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Positioning in the Arctic Region: State-of-the-Art and Future Perspectives

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ABSTRACT The positioning systems' high accuracy and reliability are crucial enablers for various future applications, including autonomous shipping worldwide. It is especially challenging for the Arctic region due to the lower number of visible satellites, severe ionospheric disturbances, scintillation effects, and higher delays than in the non-Arctic and non-Antarctic regions. In regions up North, conventional satellite positioning systems are generally proposed to be utilized, together with other situational awareness systems, to achieve the necessary level of accuracy. This paper provides a detailed review of the current state-of-the-art, satellite-based positioning systems' availability and performance and reports high-level positioning requirements for the oncoming applications. In particular, the comparative study between three Global Navigation Satellite System (GNSS) constellations is executed to determine whether they are suitable for autonomous vessel navigation in the Arctics' complex environment as the two most significant drivers for a reevaluation of the related satellite constellations. This work analyzes the ongoing research executed in different (inter-) national projects focused on Galileo, Global Positioning System (GPS), and GLObal NAvigation Satellite System (GLONASS). Based on the literature review and the simulation campaign, we conclude that all the convectional constellations achieve an accuracy of fewer than three meters in the analyzed Arctic scenarios. It is postulated that other complementary positioning methods should be utilized to improve accuracy beyond this limit. Finally, the study emphasizes existing challenges in the Arctic region regarding the localization and telecommunication capabilities and provides future research directions.

INDEX TERMS Marine navigation, Arctic, global positioning system, aerospace simulation, unmanned autonomous vehicles.

I. INTRODUCTION

The Arctic region is one of the leading developing prospects for various industries, including offshore extraction of resources and minerals, observational ecologies, such as Bentho-Pelagic monitoring [1], as well as one of the foremost maritime trading paths between the Atlantic and Pacific oceans [2]. It has been long observed that the shipping operations and the activities on the exploration of natural resources could be affected by poor navigational services and complex communication situations [3]. Furthermore, navigation in the Arctic is more demanding due to challenging weather conditions, ionospheric effects, complex properties of the ice surface, and mobility [4]. Today, the primary option for communications and navigation in the deep waters of the Arctic region is the satellite connectivity [5]. Additionally, the onshore infrastructure also provides timely notifications and precise positioning information from and to the vessels in order to minimize the possible damage caused by the potentially dangerous and unpredictable environment when available [6].

Wireless positioning is significant for the oncoming era of the Arctic region operation and, especially, autonomous vessel operation integrated with various robotic systems [7], [8]. It is vital to understand the threshold for an accurate positioning in the open sea and the harbor for safe maritime operations of crew-less vessels [9]. The positioning accuracy requirements may differ tremendously depending on

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TABLE 1. Summary of literature review and author contributions.

Topic of the Article	Contributions
Positioning requirements for autonomous vessels	Ongoing 3GPP standardization [10], [11], IMO standardization [12]
Characteristics of satellite systems	Current GNSS and Positioning services [13]–[15]; reference systems to improve accuracy [16]–[20]; scintillation mitigation techniques [21]
Satellite navigation for tracking	Satellite-based Automated Identification Data Exchange Systems (SAT-AIS) for maritime communications [22], [23]; use of microsatellites for tracking [24]–[27]
Remote sensing for positioning	Satellite-based Earth Observation (EO) techniques [28]–[33]; terrestrial techniques, including acoustic [34]–[36] and laser-ranging [37], [38] techniques
Satellite-terrestrial connectivity	Hybrid positioning techniques [8], [39]–[45]; sensor fusion [8], [46]–[48]
Ongoing strategic work	Activities on monitoring and observations in the Arctic [49]–[55]
Current article	The state-of-the-art on the related academic works and industrial projects for positioning; the description of the related challenges and possible solutions; the description of the positioning requirements for autonomous systems; the simulation performance assessment of existing positioning systems for the autonomous Arctic maritime domain in terms of satellite visibility and geometry of the satellite propagation; the assessment of future technologies and solutions to support autonomous system operation with the focus on autonomous vehicles and vessels.

the application's environment: whether the system provides primary navigation in the open sea or 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 in comparison to deep-water missions.

The Arctic region, defined as the region above the Arctic circle (or 66.56 degrees latitude North), is known for being a challenging area, not only due to severe weather but also due to wireless telecommunication and positioning limitations. Many research groups have delved into the Arctics research in this field [5], [56]–[58]. One of the challenges causing a reduction in the Arctic satellite positioning performance is related to ionospheric and tropospheric disturbances that cause random delays and scintillation of the satellite signals [5]. These effects are even greater when the satellite is closer to the horizon [59], [60]. The survey [4] mainly indicates that the GNSS performance in the Arctic is sub-optimal. The GNSS satellite constellation geometry, typically measured through the Geometric Dilution of Precision (GDOP) metric, causes another positioning-related challenge. The associated problem may be related to the constellation design of many medium Earth orbiting (MEO) positioning satellites and the affected time shifts. As discussed in [61], the satellite visibility from the low-elevation angles may be obstructed by location-specific conditions, and signals from high-elevation angles are unavailable due to time- and location-specific conditions. Moreover, the received signal suffers from possible blockages due to icebergs, hills, other vessels, etc., causing multipath. The operational scenarios of the positioning in the Arctics are, indeed, vast, see Fig. 1.

Several techniques aim to improve the positioning performance, such as differential positioning, satellite-based augmented systems, and satellite-based automated identification

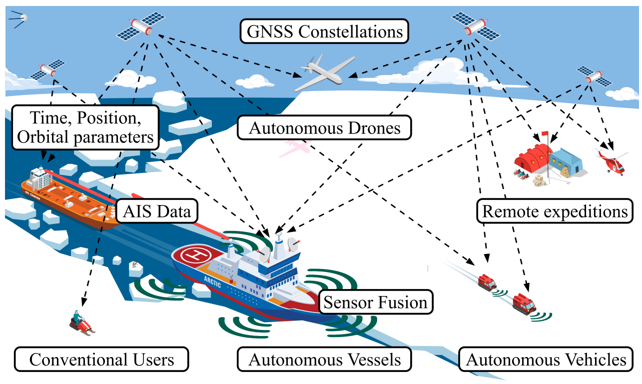

FIGURE 1. High-level autonomous vessel positioning architecture.

data exchange systems. Other techniques may involve Earth Observation (EO) systems to map the region with potential challenges, such as formations of ice or icebergs (as well as their mobility) to provide enhanced information to the vessels. Vessels may use the EO data with a geotag to identify those regions in advance and possibly avoid them. This technique will not achieve a sub-meter-level positioning, but it might support other techniques to improve positioning performance. A combination of space and terrestrial sensing techniques can provide more in-depth and more redundant information on the environment by validating both systems' information. The intelligent combination of these techniques may be vital for enabling reliable positioning in the Polar regions.

