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Extraction of geoid heights from shipborne GNSS measurements along the Weser River in northern Germany

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Abstract: In-land geoid models rely on several measuring techniques. The quality of those models is directly related to the spatial resolution of the measurement data. Occasionally, a local geoid model does not cover the coastal area at all and a local marine geoid simply does not exist. Shipborne GNSS measurements may provide a way of overcoming this problem in coastal areas. However, several corrections to the raw measurements must be applied in order to account for systematic effects induced by ship dynamics and other static and dynamic impacts from tides, atmospheric pressure or wind stress.
This paper presents the theoretical background for the method and the results of a case study in the estuary of the Weser River in Germany. A series of GNSS measurements were carried out aboard a ship and the approximate geoid height along the river was derived. For accuracy assessments of this method, the results were compared to the German Combined QuasiGeoid 2011 (GCG2011). The results are very promising and indicate the ability to extract geoid heights from shipborne GNSS measurements.

Keywords: Geoid heights determination, Global navigation satellite system, Sea surface height, Ship-based measurements

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1 Introduction

The geoid is the equipotential surface that coincides with the sea level in the absence of dynamic effects such as tides, wind, ocean currents and other disturbing forces. Geoid heights from global and regional models are widely used for geodetic applications, notably in height determination using Global Navigation Satellite System (GNSS) measurements. Nowadays, space borne gravity missions are a major tool in deriving global geoid models by providing worldwide coverage. Since their spatial resolution can reach tens and hundreds of kilometers (Breili and Rolstad 2009), additional data is commonly necessary to provide regional geoid models with acceptable spatial resolution. On land, this data can be obtained from precise levelling, GNSS and local gravity measurements. In coastal areas where precise levelling is not possible, airborne and shipborne gravity measurements become the methods of choice. Although these approaches can provide high accuracy gravity measurements, both methods are quite expensive and may present challenges in the form of dynamic movements of the platform that introduces some measuring errors (Olesen 2002; Novák et al. 2003; Yoshibumi 2010).

It is well known that the integration of airborne and shipborne gravity data into the global gravity models improves the accuracy of regional gravity fields and geoid models. An improvement of several tens of centimeters and bias removal were achieved in the geoid model around Corsica, after integrating some aerial gravimetry measurements into existing models (Duquenne et al. 2002). A new geoid model, based on a large gravity survey that took place over the Greenland continental shelf and the Baltic Sea, introduced changes of up to 30 cm to the geoid models in the open sea (Forsberg et al. 2001). It also showed an agreement between airborne and surface measurements inland.

A project carried out in the Aegean Sea was aiming to improve the local geoid models by integrating altimetry and shipborne gravimetry measuring data. Best results were achieved by combining both data sources: altimetry data contributed to the overall accuracy while the shipborne data improved the model in coastal areas (Vergos et al. 2005). Another study was carried out in Japan to achieve improvements of the local model by combining land and shipborne gravimetric data with altimetry-based gravity model and Gravity Recovery and Climate Experiment (GRACE) based global geopotential model. Results showed model improvements of several centimeters and a final accuracy within 10 centimeters (Kuroishi 2009).

In this study, we present a different approach for marine geoid determination. The method is based on shipborne GNSS measurements. Previous works have shown that the Sea Surface Height (SSH) could be obtained from shipborne GNSS measurements with reasonable accuracy. A survey carried out around Santo Island in Vanuatu, was aiming to obtain SSH near the island during calm and rough sea conditions, within a distance of up to 80 km off the coast. During post-processing, the authors corrected the measured heights using ship's attitude recordings collected by an onboard motion reference unit (MRU). However, squat corrections were neglected.

Final SSH accuracy was within 15 cm (*Bouin et al. 2009*). Another survey was carried out near Hawaii. Its goal was to obtain SSH within distances of up to 200 km off the coast. This time, any attitude prone measuring error was not treated by the authors. Final accuracies were within 10 cm (Foster et al. 2009). Another group took onboard GPS measurements one step forward and was aiming not only for SSH measurements but also for the retrieval of geoid profiles along the ship's track. No attitude corrections were applied to the measurements, although two GPS receivers were operating simultaneously aboard in order to determine some aspects of the ship's movement. The similarity of the measured geoid profiles to those provided by the NKG04 geoid model was within 15 cm (Jürgenson et al. 2008). Nevertheless, after applying all necessary dynamic corrections, final accuracy of the measured SSH could be improved to about 3-5 cm (Reinking et al. 2012). With the addition of mean dynamic topography, tidal and dynamic atmospheric corrections, approximate geoid heights could be calculated from those SSH measurements, without the use of local/global geoid models. The dynamic topography mainly results from variations in currents and salinity. If these variations are small like in the area of investigation of this study, the dynamic topography could be understood as approximately constant and treated as a constant datum offset.

