Marine Gravimetry Activities on the Baltic Sea in the Framework of the EU Project FAMOS

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Summary

FAMOS (Finalizing Surveys for the Baltic Motorways of the Sea) is a recently run project which was supported by EU to improve the safety of ship navigation on the Baltic Sea. One task of FAMOS was to work on a common height reference for the Baltic Sea, the Baltic Sea Chart Datum 2000 (BSCD2000), which will be based on a new gravimetric geoid for this sea. The German institutions German Research Centre for Geosciences (GFZ), Federal Agency for Cartography and Geodesy (BKG), Federal Maritime and Hydrographic Agency (BSH) and Technical University of Darmstadt performed several marine gravimetry surveys to contribute to this project. The primary measurement equipment was GFZ's Chekan-AM gravimeter. On two of these campaigns an iMAR strapdown inertial measurement unit (IMU) was used together with the Chekan. The data records from both instruments are of very good consistency.

Since the FAMOS project ended ahead of the planned schedule already in 2019, finalization of the new chart Datum is now coordinated by the Chart Datum Working Group within the Baltic Sea Hydrographic Commission. It is planned to implement the new BSCD2000 by 2023.

Zusammenfassung

Das durch die Europäische Union geförderte Projekt FAMOS (Finalizing Surveys for the Baltic Motorways of the Sea) dient der Verbesserung der Sicherheit in der Schiffsnavigation auf der Ostsee. Eine spezielle Aufgabe von FAMOS ist die Erstellung eines neuen Höhenreferenzsystems der Wasseroberfläche der Ostsee, dem sog. Baltic Sea Chart Datum 2000 (BSCD2000). Dieses soll auf einem neuen gravimetrischen Geoid der Ostsee basieren. Von deutscher Seite arbeiteten die Einrichtungen Deutsches GeoForschungsZentrum GFZ, Bundesamt für Kartografie und Geodäsie (BKG), Bundesamt für Seeschifffahrt und Hydrografie (BSH) und Technische Universität Darmstadt mit Schiffsgravimetrie-Kampagnen im FAMOS-Projekt mit. Das Hauptmessinstrument war dabei das Chekan-AM-Gravimeter des GFZ. Auf zwei Messfahrten kam zusätzlich ein Strapdown-Trägheitsnavigationssystem (IMU) des Herstellers iMAR zum Einsatz. Die Messdaten beider Instrumente haben eine sehr hohe Konsistenz.

Das FAMOS-Projekt endete früher als geplant schon im Jahr 2019. Deshalb wird die Fertigstellung des neuen BSCD2000 durch die Chart-Datum-Arbeitsgruppe (CDWG) der Baltischen Hydrografischen Kommission (BSHK) koordiniert. Die Implementierung des BSCD2000 ist für 2023 vorgesehen.

Keywords: Baltic Sea, Chart Datum, FAMOS, Shipborne gravimetry, Strapdown gravimetry

1 Introduction

Reliably surveyed shipping routes are a major pillar of marine transport infrastructure and a basic precondition for the safety of the increasing transports at sea. This applies especially to the Baltics, which has been connecting Northern and Eastern Europe for centuries, facilitating transport and travel across the region. But still, the most fundamental property of the Baltic Sea, its water depth, is yet to be mapped with regard to modern standards in large parts of this area. Therefore, all Baltic Sea countries, represented by their hydrographic agencies, organized in the Baltic Sea Hydrographic Commission (BSHC), have agreed upon a roadmap for the improvement of the hydrographic surveying. In this context, during the past years many hydrographic cooperation projects were performed in the Baltics, supported by the European Union, e.g. the MONALISA projects (STM 2020). The most recent project was FAMOS ("Finalizing Surveys for the Baltic Motorways of the Sea"), a cooperation project of about fifteen maritime and transport agencies and geodetic institutions of almost all EU member states around the Baltic Sea (FAMOS consortium 2014–2020). The project which was coordinated and guided by the Swedish Maritime Administration (SMA) started in 2014 and ended in 2019. It was divided in two consecutive phases, FAMOS Freja and FAMOS Odin. FAMOS was co-financed by the European Commission within the framework of the Connecting Europe Facility (CEF). CEF is a funding program that supports trans-European networks and infrastructures in the sectors of transport, telecommunications and energy (https://ec.europa.eu/inea/en/connecting-europe-facility).

