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Preliminary Study on Utilizing GNSS-based Techniques for Enhanced Height Estimation for Vessels in Finnish Waterways

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Abstract

The aim of this report is to utilise a literature search to survey various augmentation systems based on navigation satellite systems that would enable enhanced height estimation on Finnish waterways. A more accurate knowledge of a vessel's vertical position would enable more efficient use of the fairway depth and a greater cargo capacity of vessels, without compromising safety. The use of various augmentation systems increases the accuracy of satellite navigation, especially under dynamic conditions.

Correction data can be produced in different ways, depending on the scope of the geographical area in which the data is to be used. A public EGNOS service covering the entirety of the EU area is in use in Europe, providing correction data to support the GPS system. Correction data is transmitted via geostationary satellites. In addition, the Galileo system satellites are intended to provide a global precision positioning service in the future. The aim of the service is to provide a positioning accuracy of less than 0.2 m. Precision positioning services for maritime transport are also provided by several commercial operators worldwide.

There are several local satellite navigation augmentation systems available in Finland. The IALA Beacon DGNSS correction transmission system, which serves shipping, is in place throughout the Baltic Sea region, through which vessels receive free correction data to enhance the accuracy of the GPS system. In addition, the FINPOS service provides free correction information for the GPS and GLONASS systems on Finnish territory. Commercial satellite navigation augmentation services suitable for local use are also available.

The report states that a prerequisite for determining safe water depth with satellite navigation systems is the standardisation of reference levels for depth measurements throughout the Baltic Sea region and their fixation to the reference level used by satellite positioning systems. Action is being taken in this area and will be completed by 2030. Commercial augmentation services in particular already allow for very accurate height estimation for positioning. In the next few years, the Galileo system will also provide a global, highly accurate, free precision positioning service, so there is currently no need for a separate local precision positioning service as a public facility.

Afroza Khatun, Sarang Thombre, M. Zahidul H. Bhuiyan, Mirjam Bilker-Koivula, Hannu Koivula: Esiselvitys satelliittinavigointijärjestelmiin perustuvien teknologioiden hyödynnettävyydestä alusten tarkkaan korkeussuuntaiseen paikanmääritykseen Suomen vesialueilla. Väylävirasto. Helsinki 2021. Väyläviraston julkaisuja 18/2021. 60 sivua. ISSN 2490-0745, ISBN 978-952-317-854-0.

Avainsanat: satelliittinavigointi, alusliikenne, paikanmääritys

Tiivistelmä

Tämän raportin tavoitteena on kirjallisuusselvityksen avulla kartoittaa erilaisia satelliittinavigointijärjestelmiin perustuvia, tarkan korkeussuuntaisen paikannuksen Suomen vesiväylillä mahdollistavia avustejärjestelmiä. Tarkempi tietoisuus aluksen sijainnista vertikaalisuunnassa mahdollistaisi väyläsyvyyden tehokkaamman käytön ja alusten suuremman lastinottokyvyn turvallisuutta vaarantamatta. Erilaisten avustejärjestelmien käyttö lisää satelliittinavigoinnin tarkkuutta varsinkin dynaamisissa olosuhteissa.

Korjaustietoja voidaan tuottaa eri tavoilla riippuen siitä, kuinka laajalla maantieteellisellä alueella niitä on tarkoitus hyödyntää. Euroopassa on käytössä koko EU alueen kattava julkinen EGNOS -palvelu, joka tarjoaa korjaustietoja GPS järjestelmän tueksi. Korjaustiedot lähetetään geostationääristen satelliittien kautta. Lisäksi Galileo -järjestelmän satelliittien kautta on tarkoitus tulevaisuudessa tarjota maailmanlaajuista tarkkuuspaikannuspalvelua. Palvelun avulla on tavoitteena tarjota alle 0.2 m paikannustarkkuus. Tarkkuuspaikannuspalveluita tarjoavat meriliikenteen käyttöön maailmanlaajuisesti myös useat kaupalliset toimijat.

Paikallisia satelliittinavigoinnin avustejärjestelmiä on Suomessa tarjolla useita. Koko Itämeren alueella on käytössä merenkulkua palveleva IALA Beacon DGNSS korjauslähetysjärjestelmä, jonka kautta alukset saavat ilmaiseksi GPS- järjestelmän tarkkuutta parantavia korjaustietoja. Lisäksi Suomen alueella FINPOS palvelu tarjoaa ilmaista korjaustietoa GPS ja GLONASS järjestelmille. Myös kaupallisia paikalliseen käyttöön soveltuvia satelliittinavigoinnin avustepalveluita on saatavilla.

Raportissa todetaan, että ehdoton edellytys turvallisen vesisyvyyden määrittämiseen satelliittinavigointijärjestelmien avulla on syvyysmittausten referenssitasojen vakiointi koko Itämeren alueella sekä niiden kiinnittäminen satelliittipaikannusjärjestelmien käyttämään referenssitasoon. Tähän liittyvät toimenpiteet ovat käynnissä ja tullaan saattamaan loppuun vuoteen 2030 mennessä. Varsinkin kaupalliset avustepalvelut mahdollistavat jo nyt erittäin tarkan korkeussuuntaisen paikanmäärityksen. Lähivuosina myös Galileo-järjestelmä tulee tarjoamaan maailmanlaajuisen, erittäin tarkan ilmaisen tarkkuuspaikannuspalvelun, joten tällä hetkellä ei nähdä tarvetta erilliselle paikalliselle tarkkuuspaikannuspalvelulle julkisena palveluna.

Afroza Khatun, Sarang Thombre, M. Zahidul H. Bhuiyan, Mirjam Bilker-Koivula, Hannu Koivula: Förstudie om användbarheten hos tekniker som baseras på satellitnavigationssystem för exakt höjdrelaterad positionsbestämning av fartyg i Finlands farvatten. Trafikledsverket. Helsingfors 2021. Trafikledsverkets publikationer 18/2021. 60 sidor. ISSN 2490-0745, ISBN 978-952-317-854-0.

Sammanfattning

Målsättningen med denna rapport är att med hjälp av en litteraturöversikt kartlägga olika stödsystem, baserade på satellitnavigationssystem, som möjliggör exakt höjdrelaterad positionsbestämning i Finlands farleder. Mer exakt kännedom om ett fartygs position i vertikalled skulle möjliggöra effektivare användning av farledsdjupet och större lastkapacitet hos fartyg utan att säkerheten äventyras. Användning av olika stödsystem ökar satellitnavigationens noggrannhet, i synnerhet under dynamiska förhållanden.

Korrigeringsinformation kan produceras på olika sätt, beroende på omfattningen hos det geografiska område där denna information är avsedd att användas. I Europa används en offentlig EGNOS-tjänst som täcker hela EU-området och tillhandahåller korrigeringsinformation som stöd för GPS-systemet. Korrigeringsinformationen sänds via geostationära satelliter. Dessutom är avsikten att i framtiden via Galileosystemets satelliter tillhandahålla en global tjänst för exakt positionsbestämning. Målet är att med hjälp av tjänsten tillhandahålla en positionsbestämningsnoggrannhet på mindre än 0,2 m. Tjänster för exakt positionsbestämning för sjöfartens användning globalt tillhandahålls också av flera kommersiella aktörer.

I Finland finns det flera lokala stödsystem för satellitnavigation. I hela Östersjöregionen används IALA Beacon DGNSS-systemet för korrigeringssändningar som betjänar sjöfarten, genom vilket fartyg får avgiftsfri korrigeringsinformation som förbättrar GPS-systemets noggrannhet. I Finland tillhandahåller dessutom FINPOS-tjänsten avgiftsfri korrigeringsinformation för GPS- och GLONASS-system. Kommersiella stödtjänster för satellitnavigation, lämpade för lokalt bruk, finns också tillgängliga.

I rapporten konstateras att en ovillkorlig förutsättning för att fastställa säkert vattendjup med hjälp av satellitnavigationssystem är standardisering av referensnivåerna för djupmätningar i hela Östersjöregionen samt att koppla dessa till den referensnivå som används av satellitbaserade positionsbestämningssystem. Åtgärder inom detta område pågår och kommer att vara slutförda senast 2030. I synnerhet kommersiella stödtjänster möjliggör redan nu en mycket exakt höjdrelaterad positionsbestämning. Under de närmaste åren kommer Galileosystemet också att tillhandahålla en global, avgiftsfri tjänst för mycket exakt positionsbestämning, så för närvarande finns det inget behov av någon separat lokal tjänst för exakt positionsbestämning som offentlig tjänst.

Foreword

Global Navigation Satellite Systems (GNSS) are widely used to support maritime transportation by providing accurate position and navigation information for vessels. Traditionally, GNSS is expected to provide the vessels with accurate horizontal position information (i.e. latitude and longitude) while the vertical component (i.e. vessels position in relation to the seabed) is provided by other means.

This report studies the preconditions and potential benefits of using GNSS based systems for providing vessels with accurate three-dimensional position information. It is expected, that accurate three-dimensional position, combined with accurate information on the depth profile of fairway's and seabed in general, would allow the better real-time monitoring of the vessel's draft, making it possible to maximize cargo to be carried, and to reduce the fuel consumption by choosing deep route alternatives. The report compares the expected performance of different existing and emerging GNSS augmentation systems and studies candidate communication links for the emerging systems.
The potential benefits of providing vessels with accurate three-dimensional position information were identified in the GNSS Deployment Action Plan published by the Ministry of Transport and Communications in 2018 (Efficient deployment of satellite navigation systems in Finland. Action plan 2017-2020, Publications 6/2018, ISBN 978-952-243-550-7). The Action Plan recommended 17 concrete measures to promote the deployment of satellite navigation. This report implements the action number 8 quoted bellow:

> *"Action 8. Examine how assist data enabling accurate vertical GNSS positioning can be relayed to ships in Finnish waters and the Baltic area reliably and without interruption. The Finnish Transport Agency is responsible for the measures. The NLS's Finnish Geospatial Research Institute supports the activities."*

The Finnish Geospatial Institute project team consisting of Afroza Khatun, Sarang Thombre, M. Zahidul H. Bhuiyan, Mirjam Bilker-Koivula and Hannu Koivula has been responsible for compiling the report. The work has been financed by the Finnish Transport Infrastructure Agency.

Helsinki April 2021

Finnish Transport Infrastructure Agency
Fairway Unit

Contents

Abbreviations and acronyms

4G	Fourth Generation
5G	Fifth Generation
AIS	Automatic Identification System
BDS	BeiDou Navigation Satellite System
BSCD	Baltic Sea Chart Datum
BTRF	BeiDou Terrestrial Reference Frame
CNR	Carrier to Noise Ratio
CORS	Continuously Operating Reference Station
CS	Commercial Service
DGNSS	Differential Global Navigation Satellite System
DGPS	Differential Global Positioning System
DORIS	Doppler Orbitography and Radiopositioning Integrated by Satellite
EDAS	EGNOS Data Access System
EGNOS	European Geostationary Navigation Overlay Service
EPN	EUREF Permanent GNSS Network
ESSP	European Satellite Services Provider
ETRF	European Terrestrial Reference Frame
ETRS	European Terrestrial Reference System
EU	European Union
EUREF	European Reference Frame
EUREF-FIN	European Reference Frame in Finland
EVRS	European Vertical Reference System
FAMOS	Finalising Surveys for the Baltic Motorways of the Sea
FEGNOS	Finland's EGNOS Monitoring and Performance Evaluation
FinnRef	Finnish Permanent GNSS Network
FMI	Finnish Meteorological Institute
FOC	Final Operational Capability
FRP	Federal Radionavigation Plan
GBAS	Ground-Based Augmentation System
GEO	Geostationary Earth Orbit
GI	Geospatial Information
GLONASS	GLObal NAvigation Satellite System
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GSA	European GNSS Agency
GTRF	Galileo Terrestrial Reference Frame
HAS	High Accuracy Service
HF	High Frequency
HPE	Horizontal Position Error
IALA	International Association of Marine Aids to Navigation and Lighthouse Authorities
IEEE	Institute of Electrical and Electronics Engineers
IGS	International GNSS Service
IHO	International Hydrographic Organization
IMO	International Maritime Organization
IMU	Inertial Measurement Units
INSPIRE	Infrastructure for Spatial Information in Europe
IOC	Initial Operational Capability
IP	Internet Protocol

ITRF	International Terrestrial Reference Frame
ITRS	International Terrestrial Reference System
ITU	International Telecommunication Union
JPL	Jet Propulsion Laboratory
KKJ	Kartastokoordinaattijärjestelmä (Finnish coordinate system)
LEO	Low Earth Orbit
LTE	Long Term Evolution
LWL	Low Water Level
MARUSE	Maritime User Segment
MLLW	Mean Lower Low Water
MRCP	Maritime Radio Communication Plan
MSAS	Multi-functional Satellite Augmentation System
MSL	Mean Sea Level
MSM	Multiple Signal Messages
MW	Mean Water
NAP	Normal Amsterdams Peil
NAVDAT	Navigational Data
NAVTEX	Navigational Telex
NEMO	Navigation system analysis for European Maritime Operations
NLS	National Land Survey of Finland
NM	Nautical Mile
NMEA	National Marine Electronics Association
NN	Normaali Nolla (Finnish height system)
NTRIP	Networked Transport of RTCM via Internet Protocol
OS	Open Service
PPP	Precise Point Positioning
PSSA	Particularly Sensitive Sea Area
PZ	Parameters of the Earth
QZSS	Quasi-Zenith Satellite System
RIMS	Ranging Integrity Monitoring Stations
RMS	Root Mean Square
RTCA	Radio Technical Commission for Aeronautics
RTCM	Radio Technical Commission for Maritime Services
RTK	Real-time Kinematic
SBAS	Satellite-Based Augmentation System
SDCM	System for Differential Corrections and Monitoring
SIS	Signal In Space
SISNet	Signal In Space through the Internet
SLR	Satellite Laser Ranging
SOLAS	Safety of Life at Sea
SSR	State Space Representation
STD	Standard Deviation
TEC	Total Electron Content
TEU	Twenty-foot Equivalent Unit
THU	Total Horizontal Uncertainty
UKC	Under Keel Clearance
URA	User Range Accuracy
US	United States
VDES	VHF Data Exchange System
VDES ASM	VDES Application Specific Messages frequencies
VDES VDE	VDES VHF Data Exchange frequencies
VHF	Very High Frequency
VLBI	Very Long Baseline Interferometry

VPE	Vertical Position Error
VRS	Virtual Reference Station
WAAS	Wide Area Augmentation System
WGS	World Geodetic System

1 Introduction

1.1 Background

The maritime community was one of the first that recognized and exploited the opportunities and advantages provided by Global Navigation Satellite Systems (GNSS) for navigation and positioning. In fact, the introduction of GNSS represented a great revolution in the maritime field. GNSS positioning has progressively acquired more and more relevance in almost all vessels sailing around the globe. American Global Positioning System (GPS) and Russian GLObal NAvigation Satellite System (GLONASS) have been in service for years, but they are being complemented by new systems like the European Global Satellite Navigation System (Galileo) and the Chinese BeiDou Navigation Satellite System (BDS). Especially in combination, these systems are expected to provide unprecedented accuracy and availability of positioning.

Maritime navigation, especially in the coastal areas and in port approaches, will be the high priority for this report. The position of a vessel with high accuracy, especially on the height component, will have significant impact in estimating the under keel clearance (UKC) for vessels. Having better knowledge and control of the 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 vessel 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 a rough estimate. Consequently, the UKC is known but with wide uncertainty and therefore a significant height buffer has to be reserved. In other words, the vessel cannot be loaded to the theoretical maximum capacity while hoping to maintain the desired level of safety.

A more scientific method is needed to reduce the uncertainty in the real-time height estimation of the vessel. GNSS has been used mostly for accurate determination of the vessel position in the horizontal plane. Its benefits in accurate and real-time height estimation have not received comparable appreciation. This report performs 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 information. Secondly, this study also discusses the continued significance of the coordinate and reference frames to height estimation in this context.

1.2 Structure of the document

The document is structured as follows: **Section 2** discusses the role of GNSS in the maritime domain. Its technical benefits, which form a justification for the continued and improving penetration in the maritime market segment are introduced. **Section 3** summarizes the operational and end-user requirements concerning height estimation in the maritime domain as set by national and international agencies such as the International Maritime Organization (IMO). **Section 4** deals with a discussion on the rationale for exploiting GNSS for accurate height estimation in vessels. **Section 5** discusses the core content of the document. The different techniques for height computation using GNSS are presented. This section concludes with a comparative table showing the expected performance of height estimation using the different solutions described earlier. **Section 6** discusses different communication links for transmitting the augmentation information to vessels. It also discusses the different augmentation system types and correction message standards. **Section 7** is dedicated to a discussion about coordinate and height reference frames in navigation. The section concludes with a discussion about the feasibility of utilizing the existing Radio Technical Commission for Maritime Services (RTCM) standard for providing users with transformation data between the different coordinate frames. **Section 8** provides conclusions, recommendations, and brief overview of future steps in order to realize these recommendations.

