Research Article

Aive Liibusk*, Sander Varbla, Artu Ellmann, Kaimo Vahter, Rivo Uiboupin, and Nicole Delpeche-Ellmann

Shipborne GNSS acquisition of sea surface heights in the Baltic Sea

https://doi.org/10.1515/jogs-2022-0131
received November 28, 2021; accepted May 4, 2022

Abstract: For determining precise sea surface heights, six marine GNSS (global navigation satellite system) survey campaigns were performed in the eastern Baltic Sea in 2021. Four GNSS antennas were installed on the vessel, the coordinates of which were computed relative to GNSS–CORS (continuously operating reference stations). The GNSS–CORS results are compared to the PPP (precise point positioning)-based results. Better accuracy is associated with the GNSS–CORS postprocessed points; however, the PPP approach provided more accurate results for longer than 40 km baselines. For instance, the a priori vertical accuracy of the PPP solution is, on average, 0.050 ± 0.006 m and more stable along the entire vessel’s survey route. Conversely, the accuracy of CORS-based solutions decreases significantly when the distances from the GNSS–CORS exceed 40 km, whereas the standard deviation between the CORS and PPP-based solutions is up to 0.075 m in these sections. Note that in the harbor (about 4 km from the nearest GNSS–CORS), the standard deviation of vertical differences between the two solutions remains between 0.013 and 0.024 m. In addition, the GNSS antennas situated in different positions on the vessel indicated different measurement accuracies. It is suggested for further studies that at least one GNSS antenna should be mounted above the mass center of the vessel to reduce the effects of the dominating pitch motion during the surveys.

Keywords: Baltic Sea, Baltic Sea Chart Datum 2000, kinematic GNSS, postprocessing, sea surface height, shipborne GNSS.

1 Introduction

Sea surface height (SSH) is a key parameter used for understanding the marine environment and is also needed for marine geoid determination, navigation and shipping applications, and climate change research. SSH can be measured or derived from various in situ data sources (e.g., tide gauges [TGs] and global navigation satellite system [GNSS]), satellite altimetry (SA), and hydrodynamic models (HDMs) (Madsen et al., 2015). Although SA provides reasonable quantification of SSH, the method is often limited by spatial and temporal resolution characteristics and reliability that tend to diminish on approaching coastal areas due to land contamination, coastal process, etc. (Passaro et al., 2014; Mostafavi et al., 2021). Contrarily, HDMs are efficient in deriving SSH at appropriate spatial and temporal resolutions. However, HDMs are based on mathematical models and approximations that influence their accuracy. Most critically, the vertical reference data of HDMs are often undisclosed (Jahanmard et al., 2021; Varbla et al., 2021), which makes it challenging to combine HDMs with other sources of sea-level information.

As a result, in situ measurements provide an alternate solution that links and verifies SSH and HDM data. TGs have been most commonly and reliably utilized to validate other data sources (Cipollini et al., 2017; Hunter et al., 2017). However, TGs are often land bound and only representative of sea level within a particular domain around their location. Hence, there is a need for more in situ SSH measurements in the coastal and offshore areas. Thus, the GNSS technology has become favored for SSH data acquisition (Xu et al., 2016; Penna et al., 2018). The GNSS measurements can be performed at almost any marine location of interest (for instance, complex coastal areas) at a very high spatial and temporal resolution (Tranchant et al., 2021). Shipborne GNSS measurements especially are invaluable for numerous applications, such as the calibration and validation of remote sensing data (Liibusk et al., 2020; Crétaux et al., 2011), bathymetry mapping (Guo et al., 2016; Foster et al., 2009), validation of sea-level forecast
models (Liibusk et al., 2020), and marine geoid models (Varbla et al., 2020; Saari et al., 2021; Jürgenson et al., 2008; Nordman et al., 2018). The accuracy of shipborne-derived SSH generally remains within 5 cm (Saari et al., 2021; Varbla et al., 2020). Although SSH with an accuracy of only a few centimeters can be determined by airborne laser scanning (Varbla et al., 2021), shipborne GNSS measurements allow significantly lower equipment and operational costs. Conversely, the accuracy of the shipborne GNSS method exceeds roughly twice that of SA (Liibusk et al., 2020; Mostafavi et al., 2021).

Due to the necessity and urgency for connecting the vertical references of the different sea level sources, the validation of marine geoid models especially is an essential contribution to the connection of height systems, specifically for obtaining a unified chart datum and for more precise GNSS-based navigation and hydrographic surveying in the future. For example, the nine countries surrounding the Baltic Sea have agreed on a unified chart datum BSCD2000 (Baltic Sea Chart Datum 2000) that is based on the definitions of the European Vertical Reference System (EVRSS) (ESH2021). The zero level of the BSCD2000 is referred to the Normaal Amsterdams Peil (NAP), whereby the height reference surface of BSCD2000 is the equipotential surface of the Earth’s gravity field, i.e., a marine geoid model (Schwabe et al., 2020). Thus, the BSCD2000 significantly contributes to the consistency and accuracy of the Baltic Sea hydrographic surveying, marine engineering, and nautical chart publications.

Previous studies have presented the use of shipborne GNSS as a reliable and accurate technique for determining SSH (Saari et al., 2021; Varbla et al., 2020). This contribution now takes a more realistic approach to describing and explaining the different techniques and approaches that can be implemented when performing shipborne GNSS surveys in the dynamically varying sea conditions. The primary focus is on utilizing the local continuously operating reference stations (CORSs) versus global precise point positioning (PPP)-based GNSS postprocessing approaches. However, the location and the type of a GNSS antenna and the distance of the antenna’s reference point (ARP) from the instantaneous sea surface also have crucial roles in the accurate SSH determination. Therefore, these aspects are also covered in more detail. Note that the article concentrates solely on height determination, and the discussion on the horizontal coordinate components has been neglected here. Since marine conditions and geoid slope do not vary significantly over short distances, a coordinate determination accuracy of a few meters would be acceptable.

The study was conducted in the complex coastal area of the Eastern Baltic Sea during the spring and summer months of 2021. The research expeditions required collaboration between the Estonian and Latvian authorities and scientists from various institutes and backgrounds (geodesy, oceanography, hydrography, and environmental studies). Such campaigns are usually time consuming. Thus, it is valuable to implement autonomous monitoring/surveying systems that can record environmental data independently (Liblik et al., 2016; Töning et al., 2017). A similar approach was adopted in the current study, where GNSS-based SSH measurements were conducted as a by-product of various research expeditions.

This article first presents a brief overview of the interdisciplinary marine campaigns in the Baltic Sea. Next, a more detailed description of the shipborne GNSS measurements and kinematic GNSS data postprocessing is provided. In addition, the problems that may occur with such measurements and data postprocessing are emphasized. The article ends with a short discussion and conclusions.

## 2 Study area

The Baltic Sea is a shallow, semi-enclosed estuarine water body in northern Europe with nine countries surrounding it (see inset in Figure 1). The primary source of freshwater originates from the continental rivers, and salty water infiltrates from the North Sea via the narrow Danish Straits. In addition, the sea level dynamics in various spatial and temporal scales in the Baltic Sea are influenced by a number of processes: large-scale atmospheric circulation, meteorological conditions, North Atlantic mean sea-level changes, storm surges, seiches, etc. (Weisse et al., 2021). The average water depth of the Baltic Sea is approximately 52 m. The dominant wind direction in the Baltic Sea is southwest. The winter and autumn seasons tend to have the strongest winds and highest waves (Jakimavičius et al., 2018). Hence, the summer months are the most favorable for conducting shipborne GNSS surveys.