The primary objective of FAMOS was hydrographic re-surveying of the Baltic Sea in order to contribute to enhancing the safety of shipping via accurate nautical charts. Part of this objective was improvement of the maritime infrastructure, comprising equipment to ensure year-round navigability, including equipment for surveying. The second important objective of the FAMOS project was to improve the geodetic infrastructure of the Baltics in order to adapt to current and future developments, especially in GNSS positioning. This includes the work on the height reference surface for a common chart datum for the Baltic Sea, the Baltic Sea Chart Datum 2000 (BSCD2000, c.f. Ågren et al. 2019 and Schwabe et al. 2020).

So far, each of the Baltic Sea states has its own chart datum based on realizations of the mean sea level (MSL) at tide gauges at a certain time. Because the Baltic Sea

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region is strongly affected by postglacial land uplift, these MSL realizations are different, from country to country, but sometimes even between map sheets depending on the reference epoch. Updating nautical charts and references for different kind of water level information therefore implied large and steady work in the past (Schwabe et al. 2020). Furthermore, these inconsistent MSL-based chart datums complicate the prediction of the instantaneous sea level far off the coast, thus adding an extra uncertainty margin to ship navigation.

In that view, BSCD2000 signifies a change of paradigm in hydrography and ship navigation. The new datum will be based on the European Vertical Reference System (EVRS). This means that the new reference level is a geopotential surface. In order to be able to accurately refer to this surface in GNSS-based navigation and to enable for seamless transitions between different areas in the Baltic Sea, a high precision geoid model is needed. According to a decision of the Baltic Sea Hydrographic Commission (BSHC), this new geoid model shall be based on gravimetric data. Therefore, gravity measurements carried out in different parts of the Baltic Sea were an important work package of the FAMOS project to fill up data gaps, check old data and finally to contribute to the calculation of a new improved geoid model for the Baltic Sea by 2023.

GFZ German Research Centre for Geosciences Potsdam was member of the FAMOS consortium and contributed with shipborne gravimetry campaigns. This work was done in co-operation with Federal Agency for Cartography and Geodesy (BKG) and German Federal Maritime and Hydrographic Agency (BSH) as well as with Technical University of Darmstadt and further Swedish, Finnish and Latvian partners. This paper gives an overview of GFZ's FAMOS marine gravimetry campaigns, which were part of our successful activities in the fields of airborne and shipborne activities in general for many years. Further corresponding activities for FAMOS were conducted by DTU Space Copenhagen Denmark and the Swedish National Land Survey (Lantmäteriet LM), but these activities are not subject of this paper.

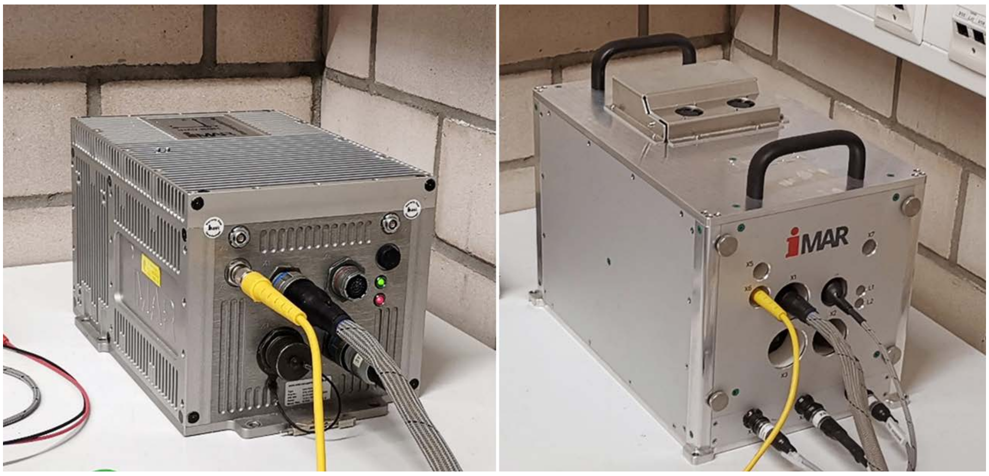
2 Measurement system

The main device used in GFZ's marine and airborne gravimetry activities is a mobile Chekan-AM gravimeter, manufactured by CSRI Elektropribor (Elektropribor 2020) which was purchased by GFZ in 2011. The measurement principle of the Chekan-AM gravimeter is based on recording the angle variations of a double quartz elastic torsion system that is arranged in a viscous damping liquid. This double sensor system is located inside a temperature stabilized case and mounted on a gyro stabilization system. This platform is kept horizontally using six one-axis floating gyros. Additionally, some accelerometers are enclosed to provide feedback to the internal system. This particular construction ensures that the sensitive axis is always held in the vertical direction during the movement when sailing or flying. Details of the construction of the Chekan instrument and recommendations by the manufacturer for the data processing can be found in Krasnov et al. (2011a and 2011b) as well as in the Chekan-AM Operating Manual. The raw recordings of the Chekan-AM gravimeter sensor unit are integer numbers of pixels detected by two light beams on two CCD photodetectors. These values represent the relative positions of the two sensor masses in terms of angles and must be converted into acceleration units using transformation parameters given by the manufacturer (Krasnov et al. 2011a, Zheleznyak et al. 2010). The transformation parameters are based on the position and the rate of change of the position (first derivative) of the proof masses.