2 Role of GNSS in the Maritime Domain

2.1 Penetration in the maritime market segment

The European GNSS Agency (GSA) has recently released the sixth (2019) edition of its popular GNSS Market Report /1/. In these reports the GSA defines the historical, current, and expected future trends in the penetration of GNSS-based localization in different commercial market segments. One of these is the maritime market segment. According to the GSA report, the maritime segment itself can be further categorized into up to nine application areas. Of these two areas are of particular importance to this study, collision avoidance (for safety, and including avoiding collisions with underwater features) and merchant navigation. Figure 1 shows the trends in the number of GNSS-enabled devices used in the maritime domain during a 20-year period between 2008 and 2029.

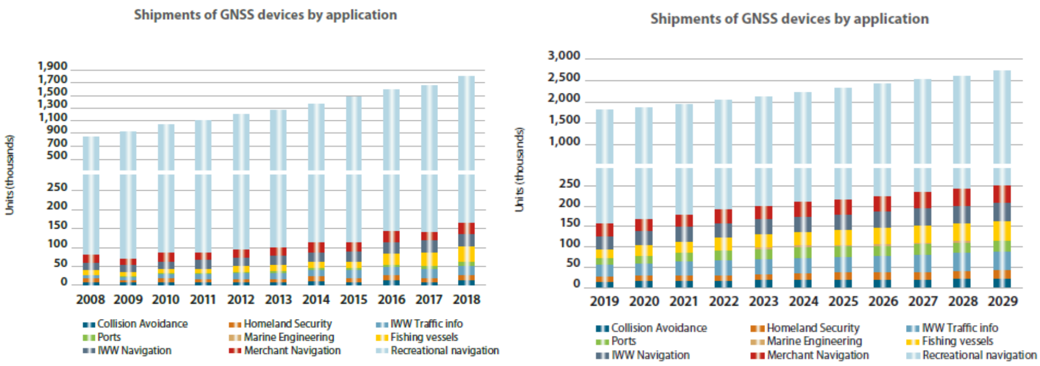

Figure 1. GNSS device penetration in the maritime market segment by application. Left: historical trend from the last 10 years. Right: Expected market evolution during the next 10 years /1/.

The Figure 1 shows that recreational navigation continues to be the dominant application area for GNSS in the maritime segment. The collision avoidance and merchant navigation are roughly equivalent to each of the other application areas, resulting in a combined total of approximately 75-100 thousand units per annum by the end of the next decade. Furthermore, if the benefits of GNSS-enabled height determination can be demonstrated over the traditional methods, a new rationale for even wider exploitation of GNSS in the maritime domain can be expected.

2.2 Main use cases

According to the distinction provided by IMO Resolution A.915 (22) /2/, use of GNSS in maritime can be split into two main categories: general navigation and positioning applications.

2.2.1 General navigation

GNSS has become a fundamental component of navigation by vessels of different classes from commercial ships to leisure boats. Practically all vessels regulated by IMO's Safety of Life at Sea (SOLAS) convention are required to carry a GNSS receiver (or other means which enable them to establish and update the vessel's position by automatic means throughout the intended voyage). GNSS is also widely used to ensure safe navigation in inland waterways, for example, rivers, canals, lakes and estuaries.

2.2.2 Positioning applications

Resolution A.915 (22) /2/ defines also wide variety of maritime positioning applications where GNSS can be used. Some of these are listed below:

- Port operations
- Traffic management
- Search and Rescue
- Fisheries monitoring
- Marine engineering
- Aids to Navigation Management
- Hydrography

2.3 Concept of Under Keel Clearance

GNSS plays a key role in the navigation of vessels by providing positioning information such that the vessel can navigate safely in fairways and port areas, stay on a predetermined route and dock at the destination harbour. Safe navigation includes ensuring that there is sufficient amount of water under the vessel's keel for the safe passage of the vessel throughout the whole voyage.

The distance between the lowest point of vessel's keel and the highest point of channel bottom is called under keel clearance (UKC). It is the master's responsibility to estimate the required minimum safe UKC for the entire voyage from berth to berth and to monitor that the safe UKC is maintained throughout the whole voyage /3/. There are many water level, vessel and sea bottom related factors that influence the estimation of the minimum safe UKC. A general summary of these factors is shown in Figure 2 /3/.

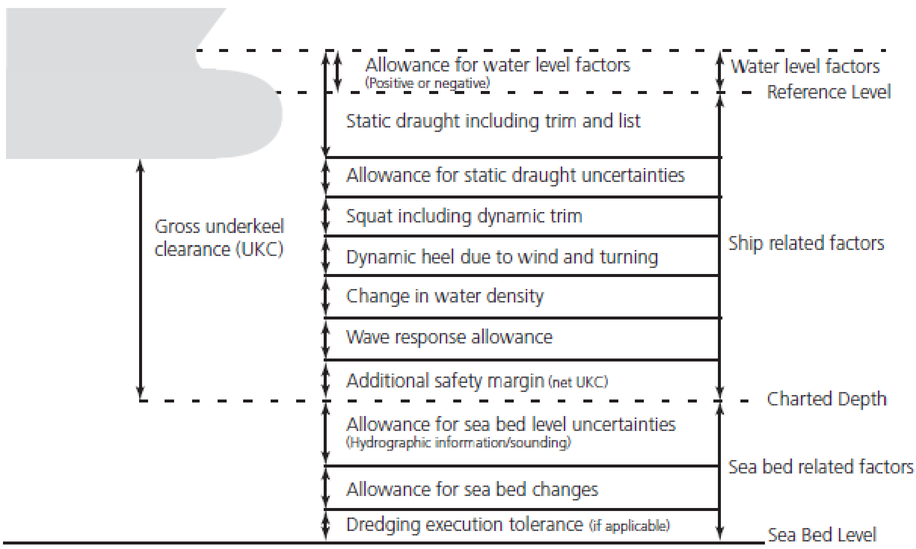

Figure 2. Factors that influence the safe UKC of a vessel /3/.

To calculate a reliable UKC, exact values are needed in at least the following aspects /4/:

- Water depth
- Zero level for water depth measurements
- The vessel's vertical position
- Pre-calculated level of water surface at sea

The geodetic chart datum includes the essential information of the water depth, mean sea level, etc. The research conducted in the EU funded FAMOS project testified that with an accurate geodetic chart datum it is straightforward 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 Figure 3.

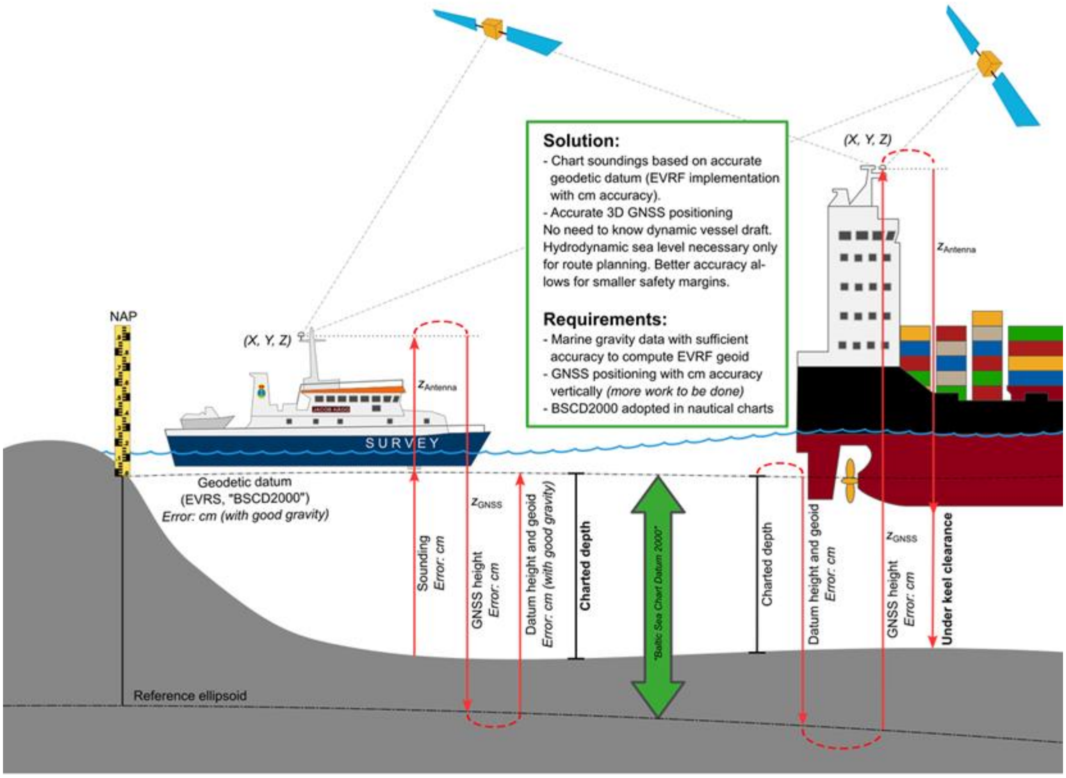

Figure 3. UKC derived from height measurement obtained by the vessel's satellite positioning system /4/.

One important precondition for determination of a vessel's vertical position using satellites, is that the vertical reference level in nautical charts is well established. Today in the Baltic Sea, a multitude of Mean Sea Level (MSL) based chart reference levels are used simultaneously. This complicates navigation, but more importantly it makes it difficult to reference the vertical aspect of a position obtained from GNSS to the soundings in the charts. Therefore, presently, the calculation of the exact actual UKC is rather cumbersome, if possible at all.

A well-defined geodetic vertical reference level that relates to GNSS coordinates, simplifies the production of uniform nautical charts. Furthermore, it enables the calculation of a vessel's vertical position in relation to the sea floor from GNSS measurements. Thereby it makes it possible to navigate with improved UKC awareness based on vessel's vertical position and reliable depth calculations. Ideally, this would enable the vessel to navigate safely without knowing the dynamic vessel draft or the prevailing water level. Accurate water level forecasts would still be needed during the voyage planning, but the real-time water level information could be replaced or verified and guaranteed with information on vessel's accurate vertical position.

3 Operational requirements for position accuracy

IMO is setting the global regulatory framework for the shipping industry, including performance requirements for GNSS /2/ and for worldwide radionavigation system in general /5/. IMO defines minimum operational user requirements for GNSS accuracy, integrity, continuity, availability and coverage. 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 and vertical accuracy requirements are not usually considered at all. Although the focus of this report is on the accuracy of the height component, the main findings corresponding to both horizontal and vertical accuracy are summarized in the following subsections.

3.1 Horizontal accuracy

The main findings corresponding to horizontal accuracy requirements (for SOLAS navigation) are summarized in Table 1. This table was initially published in GSA's report /6/. It compares the requirements from the IMO, the MARUSE project, the US Federal Radionavigation Plan (FRP), and the International Hydro-graphic Organization (IHO). The values in red correspond to those accuracy values which were validated as part of the GSA User Consultation Platform.

Table 1. Comparison of IMO, MARUSE, FRP and IHO horizontal accuracy requirements for general navigation /6/.

Phase of Navigation	IMO [m]	MARUSE [m]	FRP [m]	IHO [m]**
Ocean	10- 100	10	1800-3700	30-420
Coastal	10	10	460	5-10
Port approach and restricted waters	10	10	8- 20*	5-10
Port	1	1	-	2
Inland waterways	10	3	2-5	2

* Varies from one harbour to another
** IHO quoted accuracy is "Maximum allowable Total Horizontal Uncertainty" at 95%

3.1.1 IHO vs. IMO accuracy requirements

IHO's role is to ensure that world's seas, oceans and navigable waters are surveyed and charted. The IHO and IMO horizontal accuracy requirements are compared in more detail in Table 2 /6/. It should be noted that IHO deals with the accuracy of nautical charts, which should be better than vessel's positioning accuracy and which is an input rather than a user requirement.

Table 2. Comparison of IHO and IMO accuracy requirements /6/.

IHO Description of areas	Areas where under-keel clearance is critical	Areas shallower than 100 meters where under-keel clearance is less critical but features of concern to surface shipping may exist	Areas shallower than 100 meters where under-keel clearance is not considered to be an issue for the type of surface shipping expected to transit the area	Areas generally deeper than 100 meters where a general description of the sea floor is considered adequate
Interpretation	Shallow waters such as encountered in Ports, Inland Waterways and possibly Port Approaches	Continental shelf, such as encountered for Coastal navigation and Port Approaches	Continental shelf such as encountered for Coastal navigation and Port Approaches (low SOLAS traffic area)	Beyond continental shelf, i.e. mostly abyssal plain (depth averaged at 4000 meters); such as encountered in Oceanic navigation
IMO phase of navigation	Ports Inland waterways (Port approaches)	Coastal navigation Port Approaches	Coastal navigation Port Approaches	Ocean
IMO accuracy requirement	1 m 10 m*	10 m	10 m	10-100 m
IHO accuracy requirement (most stringent)	2 m	2 m	2 m	5 m
IHO Maximum allowable THU**	2 m	5 to 10 m (5 m + 5% of depth)	5 to 10 m (5 m + 5% of depth)	30 to 420 m (20 m + 10% of depth)
Comments	IMO accuracy requirements for port navigation are more stringent than IHO's	Consistent	Consistent	Except for isolated hazards to navigation, the IMO "en-route" accuracy requirements are more stringent than IHO's

* For inland waterways and port approaches
** Total Horizontal Uncertainty

From Table 1 and Table 2 it can be observed that the most stringent requirement for horizontal accuracy is 1 m. This requirement is applicable for scenarios involving port operations of the vessel.

3.2 Vertical accuracy

IMO does not define any requirements for vertical accuracy related to general navigation. However, IMO /2/ identifies user requirements for vertical accuracy related to some positioning applications as presented in Table 3.

Table 3. The minimum maritime vertical accuracy requirements for positioning applications /2/.

Phases	**Horizontal [m]**	**Vertical [m]**
Hydrography	1-2	0.1
Oceanography	10	10
Marine engineering, construction, maintenance and management (absolute accuracy)		
- Dredging	0.1	0.1
- Construction works	0.1	0.1
Port operations (absolute accuracy)		
- Container/cargo management	1	1
- Law enforcement	1	1
- Cargo handling	0.1	0.1
Offshore exploration and exploitation (absolute accuracy)		
- Support to production	1	N/A*
- Post-production	1	N/A*

* A vertical accuracy of a few cm (less than 10) is necessary to monitor platform subsidence

From Table 3 it can be observed that the most stringent accuracy requirement for vessel height estimation is 0.1 m. This requirement is applicable for scenarios related to hydrography, dredging and maritime construction works.

4 Expected benefits of accurate height estimation

It is expected that the better knowledge and control of the real time UKC of a vessel would result in increased navigational safety, fuel efficiency, and cargo optimization (i.e. full utilization of the vessel's draft). However, it is to be noted that in addition to accurate real time UKC awareness there are also other factors that affect vessels actual draft. During its journey, vessel may load and unload cargo in different ports and use fairways with different depths. Consequently, many decisions that affect the vessel's draft and the safe UKC needs to be taken already in advance based on estimated water levels along the planned routes.

4.1 Economical end environmental benefits

It is clear from the Section 2 that the accuracy of estimating the UKC is directly influenced by the accuracy of vessel height estimation. Thus, improvement of every inch in the accuracy improves the reliability of the UKC estimate and reduces the amount of reserve clearance that needs to be reserved. This brings economic benefits to the shipping company by allowing the vessel to carry more cargo in a single trip. For example, the US National Ocean Service /7/ reported how much cargo a vessel can carry and what its worth with one more inch of exploitable depth in a port, as illustrated in Figure 4.

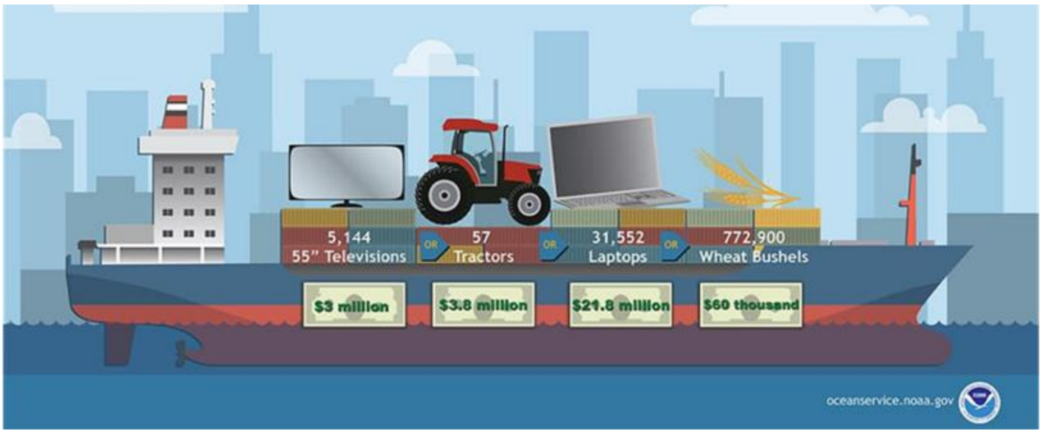

Figure 4. Economic benefit with one more inch of vessel draft in a port /7/.

The guideline for evaluation of fairway investment projects /8/ and the report on average operating costs of vessels /9/ published by the Finnish Transport Infrastructure Agency also give some estimations on the economic and environmental benefits of increasing the vessel draft.

