The application of GOCE satellite gravity data for basin and petroleum system modeling, A case-study from the Arabian Peninsula

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GOCE gravity data can improve the understanding and modeling of the Earth's interior. It can help to gain new insights into the structure of the crust and the lithosphere. With careful processing and integration with additional gravimetric data, GOCE can be used to study sedimentary basins and assist in hydrocarbon exploration in underexplored areas. In this study, GOCE gravity data is used to investigate the maturity of the main source rocks in the remote Rub' al-Khali basin in Saudi Arabia. GOCE gravity data, in combination with other data, is used to better identify the structure of the crust and the lithosphere in the region. The improved model of the crust and the lithosphere allow us to model the basal heat flow and its spatial and temporal variations in the basin. Based on the improved heat flow model, the maturity of the main source rocks is estimated. The Rub' al-Khali basin (Saudi Arabia), is an interesting hydrocarbon province in the Middle East. However the basin is underexplored because of its remoteness and harsh environment. Available data show unexpected maturity variations in the basin. A possible reason behind that could be the heat flow in the basin which could be caused by anomalous structures in the crust and possibly the underlying lithosphere. Using the gravity anomaly maps obtained from GOCE data, in combination with land-measured gravity data, gravimetrical basement inhomogeneity and Moho topography are determined. A model of the crust and lithosphere of the study area is obtained. The structural model of the crust and lithosphere, is used for modeling the basal heat flow within the basin. We included information about the deep structures as well as the sedimentary cover that help us reconstruct the evolution of the basin. The maturity of the source rocks in the basin are estimated based on the modeled heat flow and regional maturity maps are produced of the Paleozoic and Mesozoic plays in the Arabian Peninsula. Preliminary results show that heat flow in the basin is quite sanative to variations in the deep structures such as the Moho and the base lithosphere. Available models of the Moho and the lithosphere seem to be unsuitable for explaining heat flow and maturity trends at present day in the region. GOCE gradient maps over the region show some interesting anomalies that can't be fit by gravity models of known crust and the lithosphere models. The results of fitting the observed GOCE gradient components over the Rub' al-Khali basin are expected to result in new heat flow trends in the region. Consequently, the new maturity maps of Paleozoic source rocks will provide new insights into the prospectivity of the petroleum systems in the region.

GOCE Data and Formats

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GOCE has been collecting data since its launch, on March 2009. To date, three generations of Gravity solutions have been released. GOCE data availability, data format, content, and the software available for processing, is presented, together with the plans for the next gravity solutions release.

An introduction to the GOCE error variance covariance products: A user's perspective

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A novel feature of the GOCE mission is that the full error variance covariance information is provided for each of the gravity models released. However, for many end users the nature of these products will be unfamiliar. Their large size may also present a barrier to their use. In this presentation I shall present a beginner's guide to the GOCE gravity field products and the software that has been developed to facilitate their use. As way of demonstration, I will outline the steps that must be taken to derive geoid error magnitudes and error covariances. I will examine the spatial character of these error fields, and suggest ways that the computational burden may be lessened. A comparison of the errors for the 8 GOCE gravity models released to date will be provided, highlighting the major differences between the three flavours of GOCE models, and how the nature of the errors have changed between successive generations of the models as more data has been collected. Finally, I shall illustrate the use of the GOCE gravity information, with an example from oceanography.

GOCE Gravity Gradients for Solid Earth Sciences

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The GOCE gravity gradients contain highly accurate and detailed gravity field information. Their use in Earth sciences, however, may not always be straightforward because the original gradients are given in the gradiometer reference frame, not all gradients are measured with equal accuracy, the data may contain jumps, etc. For this reason the GOCE gradients are also made available in Earth related reference frames with additional data editing. Not only are gradients available at satellite altitude, but also close to the Earth's surface. We discuss which gradient products are available to the user community and address the pros and cons of the different products.

Overview GOCE+ Studies

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The ESA program Support to Science Element (STSE) aims at providing scientific support for both future and on-going missions, for example by offering support to the scientific use of ESA Earth Observation missions' data and to the promotion of the achieved results. GOCE+ is part of the thematic area "Solid Earth" and currently five studies are part of GOCE+. We give a brief summary of GOCE+ HUG and GOCE+ AirDensity, which deal with height systems and air density and wind retrieval respectively. In addition, we summarize GOCE+ GDC (Solid Earth) and GOCE+ Time-Variations (temporal gravity field from GOCE). Finally, we discuss in more detail an overview of the GOCE+GeoExplore study, which aims at lithospheric modeling and geophysical exploration.

The Earth's time-varying gravity field observed by GOCE

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The aim of the GOCE mission is to determine the Earth's time-averaged gravity field. Nevertheless, the long than planned observation period, the satellite's low orbit and the high accuracy of the gravity gradiometer may all contribute to GOCE's ability to see gravity variations with time. We present a feasibility study in which the signal due to Greenland ice melt and megathrust earthquakes is forward modelled in terms of gradient signal at GOCE altitude. We also present our tailored analysis of the GOCE data and the comparison with the forward models. Our conclusion is that temporal gravity field signal might be visible in the GOCE gradient data.

Unmapped Geologic Macrostructures identified with GOCE

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The observations of the satellite GOCE have allowed to achieve a qualitative leap ahead in the spectrum of applications feasible with gravity data. The new global field has an improved resolution of 80km and precision of 1mGal; this resolution is sufficient to study the crustal thickness variations and the upper crustal structure. Geological macrostructures accompanied by density variations can be mapped for the first time by a global satellite field in continental areas, which opens a new series of applications in geophysical exploration. We consider an area where terrestrial observations are scarce due to difficult terrain, making the new GOCE-derived field the best gravity field today available. This area is located to the north of the Congo craton, and straddles the countries of Cameroon, Central African Republic, Sudan, South Sudan, Gabon, Democratic Republic of Congo and Congo. The area is of general interest, as it is in a key position of the continent Gondwana, from which the South American and African continents were formed. The Congo craton is an old crustal nucleus with a deep lithospheric root, which constitutes an indeformable unit, against which the surrounding crustal units are defomed. We use the GOCE satellite to unscramble these deformations, which cover 2 Ga years of Earth history, and have produced important mineral deposits as gold, platinum and iron. We first show that the GOCE observations perfecetly correlate to known geologic units. We then demonstrate that GOCE allows to differentiate the geologic structures, identifying the margins of the high density units formed by metamorphic addensations of rocks, discriminating between different geologic units. The results have direct applicability in mineral exploration and show that the GOCE observations constitute an innovative tool of mineral exploration in remote areas.