The Baltic Sea is divided into several subsections that vary in geomorphology and depth. The expeditions were conducted in the subbasins of the eastern Baltic Sea: Gulf of Riga (including Väinameri), Gulf of Finland, and Eastern Baltic Proper (cf. Figure 1). Most of the GNSS survey campaigns were performed in the southern half of the Gulf of Finland. The mean water depth in the Gulf of Finland is around 37 m (the maximum depth is 123 m). The short-term sea-level dynamics (e.g., yearly, seasonal, daily) in the Gulf of Finland are affected by changes in the water balance that are mostly driven by atmospheric conditions (e.g., wind forcing), river runoff, and the presence of sea ice (Post and Köuts, 2014; Lagemaa et al., 2011; Soosaar et al., 2016). Localized events (storm surges, coastal upwellings, etc.; see, e.g., Delpeche-Ellmann and Soomere, 2017)
also affect the short-term and seasonal variability. Due to the prevailing southwest wind direction, storminess, and river discharge (including the Neva River), a higher mean sea level and extreme water levels tend to occur on the eastern coasts of the Baltic Sea.

The Baltic Proper, located in the central section of the Baltic Sea, has an average depth of 62 m. It connects the Baltic Sea western sections with its northern and eastern sections (cf. Figure 1). The Gulf of Riga and Väinameri (between the West Estonian Archipelago and the Estonian mainland) are semi-enclosed water bodies with an area of around 140 km × 150 km and 50 km × 50 km, respectively. The average water depth is 23 m in the Gulf of Riga and 4.7 m in the Väinameri. The water bodies are connected to each other and to the Baltic Proper by four narrow straits. Therefore, the sea-level variations in the Gulf of Riga and Väinameri are affected by local wind and sea-level events in the Baltic Proper.

The Baltic Sea is also extraordinary compared to other sea areas as it is strongly affected by vertical land motion due to the postglacial isostatic adjustment, where the land uplift increases from near zero in the southern section of the Baltic Sea to about 10 mm/year in the northern part (Vestøl et al., 2019). Understanding sea-level variations in the Baltic Sea is vital due to their impact on the region’s human activities, economy, and coastal safety. The Baltic Sea region is fortunate since it hosts an extensive long-term multinational network of TGs and high-quality geodetic infrastructure. The most prolonged continuous sea-level observations have been conducted in Stockholm, starting in 1774 (Ekman, 2009). The region also has a high-resolution and accurate quasigeoid model NKG2015 (Ågren et al., 2016). Such conditions around one sea are unique worldwide since it also consists of many archipelagos and dynamic ocean processes that make it challenging to capture accurate sea level data from the various data sources (e.g., SA and HDMs). Thus, the Baltic Sea makes an ideal test site to conduct shipborne GNSS studies.

3 Materials and methods

3.1 Research surveying vessel Salme as a platform for sea-level measurements

The multifunctional research surveying vessel R/V Salme (Figure 2) was used for the expeditions. In general, the
vessel is unusually small (length 31.3 m and breadth 7.2 m; see Table 1 for more details), considering the variety of challenging oceanographic conditions. The vessel's small size also affects its stability (and thus also SSH measurements), especially during strong winds and high waves. It is impractical to use this vessel for marine surveys with wind speeds and wave heights more than 15 m/s and 2 m, respectively. However, in the case of a moderate sea state, the vessel is feasible for various research campaigns and for performing national marine environmental monitoring programs in Estonia and Latvia. The R/V Salme usually conducts oceanographic surveys (e.g., vertical profiling of marine physical parameters, marine biology, chemistry, geology). In addition, the vessel can be

| Parameter                        | Value       |
|----------------------------------|-------------|
| Displacement tonnage             | 249 t       |
| Length                           | 31.3 m      |
| Breadth                          | 7.2 m       |
| Ship draft                       | 3.2 m       |
| Gross tonnage                    | 223 t       |
| Summer deadweight tonnage        | 262 t       |
| Fuel tank(s)                     | 11 m³ + 14 m³|
| Freshwater tank(s)               | 12 m³ + 5 m³|
| Wastewater tank                  | 13 m³       |
| Maximum speed                    | 9 knots     |
used as a platform for offshore GNSS-based SSH measurements, which is the focus of the current study.

There are two engines on the R/V Salme. The main engine is located almost at the vessel’s center, whereas the auxiliary engine is a bit closer to the starboard. This causes the vessel to tilt slightly to the right. Note that the influence of engine vibrations on the SSH measurement results was not detected due to the relatively low (sub-Hz) GNSS data sampling frequency. In addition, there are two freshwater tanks on the vessel – one (12 m³) in the center at the bow and the second (5 m³) in the port at the stern. The wastewater tank (13 m³) is located in front of the freshwater tank at the bow. Thus, freshwater and wastewater do not significantly influence the vessel’s tilt during the GNSS campaigns.

3.2 Survey campaigns

Six offshore survey campaigns were conducted in the Eastern Baltic Sea in spring and summer 2021 (Figure 1). Relevant to this study, some of the stops (from 15 to 150 min) on the ship routes for various marine experiments are partly overlapping, thus allowing the repeatability analysis of the GNSS-based SSH that can enable adequate quality assurance of the results. Note that the bold dots in the tracks of campaigns C1–C3 in Figure 1 indicate the stations where the vessel stopped for collecting water samples (e.g., chlorophyll, turbidity, nutrients, phytoplankton) and measuring the vertical profiles of water properties (e.g., temperature, salinity, oxygen, light attenuation).

Each cruise had a primary objective related to different projects carried out by the Tallinn University of Technology (TalTech). The times and purposes of the campaigns are listed in Table 2. During the campaigns, the GNSS receivers were deployed in an autonomous piggyback mode (thus not using specially designated GNSS profile routes). Note that the total length of the GNSS profiles reached almost 5,000 km.

3.3 On-board locations of GNSS instruments and parameters for data recording

Concurrently with all the other experiments described earlier (Table 2), the shipborne GNSS measurements were also conducted to determine SSH. At least three GNSS antennas need to be used for estimating and removing the vessel’s high-frequency attitude changes (pitch and roll motions, as well as heave) from the measurement data.

### Table 2: Marine survey campaigns in the coastal waters of Estonia and Latvia in 2021

| Campaign | Date | Length of the route (km) | Maximum wind speed (m/s) | Purpose of the campaign |
|----------|------|--------------------------|--------------------------|-------------------------|
| C1       | 06.04.2021–08.04.2021 | 844 | 18 | TalTech basic research – to map the extent of oxygen deficiency in the bottom layer of the Baltic Sea |
| C2       | 26.07.2021–30.07.2021 | 1,439 | 12 | Estonian marine monitoring program – to collect data for assessing the ecological status of the sea |
| C3       | 01.08.2021–07.08.2021 | 1,874 | 12 | Latvian marine monitoring program – to assess the ecological impact of different anthropogenic and natural factors on the Latvian marine environment on the long-term basis |
| C4       | 24.08.2021–26.08.2021 | 515 | 13 | Estonian marine monitoring program Eastern Gulf of Finland – to collect data for assessing the ecological status of the sea |
| C5       | 09.09.2021–11.09.2021 | 510° | 12 | TalTech basic research – coastal monitoring in the southern coast of the Gulf of Finland |
| C6       | 15.09.2021–17.09.2021 | 454 | 13 | TalTech basic research – servicing the monitoring station in the Baltic Proper |

*GNSS profiles were measured over a 98 km (cf. C5 in Figure 1).
(Roggenbuck and Reinking, 2019; Varbla et al., 2020). Consideration of the vessel’s attitude allows increasing the reliability of the determined SSH. This study used four multifrequency GNSS receivers on the R/V Salme to guarantee GNSS data from at least three receivers. Such an approach would leave one spare receiver, data of which could be employed if something unfortunate happened (e.g., gaps in data records or loss of power for one of the receivers). Two GNSS antennas were mounted to the vessel’s bow (A1 and A2 installed to the port and starboard, respectively) and the other two on top of the wheelhouse (A3 and A4 installed to the starboard and port, respectively; Figure 2). A detailed overview of the used GNSS instruments and their technical parameters are listed in Tables 3 and 4, respectively.