Vessel's total operating cost per day is a sum of fixed cost components (e.g. crew, service/maintenance, insurance) and fuel cost /9/. The value of all operating cost components increase with the size (i.e. draft) of the vessel. However, the vessels with larger draft have better cost efficiency (i.e. cost per carried cargo unit). Figure 5 shows the estimated daily operating costs per tons or TEUs of cargo for different vessel types (during voyage in the sea). The cost efficiency gained by size is partly lost if the vessel's draft cannot be fully utilized.

The total monetary amount of economic benefit gained will depend on type of the cargo as indicated in Figure 4.

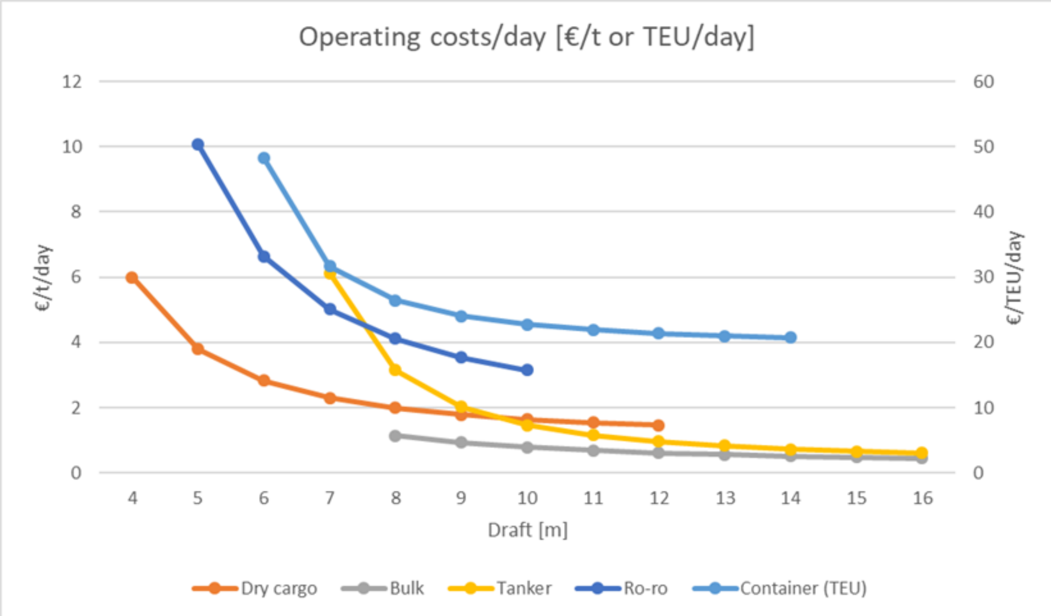

Figure 5. Average daily operating costs per tons/TEUs by vessel type /9/.

The economic and social benefits of improved UKC awareness also include more efficient pilotage in ports and harbours, lower average annual cost of downtime from accidents, lower average costs of oil spills and support for trade conveyed by shipping through environmentally sensitive areas. The Baltic Sea, for example, is a sensitive environment and challenging to navigate due to its land uplift and the incomplete water depth mapping. It is classed as a Particularly Sensitive Sea Area (PSSA) by IMO /10/. Vessels need additional safety margin due to the uncertainties in water depth levels in the Baltic Sea that leads to inefficient maritime traffic. There is a significant potential in vessels navigating with better UKC awareness, which can allow slightly deeper drafts for the vessel. The work conducted in FAMOS Odin project has shown that most of these challenges can be solved with the accurate and reliable GNSS positioning /4/.

If vessels are able to use their full capacity (i.e. draft) the same amount of cargo can be transported with less voyages and port visits leading to clear economical savings but also to less harmful emissions and less load to marine environment.

4.2 Areas of interest

Vessels would benefit from accurate UKC information in the whole Baltic Sea area but especially in restricted waters (fairways, port approaches and ports). In Finland, the fairways used by merchant vessels cover almost the whole coastline stretching around 30-50km (16-27NM) off the coast. These fairways are marked with red colour in Figure 6 and they are the primary interest areas for the accurate vessel height information.

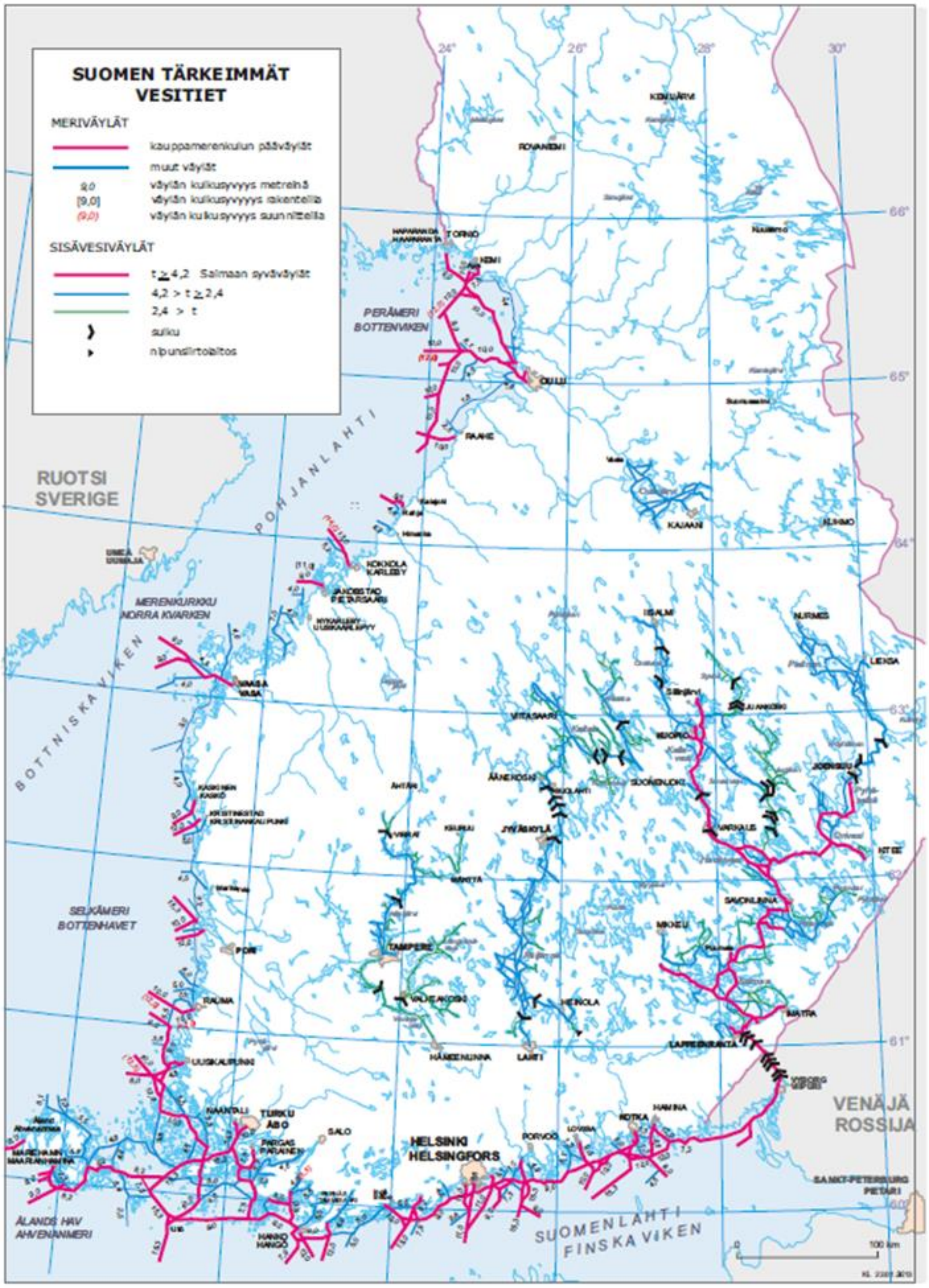

Figure 6. Finnish fairways.

5 Expected performances of height estimation

In this section, at first the baseline performance using GNSS-only to provide the vessel vertical position is presented. Then the performance assessment with different augmentation solutions is provided. Finally, a comparison of the height estimation performance between the different services is discussed as a summary of the section.

The experimental results presented in Sections 5.1, 5.4.1.1 and 5.4.1.2 are based on two test campaigns performed under the EU funded FAMOS Odin project. The tests were carried out in two different campaigns in June 2017 and in May 2018. In 2017, measurements were carried out on the research vessel Aranda of the Finnish Environment Research Institute /11/ between the 5th and 10th of June. During the campaign, the vessel operated in the Gulf of Bothnia and in the western part of the Gulf of Finland. The second campaign took place during a dedicated gravity campaign on board of the research vessel Geomari /12/ of the Finnish Geological Survey between the 21st and 25th of May 2018. During the campaign the vessel operated in the Eastern part of the Gulf of Finland. The measurement vessels and routes of both campaigns are presented in Figure 7 and the measurement and recording equipment is shown in Figure 8.

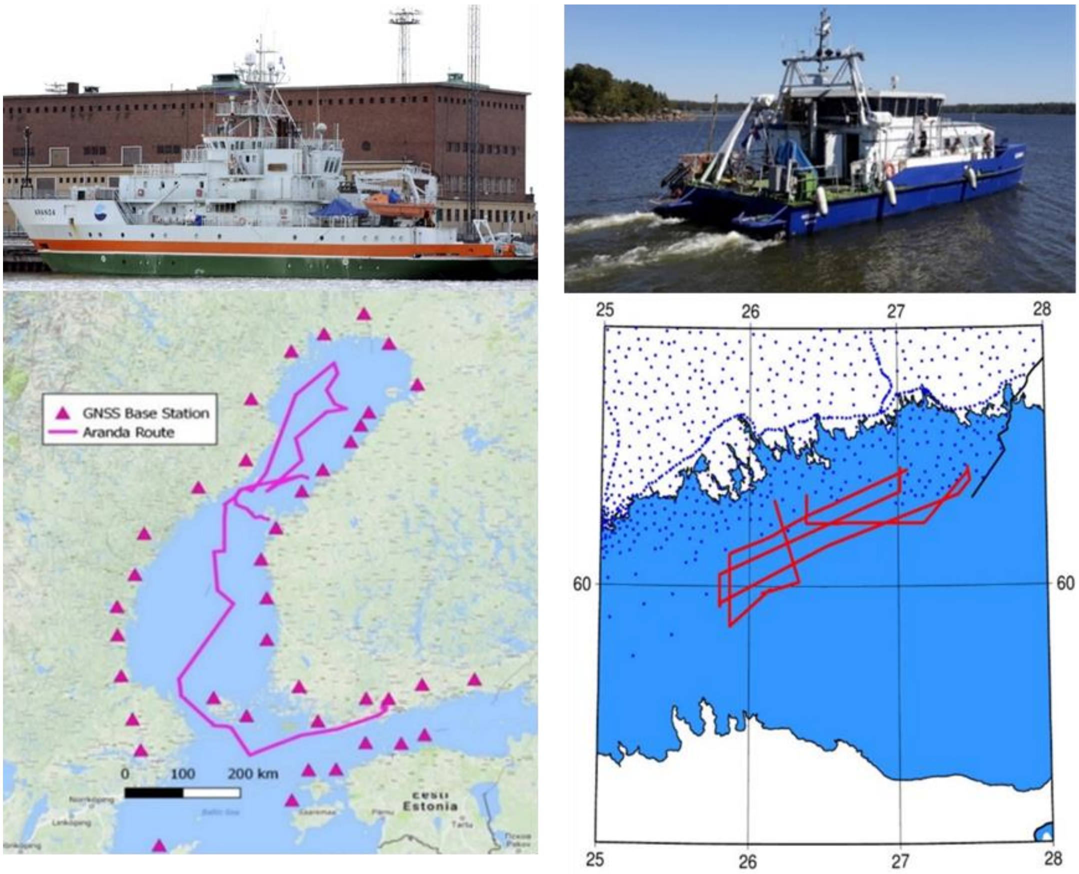

Figure 7. Aranda (left) and Geomari (right) test campaigns in the Gulf of Finland and Gulf of Bothnia as part of the FAMOS Odin project /4/.

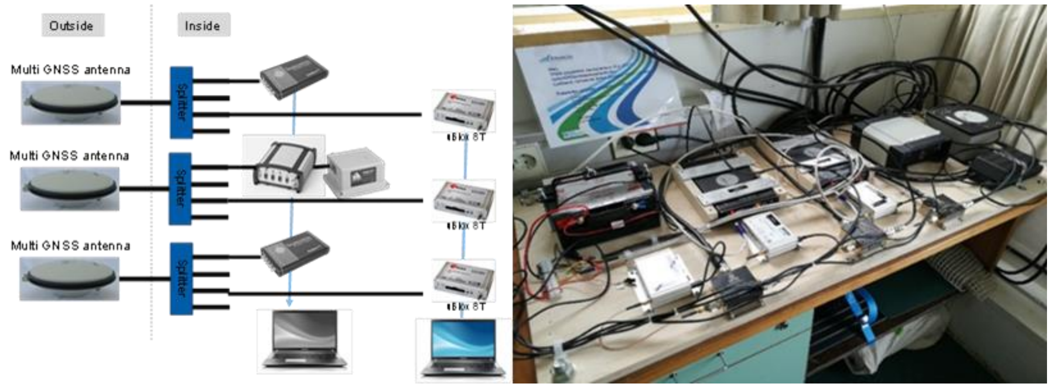

Figure 8. Schematic overview of the measurement and recording equipment installed on the vessels (left), and actual photo of the GNSS receivers and Inertial Measurement Units (right).

5.1 Baseline GNSS-only performance

Unfortunately, no references addressing the expected performance of GNSS-only height estimation in the maritime domain were found during the background literature study. However, two example references addressing horizontal GNSS-only accuracy, especially in the European maritime area were found, and are described in Appendix 1.

Baseline GPS-only results from the FAMOS Odin project are presented in Table 4 and Table 5. These provide the accuracy of the vertical (height) estimation values for the GPS-only solution using a mass-market receiver and a survey-grade receiver.

Table 4. The accuracy of height estimation for the GPS-only solution. FAMOS-Odin, June 2017 /4/.

Date	Receiver	90% spread [m]	Offset [m]	Average no. of satellites
5.-10.6.2017	Mass-market	7.3	19.7	9.7
5.-10.6.2017	Survey grade	6.9	19.1	10.3

Table 5. The accuracy of height estimation for the GPS-only solution. FAMOS-Odin, May 2018 /4/.

Date	Receiver	90 % spread [m]	Offset [m]	Average no. of satellites
21.5.2018	Mass-market	8.8	19.8	10.3
22.5.2018	Mass-market	8.0	21.2	10.6
23.5.2018	Mass-market	5.8	18.1	10.0
24.5.2018	Mass-market	5.5	17.9	10.1
25.5.2018	Mass-market	4.3	18.0	10.5
21.5.2018	Survey grade	6.1	16.0	9.6
22.5.2018	Survey grade	5.1	17.6	10.1
23.5.2018	Survey grade	5.7	18.1	10.0
24.5.2018	Survey grade	4.5	17.8	10.1
25.5.2018	Survey grade	4.0	17.9	10.8

GPS-only vertical errors are high because no ionospheric correction has been applied in the navigation solution. The 90% spread in the tables 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 satellites used for position solution are also provided in the tables.

5.2 Role of ship-based inertial sensors

Inertial Measurement Units (IMU), containing accelerometers and gyroscopes, are used to complement GNSS receiver-based positioning solutions under high dynamic conditions. Therefore, integration with IMUs help to provide better real-time trajectory information. They are able to detect the vessel displacement in terms of roll, pitch, and yaw angles caused by the environmental (sea and wind) conditions. A second benefit is to accurately determine the vessel heave, i.e. the displacement in the vertical direction due to sea waves. Figure 9 explains the terms used for describing the vessel displacement /13/.

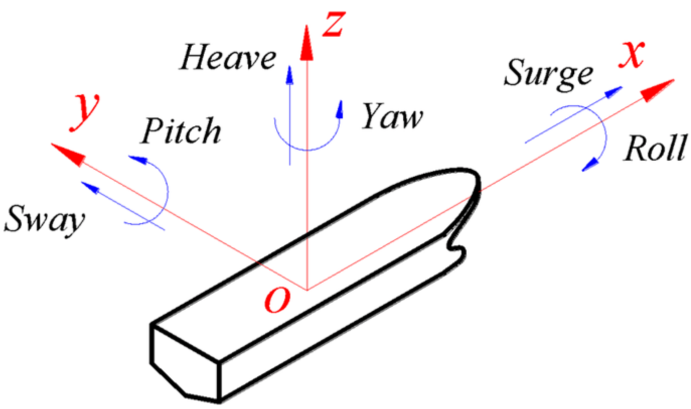

Figure 9. The six degrees of freedom for vessel displacement /13/.

These angular variations may result in quite significant degradation in the dynamic UKC /14/ even though the position of the vessel as a whole may be unaltered with a certain Mean Lower Low Water (MLLW) level. This phenomenon is depicted in Figure 10 /15/ and Figure 11 /16/.

