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Key Points:
- Reliable gravimetric measurements are critical to precision vertical navigation on fairways
- The surface correlation coefficient can be used for free-air anomaly map validation

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Analysis of Free-Air Anomalies on the Seaway of the Gulf of Gdańsk: A Case Study

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Abstract In this paper, we present an attempt to determine the accuracy of shipborne gravimetry for the needs of geoid determination. The shipborne gravity campaign, described in this article, is the beginning of a series of gravimetry measurements in the Polish Exclusive Economy Zone. The campaign was conducted in the area where the accuracy of geoid determination is crucial for the safety of navigation on numerous intersecting ships' routes. The vicinity of the seashore, various depths, and short-lasting campaign enabled determination of the level of measurement accuracy that can be obtained depending on the conditions. Internal data consistency was estimated as well as an attempt to compute external accuracy. The data were compared with satellite data available for the region. We identified which of the differences are related to the influence of external factors.

1. Introduction

Shipborne gravimetric measurements, pioneered by Vening-Meinesz, have been performed since 1923 (Bell & Watts, 1986). Although the gravity field on the sea has been measured for 97 years, there are still areas where no shipborne campaign has been performed. An example of such a region is the Gulf of Gdańsk. This area has a tremendous economic significance due to including two thriving harbors: Gdynia and Gdańsk. Annually, both ports increase transhipment. To maintain the development pace, the ports are preparing to launch deep-water terminals. Numerous waterways leading to the mentioned ports intersect in the Gulf of Gdańsk, which in many parts has shallow water. Therefore, vertical navigation accuracy is crucial for the further development of the region. It can be improved by introducing geodetic chart data based on a high-quality geoid model. In the 1970s, the Institute of Geodesy and Cartography and the Institute of Physics of the Polish Academy of Sciences in cooperation with the Institute of Earth Physics of the USSR Academy of Sciences and the Institute of Earth Magnetism and Wave Propagation in Leningrad conducted four gravimetric campaigns in the South Baltic. The Earth's gravity field was determined with shipborne gravimeters GAŁ-M and TGG-1. The mean error in determining the acceleration of gravity after alignment was ±1.6 mGal. The position was determined with a hyperbolic radio navigation system. Its accuracy was as follows: Decca = from 50 up to 1,000 m with the main station in the range of 300 nautical miles, Seafix = from 10 to 40 m in the range up to 20 nautical miles from the main station. The performed gravimetric measurements covered the area of the Polish Exclusive Economic Zone excluding the part of the Gulf of Gdańsk south from the Hel Peninsula. The analysis of the documentation indicates that no gravimetric measurements were carried out in this area. Recently, numerous Baltic States have intensified gravimetric measurements. One, and probably the main, reason is the FAMOS project, which has been ongoing since 2014 and has been cofinanced by the European Union. FAMOS encompasses four project activities. One of them is to improve vessel navigation by unifying the vertical data in the Baltic Sea. The new reference level will be the local geoid surface. During the first two phases of the FAMOS project, called “FAMOS Freja” (2014–2016) and “FAMOS Odin” (2016–2018), no gravimetric measurements meeting the assumed requirements were carried out in the Polish sea areas, except for a German campaign also covering the area west of Kołobrzeg in 2018. The gravimetry campaign presented in this article is a part of a wide approach aimed at filling the gaps in gravimetric measurements of the Baltic Sea. A shipborne gravimetric campaign requires preparation in terms of conducting the measurement itself and extracting the signal from noise generated by the environment (Boggs et al., 2004; LaCoste, 1967; Tomoda, 2010). It is crucial to determine the level of sensitivity that can be accomplished during the measurements. This requires creating a situation in which

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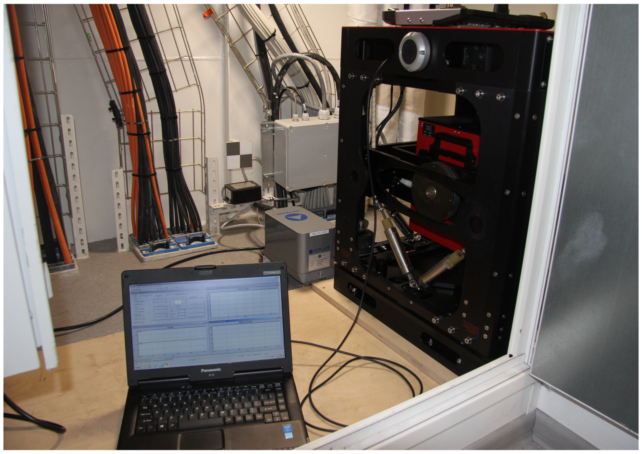