Table 1 provides a summary of related works and indicates contributions of the current work. During the literature review, it was found that the topic of positioning regarding autonomous systems is lacking. Thus, this paper contributes to the overall picture by studying the positioning requirements and performance, focusing on autonomous systems, such as autonomous vehicles and vessels operation.

The rest of the paper is organized as follows. Section II describes the positioning requirements for autonomous

TABLE 2. Positioning requirements depending on the application and service availability based on [62].

<table>
<tr><th>Application</th><th>Accuracy</th><th>Availability</th></tr>
<tr><td>Hydrography</td><td>1-2 [m] of horizontal positional accuracy</td><td rowspan="4">99.8% service availability per 30 days</td></tr>
<tr><td>Icebreakers</td><td>1 [m] of horizontal positional accuracy</td></tr>
<tr><td>Automatic collision avoidance</td><td>10 [m] of horizontal positional accuracy</td></tr>
<tr><td>Automatic docking</td><td>0.1 [m] of horizontal positional accuracy</td></tr>
</table>

vessels and the current state of standardization. Section III discusses ongoing projects aiming to advance the positional accuracy, specifically in the Polar regions, with the classification into space, terrestrial, and research activities. In Section IV, the architecture of autonomous vessels' positioning is described, including step-by-step operations and the simulation environment, focusing on GNSS constellation analysis for the Arctic region. Next, in Section V, we provide the results of our simulation system. Further, Section VI sheds some light on the future perspectives of the related positioning challenges and potential solutions. The last section concludes the discussion.

II. TECHNICAL REQUIREMENTS, STANDARDIZATION, AND REGULATIONS

A. TECHNICAL REQUIREMENTS

Positioning is an essential feature to sail safely and track goods anywhere, which is also very important in icy Arctic conditions. Accurate and reliable positioning will be especially critical in future autonomous systems that will operate without the onboard crew's support.

Positioning requirements for autonomous vessels are not standardized yet (ongoing work is described in 3GPP [10], and requirements for maritime use cases related to the goods tracking are described in [11]). Netherlands Regulatory Framework (NeRF) describes future GNSS requirements, a summary of the requirements provided in Table 2. According to the revised maritime policy [62], the general requirement for the positioning is 10 m of horizontal accuracy. However, for specific applications, such as ice-breaking and hydrography, the required accuracy is 1-2 meters with service availability of 99.8% per 30 days. The policy also specifies the cases' positioning requirements, such as automatic docking – accuracy must be 0.1 meter. The requirements might be tightened for the speed of the vessel above 30 knots.

B. THE INTERNATIONAL MARITIME ORGANIZATION REGULATIONS

Broadly, the International Maritime Organization (IMO) has published The International Regulations for Preventing Collisions at Sea (COLREGS) [12] in 1972, where the requirements and rules for the operations on a vessel are described. These requirements refer to the vessel equipment, its use, and the rules for the onboard passengers. According to these regulations, "every vessel shall at all times maintain a proper look-out by sight and hearing as well as by all available means appropriate in the prevailing circumstances and conditions to make a full appraisal of the situation, and the risk of collision" (COLREGS rule 5) [12]. Also, "vessels are required to make proper use of radar equipment to obtain early warning of the risk of collision, to use radar plotting or equivalent systematic observation of detected objects, and are warned that assumptions shall not be made based on scanty information" (COLREGS rule 7b,c) [63].

The regulatory framework is limited to human vision and hearing, and the vessel equipment such as radar, Automatic Radar Plotting Aid (ARPA), Automated Identification System (AIS), Electronic Chart Display Information System (ECDIS), and GNSS. For autonomous vessels, the use of only these technologies cannot ensure the safety of navigation. The IMO is currently conducting a regulatory campaign to provide a set of recommendations for the safe and secure operation of partly or wholly autonomous vessels and their interactions with other traffic participants. The research and development are currently limited to within national waters [64].

III. TECHNOLOGY REVIEW

Currently, the satellite capabilities in northern regions do not entirely fulfill the autonomous vehicle operation requirements in communications and positioning. These limitations include ionosphere signal disruption and attenuation, troposphere effects, etc. Due to these challenges, neither autonomous vessels nor any other unmanned surface vehicles can exploit their potential in the Arctic regions. To address these challenges, both industry and academia perform a significant number of trials and research activities. The ongoing research is mainly concentrated in several areas: the terrestrial infrastructure, the space systems, and possible techniques to mitigate the satellite reception's scintillation [21], [24], [28], [52]–[55], [65].

As of today, the Arctic region space infrastructure provides the following abilities [66]:

- Navigation satellites and space-based augmentation systems;
- Remote sensing and Earth observation techniques;
- Satellite-based Automated Identification (SAT-AIS) Data Exchange Systems for maritime communications;
- Satellite navigation for tracking and different types of vehicles (manned and unmanned).

In the current section, we will review technologies, starting from the GNSS characteristics and different positioning techniques, followed by the combination of different satellite and terrestrial applications to improve positioning. We will also review ongoing strategic work and provide highlights and objectives of each project.

A. GLOBAL NAVIGATION SATELLITE SYSTEMS AND AUGMENTATION SYSTEMS

1) SYSTEMS AND THEIR CHARACTERISTICS

The term GNSS covers all global positioning satellite systems that continuously transmit signals, which

TABLE 3. GNSS constellations' main parameters.

	GPS	GLONASS	Galileo	Beidou
Orbit type	MEO	MEO	MEO	GEO/IGSO/MEO
Altitude, km	20,200	19,100	23,222	21,528 & 35,786
Number of operational satellites	31	24	22	35
Number of orbital planes	6	3	3	3
Inclination	55^o	64.8^o	56^o	55^o
Orbital period of one satellite	11 h and 58 min	11 h and 15 min	14 h and 5 min	12 h 53 min

enable users to determine their position on the Earth: GPS (initially developed for military purposes); GLONASS, Galileo, and Beidou.

Every satellite positioning system is different concerning orbital altitude, the satellites' positioning in orbit, and the number of satellites. The main parameters of the examined GNSSs are given in Table 3 [14], [67]–[72].

The Russian GLONASS has the highest orbital inclination, compared with other systems, potentially implying better performance in the Arctic region. GPS satellite orbital planes incline 55^o, resulting in potential performance challenges at high latitudes. This tendency is also present for the other two systems – the European Galileo system and the Chinese Beidou. The latter provides its best coverage in the Asia-Pacific region [67].