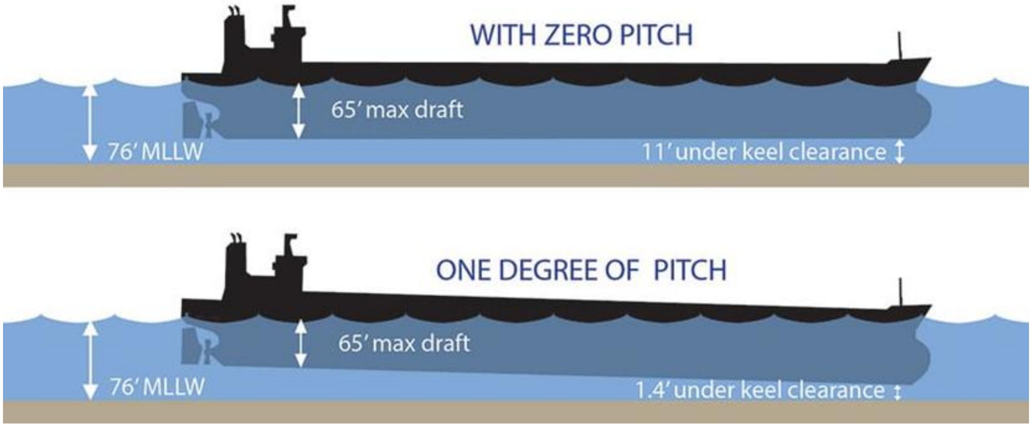

Figure 10. The effect of one-degree pitch on the UKC /15/.

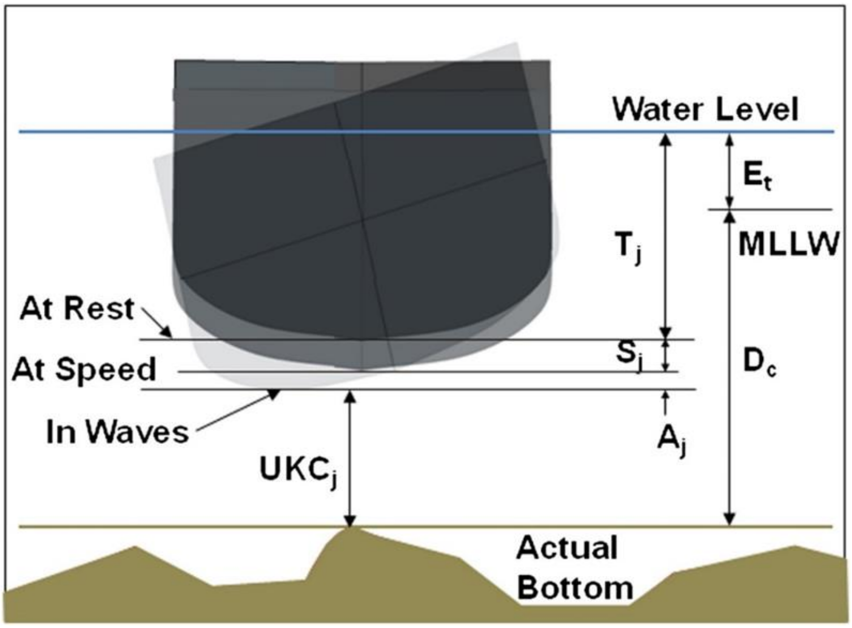

Figure 11. The effect of vessel roll, heave and squat on the UKC /16/. (T=static draft, S=squat, A=vertical motion allowance, D=nominal channel depth at MLLW, E=water level variation relative to MLLW).

There is considerable published material available describing the benefits of IMUs to vessel navigation. For this report, two academic and two industrial references has been chosen as representative background literature. Figuero et al. /17/ describe an inertial measurement unit to determine accurately movements experienced by moored vessels inside ports. It studies the effect of wave heights on the variations in the pitch, roll, and yaw angles as recorded by the on-board IMU. Auestad et al. /18/ have estimated in meters the effect of the heave motion due to surface waves using an IMU. The heave motion is shown to be differently manifested at different points of the vessel, with the bow experiencing higher displacement as compared to amidships.

iMEMS Tecnology has an IMU specially designed for maritime applications, in particular to estimate the roll, pitch, and yaw angles, and the heave of the vessel /19/. The heave measurements help in accurate and real-time estimation of the vertical motion of the vessel. The manufacturer states that the accuracy of heave measurements is up to 5 cm or 5% with maximum wave height of 10 m. Also SMC, Ship Motion Control, offers heave motion IMU sensors, which are stated to be capable of providing similar accuracy levels (5 cm or 5%) /20/. It is to be noted that these accuracy values are just for the heave measurement by the sensor, and do not indicate the accuracy of the vessel height as a whole.

Integrating IMU sensor units with the on-board GNSS receiver will help to determine the real-time UKC accurately, taking into account also the vessel angular displacement in the different degrees of freedom (Figure 9). Although an IMU contributes to the accurate estimation of the UKC, it is essentially a ship-side sensor. As the focus of this report is on external augmentation that could be provided to assist the GNSS-based height estimation of the vessel, the case of inertial sensors is not considered further.

5.3 Galileo High Accuracy Service

EU has recently decided to provide free access to the high precision positioning service provided via Galileo satellites (Galileo High Accuracy Service, HAS). The service was originally planned to be a commercial service (CS) with fee-paying access and several service providers but is now part of the free offerings from the European Galileo satellite navigation system /21/. The signal will be broadcast from Galileo satellites on the E6 band at a carrier frequency of 1278.75 MHz and it will provide users with augmentation data (i.e. satellite orbit and clock corrections) to improve accuracy via Precise Point Positioning (PPP) technique /22/. The benefit of PPP is that it provides a global augmentation service without requiring a very dense network of permanent reference stations to generate the augmentation data.

In future it is possible that the HAS will also include information to compensate for the ionosphere delay /23/. The provision of ionosphere delay information will be especially crucial to improve accuracy of height estimation.

It is currently planned that the Galileo HAS initial operational capability (IOC) would be available during 2021 and full operational capability (FOC) during 2023. EU has tentatively announced that positioning error obtained using Galileo HAS service is less than 20 cm /21/. According to some estimations this target might be achieved only for horizontal accuracy while the vertical accuracy provided by Galileo HAS could be expected to be better than 40 cm /24/. However, no real signals are yet available to validate the accuracy experientially.

5.4 Local area augmentation services

Local area augmentation systems for maritime use have been in development since the nineties to fulfil IMO requirements on GNSS based positioning in coastal areas. The differential GNSS (DGNSS) augmentation systems are based on reference stations, at precisely known locations, which generate real-time correction and integrity information for GNSS signals. Because the local augmentation services mainly use terrestrial communication links such as dedicated radio frequencies or mobile internet connection to provide the augmentation data to the users they are also called Ground Based Augmentation Systems (GBAS). Two types of GBAS services are available in Finland: public GBAS services and commercial GBAS services.

5.4.1 Public services

The public GBAS services are provided free of charge, using internationally standardised technologies and message types. Generally, this type of services are supported by wide range of GNSS receivers by different manufacturers. The IALA Beacon DGNSS service, harmonized by the International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA) and especially targeted to maritime users, covers the whole Baltic Sea including all the Finnish sea areas and the lake Saimaa area. In addition, the public FINPOS service provided by National Land Survey (NLS) provides DGNSS corrections that could be utilized in vessel navigation in Finland.

5.4.1.1 IALA Beacon DGNSS Service

A standardized maritime DGNSS service, called the IALA Beacon DGNSS, is operational in many of the most significant coastal waters throughout the world and is available free-of-charge at the point of delivery /25/. The service provides pseudo-range corrections to GPS and/or GLONASS constellations using standard RTCM messages and dedicated radiofrequencies assigned by the International Telecommunication Union (ITU). Sections 6.1.1, 6.2.1 and 6.3.1 provide some more information about the technology used.

In Finland there are nine IALA Beacon DGPS broadcasting stations, which provide GPS correction and integrity data for Finnish sea areas and for the lake Saimaa area. In sea areas, the service is complemented by transmissions from Swedish, Estonian and Russian DGNSS stations. The Finnish service does not provide corrections for GLONASS but these are available in the eastern part of Gulf of Finland provided by the Russian DGNSS broadcasting stations. The horizontal positioning accuracy obtained with the service is guaranteed to be better than 10 m with 95% confidence /26/. There is no information publicly available about the expected accuracy performance of the height estimation, but the long-time recordings of service performance indicate that the vertical accuracy achieved is slightly worse than the horizontal accuracy.

Fairbanks et al. /27/ and Christiansen et al. /28/ estimate the performance of the IALA Beacon DGNSS service in European maritime area as simulated by the NEMO software tool. Based on the simulation the horizontal accuracy (95%) achieved within the coverage area of the beacons is within the approximate range of 0.6 m to 2.5 m whereas the vertical accuracy (95%) achieved under the same coverage area is within the approximate range of 0.8 to 2.5 m.

However, the field measurements in dynamic conditions carried out during FAMOS Odin project and reported by Koivisto /29/ showed horizontal accuracies better than 3.7 m (95%) and vertical accuracies better than 5.5m (95%). These values are within the guaranteed performance but exceed the estimated performance values.

5.4.1.2 FINPOS DGNSS service

FINPOS DGNSS offers augmentation data for GPS and GLONASS constellations utilizing information from the Finnish Permanent GNSS Network (FinnRef) /30/. Galileo will also be supported in the future. FinnRef network is a large governmental investment and it offers DGNSS service free of charge. Service is accessed via internet and it provides differential corrections using standard

RTCM protocol and messages. Sections 6.1.1, 6.2.1 and 6.3.3 provide some more information about the service technology.

The current FinnRef network, as seen in Figure 12, consists of 47 Continuously Operating Reference Stations (CORS) deployed on stable bedrock in Finland. Marila et al. showed that FINPOS DGNSS service can provide 0.5-0.7 m (95%) vertical accuracy in good static conditions and 0.5-3.6 m (95%) vertical accuracy in dynamic conditions /31/. These measurements validated the performance in different road environments but did not extend to sea areas.

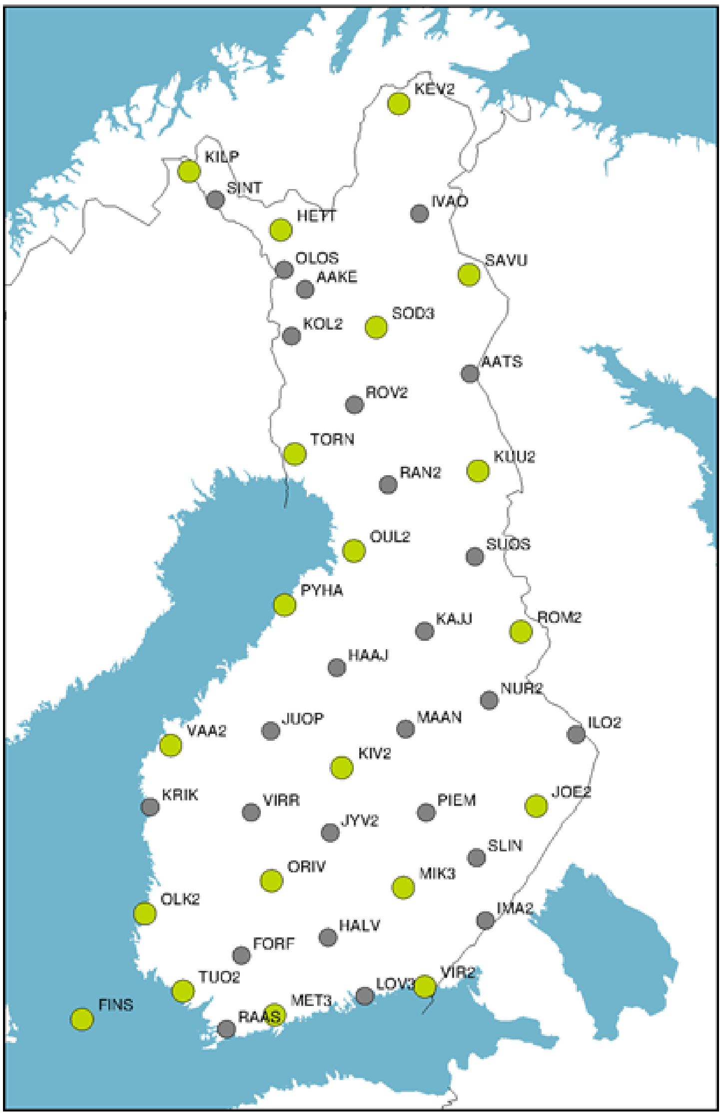

Figure 12. The Finnish Permanent GNSS Network /32/.

FinnRef network can provide accurate augmentation also for research purposes. In FAMOS Odin project /4/ FinnRef was used together with Swedish and Estonian permanent networks to create State Space Representation (SSR) corrections for maritime tests. The project presented results with PPP (GPS L1 code only) using the SSR correction model. The tests were part of the same FAMOS Odin measurement campaign described earlier in this document. The accuracy of height estimation values obtained from the experimentation are presented in Table 6 and Table 7.

Table 6. The accuracy of height estimation using FINPOS, SWEPOS, and ESTPOS PPP-SSR service. FAMOS Odin, June 2017 /4/.

Date	Receiver	90 % spread [m]	Offset [m]	Average no. of satellites
5.-10.6.2017	Mass-market	5.2	2.2	7.6
5.-10.6.2017	Survey grade	3.2	1.6	8.2

Table 7. The accuracy of height estimation using FINPOS, SWEPOS, and ESTPOS PPP-SSR service. FAMOS Odin, May 2018 /4/.

Date	Receiver	90 % spread [m]	Offset [m]	Average no. of satellites
21.5.2018	Mass-market	1.3	1.0	8.8
22.5.2018	Mass-market	1.5	1.2	9.1
23.5.2018	Mass-market	1.3	0.9	8.9
24.5.2018	Mass-market	1.4	1.0	9.3
25.5.2018	Mass-market	1.2	0.9	10.0
21.5.2018	Survey grade	1.5	0.4	9.1
22.5.2018	Survey grade	1.3	1.0	9.3
23.5.2018	Survey grade	1.2	0.8	9.2
24.5.2018	Survey grade	1.2	0.8	9.5
25.5.2018	Survey grade	1.3	0.6	10.2

The location of the central GNSS antenna was not optimal during June 2017 tests and SSR corrections where not available for all satellites resulting in relatively low number of satellite values. Overall, the noise presented was relatively large for the June 2017 test campaign, which may be caused by the ship's movements. This has resulted in lower accuracy values in Table 6.

5.4.2 Commercial services

In Finland, there are also some commercial GBAS services available, e.g. TrimNet, which is operated by Geotrim Oy /33/, and HxGN SmartNet, which is operated by Leica Geosystems Finland /34/. Both TrimNet and HxGN SmartNet networks have over 100 permanent GNSS stations in Finland as shown in Figure 13. They offer multiple services with different accuracy levels ranging from centimetre to sub-metre level. However, these services are not marketed primarily for maritime users. Koivula et al. tested both services and concluded that their vertical accuracy in static Real Time Kinematic (RTK) measurements is better than 5 cm (RMS) /35/.

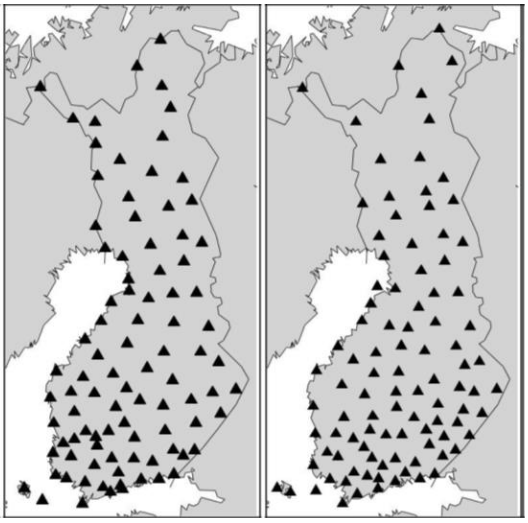

Figure 13. The TrimNet (left) and HxGN SmartNet (right) GNSS network in Finland /35/.

5.5 Wide area augmentation services

Wide area augmentation systems serve large geographical areas. They are based on network of reference stations located in the service area and the augmentation data is provided to users via geostationary (GEO) satellites. These systems are also called Satellite Based Augmentation services (SBAS). These services are beneficial when the vessels are in ocean areas and outside the range of any ground-based communication links. This does not restrict the application of SBAS services in coastal waters or inland waterways. The public and some commercial SBAS services, which can be utilized by vessels in Europe are presented in the following sections.

5.5.1 Public service - EGNOS

The European Geostationary Navigation Overlay Service (EGNOS) is a public satellite-based regional augmentation system that improves the GPS positioning accuracy and provides information on its reliability in Europe. The service uses the same standard message structure than the other regional public SBAS services (WAAS, SDCM, MSAS, etc.). EGNOS corrections are transmitted via GEO satellites but can be accessed also via internet using EGNOS Data Access Service (EDAS). Sections 6.1.2, 6.2.2, 6.4.1 and 6.4.2 provide some more information about the correction and transmission technology.

According to the "EGNOS Open Service (OS) - Service Definition Document" /36/, position accuracies better than 3 m in the horizontal and 4 m in the vertical domain are guaranteed for EGNOS OS users. An example of measured Horizontal Position Error (HPE 95%) and Vertical Position Error (VPE 95%) values for the EGNOS OS coverage area are shown in Figure 14.

