Comparative Study on GNSS Positioning Systems for Autonomous Vessels in the Arctic Region

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Abstract

Accuracy and reliability of major positioning systems is a crucial enabler for autonomous shipping worldwide and, in particular, in the Arctic region. Satellite positioning can be used in conjunction with other situational awareness systems that provide relative positioning information for decision-making. This work describes high-level requirements and concentrates on studying the current state-of-the-art performance of the satellite-based positioning systems. We provide a comparative study between three Global Navigation Satellite System (GNSS) constellations, namely Galileo, Global Positioning System (GPS), and GLObal NAvigation Satellite System (GLONASS) suitable for autonomous vessels operation in the Arctic Region. Simulation results show that all studied constellations achieve accuracy of fewer than three meters in the analyzed scenarios. The results also show that all GNSSs provide good visibility with low elevation angles, whereas with high elevation angles, which might be needed due to natural barriers, the GLONASS provides the highest number of visible satellites. The paper also outlines the main strategies applicable for improving the positioning accuracy as well as overviews active positioning projects specifically for the Arctic region.

Keywords

Autonomous systems, positioning, Arctic region, maritime, GNSS, simulations

1. Introduction

The development of the Arctic region is opening new opportunities for a variety of industries. The particular interests include offshore extraction of resources and minerals, as well as the main maritime trading paths between the Atlantic and Pacific oceans. However, the shipping operations and the activities on the exploration of natural resources are limited due to poor navigational services and complex communication situations [1]. Furthermore, navigation in the Arctic is demanding due to challenging weather conditions, complex properties of the ice surface, and movement. In order to minimize the possible damage caused by a potentially dangerous and unpredictable environment, the onshore support allows timely notifications and precise positioning information from and to the vessels. Today, the primary option for communications and navigation in this region is the satellite connectivity.

The issues mentioned earlier are significant for a trailblazing time of the autonomous vessel operation, especially when it integrates many robotic systems [2]. For safe maritime operations

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of crew-less vessels, it is vital to know the accurate position both in the open sea and in the harbor. The positioning accuracy requirements differ depending on the environment of the application: whether the system provides basic navigation in the open sea or it is a precise positioning service for heavy traffic environmental conditions such as a marine port. At sea, the accurate positioning ensures that the vessel reaches the destination on time most safely and cost-effectively. The need for accurate positioning in the harbor is critical due to short distances, increased vessel traffic, and possible obstacles that make maneuvering more difficult.

There are several systems to facilitate the accurate positioning of autonomous vessels, including GNSS with real-time kinematic (RTK) positioning, and dynamic positioning (DP). RTK positioning is a technique aiming to improve satellite-based operation using a reference radio signal from a fixed base station [3]. This method provides an accuracy of $0.01 - 0.03$ m. However, the applicability area of this method is limited, since the reference station shall be close to the receiver to provide support [4], [5].

The main components of a DP system are the positioning system itself, the DP computer, and the thrusters. The vessel is kept at the intended heading and position based on the DP computer calculations, controlling maneuvering thrusters, and main propellers of the vessel accordingly [6, 7]. The on-board positioning system complements the DP system, by providing the references of the objects on the propagation way, and around the vessel. Using these references, the collision avoidance system either makes the correction in the trajectory of the path or gives the warning about the possible collision. The most common position reference methods involve Global Positioning System (GPS) satellites and the differential GPS position reference method, which combines GPS positioning together with the fixed ground-based reference station. These methods alone, however, are not accurate enough to be utilized for maritime applications in all conditions, mostly because of the degradation of the signal due to atmospheric disturbances, or blockage of line-of-sight (LoS) [8].

The Arctic is known for being a challenging area not only due to severe weather but also telecommunication and positioning limitations. Many research groups delved into the Arctics research in this field [9, 10, 11]. One of the challenges causing the satellite positioning performance reduction in the Arctic is related to ionospheric disturbances that cause delays and scintillation of the satellite signals [11]. The survey [12] mainly indicates that the GNSS performance in the Arctic is suboptimal. The GNSS satellite constellation geometry causes another positioning-related challenge. The reason is that the medium Earth orbiting (MEO) positioning satellites are visible at low elevation angles, which makes the signal perception suffer from the possible blockage.

In this study, we contribute to the related works on positioning in the Arctic region. The novelty of this work lies in the evaluation of the performance of existing positioning systems for the autonomous maritime domain using the simulation framework, which integrates the real models of GNSS signals. We are focusing on the comparison of positional accuracy of GPS, GLONASS, and Galileo systems in terms of satellite visibility and geometry of the satellite propagation.