Note in Table 4 that the internal memory of three GNSS receivers is relatively small (∼55 MB). The first campaign (C1) data logging interval was set to 15 s for all the receivers (Table 3) since a trained crew member could download observation data during the campaign. This was not possible for subsequent expeditions. Thus, for subsequent campaigns, the logging interval was increased to 30 s for the Trimble NetR5 receivers (A1 and A2; note in Table 3 that the Trimble R4 Model 2 was replaced with a Trimble NetR5 receiver) and to 60 s for the Trimble R8s system (A3). This allowed for conducting several campaigns without the risk of running out of internal memory storage. The Trimble NetR9 receiver (A4) was continued to be operated with a data logging interval of 15 s (Table 3). All receivers created a new file every 12 h, which is the optimal file size for postprocessing of data later on.

It was possible to use Trimble GA830 antennas (A1 and A2) in connection with Trimble NetR9 and Trimble NetR5 (Table 3) during the first campaign (C1). These antennas have been specifically designed for marine applications and are convenient to use on the vessel due to their smaller dimensions (14.9 cm diameter × 9.9 cm height). For subsequent campaigns, the bow-mounted GNSS antennas were replaced with Trimble Zephyr Geodetic antennas (34.3 cm diameter × 7.6 cm height). Both types of antennas have been designed to support centimeter-level accuracy and support GNSS signals, including GPS L2C and L5, GLONASS, and even Galileo.

### 3.4 Height determination of GNSS antennas relative to the sea surface

One of the primary tasks in shipborne GNSS measurements is determining the heights of GNSS ARPs relative...
to the instantaneous sea surface to achieve accurate SSH. Therefore, all ARPs and selected locations (i.e., benchmarks) on the railing (B1, B2, and LB) were coordinated by total station measurements before the first campaign (C1) (Figure 3). Due to the slight movements of the vessel, six measurements were carefully made for determining the coordinates of every point. The measurements were then averaged (the averaged coordinates are presented in Table 5).

Table 4: Technical parameters of the used instruments

| Receiver    | Trimble NetR9 | Trimble NetR5 | Trimble R8s | Trimble R4-2 |
|-------------|---------------|---------------|-------------|--------------|
| GNSS supported | GPS, GLONASS, Galileo | GPS, GLONASS | GPS, GLONASS, Galileo, BeiDou | GPS, GLONASS |
| GNSS accuracy | H: ±8 mm + 1 ppm V: ±15 mm + 1 ppm | H: ±10 mm + 1 ppm V: ±20 mm + 1 ppm | H: ±8 mm + 1 ppm V: ±15 mm + 1 ppm | H: ±8 mm + 1 ppm V: ±15 mm + 1 ppm |
| Internal memory | 4 GB | 55 MB | 56 MB | 57 MB |
| (Hours showed based on the measurements\(^1\)) | (−5,000 h) of raw data observables based on recording data from 24\(^2\) satellites at 15 s epoch intervals | (−500 h) of raw data observables based on recording data from 15\(^2\) satellites at 15 s epoch intervals | (−960 h) of raw data observables based on recording data from 15 satellites at 15 s epoch intervals | (−450 h) of raw data observables based on recording data from 15 satellites at 15 s epoch intervals |

\(^1\)Note that the observation time for different receivers varies and could be caused by the used software version (varies between receivers). Trimble data saving format *.t02 was used during all campaigns.

\(^2\)Different number of average satellites is caused by the number of supported satellite systems. Trimble NetR9 logged GPS, GLONASS, and Galileo data. Only GPS and GLONASS data were logged by other receivers.

Figure 3: Total station survey for coordinating the ARPs (A2) and benchmarks on the vessel's railing (B1, B2, and LB; note that B1 is behind the car).
Statistics of these six measurements are shown in Figure 4. Relevantly to height determination, it can be noted that the variability (in terms of standard deviation) of the vertical coordinate components is generally around 1 cm, thus suggesting good height determination accuracy. Note that the approximate location of the vessel’s mass center was also measured during the survey (cf. Figure 2 and Table 5), which can help estimate the vessel’s attitude from the GNSS measurement data (the vessel swings around its mass center axis). Also, the total station was set up on the pier during the survey. Such an approach is recommended only during calm weather in sheltered harbors, which was the case in this study. Otherwise, the total station should be set up on board the vessel to eliminate problems caused by the vessel’s movements during the survey (Stępień et al., 2019).

In addition, all benchmark heights were referred to the instantaneous sea surface. The heights between the sea surface and points B1, LB (starboard side), and B2 (port side) were determined by conducting tape measurements (a solid rod was used to determine the distance, which was then measured) in the harbor every time before the sail off for each campaign (cf. Table 5). Since the sea surface is ever changing and the vessel sways during such measurements, but the measurements are also subjective (the surveyor must assess the optimal measure from the moving sea surface), these distance measures likely contain a relatively large error component. It is estimated that the accuracy of these distance measurements is within 5 cm.

During the first campaign (C1), tape measurements were also conducted randomly during the survey at sea (at stops). These measurements indicated that the general attitude of the vessel does not change significantly and that the vessel is always slightly tilted to the right (i.e., starboard side – notice that point B1 is always lower than point B2) due to the position of the auxiliary engine.

### Table 5: Local (in an arbitrary reference frame) coordinates of the vessel’s center of mass (CoM), GNSS ARPs (A1, A2, A3, and A4), and benchmarks (B1, B2, and LB) on the vessel’s railing, as well as heights of these points above sea surface before the campaigns

| Point | X   | Y   | Z   | Height from sea surface before a campaign |
|-------|-----|-----|-----|-------------------------------------------|
|       |     |     |     | C1  | C2  | C3  | C4  | C5  | C6  |
| B1    | -8.626 | -1.490 | -1.402 | 2.297 | 2.360 | NA  | 2.400 | 2.340 | 2.360 |
| B2    | -13.411 | -6.424 | -1.014 | 2.673 | 2.590 | 2.580 | 2.590 | 2.660 | 2.620 |
| LB    | -7.191 | -3.048 | -1.192 | 2.497 | 2.570 | 2.520 | 2.540 | 2.560 | 2.560 |
| A1    | -5.484 | -13.679 | 1.635 | 5.326 | 5.344 | 5.288 | 5.348 | 5.358 | 5.351 |
| A2    | -13.072 | 2.342 | 3.441 | 7.132 | 7.150 | 7.094 | 7.153 | 7.163 | 7.157 |
| A3    | -17.708 | -0.033 | 3.562 | 7.254 | 7.271 | 7.215 | 7.275 | 7.285 | 7.278 |
| A4    | -12.735 | -2.053 | NA  | NA  | NA  | NA  | NA  | NA  | NA  |
| CoM   | -8.626 | -1.490 | -1.402 | 2.297 | 2.360 | NA  | 2.400 | 2.340 | 2.360 |

Units are in meters.