Standard Positioning Service (SPS) is a positioning and timing service provided by all satellites in the constellation [13]. Specifically, SPS is the characteristic of GPS. However, similar technologies are implemented for GLONASS (Standard Accuracy Signal service) [14], and Galileo (Open Service (OP)) [15]. For the positioning service to work accurately, the receiver shall have an unobstructed view of at least four satellites to calculate three position coordinates and the clock deviation. The data provided from the satellites allows the user to calculate the approximate distance from the satellite to the receiver, based on the time the signal has traveled [73]–[75]. The GNSS performance in polar regions is related to the satellite constellations' geometry; the inclination data can be found in Table 3.

2) ASSISTANCE SYSTEMS TO IMPROVE ACCURACY

Besides the geometry limitations, high latitudes introduce significant oscillation and delay of the signals due to the ionosphere layer. Several techniques aim to improve the positioning performance. The most common position reference methods involve Global Positioning System (GPS) satellites and the differential GPS (DGPS) position reference method, which combines GPS positioning together with the fixed ground-based reference station. A DGPS can provide accuracy, in case of best implementation, of 1 meter for users in the range of a few tens of kilometers from the reference station [19]. However, the signal's degradation is mostly caused by the atmospheric disturbances or blockage of line-of-sight (LoS) [20]. For comparison, for a stand-alone receiver that uses only the satellites' signals, the accuracy performance levels vary from 2 to 10 meters [71].

Another technique to improve positioning is the real-time kinematic (RTK) positioning that implies the use of a reference radio signal from a fixed base station [16]. RTK is referred to as a differential GNSS, and this method suffers from similar issues as DGPS. This method provides an accuracy of 0.01–0.03 meters. However, this method's applicability area is limited since the reference station should be close to the receiver to provide support [17], [18].

3) SPACE-BASED AUGMENTATION SYSTEMS

Another method to improve the GNSS reception in high latitudes includes the use of the space-based augmentation systems (SBAS) [76].

SBAS is usually developed for specific purposes. Examples of these systems are the North American Wide Area Augmentation System (WAAS) with intended coverage over the United States, Canada, and Mexico [77] and the European Geostationary Navigation Overlay Service (EGNOS), providing service in Europe [78]; both are developed for the aviation purposes.

The EGNOS Safety of Life (SoL) service provides integrity information that is a measure of the trust that can be placed in the correctness of the information provided by a navigation system. The disadvantage is that both services rely on GEO satellites, which are not visible above 72 degrees North. However, the services have been successfully used for the GNSS-based landing operation below that latitude [79]. To resolve that problem, a new service, Advanced Receiver Autonomous Integrity Monitoring (ARAIM), is being under joint development by the EU and US and will start initial operation in 2025. The service will provide improved integrity, in particular for aviation and maritime sectors [79]. Currently, the EGNOS system supplements the GPS, but the system will also supplement the European Galileo in the future.

Meanwhile, the GALILEO Open Service and Search and Rescue (SaR) service are available in the Artic [79]. The Galileo Open Service supports positioning, navigation, and timing synchronization. The SAR Service improves the localization of the distress signals and is used for SAR operations and covers the Arctic region up to 85 degrees North latitude. This service helps to reduce the uncertainty down to less than 5 kilometers. The service's major upgrade is the Galileo Return Link option that became operational on January 21, 2020 [80]. The return link broadcasts a confirmation to the user that the distress message has been received.

4) GROUND-BASED AUGMENTATION SYSTEMS (GBAS)

GBAS is a system that provides a local augmentation of the primary GNSS constellations. This method offers integrity assurance and increased portioning accuracy with position errors below 1 meter. GBAS was developed for civil aviation in order to resolve real-time integrity monitoring issues. Pseudolites can be considered as an example of GBAS. Pseudolites are transceivers that are used to create a local ground-based alternative to GPS. They are used to provide extended coverage during poor satellite availability and improve GPS integrity and reliability. Pseudolites are independent of GPS and are used to augment the GPS by improving dilution of precision [81], [82].

5) MULTI-GNSS POSITIONING

Many works have considered the use of multiple GNSS constellations to improve integrity and coverage [83], [84]. Due to the GNSS constellations' design, the positioning performance is better in mid and low latitudes. In this case, especially in the polar regions, multi-GNSS advantages may include increasing satellites' availability and positional accuracy and reliability. However, the combined usage requires taking into account the variable interference and time offset between the individual system times, thus increasing the complexity of the system [85]. One of the major international activities related to multi-GNSS positioning is the International GNSS Service (IGS) - an international organization that involves over 200 participants, with the primary goal to support research related to the highly accurate combined utilization of GNSS. IGS has organized the multi-GNSS Experiment (MGEX) pilot project to collate and analyze all available GNSS signals. A network of multi-GNSS stations was established and integrated with the existing network of reference stations, including the polar regions [86], [87].

B. CURRENT TRACKING SYSTEMS

Potentially, satellite technologies may provide tracking capabilities at high latitudes to overcome terrestrial coverage limitations. The current section provides an overview of such used and future systems.

1) SATELLITE-BASED AUTOMATED IDENTIFICATION DATA EXCHANGE SYSTEMS (SAT-AIS) FOR MARITIME COMMUNICATIONS

The Automatic Identification System (AIS) is an automatic tracking system that is executed by transceivers on the vessels or by land-based systems and is used by vessel traffic services (VTS) [22]. The vessels of 300 gross tonnage or more sailing in the international waters and all passenger ships, regardless of the size, are required by IMO to have the AIS equipment operational.

The AIS signals have a horizontal range of about 40 nautical miles (74 km). That means that AIS information can only be available near the coastal areas or in a ship-to-ship line of sight. AIS equipment integrates the Very High-Frequency (VHF) transceiver (frequencies 161.975 MHz and 162.025 MHz, using 25 kHz bandwidth) and a satellite positioning system with other electronic navigation sensors. The satellites are used to detect AIS signatures, such as unique identification, position, course, and speed beyond the coastal area. This information is used to supplement marine radar. It should be noted that the degraded navigation solution will degrade the AIS use as well. The work [88] demonstrated the performance of AIS when the GPS signal was jammed. With total GPS denial, the AIS was unable to calculate the range to nearby vessels.

In order to provide the integrity of the navigational system for AIS use, ESA is cooperating with the European Maritime Safety Agency (EMSA) in order to deliver a European-based, satellite-based AIS (SAT-AIS) system that will increase the coverage and effectiveness of vessel traffic services [22], [23].

