GNSS-based Techniques for Accurate Height Component Estimation of Vessels in Finnish Waterways – A review

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Abstract

One way to determine the Under-Keel Clearance (UKC) is to first compute the height component of the vessel's 3-dimensional position. This can be achieved using a maritime-grade Global Navigation Satellite System (GNSS) receiver. In standalone mode the GNSS receiver is unable to estimate the height component at the accuracy necessary for some application scenarios, for example, hydrography and cargo handling in port. Correction data is therefore provided to the on-board receivers using satellite or ground based augmentation systems (SBAS and GBAS) to improve the accuracy. This paper presents a review of the GNSS-based technological options for accurate height component estimation of vessels with specific focus in Finnish waterways. We present different augmentation services, both commercial and publicly owned that are available in this area. For each of the services expected accuracy metrics are provided. It was observed that accuracy of height component estimation varies from 0.06 m to 4.00 m depending on the applications. Lastly, the coordinate and height reference frames currently in use in the Baltic Sea is addressed, with some outlook to the future.

Keywords 1

maritime, under-keel clearance, augmentation, GBAS, SBAS, FinnRef, FINPOS

1. Introduction

Maritime navigation, especially in the Finnish coastal area and in port approach, will be the focus of this paper. The position of a vessel with high accuracy particularly on the height component will have significant impact in estimating the Under-Keel Clearance (UKC) [1]. Having reliable knowledge of the real-time UKC of a vessel is expected to result in significant benefits in safety, fuel efficiency, and cargo optimization. Traditionally, vessel operators rely on the draft markings (also called waterline or load line) observations to compute the depth to which the ship penetrates below the water after cargo loading. This is complemented by fresh information about the water level from local tide-gauges, wave heights from ship-sensors, and the available information from surveying the sea floor to estimate the UKC in real-time along the route. This method is not very straightforward and provides only rough estimates. Consequently, the UKC is known but with wide *uncertainty* and therefore a significant height buffer must be reserved. In other words, the vessel cannot be loaded to the theoretical maximum capacity while hoping to maintain the desired level of safety.

An alternative method to compute the UKC is based on the height component of the vessel's 3-dimentional (3D) position. Global Navigation Satellite Systems (GNSS) have been used mostly for accurate determination of the vessel position in the horizontal plane. Its benefits in accurate and real-time height component estimation have not received comparable appreciation. In this study [2], we perform a background literature survey of different techniques by which on-board accurate GNSS-based height estimation can be accomplished in Finnish territorial waters using diverse augmentation

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information provided by entities (public or commercial) external to the vessel. Secondly, this study also discusses the significance of the coordinate and reference frames to height estimation in this context. Our survey revealed few, if any, existing literature providing a comprehensive focus on these topics, a gap which this paper aims to fill.

The reminder of this paper is as follows: Section II deals with a discussion on the rationale for exploiting GNSS for accurate height estimation in vessels. Section III discusses the role of GNSS in the maritime domain and the operational and end-user requirements concerning height estimation accuracy in maritime applications. In Section IV the state-of-the-art expected performance of vessel height estimation using GNSS and different augmentation services is presented. Section V is dedicated to a discussion about coordinate and height reference frames and related challenges for seamless maritime navigation in the Baltic Sea. Section VI provides the conclusions and recommendations.

2. Background

2.1. Concept of under-keel clearance

UKC is a vertical distance between the lowest underwater point on the ship's hull (or keel) and the highest point on the channel bottom beneath the ship [3]. The main components for UKC estimation are shown in Fig.1 and (1) as follows:

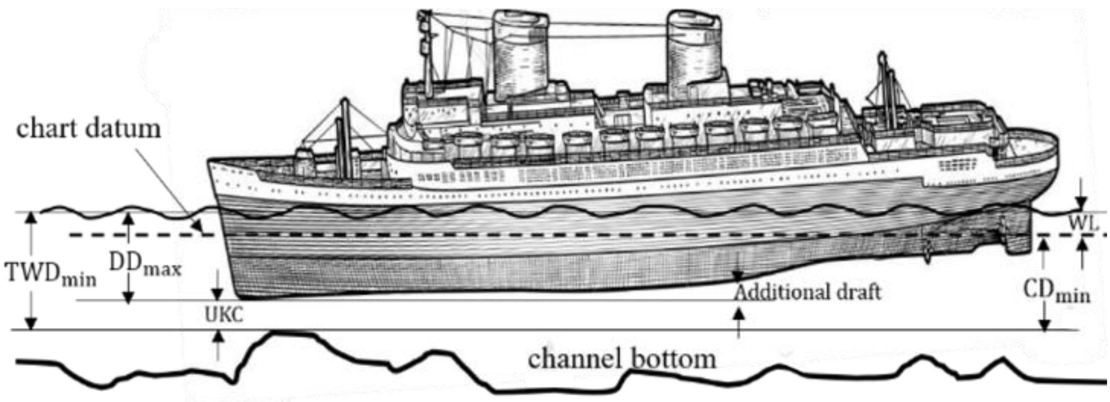

Figure 1: Traditional method of estimating the UKC.

$$UKC = [\text{Minimun total water depth } (\mathrm{TWD_{min}})] - [\text{Maximum dynamic draft } (\mathrm{DD_{max}})]$$

$$UKC = [\text{Minimum charted depth } (\mathrm{CD_{min}}) + \text{water level (WL)}] - [\text{Static draft} + \text{sinkage} + \text{additional draft due to speed, turning and wave effect}] \quad (1).$$

According to (1), UKC is computed by subtracting the maximum dynamic draft($\mathrm{DD_{max}}$)of the ship from the minimum total water depth ($\mathrm{TWD_{min}}$) at the location of the ship [3]. The dynamic draft is referred to the distance from the water's surface to the lowest point on the ship's keel while the ship is in motion. The total water depth consists of the charted depth ($\mathrm{CD_{min}}$) plus the Water Level (WL) above the chart datum. The geodetic chart datum includes the essential information of the water depth, mean sea level, etc. and the water level information is found from the local tide-gauges. Because traditionally the dynamic draft is estimated from manual observation of the vessel's draft line, the UKC computed from (1) is not straightforward and provides only a rough estimate of it.

The research conducted in [1] testified that with an accurate geodetic chart datum it is straight-forward to calculate UKC from a height measurement obtained by the vessel's satellite positioning system. This gives the navigator better control of the actual UKC of the vessel without compromising safety, as illustrated in Fig. 2. The UKC prediction formula is presented in (2) as follows:

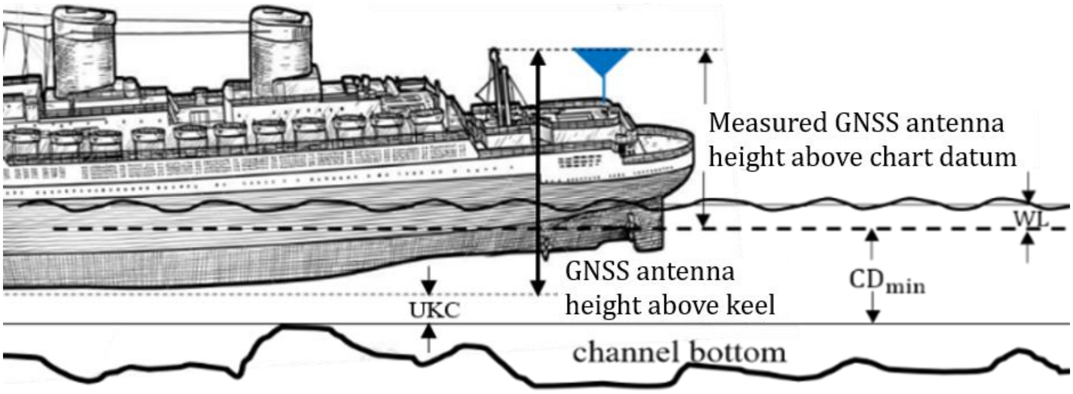

Figure 2: UKC derived from height measurement obtained by the vessel's satellite positioning system.

$$UKC = [\text{Minimum charted depth } (CD_{min})] + [\text{Measured GNSS antenna height above chart datum}] - [\text{GNSS antenna height above keel}] \quad (2).$$

As seen in (2) utilizing the vessel's 3D position obtained from the on-board GNSS equipment provides improved UKC awareness without the need to know separately the dynamic draft or the prevailing water level [4].