To get the position and velocity information for the gravity recordings, GFZ operates two Javad GNSS receivers together with the Chekan-AM gravimeter. In most of the campaigns, the Chekan-AM was directly connected to one of the used GNSS receivers. The Javad GNSS antennae were installed on top of the used vessels. Fig. 1 shows a typical installation of the Chekan-AM ship gravimetry equipment onboard a survey vessel.

In addition to the Chekan-AM gravimeter, a strapdown inertial measurement unit (IMU) of the type

Fig. 1: Installation of GFZ's Chekan-AM gravimeter onboard the ferry Stena Line Urd. The main components are the Chekan sensor (1), power supply (2), Javad GNSS receiver (3), a rack (4) with various control computers and an uninterrupted power supply and one of the Javad GNSS antennae on top of the wheelhouse (5).



Source: TU Darmstadt

Fig. 2:
The iNAV-RQH-1003 strapdown gravimeter of TU Darmstadt (left) and the thermal stabilization housing iTempStab-AddOn used for this strapdown instrument (right).

iMAR iNAV-RQH-1003 (iMAR Navigation 2012, Fig. 2), owned and operated by the Technical University of Darmstadt, was installed at two of GFZ's FAMOS campaigns in 2017 and 2018 on the German survey vessel Deneb (see below). In strapdown gravimetry, an IMU is mounted in the vehicle measuring the full acceleration vector. Attitude changes are observed using a triad of gyroscopes. Hence, a horizontally stabilized platform is not needed. The main advantages of strapdown gravimeters compared to spring-type gravimeters are the lower space and power consumption, the lower weight and the higher robustness against steering maneuvers and harsh sea conditions or turbulences. Non-linear accelerometer drifts may be problematic, but they can be significantly reduced if thermal calibration methods are applied (Becker 2016). In most cases, a simple thermal calibration of the vertical accelerometer eliminates the bulk of the significant sensor drifts (Becker et al. 2015). Bias stability can be further improved by encasing the IMU in a thermally stabilized housing like TU Darmstadt's iMAR iTempStab-AddOn (Jensen et al. 2019, Simav et al. 2020), see Fig. 2.

3 FAMOS ship gravimetry measurement campaigns

The ship gravimetry campaigns done for FAMOS served for two purposes: 1) Mapping gravity in regions without already existing gravity data i.e. filling data gaps and 2) Re-measuring regions with existing gravity data for harmonizing and datum correction of old gravity data patches. To fulfill these aims, two kinds of gravimetry campaigns were performed: Dedicated and non-dedicated campaigns. The first kind of campaigns here is surveys that were done on research vessels, sailing along particular track plans, which were designed according to the gravity measurement needs. In such vessels, the centers of mass and rotation of the ship as well as the relative positions of the gravimeter (gravity sensor) w.r.t. the GNSS antennae are usually very accurately known within the vessel's local coordinate system. On the other hand, non-dedicated campaigns mean that the ship in question is sailing for other aims like hydrographic measurements or for commercial shipping. In such cases, the installation of the gravimetry equipment may not be possible at the most suitable place nearby the centers of mass or rotation. Furthermore, a local coordinate system is usually not established on such vessels and additional effort is needed to estimate the eccentricities between the gravity sensor(s) and the GNSS antennae.

For FAMOS, GFZ performed eight ship gravimetry campaigns, twice a year between 2015 and 2018. Four of these campaigns (one per year) were done onboard the BSH's survey vessel Deneb in German waters and adjacent Danish, Swedish and Polish regions, respectively. The main purpose of these campaigns was dense gravity mapping of the German part of the Baltic Sea. These campaigns were done jointly by GFZ and BKG. Management and track planning for these campaigns were done by BKG while GFZ operated the Chekan-AM and GNSS measurements. BKG arranged the local tie measurements on the various harbor piers and the eccentricity estimation for the GNSS antennae and gravimeter reference points onboard the ship. The partnership between GFZ and BKG regards also the data processing for these campaigns. At first, GFZ did the processing of the raw GNSS and Chekan-AM data incl. drift estimation and crossover analyses for the individual campaigns. Subsequently, BKG performed a refined bias and drift adjustment of all campaigns together to generate a harmonized and evaluated data set of all Deneb gravimetry surveys. The latter work is still ongoing and the finalization of the data set is envisaged by the end of this year. Fig. 3 shows the track scheme of the four Deneb campaigns together with the final gravity disturbances measured. The total track length of the Deneb campaigns was about 7300 km. During the campaigns in 2017 and 2018, the strapdown gravimeter of TU Darmstadt was also installed onboard side-by-side with GFZ's Chekan-AM.