Figure 1. Gravity meter MGS-6 assembly on board the survey vessel.

the maximum possible number of sources interfering with the measurement are eliminated. One and all gravimetric surveyors are guided by this aim (Bell & Watts, 1986; Dehlinger, 1978). It can be assumed that the level of precision and accuracy is determined by the manufacturer of the measuring device. The first alternative solution is to examine the measurement precision of the device in laboratory conditions and implement it as a reference value. The second one is presented in this paper. The manufacturer, Micro-g LaCoste (Lafayette, US-CO), states that the measurement accuracy is 1 mGal (Przyborski et al., 2019). The method of assessing the gravimetric measurements' accuracy is a separate issue. It can be divided into the assessment of internal and external accuracy. The first one defines to what extent data collected during the measurements are subject to random disturbances and their signal-to-noise ratio. It is an analysis of internal data consistency. A common way for its determination is an analysis of data at crossover points. A measurement repeated at a point at least twice enables determination of data consistency through the analysis of the distribution of residual differences. However, such an analysis gives no information about the external accuracy of the data. To determine the value of the absolute error, it is insufficient to analyze only the data's internal consistency. Comparing the results with reliable data from an independent campaign is the right solution. However, it is only possible if, for a representative group of collected data, there will be reliable data for comparison. Considering the number of areas not covered with any gravimetric data, the team focused on an alternative approach to estimate the level of external accuracy. An attempt to perform such an analysis is made in the present paper. Such an approach is based on the analysis of the environmental conditions during the campaign. In section 2, a description of the marine gravimetric campaign is provided. This campaign was performed in the area that was not yet studied using marine gravimetry so far, so there were no valid historical data for comparison. The results of the collected data analysis are presented in section 3. As an estimate of disturbance of external conditions to measurements, the vibrations registered by the inertial measurement unit (IMU) were used. These data were used for an analysis of collected gravity data that could improve the global geopotential model for the studied area.

2. Materials and Methods

The marine-based dynamic gravity meter MGS-6 (Micro-g LaCoste) was used for registering the gravity changes during the campaign. The system's frame supports the gimbal and sensor and isolates them from vibration using air dampers, suspension cords, and air-filled vibration mounts. The gimbal holds the gravity meter sensor and keeps it level when the system is moving. The gravity meter sensor contains the gravity-sensing element, heater, and electronics for the platform. It is operated from a laptop, which also records the gravity data. Figure 1 shows the installation of the complete system on board the survey vessel. During the campaign, data were also recorded from Octans IXSEA, an all-in-one fiber-optic gyrocompass and motion sensor, and GPS receiver Trimble SPS 855. The Octans IXSEA has a heading accuracy of 0.1 deg secant latitude, heave, surge, and sway accuracies of 2.5 cmor 2.5% and roll, pitch, yaw dynamic accuracies of 0.01°. The data interface was an ethernet port. The gravity meter and Octans IXSEA were mounted on the ship “Oceanograf” 0.18 m from the ship's center of gravity (motion). The GNSS receiver with a Zephyr antenna tracked signals of GPS (L1C/A, L1/L2/L2C), GLONASS (L1/L2C/A, L1/L2P Full Cycle Carrier), Galileo, Quasi-Zenith Satellite System (QZSS), and Compass (CCNS). During the campaign, the RTK positioning was used with the accuracy 8 mm + 1 ppm horizontally and 15 mm + 1 ppm RMS vertically.

The data recorded from different sensors/receivers during the campaign were merged in postprocessing. Analysis of the data led to the computation of the free-air anomaly. The gravity anomaly is defined as the difference between the actual gravity as measured on the ground and the normal gravity on the telluroid (Hofmann-Wellenhof & Moritz, 2006). For the data analysis and processing, the Intrepid software Sea-g was used. A Blackman FIR filter with a window length of 120 s and a cutoff frequency of 1/(window length) was used to filter out the noisy component of the raw measurements. To avoid introduction of a phase shift, the forward-backward method was used (Gustafsson, 1996). During processing, filters with window length from