The rest of the paper is organized as follows. Section 2 describes the positioning of autonomous vessels, including step-by-step operations. In Section 3, we describe the simulation environment, focusing on GNSS constellation analysis for the Arctic region. Next, in Section 4, we provide the results of our simulation system. Further, Section 5 discusses on-going projects that are aiming to advance the positional accuracy, specifically in the Arctic. Possible solutions on how to improve the positioning accuracy are also discussed. The last section concludes the paper.

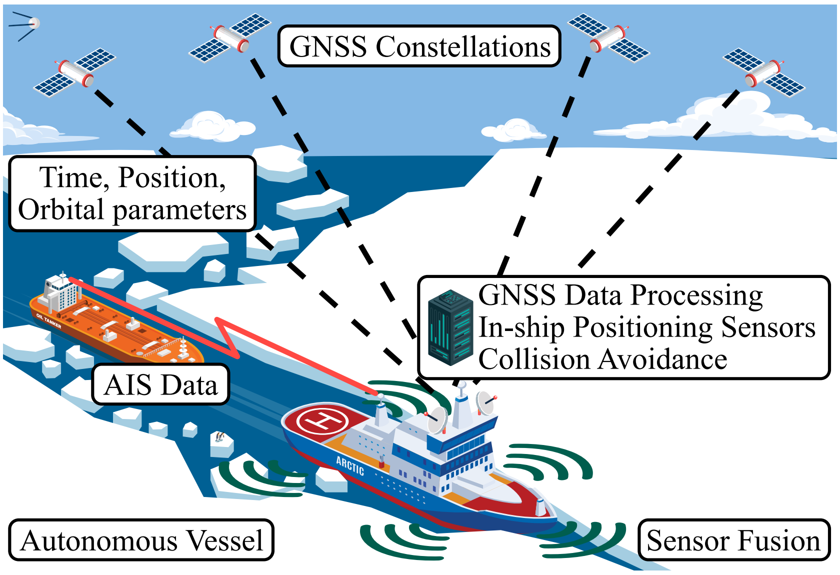

Figure 1: High-level autonomous vessel positioning architecture.

2. Main Positioning System Operation

The system architecture is depicted in Fig. 1. We assume that an autonomous vessel is operating in the Arctic conditions. The vessel uses a DP system with situational awareness sensors for collision avoidance (CA) updating its position information with other vessels using an automatic identification system (AIS). The used GNSS comprises three major segments: the space segment, the control segment, and the user segment.

The space segment consists of the GNSS satellite constellation. For the GNSS positioning to work, at least four satellites must be visible at all times. More than four visible satellites will increase the estimation robustness and minimize the degradation in the accuracy. Every satellite positioning system is different with respect to orbital altitude, the positioning of the satellites in orbit, and the number of satellites. The main parameters of the examined GNSSs are given in Table 1.

The GNSS control segment is responsible for the management of the satellite constellation. It includes tracking, deployment, and maintenance of the system. The GNSS control segment is generally comprised of three main systems: (i) Master Control Station (MCS), (ii) network of four ground antennas (GAs), and (iii) network of monitor stations (MSs). MCS is responsible for the monitoring of the satellite's payload status and maintenance performance of constellation. The GAs track the satellites, and the MSs monitor the transmissions. There might be a Backup Master Control Station (BMCS) deployed, which role is to support GNSS constellation operation during the MCS outage [13, 14].

The user segment consists of L-band radio receiver and processors that solve navigation equations. The vessel navigation transponders operate in the very high-frequency (VHF) maritime bands. The obtained positioning information is transmitted to other vessels or shore stations within the AIS. This information is used for vessel traffic control and provides general situational awareness.

Standard Positioning Service (SPS) is a positioning and timing service provided by all satel-

Table 1
GNSS Constellations Main Parameters

	GPS	**GLONASS**	**Galileo**
Orbit type	MEO	MEO	MEO
Altitude	$20,200$ km	$19,100$ km	$23,222$ km
Number of operational satellites	31	24	22
Number of orbital planes	6	3	3
Inclination	55^o	64.8^o	56^o
Orbital period of one satellite	11 h and 58 min	11 h and 15 min	14 h and 5 min

lites in the constellation [13]. Specifically, SPS is the characteristic of GPS, however similar technologies are implemented for GLONASS (Standard Accuracy Signal service) [15], and Galileo (Open Service (OP)) [16]. The GNSS constellation is developed so that the user is able to observe at least four satellites from any point of the planet. All four satellites broadcast the message containing the navigational data that indicates the extremely accurate timestamp obtained from atomic clocks on-board the satellites and the position of each satellite. For the positioning service to work accurately, the receiver shall have an unobstructed view to at least four satellites to calculate three position coordinates and the clock deviation. The data provided from the satellites allows the user to calculate, so-called, pseudorange – the approximate distance from the satellite to the receiver based on the time the signal has traveled [17, 18].