![Figure 4](image.png)

*Figure 4:* Statistical properties (with respect to mean values) of the total station measured coordinate components. The colored bars denote standard deviation estimates, whereby minimum and maximum coordinate component differences are shown with crosses.
(see the survey vessel characteristics mentioned earlier). In addition, the tape measurements were also conducted after the campaigns (Table 6). The difference (compare values in Table 5 to those in Table 6) in railing’s height before and after a campaign can later help estimate the vessel’s total static draft (due to fuel consumption).

The heights of the ARPs above the sea surface \(H_{ARP}\) were estimated as follows:

\[
H_{ARP} = H_{ARP}^{TS} - H_{Railing}^{TS} + H_{Tape}^{Railing},
\]

where \(H_{ARP}^{TS}\) and \(H_{Railing}^{TS}\) denote total station measured heights of ARP and benchmarks on the vessel’s railing, respectively, and \(H_{Tape}^{Railing}\) are the corresponding tape measurements (cf. Table 5). Each ARP was determined relatively to each benchmark on the railing. For instance, the antenna A1 associated values for the C1 campaign are 5.334 m (using benchmark B1), 5.322 m (using benchmark B2), and 5.324 m (using benchmark LB). These values indicate that the distances between sea surface and benchmarks on the railing have been determined accurately. The final ARP height was then estimated as an average of those (for each antenna and campaign separately). The final ARP heights above the sea surface are presented in Table 5 for all the campaigns.

By examining the heights of points B1, B2, and LB in Table 5, it can be noted that after the first campaign (C1), a slight change in the vessel’s general attitude occurs—the starboard points B1 and LB rise, whereas the port point B2 decreases. For subsequent campaigns (C2–C6), however, no further significant change occurs. Note that after the first campaign (C1), the vessel had to be maintained due to engine failure, which may have caused the change in the vessel’s general attitude. Ideally, total station measurements should thus have been repeated before the second campaign (C2). Yet, Table 5 also reveals that the differences between the four ARPs above sea surface remain relatively unchanged despite the change in vessel’s attitude, which is due to considering all points on the railing during the estimation of ARPs (the averaging more or less eliminates the attitude change).

### 3.5 Configuration of GNSS receivers

GNSS measurements were configured to work autonomously. The GNSS receivers were turned on a few hours before the vessel left the harbor (or even a day before the departure). The receivers logged data during the campaigns, and the data were downloaded upon arrival at the harbor. Due to technical problems caused by the data logging of Trimble R8s (the automatic compression of files was unsuccessful due to software error), this routine was not followed during the C1 campaign, and Trimble R8s data were downloaded every 12 h into the field computer. For the subsequent campaigns, the technical problem was eliminated, which enabled data logging into the receiver’s internal memory, similar to other instruments. Note that there were also problems (due to loss of power) with antenna A1 during the first half of the C2 campaign and antennas A3 and A4 during the C4 campaign. These power-related issues caused a loss of data as the instruments were not logging during the campaigns.

Trimble NetR5 and NetR9 are designed for base stations, and therefore, it is easy to configure these receivers through Ethernet cable. Conversely, Trimble Configuration Toolbox had to be used to set up Trimble R8s for the campaigns. This software enables to configure the interval of logging and the duration of every compiled file. Due to the configuration, the GNSS receiver starts to log data automatically when it is turned on. This is advantageous since after restoring power following a sudden power failure, the GNSS receiver continues its operation (although during the C4 campaign, power failure of Trimble R8s and NetR9 was unfortunately permanent).

#### Table 6: Dynamic topography (DT) measured at the harbor and at the Pirita automatic TG station (roughly 5 km away), as well as heights of benchmarks (B1, B2, and LB) above sea surface after the GNSS campaigns

| Point | C1 | C2 | C3 | C4 | C5 | C6 |
|-------|----|----|----|----|----|----|
| Measured DT at the port with respect to geoid | DT before/after a GNSS campaign | 0.408/NA | 0.154/0.324 | 0.424/0.174 | 0.525/0.355 | 0.235/NA | NA/0.045 |
| DT at the Pirita TG | 0.391/0.689 | 0.242/0.401 | 0.502/0.222 | 0.526/0.367 | 0.244/0.136 | 0.149/0.059 |
| Height from the instantaneous sea surface after a GNSS campaign | B1 | 2.340 | NA | NA | 2.390 | NA | 2.330 |
| B2 | 2.700 | 2.640 | 2.720 | 2.600 | NA | 2.640 |
| LB | 2.550 | 2.610 | 2.660 | 2.600 | NA | 2.530 |

Units are in meters.

| 1 | DT was measured before and after a campaign from the benchmark on the pier. |
3.6 The used GNSS–CORS networks

Estonian and Latvian GNSS–CORS were used as the reference for kinematic data postprocessing. The stations belong to Estonian and Latvian national GNSS–CORS networks named ESTPOS (managed by Estonian Land Board) and LATPOS (managed by Latvian Geospatial Information Agency), respectively. Four Estonian and two Latvian CORS are also incorporated into the EUREF Permanent GNSS Network (EPN). The primary goal for EPN is to implement the European Terrestrial Reference System ETRS89 across the continent. In addition, GNSS–CORS have importance for monitoring the national geodetic reference systems and their components. Nowadays, GNSS–CORS are widely used for different types of kinematic applications as well, for instance, to determine not only airborne and mobile laser scanning trajectories but also shipborne trajectories, and for real-time network (RTN) measurements by surveyors. Currently, 29 GNSS–CORS equipped with Leica GR25 receivers and Leica AR25 Choke Ring antennas are working in ESTPOS (Metsar et al., 2018). Raw data (GPS, GLONASS, and Galileo) with logging intervals of 1 s in RINEX ver 3.02 format are available on the ESTPOS system Spider Business Center (gnss-rtk.maamet.ee).

In total, 27 GNSS–CORS are working in LATPOS in 2021, mainly equipped with Leica GR30 and LEIAR20 LEIM Choke Ring Antennas (Maciuk et al., 2020). Raw data (GPS, GLONASS, Galileo, and BeiDou) in RINEX ver 3.04 format (including BeiDou data) are available on the LATPOS system Spider Business Center (latpos.igia.gov.lv). The locations of coastal GNSS–CORS used for the GNSS postprocessing are shown in Figure 1.

4 Data processing

4.1 GNSS data postprocessing

All the collected GNSS kinematic data were postprocessed using the commercial Trimble Business Center (TBC) software ver 5.52. Precise ephemerides (final orbits) by IGS (International GNSS Service) were incorporated into all GNSS data postprocessing. GPS and GLONASS data with an elevation mask of 10° were used. These two GNSS were incorporated into data postprocessing because two onboard receivers (A2 and A4) supported only GPS and GLONASS. Data from Estonian and Latvian national GNSS–CORS networks were used as base stations, whereby the closest GNSS–CORS was always chosen for postprocessing of a route portion (cf. Figure 1; note that TBC allows only selecting one base station at a time for kinematic data postprocessing). All used GNSS–CORS coordinates were corrected for vertical land motion using the NKG2016LU model (Vestel et al., 2019) to obtain the actual SSHs at the contemporary measurement epochs (not the artificial BSCD2000 at epoch 2000.0).