Gravity and topography signature of global petrological lithosphere

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The Earth's interior is largely inaccessible and geophysical observations provide the main source of information. Seismic data have been extensively used to study the structure of the crust and the upper mantle. However, seismic data alone are not able to constrain lateral variations in composition, being mostly sensitive to temperature. Adding gravity data and topography, which depend on the density distribution is, therefore, essential. In our work, we have used available global seismic models to derive full density and viscosity distribution of the Earth's mantle on the basis of current knowledge of material properties. We added petrological constraints to determine the effect of first-order lateral variations in composition in the Earth's lithosphere. Modeling a chemically depleted, petrological lithosphere gives cratonic temperatures at 150 km depth that are only 100 K hotter than those obtained assuming pyrolite, but density is ∼0.1 g cm−3 lower. We determined the geoid and topography associated with the density distributions by computing the instantaneous flow with an existing code of mantle convection, STAG-YY (Tackley 2008). Models with and without lateral variations in viscosity have been tested and crustal model CRUST 2.0 (Bassin et al. 2000) was assumed. Models that include a petrological lithosphere fit the geoid, gravity and topography better than those obtained by assuming no lateral compositional variations. Surprisingly, the improvement is mostly due to effects on very large-scale (harmonic degree < 6) structure, mostly related to oceanic lithosphere. The signature of continental lithosphere worsens the fit, even in simulations that assume an extremely viscous lithosphere. Therefore, an overall less depleted, and thus less buoyant, continental lithosphere is required to explain gravity data. The seismic tomography models are not able to reproduce accurately the thermal structure of the oceanic lithosphere. All of them show their lowest seismic velocities at∼100 km depth beneath mid-oceanic ridges and have much higher velocities at shallower depths compared to what is predicted with standard cooling models. Despite the limited resolution of global seismic models, this seems to suggest the presence of an additional compositional complexity in the lithosphere. Currently, we are expanding our interdisciplinary approach to account for crustal variations in composition and temperature and to extract robust physical constraints from seismic data. In this framework, the resolution of GOCE gravity data will allow us to move towards high resolution. The combined interpretation of GOCE gravity with seismic data is indeed promising for improving considerably the knowledge of thermo-chemical conditions of the Earth's lithosphere.

Towards an integrated model of Earth's crustal density structure: gravity and topography effects on global scale

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An accurate knowledge of the Earth's crustal density structure plays a central role in our understanding of its composition and thermal conditions and it is also crucial to obtain a correct seismic interpretation of the Earth's mantle. Nowadays the most updated and used crustal model is the CRUST 2.0 (Bassin et al., 2000) in which the density structure of the crust is inferred from empirical Vp-density relationships. Our first step is to compute the crustal density structure trough a self-consistent thermodynamical modeling starting from average composition for upper, middle and lower crust (Rudnick and Gao, 2003). This way, the relationship between Vp and density exploits further petrological constraints and knowledge of mineral properties. Subsequently we determine the influence on gravity, geoid and topography of the CRUST2.0 and the computed density distribution by using the same mantle structure. On this purpose, we use an instantaneous mantle-flow computation with the code STAGYY (Tackley et al., 2005). Both results are compared with observations. We are now setting up a complete forward procedure for inverting gravity data for crustal and mantle density structure. We will exploit the information about seismic structure, but refining the 3-D composition on the base of gravity data, that are characterized by a much higher sensitivity to composition than seismic data. The GOCE data are now giving us the opportunity to investigate the compositional structure of the Earth's crust at unprecedented detail. Our preliminary result shows the strong potential of such an interdisciplinary approach to study the Earth's interior.

GOCE+ GeoExplore for geophysical research

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In the project GOCE+ GeoExplore, we explore how GOCE gravity gradient data can improve modeling of the Earth's lithosphere and thereby contribute to a better understanding of the Earth's dynamic processes. The idea is to invert satellite gravity gradients and terrestrial gravity data in the well explored and understood North-East Atlantic Margin and to compare the results of this inversion, providing improved information about the lithosphere and upper mantle, with results obtained by means of models based upon other sources like seismics and magnetic field information. Transfer of the obtained knowledge to the less explored Rub' al Khali desert is foreseen.

Depth sensitivity GOCE gravity gradients for lithospheric modelling

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Modeling of the crustal structure on a regional scale is often affected by uncertainties in the upper mantle structure. For example, the gravity field might feature a regional trend, which reflects density changes in the upper mantle. This long-wavelength part in the signal can be associated with the base lithosphere or simply removed from the data. Gravity gradient data are less affected by such regional trends, which makes them a useful addition to optimize model parameters and to separate the crustal and sub-crustal density structure. Here, we discuss the sensitivity of the gravity gradient data acquired by the GOCE satellite mission to the lithospheric density structure. We make use of a well-defined model of the Northeast Atlantic region, which is based on the compilation of a series of geophysical data sets and optimized against the gravity field. The 3D model shows significant variations in the composition and thermal structure of the lithospheric mantle from the oceanic domain towards the continental shelf and the Scandinavian mainland. This variation is well imaged by teleseismic data and has a huge effect in the gravity field. To test the sensitivity on the gravity gradients, we forward calculated all gravity gradients for depth slices from 300 km depth to the surface. The fields are calculated at mean satellite height, and the results show that the gradients are almost insensitive to the sublithospheric density distribution and even to the lower lithosphere. Only in the vertical component a small signal can be observed for depths from 100 km to 200 km, which represents the depth range of the base lithosphere. Density changes in the uppermost mantle (60-100km depth), which can have a significant effect on the gravity field (10-15 mGal), have only a small signalin the tensor components. Crustal thickness is, in addition to topography, the dominating signal in the gravity gradients, which makes the GOCE data an ideal tool to verify and estimate the crustal density distribution both vertically and laterally. This in turn allows to estimate the long-wavelength component in the gravity field from sub-crustal domains, and to correlate those with the composition and thermal structure of the upper mantle.