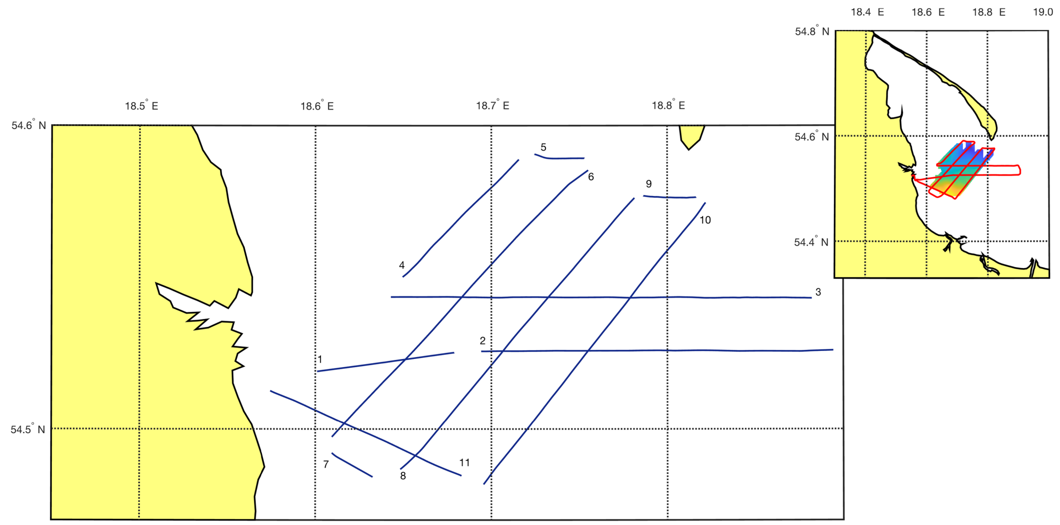

Figure 2. The survey vessel track divided into measurement lines.

90 to 200 s were tested. According to the results, the optimal filtration in the sense of crossover analysis was 120 s window length. The data were cleaned, and heavily disturbed data were removed. The effect is shown in Figure 2. The remaining data created measurement lines. These lines have undergone additional cleaning and processing. One essential step in marine campaign gravity data processing is drift removal. Because this campaign was ≈12 hr, it can be considered as short. During such short periods the MGS-6 gravimeter drift is not very significant because in stationary condition it does not exceed 1.4 mGal/month (Przyborski et al., 2019).

Another important step in data processing is the reference to the land absolute gravity. On the harbor pier there was a gravimetric reference point created during preparation for the campaign. The value of this point was estimated using a relative gravimeter to transfer the absolute value from the absolute point of the Gravity Control in Poland 5403 POLREF-GORA DONAS (id. 315302200 5418273255.113). The ship was moored near the same place before and after the campaign. The comparison of the relative value of the ship's meter with the absolute pier point was made twice. The first still meter value was 1,533.4342 mGal. The second was 1,533.3843 mGal. The difference between these values is −0.0499 mGal. The time difference between both reads was 11.08 hr. Based on these values we were able to estimate linear drift. In the case of this campaign, we considered a linear drift model. The linear drift during the campaign was estimated as −3.24 mGal/month.

The measurement lines were the basis for creating a free-air anomaly grid using the method of variable density. The obtained grid is shown in Figure 3. The presented grid creates a 100 × 290 matrix.

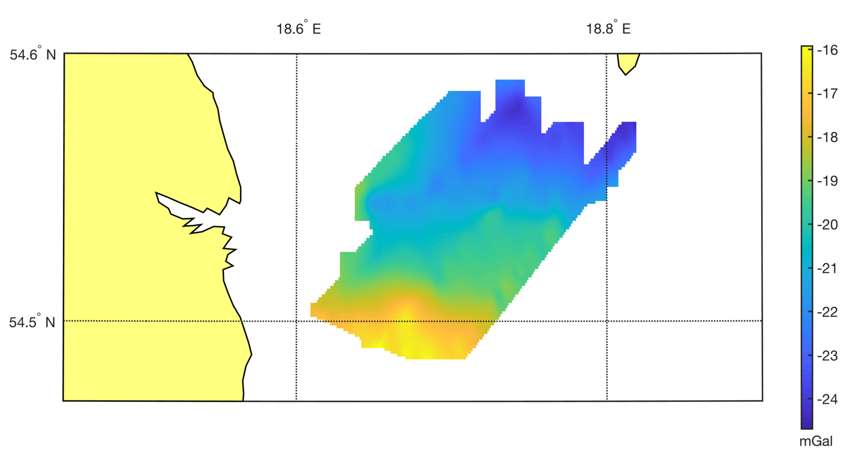

Figure 3. The free-air anomaly grid obtained from postprocessing of the measurements.