Two further dedicated campaigns for FAMOS were conducted in 2015 and 2016 mainly on the Bothnian Sea and in the Bothnian Bay onboard the Finish vessel

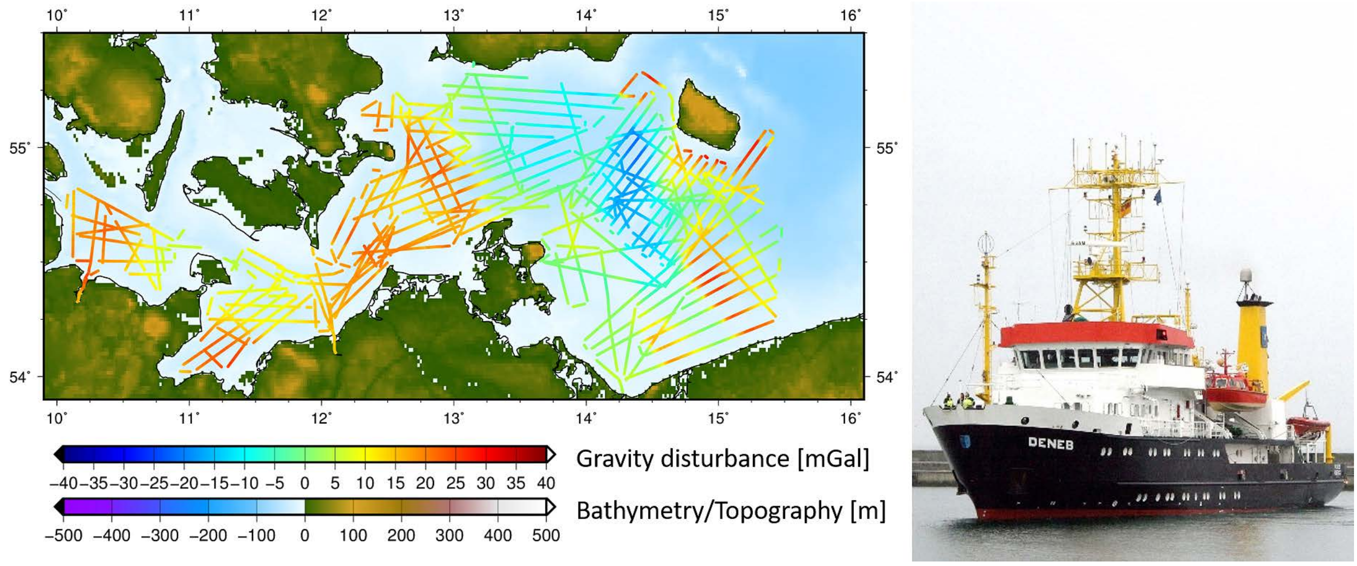


Fig. 3: The track scheme of the four dedicated campaigns done on BSH's survey vessel Deneb. The plot shows the measured gravity disturbance along the tracks together with bathymetry on the sea and topography on land. A picture of the vessel Deneb is given on the right.

MPV Airisto and the Swedish vessel R/V Jacob Hägg. Both ships are hydrographic survey vessels. The main purpose of these campaigns was validation and harmonization of old gravity data in these regions. The total track length of both campaigns together was about 5000 km. Fig. 4 shows the track scheme of these two campaigns. Management and track planning were done by GFZ in close cooperation with Lantmäteriet (LM), Sweden, and Finish Geospatial Research Institute (FGI). Both institutions provided the local tie references on the harbor piers. The data processing (GNSS and Chekan data) was carried out completely by GFZ. The gravity data collected during the campaign onboard MPV Airisto have been used in the meantime for the validation of previous gravity data and generation of a regional geoid for the Bothnian Sea (Bilker-Koivula et al. 2017).