Extracting Earth structure from satellite gravity data using 3D object based image analysis techniques

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Satellite gravity data has played a very important role in understanding and developing tectonic theories over decades. But, as any potential field data, it needs an additional source of information about the Earth subsurface in order to reduce the non-uniqueness problem of the interpretation. In this research, we will use 3D object oriented image analysis techniques to derive information on subsurface objects. We do this through the analysis of density models derived from seismic tomography models to constrain the interpretation and the inversion of satellite gravity data. The study area is the East African rift system which is a tectonically interesting area that includes two rift branches, the Tanzania craton, basement complex, and volcanism, all of which is underlain by plume at large depth. A seismic tomography model for the region is converted into densities using petrological relations and forward modeled into a gravity response. 3D object based image analysis techniques are then applied to derived the location and extent of anomalous structure in the subsurface. All anomalous structures are combined into a 3D object based density model which is forward modeled into a gravity response. It is then compared to the response of the full 3D density model and to GOCE data. To truly assess the added value of 3D object based image analysis techniques the outcome is compared to anomaly extraction on GOCE data using traditional geophysical techniques like derivatives and Euler deconvolution.

The GOCE mission: status and future plans

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This contribution introduces the main aspects of the GOCE mission, including its status and overall performance, and major achievements till date. GOCE mission operations are currently funded until the end of 2012. A further extension of the mission has been requested for as long as technically feasible (i.e., until the Xenon gas used by the ion propulsion system is depleted), and will be decided at a ESA ministerial conference in late November 2012. We therefore also intend to describe the mission plans for this final operations phase of the mission.

A prism mass model for direct inversion of GOCE gravity gradients retrieving Earth's interior

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GOCE gravity gradients enable a global high resolution view on the geoid, but the inversion of the measurements to mass densities is non-unique. We present method that tries to solve the problem by incorporating geophysical information and additional constraints. We use a stacked prism mass model estimating relative densities in a least squares sense, applying relative weighting of the observations and model information. In the local retrieval process the four accurate GOCE gravity gradients, measured in the gradiometer reference frame, can be directly applied.

3D Geophysical-petrological modelling of the lithosphere: how can GOCE data help us assessing the geothermal potential of Ireland?

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A marked regional increase in surface heat-flow is observed across Ireland, from ~40 mW/m2 in the south to >80 mW/m2 in the north. The origins of both the observed regional heat-flow trend and local temperature anomalies have not been investigated and are not understood. Although variations in the structure of the crust and lithosphere have been revealed by seismic experiments, their effects on surface heat-flow have not been modelled. Bulk variation in crustal heat-production across Ireland that may contribute significantly to the observed regional and local temperature variations has also not been determined. We propose investigating the origins of both the observed regional heat-flow trend and regional and local temperature variations across Ireland, using the software package LitMod. This software combines petrological and geophysical modelling of the lithosphere and sub-lithospheric upper mantle within an internally consistent thermodynamic-geophysical framework, where all relevant properties (e.g. density, seismic velocities, electrical conductivity) are functions of temperature, pressure and composition. The major regional controls on both surface heat-flow and crustal temperatures are (a) crustal thickness and heat-production and (b) lithospheric thickness. These unknown variables are modelled in LitMod3D against known observations at surface – heat-flow, topography, gravity and geoid data – to identify a crustal and lithospheric mantle model that satisfies and accounts for all the observations at surface. Furthermore, recently released gravity gradient data from the GOCE satellite are integrated, as an independent constraint, and their impact in the alternative lithospheric models is explored. The 3-D crustal and lithospheric models that emerge satisfying all observable constraints will, by accounting for the regional sources of heat in Ireland, allow us to isolate and examine in detail the extent to which local variations in both heat-production and thermal conductivity of subsurface lithologies might affect the distribution of temperatures in the depth range above 5 km.

Local gravity field solution from GOCE mission by 1dfft integral inversion of the potential second radial derivative

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An analysis is made on the geopotential solution in the space domain using the second radial derivative of the gravitational potential produced by a gradiometric satellite mission like GOCE. The model presented is based on a close form integral that relates the disturbing potential T(R) at the Earth's surface to its second radial derivative Trr(r) at satellite altitude. The integral involved is inverted using 1D-FFT to solve for T(R) an the Earth surface. Regularization is required to stabilize the system. The Tikhonov method is employed for this purpose. Two monthly data set of the mission were used in the simulation test, the EGM2008 geopotential model was employed as measured and true field. The solutions were obtained on a quasi-global scope (polar gap), avoiding the cyclic convolution errors along the parallels. The optimum regularization parameter was estimated by iteration, by comparing to the true values in the simulation process, and using the selected for the corresponding configuration when applying to real measurements. Results indicate that with the method presented and the expected GOCE errors for Trr with two months of data, a 7 cm geoid with 100 km resolution and 3cm geoid with 200 km resolution are possible. However, when using the real data the estimated errors were about twice larger. Nevertheless, they were smaller than the estimated errors of published geopotential models.

Accuracy assessment of the 3rd release of GOCE GGMs over the area of Poland using EGM2008 and GPS/levelling

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Accuracy assessment of the 3rd release of GOCE GGMs over the area of Poland using EGM2008 and GPS/levelling Walyeldeen Godah1, 2 and Jan Krynski1 1 Institute of Geodesy and Cartography, 27 Modzelewskiego St., 02-679 Warsaw, Poland 2 University of Khartoum, AL-Jama'a St., 321-11115 Khartoum, Sudan E-mail: godah@kth.se ; krynski@igik.edu.pl Abstract A series of global geopotential models (GGMs) from the European Space Agency (ESA)'s Gravity Field and Steady-State Ocean Circulation Explorer (GOCE) satellite gravimetry mission have been released since 2010. Recently, the GOCE GGMs third release developed using data covering 20 months (from November 2009 to June 2011) have been made available by ESA with three different solutions, namely the direct, the time-wise and the GOCO (Gravity Observation COmbination) solution. The accuracy of those models was assessed over the area of Poland, using the EGM2008 and the high precision GPS/levelling control traverse of 870 km consisting of 184 stations. The EGM2008 has shown an excellent performance in that area; its fit to gravimetric quasigeoid is below 2 cm (1σ). On the other hand, the availability of the high precision GPS/levelling control traverse data across the country offers a unique possibility of accuracy assessment. The results obtained reveal that, height anomalies and gravity anomalies calculated from the third release of GOCE GGMs agree with the respective ones from the EGM2008 with standard deviation of 4~5 cm, and beneath 2 mGal, respectively. Their agreement with the GPS/levelling height anomalies in terms of standard deviation is about 10 cm. The assessed accuracy of the GOCE GGMs third release indicates that the objectives of GOCE mission "1~2 cm in geoid and 1 mGal in gravity anomaly at 100 km spatial resolution" have not been achieved yet. Further improvements might be expected from the next releases as more data become available and more advanced models are applied. Keywords: EGM2008, height anomalies, GOCE GGMs, GPS/levelling, gravity anomalies.

