradient anomalies of 9.9 mE, 11.5 mE, 11.6 mE and 10.4 mE (T_{XX}, T_{YY}, T_{ZZ} and T_{XZ}). A more precise airborne gravity survey of the southern polar gap which is not observed by GOCE would thus provide gradient predictions at a better accuracy, complementing the GOCE coverage in this region.

1. INTRODUCTION

An airborne survey (Dome-C) was carried out around Antarctica's Dome-C/Concordia station on 17-22 January 2013. The Dome-C survey aimed to collect radiometric and gravity data for calibration and validation of measurements made by the Soil Moisture and Ocean Salinity (SMOS) (Mecklenburg et al., 2012) and Gravity Field and Steady-state Ocean Circulation Explorer (GOCE) (ESA, 1999) satellites, two European Space Agency (ESA) Earth Explorer missions. The investigation was limited to a 300 km by 300 km area around the wintering station Concordia on Dome-C in East Antarctica (Fig.1). Field operations for both the radiometer and airborne gravity measurements are described in detail by Steinhage et al. (2013). Validation of the SMOS data is reported by Kristensen et al. (2013). By comparison to the Dome-C aerogravity data, this study aims to compare the upward continued airborne gravity data with GOCE gradients in the gradiometer reference frame (GRF) at satellite altitude. If this can be demonstrated to give satisfactory results, upward continuation of airborne gravity survey data proposed by Forsberg et al. (2011) could be an efficient solution to the Antarctic polar gap problem in GOCE (Rudolph et al., 2002; Tscherning et al., 2000).

Different methods and concepts have been suggested for the external validation of satellite gravity gradients. Validation with gravity field models are used in Visser et al. (2000), Bouman et al. (2004) and Bouman and Fuchs (2012). Numerical integration approach with truncated kernels using ground gravity data was suggested by Haagmans et al. (2003), Denker (2003), Pail (2003), Kern and Haagmans (2005), Wolf and Denker (2005). Eshagh (2009 and 2010) proposed the use of least-squares modified integral formulas for transformation of ground gravity onto satellite gravitational gradients. Eshagh (2011a) suggested validation of the radial gravitational gradient by the geoid undulation using semi-stochastic modifications of the Abel-Poisson integral equation. Šprlák et al. (2015), extending the study of Eshagh (2011a), presented new integral equations for all six components of the gradiometric tensor at satellite altitude and validated the GOCE vertical gravity gradient using satellite altimetry data at 11 mE level. Least squares collocation with ground gravity data was used for the same purpose by Arabelos and Tscherning (1998), Wolf and Denker (2005), Arabelos et al. (2007) and Pail (2003). Zielinsky and Petrovskaya (2003) suggested the use of gravitational gradients measured by a balloon-borne gradiometer whereas Tóth et al. (2005) suggested the use of terrestrial torsion balance observations to validate satellite gravitational gradients.

On the other hand, the least squares collocation method was applied to satellite gravitational gradients for regional gravity field recovery by Schwarz and Krynski (1977), Arabelos and Tscherning (1990), Barzaghi et al. (2009), Yildiz (2012) and Herceg et al. (2015). Implementation of integral formulas to satellite gravitational gradients for regional gravity field recovery were proposed by van Gelderen and Rummel (2001), Tóth et al. (2002), Martinec (2003), Bölling and Grafarend (2005), Eshagh (2011b). Radial base functions were used by Eicker et al. (2014) and

Lieb et al. (2014) whereas multi-scale approach was used by Freeden et al. (2002), Freeden and Nutz (2011) for regional gravity field recovery using satellite gravitational gradients.

This manuscript firstly describes the Dome-C airborne gravity data collection and comparison to GOCE spherical harmonic models and consequently focuses on the upward continuation of Dome-C airborne gravity to observed GOCE gradients in the GRF at orbital altitude using the LSC method.

2. AIRBORNE GRAVITY: THE DOME-C SURVEY

The gravity measurements at Dome-C were carried out on all the main lines of the regular planned flight pattern, as well as a few cross lines and opportunistic flights. The gravity measurements were made using the Alfred Wegener Institute's (AWI) Lacoste and Romberg S-56 gravimeter, upgraded by Zero-Length Spring (ZLS) corporation for airborne data collection. This kind of instrumentation is common in airborne surveys worldwide, including in Antarctica (e.g. Forsberg et al., 2011; Riedel et al., 2012). The basic principle of the instrument is a servo-feedback spring system on a gyro stabilized table. To obtain sufficiently accurate results it is essential to understand and model the numerous potential errors in the system, especially scale factors and platform off-level errors. For more details of airborne gravity measurement principles and corrections see e.g. Olesen (2002) and Forsberg and Olesen (2010).

The airborne gravity survey at Dome-C took place in the period 17-22 January 2013, with gravity additionally collected on the ferry flights to Dome-C from Novolazarevskaya via South Pole. The list of the survey flights for the Dome-C air campaign can be found in Steinhage et al. (2013).

As gravity cannot be measured during aircraft turns, and filters are needed to settle the measurements after turns, only parts of the longer lines could be processed to give useful gravity data, cf. Fig. 2. The airborne gravity processing was done at AWI, using software originally based on code from Olesen (2002), and further modified over a number of years by U. Meyer, Bundesanstalt für Geowissenschaften und Rohstoffe (BGR)-Germany and AWI. The measurements were tied to an absolute International Gravity Standardization Net (IGSN) gravity reference point at University of Cape Town: reference value 979616.80 mGal. Then, the measurements were transferred to Novo runway, Amundsen-Scott South Pole Station and Dome-C, using measurements with a portable Lacoste and Romberg land gravity meter (serial number G744). A recent absolute g-value measured by Finnish Geodetic Institute at Novolazerevskaya in Antarctica (Fig. 1) has been used for a final adjusted value for the Dome-C reference gravity g=981861.29 mGal. The revised value was used in this manuscript. GPS positions, velocities and accelerations were computed with the commercial "Waypoint" software package "GrafNav" (NovAtel Inc. Calgary, Canada), which is state-of-the art kinematic GPS software allowing both differential phase and precise point positioning techniques to be used with the highest precision. Filtering used in the processing was a 3-stage forward-backward Butterworth filtering with time constant 20 s, and clipping 200 s, a typical set up for airborne gravimetry.