Finally, GFZ performed two non-dedicated campaigns in 2017 and 2018 onboard the ferry liners M/V Urd (Stena Line) between Travemünde and Liepaja respectively onboard M/S Finnlady (Finnlines) between Travemünde and Helsinki (for details c. f. Ince et al. 2020a and 2020b). The total track length of both campaigns was about 9700 km. A plot is given in Fig. 5. The main purpose of these campaigns was collecting records along very long lines in a cost-efficient way. Such ferry campaigns with individual track lengths up to 1500 km allow for a contribution to longer wavelength components of the Earth's gravity field as well as again for the validation and harmonization of existing marine gravity data. Both

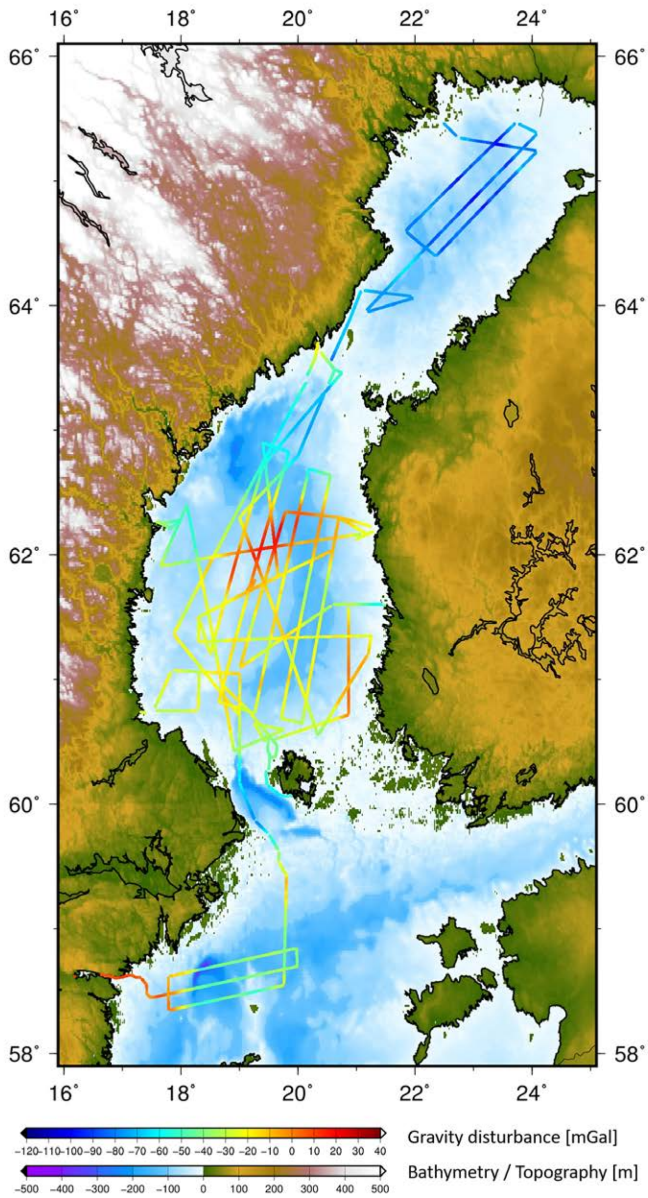


Fig. 4: The track scheme of the two dedicated campaigns onboard the vessels MPV Airisto and R/V Jacob Hägg on Bothnian Sea and Bothnian Bay