The following steps describe the operation of the position calculation for the user equipment:

1. The receiver selects at least four satellites. The satellite selection can be based on the signal state, or the optimal geometries, by defining the smallest dilution of precision value [19], [20], [21].
2. After the selection of four satellites, the receiver calculates the pseudorange p_i for each satellite. The pseudorange is different from the real range due to errors such as receiver clock error, errors caused by ionosphere refraction, and multipath propagation [22]. The receiver uses the correction data from the satellite to minimize the difference and reach the accurate results.
3. After defining the pseudorange, the receiver defines the known position vector for each i^{th} satellite, using the orbit parameters extracted from the navigation message. Based on that information, the receiver calculates its own unknown position vector according to the following equation [17]

   $$p_i = \sqrt{((X_i - x)^2) + ((Y_i - y)^2) + ((Z_i - z)^2)} + c\Delta t, \tag{1}$$

   where c is the speed of light, Δt is the time offset between the receiver clock and the satellite timestamp. This way, the position of the receiver is given in the Cartesian coordinates (X_i, Y_i, Z_i) for each i^{th} satellite.

In order to evaluate the considered scenario, we have executed the simulation campaign.

Table 2
Satellite visibility for different GNSS

		Number of visible satellites		
System	**Degrees, ϵ**	**maximum**	**minimum**	**average**
GPS	10^o	13	6	8
	20^o	11	3	6
	30^o	8	2	4
GLONASS	10^o	11	6	9
	20^o	10	4	7
	30^o	9	3	5
Galileo	10^o	11	6	8
	20^o	9	4	6
	30^o	6	2	4

3. Simulation Environment Description

The comparison was executed between three satellite positioning systems: GPS, Galileo, and GLONASS. The comparison was made using the extensive set of simulations of Systems Tool Kit (STK) [23]. In the simulations, the vessels were distributed through the entire area of the Arctic region. In total, ten vessels were distributed in the area of interest, covering the main shipping routes. The vessels were moving at the speed of 20 knots [24].

STK provides real models of the GNSS constellation. It provides the GNSS almanacs that contains an up-to-date set of data that every GNSS satellite transmits, and includes information such as state of the entire constellation and coarse data on every satellite's orbit. The repeat cycle of a satellite constellation is the period after which the entire constellation returns to the initial position. While the repeat cycle of the entire GPS constellations is equal to 1 sidereal day (approximately 23 hours and 56 minutes), GLONASS and Galileo constellations will return to the initial position in 8 and 10 sidereal days respectively [25, 26]. We evaluated an entire 10 days period and noticed that 48 hours is enough to capture a relevant range of variation regarding the visibility of satellites in the region of interest (Fig. 2)). Thus, the results achieved with 48 hours period are used to analyze the maximum and the minimum number of satellites. The period of the simulations was from 20.02.2020 10:00 UTC to 22.02.2020 10:00 UTC.

4. Numerical Results

This section outlines the numerical results related to the positioning accuracy of various systems and elevation angles.

4.1. Satellite visibility comparison

We have compared the GNSSs in terms of the visibility of the satellites in the Arctic region. The simulation results are presented in Table 2 and show the satellite visibility during the 48