The airborne gravity data was processed without use of geoid heights, and the anomalies are therefore to be considered as gravity disturbances (Fig. 2). The gravity disturbances were converted to free-air gravity anomalies using geoid values from GOCE RL4 "direct" spherical harmonic model (Bruinsma et al., 2013). The conversion from gravity disturbances to gravity anomalies is a geodetic convention, in line with common global practice for airborne gravimetry; with the GOCE geoid being accurate at the 0.5 m level or better, the associated error in applying the geoid correction is less than 0.2 mGal and thus negligible, compared to the accuracy of the airborne data.

The cross-over error statistics of the free-air gravity anomalies for the few cross-lines are shown in Fig. 3, indicating a relatively noisy survey of 12.8 mGal r.m.s. error for 22 line crossings. Eliminating two very large outliers, the survey cross-over error is at 11.3 mGal r.m.s., corresponding to an r.m.s. line error of 8.0 mGal. This number is relatively large due to the rough flight conditions, short lines and field handling procedures used.

3. UPWARD CONTINUATION AND COMPARISON TO OBSERVED GOCE DATA

a. Methodology

The airborne gravity data were compared with GOCE RL4 "direct" spherical harmonic model data, and upward continuation was done to GOCE orbit altitude. This processing was done with the GRAVSOFT suite of programs (Tscherning et al, 1992; Forsberg and Tscherning, 2008), implementing the upward continuation using LSC method.

In the LSC method the upward continuation to gravity gradients is performed by solving a set of equations, of dimensions equal to the number of data

$$\hat{s} = C_{sx}\left[C_{xx} + D\right]^{-1} x \tag{1}$$

where the signal s is the desired set of gradient components, x are the airborne gravity observations, and C_{sx} and C_{xx} the cross- and auto-covariances of the gravity field components, derived from a self-consistent covariance model, and D the errors. For details see Heiskanen and Moritz (1967). The

LSC method is implemented by the latest version of GRAVSOFT's GEOCOL program, GEOCOL19, using multi-processing (Kaas et al., 2013).

For the least squares collocation computation a spherical harmonic reference field

$$T_{ITG\,2010S}(r,\varphi,\lambda) = \frac{GM}{R}\sum_{n=2}^{90}\left(\frac{R}{r}\right)^{n+1}\sum_{m=0}^{n}\left(C_{nm}\cos m\lambda + S_{nm}\sin m\lambda\right)P_{nm}(\sin\phi) \qquad (2)$$

is used in a remove-restore fashion, where r,φ,λ are spherical geocentric coordinates of the computation point (radius, latitude, longitude), R is the mean semi-major axis of the Earth, GM is the gravitational constant times mass of the Earth, n and m are spherical harmonic degree and order, respectively, P_{nm} are fully normalized Legendre functions and C_{nm}, S_{nm} are fully normalized Stokes' coefficients.

In the Dome-C computations we have used the ITG-GRACE2010S field to degree and order 90 as the fundamental reference field. The degree 90 reference field corresponds to a spherical harmonic resolution of 2°, smaller than the size of the Dome-C survey area. It is also a spherical harmonic range in which the accuracy of ITG-GRACE2010S is very good, being determined by GRACE data and therefore independent of GOCE.

b. Data and Covariance Function Computation

The AWI-processed airborne gravity data were compared to the GOCE "direct" RL4 model, after corrections removing the effects of the atmosphere (approx. +0.6 mGal), and adjustment of the gravity tie measurements provided by AWI in the light of the new absolute measurements at Novolazarevskaya. The estimated error in the adjusted *g* value at Dome-C is 0.2 mGal. Using this value, the AWI data were corrected for the atmosphere and geoid undulations, using the GOCE direct RL4 model, giving the final free-air anomaly data set, used for all computations in the following.

Statistical comparisons of the AWI airborne free air gravity anomaly data to the GOCE RL4 "direct" and "timewise" models (Pail et al., 2011), as a function of maximal degree, are shown in Table 1. The comparison in Table 1 shows that the standard deviation of the difference seems to decrease consistently with the higher cut-off in the RL4 fields, all the way to the maximal degree (260 or 250). The small bias of ~ 1 mGal is likely due to the limited size of the comparison region. Fig. 4 shows the airborne and GOCE gravity anomalies obtained from GOCE RL4 "direct" model to degree 200.