2.2. Economic and Environmental Benefits

It is clear from the preceding section that the accuracy of estimating the UKC is directly influenced by the accuracy of vessel's height component estimation. Thus, improvement of every centimeter in the accuracy reduces the amount of necessary reserve under-keel clearance. This brings economic benefits to the shipping company by allowing the vessel to safely carry more cargo in a single trip.

The guideline for evaluation of fairway investment projects [5] and the report on average operating costs of ships [6] published by the Finnish Transport Infrastructure Agency (FTIA) gives some estimations on the economic and environmental benefits of increasing the vessel draft in Finland. Based on [6], every additional 10 cm in draft allows the vessel to carry approximately 1000 tons equivalent to about 50 containers of additional cargo. The economic and social benefits of improved UKC awareness also include more efficient pilotage in ports and harbors, lower average annual cost of downtime from accidents, lower average costs of oil spills and support better navigation through environmentally sensitive areas. The Baltic Sea, for example, is a sensitive environment and challenging sea due to its on-going land uplift and the incomplete water depth mapping [1]. It is classed as a 'Particularly Sensitive Area' by International Maritime Organization (IMO) [7]. Vessels need additional safety margin due to the uncertainties in water depth levels in the Baltic Sea that leads to inefficient maritime transportation. Therefore, there is a significant potential in vessels navigating with better UKC awareness, which may allow slightly deeper drafts for the vessel without compromising on safety.

3. Requirements for Height Accuracy in Maritime Applications

The IMO is setting the regulatory framework for the shipping industry, including performance requirements for GNSS. Some of the most important parameters of operational requirements for GNSS are accuracy, integrity, continuity, availability and coverage [7-8]. These requirements are developed based on risk analysis, considering risk exposure time and critical risk exposure time. However, the GNSS user requirements in maritime domain are often complex and even contradictory. In this study, we only focus on the accuracy of the height or vertical component of the vessel's 3D position. Nevertheless, the main findings corresponding to both horizontal and vertical accuracy requirements for different maritime application scenarios are summarized in Table 1. The 'N/A' in the table stands for '*Not Applicable*'. It can be also noted that if the information is not available, the cell is left blank.

Table 1
Maritime user requirements for navigation and positioning [7-8].

Maritime Applications	**Accuracy (95%) Requirement [m]**	
	Horizontal	**Vertical**
	Navigation (Absolute accuracy)	
Ocean	10-100	
Coastal	10	
Port approach and restricted waters	10	
Port	1	
Inland waterways	10	
	Positioning	
Traffic management	*Absolute accuracy*	
Ship-to-ship co-ordination	10	
Ship-to-shore co-ordination	10	
Shore-to-ship traffic management	10	
Operations	*Relative accuracy*	
Tugs and pushers	1	
Icebreakers	1	
Automatic collision avoidance	10	
	Absolute accuracy	
Track control	10	N/A
Automatic docking	0.1	
SAR	10	N/A
Hydrography	1-2	0.1
Oceanography	10	10
Marine engineering, construction, maintenance and management		
Dredging	0.1	0.1
Cable and pipeline laying	1	N/A
Construction works	0.1	0.1
Aids to navigation management	1	N/A
Port operations	*Absolute accuracy*	
Local vessel traffic service	1	N/A
Container/cargo management	1	1
Law enforcement	1	1
Cargo handling	0.1	0.1
Casualty analysis	*Predictable accuracy*	
Ocean	10	N/A
Coastal	10	N/A
Port approach and restricted waters	1	N/A
Offshore exploration and exploitation		
Exploration	1	N/A
Appraisal drilling	1	N/A
Field development	1	N/A
Support to production	1	N/A
Post-production	1	N/A
Fisheries	*Absolute accuracy*	
Location of fishing grounds	10	N/A
Positioning during fishing	10	N/A
Yield analysis	10	N/A