SAT-AIS is being developed through the Advanced Research in Telecommunications Systems (ARTES) program elements that include

- ARTES 5 – technology pre-development activities, such as antenna miniaturization, receiver developments, and a performance testbed;
- ARTES 20 – implementation and validation of a Data Processing Centre in cooperation with the European Maritime Safety Agency;
- ARTES 21 phase 1 – initial steps of the system design and implementation;
- ARTES 21 phase 2 – covers the detailed design and implementation of the SAT-AIS microsatellites and payloads and the development of innovative SAT-AIS applications and services.

2) MICROSATELLITES

Following the system definition and trade-off analysis carried out within SAT-AIS work, a new microsatellite ESAIL project was established due to the Public-Private-Partnership of LuxSpace with ESA in the ARTES program [24], [25]. Within the current project, a constellation of microsatellites has been designed to be the most cost-effective solution for providing SAT-AIS services and maintaining its viability [89]. The developed ESAIL microsatellites provide worldwide tracking capabilities for the vessels. ESAIL satellites will be launched into a Sun-synchronous orbit at an altitude of around 500 kilometers.

Generally, small satellite constellations nowadays are becoming more popular due to faster production and relatively cheaper launch into the orbits [90]. Usually, those satellites are placed at the LEO or Sun-synchronous orbits at a very low altitude. Several companies are developing and launching the constellations of small satellites for a variety of missions. Some of them include tracking services for maritime (ESAIL), aviation (Aistech [26]), and land vehicle (Astrocast [27]) domains.

C. REMOTE SENSING AND EARTH OBSERVATION TECHNIQUES TO IMPROVE POSITIONING

A combination of space and terrestrial sensing techniques can provide more in-depth and more redundant information on the environment by validating both systems' information. The current section describes examples of these techniques.

1) SATELLITE-BASED EARTH OBSERVATION (EO) TECHNIQUES

Earth observation and remote sensing techniques can provide strong support for safe navigation in the Arctic. While space-borne AIS receivers are used to track AIS-enabled vessels, Earth observation satellites can detect other non-AIS-enabled vessels; for example, the vessels are less than 300 gross tonnage and are not required to have AIS equipment on board. The information about the position of such non-AIS-enabled vessels can be distributed to other neighboring vessels to avoid the collision [91].

Another usage of EO satellites is the mapping of the ice conditions in the sea [79]. One of the challenges the vessels face in the Arctic regions is the lack of accurate maps, especially depth maps. An inaccurate depth map could lead to vessel grounding.

One of the Earth observation programs is the Copernicus program, which includes six dedicated satellites for information gathering and six operational thematic services for information distribution in the Arctic [28], [79]. The Copernicus Marine Environment Monitoring Service (CMEMS) provides information about the marine environment, such as water conditions, sea ice coverage, iceberg concentration, and so on [29].

The Copernicus Atmosphere Monitoring Service (CAMS) provides information on atmospheric composition and solar radiation [30]. The Copernicus Climate Change Service (C3S) delivers maps of sea ice in both the Arctic and Antarctic areas [32]. The Copernicus Land Monitoring Service (CLMS) monitors the snow cover, lake ice, inland water volume, and its quality [31].

Artificial Intelligence (AI) for space technologies is currently extensively studied by many researchers. The Danish Meteorological Institute (DMI), the Technical University of Denmark, and Harnvig Arctic & Maritime have initiated the Automated Sea Ice Products (ASIP) project, where the aim is to develop an automatic sea-ice service that can provide timely ice-mapping information and thus increase efficiency and safety of marine operations [33]. The project aims to merge the satellite imagery with other sensor data, such as passive microwave data, to resolve uncertainty in synthetic-aperture radar (SAR) imagery using Convolutional Neural Networks (CNN).

2) TERRESTRIAL TECHNIQUES

The terrestrial sensors may compliment EO satellites by providing information used to validate the satellite images and increase the accuracy of positioning by using additional reference frames to improve the satellite imagery data. In this review, we highlight acoustic and laser ranging techniques as mostly studied in modern literature.

a: ACOUSTIC TECHNIQUES

An example of such implementation can be named the Integrated Arctic Observing System (INTAROS) project [34]. INTAROS is an ongoing research and innovation project under the H2020-BG-09 call, which began in 2016 and will run until 2021. The project's overall objective is to develop a sustainable integrated Arctic Observation System (iAOS) by complementing the existing systems in the Arctic. The iAOS will contain a multi-purpose acoustic network designed for positioning, tomography, and communications. These networks have been used locally in the Arctic for underwater acoustic thermometry and for positioning for floats and gliders.

In the future, the Coordinated Arctic Acoustic Thermometry Experiment (CAATEX) is planned within the INTAROS project [36]. The problem that is being observed within the CAATEX is secure data delivery. The current solution lies in using submarine cables that are the dedicated cabled observatories. Several large-scale cabled observatories are existing coastal areas in the world oceans, but none on the Arctic Ocean. The considered solution consists of integrating sensors into future undersea telecommunications cables, which would create Science Monitoring And Reliable Telecommunications (SMART) subsea cable systems. The SMART sensor will take measurements of underwater pressure and temperature [35]. The INTAROS project is currently developing a Roadmap for the integrated Arctic Observing System [36].

b: LASER-RANGING TECHNIQUES

In 2017, the National Aeronautics and Space Administration (NASA), together with the Norwegian Mapping Authority, has started the development of a laser-ranging station within NASA's Space Geodesy Project (SGP) [37]. The laser-Ranging station will be placed around 1, 050 kilometers away from the North Pole in the scientific base of $Ny - lesund$, Svalbard. Continued development of the station will contribute to the satellites' high-precision positioning and operations on ice sheet tracking and improving transportation in the current region. The current station will complement the global network of space geodetic stations to provide information about the Earth by monitoring the position over time, the planet's size, and shape. The system uses the light measurements (the time it takes for the light to travel back to its point of origin) due to which the satellite location can be established with respect to the ground station with an accuracy of around 1 millimetre [38].

The purpose of the SGP is to develop sustainable NASA's legacy Space Geodesy Networks by constructing, deploying, and maintaining the next-generation Space Geodesy stations and contributing to the Global Geodetic Observing System. One of the main objectives of the SGP is to develop a

Terrestrial Reference Frame that has an accuracy of 1 mm with stability at 0.1 mm/year [37], [92].

D. HYBRID SATELLITE-TERRESTRIAL SYSTEMS

Hybrid satellite-terrestrial techniques to improve positioning include utilizing different systems, such as land-based external reference systems, cameras, radars, etc. These pose a challenge for an appropriate sensor fusion algorithm application. The current section discusses how data from multiple systems can be combined to improve positioning.