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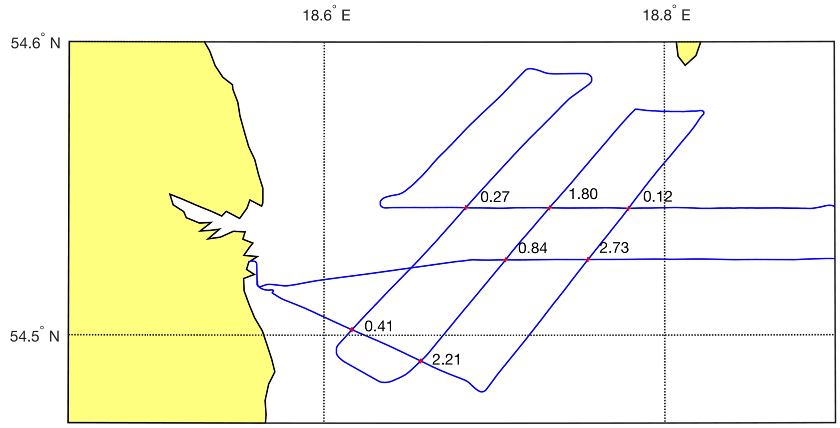

Figure 4. The result of the crossover analysis. Each point indicates the absolute value of misclosure in mGal between filtered and corrected gravity on crossing profiles.

To estimate the internal consistency of the data, an analysis of the crossover differences was performed (Olesen, 2002). The analysis was performed using the filtered values of gravity corrected by the drift. Based on the analysis, the internal error of the measurements was estimated at 1.13 mGal (standard deviation estimate). The results of crossover analysis are shown in Figure 4.

Because no gravimetric measurements have been carried out in the area of Zatoka Gdańska before, historical data could not be used for comparison. Accordingly, it was decided to validate the external accuracy by comparing with a global geopotential model. For this purpose, data from the SGG-UTM-1 model, a combination of EGM2008 data and GOCE satellite data, were used (Liang et al., 2018). The free-air anomaly based on this model was calculated with the ICGEM service (Barthelmes, 2016; Ince et al., 2019). To avoid the Gibbs effect, ICGEM's "gentle cut" option was used from degree 2000 up to degree 2159 (the maximum degree of the model). The resolution of the grid obtained even from such a high-degree model is about 9 km. To enable direct comparison, the data calculated on the basis of the SGG-UGM-1 model were interpolated to the grid nodes in Figure 3. MATLAB software with the Curve Fitting Toolbox was used for interpolation. Biharmonic interpolation consistent with Sandwell (1987) was used.

3. Results

The difference between the SGG-UTM-1 model and the measurements is shown in Figure 5. The average values were not included in the analysis; the mean value over the grid was removed.

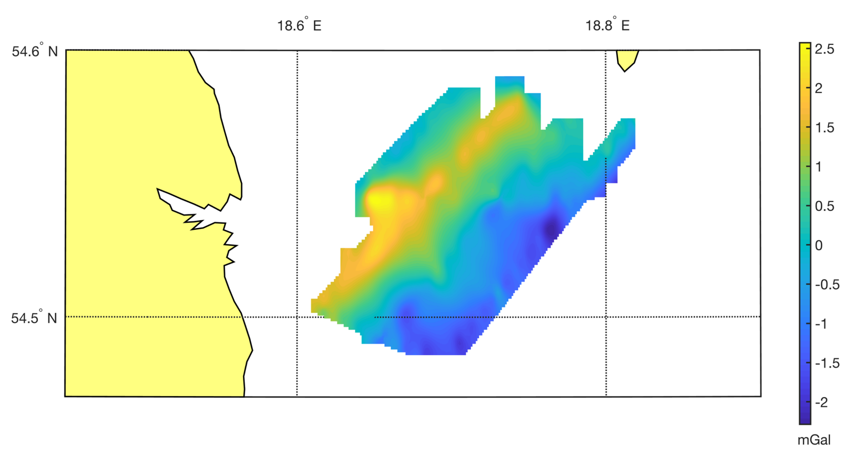

Figure 5. The difference between the grid based on satellite gravity data and the grid obtained from measurements. The constant component of the grid is removed.