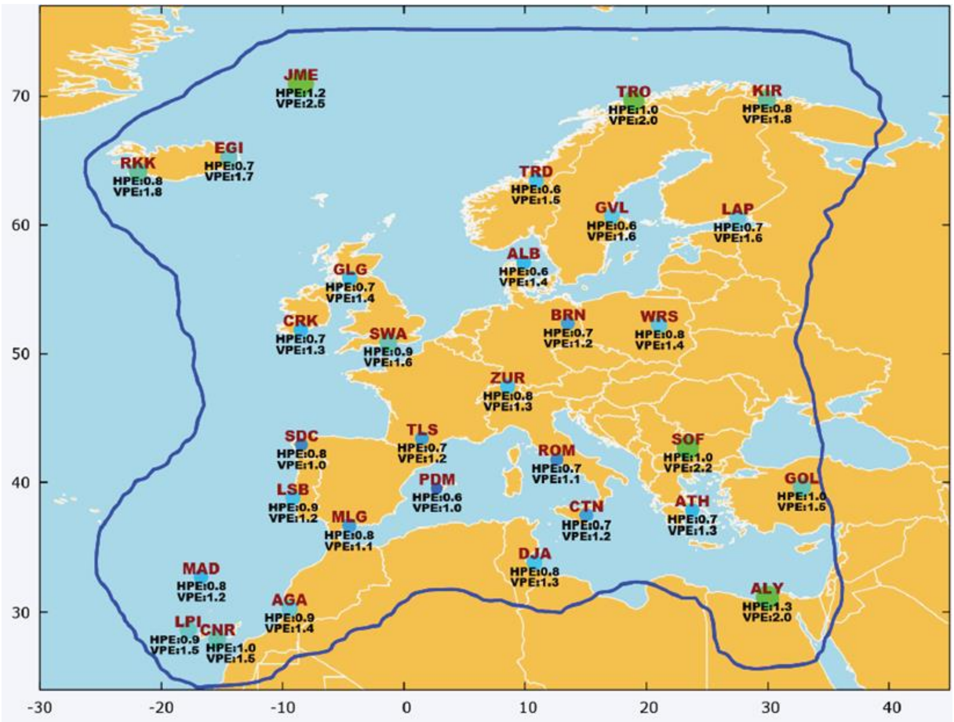

Figure 14. The HPE (95%) and VPE (95%) for the EGNOS OS coverage area measured during March-August 2017 /36/.

According to the Figure 14 HPE (95%) of 0.7 m and VPE (95%) of 1.6 m can be expected around the EGNOS ranging and integrity monitoring station (RIMS) located in south-east Finland in Lappeenranta (LAP in Figure 14).

An independent EGNOS OS service performance assessment report is presented by Magdaleno et al. /37/. The EGNOS OS performance was monitored along the Norwegian coast as part of a project undertaken by the European Satellite Services Provider (ESSP) and GSA. This report however assesses only the horizontal accuracy which was reported to be better than 1.5 m.

In Finland, EGNOS OS performance has been evaluated in the FEGNOS project. During the project all navigation, GNSS observation and EGNOS OS correction data was collected from 20 FinnRef stations for post processing purposes. The HPE (95%) and VPE (95%) values computed with these yearlong data sets confirmed that the current EGNOS OS minimum performance levels (i.e. HPE (95%) < 3m and VPE (95%) < 4m) are well achieved when monitored over longer time periods /38/. The summary of FEGNOS results for HPE (95%) are shown in the Figure 15 and for VPE (95%) in the Figure 16. It is to be noted, that the best results were achieved while using data directly through internet from EDAS. When EGNOS OS data was received from GEO satellites at FinnRef stations (Rx-Decoded), the results were degraded, possibly because of occasional disturbances in the satellite data link. It is also to be noted that these results are from stationary measurements.

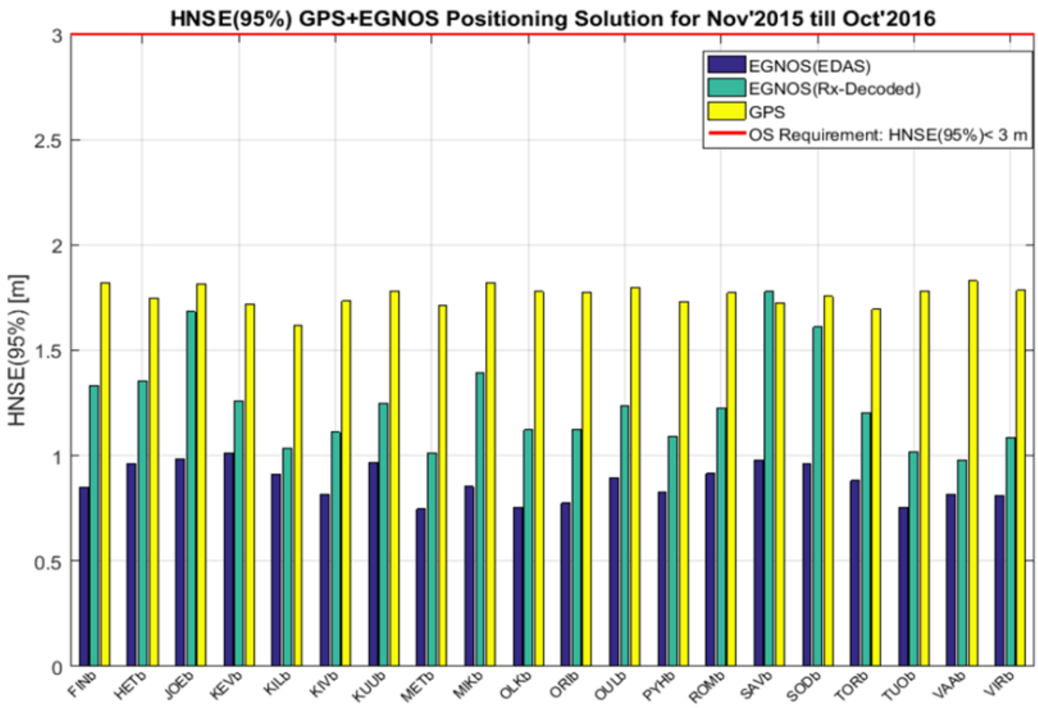

Figure 15. EGNOS OS HPE (95%) in all FinnRef stations /38/. Refer to Figure 12 for the location of individual stations.

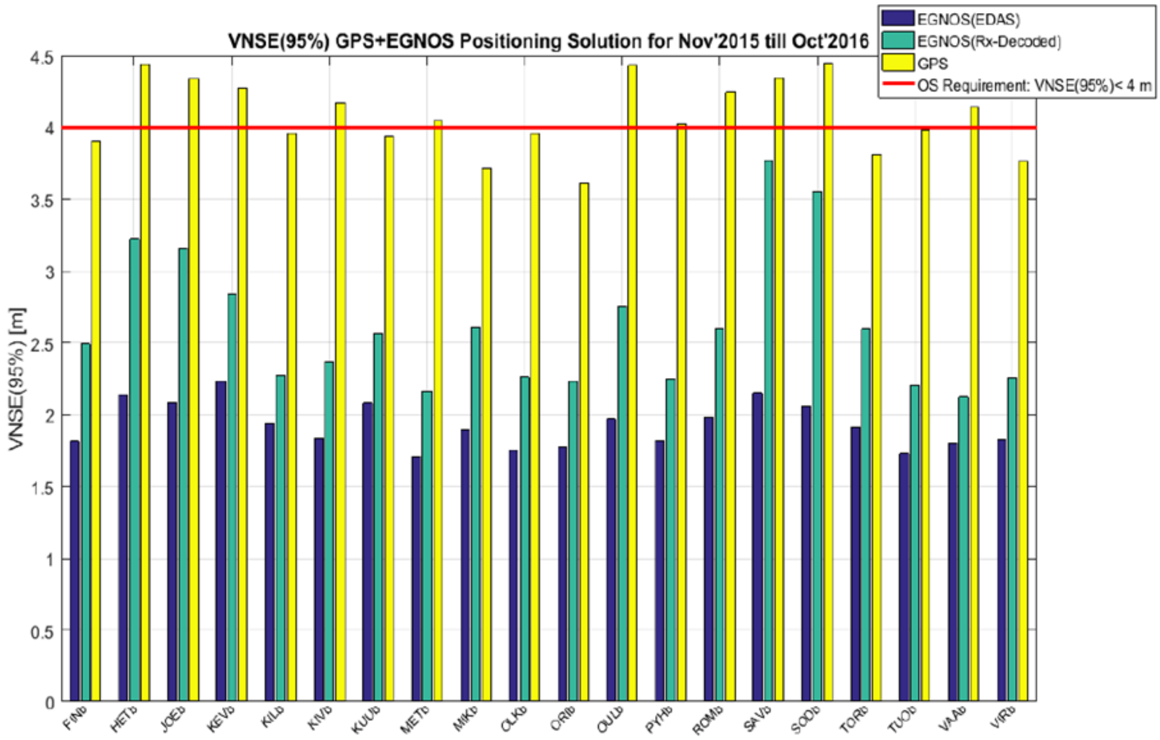

Figure 16. EGNOS OS VPE (95%) in all FinnRef stations /38/. Refer to Figure 12 for the location of individual stations.

Marila et al. /31/ reported EGNOS OS vertical accuracies better than 1.5-1.7 m (95%) in good static conditions and better than 4.2-9.4 m in dynamic conditions. Dynamic measurements validated the performance in different road environments and did not extend to sea areas. Additional field measurements of EGNOS OS accuracy in dynamic sea conditions carried out during FAMOS Odin project and reported by Koivisto /29/ showed horizontal accuracies better than 5.6 m (95%) and vertical accuracies better than 7.5m (95%). It is assumed that the accuracy in these measurements was mainly degraded because corrections were received only for a subset of satellites tracked by the GNSS receiver. This is a known problem experienced near the edge of EGNOS coverage area.

5.5.2 Commercial services

In case of satellite-based GNSS augmentation, there are several commercial service providers worldwide, including Fugro, Hexagon and Oceaneering, which provide services for general navigation and positioning applications for maritime use /39/. Services are based on variety of technologies, mostly PPP (generally proprietary), and might require the use of a specific GNSS receiver. These services are also available in Finnish territorial waters. The following subsections provide more detailed information on some of the services provided.

5.5.2.1 Fugro augmentation services

Fugro offers wide range of augmentation services in different accuracy levels for maritime users /40/. Services include multi-GNSS (i.e., GPS, GLONASS, BDS and Galileo) corrections which are generated with a global network of reference stations. Correction messages are transmitted to fee-paying customers directly via GEO satellites or by using vessel's internet connection. Services are stated to provide worldwide reliable, real-time satellite positioning up to few centimetres' accuracy. Some Fugro service families are introduced in more detail in the following subsections.

5.5.2.1.1 Fugro Starfix®

Starfix® provides precise positioning services for offshore construction vessels, survey operations, pipe lay and cable lay activities, seismic surveys, dive support and other similar applications. Services are provided with different stated accuracy levels which are summarized in Table 8 /39//41/.

Table 8. Vertical Accuracies of different Fugro Starfix® augmentation services /39//41/.

Service	GNSS systems supported	Vertical Accuracy [95%]
G4	GPS +GLONASS + BDS + Galileo	10 cm
G2	GPS +GLONASS	10 cm
XP2	GPS +GLONASS	20 cm
G2+	GPS +GLONASS	6 cm
L1	GPS	1.5 m

The Fugro Starfix® G4 service performance assessment is presented in a realistic maritime environment by Tegedor et al. /42/. For assessing the G4 performance, a dual antenna GNSS positioning system was installed on the Baronen vessel, a high-speed passenger ferry in Oslo fjord as depicted in Figure 17. The vessel was equipped with two GA810 antennas, each of them was connected to a Fugro 9205 multi-GNSS receiver. Both on-board receivers had been configured to deliver G4 solutions. The real-time absolute positions were stored on-board in National Marine Electronics Association (NMEA) format and retrieved routinely for the performance assessment.

Figure 17. Baronen vessel including location of GNSS antennas /42/.

The vessel trajectory in the Oslo fjord on January 14th, 2017 is shown in Figure 18. In order to assess the quality of the positioning solution, the baseline (distance) between the two antennas has been computed, by differencing the absolute antenna positions at every epoch. Antenna distance is very stable over the whole day even under high-dynamic conditions, and the standard deviation of the antenna distance is 1.9 cm, for the 24 hours under analysis. The paper also presented the real-time G4 performance for a stationary receiver located in Oslo, Norway and Perth, Australia for the first week of 2017. The 1-sigma position accuracy was about 1.2 cm for the horizontal component and 4.0 cm for the vertical component.

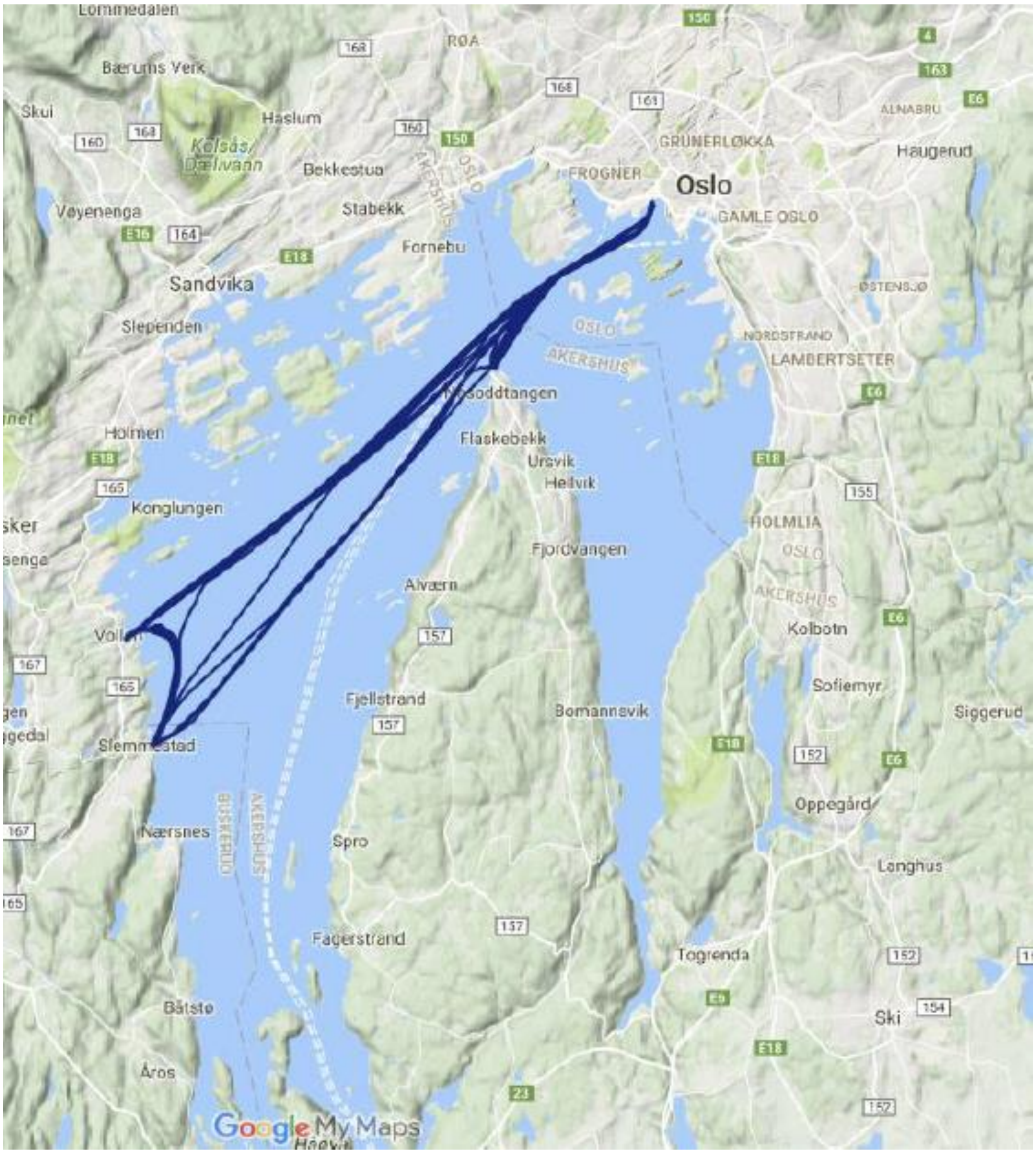

Figure 18. Trajectory of the Baronen vessel on January 14th, 2017 /42/.

The Fugro Starfix® G2 service performance assessment is presented by Melgård et al. /43/. A detailed accuracy analysis and statistics for the real-time orbits and clocks compared to data from the International GNSS Service (IGS) for both GPS and GLONASS are presented. Real-time positioning results are presented from both gentle and challenging environments and for both static and dynamic positioning. The G2 system was installed on the vessel Bourbon Topaz and continuously compared against the GPS only reference systems on-board. The vessel was going frequently out into the North Sea and back into port in Norway. The test results confirm decimetre level position accuracy in real-time navigation with G2.