Fisheries monitoring	10	N/A
Recreation and leisure	*Absolute accuracy*	
Ocean	10	N/A
Coastal	10	N/A
Port approach and restricted waters	10	N/A

From Table 1 it can be observed that the most stringent requirement for both horizontal and vertical accuracy (95%) is 0.1 m which is applicable for scenarios involving cargo handling in ports, dredging, maritime construction works, and hydrography.

4. Performance Review of Height Estimation Accuracy in Maritime Navigation using GNSS-based Techniques and Augmentations

In this Section, at first the baseline performance using standalone GNSS to provide the vessel's vertical position is presented. Then the performance assessment with different augmentation techniques is provided. Finally, a comparison of the height estimation performance between the different services is services is discussed as a summary of the Chapter.

4.1. Baseline (Standalone GNSS) Performance

The most common and straightforward way to estimate the height component of the vessel's position in maritime environment is to utilize a maritime-grade GNSS receiver. The receiver standalone performance matric is mostly presented as horizontal accuracy (rms) which is in the range from 1.2 m to 1.5 m [9]. No literature has found where the height component estimation using the maritime-grade receiver has validated experimentally. The indicative baseline performance for vertical accuracy (rms) can be set to 1.9 m as depicted in [10].

4.2. Performance with Augmentation Techniques

4.2.1. Integration of GNSS and Ship-Based Inertial Sensors

Ship-based internal sensor is one option as augmentation technique, but we have not considered it here. The reason is that the sensor is essentially a property of the individual vessel. Meaning that this feature cannot be provided by public authorities as an external augmentation to the GNSS-based height estimation of the vessel. Therefore, this technique was outside the scope of this study.

4.2.2. Galileo High Accuracy Service

An introduction to the Galileo High Accuracy Service (HAS) is presented in [11]. This service will be part of the offerings from the European Galileo satellite navigation system. The signal will be broadcast on the E6 band at a carrier frequency of 1278.75 MHz. In addition to the Open Service (OS) signal components for performing user localization, this signal also offers users with augmentation data (satellite orbit, clock corrections and ionospheric corrections) to improve accuracy via Precise Point Positioning (PPP). The provision of ionosphere delay information will be especially crucial to improve accuracy of height estimation. It is estimated that the first complete HAS signal in space will be available in 2020. Phase 1 of the service will initiate in 2021 and phase 2 in 2023-24. Therefore, as no real signals are available to validate experimentally the expected benefits of HAS to height estimation, we must rely on official notes from the European Commission. According to [12], it is targeted that Galileo HAS will provide a horizontal accuracy better than 0.2 m and vertical accuracy better than 0.4 m. It remains to be validated if this projected performance can be achieved in maritime conditions.

4.2.3. Ground-Based Augmentation System Services

Ground-Based Augmentation System (GBAS) services have been in development since the 1990s to fulfill IMO requirements on GNSS based positioning in coastal areas. Two types of GBAS services are available in Finland: public and commercial. The GBAS services use ground communication links such as dedicated radio frequencies or the internet to provide augmentation data to the users.

4.2.3.1. Public GBAS services

In Finland, vessels use the public GBAS services provided by Väylävirasto. In the future the FINPOS service provided by the National Land Service (NLS) will play an important role for providing the ground-based differential correction services to the vessels especially within the Finnish economic borders but also in a wider Baltic and global context.