GOCE observed the six gravitational gradients in the GRF that co-rotates with the satellite, where the V_{XX}, V_{YY}, V_{ZZ} and V_{XZ} gradients have been observed with high accuracy in a measurement band (MB) that roughly corresponds to a spatial resolution of 80 – 1500 km, and error increase above and below the MB (Bouman et al., 2011a). One could transform the measured gradients into the local North-East-Up reference frame using model values for the less accurate V_{XY} and V_{YZ} components and replacing the GOCE gradient signal below the MB with model values also for the accurate gradients, circumventing the affection through the GOCE gradient long wavelength errors (Fuchs and Bouman, 2011). However, this inherently introduces a mixture in the MB of measured and model gradients in the local North-East-Up reference frame, which may be undesirable. For the GOCE validation, it is therefore preferable to do the validation directly in the GRF, rather than the local North-East-Up reference frame. A persisting problem of the GOCE gradients in the GRF, however, is the error increase above and below the MB. We therefore used band-pass filtered gravity gradients, replacing the signal below the MB with signal derived from GOCO03s model (Mayer-Gürr et al., 2012), where the model gradients were filtered with the complement of the band-pass filter to guarantee that the sum of the band-pass filtered GOCE and low-pass filtered model gradients contains the full signal content. The cut-off frequency of 10 mHz in the lower MB roughly corresponds to spherical harmonic degree 54. In other words, GOCO03s has little or no contribution above degree 54, whereas the GOCE gradients do not contribute below degree 54. Because we subtract the reference model ITG-GRACE2010S up to degree 90 from the GOCE-based gradients and because GOCO03s mainly contains GRACE information for low degrees, it is reasonable to assume that the error of the reduced GOCE-based gradients mainly reflects the error of the original GOCE gradients in the MB above 10 mHz.

GOCE gravity gradients – combined with GOCO03s for the long wavelengths – were selected in a central region (76-73°S, 113-126° E) for the year 2011, yielding 4 × 19208 data points in total. From the GOCE-based GRF gravity gradient data the ITG-GRACE2010S contribution up to degree 90 was subtracted and gradient anomalies (T_{XX}, T_{YY}, T_{ZZ} and T_{XZ}) are obtained.

The prediction of gravity gradient anomalies in the local North-East-Up reference frame from the airborne gravity anomalies has been done using the LSC method described in Tscherning (1993), as implemented in the GEOCOL19 program. First, gravity gradient anomalies are predicted in the GOCE orbit points in the local North-East-Up reference frame. Next the predicted gradients are rotated to the GRF using as input the level 1 attitude quaternion data that define the transformation between the inertial reference frame and the GRF, as well as level 2 precise orbit information that allows to derived the transformation from the inertial reference frame to the local North-East-Up reference frame (Gruber et al., 2010). Subsequently, the upward continued gravity gradient anomaly data from the airborne survey were compared to the GOCE gradient anomalies.

Airborne free air gravity anomaly data of 6444 points were selected (pixel binning to approximately 2 km resolution), to which an empirical, self-consistent covariance function of the Tscherning and Rapp (1974) type was fitted. Fig. 5 shows the estimated and fitted covariance model, which represents a typical data covariance function (after subtraction of the ITG-GRACE2010S up to degree 90 reference field), with the depth to the Bjerhammar sphere of 5.1 km. This covariance function has been used to predict gravity gradient anomaly errors at altitude in the local North-East-Up reference frame, using the GRAVSOFT program GEOCOL19 taking the standard error of the airborne gravity anomaly as 8 mGal to investigate the error propagation of the airborne gravity survey to the estimated gravity gradients. We obtained estimated gradient anomaly errors of 5.9 mE, 5.5 mE, 8.0 mE and 6.8 mE for T_{XX}, T_{YY}, T_{ZZ} and T_{XZ} at altitude in the local North-East-Up reference frame, respectively, showing that the available airborne gravity data can validate the GOCE gradients, considering that the expected noise of GOCE gravitational gradients for short time intervals is about 10 mE (Bouman et al. 2011b; Šprlák et al. 2015).

Subsequently, we assumed a standard error in the airborne gravity anomaly of 3 mGal r.m.s. (this avoids filtering surface data too heavily, and partially takes into account the surface data selection process) to predict gravity gradient anomalies and their errors at altitude in the local North-East-Up reference frame. These were then rotated to the GRF to compare with GOCE gradients in the next section.

c. Comparison of observed and predicted GOCE gravity gradients

Figures 6 shows the predicted GOCE gradients (minus the reference field) by LSC, and Figure 7 shows the difference between GOCE observations and upward continued values for ascending and descending tracks. As the gravity gradients have directional sensitivity and especially the GRF X-axis and Y-axis have a different orientation for ascending and descending tracks, T_{XX}, T_{YY} and T_{XZ} are plotted separately for ascending and descending tracks. Partially the differences are spatially correlated, which may be caused by remaining long wavelength errors in the airborne or GOCE data or both. In addition, some satellite tracks show larger differences that may be caused by unflagged erroneous GOCE data, e.g., after filter re-initialization.

Table 2 shows the statistics of the comparison of gradient anomalies. This comparison shows standard deviations, between the predicted and GOCE gradient anomalies of 9.9 mE, 11.5 mE, 11.6 mE and 10.4 mE in the gradient anomalies $T_{XX,}$ T_{YY}, T_{ZZ} and T_{XZ} respectively, thus validating GOCE measurements in agreement with the expected noise of GOCE gravitational gradients which is about 10 mE (Bouman et al.,2011b; Šprlák et al.,2015).

4. CONCLUSION

The Dome-C gravity survey successfully covered a hitherto unsurveyed and logistically very difficult region of Antarctica. The survey provided a consistent gravity data set with a reasonably small bias of 1 mGal compared to GOCE, and an estimated track r.m.s. noise of 8 mGal. We believe that the bias is primarily due to the small size of the survey area, as airborne gravity is usually biased by less than 1 mGal (Forsberg and Olesen, 2010).

The airborne gravity data agrees with the GOCE data with ~14 mGal r.m.s. difference; results for the "direct" and "timewise" R4 spherical harmonic models are nearly identical. This difference is mainly due to the omission error that has its origin in the limited resolution of GOCE. The comparison for various spherical harmonic degrees shows that the GOCE data provide an improving r.m.s. fit to the airborne data with increasing degree of the maximal spherical harmonic expansion, all the way to the maximal degree (250 for timewise, and 260 for direct).