1) CONNECTIVITY DEVELOPMENT AND 3-DIMENTIONAL NETWORKS

In order to improve the positioning accuracy, *hybrid positioning techniques* can be applied. Extensive work has been already done on the existing solutions to add positioning and collision avoidance redundancy in the autonomous vessel operation [8], [39]–[44]. 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 GNSS signals may not always be available and sufficient, the cellular-based positioning techniques can also be useful when available [45].

Several methods are used to determine the position of an autonomous vehicle or a vessel. Those methods include various communication technologies, such as utilized in urban/rural areas – Wi-Fi, LTE, etc., as well as cameras, radars, and physical landmarks [39]. The location can be determined through the sensor fusion of several technologies. In this case, the need for communications increases as vehicles can send information about their location through the mobile communications network infrastructure.

For air navigation in the Arctic region, a satellite navigation system or ground-based radio navigation equipment is used as the primary system. Standard ground-based navigation equipment operates using Distance Measuring Equipment (DME) and the Instrument Landing System (ILS). The ground-based systems are used for rail traffic as well. Satellite-based positioning has replaced the VHF Omni-directional Range (VOR) and is supported by radar control for location determination. The satellite navigation will also complement the radars and radio systems for vessels and the visual safety systems [93].

The maritime solutions to support activities in the Arctic are also being investigated by the Technical Research Centre of Finland VTT Ltd [94]. 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.

2) COMBINATION OF SENSOR DATA TO IMPROVE POSITIONING

The autonomous vessels and vehicles are likely to use many supporting systems for positioning estimation, and another intuitive step to improve positioning accuracy is to use *sensor fusion for navigation*. Both autonomous systems get 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 [8], [46], [47]. The use of many technologies is essential, as no single sensor technology can provide satisfactory performance considering different environmental conditions. Therefore, to guarantee that the vessel's or vehicle's surroundings are accurate, the data from multiple sensors shall be combined and analyzed. A robust sensor fusion algorithm is needed to aggregate data from different sensors for continuous positioning and situational awareness [48].

E. ONGOING STRATEGIC WORK

There are many monitoring activities and improving positioning and communication infrastructure in the Arctic described in the current section. The summary of the projects is presented in Table 4.

1) SAON

Sustaining Arctic Observing Networks (SAON) is a joint activity of the International Arctic Science Committee (IASC) and the Arctic Council, which started in 2007, whose purpose is to support the development of multinational cooperation for sustained and coordinated pan-Arctic observation and data sharing systems [65]. SAON's main vision is to offer users free, open, and high-quality data to provide global societal benefits. Aiming to achieve that, in 2018, SAON issued a strategy [49] and implementation [98] plan for the next ten years. The strategy aims to address current and future Arctic observing needs to promote free and ethically open access to all Arctic observational data and ensure Arctic observing's sustainability.

2) EU-POLARNET

EU-PolarNet is the world's largest consortium of expertise and infrastructure for polar research, consisting of seventeen countries [50]. EU-PolarNet will develop a strategic framework and mechanism to optimize the current Arctic infrastructure. The consortium aims to develop an integrated EU Polar research program by identifying short- and long-term scientific needs and optimizing the use of coordinated Polar infrastructure for multi-platform science missions, while fostering trans-disciplinary collaboration on Polar research. One of the topics of the research is to improve satellite communication and navigation capabilities. In particular, the satellite limitations will be studied, i.e., ionosphere effects, lack of augmentation systems.

TABLE 4. Summary of the national and international projects.

Project	Objective	Year	Ref
NASA SGP	Development of Space Geodesy stations, incl. Laser-Ranging station, and contribution to Global Geodetic Observing System	2012–PR	[37], [38]
INTAROS	Development of an sustainable integrated Arctic Observation System (iAOS)	2016–2021	[34]
EU-PolarNet	Development of a strategic framework and mechanism to optimize the current Arctic infrastructure	2015–2020	[50]
ARKKI	Exploration of the most significant challenges in navigation and geospatial information-based applications in the Arctic region	2017–PR	[51], [93]
AMNAS (ESA's Discovery & Preparation program)	Investigation of the ways of navigation messages broadcasting via satellites to vessels in order to correct the vessel's trajectories and support navigation in the Arctic	2019–PR	[52], [95], [96]
NARWHALS	Investigation of solutions for robust, high-accuracy positioning in the Arctic regions both in shallow water and within ports	2019–PR	[53], [97]
ARTICOM	Assessment of the communication demands in the Arctic region	2015–2020	[54]
5GIVE	Development of the methods of GNSS and terrestrial positioning signal fusion for robust and seamless navigation	2019–2020	[55]
SAON	Addressing current and future Arctic observing needs in order to promote free and ethically open access to all Arctic observational data; to ensure the sustainability of Arctic observing	2018–2028	[49], [65], [98]
Copernicus Programme	European Union's Earth observation programme, aiming at achieving a global, continuous, autonomous, wide-range Earth observation capacity	1998–PR	[28]–[32]
ESAIL Microsatellite Programme	Microsatellites for provisioning worldwide tracking capabilities	2009–PR	[24], [25], [89]

3) ARKKI PROJECT

The ARKKI project is conducted by the Finnish Geospatial Research Institute in collaboration with the Finnish Ministry of Transport and Communications and aims to identify the most significant challenges in navigation and geospatial information-based applications in the Arctic region [51]. Within the project, the Action plan for the efficient deployment of satellite systems in Finland has already been published, which defines the necessary steps for improving positioning services in the Arctic [93].

4) ESA's PROGRAM AND PROJECTS

To address positioning problems, the European Space Agency (ESA) started supporting several projects within ESA's Discovery & Preparation program in 2019. One of the projects, AMNAS [52], [95], aims to explore ways of broadcasting navigation messages via satellites to vessels 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 [96].

In spring 2019, ESA allocated the NARWHALS project funding [53], [97] in collaboration with SpacEarth Technology, the primary 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 from ESA, the ArctiCom, aims to assess the demands and offer communication solutions in the Arctic region [54]. The assessment included many business sectors, such as shipping, mining, oil and gas exploration, etc., and geostationary and non-geostationary satellite communication systems and terrestrial communication systems.

Another project, titled "5G-assisted Ground-based Galileo-GPS receiver Group with Inertial and Visual Enhancement" (5GIVE), carried out by the University of Helsinki, is also funded by ESA and aims to develop the methods of GNSS and terrestrial positioning signal fusion for robust and seamless navigation [55]. The project's objective is to investigate how to combine the satellite positioning techniques with motion sensors and terrestrial radio signals to gain sufficient accuracy for the mission, even in challenging environments, where satellite signals suffer from multipath propagation.