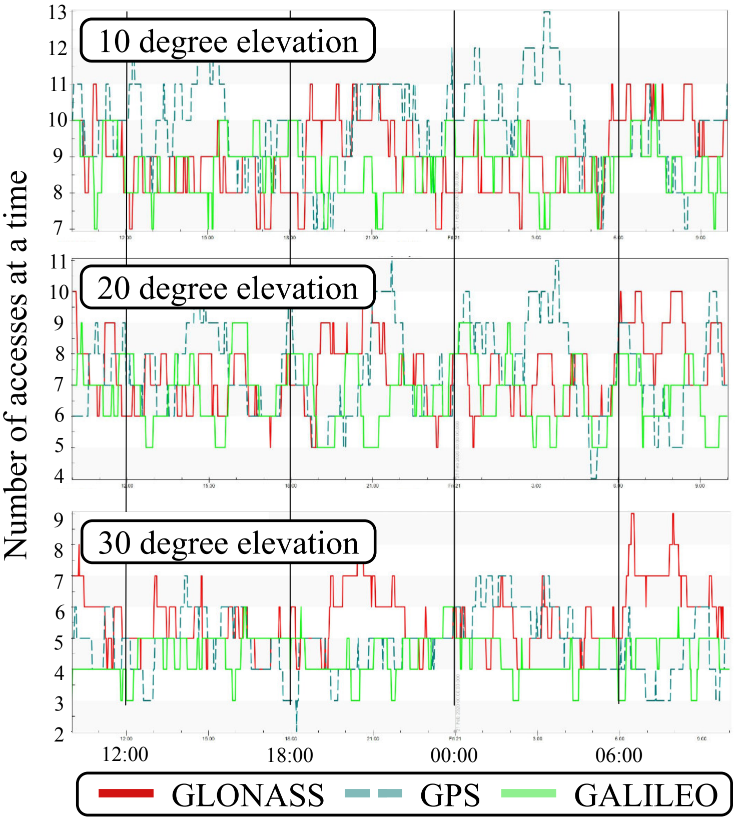

Figure 2: Comparison of the GNSSs: 20.02.2020 10:00 UTC – 21.02.2020 10:00 UTC.

hours period. The values presented in the table reflecting the satellite visibility from all ten vessels distributed in the Arctic region. The single satellite coverage area is defined as a region of the Earth from where the satellite is seen at a minimum predefined elevation angle ϵ [27].

In our simulations, a simple receiver model for the vessel has been used. The receiver shall have a clear view of the sky, ensuring a direct LoS with as many visible satellites as possible [28]. The target of our study was to know the ability of the vessels to locate themselves with different values of ϵ. The value $\epsilon = 10^o$ was chosen as the minimum elevation angle for the Arctic environment in order to prevent possible blockage caused by natural barriers at the open sea, such as icebergs, or by the vessel itself [12]. Then ϵ was increased up to 30^o in order to simulate possible blockage of the LoS caused by the infrastructure at the port. At $\epsilon = 30^o$, some of the systems have shown uncertain performance, which is discussed further.

According to Fig. 2, GPS provides a maximum number of visible satellites for the lowest elevation angle (10^o) while comparing to other systems. However, by increasing the elevation angle of the receiver, the performance of the GPS (as well as Galileo) reduces. The GLONASS system, however, is able to provide sufficient coverage even with the high elevation angles. Fig. 3 shows that more GLONASS satellites are present at some of the time instants (20.02.2020 10:00-11:00 UTC, 20.02.2020 19:30-22:10 UTC, and 21.02.2020 6:00-8:30 UTC), which may potentially result in better accuracy at that time. However, GLONASS shows equal performance as other GNSS for other time instants. One of the explanations for these results is that orbits of GPS, as well as Galileo constellations, are more inclined from

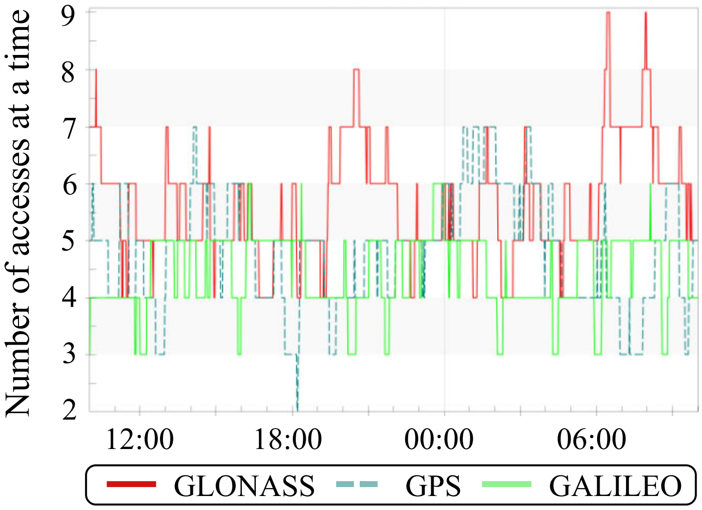

Figure 3: Number of visible satellite accesses from a single vessel, elevation angle $\epsilon = 30^o$: 20.02.2020 10:00 UTC – 21.02.2020 10:00 UTC.

the Polar Regions. In general, it can be concluded that the satellite visibility of all GNSSs is sufficient in the area of interest while having a maximum elevation angle of less than 20^o. However, such low elevation angles might be a reason for the high noise level satellite signals, which can lead to the positioning accuracy reductions [12].