Collocation upward continuation of the airborne gravity anomaly data to gravity gradient anomalies in the North-East-Up reference frame and transformation to GRF at orbital altitude were carried out for the accurate gradient anomalies (T_{XX}, T_{YY}, T_{ZZ}, T_{XZ}), using quaternions of the GOCE level 1 data. This comparison shows a common error of ~10 mE for gradient anomalies (T_{XX}, T_{YY}, T_{ZZ}, T_{XZ}) thus validating GOCE gradients at this level.

A more precise airborne gravity survey of the southern polar gap as proposed by Forsberg et al. (2011) would thus be expected to provide gradient predictions at a better accuracy, complementing the coverage of GOCE in this region.

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Figure Captions

Figure 1. The location of the Dome-C airborne gravity survey. Flight tracks are indicated by the yellow lines. The red line indicates the ferry flight from Neumayer to Dome-C.

Figure 2. Dome-C gravity disturbances (colour-coded), on top of flight lines (black). Units: mGal.

Figure 3. (a) Cross-over errors in the free-air gravity anomalies of Dome-C (b) the histogram of the absolute value of the track misties (green are "good" and yellow "bad" cross-overs relative to 10 mGal). The estimated r.m.s. error of the airborne gravity survey, based on the cross-over analysis, is 8.0 mGal.

Figure 4. Airborne free-air gravity anomalies and free-air gravity anomalies calculated from GOCE Direct RL4 direct global geopotential model up to spherical degree and order 200. Color scale is in mGal.

Figure 5. The empirical covariance function (blue) derived from the airborne gravity data, and the corresponding fitted analytical Tscherning-Rapp covariance model (red). This is typical for a good fit.

Figure 6a. Gradient anomalies in GRF transformed from predicted gradient anomalies in the local North-East-Up reference frame, minus ITG-GRACE10S to degree 90, for ascending tracks (left) and descending tracks (right) (a) T_{XX} (b) T_{XZ} (c) T_{YY}. Colour scale -0.04 to 0.04 Eötvös.

Figure 6b. Vertical gravity gradient anomalies in GRF transformed from predicted gradient anomalies in the local North-East-Up reference frame, minus ITG-GRACE10S to degree 90, T_{ZZ}. Colour scale -0.04 to 0.04 Eötvös.

Figure 7a. Differences between GOCE gradient anomalies in GRF and predicted gradient anomalies in GRF for ascending tracks (a) T_{XX} (b) T_{XZ} (c) T_{YY} (d) T_{ZZ}. Colour scale is -0.04 to 0.04 Eötvös. Gradient anomalies are predicted in the local North-East-Up reference frame and transformed to gradients in GRF.

Figure 7b. Differences between GOCE gradient anomalies in GRF and predicted gradient anomalies in GRF for descending tracks (a) T_{XX} (b) T_{XZ} (c) T_{YY} (d) T_{ZZ}. Colour scale is -0.04 to 0.04 Eötvös. Gradient anomalies are predicted in the local reference North-East-Up frame and transformed to gradient anomalies in GRF.

Figures

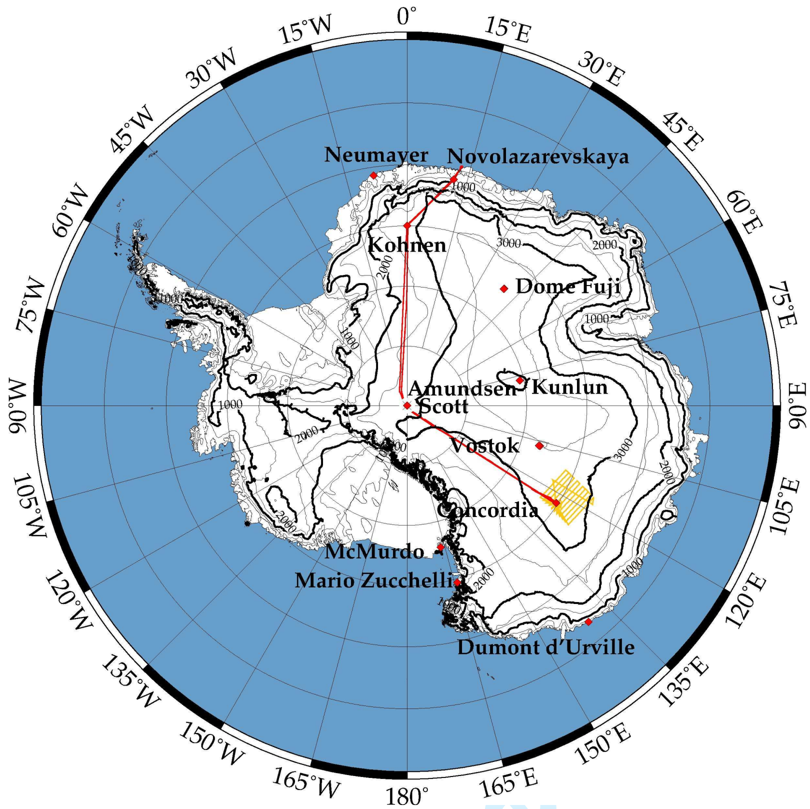
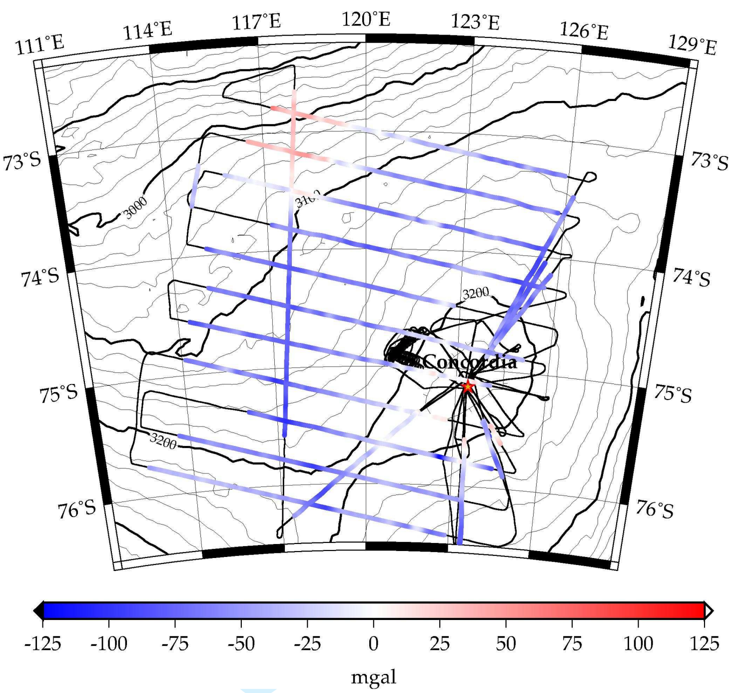