This paper describes an experiment carried out in northern Germany. The GNSS-derived geoid heights are compared to their equivalent from the reference geoid model GCG2011. Both sets of data are of type quasigeoid. Hence, to be exact, this paper deals with the estimation/comparison of quasigeoid data. Nevertheless, the particular topographic situation in the area under investigation allows assuming a coincidence between the geoid and the quasigeoid that is much better than the expected quality of the GNSS-derived geoid heights of some centimeters.

The paper presents the methodology steps required for the determination of the approximate geoid surface in chapter 2. Chapter 3 describes the experiment carried out in northern Germany. Chapter 4 presents the data processing while chapter 5 deals with the validation of the resulting surface by comparison against the local quasigeoid model. Chapter 6 contains some brief conclusions of our findings.

2 Methodology

The determination of the SSH is based on ellipsoidal heights collected through means of shipborne GNSS measurements, and it encompasses two main steps. In the first

step, corrections for the height variations induced by the vessels dynamic behavior are applied to the raw measured GNSS heights. The second step is the application of tidal, atmospheric pressure and wind stress corrections.

When reviewing the dynamic behavior of the vessel, three major effects have to be considered and treated: attitude changes (pitch and roll), heave and squat. The heave must be known at the position of the GNSS measurement. Using an Inertial Measurement Unit (IMU) would require an extrapolation of the observed heave to the position of the GNSS measurements, which might introduce some additional systematic errors due to possible long lever arms. It has been shown in a large number of experiments that the heave can best be derived from double-differenced raw GNSS phase measurements in time, which yields position changes between consecutive epochs. The height changes can be cumulated and high pass filtered (Reinking and Härting 2002).

Before the height variations can be used to calculate the heave, they must be corrected by the influences from pitch and roll that could easily be calculated using several GNSS antennas - at least three - mounted aboard the vessel through simple calculation of a spatial rotation between two sets of coordinates (Arun et al. 1987). On a small vessel under moderate sea state conditions, the influence from pitch and roll will be small. Hence, an acceptable heave correction can be derived approximately by the use of only one GNSS antenna aboard the vessel with negligible error (Harting et al. 2004).

Squat is a hydrodynamic phenomenon that results from the reduction of the pressure underneath a moving ship according to the fundamental physical law of energy conservation, which is governed by Bernoulli's principle. The variation of the pressure produces the typical wave system with a bow and stern wave and a trough in the middle. This waves system yields an apparent draft increase with respect to the static ship.

The height variation caused by the squat cannot be corrected with acceptable quality by using existing empirical approximation formulae as those from ICORELS, Barras, Millward etc. (Briggs 2006), since these formulae provide only approximate values of the squat. Hence, a specific squat function should be derived for the vessel used in the survey. Such a function could be achieved using the SHIPS method (Harting et al. 2004; Harting and Reinking 2002). This method is based on the modeling of the squat-velocity relation for a specific vessel using a dynamic reference station in a form of an escort vessel.

After applying all necessary hydrodynamic corrections, one should get the instantaneous water level. The next step would be to apply tidal and dynamic atmospheric corrections. The tidal corrections will be calculated from tide gauge readings of the water surface and subtracted from the GNSS derived heights later. Since both observations are carried out at the same time, they will be influenced by the same atmospheric effect which cancels out in the difference.

Tidal corrections may be calculated using the Tidal Constituent and Residual Interpolation (TCARI) method that is based on the spatial interpolation of tidal components, amplitude and phase, and a non-tidal component (residuals) (Hess 2003; Lavrov et al. 2015). Tidal constituents are extracted through classic tidal analysis, from recorded tidal time series in every tide gauge located within the survey area. The residuals are the differences between the calculated tidal values based on the extracted constituents and the actual measured tidal values in each tide gauge. Figure 1 presents a flow chart of the methodology steps.