IALA DGPS Service

Differential GNSS (DGNSS) involves having Reference Stations (RS), at precisely known locations that provide real-time corrections and integrity information for GNSS signals. Marine Aids to Navigation providers established a DGNSS service based on the broadcast of augmentation data using marine Medium Frequency (MF) radio beacons. This standardized service termed as IALA (International Association of Marine Aids to Navigation and Lighthouse Authorities) DGNSS service is operational in many of the most significant coastal waters throughout the world and is available free-of-charge at the point of delivery [13]. In [14-15], the performance of the current IALA Differential Global Positing System (DGPS) service in the *European Maritime Area* is presented, as simulated by the NEMO software tool. The horizontal accuracy (95%) achieved within the coverage of the IALA radio beacons is in the range from 0.6 m to 2.5 m, whereas the vertical accuracy (95%) is in the range from 0.8 to 2.5 m. In Finland, Väylävirasto provides the IALA DGPS service in co-operation with Vessel Traffic Service, Finland. There are nine DGPS broadcasting stations providing correction data for maritime navigation in the Finnish territorial waters. The horizontal positioning accuracy obtained with the service is expected to be better than 10 m with 95% confidence. However, in practice, it can be in the order of 1-2 meters [16], which is in-line with the simulated performance described in [14-15].

FINPOS precise positioning service

FINPOS is the precise positioning service offered by NLS that utilizes the Finnish Permanent GNSS Network (FinnRef) data [17]. This network is a large governmental investment and it offers DGNSS service to citizens free of charge. In [1] vertical accuracy results with PPP using only L1 C/A code with the State Space Representation (SSR) correction model is generated from a network of Continuously Operating Reference Stations (CORS) from Finland, Sweden and Estonia.

Note that the experimental results presented in the following are based on a campaign performed in May 2018 under the EU-funded FAMOS Odin project as described in [1] and partly in [18]. Part of the results have been recently computed and are yet to be published in scientific forums. The test campaign took place during a dedicated gravity campaign on board of the research vessel *Geomari* [19] of the Finnish Geological Survey between the 21st and 25th of May 2018. Here, measurement campaign was carried out in the Eastern part of the Gulf of Finland. The details of the measurement campaign and equipment are presented in detail in [18]. The experimental results are presented in Table 2. It provides the accuracy of the height component estimation of the vessel's position using a mass-market grade receiver and a survey-grade receiver. The offset presented in the table is the vertical navigation error with respect to the true position. The 90% spread stands for that 90% of all position errors are smaller than this error after removing the absolute offset from the data. The average number of Satellite Vehicles (SVs) used in navigation computation are also provided.

Table 2
The Accuracy of Height Estimation with PPP-SSR Service [1].

Campaign	Receiver	90 % spread (m)	Offset (m)	No. of SVs (avg.)
Day 1	Mass-market grade	1.3	1.0	8.8
	Survey grade	1.5	0.4	9.1
Day 2	Mass-market grade	1.5	1.2	9.1
	Survey grade	1.3	1.0	9.3
Day 3	Mass-market grade	1.3	0.9	8.9
	Survey grade	1.2	0.8	9.2
Day 4	Mass-market grade	1.4	1.0	9.3
	Survey grade	1.2	0.8	9.5
Day 5	Mass-market grade	1.2	0.9	10.0
	Survey grade	1.3	0.6	10.2

4.2.3.2. Commercial GBAS services

There are a few commercial GBAS service providers in Finland, e.g., TrimNet is operated by Geotrim Oy [20] and HxGN SmartNet is operated by Leica Geosystems Finland [21]. TrimNet is based on the Virtual Reference Station (VRS) technology providing DGNSS corrections with the vertical accuracy (rms) of 0.5 m [20]. HxGN SmartNet offers corrections with accuracy from centimeter to decimeter levels [21]. In both cases, we did not locate any specific mention of the performance of the height accuracy estimation or results specifically pertaining to the maritime domain.

4.2.4. Satellite-Based Augmentation System Services

Satellite-Based Augmentation System **(**SBAS) services utilize satellites to provide the augmentation data to end-users. These services are beneficial when vessels are in open sea and outside the range of any ground-based communication channels. However, this does not restrict the application of SBAS services in territorial waters or inland waterways. Here we present the public and commercial SBAS services which could be utilized by vessels in Finnish waters.