IV. SIMULATION FRAMEWORK AND MAIN POSITIONING SYSTEM OPERATION

A. POSITIONING SYSTEM OPERATION

As discussed before, the foremost positioning system in the Arctic region remains the GNSS. Thus, we have conducted a study to determine current satellite systems' performance in the Arctic from the autonomous vessel perspective. We describe the current chapter's simulation environment, focusing on GNSS constellation analysis for the Arctic region. The modeled systems include GPS, Galileo, and GLONASS.

We assume that an autonomous vessel is operating in the Arctic conditions. The vessel uses a dynamic positioning system with situational awareness sensors for collision avoidance (CA), updating its position information with other vessels using an AIS. In order to evaluate the considered scenario, we have executed the simulation campaign.

B. SIMULATION ENVIRONMENT DESCRIPTION

The simulations were executed in several steps. First, as a comparison between Arctic and non-Arctic regions, the Geometric Dilution of Precision was analyzed based on 50, 000

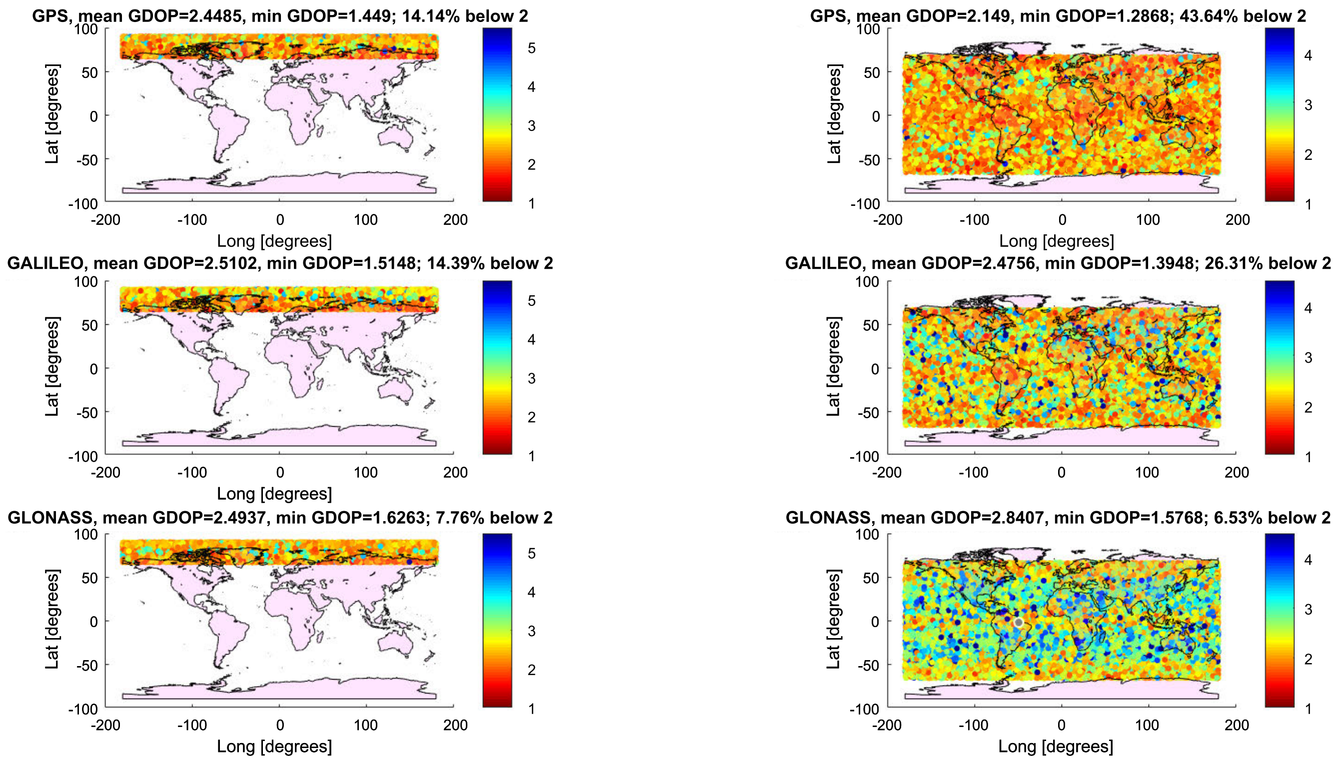

FIGURE 2. Comparison of GDOP in Arctic region with GDOP values in non-Antarctic (right) and non-Arctic (left) regions for $\epsilon = 10^o$ minimum elevation mask.

Monte Carlo simulations, looking at GDOP values based on visible satellites with at least 10^o elevation, i.e., the cut-off elevation angle was set to 10^o. The GDOP simulator was built in Matlab, based on ephemeris data collected from a Spectracom GSG-64 multiple constellation simulator with 64 channels, supporting all 4 GNSS (GPS, Galileo, GLONASS, Beidou) systems. Only the geographical points above the Arctic circle (i.e., above 66.56 North latitude) were considered, and user data was generated with a uniform distribution along with the longitude values at latitudes above the Arctic circle. The GDOP equation was based on [72] book and using all satellites in view above the cut-off elevation angle.

Next, the comparison of GNSSs was made using an extensive set of simulations with Systems Tool Kit (STK) [99]. 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 simulated vessels were moving at the speed of 20 knots [100].

STK provides real models of the GNSS constellation. It provides the GNSS almanacs that contain an up-to-date set of data that every GNSS satellite transmits and includes information, such as the state of the entire constellation and coarse data on every satellite's orbit. The repeat cycle of a satellite constellation is when 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 [69], [101]. We evaluated an entire ten-day period and noticed that 48 hours is enough to capture a relevant range of variation regarding satellites' visibility in the region of interest (see Fig. 3). Thus, the results achieved within a 48-hour 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.

V. NUMERICAL RESULTS

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

A. GEOMETRIC DILUTION OF PRECISION

GDOP is a measure of the 'goodness' of the satellite geometry, and it is inversely proportional to the achievable positioning accuracy. Typical 'excellent' GDOP values are below 2 and 'good' GDOP values range between 2 and 5 [72]. The results are shown in Fig. 2. Among the three considered GNSS systems, GPS offers the best satellite geometry (i.e., the lowest GDOP), and Galileo offers the worst satellite geometry in the Arctic region. While the average GDOPs in the Arctic region is only slightly worse than the average GDOP in the non-Arctic and non-Antarctic region, the best (i.e., minimum GDOP) is significantly better outside the Arctic region. The percentages of excellent GDOP (i.e., below 2) are significantly lower for GPS and Galileo in the Arctic region than the other considered regions in Fig. 2. GLONASS has comparative performance in GDOP in both Arctic and non-Arctic regions. However, the percentages of excellent-level GDOP for GLONASS are significantly lower than the percentages of excellent-level GDOP for Galileo and GPS in both Arctic and non-Arctic regions.