4.2. Arctic Region Positioning Accuracy Analysis

User accuracy refers to how close the device's calculated position is from the truth, expressed in meters. Fig. 4 shows the snapshot of the positioning accuracy of three GNSS constellations, Galileo, GLONASS, and GPS, for the Arctic Region. The snapshot is captured at 21.02.2020 07:17 UTC, and it shows that the GLONASS system provides the highest accuracy at this particular time. The positioning accuracy calculation is based on the one-way range measurements from the constellation. If four or more of the satellites are in the view of the ground receiver, the position of the receiver and the offset between the receiver clock and the GNSS clock can be computed. During these measurements, the elevation angle of the receiver is not taken into account. The accuracy measurements take into account the geometry of the satellite propagation and the uncertainty in the one-way range measurements. The uncertainty range was equal to 1 m. The positioning accuracy varies dynamically with time. The dynamic map of the positioning accuracy in Fig. 4 shows the accuracy variations between $0.9 - 2.7$ meters. On average, for the entire period of simulations, the GPS constellation provided $0.9 - 2.7$ m accuracies, the GLONASS provided the accuracy performance of $0.9 - 2.5$ m and the Galileo provided the accuracy of $1 - 2.3$ m. For the autonomous vessel positioning, the accuracy in the range of $1 - 3$ meters in the open sea in most cases is sufficient.

5. On-going projects and potential future research directions

As it was highlighted before, the positioning accuracy requirements vary depending on the environment. If positioning accuracy in the range up to 3 meters is sufficient in most cases in the open sea, the positioning requires higher accuracy in the marine more than current GNSSs can

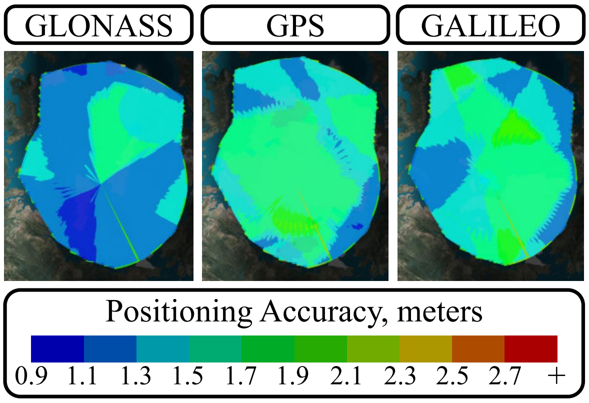

Figure 4: The snapshot (21.02.2020 07:17) of positioning accuracy of the Galileo, GLONASS and GPS constellations created using the simulation environment STK: Coverage module [29].

provide [30, 31, 32]. To address positioning problems, European Space Agency (ESA) started the support of several projects within ESA's Discovery & Preparation program in 2019. One of the projects, AMNAS [33, 34], is aimed to explore ways of broadcasting navigation messages via satellites to vessels in order to correct the vessel's trajectories and support navigation in the Arctic. The study is lead by Kongsberg Seatex, Space Norway, and General Lighthouse Authorities of the United Kingdom & Ireland [35].

In spring 2019, ESA allocated the NARWHALS project funding [36, 37] in collaboration with SpacEarth Technology, with the main objective to investigate solutions for more robust, high accuracy positioning in the Arctic regions both in shallow water and within ports. The project is oriented at maritime applications, such as transportation, search and rescue operations, research, and resource extraction activities.

Another project 5GIVE (5G-assisted Ground-based GalileoGPS receiver Group with Inertial and Visual Enhancement), carried out by University of Helsinki, is also funded by ESA, and is aimed to develop the methods of GNSS and terrestrial positioning signal fusion for robust and seamless navigation [38]. Unfortunately, the current status of the project is unknown.

The maritime solutions to support activities in the Arctic are also being investigated by the Technical Research Centre of Finland VTT Ltd [39]. The current study is partly carried out in the ongoing internal project FAST4NET (Feasibility Studies and Tools for Multilayered Non-Terrestrial and Terrestrial 3GPP Networks), where one of the main study items is the heterogeneous architecture for different autonomous system use cases for in-land and maritime environment besides the positioning.

In order to improve positioning accuracy for autonomous vessels' operation, we outline different strategies that shall be taken into account in further studies.

One of the most widely used techniques to achieve this goal is to apply *hybrid positioning techniques*. Generally, the level of autonomy of the vessel will depend on the vessel type, size, and the operational environment. The more complex the mission of the autonomous vessel is, the more strict requirements it will have to the positioning systems. Extensive work has been already done on the existing solutions to add positioning and collision avoidance redundancy in the autonomous vessel operation [32, 40, 41, 42, 43, 44, 45]. For example, the hybrid positioning techniques may include land-based external reference systems for aided navigational reliability when operating in the proximity of the shore. Land-based cameras and radars can be used to navigate the vessel along the shore safely. As GPS may not always be available and sufficient, the cellular-based positioning techniques also can be useful when available [46].