For most survey routes, the baselines between the measured points and the GNSS–CORS generally remained under 40 km, the exception being route C2 with longer baselines. The change from one GNSS–CORS to another caused changes in the baseline lengths (e.g., from 40 to 15 km), but no significant jumps in the resulting heights were detected. By overlapping profiles postprocessed relative to the two GNSS–CORS, the mean height differences (representing jumps) generally remained around 2 cm, decreasing with shorter baselines. Note that for the C2 expedition (mainly in the Baltic Proper), the baselines from the GNSS–CORS to the measured points reached up to 120 km. Since TBC does not allow estimation of atmospheric parameters for kinematic postprocessing, such lengthy baselines may result in unreliable postprocessing results. Previous studies (Varbla et al., 2017; Shih et al., 2021) have shown that the Canadian Spatial Reference System Precise Point Positioning (CSRS-PPP) online service (webapp.geod.nrcan.gc.ca) can provide reliable postprocessing results for shipborne GNSS measurements far from shore. Thus, due to the long baselines for the C2 expedition, the remote data postprocessing utilizing the CSRS-PPP solution was employed. Note that only fixed TBC and CSRS-PPP solutions for every baseline are considered valid data for further analysis. A detailed overview of the online PPP technique can be found in the studies by Mireault et al. (2008) and Banville et al. (2021).

As the data files postprocessed by using CSRS-PPP online service contain no GPS seconds, the GPS seconds were first calculated by using the available decimal day of the year data. It then became evident (due to the mismatch of coordinates and height variations between subsequent measurements) that the timestamps given by CSRS-PPP have a +30 s offset for antennas A1, A2, and A4 and a +60 s offset for antenna A3 with respect to the timestamps given by TBC (likely due to GPS “leap seconds”). Thus, the following time corrections were introduced to the CSRS-PPP-based GPS seconds: −30 s for antennas A1, A2, and A4 and −60 s for antenna A3. To compare the results of the two software, all the TBC and CSRS-PPP results were then matched by using the GPS seconds.
4.2 Comparisons between the GNSS postprocessing height solutions

Figure 5b shows that the TBC postprocessed data degrade significantly westward from 22°E meridian (antennas A2 and A4 show similar tendencies in data quality degradation, whereby the performance, in general, is slightly better than the one of antenna A3 presented in Figure 5b), whereas CSRS-PPP appears to provide more or less consistent results along the whole route (Figure 5a and b; also compare the presented standard deviation estimates of TBC and CSRS-PPP a priori vertical accuracies). Note also in Figure 6 how the discrepancies between CSRS-PPP and TBC solutions become significantly larger from GPS time 45–70 h, which roughly corresponds to data westward from 22°E meridian (largest differences can be seen for antenna A3). These data are the measurements furthest from the used coastal GNSS–CORS.

The differences in Figure 6 were further plotted in relation to the TBC solution-associated baseline lengths (Figure 7a; note that antenna A1 was excluded since there are no data associated with extensive baselines – refer to Figure 5a). It appears that the differences between CSRS-PPP and TBC solutions remain relatively similar up to CORS reckoned baseline lengths around 40–50 km. After that threshold, however, the scattering of differences increases. To further examine the performance of these differences, functions of standard deviation estimates were compiled for each antenna (except antenna A1). The differences between CSRS-PPP and TBC solutions were divided into sets according to the TBC solution-associated baseline lengths. Each set represents an increase of 1 km in the baseline length (for instance, a set representing baselines from 23 to 24 km). A standard deviation estimate was then calculated for each set. The results presented in Figure 7b confirm the previous assumption – the differences between the two solutions become noisier with TBC solution baseline lengths more than 40–50 km.

An additional independent test was also conducted by using the GNSS time series of CORS. Data from five Estonian CORS (SUR4, KOSI, KUSA, MRJA, and PYRK; cf. Figure 1) were postprocessed in the kinematic mode (postprocessing parameters remained as described earlier) using both TBC and CSRS-PPP. The used time series was 24 h long with a logging interval of 15 s (i.e., 5,761 data samples were examined). The Estonian CORS denoted as MUS2 was chosen as the base station for TBC-based postprocessing. The resulting TBC and CSRS-PPP height solutions were then compared to the official heights. Statistics of these comparisons are presented in Figure 8a. It appears that the TBC-associated statistics remain relatively similar up to baseline lengths of 41 km. With a baseline length of

![Figure 5: A priori vertical accuracies of the bow-mounted antenna A1 (a) and the top-mounted A3 (b) during the C2 campaign, estimated by TBC (top) and CSRS-PPP (bottom).](image-url)
61 km, a 2 cm bias appears, and with a baseline length of 81 km, the bias increases further, as does the standard deviation estimate. Note that such biases can also appear in TBC marine data solutions when changing from one GNSS–CORS to another. Conversely, the CSRS-PPP-associated statistics remain relatively similar at all times.

Figure 8b shows statistics of these postprocessing solutions’ formal accuracies. Compared to the determined errors in Figure 8a, the a priori estimates appear overestimated, especially for the CSRS-PPP solutions (different software use different algorithms). Although TBC-related a priori estimates (generally around 3 cm) are

---

**Figure 6:** Differences between the CSRS-PPP and TBC SSH solutions for the whole C2 campaign.

**Figure 7:** Differences between the CSRS-PPP and TBC SSH solutions (cf. Figure 6) in relation to TBC-associated baseline lengths (a) and differences as a function of standard deviation (b).
more similar to the actual errors, the actual data quality degradation with the increased baseline lengths is not as apparent. According to Figure 8b, the best formal accuracy is obtained for the shortest baseline, whereas the estimates remain similar for the other four tests. Thus, the a priori estimates output by the software may not be reliable in estimating the absolute data errors (but could be helpful in relative comparisons as discussed at the beginning of Section 4.2). The comparisons and tests described earlier suggest that the maximum baselines should be kept under 40 km in CORS-based postprocessing. Since the TBC postprocessed data performance degrades westward 22°E, which also represents longer baselines, these data should be replaced by more reliable CSRS-PPP results.

Besides erratic behavior between TBC and CSRS-PPP height solution differences at longer TBC-associated baselines, it appears from Figure 6 that the differences may also contain a systematic component. Therefore, the differences were further investigated in five separate cases for all four antennas. Statistics of these investigations are presented in Figure 9 (note that antenna A1 has data available for only one of these cases). Although all the antenna types and ARPs were defined in the raw data before GNSS postprocessing using TBC and CSRS-PPP, the comparisons show that the systematic component differs slightly between the antennas (Figures 6 and 9). For instance, the systematic difference (considering all data) for antennas A2 and A4 is around –2 cm, but for antenna A3, it is around 4 cm. It can also be noted that the systematic component is not a constant during the whole campaign and tends to change a few centimeters (notice variability in Figure 6). However, note that according to Figure 8a, a bias may appear in TBC-based solutions with longer baselines. The mean differences representing data westward from 22°E may therefore not be suitable for use since these represent primarily long baselines. Thus, the offsets (i.e., the systematic components under discussion) computed by considering all data (mean differences associated with blue bars in Figure 9) were applied to the CSRS-PPP postprocessed data (it appears that the variability of the systematic component in Figure 6 is random).
assumed that the residual differences in all the investigated cases act as random errors (i.e., the presented standard deviation estimates in Figure 9 are not considered while choosing the suitable offsets). A meridian of 22°E was next chosen as a cut-off limit (according to the previous discussion), meaning that all TBC postprocessed data westward the limit were replaced by CSRS-PPP postprocessed data (with the applied offsets). No data were replaced for antenna A1 since the CSRS-PPP data do not extend westward from 22°E (Figure 5a).

Figure 9 also shows relatively good consistency (in terms of standard deviation) between the TBC and CSRS-PPP height solutions: 0.013–0.024 m when the vessel was static at the harbor (TBC-associated baselines are around 4 km) and 0.036–0.052 m for the whole dataset. Slightly larger estimates of 0.044–0.075 m (in terms of standard deviation) by considering only the replaced route sections could be due to the poorer performance of the TBC postprocessed data, as the performance of CSRS-PPP appears to be more or less consistent along the whole route of the vessel (see the bottom subpanels of Figure 5). These results suggest that CSRS-PPP data are suitable to complement the TBC postprocessed data in the poorer performing areas (e.g., at distant locations from GNSS–CORS).