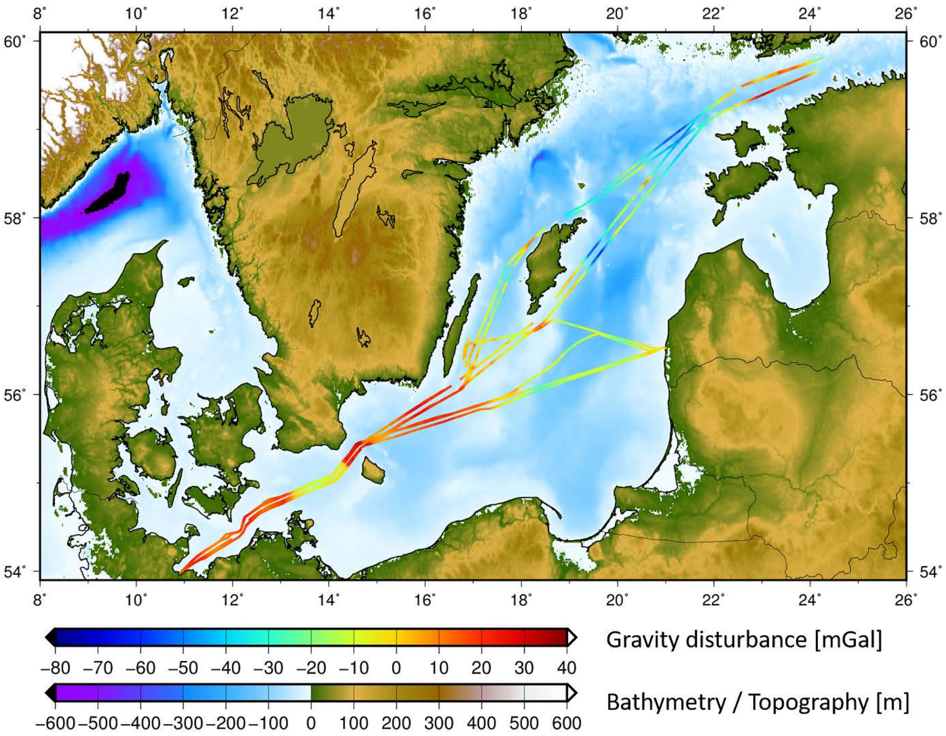


Fig. 5:
The track scheme of the two non-dedicated campaigns onboard the ferry liners M/V Urd and M/S Finnlady

campaigns were organized and managed by GFZ, while BKG and FGI provided the local ties in Travemünde and Helsinki, respectively. The local reference gravity value in the harbor of Liepaja was measured by GFZ, supported by Riga Technical University.

4 Aspects of data processing

The data processing in ship gravimetry from the raw data to the final gravity product comprises a sequence of dedicated and sophisticated working steps. Many of these working steps are hardly done automatically by software tools alone. First of all, the raw gravity records are heavily contaminated by noise caused by disturbing kinematic movements of the ship like rolling and pitching. Further disturbances may be caused e.g. by noise of the engine. And in case of classical spring gravimeters like our Chekan-AM, abrupt speed variations and strong deviations from straight-ahead-movement like turnings may generate additional disturbances.

The disturbing noise in the gravimetric recordings is usually some orders of magnitude larger than the gravity signal. But fortunately, in the case of marine gravimetry this noise affects mainly just the higher frequencies and can be removed by low pass filtering. Therefore, in contrast to airborne gravimetry, estimation of the velocity including vertical disturbing kinematic acceleration is usually not needed in shipborne gravimetry. The optimum filter lengths for the lowpass filter depend on the particular measurement conditions like speed and size of the vessel as well as on the particular weather conditions on sea. Typical filter lengths (i.e. cut-off wavelength) in shipborne gravimetry are about 200 … 400 sec (e.g. Lu et al. 2019 or Ince et al. 2020a). Usually, the removal of very strongly disturbed parts, where filtering does not work properly, is needed. This is often done by visual inspection of the results and manual editing of the data.

For the positioning of the gravity records, an estimation of the trajectory of the vessel respectively the gravity sensor is needed. For this purpose, GNSS data are simultaneously recorded together with the gravity data. It is common practice to install more than one GNSS receiver resp. antenna onboard. This gives among others the option to compute GNSS-based orientations of the particular vessel.

Last but not least, after filtering and trajectory estimation, the reduction of the centrifugal and Coriolis accelerations caused by the vessel's movement on the curved surface of the rotating Earth (Eötvös correction) has to be done.

Classical spring gravimeters as well as novel strapdown instruments are relative measurement instruments featuring a drift. Drift and bias estimation are usually performed on the basis of local ties in the harbors. This means, ship gravimetry includes measurement of gravity ties at the harbor piers to absolute gravity points. In cases where the height of the gravimeter sensor above the pier is larger than a couple of meters an estimation of the local gravity gradients at the harbor pier is advisable to link the absolute gravity reference value to the instrumental sensor height onboard as accurate as possible (Ince et al. 2020a).

At the end, careful validation of the obtained results is recommended. This includes comparisons resp. consistency checks to external data like global gravity field models, bathymetry data and already existing gravity data on the sea. The main and commonly applied approach to validate drift and bias estimation of shipborne gravimetry data is performing cross-over point analyses, which gives a reliable measure of the achieved accuracy for the particular gravimetry survey. For the Chekan based marine gravity data, the accuracy obtained from cross-over point residuals is usually below 1 mGal, primarily depending on the sea condition (Krasnov et al. 2014, Lu et al. 2019, Ince et al. 2020a).

Detailed explanation of our ship gravimetry data processing is not the aim of this paper and for interested readers we refer to other recent publications from our side like Lu et al. (2019) and Ince et al. (2020a). Here we focus on one particular data processing aspect only, a comparison between GFZ's Chekan-AM and TU Darmstadt's strapdown measurements, which is outlined in the following chapter.