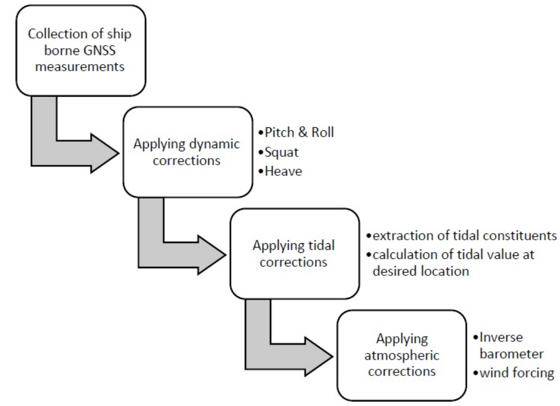

Figure 1: Flow chart of the methodology steps.

3 Experiment Set Up

An experiment was conducted in October 2013 along a 15 km long segment of the lower Weser River in northern Germany that stretches between the cities of Brake (in the north), Elsfleth and Farge (in the south) (Figure 2).

The lower Weser is an estuary that is influenced by the tidal behavior of the North Sea. Up to Bremen, the water level shows a tidal range of up about 4 m. The corresponding change of the flow direction leads to variation of the currents between about 1.2 m/s down- and upwards the river. Since the wider surrounding topography could be stated as lowland with heights that seldom reach more than 30 m up to a distance of 80 km from the area under investigation, the mean water level coincides in good approximation with the geoid.

The area was selected because it provides laboratory-like conditions for the investigation of the proposed method. The existing German Combined QuasiGeoid 2011 (GCG2011) allows the extraction of the quasigeoid height along the river with an accuracy of about 1 cm (Schäfer et al. 2012). Its spatial resolution, about 1.7 km,

allows resolving the geoid details within the area of investigation. Due to the structure of the topography and morphology of the surrounding area, the differences between the quasigeoid and the geoid and in particular their variations are very small. Hence, for experimental purposes, the quasigeoid heights are treated as the geoid heights along the river segment and later on will be used for comparison and validation of the experiment results.

For the survey, a small survey vessel "Marvin" (Figure 3) was used, for which the dynamic squat is known from different calibration experiments. The boat is equipped with one Trimble 4700 receiver and Compact L1/L2 antenna without ground plane. During twelve measuring days, the boat sailed twice in eight hours along this river segment up and down the river. The GNSS data was collected with a sample rate of 1 Hz.

Figure 2: Illustration of the river segment under investigation (Google Earth). Red markers indicate the location of the three tide gauges along this river segment. The river flows from Farge in the south to Brake in the north.

Figure 3: "Marvin", the survey vessel used in the experiment.

4 Data Processing

4.1 Instantaneous water level heights from GNSS data

GNSS data from the receiver aboard the ship was processed in conjunction with GNSS raw data from the German reference station network SAPOS in a kinematic mode using a self-developed software package. The resulting ellipsoidal GNSS antenna heights were hence derived in the European Terrestrial Reference System 1989 (ETRS89).

The distance between the antenna reference point and water surface was measured with a tape at the berth and corrected for draft changes due to change of loading and fuel consumption during the survey.

The heave of the boat was calculated as described above from epoch-to-epoch double-differenced GNSS phase differences and applied as a correction to the observed heights. The squat of the boat depends on the speed through water, which was in our case observed by a Doppler log installed aboard the boat.

After applying the mentioned correction, the instantaneous water level heights are known as ellipsoidal heights with respect to ETRS89.

4.2 Water level from tide gauges

Three tide gauges are located along the river segment under investigation (Figure 2) which provide water level heights with respect to the German height system DHHN92. Due to data restrictions, tidal records of about two years, from 1/1/2012 up until the day of the survey were used at each tide gauge station. The tidal records were analyzed using the UTide Matlab Functions (Codiga 2011).

Essentially, tidal values will be combined with the ship-based water level measurements. Due to the large amount of ship-based measuring data, we decided to create an equally spaced grid along the river for tidal correction (Figure 4). The grid was created within the area enclosed by the sailing profiles. The spacing of the grid points was designed so that a similar tide value can be assumed for the grid points and the observation positions of the ship-based data.