4.2.4.1. Public SBAS Services

The European Geostationary Navigation Overlay Service (EGNOS) is a free of charge SBAS service that improves the GPS positioning accuracy and provides information on its reliability in Europe. EGNOS is suitable for safety critical applications in maritime sector such as navigating ships through narrow channels, applications where an accuracy of less than 1 m is required, e.g. port operations. According to the EGNOS OS definition document [22], the standalone GPS position accuracy can be improved by around 2-3 m by correcting several error sources affecting the GPS signals. The Horizontal Position Error (HPE 95%) and Vertical Position Error (VPE 95%) for the EGNOS OS coverage area are presented in [22]. According to [22], HPE (95%) of 0.9 m and VPE (95%) of 1.6 m can be expected at the reference monitoring station located in Lappeenranta, Finland.

EGNOS performance was evaluated for different applications (static, road test and flight test) over a year-long data campaign from 20 FinnRef stations under the FEGNOS project [23]. Another independent EGNOS service performance assessment is presented in [24]. However, here only the horizontal accuracy is evaluated along the Norwegian coast as part of a project undertaken by the European Satellite Services Provider (ESSP) and GSA. There is, therefore, no independent investigation available from Finnish territorial waters regarding the expected accuracy performance of EGNOS for vessel height estimation.

4.2.4.2. Commercial SBAS services

There are several commercial service providers worldwide, including Fugro, Veripos, TerraStar, OmniSTAR and StarFire which are used for both general navigation and positioning applications in maritime. These services are also available in Finnish territorial waters. There is little literature in the public domain to validate experientially the expected vertical accuracy in maritime conditions provided by different commercial SBAS services. For example, the Fugro Starfix G4 service performance assessment is presented in a realistic maritime environment in [25]. However, the height accuracy performance has not been presented for this scenario. Instead, it provides the performance for a stationary receiver located in Oslo, Norway and Perth, Australia for the first week of 2017. The rms position accuracy is about 1.2 cm horizontal and 4.0 cm vertical. Table IV lists the vertical accuracy information provided in the official documentation of the different commercial SBAS providers.

4.3. Performance Comparison

This Section is a summary of the expected vertical accuracy from all the GNSS-based augmentation techniques described earlier. It compiles and compares the information from publicly available scientific and commercial literature provided by the authorities and entities responsible for the maintenance and transmission of the services. The comparison is presented in Table 3. Many of these figures pertain to performance in maritime conditions, while few relate to land-based applications, i.e., services provided by commercial GBAS systems.

Table 3
Comparison of Expected Vertical Accuracy from Different Positioning Techniques and Augmentation Strategies.

Augmentation systems	Service	Vertical accuracy	Unit
Standalone GNSS-only	GNSS [10]	1.90	rms [m]
Galileo HAS	Galileo HAS [12]	0.40 (planned)	95% [m]
Public GBAS	FINPOS PPP-SSR [1]	1.20 – 1.50	90% [m]
	IALA DGNSS [14-15]	0.80 – 2.50	95% [m]
Commercial GBAS	TrimNet [20]	0.50	rms [m]
	HxGN SmartNet [21]	0.10	95% [m]
Public SBAS	EGNOS [22]	1.60	95% [m]
Commercial SBAS	Fugro [26]	0.06 – 4.00	95% [m]
	OmniSTAR [27]	0.10 – 0.50	95% [m]
	Oceanix [28]	0.06	rms [m]
	C-Nav [29]	0.15	rms [m]
	Veripos [30]	0.12 – 1.00	95% [m]

5. Significance of Coordinate and Height Reference Frames in maritime Navigation

Coordinates in accurate navigation can relate to global or national coordinate systems. The International Terrestrial Reference System (ITRS) is the most important global reference system [31]. Its realizations ITRFyy are given with epoch and velocity information since the Earth is continuously changing. GNSS systems all use their own global coordinate systems: for example, GPS uses WGS84 (World Geodetic System 1984) [32]. All frames of GNSS systems are compatible with ITRF on the cm level.