5.5.2.1.2 Fugro Seastar™

Seastar™ offers high performance positioning services, mainly to the offshore oil and gas industry /44/. The service is announced to provide position reference for dynamic positioning systems and a precise, reliable, high-accuracy differential GNSS correction service optimized for dynamic positioning safety critical applications. Fugro Seastar™ users include offshore support vessels, drilling ships and rigs, floating production units, shuttle tankers, service vessels and offshore loading vessels. In addition to Furgo Starfix® services, Seastar™ provides Fugro Seastar™ XP which is stated to give 10 cm accuracy by utilizing dual frequency GPS constellation and Fugro Seastar™ SGG which is stated to give less than 1 m accuracy by utilizing dual frequency GPS+GLONASS constellations.

5.5.2.1.3 Fugro Marinestar™

Marinestar™ provides high accuracy positioning services in coastal and deep-sea areas and inland waterways on various types of vessels such as navy vessels, hydrographic vessels, dredging vessels, research vessels, wind farm support vessels and other specialist vessels. The different Marinestar™ GNSS Augmentation Services are listed in Table 9 with the stated vertical accuracies and supported GNSS constellations /40//45/.

Table 9. Vertical Accuracy of Fugro Marinestar™ augmentation service /40//45/.

Service	GNSS systems supported	Vertical accuracy [95%]
VBS	GPS	60 cm - 4 m
HP	GPS	6-10 cm
XP	GPS	16 cm
XP2	GPS+GLONASS	12 cm
G2	GPS+GLONASS	12 cm
HPG2	GPS+GLONASS	6-12 cm
G4	GPS+GLONASS+BDS+Galileo	10 cm

5.5.2.2 Hexagon AB augmentation services

The VERIPOS service family offers GNSS augmentation services that deliver centimetre, decimetre or meter level accuracy for marine positioning and navigation applications /46/. NovAtel® Oceanix compliments these services with additional nearshore centimetre services /47/. Corrections are transmitted via GEO satellites but can also be provided via internet. These service families are introduced in more detail in the following subsections.

5.5.2.2.1 VERIPOS Apex

The VERIPOS Apex services use PPP technique based on information provided by 80 VERIPOS GNSS references stations located worldwide. Apex includes three service types: Apex, $Apex^2$ and $Apex^5$. Each service is stated to offer horizontal position accuracy (95%) of better than 5 cm and vertical accuracy (95%) of better than 12 cm. Apex utilizes the GPS constellation whereas $Apex^2$ and $Apex^5$

utilize GPS+GLONASS and GPS + GLONASS + BDS + Galileo + QZSS observations, respectively.

5.5.2.2.2 VERIPOS Ultra

The VERIPOS Ultra services also use PPP technique but based on information provided by NASA Jet Propulsion Laboratory (JPL) GNSS reference stations. Ultra includes two service types: Ultra and Ultra². Both service types are stated to offer horizontal position accuracy (95%) of better than 10 cm and vertical position accuracy (95%) of better than 20 cm. The Ultra service utilizes GPS constellation while the Ultra² service utilizes both the GPS and GLONASS constellations.

5.5.2.2.3 VERIPOS Standard

The VERIPOS Standard offers pseudorange corrections based on information provided by VERIPOS GNSS references stations. It includes two service types: Standard and Standard². Both service types are stated to provide meter-level position accuracy in horizontal and vertical domains. Standard² utilize both GPS and GLONASS dual frequency observations and Standard utilizes GPS observations only.

5.5.2.2.4 NovAtel® Oceanix

The Oceanix nearshore correction service is announced to deliver reliable sub-decimetre positioning for diverse marine applications such as dredging, hydrographic survey, mapping and coastal patrolling up to 60 km offshore. Oceanix precise correction data is generated by a network of over 100 GNSS reference stations which are strategically located globally. The correction service is stated to provide 3 cm horizontal and 8 cm vertical accuracy (95%).

5.5.2.3 OceanEngineering augmentation services

The C-Nav® service family is announced to provide sub-meter (SF1) and sub-decimetre (SF2) augmentation services worldwide. Services utilize both GPS and GLONASS constellations. The C-Nav® SF2 service is stated to provide 1-sigma accuracy of better than 5 cm horizontally and 15 cm vertically /48/.

5.6 Comparison of height estimation performances

The summary of the performance of height estimation using different augmentation solutions described in Sections 5.1 and 5.3–5.5 is presented in Table 10. The table includes guaranteed, stated, expected and measured values gathered from various sources. The intention of the table is to give an overview of approximate accuracy levels available, not to provide a consistent comparison of the different services.

Table 10. Comparison of expected performance of height estimation from different positioning and augmentation techniques.

Augmentation system type	Service	Vertical accuracy	Unit	Source
n.a.	standalone GPS	4-8.8	90% [m]	measured, dynamic /4/
Public GNSS	Galileo HAS	0.2	95% [m]	planned /21/
Public GNSS	Galileo HAS	0.4	95% [m]	estimated /24/
Public GBAS	IALA Beacon DGNSS	10	95% [m]	guaranteed /26/
Public GBAS	IALA Beacon DGNSS	0.8-2.5	95% [m]	estimated /27//28/
Public GBAS	IALA Beacon DGNSS	5.5	95% [m]	measured, dynamic /29/
Public GBAS	FINPOS DGNSS	0.5-0.6	95% [m]	measured, static /31/
Public GBAS	FINPOS DGNSS	0.4-3.6	95% [m]	measured, dynamic /31/
Research only	FINPOS PPP-SSR (L1 code)	1.2-5.2	90% [m]	measured, dynamic /4/
Research only	FINPOS Network RTK	0.056	RMS [m]	measured, static /35/
Commercial GBAS	TrimNet RTK	0.05	RMS [m]	measured, static /35/
Commercial GBAS	HxGN SmartNet RTK	0.05	RMS [m]	measured, static /35/
Public SBAS	EGNOS	4	95% [m]	guaranteed /36/
Public SBAS	EGNOS	1.6-3.7	95% [m]	measured, static /36//38/
Public SBAS	EGNOS	7.5	95% [m]	measured, dynamic /29/
Commercial SBAS	Fugro Starfix®	0.06-0.2	95% [m]	stated /41/ and measured /42//43/
Commercial SBAS	Fugro Seastar™	0.1-1	95% [m]	stated /44/
Commercial SBAS	Fugro Marinestar™	0.06-4	95% [m]	stated /45/
Commercial SBAS	Veripos Apex	0.12	95% [m]	stated /46/
Commercial SBAS	Veripos Ulta	0.2	95% [m]	stated /46/
Commercial SBAS	Veripos Standard	1	95% [m]	stated /46/
Commercial SBAS	Oceanix	0.08	95% [m]	stated /47/
Commercial SBAS	C-Nav®	0.15	STD [m]	stated /48/

6 Communication links for augmentation data

The communication links for different publicly available augmentation services are presented in this section. The local area services use ground communication links such as dedicated radio frequencies or the internet to provide the augmentation data to the users whereas wide area services transmits data primarily via GEO satellites. General explanation on different correction types and correction message types is also given in this section.

6.1 Correction types

The stand-alone GNSS position accuracy is affected by many different error sources. There are errors related to the originator of the signal (i.e. satellite), propagation medium (i.e. atmosphere) and the GNSS receiver itself. Part of these errors can be compensated by providing users with correction data based on observations from one or more surveyed receiver sites, called reference stations. Corrections can be summarised together (scalar correction) or they can be sent separately for different error components (vector correction).

6.1.1 Local Area Differential GNSS

Differential augmentation systems might use only one single reference station that computes an individual scalar correction for all GNSS satellites in view, as shown in Figure 19. These error corrections are then broadcast to users in the vicinity via terrestrial radio link or over Internet. This type of system is called local area differential GNSS service.

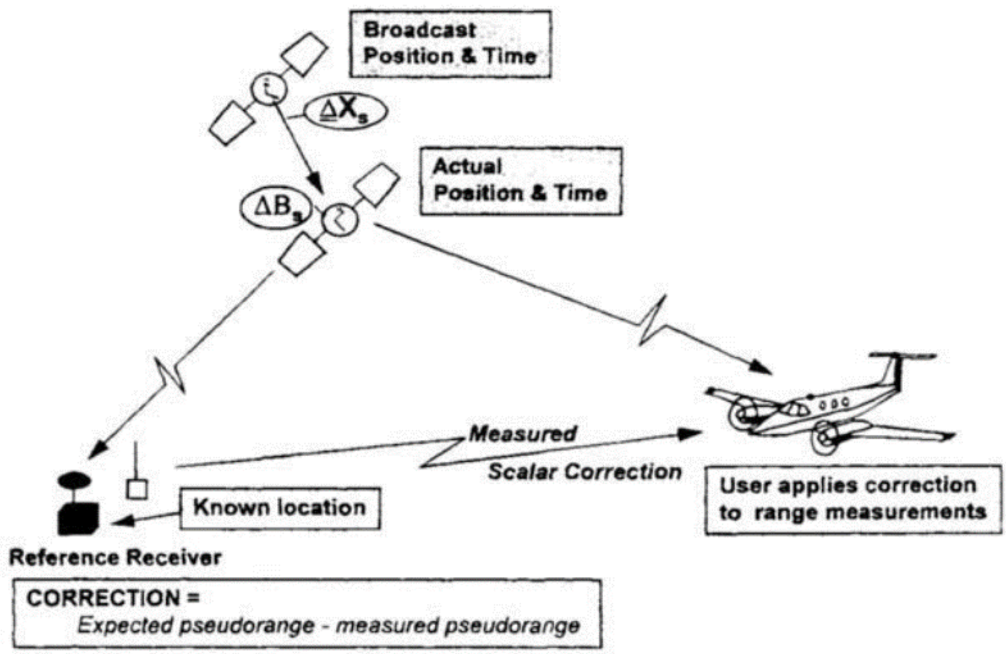

Figure 19. Local area DGNSS /49/.

Scalar error correction summarizes the effects of multiple error sources. It does not separate the errors caused by different individual error sources like satellite orbit and clock errors and atmospheric propagation delay errors. The magnitude of all the corrected errors vary over time but some vary also depending on the receiver location. Consequently, the accuracy of scalar corrections degrades with the increased distance between the user and the reference station. Beyond a separation distance of 100 km, measured correction is not sufficiently accurate for the user to acquire full advantages of the DGNSS anymore. However, a user within a 100 km range from the reference station can typically improve the position accuracy down to 2 to 5m /50/.

6.1.2 Wide Area Differential GNSS

Wide area differential GNSS is a system that uses multiple reference stations to form a vector correction for each satellite for achieving virtually the same accuracy as by local are DGNSS but over larger area. An example of wide area DGNSS system is shown in Figure 20. The wide area correction information is typically provided to users in the service area via GEO satellites but it can also be provided over internet.

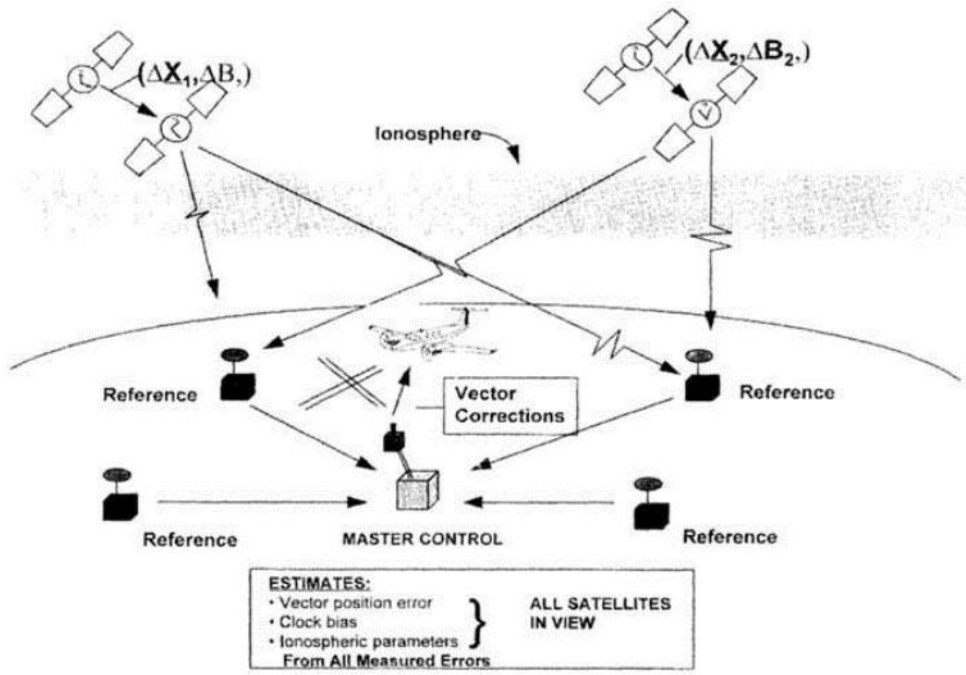

Figure 20. Wide area DGNSS /49/.

Vector corrections are divided into separate components by the error source and additional information can be provided about the spatial variation of corrections, enabling the user to adjust the corrections based on its own location. Compared to scalar corrections, vector corrections are thus valid over much greater geographical area. Moreover, wide area system requires less communication capacity than the equivalent network of local area DGNSS systems would require.

6.2 Correction message types

In the maritime transport sector, the most widely used standard message formats for GNSS corrections have been developed by two international organisations. These organisations are the Radio Technical Commission for Maritime Services (RTCM) and the Radio Technical Commission for Aeronautics

(RTCA). As the name suggests, the main priority of RTCM is to support maritime augmentation services while RTCA publishes standards to primarily support augmentation services for aviation.

Standard RTCM and RTCA messages have the same goal; to compensate errors in stand-alone GNSS measurements. However, the message structures and parameters used are different and navigation receivers need to use different algorithms when calculating the augmented navigation solution.

6.2.1 RTCM messages

RTCM standards define the detailed structure of messages that can be used to provide GNSS correction data /51/. Legacy RTCM message types (version 2.3) support fully only GPS L1 and GLONASS L1 corrections but the new standard versions introduce Multiple Signal Message (MSM) types to provide support also to other GNSS constellations and signals. These new message types will gradually replace the legacy messages, allowing better support to multi-system multi-frequency receivers and thus enabling better position accuracies. These message types still provide scalar type corrections.

To illustrate the size of MSM correction messages, some examples have been presented in Table 11 with different number of satellite (N_{sat}) and number of signal (N_{sig}) configurations. It is to be noted that these examples represent the upper bounds of message size, because currently four different signals are not available from GNSS satellites. It is also to be noted that one MSM message can contain corrections for only one GNSS system and the number of required messages must be multiplied with the number of GNSS systems supported. These messages are typically sent once per second.

Table 11. Example message sizes of MSM types 1, 4 and 7.

MSM type	Content	No. of bits	Message size [bits] N_{sat}=10, N_{sig}=4	Message size [bits] N_{sat}=16, N_{sig}=4
1	Compact GNSS Pseudoranges	$169+N_{sat}*(10+16*N_{sig})$	909	1353
4	Full GNSS Pseudoranges, PhaseRanges, and Carrier to Noise Ratio (CNR)	$169+N_{sat}*(18+49*N_{sig})$	2309	3593
7	Full GNSS Pseudoranges, PhaseRanges, PhaseRangeRate and CNR (high resolution)	$169+N_{sat}*(36+81*N_{sig})$	3769	5929

RTCM is currently developing new SSR message types to support also vector corrections. The standard already defines SSR message types for satellite orbit corrections, clock corrections and code biases. The future versions of RTCM standard will include additional messages for ionospheric corrections and tropospheric corrections. One advantage of the new SRR messages is that they can be sent with different frequencies. The rate of change of the different error components varies and consequently, the optimal update rate required to compensate the errors varies.

Because some of the SSR messages are still under development and the message transmission schedule has not been fixed it is not yet possible to define the final message sizes and data rates of SSR correction transmissions.

6.2.2 RTCA messages

RTCA has developed a set of standard correction messages which are applicable to all public SBAS services /52/. Use of standard message types enable the use of same SBAS receiver equipment all over the world. Standard supports only vector type corrections because of the large service area of SBAS.

RTCA standard define messages for two kinds of corrections; fast and long-term corrections. Fast corrections compensate rapid changes like GNSS clock errors and long-term corrections compensate slower changing errors like atmospheric errors and ephemeris errors. RTCA messages also allow to provide users information about the spatial variation of ionospheric errors. Based on that information users can apply such an ionospheric correction that best compensates the errors in their own location.

6.3 Communication links for RTCM type messages

RTCM standards were primarily developed to support maritime sector but can be used by other sectors as well. The same messages can be transmitted using different communication links depending on the use case. RTCM messages can support both local area and wide area augmentation.

There are currently two standardised dedicated RTCM communication links available for maritime users. These are maritime DGNSS frequencies and AIS frequencies. Most merchant vessels carry certified receivers that enable them to receive GNSS corrections via either one or both of these frequencies. Unfortunately, both communication links have limited bandwidth and it seems that they might not be able to support all the new emerging RTCM message types. Introduction of new dedicated and standardized communication links would be a long process involving several years of international standardization work and several more years before certified equipment would have been installed on-board vessels extensively. Without mandatory carriage requirement, wide deployment of equipment among the global fleet might never happen.