Figure 1. The location of the Dome-C airborne gravity survey. Flight tracks are indicated by the yellow lines. The red line indicates the ferry flight from Novolazarevskaya.



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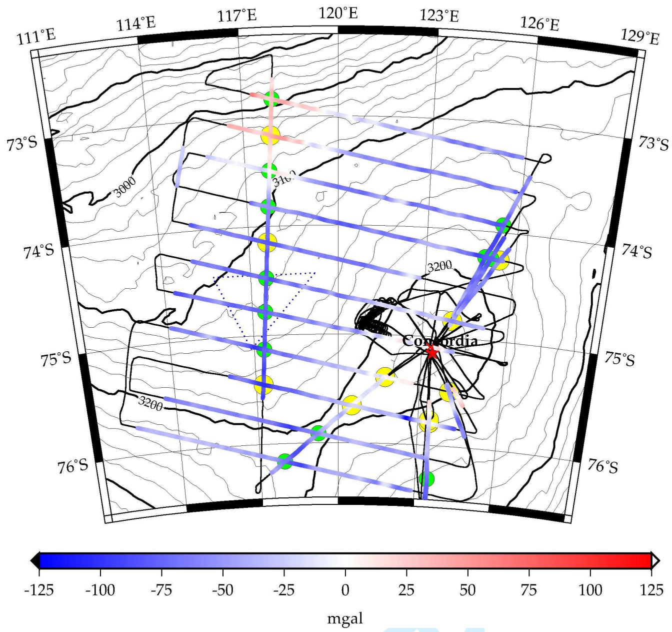
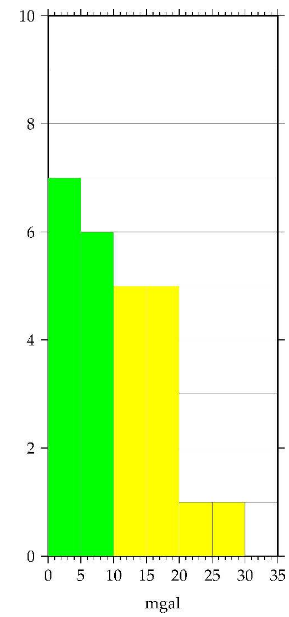
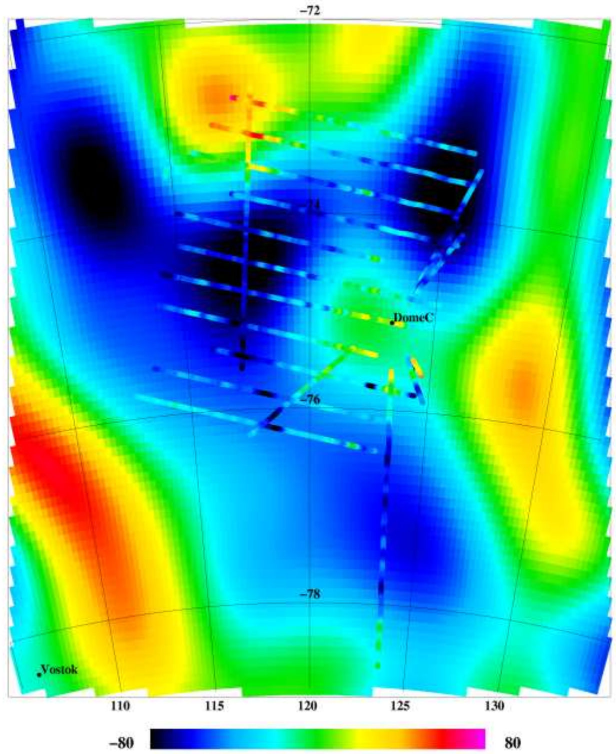




(a) (b)

Figure 3. (a) Cross-over errors in the free-air gravity anomalies of Dome-C (b) the histogram of the absolute value of the track misties (green are “good” and yellow “bad” cross-overs relative to 10 mgal). The estimated r.m.s. error of the AWI-processed airborne gravity survey, based on the cross-over analysis, is 8.0 mGal.