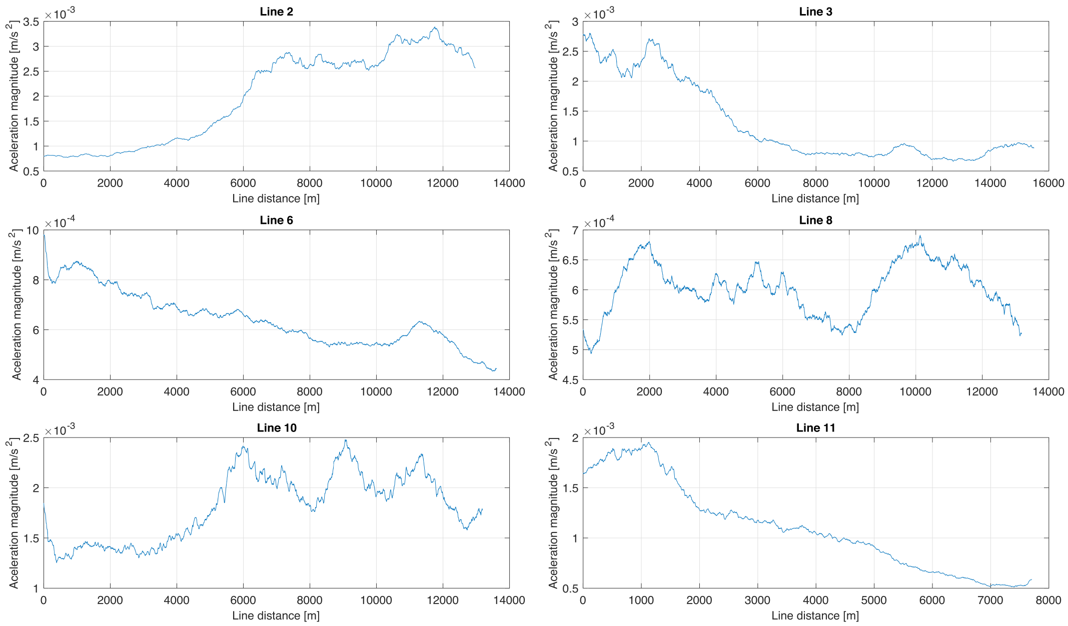

Figure 6. Vibration density distribution on selected profile lines.

It was decided to examine if and to what extent the differences observed were related to the external conditions during the measurements. To achieve this objective, data collected by the ship's IMU were used. The IMU installed on board the "Oceanograf" records the linear accelerations. Fundamentally, the principle of operation of the gravity meter and the IMU differ significantly. Basically, they will react differently to the research vessel's acceleration. The parameters, whose difference is the most important for our investigations, are sensitivity and impulse response. To simplify, it was decided not to analyze the values of momentary acceleration of the ship. Instead, a surface analysis was performed. As part of this analysis, an assumption was made, which was met mainly due to the specific condition of the described measurement campaign. It was assumed that the areas of worse measuring conditions do not move during measurements. This assumption is justified due to the short period of measurements and due to the stability of weather conditions at that time. We decided to analyze the average acceleration amplitude recorded by the IMU. Such an approach is somewhat of a simplification, although it has two advantages: The selected value is a scalar and can be compared with the data from the gravity meter without the knowledge of its impulse response. The average vibration amplitude was calculated as follows. On the grounds of an IMU record of three-axis acceleration, the momentary acceleration vector was calculated. The changes in the modulus of the acceleration vector in time were filtered with a moving mean filter, window width of 120 s. The obtained average values of vibration amplitude for the measurement lines are shown in Figure 6.