For practical purposes time dependent reference frames are not useful. In Europe the European Terrestrial Reference System 1989 (ETRF1989) is fixed to the Eurasian tectonic plate. The realizations of ETRS89 are called ETRFyy. The official coordinate reference frame in Finland is EUREF-FIN. It is the national ETRF89 realization, ETRF96, realized in epoch 1997.0 [33].

In accurate navigation the difference between time dependent global reference frames like ITRF or WGS84 and the time-fixed national frame EUREF-FIN must be understood. In 2019 the difference between EUREF-FIN and WGS84 was over 0.7 m in horizontal direction and at dm level in the vertical component.

In Finland the coordinate system of the nautical charts is EUREF-FIN. Some older charts can still be in KKJ [34] that differs significantly from WGS84 or EUREF-FIN. Local Finnish augmentation systems typically work in the national EUREF-FIN frame. Global augmentation services are typically using global reference frames being in cm level agreement with WGS84.

Sea level data and depths in nautical charts are in Finland currently given with respect to a theoretical mean sea level that is updated yearly [35]. The use of the theoretical mean sea level requires that mariners are alert as the level changes yearly and the level in use at the mareograph may not coincide with the level used in the nautical chart. Also, the sea level given at the mareograph may not be representative for the sea level at the open sea.

In the future this is going to change as Finland will adopt the Baltic Sea Chart Datum 2000 (BSCD2000) [36] as its height reference for sea levels and depths, as will most countries around the Baltic Sea. In Finland the BSCD2000 is realized by N2000, which is the height reference system on land [34]. The BSCD2000 is offshore realized by GNSS positioning services, working in the national reference frames (e.g. FinnRef in Finland) and a model of the BSHD2000 height reference surface. The height reference surface is realized by a gravimetric quasigeoid model.

When the BSCD2000 is fully introduced the UKC can directly be determined using a combination of heights obtained from GNSS positioning, depths from the chart, and the model for the reference surface (the geoid model). The accuracy with which the UKC can be determined will then depend on the accuracy of the GNSS positioning, the accuracy of the geoid model, and on how well the different measures and movements of the vessel are known, but not on the water level measurements.

6. Conclusions

More accurate information on Under-Keel Clearance offers significant potential for improvement in navigational safety, fuel efficiency, and cargo optimization. UKC systems require the information of the position of a vessel with high accuracy especially on the height component. In this project, we have performed a background literature survey of different technological options by which on-board accurate GNSS based height estimation can be accomplished in Finnish waterways through the use of diverse augmentation information. The augmentation techniques discussed here are ship-based inertial sensors, Galileo high accuracy service, ground-based, and satellite-based augmentation systems.

The accuracy performance of the height estimation using different augmentation options were presented in the context of Finnish waterways. Furthermore, we discussed the significance of the coordinate and reference frames to height estimation in maritime navigation. The following key findings and recommendations can be made based on the literature survey:

- Actual values of height accuracy that can be achieved via existing public services are:
  - FINPOS PPP-SSR service 1.2 – 1.5 m
  - IALA Beacon DGPS 0.8 – 2.5 m
  - EGNOS <1.6 m
- There are very good commercial solutions for precise height estimation. The accuracy of these solutions ranges between 0.06 m to 4.00 m.
- Galileo HAS is expected to provide a high accuracy free of charge service by 2025. Height accuracy of Galileo HAS is expected to be better than 0.4 m.
- The difference between time dependent global reference frames like ITRF or WGS84 and the time-fixed national frame EUREF-FIN must be understood. The difference in 2019 was 0.7 m horizontally and up to several dm vertically.

- Once the BSCD2000 is fully introduced in Finnish waters, the UKC can directly be determined using a combination of heights obtained from GNSS positioning, depths from the chart, and the model for the reference surface (the geoid model).

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