Digitalisation and the increasing requirement of maintaining internet connectivity on-board vessels throughout voyages might introduce new possibilities for providing RTCM correction messages in the future. Internet connection can be established for example via satellites or terrestrial mobile networks in coastal areas and would provide generic communication link for large variety of digital services including correction services.

It is planned that some standard RTCM correction messages will be provided globally via Galileo satellites/signals in the future (Galileo HAS).

6.3.1 Maritime DGNSS frequencies

The IALA Beacon DGNSS service is a standardized local area GNSS augmentation technique for maritime use /25/. Most IALA DGNSS transmissions support GPS corrections, but GLONASS differential correction can also be implemented. Transmissions follow the ITU recommendation ITU-R M.823[1]. The maritime beacons transmit the real-time differential pseudorange corrections in an unencrypted RTCM 2.3 format (Message type 1 or 9) at the frequency band 283.5 - 325.0 kHz, which is assigned by ITU for this purpose worldwide. These frequencies propagate primarily as ground wave and especially well over salty seawater enabling wider coverage ranges than higher, line-of-sight, frequencies. Normal coverage area of an IALA Beacon DGNSS transmitting station is somewhere around 200km, which covers well the area where corrections are applicable. The coverage area is also sufficient to cover all the Finnish fairways along the coastline. The data transmission rate is typically 100 bps but may vary between 50-200 bps. In Baltic Sea area, the transmission rate of 100 bps is used.

RTCM corrections via maritime beacon frequencies are provided by many administrations around the world and also widely used by merchant shipping. All countries around the Baltic Sea provide the IALA Beacon DGNSS service.

6.3.2 AIS frequencies

Automatic Identification System (AIS) is primarily a ship reporting system providing other ships and shore authorities real-time information about the vessel's identity, position and other navigational parameters. However, the system also allows transmitting limited amount of information from shore to ships, including GNSS differential correction information. AIS is a time division multiple access system meaning that transmissions happen in same frequencies but at different times. ITU has reserved globally two frequencies from maritime VHF band exclusively for AIS system; these are 161,975 MHz (AIS1) and 162,025 MHz (AIS2). Transmissions in these frequencies follow the ITU recommendation ITU-R M.1371[2]. The differential pseudorange corrections in RTCM 2.3 format can be transmitted using a dedicated AIS message type (i.e. Message 17) defined in the ITU recommendation. Maritime VHF frequencies propagate mainly via line-of-sight path and the maximum coverage area is slightly above 100km depending on the transmitter and receiver antenna heights and the transmitted power.

Because RTCM correction transmissions continuously reserve capacity from AIS frequencies, many administrations have chosen not to provide GNSS correction service via AIS. Practically all merchant ships have AIS equipment installed and would be capable of receiving RTCM correction messages via AIS. However, transferring the received correction information from AIS receiver to vessels

[1] ITU-R M.823-3, Technical characteristics of differential transmissions for global navigation satellite systems from maritime radio beacons in the frequency band 283.5-315 kHz in Region 1 and 285-325 kHz in Regions 2 and 3 (available free of change from www.itu.int)

[2] ITU-R M.1371-5, Technical characteristics for an automatic identification system using time division multiple access in the VHF maritime mobile frequency band (available free of change from www.itu.int)

navigation system is not common. Only few Baltic Sea countries provide differential corrections via AIS frequencies.

6.3.3 Internet

Networked Transport of RTCM via Internet Protocol (NTRIP) is a protocol for streaming DGNSS correction data from a reference station to users over the Internet. NTRIP specification is developed and published by RTCM /53/. Other RTCM standards /51/ then specify the detailed data structure of correction messages transported via NTRIP. Internet connection could be provided for example by mobile phone network or satellite and should be chosen to cover the area where correction data is valid.

The NTRIP is used for the public DGNSS services provided by FINPOS /54/. To be able to use FINPOS DGNSS services in real-time, the user (e.g. vessel) would need to have a continuous Internet connection, equipment that support NTRIP protocol and a GNSS receiver that can use RTCM corrections. The current public FINPOS NTRIP services provide pseudorange (code based) correction service for GPS and GLONASS constellations in two versions of the RTCM standard: RTCM 2.2 (message types 1 and 31) and RTCM 3.2 (MSM types 1071 and 1081). Corrections are valid in Finnish land areas and nearby sea areas. Other Baltic Sea countries provide similar services in their own areas. Some NTRIP services are provided also by EDAS for the whole Europe.

FINPOS is also able to model and produce corrections for receivers using carrier phase observations (Network RTK, like VRS), which would provide even better position accuracies /35/. Additionally, generation of PPP corrections (SSR messages) has been tested during FAMOS project /4/ and results are summarized in Section 5.4.1.2. Both FINPOS Network RTK and PPP services are for the moment available only for research purposes.

Table 12 lists a subset of possible real-time DGNSS and Network RTK correction services from FINPOS service and examples of the data rates (bytes/s) of different services obtained from a short test period.

Table 12. FINPOS NTRIP correction services and examples of the data rates.

Services	Constellations and configurations	Data Rates [bytes/s]
DGNSS (public)	GPS+GLONASS (RTCM 2.2, legacy messages)	183
VRS	GPS+GLO+GAL+BDS (RTCM 3.2, MSM4)	894
SINGLE	GPS+GLO+GAL+BDS+SBAS (RTCM 3.2, MSM7)	1954

Currently NTRIP correction services are not widely used by merchant shipping. Even though services are freely available, the use of services require continuous Internet connection, which need to be payed separately. In the future, when the low-cost continuous broadband Internet connection becomes available for vessels, NTRIP correction services may provide a good augmentation service option also for merchant shipping.

6.3.4 GNSS signals

European Commission has plans to provide GNSS augmentation data via Galileo satellites in the future. The Galileo HAS will transmit PPP corrections on Galileo E6 B signal. The service will provide corrections for Galileo and GPS using RTCM compact SSR messages. Other GNSS systems may be included later. However, as mentioned in Section 6.2.1 there are still open issues related to standardisation of compact SSR messages.

The HAS IOC is currently estimated to be reached already during 2021 and the FOC during 2023. Following Table 13 gives the details of the possible Galileo HAS corrections as indicated in /55/.

Table 13. Planned correction types and numbers of bits of Galileo HAS using RTCM Compact SSR /55/.

Sub type	Sub type name with correction item	No. of bits
1	Compact SSR mask	$37 + 60 \times N_{sys}$
2	Compact SSR GNSS orbit correction	$25 + (51 \text{ or } 49) \times N_{sat}$
3	Compact SSR GNSS clock correction	$25 + 15 \times N_{sat}$
4	Compact SSR GNSS satellite code bias	$25 + 11 \times N_{code} \times N_{sat}$
5	Compact SSR GNSS satellite phase bias	$25 + 17 \times N_{phase} \times N_{sat}$
6	Compact SSR GNSS satellite code and phase bias	$28 + 28 \times N_{sig} \times N_{sat}$
7	Compact SSR GNSS User range accuracy (URA)	$25 + 6 \times N_{sat}$
8	Compact SSR total electron content (TEC) correction	$25 + 34 \times N_{grid}$

Because HAS is transmitted via Galileo satellites, the coverage area of the communication link is expected to be global.

6.3.5 Other communication link options

According to the IALA Maritime Radio Communication Plan (MRCP) /56/, there are several candidates for providing communication link between vessels and shore services (Table 14). Those land-based communication systems that are estimated to have sufficient coverage (i.e. 30-50km measured from the coast-line) to serve all the Finnish fairways (Figure 6) are highlighted with light green colour in the Table 14.

Table 14. Candidates for providing communication link between vessels and shore services /56/.

Communication Technology	Data rate	Infrastructure	Coverage	Transmission	Maritime /public
NAVDAT (500 kHz)	12-18 kbps	Based on NAVTEX	250-300NM (460-555km)	Broadcast	Maritime
VDES VDE (157.2-157.275 MHz and 161.8-161.875 MHz)	307 kbps	VHF Data link, RR Appendix 18 channels	15-65NM (27-120km) Satellite component provides further coverage	Addressed / broadcast	Maritime
VDES ASM (161.95 MHz and 162.2 MHz)	19.2 kbps	VHF Data link, RR Appendix 18 channels	approx. 15-65NM (27-120km)	Addressed / broadcast	Maritime
Wi-Fi (IEEE 802.11ac)	1,300 kbps	Routers/Access points	50 m	Addressed	Public
WiMax	75 Mbps	Routers/Access points	2-5 km	Addressed	Public
Digital VHF	9.6 – 19.2 kbps	Base station/mobile radios	approx. 15-65NM (27-120km)	Addressed	Maritime
Digital HF	19.2 kbps	Base station/mobile radios	Global	Addressed	Maritime
4G (including LTE)	600 Mbps	4G Base stations	5-30 km (3-16 NM)	Addressed	Public
5G	1,200 Mbps	5G base stations	5-30 km (3-16 NM)	Addressed	Public
Inmarsat C	600 bps	GEO Satellite service	Global, spot beams	Addressed / broadcast	Maritime
Inmarsat GX	50 Mbps	GEO Satellite functioning on Ka band	Global, spot beams	Addressed / broadcast	Cross Industry
Iridium	Up to 134 kbps	LEO Satellite functioning on L band	Global, dependent on constellation size	Addressed / broadcast	Cross Industry (Iridium Pilot Maritime)

NAVDAT and two different components of VHF Data Exchange System (VDES) could all provide broadcast service with higher data rate than those communication links that are currently available and used for dedicated maritime RTCM correction services. In principle, a new maritime RTCM correction service using one or more of these frequencies could be developed. NAVDAT coverage area is large and it would be better suited for transmitting wide area corrections while VDES could be used for transmitting local area corrections. However, development of new standardised services, which use dedicated communication links, is a very long process and requires contribution from many international organisations.

None of the highlighted systems in Table 14 is currently capable of providing Internet connection. However, there is work going on to develop and standardize methods that would enable to create an IP based, content agnostic, data link for different shore services via the VDES VDE. The stable standard could be expected to be available earliest by 2025.

In Table 14, 4G and 5G coverage is estimated to be less than 30km, but there is research going on in Finland and other parts of the world to test the possibilities to extend the 4G and 5G coverage along the fairways. This could be done for example by exploiting the existing fairway infrastructure to host additional 4G or 5G base stations or by using very high transmitting sites along the coastline. With extended coverage, these systems would enable the broadband internet connection in the coastal area.

6.4 Communication links for RTCA type messages

All the current public SBAS systems use correction message types developed by RTCA[3]. SBAS is based on a network of ground monitoring stations located at accurately surveyed points that monitor the signals of GNSS satellites. GNSS constellation signals is then processed in data processing centres to obtain estimations of the errors that are also applicable to the users. Corrections are transmitted to users using standard RTCA message types. Transmission are made primarily via GEO satellites which serves very well the original user group, aviation sector. These corrections are called Signal In Space (SIS) corrections.

However, there are increasing number of SBAS users from other sectors, including maritime sector. These users might face challenges while receiving corrections directly from GEO satellites. Signals might be blocked by manmade structures or terrain shapes. To support all user groups, some SBAS operators provide corrections also via internet.

6.4.1 GEO satellites

SBAS corrections are up-linked to one or more GEO satellites in the form of RTCA differential corrections and finally broadcast to the end users in the SBAS coverage area, which is the satellite footprint area. In consequence, users (e.g. vessels) can receive these SBAS corrections from SBAS GEO satellites and apply them in order to obtain an enhanced navigation position with respect to GPS standalone. The GEO satellite communication link of the EGNOS, the SBAS service in Europe is presented in Figure 21.

[3] RTCA MOPS DO 229D

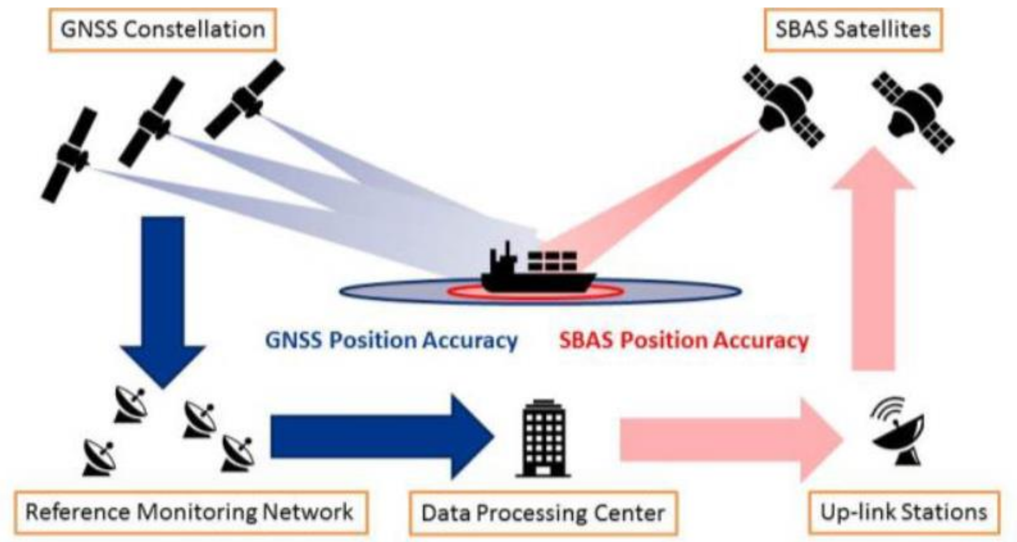

Figure 21. EGNOS architecture /37/.

EGNOS uses the same frequency (L1 1575.42 MHz) as GPS. The service will be extended also to L5 frequency in future versions. In open areas, the signals in this frequency band can normally be received very well throughout the whole satellite footprint area. However, in areas where the satellite elevation is low, signals can be blocked by line-of-sight obstacles like buildings, bridges and mountains, which can cause problems for maritime users near coastline or in ports. Signals are also vulnerable to occasional disturbances in ionosphere caused by solar events.

EGNOS corrections are transmitted from three GEO satellites. These are PRN 136 (SES-5), PRN 123 (Astra 5B) and PRN 126 (Inmarsat 4-F2). Locations and footprints of these GEO satellites are shown in Figure 22. Normally at least two of the three GEO satellites are operational while one of them can be temporarily in test mode. The availability of the EGNOS signals in Finnish fairways and coastline is being validated by field measurements during 2020-2021.

Figure 22. Locations and footprints of EGNOS GEO satellites PRN136 (left), PRN123 (middle) and PRN126 (right) /57/.

Use of SBAS is increasing in the maritime sector. It is however to be noted that because RTCA correction messages were originally developed for aviation sector, the use of these messages in maritime navigation equipment has not yet been properly standardised.

6.4.2 Internet

The same EGNOS corrections which are transmitted via GEO-satellites are also available from EDAS via internet. EDAS provides GNSS corrections in few different formats and the RTCA messages are provided via EDAS Signal In Space through the Internet (SISNeT) service.

To be able to use RTCA over Internet vessel needs to have continuous Internet connection, equipment that supports SISNet protocol and navigation receiver that can use RTCA corrections.

7 Coordinate and height reference frames in navigation

Plate tectonics, earthquakes, land uplift and other phenomena are continuously changing the coordinates of any given point on the Earth. In order to accurately measure coordinates and heights and to navigate we need an accurate reference system and its realization called the reference frame. Navigation is always done in some defined coordinate reference frame and the depths represented in nautical charts are given with respect to a defined reference surface. GNSS satellites are in a global reference system and therefore also the coordinates defined using GNSS are in global system (i.e. WGS84). However, for practical purposes local reference systems are usually used of which coordinates are not changing. In the following, both global and regional coordinate systems and heights used in Finland are introduced.

7.1 Coordinate frames

7.1.1 Global and local reference frames

The International Terrestrial Reference System (ITRS) is the most important global reference system /58/. The global realization of ITRS is the International Terrestrial Reference Frame (ITRF). Simplified, realization of reference system means that the exact coordinates of a set of chosen physical sites at a certain point of time are defined according to the reference system rules. This ties the abstract reference system into the physical world. In practice the process is naturally much more complicated. ITRF is defined using four different space geodetic techniques: Doppler orbitography and radiopositioning integrated by satellite (DORIS), Global Navigation Satellite Systems (GNSS), satellite laser ranging (SLR) and very long baseline interferometry (VLBI). All these techniques are based on a global network of monitoring stations[4]. In Finland, NLS hosts stations belonging to all of the mentioned networks. The coordinates of stations realizing an ITRF are given with epoch (time of realization) and velocity (speed of change) information since the Earth's crust is continuously moving. Use of epoch and velocity information makes it possible to maintain the accuracy of the original coordinates over time. The latest ITRF realization is called ITRF2014 (2010.0)[5] /59/.

The GPS positioning system is using an own global reference system called World Geodetic System 1984 (WGS84) /60/. The GPS monitoring stations are used to determine the realization of WGS84. The coordinates of these monitoring stations are defined in ITRF. The current realization called WGS84 (G1762) was implemented on GPS week 1762 (16th October, 2013) and it agrees with ITRF2008 (2005.0) /60/. GLONASS, Galileo and BDS also use their own reference frames, Parameters of the Earth 1990 (PZ-90), Galileo Terrestrial Reference Frame (GTRF) and BeiDou Terrestrial Reference Frame (BTRF),

[4] International DORIS Service (IDS), International GNSS Service (IGS), International Laser Ranging Service (ILRS) and International VLBI Service (IVS)
[5] realized in epoch 2010.0, i.e. January 1st 2010

respectively. All frames used by GNSS systems are compatible with ITRF on the cm level.