It was assumed that the surface distribution of the measurement conditions in the area was constant, thus a map of the surface distribution of average vibration amplitude was made. Biharmonic interpolation (Sandwell, 1987) of the vibration amplitude's data on measurement lines was used to perform it. To remove artifacts arising as a result of interpolation, we used blurring with Gaussian filter with a half-value width of 50". An analysis of the correlation of the obtained vibration map with the map is shown in Figure 5. To determine the correlation of the respective map's areas, the method derived from image analysis was used. The linear correlation coefficient between two matrices X and Y can be calculated as

$$\rho = \frac{\mathrm{cov}(X, Y)}{\sqrt{\mathrm{var}(X)\mathrm{var}(Y)}} \tag{1}$$

Suppose for simplicity that the X and Y matrices have the same dimensions. In equation (1), $\mathrm{cov}(X, Y)$ means the covariance of the matrix X with the matrix Y calculated as

$$\mathrm{cov}(X, Y) = \frac{1}{N-1}\sum_{x,y}(X - \bar{X})(Y - \bar{Y}), \tag{2}$$

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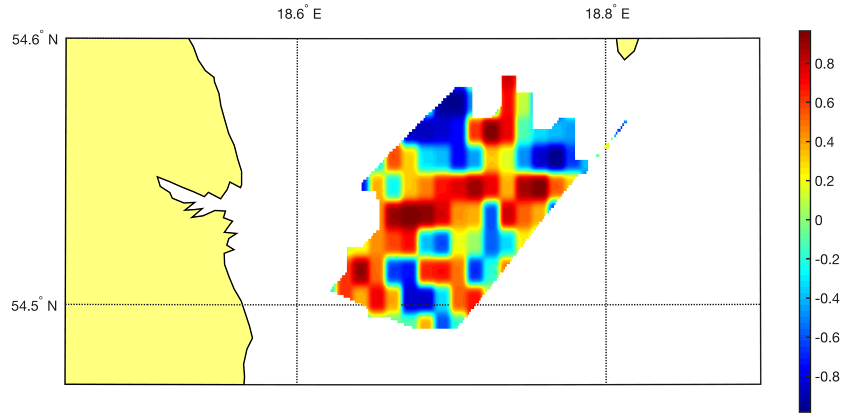

Figure 7. Distribution of the correlation coefficient between the difference grid and vibration density.

where $\bar{X}$ means the average value of X (Y analogously), summing is performed on the elementwise product of matrices. N is the number of elements in the X matrix. Variance (var) was calculated in the following way:

$$\mathrm{var}(X) = \frac{1}{N-1}\sum_{x,y}(X-\bar{X}). \quad (3)$$

Analogous designations as above. The correlation coefficient defined by equation (1) has been used many times as one of the methods of searching for elements in images (Lewis, 1995; Potetz & Lee, 2003). The issue in this article is slightly different, therefore, the method was adapted to the new conditions. To calculate the value of the correlation of the corresponding map's parts, the matrices representing the grids were divided into nonoverlapping 10 × 10 pixels submatrices. Afterward, the correlation coefficient between the corresponding submatrices was calculated. The value of the correlation coefficient was assigned to the entire area of a given submatrix. To soften transitions between areas, a 2-pixel Gaussian blur was used. The grid obtained as a result of these operations is shown in Figure 7.

On the day of the measurement the state of the sea monotonically deteriorated eastward. This observation is confirmed by the graphs of the average amplitude acceleration in Figure 6. The correlation coefficient denotes that all areas where the divergence between model and measurements data had the greatest value (about 2 mGal) are strongly correlated with areas of increased oscillation of the research vessel's hull. Therefore, an assumption can be made, that the presented analysis may allow determining the valency of each data part.