Figure 5 presents the calculated tide values, using the TCARI method, during one of the measuring days in all grid points created. Because the tide advances as a single front up the river, it is expected to reach the northern grid points before it reaches the southern ones. However, although roughly 15 km separate the most northern and the

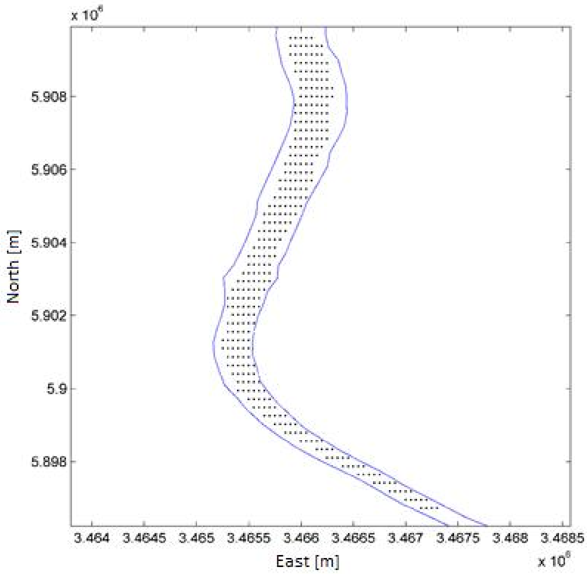

Figure 4: Not-to-scale and slightly skewed illustration of the grid points within the river segment under investigation.

most southern points, it is almost impossible to detect any temporal shift in the calculated tide values, which is very unlikely and indicates a possible problem of the application of the TCARI method to this area.

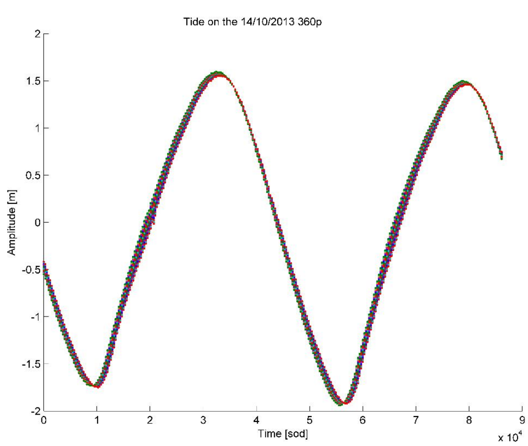

Figure 5: Calculated tide values in the grid points along the river segment using TCARI. Each color represents different grid point.

The survey area characteristics differ from those presented in previous works (Hess 2003; Cisternelli and Gill 2005; Cisternelli et al. 2007; Lavrov et al. 2015) and we assume that this strongly affects the performance of the method. The segment of the Weser River is long, narrow and shallow, in which the tide wave advances as a single front with negligible changes between both banks. Hence we decided to treat this problem alternatively as a two dimensional problem, where the river is unwrapped as a straight line and the several components (amplitude, phase, residuals) are interpolated along it using a thin plate spline. Later, the tide at each grid point is reconstructed based on the interpolated components. Figure 6 presents the results for the same measuring day as presented in Figure 5 using the spline interpolation approach. We can clearly see the temporal shift in the tide values (25 minutes at high tide and 40 minutes at low tide) between the most northern and most southern grid points, which is what one would expect. In addition, these results correspond to hydrological data from the port authorities in Bremerhaven. Hydrological data states an approximate 27 minutes time difference at high tide between Brake and Farge and 41 minutes at low tide.

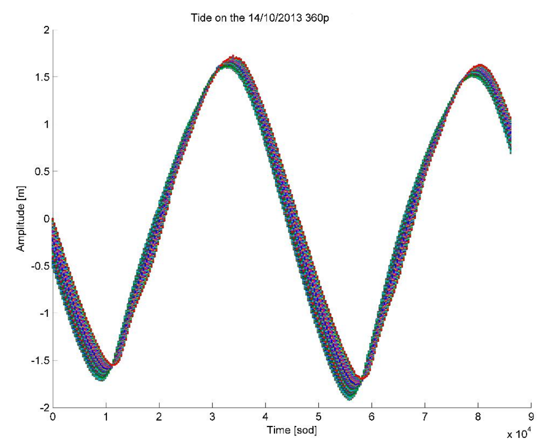

Figure 6: Calculated tide values in the grid points along the river segment using the alternative calculation method.