The autonomous vessel navigation is likely to use many supporting systems and another intuitive step to improve positioning accuracy is to use *sensor fusion for navigation.* As it is shown in [40], the autonomous vessel autopilot system gets the positioning data not only from GNSS satellites, but also from the gyro-compass, internal motion units (IMU), and additional sensors such as Sound Navigational Ranging (SONAR), laser-based position reference systems such as Light Detection and Ranging (LiDAR), as well as the radar-based systems [47]. Thus, one of the key technology for autonomous vessel navigation is sensor fusion, as no single sensor technology is able to provide sufficient performance considering different environmental conditions. Therefore, in order to guarantee that the information about the vessel's surroundings is accurate, the data from multiple sensors shall be combined and analyzed. An autonomous vessel shall utilize all available positioning methods to provide sufficient positioning. A robust sensor fusion algorithm is needed to aggregate data from different sensors employed on the autonomous vessel for continuous vessel positioning and situational awareness [48].

Finally, *vessel and satellite system simulations* could also significantly assist in achieving additional improvements. In this work, the comparative modeling provided useful initial information about the existing GNSSs and their performance in the Arctic. However, long-term simulations and more detailed analysis are needed in the future. That would include both defining the requirements for accuracy of positioning for certain ship types in selected places and finding out whether GNSSs alone or as a joint constellation could support the operations. The study can also be extended to cover other autonomous and remotely operated systems such as forestry machines or aerial vehicles.

6. Conclusions

The Arctic region has faced a growing interest due to the potential in an exploration of natural resources and marine transportation, including autonomous vessel navigation. There is a number of challenges related to localization and telecommunication capabilities in this area to unleash the potential fully. We have modeled and compared existing GNSS constellations and studied the positioning in the Arctic for the autonomous vessels. The simulations have shown sufficient visibility of the GNSS satellites, considering low minimum elevation angles at the receiving antennas and the accuracy of fewer than three meters in all studied constellations. However, the visibility of satellites in a single system can be limited at high minimum elevation angles. Accurate positioning can be achieved by the simultaneous utilization of a number of positioning systems.

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References

[1] S. Plass, F. Clazzer, F. Bekkadal, Current Situation and Future Innovations in Arctic Communications, in: Proc. of 82nd Vehicular Technology Conference (VTC2015-Fall), IEEE, 2015, pp. 1–7.

[2] J. V. Escusol, J. Aaltonen, K. T. Koskinen, Kategoria: Autonomous and Collaborative Offshore Robotics, 2017.

[3] M. Hoffmann, P. Kryszkiewicz, G. P. Koudouridis, Modeling of Real Time Kinematics Localization Error for Use in 5G Networks, EURASIP Journal on Wireless Communications and Networking (2020) 31.

[4] N. Joubert, T. G. Reid, F. Noble, Developments in Modern GNSS and its Impact on Autonomous Vehicle Architectures, arXiv preprint arXiv:2002.00339, 2020.

[5] K. de Jong, M. Goode, X. Liu, M. Stone, et al., Precise GNSS Positioning in Arctic Regions, in: Proc. of OTC Arctic Technology Conference, Offshore Technology Conference, 2014, pp. 1–10.

[6] A. Loria, T. I. Fossen, E. Panteley, A Separation Principle for Dynamic Positioning of Ships: Theoretical and Experimental Results, IEEE Transactions on Control Systems Technology 8 (2000) 332–343.

[7] H. Zheng, J. Wu, W. Wu, Y. Zhang, Robust Dynamic Positioning of Autonomous Surface Vessels with Tube-based Model Predictive Control, Ocean Engineering 199 (2020) 106820.

[8] K. Su, S. Jin, M. Hoque, Evaluation of Ionospheric Delay Effects on multi-GNSS Positioning Performance, Remote Sensing 11 (2019) 171.

[9] T. Reid, T. Walter, J. Blanch, P. Enge, GNSS Integrity in the Arctic, Navigation: Journal of the Institute of Navigation 63 (2016) 469–492.