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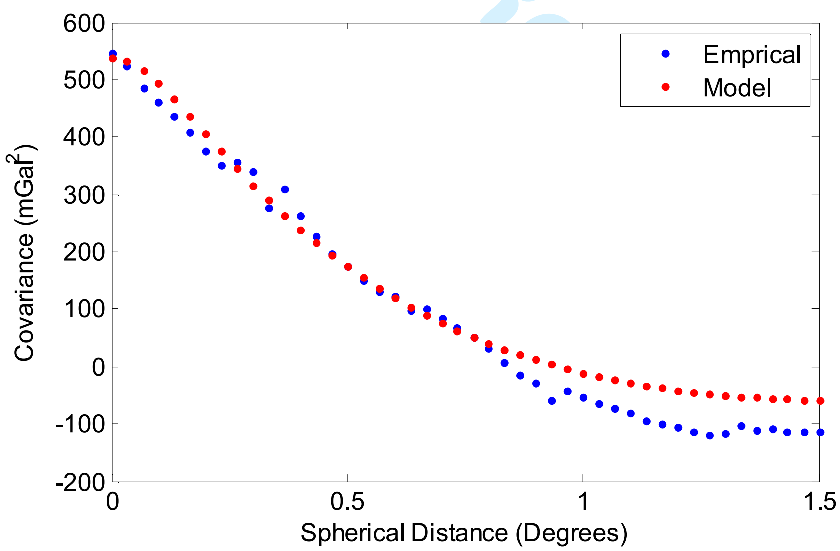

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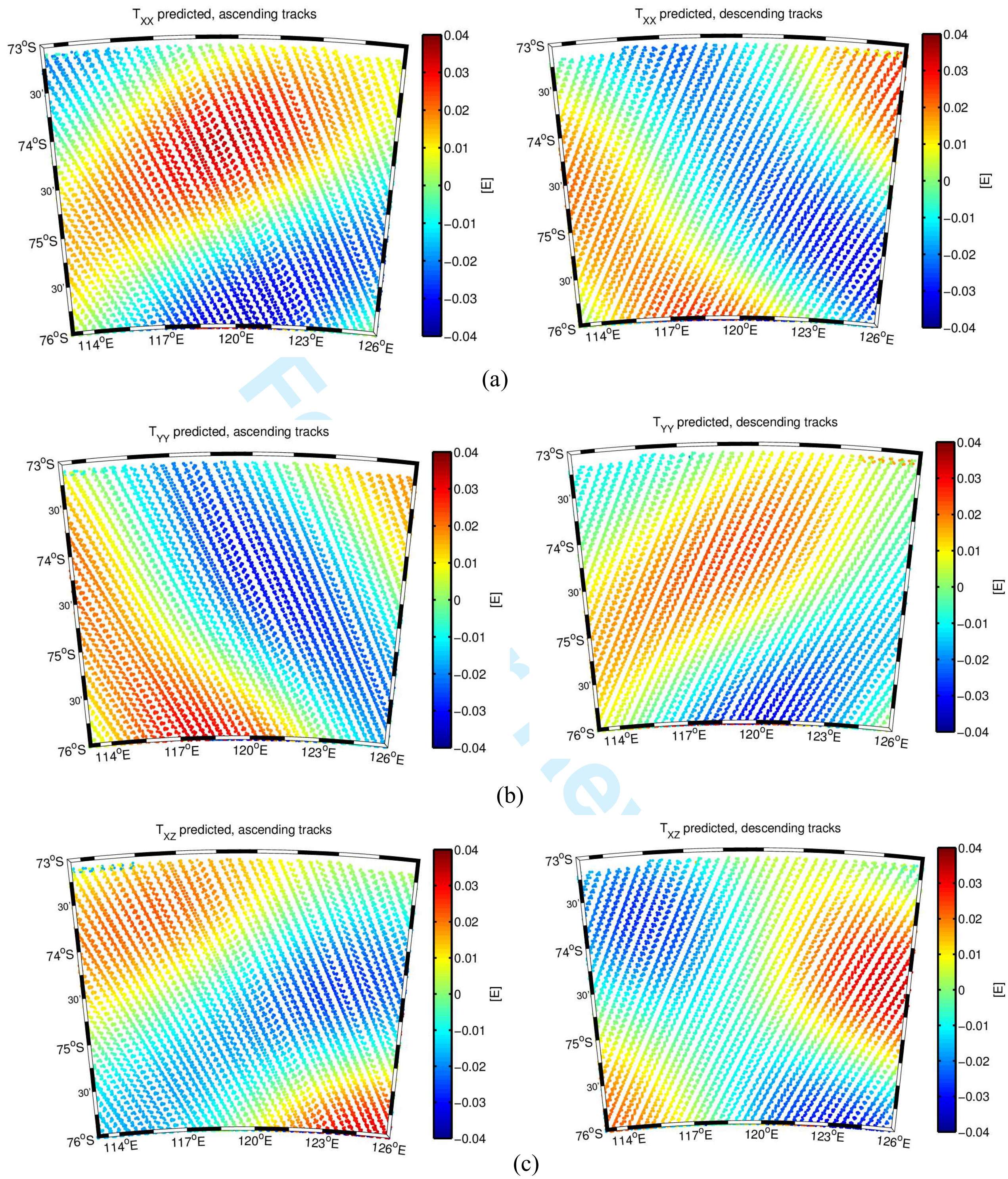


Figure 6a. Gradient anomalies in GRF transformed from predicted gradient anomalies in the local North-East-Up reference frame, minus ITG-GRACE10S to degree 90, for ascending tracks (left) and descending tracks (right) (a) T_{XX} (b) T_{XZ} (c) T_{YY}. Colour scale -0.04 to 0.04 Eötvös.