4.3 Approximate geoid heights

At this point, the instantaneous water level at each measuring point along the sailing profiles should be corrected using the calculated tidal values at the closest grid point. Essentially, those corrected water levels, measured by means of GNSS, are the approximate geoid heights along the sailing profile. Based on them we can later on create an approximated geoid surface and compare it with the GCG2011 model. It is mandatory to correct for the atmospheric dynamic effects. However, in this case, the same correction is applied to all measurements (tidal values and ship-based observations) and therefore it can be neglected because it cancels out in the difference between them.

5 Results

Figure 7 presents a north south cross section of the river with the measured water levels (blue dots). Additional markers represent the geoid height based on the GCG2011 model (red dots) and location of the tide gauge along the river (black squares). There is a quite strong variation in the results, which might be the cause of neglected effects from ships traffic or other time-variable systematic effects that are related to the time of measurement.

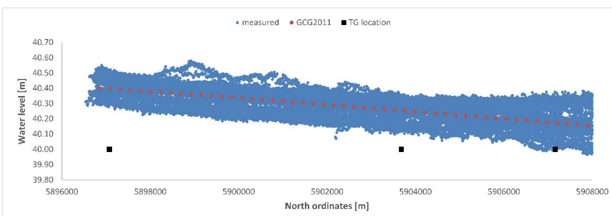

Figure 7: North-south cross section of the river segment under investigation. Results obtained using all measured data points. Red dots representing the geoid heights obtained from the GCG2011 model. Black squares represents the tide gauge location along the river.

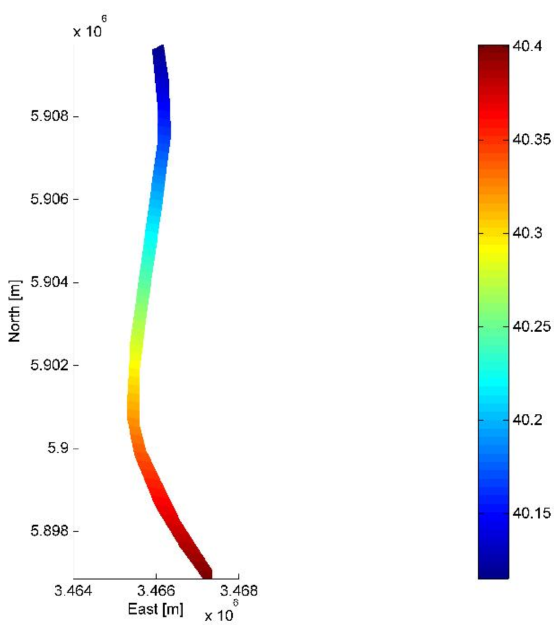

Figure 8: Not-to-scale plane surface fit for the GCG2011 geoid heights along the Weser River.

In order to assess the quality of the results, we decided to examine the differences between the calculated approximate geoid heights and the assumed real geoid heights from GCG2011. Geoid heights for all grid points were derived from the GCG2011 model, which served as a basis for a fitted surface (Figure 8). It is a linear surface of the form presented in Eq. (1), its coefficient of determination equals to one and the mean square error is less than a millimeter.

$$a \cdot X + b \cdot Y + c \cdot Z + d = 0 \tag{1}$$

Figure 9 presents the histogram of the differences between the linear surface fitted for the GCG2011 model geoid heights and the approximately calculated geoid heights.

The maximum absolute difference reached 0.33 m and the root mean squared error (RMSE) is 0.085 m. RMSE is calculated from

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} v_i^2}{n-1}} \tag{2}$$

where v represents the difference between the GCG2011 model and the approximate geoid height at each measuring location and n is the number of observations.

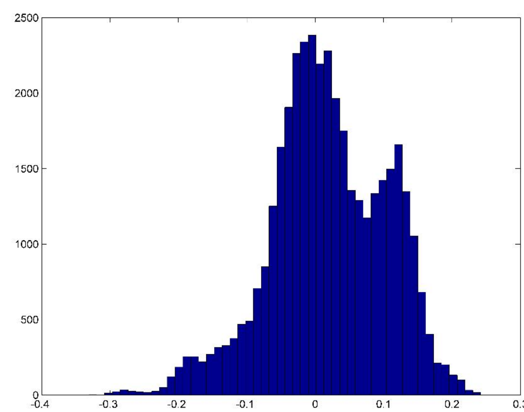

Figure 9: Histogram of the differences between the GCG11 and the approximated calculated geoid heights.

Eventually the goal is to create a surface from the measured data and compare it to the surface fitted for the GCG2011 geoid heights. A surface was fitted to the measured approximate geoid heights using a local linear regression (Figure 10).