4. Conclusion

In this article, an accuracy assessment of gravimetry data on an area where vertical accuracy is exceptionally crucial is studied. The Gulf of Gdańsk is a basin where shipping routes to developing ports intersect, traffic density is increasing, and annually, the difference between the draft of vessels sailing to the seaports and the depth on the shipping routes is decreasing. The determination of the geoid and the usage of physical heights in ship navigation in this region is becoming more important, as it has done in the other Baltic states. The geoid determination requires accurate and reliable data on the distribution of the gravitational field in a given area. Shipborne gravimetric measurements are one of the effective techniques for obtaining detailed local data. The accuracy of recorded data largely depends on the external conditions prevailing during the measurement. In the paper, the analyzed parameter describing the Earth's gravitational field is the free-air anomaly. It has been shown that there are noticeable differences between the free-air anomalies synthesized from a global geopotential model and the results of the marine measurements. Some of those dissimilarities are significantly correlated with areas where the amplitude of the hull oscillations of the test unit was higher. This implies that the differences do not constitute a real divergence from model data but are the result of local data deterioration due to external conditions. Assessment of the accuracy of gravimetric data recorded during the campaign is critical. Typically used for this purpose, the analysis of differences at the intersection of measurement lines can only answer the question of what is the internal data's accuracy. Assessment of the external accuracy is much more challenging when it comes to shipborne data. Measurements cannot be compared with external data because the available data from global models are characterized by both lower resolution and accuracy. Nevertheless, they allow the identification of regional trends in the data that should also be evident in local maps (grids). Comparison with archival data is often not an option because, in numerous regions, there were no such measurements before, for instance, the area analyzed in this paper. The authors assume that an analysis of the environmental conditions of the gravimetric campaign is an efficient method for determining the external accuracy of gravimetric data. The parameter which can be used to quantify the conditions in a given area is the average vibration amplitude of the research vessel. If the data obtained during the gravimetric campaign does not coincide with the model data available for a given area, it is important to indicate the reason for this. In the paper, we checked whether the two-dimensional correlation coefficient used in image analysis could be used for this purpose. It was proposed to use this function to describe the significance of the relationship between deviations of measurement results from the model and external conditions prevailing at the time of measurement. The average vibration amplitude recorded by the ship's inertial system was adopted as the function estimating the measurement conditions. Based on the results obtained, it has been shown that the use of such an approach can help to decide whether the obtained discrepancies in the results are due to the occurrence of gravimetric anomalies or due to local deterioration of the measurement conditions. From our investigations, we also find that the vessel's average vibration amplitude is correlated with the difference between the recorded data and the data from a global geopotential model. The investigation indicated that the available data of the gravitational field in the area of the Gulf of Gdańsk requires the performance of complementary gravimetric campaigns.

Acknowledgments

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References

Barthelmes, D. F. (2016). International Centre for Global Earth Models (ICGEM).

Bell, R. E., & Watts, A. B. (1986). Evaluation of the BGM-3 sea gravity meter system onboard R/V Conrad. *Geophysics*, *51*(7), 1480–1493.

Boggs, D. B., Dransfield, M. H., & Lane, R. (2004). Analysis of errors in gravity derived from the Falcon airborne gravity gradiometer, *Airborne gravity 2004—Abstracts from the ASEG-PESA airborne gravity 2004 workshop: Geoscience Australia record* (Vol. 18, pp. 135–141). Sydney.

Dehlinger, P. (1978). *Marine gravity* (Vol. 22). Amsterdam: Elsevier.

Gustafsson, F. (1996). Determining the initial states in forward-backward filtering. *IEEE Transactions on signal processing*, *44*(4), 988–992.

Hofmann-Wellenhof, B., & Moritz, H. (2006). *Physical geodesy*. Springer Wien New York: Springer Science & Business Media.

Ince, E. S., Barthelmes, F., Reißland, S., Elger, K., Förste, C., Flechtner, F., & Schuh, H. (2019). ICGEM—15 years of successful collection and distribution of global gravitational models, associated services, and future plans. *Earth System Science Data*, *11*(2), 647–674.

LaCoste, L. J. B. (1967). Measurement of gravity at sea and in the air. *Reviews of geophysics*, *5*(4), 477–526.

Lewis, J. P. (1995). Fast normalized cross-correlation, 1995. Vision interface pp. 120–123, The Vision Interface '95 conference, Quebec, Canada, May 15-19 1995.

Liang, W., Xu, X., Li, J., & Zhu, G. (2018). 425 The determination of an ultra-high gravity field model SGG-UGM-1 by combining EGM2008 gravity anomaly and GOCE observation data.

Olesen, A. V. (2002). Improved airborne scalar gravimetry for regional gravity field mapping and geoid determination. *Copenhagen: University of Copenhagen*.

Potetz, B., & Lee, T. S. (2003). Statistical correlations between two-dimensional images and three-dimensional structures in natural scenes. *JOSA A*, *20*(7), 1292–1303.

Przyborski, M., Pyrchla, J., Pyrchla, K., & Szulwic, J. (2019). MicroGal gravity measurements with MGS-6 Micro-g LaCoste gravimeter. *Sensors*, *19*(11), 2592.

Sandwell, D. T. (1987). Biharmonic spline interpolation of GEOS-3 and SEASAT altimeter data. *Geophysical research letters*, *14*(2), 139–142.

Tomoda, Y. (2010). Gravity at sea—A memoir of a marine geophysicist—. *Proceedings of the Japan Academy, Series B*, *86*(8), 769–787.