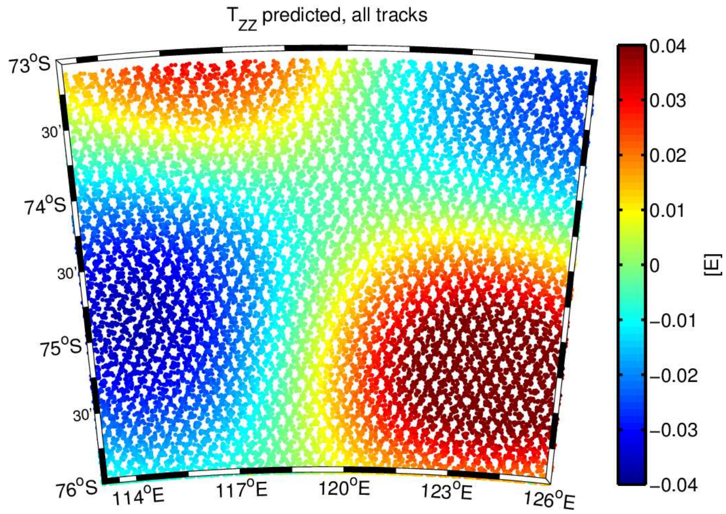
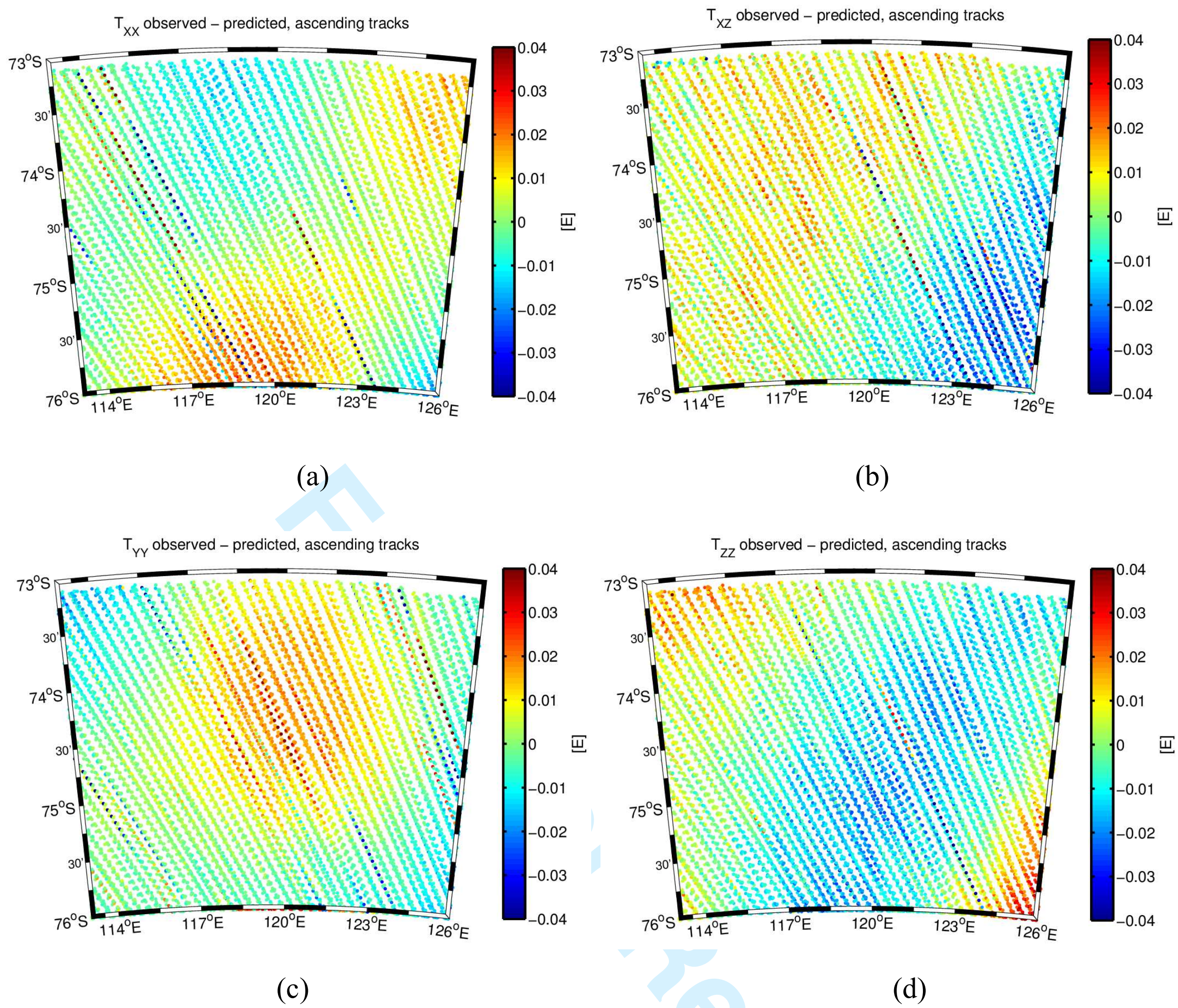


Figure 6b. Vertical gravity gradient anomalies in GRF transformed from predicted gradient anomalies in the local North-East-Up reference frame, minus ITG-GRACE10S to degree 90, T_{ZZ}. Colour scale -0.04 to 0.04 Eötvös.