Sensitivity of GOCE along the Andean subduction zone

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Through interactive 3D gravity modelling we can calculate the state of stress and Gravitational Potential Energy (GPE) from density models along the Central Andean subduction zone. The state of stress on top of the subducting oceanic plate at the western Andean margin of North-Central Chile suggests that the fore-arc region is characterized by trench parallel normal stress anomalies (higher by 50 to 100 MPa than in the adjacent regions). These domains are attributed to high density structures which are located above the plate interface and indicate regions of enhanced strain energy. Seismicity east of the trench correlates reasonably well with peaks of the high stress anomaly. Sensitivity studies of gravity and gravity gradients at 254 km altitude indicate that short wavelength lithospheric structures are more pronounced in the gravity gradient tensor than in the gravity field. We see that – despite GOCE's good accuracy – the spatial resolution of the new satellite-only gravity models is lower than what would be required in order to resolve crustal structures like coastal batholiths. The near surface model gravity gradient tensor, however, draws near dimensions expected for the test region. The high topography of the Andean mountains and the ridges in the Nazca plate exhibits high GPE values (+10E13 N m-1) relative to the global and regional mean at the Moho and 125 km depth level, respectively. The resulting stress from GPE could influence the state of stress in the Nazca plate and adjacent regions. These estimates could as well be derived from density modelling based on satellite-only gravity models and topographic data. Further studies are under way and forward modelling of combined GOCE gravity and gravity gradient models is expected to provide new insights into crustal and lithospheric structures at regional scales.

GOCE data for local geoid enhacement

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The GOCE gradients, having a spatially dense data distribution, may potentially provide better predictions of the regional gravity field than those obtained using a spherical harmonic Earth Geopotential Model. Thus, the success of GOCE is depending on adequate methodologies for extracting the gravity field from its observations as well as on the combination of the gravity field with information from other sources. The aim of this study is to develop a methodology to improve the use of GOCE gradients and to determine the Earth's gravity field with better accuracy than by using global models, which have been truncated at a specific harmonic degree and order. The method makes use of all available GOCE gradient data in addition to the global models and aims at improving the determination of Earth's gravitational field in regional areas. Subsequently, the calculated equipotential surface, i.e. geoid, is used together with measurements of sea surface height in a calculation of the Mean Dynamic Topography (MDT). This reflects the geostrophic ocean currents and leads to a better understanding of ocean mass and heat transfer. In regional geoid recovery from GOCE gradients, two methods are used, one of them being Least-Squares Collocation (LSC). The second method is developed as a part of this study, and it is based on the Reduced Point Mass (RPM) response. The results show that the RPM method and LSC method gives very similar results, i.e. the difference is insignificant when compared to the Earth's Gravitational Model 2008 (EGM2008) results. However, when all the GOCE gradient data are used with the RPM method, an improvement in the gravitational field determination is achieved.

Consistent combination of GOCE gravity gradiometry and terrestrial gravimetry in active plate margins

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Our main focus is the active continental margin of the subduction zone in South America, where a combined gravity field model from satellite and ground data shall provide a new constraint for lithospheric modelling. New gravity field data from GOCE provide new, high-accuracy and globally uniform information of the Earth's gravity field. Comparison of global GOCE gravity models with terrestrial gravity data reveals that there are large systematic differences in South America, which can be attributed to a low data quality of the terrestrial data. Consequently, most lithospheric models of the study region, which did not yet include GOCE, are affected with large-scale errors as well. Apart from the direct geophysical interpretation of GOCE gravity gradients, a major goal is to derive a consistent combined regional gravity field model from GOCE gradients, GRACE, and terrestrial data in the study region, by applying Least Squares Collocation (LSC). Such a combination task provides a number of methodological challenges, which shall be addressed in this contribution. In a first step, the ground data (gravity anomalies and associated heights) have to be validated thoroughly. In order to validate ground gravity satellite data, the high-frequency signal content (mainly contained in terrestrial data) has to be reduced consistently by a topographic-isostatic reduction. GOCE gravity gradient observations and terrestrial data (both consistently corrected for topographic-isostatic effects) are combined for a regional gravity field determination by LSC. Special attention is put on the realistic stochastic modeling of the error covariances of the GOCE gradients, which shall be introduced as direct gravity field observations into the LSC procedure.

Improvement of Latvian Geoid Model using GOCE Data and Vertical Deflection Measurements

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The high precision geoid model is essential for the normal height determination when the GNSS positioning methods are used. The eventual possibility to use the GOCE geoid for improvement of the Latvian LV'98 geoid model would be preferable. Currently the development of mobile digital zenith telescope for determination of vertical deflections is commenced at University of Latvia, Institute of Geodesy and Geoinformation for the improvement the Latvian geoid model for scientific purpose. Estimated accuracy of determination of vertical deflections is at least about 0.05" (arc seconds). The results of observations of digital zenith telescope will be used for the studies of anomalies of regional gravitation field. The priority task for scientific purposes will be implementing GOCE gravity data in calculations of Latvian geoid model. The national geoid model LV'98 mostly was based on the former Soviet gravimetric map data obtained by digitizing the gravity field isogonic lines. The estimated accuracy is about 7 cm. To achieve geoid accuracy of 1 cm, ~65 000 gravimetric measurements in the territory of Latvia are required. With digital zenith telescope just only ~4000 measurements are needed. In spite of the fact that gravimetric measurements have been carried out by Latvian Geospatial Information Agency recently a very limited local gravimetric information has been used till now. The vertical deflection data will contribute to considerable reinforcement in the determination of geoid. Additionally, the high precision GNSS observation data at the Latvian permanent GNSS network has been reduced from 4 year period. The results describe the tectonic deformation model for this period and could be used for geoid modelling.