[10] N. Linty, R. Romero, C. Cristodaro, F. Dovis, M. Bavaro, J. T. Curran, J. Fortuny-Guasch, J. Ward, G. Lamprecht, P. Riley, et al., Ionospheric Scintillation Threats to GNSS in Polar Regions: The DemoGRAPE Case Study in Antarctica, in: Proc. of European Navigation Conference (ENC), IEEE, 2016, pp. 1–7.

[11] M. Kirkko-Jaakkola, L. Leppälä, G. Ferrara, S. Honkala, M. Mäkelä, H. Kuusniemi, S. Miettinen-Bellevergue, Challenges in Arctic Navigation and Geospatial Gata: User Perspective and Solutions Roadmap, [Online] http://urn.fi/URN:ISBN:978-952-243-576-7, 2020.

[12] L. Leppälä, S. Honkala, G. Ferrara, M. Kirkko-Jaakkola, H. Kuusniemi, H. Miettinen-Bellevergue, Challenges in Arctic Navigation: The User Perspective, in: Proc. of European Navigation Conference (ENC), IEEE, 2019, pp. 1–8.

[13] J. G. Grimes, Global Positioning System Standard. Positioning Service Performance Standard, Department of Defense, Global Positioning System, 2008.

[14] National Coordination Office for Space-Based Positioning, Navigation, and Timing, Official US Government Information about the Global Positioning System (GPS) and Related Topics, [Online] https://www.gps.gov/systems/gps/space/, 2020.

[15] ESA Navipedia, GLONASS General Introduction, [Online] https://gssc.esa.int/navipedia/index.php/GLONASS_General_Introduction, 2018.

[16] European Global Navigation Satellite Systems Agency, Galileo Services, [Online] https://www.gsa.europa.eu/galileo/services, 2018.

[17] S. Dawoud, GNSS Principles and Comparison, Potsdam University, 2012.

[18] R. Wu, W. Wang, D. Lu, L. Wang, Q. Jia, Principles of Satellite Navigation System, in: Adaptive Interference Mitigation in GNSS, Springer, 2018, pp. 1–29.

[19] B. Wu, Q. Yang, X. Mao, Q. Ren, H. Su, A Novel Fast Satellite Selection Algorithm for multi-GNSS Positioning, in: Proc. of Chinese Automation Congress (CAC), IEEE, 2019, pp. 664–668.

[20] M. Zhang, J. Zhang, A Fast Satellite Selection Algorithm: Beyond Four Satellites, IEEE Journal of Selected Topics in Signal Processing 3 (2009) 740–747.

[21] T. Walter, J. Blanch, V. Kropp, Satellite Selection for multi-Constellation SBAS, in: Proc. ION GNSS, 2016, pp. 1350–1359.

[22] M. Z. H. Bhuiyan, E. S. Lohan, Multipath Mitigation Techniques for Satellite-based Positioning Applications, Global Navigation Satellite Systems: Signal, Theory and Applications; Jin, S., Ed (2012) 405–426.

[23] Analytical Graphics, Inc., AGI's ready-to-use STK and ODTK families of products, enterprise software, and developer tools, [Online] https://www.agi.com/products, 2020.

[24] A. Afonin, E. Ol'Khovik, A. Tezikov, Study of Ship Speed Regimes in the Arctic Sea Ice Conditions, in: Proc. of IOP Conference Series: Earth and Environmental Science, IOP Publishing, 2018, pp. 1–5.

[25] R. Dach, E. Brockmann, S. Schaer, G. Beutler, M. Meindl, L. Prange, H. Bock, A. Jäggi, L. Ostini, Gnss processing at code: status report, Journal of Geodesy 83 (2009) 353–365.

[26] L. Pan, X. Zhang, X. Li, X. Li, C. Lu, J. Liu, Q. Wang, Satellite Availability and Point Positioning Accuracy Evaluation on a Global Scale for Integration of GPS, GLONASS, BeiDou and Galileo, Advances in space research 63 (2019) 2696–2710.

[27] S. Cakaj, B. Kamo, A. Lala, A. Rakipi, The Coverage Analysis for Low Earth Orbiting Satellites at Low Elevation, International Journal of Advanced Computer Science and Applications (IJACSA) 5 (2014).

[28] UBX-15030289 – R03, GNSS antennas: RF design considerations for u-blox GNSS receivers, [Online] https://www.u-blox.com/sites/default/files/products/documents/GNSS-Antennas_AppNote_%28UBX-15030289%29.pdf, 2020.

[29] Analytical Graphics, Inc., Introduction to STK Coverage, [Online] https://help.agi.com/stk/index.htm#cov/intro.htm, 2020.

[30] E. S. Lohan, K. Borre, Accuracy Limits in multi-GNSS, IEEE Transactions on Aerospace and Electronic Systems 52 (2016) 2477–2494.