Figure 10 presents a priori vertical accuracies for all the antennas during all the GNSS campaigns. It appears from these figures that antenna A3 (Figure 10c) shows the worst performance, whereas antenna A4 (Figure 10d) seems to perform the best (compare the mean and standard deviation estimates presented in figures). However, the statistical properties of antenna A3 with respect to the other antennas are at the millimeter level, which can be considered negligible considering the application. Therefore, both the external Trimble Zephyr Geodetic antennas and Trimble R8s receiver with an internal GNSS antenna are suitable for shipborne GNSS measurements. The choice depends more on the ease of use for such expeditions.

4.3 Determination of SSHs

After GNSS postprocessing, the computed ellipsoidal heights \( h_{\text{ARP}} \) of the ARPs can be reduced into SSH by subtracting the previously determined ARPs above the sea surface \( H_{\text{ARP}} \); cf. equation (1) and Table 5:

\[
\text{SSH} = h_{\text{ARP}} - H_{\text{ARP}}.
\]

An example of the determined SSH during the second campaign \( \text{(C2)} \) is presented in Figure 11. First, it can be seen how the SSH follows roughly the height of the NKG2015 quasigeoid model (Ågren et al., 2016) but contains a significant amount of noise (primarily due to the heave motion of the vessel caused by the waves). It appears that the noise is more prominent during the last portion of the campaign, suggesting slightly rougher sea conditions in comparison to the beginning of the campaign. However, the determined SSH should ideally follow a similar line to the geoid, meaning that a low-pass filter needs to be applied to the data (see, e.g., Varbla et al., 2017). Also, note that at the beginning of the campaign, the NKG2015 model appears higher than the determined SSH, but the opposite is true at the end of the campaign. This could be due to ever-changing dynamic topography (DT), travel distance-dependent linear static
draft, or both (cf. Tables 5 and 6). For instance, if the aim is to validate the NKG2015 quasigeoid model, DT and static draft corrections must be added to the determined SSH (see, e.g., Varbla et al., 2020). According to Jahanmard et al. (2021), the study area mean DT in the summer season (during which most of the campaigns were conducted) ranges from 0.10 to 0.35 m, suggesting the expected DT. However, it is essential to emphasize that instantaneous DT can vary significantly. For example, in the study by Varbla et al. (2021), the DT was only a few centimeters, whereas in the study by Varbla et al. (2020), the maximum DT reached almost 0.6 m (both studies were conducted in the same area as this one). Importantly, since the Baltic Sea is connected to the Atlantic Ocean via narrow Danish straits, the tides are minimal, remaining within a few centimeters. Considering geoid modeling, DT estimation, and height determination accuracies, the influence of tides in the study area can be regarded as negligible. Thus, these are not considered.

Figure 11 also suggests that the SSH of antenna A2 (at the vessel’s bow) is more scattered than the one of antenna A4 (on top of the wheelhouse). This becomes evident if the measured SSH is compared to the NKG2015 model, which yields standard deviation estimates of 0.224 and 0.162 m for antennas A2 and A4, respectively. The more significant differences for antenna A2 are due to dominating pitch motion of the vessel, which is more prominent at the bow of the vessel compared to the wheelhouse, which is near its more stable center (cf. Figure 2). These results indicate that the high-frequency attitude changes of the vessel need to be considered as well, for instance, by determining SSH at the more or less stable mass center of the vessel by combining data from at least three GNSS antennas (see, e.g., Varbla et al., 2020).

Figure 10: A priori vertical accuracies of antenna A1 (a), A2 (b), A3 (c), and A4 (d) during all the campaigns. Note that the estimates westward 22°E meridian of C2 campaign (cf. Figure 1) represent the CSRS-PPP.
To further assess the performance of the determined SSH, the SSH of the same or different campaigns can be compared at intersections. However, Figure 11 suggests that the data scattering may dominate such a comparison. Thus, a low-pass filter (a combination of moving median and average) developed by Varbla et al. (2017) and successfully employed by Varbla et al. (2020) was used to filter SSH (i.e., to reduce the impact of the vessel’s attitude and waves on comparisons). The filter window was set to 51 measurements, as was appraised suitable by Varbla et al. (2020). Two criteria were then defined to search intersections between filtered SSH of different campaigns: (i) distance between points less than 250 m and (ii) time between intersections (also consecutive points) more than 30 min. The resulting statistical properties are presented in Figure 12. It can be noted that the results differ slightly, for example, if campaign C2 is compared to C4 and vice versa. Since the algorithm searches intersections by moving along the validated campaign, the two tests may yield different points for comparisons (i.e., the algorithm moves along different routes for the two validation cases).

The statistics presented in Figure 12 show relatively good agreement, especially considering that the compared SSH contains ever-changing DT and is not corrected for the static draft. For instance, the mean differences suggest that DT was highest during the C1 campaign and lowest during the C6 campaign. The DT measurements in Table 6 seem to confirm this result. Table 6 also shows that up to 30 cm change in DT can be expected during a campaign. Such a large variability can contribute significantly to the standard deviation estimates. Therefore, the estimates in Figure 12, which mainly vary between 5 and 15 cm, indicate high accuracy of the determined SSH. Also, note that the antenna A4 (Figure 12b)-associated standard deviation estimates are generally lower than those of antenna A2 (Figure 12a), demonstrating again a better performance of the near mass center-mounted antenna.

Since DT appears to affect the intersection assessments between various campaigns, the two criteria described earlier were employed to also search for campaign-internal intersections. It is assumed that the DT change may have a reduced effect on the assessment results during a single campaign. Statistics of the detected campaign-internal intersections are presented in Figure 13.

Indeed, the standard deviation estimates are reduced compared to the results shown in Figure 12. The highest estimate of around 11 cm is associated with the A2 antenna during the C2 campaign (Figure 13a). Note also how the larger estimates are associated with longer campaigns (cf. Table 2). This result again indicates the impact of DT and also static draft (since fuel consumption increases with travel distance). In addition, the mean differences are less biased, being generally within 5 cm. It can also be seen that antenna A4 results (Figure 13b) indicate slightly
Figure 12: Statistical properties of differences between low-pass filtered SSH of antennas A2 (a) and A4 (b) at intersections between campaigns. The black lines are mean differences, and colored bars denote standard deviation estimates of differences. Crosses denote minimum and maximum differences. Note that color shows the validated campaign and the $X$-axis validation dataset. In square brackets are the total number of detected intersections for each comparison.
superior performance in comparison to antenna A2 (Figure 13a), which is consistent with the previous assessments.

5 Discussion

Results of six shipborne GNSS survey campaigns performed in the Baltic Sea demonstrated that it is possible to obtain reasonable quantification of SSHs in the coastal and offshore areas. Such surveys, however, are often challenged by other unexpected circumstances. For example, during the campaigns, some of the main problems/challenges encountered were caused by: (i) the GNSS receiver’s software error. The problem was not detected before the campaign. Therefore, the Trimble R8s GNSS system could not produce correctly compressed data files, and the system’s internal memory became full at sea; (ii) the hardware and logistical issues. Most of the GNSS equipment were rented in this study, and the GNSS receivers and antennas had to be changed between the C1 and C2 campaigns (cf. Table 3). This required meticulous checks of GNSS receivers’ settings and the type of GNSS antennas; (iii) the GNSS kinematic data postprocessing. Two different data processing software were used due to the distance of some of the GNSS measurements from the coast. The GNSS–CORS-based (by using TBC) and CSRS-PPP-based (for more distant GNSS profiles) results were combined to achieve the best height accuracy for nearshore and offshore data points; (iv) the vessel’s high-frequency attitude changes and marine conditions.