Different topographic reduction techniques for GOCE gravity data

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Topographic reduction of gravity (gradients) is crucial for computation of gravitational anomaly and combined satellite gravity models. The topographic signal can obscure subsurface anomalies, so measurements have to be corrected for its influence. Several algorithms are available for topographic reduction. Most of them use fixed resolution of topography dependent on the distance to the station (e.g. Hammer zones) and mass elements approximating the topography (e.g. mass lines, cubes, etc.). Although mass correction is a crucial processing step, these standards are often used without modification. However, the choice of limiting radius is questionable and the approximation error can be higher than the accuracy of the measurements. Furthermore, application of satellite data often includes the investigation of large areas. Here, planar corrections are erroneous. In our study, we analysed the influence of distant topography (>167 km) and approximations on gravity data. We developed two algorithms for this purpose which are also capable to correct for gradients. The first method represents the Digital Elevation Model (DEM) as tesseroids (spherical prisms) organized in a tree structure. This allows local change in resolution, small consumption of memory and a good scalability of even large datasets. The algorithm changes the resolution depending on the gravitational effect of the terrain on the station. The error in the final terrain effect is below a user specified error threshold (e.g. standard deviation). The adaptive algorithm speeds-up the calculation time significantly. Thus, the initial DEM can have a higher resolution and great lateral extent. Compared to the methods that use fixed resolution to estimate terrain effects, our new approach provides better estimates of distant topographic effects. The second method represents the DEM as a triangulated surface. This leads to an exact mass representation of the topography which is suitable for coastal areas and rugged terrain. Both algorithms are based on a spherical Earth model. Thus, they account for the curvature of the Earth. Data from high mountains (the Andes and the Himalaya) were examined to test the new methods. Finally, we identify a) the influence of distant topography on the measured gravity, b) the effect of different topography resolutions and c) the differences to other approaches. We conclude that a) distant topography (beyond 167 km) can have an impact on the measured gravity; b) resolution should be chosen carefully. Depending on the investigation area and the objective of the survey, it is advisable to put more effort into obtaining an accurate, exact and reliable method for the reduction of topographic effects.

Detecting and monitoring the time-variable Greenland gravity field using reprocessed GOCE gradients

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Whereas the GOCE mission was originally planned to determine the Earth's static gravity field with an unprecedented spatial resolution down to approximately 100 km, the GRACE mission focuses on the observation of gravitational time variations. However, the current status of GOCE measurements indicates that the mission also delivers very accurate gravity field information for short observation time spans of only a few months. On the one hand this favorable feature can now be accessed by the recently reprocessed L1B release, which shows up with an increased data accuracy and consistency. On the other hand the longer time-span of available measurements from September 2009 to March 2012 is now sufficient to analyze time-variable signals. One prominent example to study time variations of the gravity field induced by mass changes is ice melting. This geophysical process causes gravity variations and can occur in terms of trends and seasonal oscillations. To detect and monitor these variations we split the observation period into windows of two months with one month overlap. This period is almost consistent with the GOCE repeat cycle of around 61 days and sufficient to calculate high resolution models from the GOCE gravity gradients. The temporal variation is then obtained by connecting the successive static solutions. For the regional gravity field modeling we use the original Vzz tensor elements, measured in the Gravimeter Reference Frame (GRF) and filtered within the Measurement Bandwidth (MB) to achieve the highest sensitivity within the frequency spectrum. The observation equations for regional gravity field modeling are set by using series expansions in terms of spherical base functions after subtracting a background model. The results are compared with a long-time regional gravity field solution obtained from GOCE, GRACE and also with the monthly global GRACE-GSM solutions of the recently published 05-release. For this study Greenland offers an optimal test area as the melting of glaciers is already observed by GRACE and other measurement techniques. However, the essential advantage of the GOCE measurement technique is the increased spectral sensitivity in higher frequency parts. Thus we aim for enhancing the spatial resolution of gravity time variations presenting first GOCE-only and combined results of GOCE and GRACE for Greenland.

GOCE data demonstrate magmatic underplating beneath the Paraná basin

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The Paraná is an intracratonic basin located on the stable South American platform. The shallow stratigraphy of the basin is composed of 3500 m of Paleozoic rocks, 1500 m of Serra Geral Formation and 300 m of Late Cretaceous sediments. The recent seismological studies have shown that the crust-mantle interface below the basin is deep between 40-46 km, depending on the specific model. Thick crust and thick sediments generally generate a strongly negative Bouguer anomaly that is not found in the Paraná basin. Instead of the expected Bouguer minimum, a relative anomaly high along the maximum sediment accumulation is found. During the Early Cretaceous, the same basin was affected by a large amount of basalt deposits of (Serra Geral Formation) that belong to a Large Igneous Province (LIP). The volcanic deposits in the basin are however too thin to explain the relative gravity high. The goal of this work is to explain the apparent discrepancy between crustal thickness and the Bouguer anomaly by modeling the crustal densities of and below the Paraná basin. Our approach integrates the new gravity observations of the GOCE satellite, and the constrains provided by the geophysical and seismological information to define geometry and densities. We reduce the gravity value for these known structures. The final residuals we obtain are interpreted as deviations from the assumption of a contrast density contrast located either in the crust or mantle according to the involved wavelengths of the residual gravity signal. Assuming a fixed density contrast, we estimate the thickness of the underplated body by inverting the gravity residual. The clear positive Bouguer residual anomaly suggests the presence of hidden mass. This hidden mass is located in the mid to lower crust, with a thickness over 10 km, and is probably made of gabbro. This mass is a magmatic material left behind by the ascending basalts, and contributes to isostatic balance. The study of underplating under the LIP is very useful to understand the relationship between the alteration of the thermal gradient of the crust and the hydrocarbon maturation of sediments.

Mass-density Green's functions for gradiometric data

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The inverse gravimetric problem (IGP) for inferring the Earth's internal mass density distribution belongs to a category of ill-posed problems. That is why the IGP is traditionally solved in combination with other geophysical, e.g., seismological, or geological evidence. However, additional constraints on a solution of IGP do not, in principal, remove its ill-posedness. Furthermore, if the IGP is solved for cases of regional or local mass density determination, it suffers from the non-local character of the mass-density Green's functions for gravity data, meaning that there is a contribution to the gravity signal from masses outside the area of interest. The known fact that this spatial 'aliasing' effect is reduced for gradiometric observables is in this work quantified for all components of the gradiometric tensor in spherical geometry. The degree of the spatial concentration of the mass-density Green's functions is demonstrated for various altitudes when downward-continuing the GOCE gradiometric data from the satellite's altitude to the Earth's surface. Here, we present our first attempts to interpret GOCE data over the Congo basin and the Arabian Peninsula using this analysis method.

Crustal Models from Seismology and Satellite Gravity; is There Any Relation?