B. 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 5 and show the satellite visibility during the 48-hour period. The values presented in the table reflect 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 where the satellite is seen at a minimum predefined elevation angle ϵ [102].

TABLE 5. Satellite visibility for different GNSS.

System	Degrees, ϵ	Number of visible satellites 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

In our simulations, the receiver shall have a clear view of the sky, ensuring a direct LoS with as many visible satellites as possible [103]. One of this study's goals was to know the vessels' ability to locate themselves with different elevation values ϵ varying from 10^o to 30^o in clear-sky conditions. The value $\epsilon = 10^o$ was chosen as the minimum elevation angle for the Arctic environment to prevent possible blockage caused by natural barriers at the open sea, such as icebergs, or by the vessel itself [4]. Then ϵ was increased up to 30^o to simulate possible LoS blockage caused by the port's infrastructure. At $\epsilon = 30^o$, some of the systems have shown uncertain performance, which is discussed further.

According to Fig. 3, GPS provides a maximum number of visible satellites for the lowest elevation angle (10^o) compared to other systems. However, by increasing the receiver's elevation angle, the GPS (as well as Galileo) is reduced. The GLONASS system, however, can provide sufficient coverage, even with the high elevation angles. Fig. 4 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 the Polar Regions. In general, it can be concluded that the satellite visibility of all GNSSs is sufficient

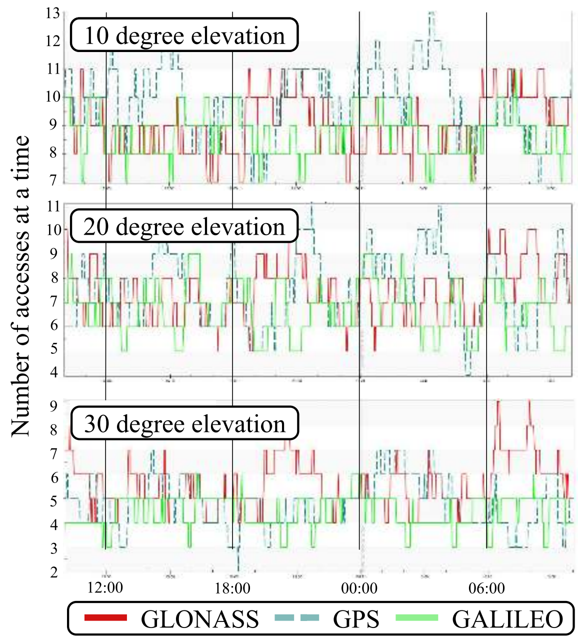

FIGURE 3. Comparison of the GNSSs: 20.02.2020 10:00 UTC – 21.02.2020 10:00 UTC.

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 of satellite signals, which can lead to the positioning accuracy reductions [4].

C. ARCTIC REGION POSITIONING ACCURACY EVALUATION

User accuracy refers to how close the device's calculated position is from the truth, expressed in meters. Fig. 5 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 was performed by STK AGI software [104]. The positioning accuracy (also referred to as Navigation Accuracy by AGI developers) calculation is related to the Dilution of Precision (DOP) in the definition of DOP with an assumption of a single value for the uncertainty in the one-way range measurement from the constellation. If four or more satellites are in the ground receiver's view, the receiver's position and the offset between the receiver clock and the GNSS clock are being 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 positioning accuracy varies dynamically with time. The top row of snapshots of positioning accuracy are presented in Fig. 5. They show the accuracy variations between 0.9 – 2.7 meters for the systems' standalone operation. On average, for the entire period of simulations, the GPS constellation provided 0.9 – 2.7 meters accuracy range, the GLONASS provided the accuracy performance

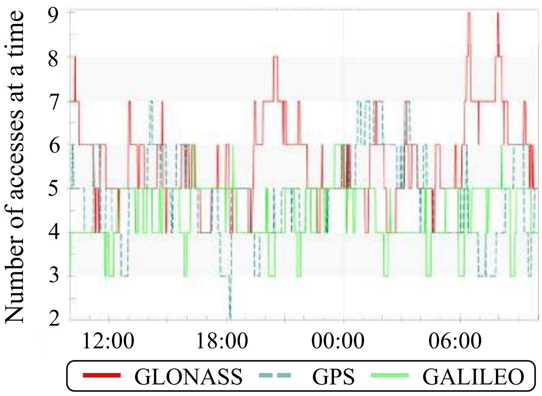

FIGURE 4. Number of visible satellite accesses from a single vessel, elevation angle $\epsilon = 30^o$: 20.02.2020 10:00 UTC – 21.02.2020 10:00 UTC.

of 0.9 – 2.5 meters, and the Galileo provided the accuracy of 1 – 2.3 meters. For the autonomous vessel positioning, the accuracy in the range of 1 – 3 meters in the open sea in most cases is sufficient.

Many works propose utilizing an intelligent hybrid combination of different systems available on the node to increase accuracy. Even though GLONASS appears to be the best standalone candidate, coupling it with GALILEO and GPS clearly shows the better results, see the bottom row in Fig. 5. Here, we have modeled two scenarios: *assisted* and *combined* operation modes. The *assisted* scenario presumes that the vessel has been tracking its position constantly. Thus, it can achieve a significantly higher level of precision by applying additional knowledge of the best positioning technology accuracy in this area.

However, the vessel may face a rare situation when the position should be estimated for the first time, e.g., after reboot, initial launch, etc. In this case, a *combined* scenario does not know the vessel's approximate location. Generally, it may be recommended to utilize, e.g., GLONASS for initial calibration and switch to the *assisted* mode after it for better accuracy.

VI. CHALLENGES AND FUTURE PERSPECTIVES

To improve positioning accuracy for autonomous vessels' operations, we outline different strategies that shall be taken into account in further studies.