The derived SSH can be applied for various applications, such as the validation of geoid models, HDM fields, and altimetry products. However, further data processing needs to be conducted. For instance, the high-frequency attitude changes must be eliminated from measurements data, and vessel-related corrections must be implemented. However, such data processing is out of the scope of the current contribution that focuses on designing the marine GNSS surveys and on potential problems (and solutions to these) that may arise during these campaigns. Details of further data processing are reported in Varbla et al. (2022).

The procedures used in this study for obtaining SSH via shipborne GNSS can also be implemented for other marine regions. However, it is essential to be aware that (i) the position of GNSS antenna on the vessel affects the results; (ii) reliable GNSS results can still be achieved with long baselines (e.g., by using CSRS-PPP); (iii) mounting of GNSS equipment should be carefully considered; and (iv) unexpected events may occur during shipborne GNSS measurements (e.g., unfavorable weather conditions, equipment, and software malfunctioning).
6 Concluding remarks

This article describes the technical procedures for acquiring shipborne GNSS data, with the primary focus on equipping the designated survey vessel and processing the GNSS data. A case study was performed in the eastern section of the Baltic Sea during the spring and summer of 2021. These surveys consisted of six different campaigns (with a total length of nearly 5,000 km), where the GNSS–CORS network stations of Estonia and Latvia served as base stations for the postprocessing of GNSS kinematic data.

It is expected that the distances from the GNSS–CORS vary during shipborne GNSS surveys. Thus, two different processing methods were employed. These were GNSS–CORS-based and CSRS-PPP-based kinematic postprocessing approaches. Results demonstrate that for long baselines (i.e., 40–120 km between a GNSS–CORS and a measurement), better results were obtained using the CSRS-PPP, while for shorter baselines (i.e., 4–40 km), the GNSS–CORS-based kinematic postprocessing is preferred. Therefore, CSRS-PPP is the recommended method for offshore surveys with significant distances from the coast (and thus also from GNSS–CORS).

Different GNSS antennas (cf. Table 3) were utilized in this study, and a slight difference was observed in their performance. The resulting accuracy is related to the antenna’s location on the vessel (due to high-frequency attitude changes) and to some technical aspects (external antennas appear to have more accurate results). Also, to obtain accurate SSH, the computed GNSS ellipsoidal heights must be corrected for ARP. Once this was performed, a comparison between computed SSH and the NKG2015 geoid model yielded standard deviation estimates of 0.224 and 0.162 m for the antenna at the vessel’s bow and on top of the wheelhouse, respectively. This emphasizes that the position choice of the GNSS antenna influences the resulting SSH.

Performing shipborne GNSS surveys can be challenging at sea due to potential equipment and software failure, unpredictable weather conditions, vessel limitations, etc. All these factors can affect the data quality and results. For the results to be successful, careful consideration needs to be given to the mounting of the GNSS equipment, vessel’s parameters and appropriateness, and processing methods of the GNSS data. Although shipborne GNSS surveys can be expensive, they can be incorporated with other expeditions (a piggyback approach). The resulting SSH datasets can provide an alternate source of accurate sea level data, especially in challenging coastal locations that are not surveyed by other sensors (e.g., SA, TGs). Such SSH can also assist in improving marine geoid and hydrodynamic modeling.

Acknowledgments: The authors are grateful to the crew of R/V Salme, who all were very professional and helpful. The three anonymous reviewers are thanked for their contribution to the quality of the manuscript. Special thanks to OÜ Geosoft, who provided the used GNSS equipment. In addition, our thanks to the Estonian Land Board and Latvian Geospatial Information Agency for GNSS–CORS data. This research was partly supported by the grant P200188MIGX: “A 3D model of intraplate deformations combining remote sensing and in-situ measurements with an application to implement a semi-dynamic reference frame in Estonia,” and by the Estonian Research Council grant PRG330: “Development of an iterative approach for near-coast marine geoid modelling by using re-tracked satellite altimetry, in-situ and modelled data.”

Author contributions: A. Liibusk, S. Varbla, and A. Ellmann designed the research concept and drafted the manuscript. A. Liibusk and S. Varbla conducted data processing and visualized the manuscript. All authors contributed to data collection, discussion, review, and editing and approved the final manuscript.

Conflict of interest: The authors declare that they have no conflict of interest.

References

Ågren, J., G. Strykowski, M. Blikr-Koivula, O. Omang, S. Märdla, R. Forsberg, et al. 2016. “The NKG2015 gravimetric geoid model for the Nordic Baltic region.” 1st Joint Commission 2 and IGFS Meeting International Symposium on Gravity, Geoid and Height Systems. Thessaloniki. doi: 10.13140/RG.2.2.20765.20969.

Banville, S., E. Hassen, P. Lamothe, J. Farinaccio, B. Donahu, Y. Mireault, et al. 2021. “Enabling ambiguity resolution in CSRS-PPP.” Navigation-Journal of the Institute of Navigation 68(2), 433–51. doi: 10.1002/navi.423.

BSHC. Baltic Sea Hydrographic Commission. Retrieved from BSHC Chart Datum Working Group, 2021 http://www.bshc.pro/working-groups/cdwg/.

Cipollini, P., F. Calafat, S. Jevrejeva, A. Melet, and P. Prandi. 2017. “Monitoring sea level in the coastal zone with Satellite Altimetry and Tide Gauges.” Surveys in Geophysics 38, 33–57. doi: 10.1007/s10712-016-9392-0.

Crétaux, J. F., S. Calmant, V. Romanovski, F. Perosanz, S. Tashbaeva, P. Bonnefond, et al. 2011. “Absolute calibration of Jason radar altimeters from GPS kinematic campaigns over lake Issyk-kul.”
Delpeche-Ellmann, N. and T. Soomere. 2017. “Examining Lagrangian surface transport during a coastal upwelling in the Gulf of Finland, Baltic Sea.” *Journal of Marine Systems* 171, 21–30. doi: 10.1016/j.marsys.2016.10.007.

Ekman, M. 2009. *The changing level of the Baltic Sea during 300 years: A clue to understanding the Earth*. Summer Inst. for Historical Geophysics.

Foster, J., G. Carter, and M. Merrifield. 2009. “Ship-based measurements of sea surface topography.” *Geophysical Research Letters* 36(11), L11605. doi: 10.1029/2009GL038324.

Guo, J., Z. Dong, Z. Tan, X. Liu, C. Chen, and C. Hwang. 2016. “A crossover adjustment for improving sea surface height mapping from in-situ high rate ship-borne GNSS data using PPP technique.” *Continental Shelf Research* 125, 54–60. doi: 10.1016/j.csr.2016.07.002.

Hunter, J., P. Woodworth, T. Wahl, and R. Nicholls. 2017. “Using global tide gauge data to validate and improve the representation of extreme sea levels in flood impact studies.” *Global and Planetary Change* 156, 34–45. doi: 10.1016/j.gloplacha.2017.06.007.

Jahanmard, V., N. Delpeche-Ellmann, and A. Ellmann. 2021. “Realistic dynamic topography through coupling geoid and hydrodynamic models of the Baltic Sea.” *Continental Shelf Research* 222, 104421. doi: 10.1016/j.csr.2021.104421.