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The improved resolution and accuracy of GOCE is especially of great interest for the studies of the Earth in places where limited Earth science data is available like for the African continent, one of the least studied areas in the world. This results in very limited knowledge on African tectonic processes and their relation with and influences on crustal thickness and upper mantle structures. To assess the reliability of satellite gravity derived structural upper mantle models in data sparse areas we have compared crustal and upper mantle models from satellite gravity with seismologically derived models. We have derived a crustal thickness model for South America based on GOCE satellite gravity data. The model was validated with receiver function analysis and results from deep seismic surveys. This resulted in a good correlation, except in areas of sharp lateral transitions in crustal thickness. Interesting features are the spatial extent of the thinned crust 'behind' the Andes and the different insights on the crustal thickness in the stable part of the continent.

Seismology and GOCE - visibility of seismic tomographic variations in GOCE

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Theoretically GOCE data can contribute to our understanding of upper mantle dynamics and composition. Foreseen is that in a combined inversion with either surface waves or body waves improved models will be obtained, better constraining the extent but also the densities and velocities. But in order to make a difference the GOCE signal should be sensitive to small compositional variations in the upper mantle. To study the influence of and detectability of petrological variations we convert a tomographic model in densities using assuming different compositional extremes within realistic petrological bounds. Forward modelling and comparions between the different models will provide insight into the resolving capacity of GOCE for density variations in seismological models.

EGM08/GOCE quasigeoid performance for Norway

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We have compared the EGM08/GOCE quasigeoid with the height anomalies of the new official Norwegian GPS-levelling network for the south of Norway. The computation of the necessary associated Legendre functions were executed using the new method of Fukushima (2012).

A Web Processing Service for GOCE data exploitation

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The full exploitation of GOCE data can bring significant improvement in many fields of Earth sciences. In this framework one example is the GEMMA project (GOCE Exploitation for Moho Modelling and Applications), supported by ESA - STSE, where the Moho depth is recovered by using GOCE grids of second radial derivatives of the gravitational potential computed by the so called space-wise approach. However, due to the novelty of the GOCE mission and to the extreme advanced technology of GOCE instruments, the use of GOCE raw data can be very complex requiring high computing power, ad hoc software and detailed knowledge of the mission itself. On the other hand GOCE spherical harmonic models released by ESA are easy to be used but could not fully represent the whole information carried by GOCE: firstly they are optimal in a global sense but not necessarily at local level and secondly they contain only the information averaged in time during the whole operational period of the GOCE mission. In this work first results of the development of a WPS (Web Processing Service) for spatio-temporal exploration and exploitation of GOCE data is presented. First of all the service gives the possibility to download space-wise filtered GOCE data, currently in the form of geographical grids at satellite level and in the future along the orbit after pre-processing. These grids can extend all over the world or be dynamically interpolated by the WPS on a user-defined local area and resolution; interpolation on selected points is possible too. Separate solutions for each GOCE repeat cycle (corresponding to about two months) can be provided for time-dependent studies. All delivered products are accompanied with either error variances or the full covariance matrix for the specific region computed from Monte Carlo samples. Apart from providing observations, the WPS is dedicated to deliver and display the output of GOCE based applications. For example in the case of the GEMMA project it gives the possibility to download, interpolate and display not only the estimated Moho depth but also the crustal model in terms of thickness, density as well as gravitational effect of any layer for any specific geographical region. GOCE WPS is developed according to standards defined by OGC (Open Geospatial Consortium), an international consortium of more than 400 companies, government agencies and universities participating in a consensus process to develop publicly available interface standards. These standards support interoperable solutions that "geo-enable" the Web, wireless and location-based services. Furthermore the GOCE service is implemented with free and open source software, namely GRASS GIS for data processing and pyWPS for the WPS interface, enabling everybody to directly access the code and improve it. The output products are now delivered in widely used formats, like ASCII or GeoTIFF, that can be later on imported in many GIS (Geographical Information System). In this sense, WCS, WMS, WFS standard protocols will be implemented too.

Towards a better understanding of the Earth's interior and geophysical exploration research

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Within the ESA's GOCE+ program a consortium of researchers from 6 European institutes investigates capabilities of GOCE gravitational gradients to improve geophysical models over two areas. The area of the Reykjanes Ridge close to Iceland covers a mid-ocean ridge that plays a key role for creation of a new crust and for generation of ridge push driving partly the plate motion. GOCE gravitational gradients are used for refined local mass density modelling that cannot uniquely be achieved through seismic measurements. In Africa, the second area, GOCE gravitational gradients are combined with seismic tomographic models of a continental lithospheric mantle in order to refine initial mass density models. Over both areas, GOCE gravitational gradients are continued to ground and combined with gravitational gradients either derived from measured ground and marine gravity and altimetry or modelled from terrain elevation and mass density models, seismic tomographic and mantle flow models and crustal thickness models. The presentation summarizes the progress of the consortium within the first year of the project.

Design a Laboratory for the Gravity Measurement

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The purpose of this project is to identify the conditions that affect the measurements of gravity when gravimeter are in operation. Knowledge and tools that provide information for the acceleration of the gravity are critical to determine the operational conditions of a laboratory created, specifically, for an absolute gravimeter. The measurement of absolute gravity, in some regions of Mexico, has been an area of opportunity where its development is limited. Actually speaking, the build of an absolute gravimeter have the following input: create traceability between commercial or self-made gravimeters used in different regions and thus, provide information for their corresponding corrections that allows the understanding of the gravity and its usage for other primary references, such as hardener testers, load cells, torque devices, etc... The results of this project have been set the critical to quality conditions to make sure the absolute gravimeter and those gravimeters to be compared have the cleanest environment when they are tested or tried out; those conditions are the control of temperature and pressure and the creation of a vibration isolation system.

GOCE data products: GOCE models

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Up to now 3 releases of GOCE gravity field models have been processed in the frame of the ESA project “GOCE High-Level Processing Facility (HPF)” and released to the science and user communities. They are based on three different processing philosophies, the direct, time-wise and space-wise approach, and include different data types (GOCE-only or combination with other gravity field information). In this presentation the key characteristics of these models and their specific differences shall be discussed. Based on external validation results, the status of these models and their estimated accuracy will be presented. In a performance prediction, the final performance of GOCE after completion of the mission shall be estimated. Additionally, first results from the GOCE Level 1B reprocessing of gravity gradient and attitude products and their impact on the gravity field performance will be shown. Since this reprocessing results in a significant noise reduction of the gravity gradients especially concerning the long wavelengths, it is expected that this improvement will facilitate the direct use of gravity gradients for geophysical interpretation.