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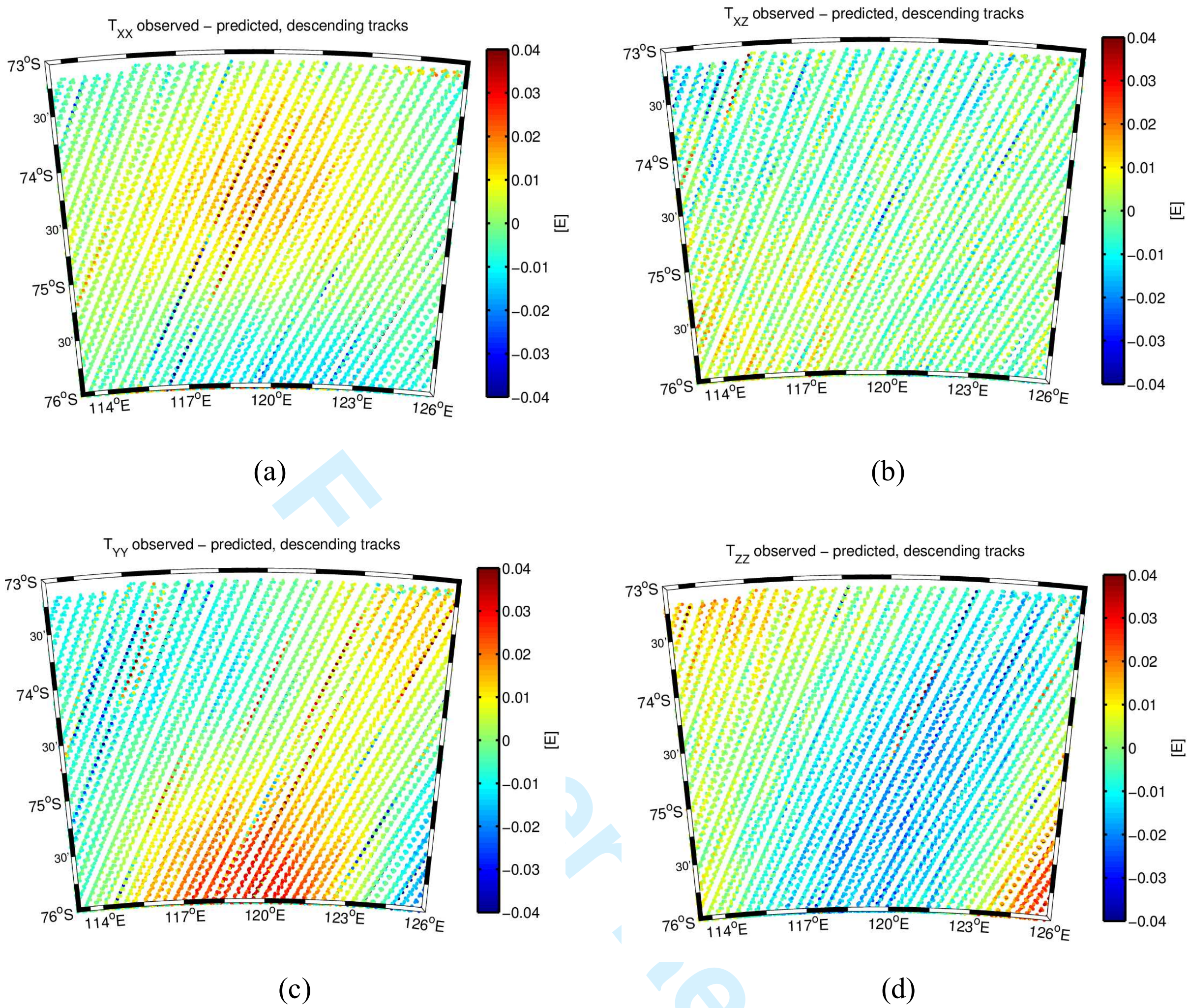

Figure 7b. Differences between GOCE gradient anomalies in GRF and predicted gradient anomalies in GRF for descending tracks (a) T_{XX} (b) T_{XZ} (c) T_{YY} (d) T_{ZZ}. Colour scale is -0.04 to 0.04 Eötvös. Gradient anomalies are predicted in the local North-East-Up reference frame and transformed to gradient anomalies in GRF.

Tables

Table 1. Comparison of Dome-C airborne free air gravity anomaly data to GOCE RL4 expansion (Unit is mGal).

Data for statistics	Max.	Min.	Mean	Std.dev.
Observed airborne data (51303 points)	67.9	-116.0	-40.7	28.9
Observed minus ITG-GRACE2010S to degree 90	73.9	-77.9	-2.6	24.9
Observed minus GOCE direct (max degree 120)	64.1	-87.6	0.9	22.3
- direct (max degree 180)	52.4	-93.4	0.7	18.1
- direct (max degree 200)	58.1	-91.7	2.4	16.3
- direct (max degree 220)	62.5	-97.4	1.5	15.0
- direct (max degree 250)	60.6	-96.9	1.1	14.4
- direct (max degree 260)	55.0	-91.9	0.9	16.3
Observed minus GOCE timewise (max deg 120)	64.6	-86.5	0.9	22.6
- timewise (max deg 180)	52.5	-93.1	0.7	18.1
- timewise (max deg 200)	57.5	-91.2	2.4	16.2
- timewise (max deg 220)	63.7	-95.9	1.4	14.9
- timewise (max deg 250)	62.2	-96.3	0.5	14.6

Table 2. Statistics of collocation upward continuation comparisons of GOCE gravity gradient (GG) anomalies in the GRF (unit: milliEötvös [mE]).

Data statistics	Txx	Txz	Tyy	Tzz
GOCE GG – GOCO03S (degree 90)				
mean	1.5	-3.0	1.7	-3.4
std.dev.	17.0	19.0	16.0	26.0
max.	106.6	93.7	102.6	111.2
min.	-113.7	-87.1	-73.6	-110.1
GOCE GG – predictions				
mean	1.9	-0.6	2.4	-4.5
std.dev.	9.9	10.4	11.5	11.6
max.	88.9	111.8	102.3	92.5
min.	-90.1	-72.7	-72.0	-91.9
Predicted error (mean) by collocation in the North-East-Up reference frame	5.8	6.7	5.5	7.9