Jakimavičius, D., J. Kriauciūnienė, and D. Serauskienė. 2018. “Assessment of wave climate and energy resources in the Baltic Sea nearshore (Lithuanian territorial water).” *Oceanology* 60(2), 207–18. doi: 10.1016/j.oceano.2017.10.004.

Jürgenson, H., A. Liibusk, and A. Ellmann. 2008. “Geoid profiles in the baltic sea determined using GPS and sea level surface.” *Geodesy and Cartography* 34(4), 109–15. doi: 10.3846/1392-1541.2008.34.109-115.

Lagemaa, P., J. Elken, and T. Küuts. 2011. “Operational sea level forecasting in Estonia.” *Estonian Journal of Engineering* 17(4), 301. doi: 10.3176/eng.2011.4.03.

Liblik, T., M. Skudra, and U. Lips. 2016. “On the buoyant sub-surface salinity maxima in the Gulf of Riga.” *Oceanologia* 59(2), 113–128. doi: 10.1016/j.oceano.2016.10.001.

Liibusk, A., T. Kall, S. Rikka, R. Uiboupin, U. Suursaar, and K. Tseng. 2020. “Validation of copernicus sea level altimetry products in the Baltic Sea and Estonian Lakes.” *Remote Sensing* 12(24), 4062. doi: 10.3390/rs12244062.

Maciuk, K., I. Värna, and C. Xu. 2020. “Characteristics of seasonal variations and noises of the daily double-difference and PPP solutions.” *Journal of Applied Geodesy* 15(1), 61–73. doi: 10.1515/jag-2020-0042.

Madsen, K., J. Hayer, W. Fu, and C. Donlon. 2015. “Blending of satellite and tide gauge sea level observations and its assimilation in a storm surge model of the North Sea and Baltic Sea.” *Journal of Geophysical Research: Oceans* 120(9), 6405–18. doi: 10.1002/2015JC01070.

Metsar, J., K. Kollo, and A. Ellmann. 2018. “Modernization of the Estonian National GNSS reference station network.” *Geodesy and Cartography* 44(2), 55–62. doi: 10.3846/gac.2018.2023.

Mireault, Y., P. Tétreault, F. Lahaye, P. Héroux, and J. Kouvera. 2008. “Online precise point positioning: A new, timely service from natural resources Canada.” *GPS World* 19(9), 59–64.

Mostafavi, M., N. Delpeche-Ellmann, and A. Ellmann. 2021. “Accurate sea surface heights from Sentinel-3A and Jason-3 retrackers by incorporating high-resolution marine geoid and hydrodynamic models.” *Journal of Geodetic Science* 11(1), 58–74. doi: 10.1515/jogs-2020-0120.

Nordman, M., J. Kuokkanen, M. Bilker-Koivula, H. Koivula, P. Häkli, and S. Lahtinen. 2018. “Geoid validation on the Baltic sea using ship-borne GNSS data.” *Marine Geodesy* 41(5), 457–76. doi: 10.1080/01490419.2018.1481160.

Passaro, M., P. Cipollini, S. Vignudelli, G. Quartly, and H. Snaith. 2014. “ALES: A multi-mission adaptive subwaveform retracker for coastal and open ocean altimetry.” *Remote Sensing of Environment* 145, 173–189. doi: 10.1016/j.rse.2014.02.008.

Penna, N., M. Morales Maqueda, I. Martín, J. Guo, and P. Foden. 2018. “Sea surface height measurement using a GNSS wave glider.” *Geophysical Research Letters* 45(11), 5609–16. doi: 10.1002/2018GL077950.

Post, P. and T. Küuts. 2014. “Characteristics of cyclones causing extreme sea levels in the northern Baltic Sea.” *Oceanologia* 56(2), 241–58. doi: 10.5697/oce.56.2.241.

Roggenbuck, O. and J. Reinking. 2019. “Sea surface heights retrieval from ship-based measurements assisted by GNSS signal reflections.” *Marine Geodesy* 42(1), 1–24. doi: 10.1080/01490419.2018.153220.

Saari, T., M. Bilker-Koivula, H. Koivula, M. Nordman, P. Häkli, and S. Lahtinen. 2021. “Validating geoid models with marine GNSS measurements, sea surface models, and additional gravity observations in the gulf of Finland.” *Marine Geodesy* 44(2), 196–214. doi: 10.1080/01490419.2021.1889727.

Schwabe, J., J. Ågren, G. Liebsch, P. Westfeld, T. Hammadkint, J. Mononen, and et al. 2020. “The Baltic Sea Chart Datum 2000 (BSCD2000) – Implementation of a common reference level in the Baltic Sea.” *International Hydrographic Review* 23, 63–83.

Shih, H.-C, T-K Yeh, Y. Du, and K. He. 2021. “Accuracy assessment of sea surface height measurement obtained from shipborne PPP positioning.” *Journal of Surveying Measurements* 147(4), 04021022. doi: 10.1061/ASCE/SU.1943-5428.0000374.

Soosaar, E., I. Maljutenko, R. Uiboupin, M. Skudra, and U. Raudsepp. 2016. “River bulge evolution and dynamics in a nontidal sea – Daugava River plume in the Gulf of Riga, Baltic Sea.” *Ocean Science* 12(2), 417–32. doi: 10.5194/os-12-417-2016.

Stępień, G., A. Tomczak, and T. Zięبك. 2019. “Application of total free station method (TFS) for offshore surveying in oblique coordinate system.” *International Journal of Advances in Science Engineering and Technology* 7(2), 32–7.

Toming, K., L. Testut, C. Chupin, V. Ballu, and P. Bonnefond. 2019. “Assessment of extreme sea levels from sentinel-3A and Jason-3 retracker.” *Remote Sensing* 11(5), 649–72. doi: 10.3390/rs11050649.

Varbla, S., A. Ellmann, and N. Delpeche-Ellmann. 2021. “Applications of airborne laser scanning for determining marine geoid and surface waves properties.” *European Journal of Remote Sensing* 54(1), 557–67. doi: 10.1080/22797254.2021.1981156.
Varbla, S., A. Ellmann, and N. Delpeche-Ellmann. 2020. “Validation of marine geoid models by utilizing hydrodynamic model and shipborne GNSS profiles.” Marine Geodesy 43(2), 134–62. doi: 10.1080/01490419.2019.1701153.

Varbla, S., A. Ellmann, S. Märdla, and A. Gruno. 2017. “Assessment of marine geoid models by ship-borne GNSS profiles.” Geodesy and Cartography 43(2), 41–9. doi: 10.3846/20296991.2017.1330771.

Varbla, S., A. Liibusk, and A. Ellmann. 2022. “Shipborne GNSS-determined sea surface heights using geoid model and realistic dynamic topography.” Remote Sensing 14(10), 2368. doi: 10.3390/rs14102368.

Vestøl, O., J. Ågren, H. Steffen, H. Kierulf, and L. Tarasov. 2019. “NKG2016LU: a new land uplift model for Fennoscandia and the Baltic Region.” Journal of Geodesy 93, 1759–79. doi: 10.1007/s00190-019-01280-8.

Weisse, R., I. Dailidiene, B. Hünicke, K. Kahma, K. Madsen, A. Omstedt, et al. 2021. “Sea level dynamics and coastal.” Earth System Dynamics 12(3), 871–98. doi: 10.5194/esd-12-871-2021.

Xu, X., K. Xu, H. Shen, Y. Liu, and H-G Liu. 2016. “Sea surface height and significant wave height calibration methodology by a GNSS Buoy campaign for HY-2A altimeter.” IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing 9, 5252–61. doi: 10.1109/JSTARS.2016.2584626.