5 Comparison between Chekan-AM and strapdown measurements

In strapdown airborne and marine gravimetry two basic processing approaches can be distinguished: the direct and the indirect method (Jekeli and Garcia 1997, Jekeli 2001). Using the indirect method, all IMU and GNSS observations are integrated in a single Extended Kalman Filter. Gravity is obtained indirectly from the position domain. Alternatively, gravity can be computed directly in the acceleration domain: In the direct method, gravity is obtained by taking the difference of the kinematic accelerations and the accelerometer measurements, the so-called specific force, considering the Eötvös correction. However, a GNSS/IMU integration is still necessary to account for the IMU's changing 3-D attitude vector. The kinematic acceleration is obtained by numerically differentiating twice the GNSS position solution, which can be determined by Precise Point Positioning (PPP).

In several marine and airborne campaigns (FAMOS Deneb 2017, among others), both strapdown processing methods have been tested, resulting in similar accuracies (Johann et al. 2020). The FAMOS Deneb 2018 campaign was processed applying the direct method. Detailed insights in the processing strategies of the indirect and the direct method can be found in Becker (2016) and Johann et al. (2019). For the Deneb campaigns, the kinematic acceleration was neglected.

Since the strapdown IMU and the Chekan-AM ran side-by-side in the FAMOS campaigns onboard the vessel Deneb in 2017 and 2018, their results can be compared directly, e. g. based on the RMSE (RMS divided by the square root of 2) of the cross-over point gravity residuals. Regarding approximately straight track segments without harsh sea conditions in 2017, RMSE of 0.33 mGal and 0.7 mGal were obtained with the Chekan-AM and the strapdown IMU, respectively. Encasing the strapdown IMU in the thermally stabilized housing in 2018, the cruise-wise adjusted RMSE improved to about 0.41 mGal (0.52 mGal before adjustment), which indicates a precision similar to the Chekan-AM (0.39 mGal). More details are given in Johann et al. (2020).

Fig. 6 shows strengths and weaknesses of both measurement systems for the example of the gravity disturbance results obtained from the last cruise of the FAMOS Deneb 2018 campaign. On the one hand, the Chekan data contain clearly visible erroneous spikes. They usually arise during turning maneuvers. Moreover, the Chekan results are impaired during periods of harsh sea conditions. Note that these periods are usually cropped in post-processing. In contrast, removing such periods is not necessary in marine strapdown gravimetry since the impact of non-uniform vehicle motion is much smaller here. On the other hand, the remaining long-wavelength differences between the results of both instruments are expected to be primarily caused by non-linear IMU drifts – a challenge in strapdown gravimetry, especially at the multi-day cruises of the Deneb campaigns. Therefore, a combination of both measurement systems might enable enhanced results with complete and reliable short-wavelength results and also a high long-wavelength stability.

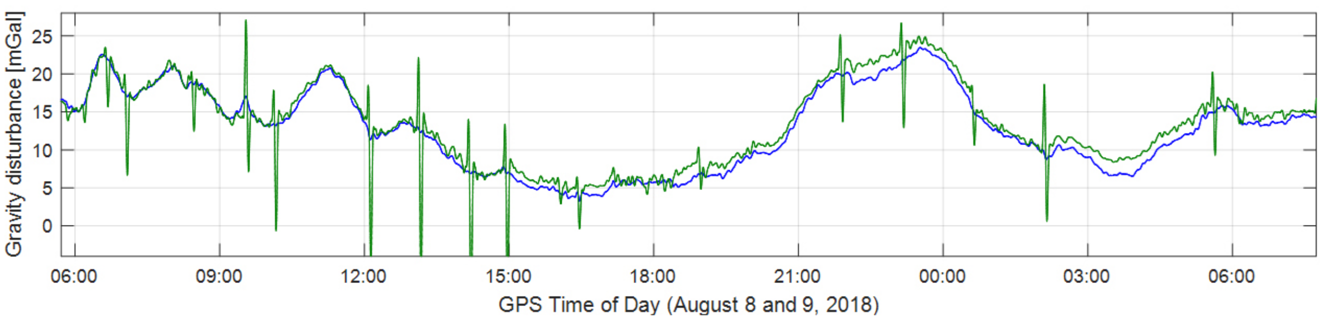


Fig. 6: Comparison of estimated vertical gravity disturbances at the last cruise of Deneb 2018 (blue: strapdown; green: Chekan-AM)

6 Results and outlook

The described shipborne activities of GFZ and BKG together with TU Darmstadt are an important contribution to the generation of the new Baltic Sea Chart Datum. The measured gravity data are collected at the FAMOS data base managed by DTU Space Copenhagen, Denmark. In addition, the final processed data set of the two ferry campaigns (Urd 2017 and Finnlady 2018) is freely available for download from GFZ Data Services (Ince et al. 2020b).