Geological appraisal of the 85oE Ridge, Bay of Bengal using GRACE and GOCE anomaly

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Abstract In the eastern offshore, India, the 85oE ridge is one of the most complex regional crustal features, which has been not so well defined from ship-borne geophysical survey, particularly it's northern extension in the Bay of Bengal (BOB). The 85oE Ridge is more mysterious due to its peculiar anomalous negative free-air gravity field. This has been a subject of discussion since more than a decade and subsequently led to different models that emphasis much on flexural down-going or crustal overcompensation of the ridge, predominantly by the excessive overburden of the sediment load. However, by considering the hot spot origin of the 85oE Ridge system, the possibility of sub-lithospheric low density mantle melts' presence beneath the ridge as an overcompensating negative gravity aiding load cannot be ruled out. Moreover, it is geographically closer to the Eastern Continental Margin of India (ECMI), though it was formed later. The net negative gravity field of the ridge can be accounted by considering the gravity effect of lithospheric subsidence as a result of initial rifting of ECMI from the Antarctic Margin. Otherwise, the present day oceanic lithospheres juxtapose to the ECMI hold the residue of lithospheric stretching as a result of previous India-Antarctica rifting. Hence, mapping the features using satellite-derived geoid/gravity anomalies may be useful for further detailed study. The GOCE (Gravity field and steady-state Ocean Circulation Explorer), launched in March 17, 2009, is an ESA mission dedicated to measuring the Earth's gravity field and modelling the geoid with extremely high accuracy and spatial resolution. EIGEN-6C gravity model data at a grid interval of 0.10 x 0.10, which is generated by assimilation of GOCE, GRACE, and LAGEOS (Laser GEOdynamics Satellite) satellite tracking data, with ancillary terrestrial data and altimetry data, have been utilized for geological appraisal of the 85oE Ridge. EGM2008 geoid/gravity model data at a grid interval of 0.10 x 0.10, which is generated by assimilation of Gravity Recovery and Climate Experiment (GRACE) satellite gravity data, ancillary terrestrial data and altimetry data, have also been utilized for geological appraisal of the 85oE Ridge. EGM2008 is a spherical harmonic model of the Earth's gravitational potential, developed by a least squares combination of the ITG-GRACE03S gravitational model and its associated error covariance matrix, with the gravitational information obtained from a global set of area-mean free-air gravity anomalies defined on a 5 arc-minute equiangular grid. This grid was formed by merging terrestrial, altimetry-derived, and airborne gravity data. Over areas where only lower resolution gravity data were available, their spectral content was supplemented with gravitational information implied by the topography. EGM2008 is complete to degree and order 2159, and contains additional coefficients up to degree 2190 and order 2159. The gravity data generated from GOCE using the EIGEN-6C model and also, the geoid/gravity data generated from GRACE using EGM2008 model have been utilized to infer subsurface geological structures. The generated gravity data have been enhanced using the 1st and 2nd Vertical Derivatives, Horizontal Derivatives and Analytical Signal mapping techniques. Geological structural map of the 85oE ridge area of the Bay of Bengal has been overlapped over different derivative maps

and the analytical signal map to analyze the correlation with the subsurface geological structures of the area. Major distinct signatures on different derivative maps and analytical signal map correlate well with the existing geological map. Moreover, the geoid/gravity data generated from GRACE using EGM2008 model provides better agreement and understanding for geological setting of the 85oE ridge area.

Multi-scale investigation of the African lithosphere using GOCE gravity and gradiometric data

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The complex geology of Africa 1- attests for past and on-going tectonic and geodynamic processes which affect the African plate at the lithospheric scale 2- finds expression in density variations inside the African crust and mantle, corresponding to gravity signatures at variable wavelengths. For this reason and because African deep structures remain among the less known of continental areas, we have focused our study on the density structure of the African lithosphere. The GOCE satellite mission is mapping the Earth's gravity with unprecedented detail at the global scale and it provides a new class of gravity observations. The European space agency made available 1- global gravity field models with resolutions suitable for a study at global or continental scale, 2- the gravity tensor components which are more suited to regional scale studies. We therefore conducted two parallel studies in order to take advantage of all the new information made available by GOCE mission. The common starting point of these two studies is a 3D density model of the African crust combining two global models mainly based on seismological data: CRUST 2.0 and the global digital map of sediment thickness. The overall resolution of the model is 1°x1° and the crust is subdivided in six layers (three sedimentary and three crystalline crust layers). Densities vary within each layer accordingly with seismic velocities. For the continental scale study, we computed the gravity effect of our model in spherical geometry using Tesseroid software (Uieda et al) in order to remove it from the Bouguer anomaly map deduced from direct solution of the gravity field model combining eighteen months of GOCE data. This allowed isolaringmantellic gravity components included in GOCE data, which were interpreted in relation with the presence of cratons, margins, plume. For the regional scale study, our area of interest 1 - comprises a land/sea transition 2- include complex tectonics 3- is located on an area of Africa where the GOCE gravity model significantly improves the existing EGM2008. We focused our study on a 30 °x30 ° area that includes the Congo sedimentary basin, the Congo craton and the Cameroon volcanic line. The computation is performed using 3D Geomodeller software (©Intrepid-geophysics, BRGM): forward gravity and gradiometric responses were derived. In order to compare these effects with GOCE data, we had to compute the normal field and the terrain effect to remove it to the gravity tensor component. We present here, how to use gravity tensor components relatively to the standard gravity data. On-going work addresses the inversion of these data to refine our initial seismology-based crustal model.

A new global crustal model based on GOCE data grids

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The boundary between Earth crust and mantle, the so called Moho, is commonly estimated by means of seismic or gravimetric methods. The former methods can be locally very accurate since seismic profiles give an almost direct observation of the actual crustal structure, but can be quite far from reality in large regions where no data are available. The latter methods, although often based on simplified hypotheses to guarantee the uniqueness of the solution, are nowadays becoming more and more important thanks to the improved knowledge of the gravitational field. In particular satellite gravity missions, like GOCE, provide a very accurate and spatially homogeneous dataset that can be used to validate the existing global crustal models or to estimate a new one by constraining the relation between Moho depth and crustal density. In this work a new crustal model with a spatial resolution of 0.5°x0.5° and constrained with GOCE observations is computed. For this purpose several additional external information has been used, such as topography, bathymetry and ice sheet models from SRTM, a recent 1°x1° sediment global model and some prior hypotheses on crustal density. In particular the main geological provinces, each of them characterized by its own relation between density and depth, have been considered. A model describing lateral density variations of the upper mantle is also taken into account. Starting from this prior information, an inversion algorithm is applied to the GOCE space-wise grid of second radial derivatives of the gravitational potential to estimate the bottom of the crust in such a way that the whole crustal model is consistent with the observed gravitational field.