Time dependent reference frames are not used for practical purposes like for building infrastructures. European Reference Frame (EUREF) suggested that Europe should use a system attached to the permanent part of the Eurasian tectonic plate. The system is called European Terrestrial Reference System 1989 (ETRS89). The realization of the ETRS89 is maintained using EUREF Permanent GNSS Network (EPN) GNSS stations /61/. The realizations of ETRS89 are called European Terrestrial Reference Frame (ETRF).

In Finland the national ETRS89 realization, ETRF96, is called EUREF-FIN and is described by Ollikainen et al. /62/. EUREF-FIN is tied to the EPN through four EPN stations in the FinnRef network. EUREF-FIN was realized in epoch 1997.0. The coordinates were corrected with plate tectonics to the epoch 1989.0. In Finland the Eurasian tectonic plate moves annually about 2.5 cm to the north-east. The heights refer still to epoch 1997.0 because no land uplift models were applied in the transformation. Annual vertical velocities in Finland vary between 1 and 9 mm and horizontal velocities are up to 2 mm. EUREF-FIN is the official reference frame of Finland fulfilling the requirements of the Infrastructure for Spatial Information in Europe (INSPIRE) directive.

7.1.2 Differences between WGS84 and EUREF-FIN

In navigation it is essential to understand the difference between time dependent global reference frame like ITRF or WGS84 and national frame EUREF-FIN where coordinates do not change in time. These frames differ from each other due to plate motion and land uplift as described in the previous subsection. Figure 23 shows that in 2019 the difference between EUREF-FIN and WGS84 is over 0.7 m in horizontal direction and in decimetre level in the height component.

7.1.3 Ports, nautical charts and augmentation systems

In Finland the coordinate system of the nautical charts is EUREF-FIN. Some older charts can still be in KKJ /63/ that differs significantly from WGS84 or EUREF-FIN. Coordinate systems of the ports are not harmonised and they may be in local systems like EUREF-FIN or KKJ. Local Finnish augmentation systems typically work on national EUREF-FIN frame. This is the case for HxGN SmartNet, Trimnet, FINPOS and IALA Beacon DGNSS services. Global wide-area augmentation services like Fugro, Galileo HAS etc. are typically using global reference frames being in cm level agreement with WGS84.

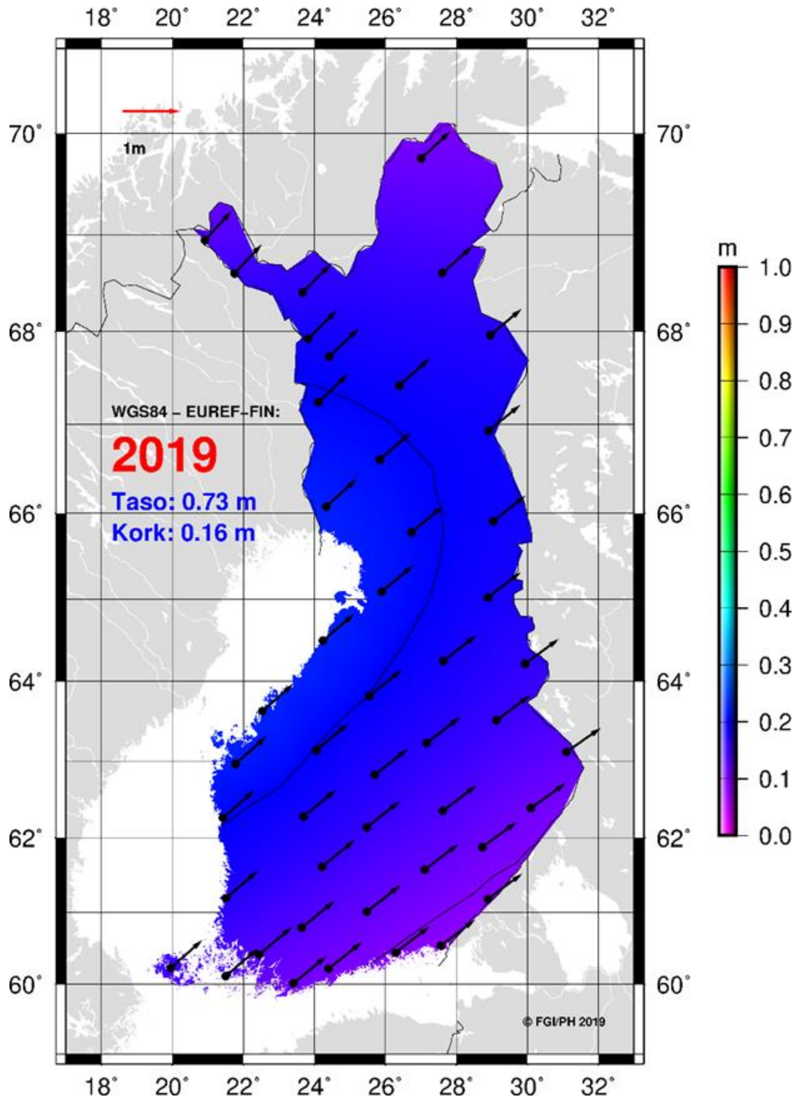

Figure 23. Difference between WGS4 and EUREF-FIN in 2019

7.2 Maritime height reference levels

7.2.1 Mean Sea Level

At present, depths in nautical charts in Finland are given with respect to the MSL or sometimes the NN system. On inland waterway charts depths are usually given with respect to the Low Water Level (LWL) in the watercourse.

The Finnish Meteorological Institute (FMI) provides sea levels at mareographs and sea level forecasts with respect to MSL or more accurately with respect to the theoretical Mean Water (MW). MW level is not stable and is updated yearly. Also, the depths in a nautical chart refer to the MW of its particular year. The difference of the yearly MW with the national geodetic height systems used on land (NN, N43, N60 and N2000) can be found on the FMI's website /64/. If requested, also mareograph data and forecasts can be provided.

The use of MW requires that mariners are alert as the level changes yearly and the MW level in use at the mareograph may not coincide with the level used in the nautical chart. Also, the sea level given by mareographs along the coastline may not be representative for the sea level at the open sea. In addition, the levels differ from country to country in the Baltic Sea area. All of these factors result in large margins of uncertainty in the estimated UKC.

7.2.2 Baltic Sea Chart Datum 2000

The IHO Baltic Sea Hydrographic Commission has agreed on the adoption of the Baltic Sea Chart Datum 2000 (BSCD2000) as the common chart datum in the Baltic Sea. The BSCD2000 is a geodetic reference system, as it refers to the realization of the European Vertical Reference System (EVRS) with land-uplift epoch 2000. The reference level is the equipotential surface of the Earth's gravity field and its zero level is connected to the Normal Amsterdams Peil (NAP).

For most countries in the Baltic Sea the BSCD2000 coincides with their national height reference systems on land. In Finnish territory it is the N2000 height system. Figure 24 shows the differences between the old reference levels in sea areas and the BSCD2000. In Finland the difference varies between 9.2 cm in Kemi, 6.8 cm in Pietarsaari and 21.1 cm in Hamina /65/.

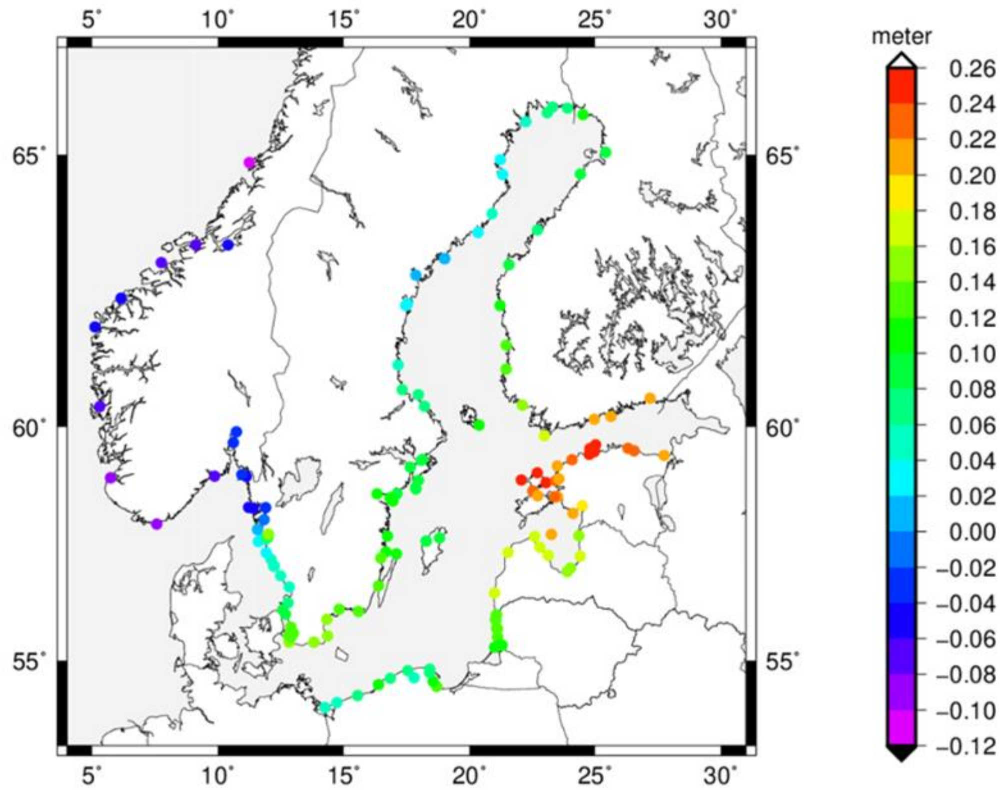

Figure 24. Differences between the reference levels of the old national chart datums with respect to BSCD2000 /66/.

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. This model is one of the end products of the FAMOS project /4/ and was initially planned to be ready by the year 2021. However, the delivery of the final model is delayed due to the discontinuation of the FAMOS project. The goal is that the combined standard uncertainty of the geodetic infrastructure realizing the BSCD2000 is 5 cm over the whole region /66/.

The Baltic Sea countries are gradually making the transition to the new BSCD2000. In Estonia the transition is already complete on all levels. In Sweden the transition has started in 2019 and will be ready by 2024 when the last charts will be transferred /67/. Since June 2019 Swedish sea level observations and forecasts have been provided in the Swedish RH2000 system, which for Sweden coincides with the BSCD2000.

In Finland preparations are being made to start the transition to N2000, which is the Finnish realization of the BSCD2000. Production of nautical charts in the new reference system will start in 2021. The whole transition will last about 5 years /68/. In the Finnish paper charts the new chart datum will be shown as BSCD (N2000). In the IHO Geospatial Information (GI) Registry, the BSCD2000 is included as chart datum number 44 /69/.

In principal, when the BSCD2000 is fully introduced the UKC could be directly 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 could be determined would 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.

7.3 Possibilities for better support to reference level transformations

As reported in Section 6.2, RTCM defines standards that are commonly used for transferring corrections for differential navigation. Depending on the service the coordinates of the users are typically given in ITRF or its realizations like EUREF-FIN as geocentric or ellipsoidal coordinates. However, users may want to instead use local or regional coordinate or height systems. Therefore, transformations are necessary.

RTCM version 2.x standards are most commonly used in regular navigation based on GNSS. The later RTCM version 3.x standards are commonly used in land surveying applications. They give a possibility to send transformation parameters to the users. RTCM standards from 3.1 support seven types of transformations as message numbers 1021-1027 /51/. These messages give a possibility to send geoid information and transform from ellipsoidal heights into physical ones. Technically, it would be possible to include into the Finnish RTCM correction streams messages that would transform ellipsoidal heights into N2000 heights, which are used in the new Baltic Sea Chart Datum 2000. It could even be possible to send corrections in global coordinate frame and transformations into EUREF-FIN and N2000. These features are not yet commonly used even globally and not utilized in Finland. Taking these transformations into production would require intensive evaluation and testing that transformations are correctly generated as well as standardization to ensure that the receiver on board the vessel utilizes the information as intended.

8 Conclusions

More accurate information on UKC 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. This report provides 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, local area, and wide area augmentation systems.

The accuracy performance of the height estimation using different augmentation options were presented in the context of Finnish waterways. The diverse communication links for transmitting the augmentation information to vessels were discussed and the significance of the coordinate and reference frames to height estimation in navigation was noted.

The following key findings and recommendations can be made based on the literature surveys:

- There are very good commercial services available for providing precise GNSS based height estimation.
- 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 (95% of time), possibly even better than 0.2 m (95%).
- Actual values of height accuracy (95%) that can be achieved via existing public services (based on dynamic measurements) are:
  - FINPOS <3.6 m
  - IALA Beacon DGPS <5.5 m
  - EGNOS <7.5 m
- IALA Beacon DGNSS and EGNOS have their own existing communication links already. FINPOS uses wireless internet for streaming the NTRIP DGNSS corrections to users, for example via 4G or 5G. VDES might provide an alternative free of charge communication link for FINPOS services, however standardisation would take several years.
- Currently, there are still many different vertical datums used in Baltic Sea nautical charts. By 2030, chart datums will be harmonized to a common geodetic vertical Baltic Sea chart reference level. This will help to eliminate the water level variances and is necessary precondition for accurate GNSS based height estimation.

The Baltic Sea area nautical charts will have the joint height reference by 2030. It is expected that the global Galileo HAS service will be available few years before that. Currently it seems that there is no compelling need to develop other new public augmentation services. The development of Galileo HAS service should however be followed closely, keeping in mind that:

- The RTCM messages that are planned to be used by HAS are still not fully standardised.
- The global end-user performance of HAS has not been presented yet.

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GNSS baseline horizontal accuracy performance within the European Maritime Area

The GNSS baseline horizontal accuracy performances within the European Maritime Area are presented by Fairbanks et al. /1/ and Christiansen et al. /2/. These studies have shown that with GPS-only the horizontal accuracy achieved at 95% confidence level varies over a range of approximately 13 m to 23 m depending on location (Figure 1). GPS alone will not be sufficient to meet any of the maritime requirements presented in Section 3 except in ocean areas.

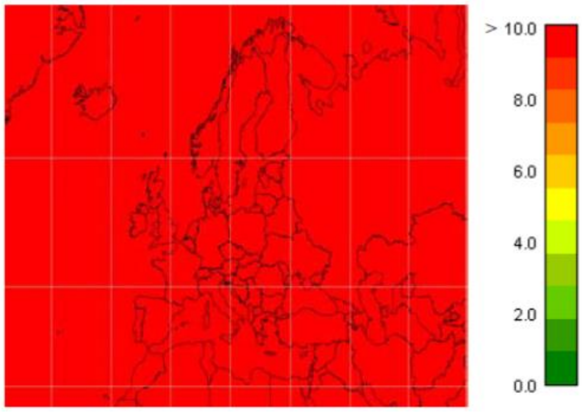

Figure 1. Accuracy (m) (95% confidence level) achieved by GPS alone in the European maritime area /2/.

The horizontal accuracy performance expected from Galileo for both single and dual frequency modes of operation are shown in Figure 2. The single frequency mode does not meet the minimum required accuracy performance which is anticipated and consistent with the Galileo Mission Requirements Document /3/. The dual frequency mode of operation offers accuracy levels in the approximate range of 2 m to 4 m for the Galileo service. Thus, standalone Galileo will not be able to meet the requirements for those applications requiring accuracy below 1 m, e.g., port operation.

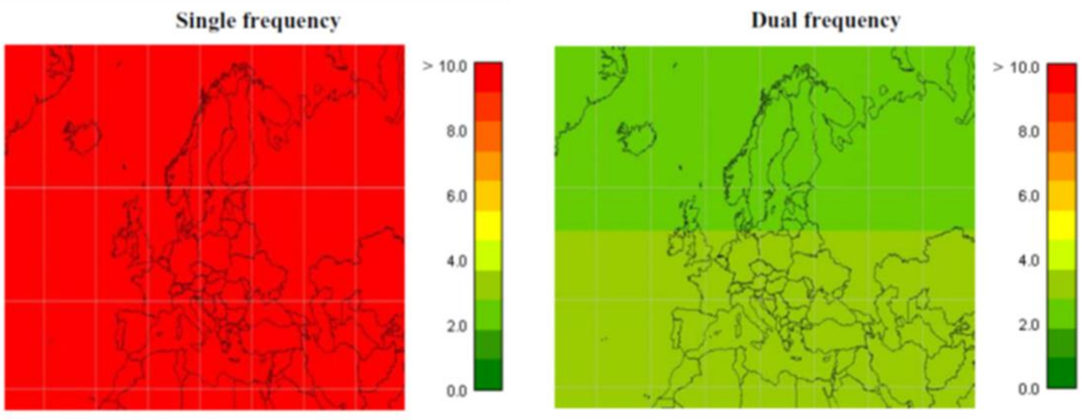

Figure 2. Accuracy (m) (95% confidence level) expected from Galileo /2/.

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