Later, the differences between both surfaces, the CGC2011 and the one created from the measured data, were calculated. Figure 11 presents the histogram of the differences. Maximum difference reaches 0.026 m and the RMSE is 0.005 m.

The results were achieved based on 12 measuring days. In retrospective, one would expect to achieve high ac-

Table 1: Statistics summary of individual measuring days at the river.

Date	Maximum absolute error [m]	Mean absolute error [m]	RMSE [m]
12/10/2013	0.095	0.087	0.008
13/10/2013	0.082	0.039	0.026
14/10/2013	0.045	0.025	0.027
15/10/2013	0.224	0.088	0.068
17/10/2013	0.183	0.084	0.052
18/10/2013	0.132	0.068	0.050
19/10/2013	0.088	0.046	0.022
20/10/2013	0.062	0.028	0.019
22/10/2013	0.075	0.053	0.019
23/10/2013	0.119	0.081	0.030
24/10/2013	0.131	0.105	0.014
25/10/2013	0.039	0.021	0.018
Average values	**0.106**	**0.060**	**0.029**

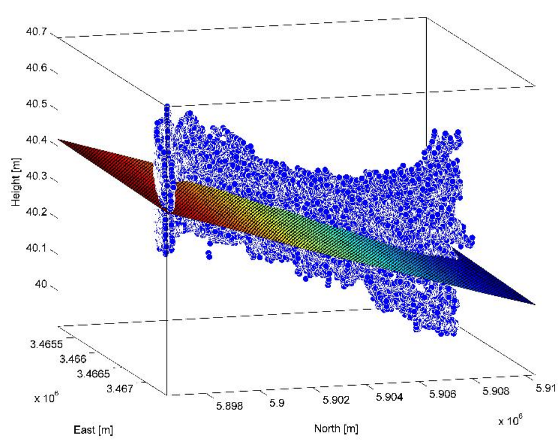

Figure 10: Fitted surface for the approximate geoid heights using local linear regression.

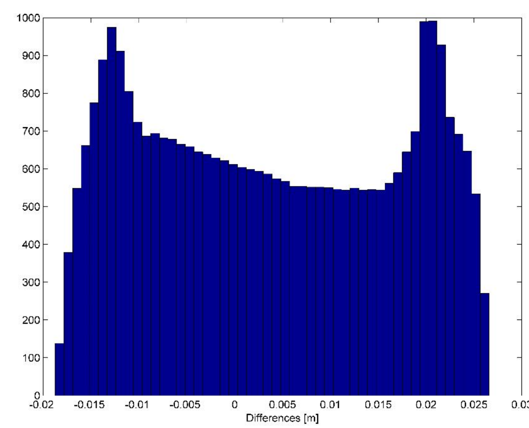

Figure 11: Residuals histogram between the fitted surface for the GCG2011 geoid heights and the approximately calculated geoid heights.

curacy results, as the amount of raw measurements increases. Therefore, we need to assess the expected accuracy of this method for one measuring day only. In order to do so, we have calculated the linear trend of each measuring day separately and examined the differences between it and the GCG2011 geoid heights.

Table 1 presents the results.

It could be seen in Table 1 that the results achieved from the examination of the individual days are slightly worse than those obtained using the whole 12 measurement days. Several days have quite high mean absolute error, indicating some sort of bias in the measurements. A possible reason could be increased ship traffic along the river that may have affected the measurements.

6 Conclusions

A method for extraction of approximate geoid heights from shipborne GNSS measurements was presented and a field test was conducted. Based on the test results we can fairly say that the accuracy of the calculated approximate geoid surface is better than 0.02 m. A potential cause is the fact that this method is simply not perfect for the modeling of the tide in the river. This method does not incorporate any physical and hydrological elements of the problem. We can assume that incorporating such elements into the methodology would increase the accuracy of the results.

Overall, we can state that based on the results presented in Table 1, it is possible to extract the approximate geoid, based on a single measuring day, with accuracy better than 0.06 m and a standard deviation of less than 0.03 m. Although these results are quite encouraging, one should keep in mind that this type of calculation would probably produce those types of results while performed in a specific environment such as bays, semi-enclosed area and rivers. On the other hand, in the open sea or areas with rough bathymetry changes that affects the gravity field, results produced by this calculation method may be of a lower quality.

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