Interpreting gravity anomalies in Northwestern Europe, crustal thickening or GIA?

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The European satellite mission GOCE is now orbiting Earth for 3.5 years. GOCE is accurately measuring the gravity field at small wavelengths. These measurements are capable to locate small density anomalies in the crust, which were invisible for the GRACE satellite mission. A good model for the gravity field in the medium wavelengths (300-3000 km) domain is needed, before we can optimally use the GOCE observations. Especially in the research area Fennoscandia this is challenging, because the medium wavelengths are composed of several signals: thickening of the crust and lithosphere, Global Isostatic Adjustment (GIA) and even dynamic deep-mantle effects, such as related to the hotspot beneath Iceland. The ultimate goal is to increase knowledge on passive continental plate margins by using the gravity field as constraint on the crust and upper mantle. The gravity effect of the GIA is modeled by using a model, using ICE-5G with regional sea-level data to constrain mantle viscosity. We assume that the dynamic deep-mantle effects are negligible after cutting the low degree (0-9) spherical harmonic coefficients from the solutions. The gravity signal of the crust is modeled using the CRUST2.0 density model. The calculations are performed using an existing model for forward modeling of gravity anomalies for layers with variable thickness and lateral density changes [Tenzer et al. 2012]. The modeled gravity fields are all available in spherical harmonic representation which makes it straight-forward to focus on a specific wavelength area. We focus on the gravity signal with a spherical harmonic degrees representation between 10-60. It is found that the low degrees 0-9 mainly represent the deep mantle signal due to the Iceland hotspot. GIA signal is important up to degree 60. In this bandwidth the maximum negative gravity anomaly in the EIGEN-GL04C model is -40 mGal while our preferred GIA model results in a maximum negative geoid anomaly of -16 mGal. This could indicate that crustal thickening has a larger effect in the Fennoscandian area than GIA.

GOCEXML2ASCII - an XML to ASCII converter for GOCE level 2 EGG_NOM and SST_PSO data

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ESA provides the GOCE data in XML format. This format is very easy to understand for a human reader. However, it has to be parsed by a computer to extract the data before it can be used in the computations. This parsing is time consuming, especially if it has to be done repeatedly in case of recomputations. Hence, in a normal workflow, the XML data will be converted to plain ASCII files (tables) in a preprocessing step prior to the actual computations. The offical GOCE L1b-L2 XML parser is available at ESA's website. It is programmed in Perl which is an interpreted programming language. Therefore, the conversion is slowed down (~20 min for a single SST_PSO_2 file). The advantage of this parser is that it can be run on any operating system if Perl is installed. The faster GOCEPARSER of the Finnish Geodetic Institute (K. Arsov, 2012) is implemented in C++. According to K. Arsov, the GOCEPARSER needs ~7 min to convert a SST_PSO_2 file. This parser can only be run on a Windows operating system without modification. However, our production system runs Linux. Hence we implemented another converter in C using the XML2 library. In contrary to the above mentioned parsers, our can only convert EGG_NOM_2 and SST_PSO_2 at the moment. This parser is small (~30 kB) and fast (~2.5 min for a SST_PSO_2 file). Additionally, we wrote a number of bash shell scripts to automate the GOCE archive download, archive unpacking, parser calls and the packing of the converted data to a new archive. The source code of the parser, as well as the bash shell script collection, are available on request.

A brief introduction into interpreting GOCE observations

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The GOCE instrument suite provides the observations required for deriving a high spatial resolution map of the Earth's gravity field. These observations include GPS satellite to-satellite tracking (SST) observations, quaternions derived from the star trackers, common-mode accelerometer observations representing the remaining non-gravitational accelerations left by the drag-free control, and gravity gradients derived from the differential mode of the gradiometer instrument. These observations are provided to the user community as so-called Level 1b data. Several aspects will be addressed concerning the interpretation of these data. Concerning the GPS SST observations, these aspects include the noise characteristics, peculiarities such as so-called L2 losses, and azimuth/elevation dependent corrections. Concerning the star tracker observations, attention will be paid to the different quality of orientation angles for different directions ("bore sight"), the conversion of quaternions to Euler angles (yaw, pitch and roll), continuity in the time series of quaternions, and the combination of observations by different star trackers to enhance the quality of the quaternions. The common-mode accelerometer observations are affected by slowly drifting biases, which can be precisely determined by precise orbit determination. An optimal use of these observations for not only gravity field determination, but also thermospheric density and wind retrieval, requires a precise definition/reconstruction of the orientation of the accelerometers ("mounting matrices"). Finally, gravity gradients are not observed directly by GOCE's gradiometer. In fact, the proper so-called differential mode combinations of accelerometer observations need to be taken and corrected for centrifugal and angular accelerations terms. The latter requires a careful fusion of - again - combinations of accelerometer observations on the one hand and star tracker observations on the other hand. The quality of the resulting gravity gradients depends on the frequency: in general some kind of high-pass filter is required in order to mitigate relatively large errors at low frequencies.

Interpreting gravity data from GRACE and GOCE in Scandinavia and Iceland

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Interpreting gravity data requires separating processes in different wavelength regimes, or using simple conceptual models such as isostasy, or using more complex forward models of density anomalies and dynamic processes. Here we show examples of each of those in Iceland and Scandinavia. In Scandinavia, past studies have attributed part of the free-air gravity anomaly to the incomplete response to the melting of the ice sheet in the last glaciation. Indeed, a significant isostatic gravity anomaly is visible in the gravity field at spatial scales of 300 to 2000 km which suggests that GIA plays a role. Forward modeling glacial rebound results in a free-air gravity anomaly of -15 mGal. We show that this anomaly can also be modeled by a Bouguer correction with the induced topography change using the density of the layer of the upper most mantle layer in the GIA model. The observed topography contains GIA signal, but this is small compared to the crustal thickening that is indicated by the seismic Moho depth. In Iceland, a clear signal of the mid-ocean ridge is visible in the GOCE gravity gradients at orbit height. The contribution of the upper mantle to gravity gradients is in the order of several Eötvös while the contribution from dynamic topography results in a signal of tenths of Eötvös.