[31] Y. Lou, F. Zheng, S. Gu, C. Wang, H. Guo, Y. Feng, Multi-GNSS Precise Point Positioning with Raw single-Frequency and dual-Frequency Measurement Models, GPS Solutions 20 (2016) 849–862.

[32] Y. Dobrev, M. Vossiek, M. Christmann, I. Bilous, P. Gulden, Steady Delivery: Wireless Local Positioning Systems for Tracking and Autonomous Navigation of Transport Vehicles and Mobile Robots, IEEE Microwave Magazine 18 (2017) 26–37.

[33] GRAD. Driving Innovation for Safer Maritime Navigation, AMNAS, [Online] https://www.gla-rad.org/projects/amnas/, 2020.

[34] Kongsberg, AMNAS project. Challenges and Opportunities for Satellite Communications and Navigation Augmentation Systems in Maritime VHF Bands, [Online] https://nebula.esa.int/sites/default/files/neb_study/2480/C4000119199ExS.pdf, 2019.

[35] ESA, Enhancing satnav for Arctic voyagers, [Online] https://www.esa.int/Enabling_Support/Preparing_for_the_Future/Discovery_and_Preparation/Enhancing_satnav_for_Arctic_voyagers, 2019.

[36] ESA, NARWHALS – Navigation in ARctic With gnss High Accuracy Low power Solution, [Online] https://business.esa.int/projects/narwhals, 2019.

[37] SPACEARTH Technology, NARWHALS, an ESA funded project to support the

maritime navigation in Arctic, [Online] http://www.spacearth.net/images/blog/2019_NARWHALS.pdf, 2019.

[38] University of Helsinki, 5G-assisted Ground-based Galileo-GPS receiver Group with Inertial and Visual Enhancement, [Online] https://researchportal.helsinki.fi/en/projects/5g-assisted-ground-based-galileo-gps-receiver-group-with-inertial, 2020.

[39] Arctic Finland Portal to Finnish Arctic Policies, Research and Business, VTT Technical Research Centre of Finland Ltd, [Online] https://www.arcticfinland.fi/EN/Research/vtt, 2020.

[40] A. Felski, K. Zwolak, The Ocean-going Autonomous Ship–Challenges and Threats, Journal of Marine Science and Engineering 8 (2020) 41.

[41] M. Mukhtar, GPS based Advanced Vehicle Tracking and Vehicle Control System, International Journal of Intelligent Systems and Applications 7 (2015) 1.

[42] T. Suzuki, M. Kitamura, Y. Amano, T. Hashizume, High-accuracy GPS and GLONASS Positioning by Multipath Mitigation Using Omnidirectional Infrared Camera, in: Proc. of IEEE International Conference on Robotics and Automation, IEEE, 2011, pp. 311–316.

[43] A. Yastrebova, M. Höyhtyä, M. Majanen, Mega-constellations as Enabler of Autonomous Shipping, in: Proc. of AIAA International Communications Satellite Systems Conferences (ICSSC) [To appear], 2019, pp. 1–7.

[44] E. Jokioinen, J. Poikonen, R. Jalonen, J. Saarni, Remote and Autonomous Ships–The Next Steps, [Online] https://www.rolls-royce.com/~/media/Files/R/Rolls-Royce/documents/customers/marine/ship-intel/aawa-whitepaper-210616.pdf, 2016.

[45] C. Castillo, A. Pyattaev, J. Villa, P. Masek, D. Moltchanov, A. Ometov, Autonomous UAV Landing on a Moving Vessel: Localization Challenges and Implementation Framework, in: Proc. of Internet of Things, Smart Spaces, and Next Generation Networks and Systems, Springer, 2019, pp. 342–354.

[46] S. Kavuri, D. Moltchanov, A. Ometov, S. Andreev, Y. Koucheryavy, Performance Analysis of Onshore NB-IoT for Container Tracking During Near-the-Shore Vessel Navigation, IEEE Internet of Things Journal, 2020.

[47] M. Kiviranta, I. Moilanen, J. Roivainen, 5G Radar: Scenarios, Numerology and Simulations, in: Proc. of International Conference on Military Communications and Information Systems (ICMCIS), IEEE, 2019, pp. 1–6.

[48] J. Kang, M. Jin, J. Park, D. Park, A Study on Application of Sensor Fusion to Collision Avoidance System for Ships, in: Proc. of International Conference on Control, Automation and Systems (ICCAS), IEEE, 2010, pp. 1741–1744.