The work on the new Baltic Sea Chart Datum is not yet finished. Since the support by EU for the FAMOS project ended mid of last year, the work cannot be continued in the context of this project. Therefore, to finalize the generation of the new height reference for the Baltic Sea, the Chart Datum Working Group (CDWG) within the Baltic Sea Hydrographic Commission (BSHC) has agreed to take over the coordination for the production of the final BSCD2000. This comprises several tasks. At first, still existing significant data gaps should be closed if possible. Fig. 7 shows a map of the currently available gravity data in the FAMOS data base. This data collection comprises gravity data recordings within the FAMOS project as well as gravity data from decades back to 1956. It is worth noting that these old data sets comprise previous ship- and airborne data but also field gravimeter measurements on the ice surface taken in cold winters when the sea was frozen, especially on the Gulf of Bothnia (Noréus et al. 1997). The largest remaining data gaps are in the eastern part of the Gulf of Finland and in waters North of Poland. At least for the latter region there exists a good chance to close the gap since institutions from Poland (University of Gdansk in cooperation with the Polish Navy) cooperate with the CDWG and have started marine gravimetry surveys in the meantime. A further aspect is the generation of the new geoid for the Baltics which should be a combined geoid model comprising contributions from those of the FAMOS cooperation partners working in the field of regional gravity field modelling. Finally, it is planned to implement the new BSCD2000 by 2023.

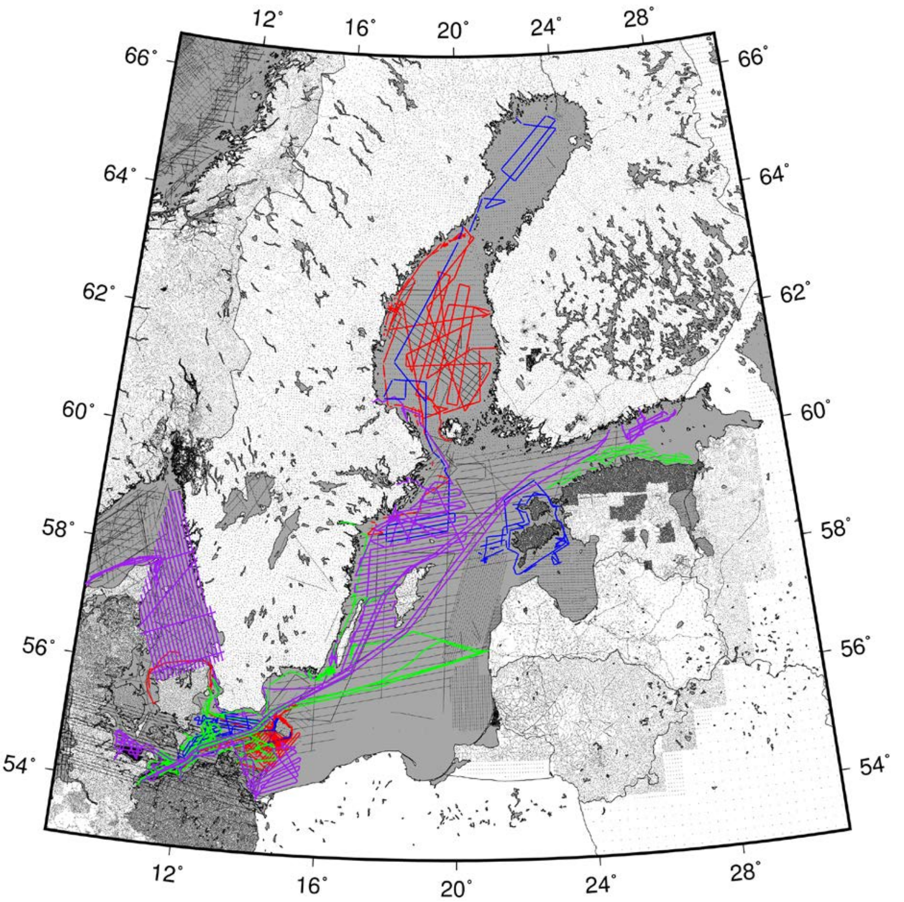


Fig. 7:
Map of the currently available gravity data in the FAMOS data base. The purple, red, blue and green lines are the tracks of the ship- and airborne gravimetry surveys in the framework of FAMOS done since 2015. The grey lines and dots in the sea areas are gravimetry data from previous decades (by courtesy of Jonas Ågren, Lantmäteriet).

Apart from FAMOS, the cooperation partners GFZ, BKG and TU Darmstadt will continue their successful cooperation. For instance, shipborne gravimetry on the North Sea is planned for 2021 again on the vessel Deneb. This campaign will be a continuation of a survey in the German Wadden Sea done in 2015. The purpose of these campaigns in the North Sea is the improvement of the marine geoid there.

Acknowledgements

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