A. HYBRID POSITIONING TECHNIQUES

The vessel's autonomy level will depend on the vessel type, size, and operational environment. The more complex the autonomous vessel's mission is, the more strict requirements it will have to the positioning systems. Extensive work has already been done on the existing solutions to add positioning and collision avoidance redundancy in the autonomous vessel operation [8], [39]–[44]. 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 GNSS

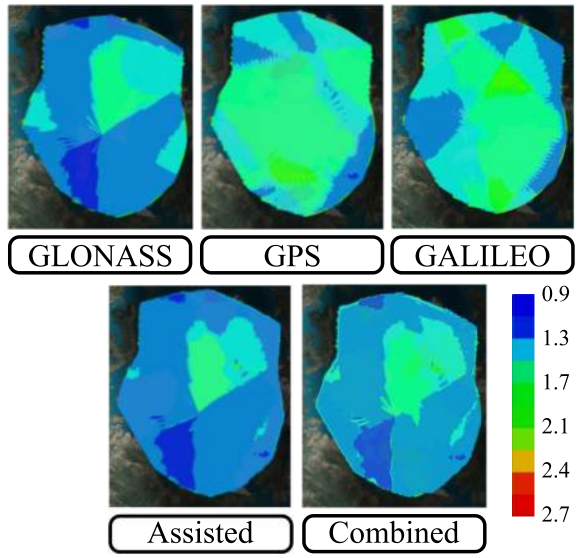

FIGURE 5. The snapshot (21.02.2020 07:17) of positioning accuracy of the Galileo, GLONASS, and GPS constellations. The data is obtained using the simulation environment STK: Coverage module [105].

may not always be available and sufficient, the cellular-based positioning techniques can also be useful when available [45].

B. SENSOR FUSION

Several methods are used to determine the position of an autonomous vehicle or a vessel. Those methods include various communication technologies such as ITS-G5, WiFi, LTE, etc., as well as cameras, radars, and physical landmarks [39]. The location can be determined through the sensor fusion of several technologies.

C. COMBINATION OF EARTH OBSERVATION DATA WITH GNSS AND COMMUNICATION SATELLITES

The satellites' observation data can help determine the challenges on terrestrial or marine vehicles' routes in real-time. Like this, the sea ice maps can be created and sent to the vessel to reduce the possible damage caused by heavy ice. A combination of Earth observation data and terrestrial observations and weather conditions will provide the best possible traffic conditions for terrestrial vehicles. One method of obtaining the observation data is available as part of the Copernicus Earth observation program. However, the program is still in the early stages, and only a small part of the data is available. Some of the advantages of integrated EO techniques with positioning satellites were described previously by a Polaris study from ESA [106] and in a study from the Ministry of Transports and Communications [107]. The Internet of Things (IoT) applications can serve as a great example of the combination of GNSS, EO, and communication satellites bringing together improved connectivity, geopositioning, and image data [79]. Another example of a combination of satellite systems is crowd-sourcing: users in the Arctic regions can provide geolocated information about the current region (such as unexpected weather conditions, wildlife, sea

TABLE 6. Summary of the Arctics positioning challenges and possible solutions.

Challenge	Solution	Ref
Positioning and collision avoidance redundancy, complementing GNSS, when it is not available	Hybrid positioning techniques	[8], [39]–[44]
Positioning and collision avoidance redundancy, achieving cm-level positioning accuracy	Sensor fusion	[39]
Early determination of challenges on the route to provide information on traffic conditions	Utilization of Earth observation data; combination of EO data with positioning satellites	[106], [107]
Lack of communication channels for information sharing that could benefit in navigation and environmental awareness; indirect location of the vehicles	Utilization of small satellite constellation or swarms to increase the communication capabilities	[93], [108]
Improved navigation performance with reduced navigation errors	Utilization of quantum technologies	[109]
Estimation of the performance of current GNSS	Simulation campaigns	Current work

conditions, local environment monitoring). These data can help to build a complete picture in the region of interest. In [5], an example is given about how crowd-sourcing can provide information on the sea depth to create the depth maps using the vessels' data.

D. SMALL SATELLITE CONSTELLATIONS OR SWARMS

Small satellites gain popularity to overcome the lack of communications in remote areas due to their small size and, thus, the relatively more straightforward launching process. However, the small-satellite communication system experience challenges with station keeping. It has been proven that by using the small-satellite swarms, the average end-to-end time can be significantly reduced [108]. These small satellite systems can be considered a solution to support time-limited missions or transmission of recorded data regularly, thus improving environmental awareness and navigation in this region. Moreover, small satellites utilize GNSS, allowing them to more effectively locate air-, marine-, and terrestrial vehicles indirectly. Small satellites can correct GNSS positioning inaccuracies caused by ionospheric disruptions. If larger constellations of small satellites are deployed, the guiding of autonomous vehicles can be made efficiently [93].

E. QUANTUM TECHNOLOGIES

In the future, satellites may be using Quantum technologies that could also provide benefits to Arctic regions. Such advantages include different applications, such as Quantum Key Distribution (QKD) for systems and services encryption, inertial navigation, gravity measurements, and many more [109].

F. SIMULATION CAMPAIGNS

Finally, vessel and satellite system simulations could also significantly assist in achieving additional improvements; an example of such simulations was provided in the current work. The comparative modeling can provide useful initial information about the existing GNSSs and their performance in the Arctic. However, long-term simulations and more detailed analyses are needed in the future, thus, bringing the need to combine various techniques in one system efficiently. That would include defining the requirements for accuracy of positioning for certain ship types in selected places and determining whether GNSSs alone or joint constellation could support certain operations. It is also essential to understand how different techniques, such as the use of pseudolites and the use of L-Band correction data, may improve positional accuracy [110].

VII. SUMMARY

To improve GNSS positioning in the Arctic region is an interest sustained by several ongoing research and industrial activities in the current region, the North Pole is a place of potential to explore natural resources. Based on the extensive review, we have outlined the main projects currently executed in this field, highlighting the most significant challenges and the corresponding potential solutions as recommendations for other researchers in Arctic navigation systems development.

As a baseline, we have modeled and compared existing GNSS constellations and studied the Arctic positioning for the autonomous vessels. The simulation campaign consisted of identifying geometric dilution of precision and the satellite visibility in the Arctic. 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 several positioning systems.

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REFERENCES

[1] J. Aguzzi, J. Albiez, S. Flögel, O. R. Godø, E. Grimsbø, S. Marini, O. Pfannkuche, E. Rodriguez, L. Thomsen, T. Torkelsen, J. Valencia, V. López-Vázquez, H. Wehde, and G. Zhang, "A flexible autonomous robotic observatory infrastructure for Bentho-pelagic monitoring," *Sensors*, vol. 20, no. 6, p. 1614, Mar. 2020.

[2] G. Jialin, W. Wenfeng, Z. Jiakuo, T. Jiaoyang, W. Xuxiu, and Y. Shuai, ''Numerical simulation analysis of oil heating process of oil tanker in Arctic route,'' in *Proc. 2nd World Conf. Mech. Eng. Intell. Manuf. (WCMEIM)*, Nov. 2019, pp. 420–423.
[3] S. Plass, F. Clazzer, and F. Bekkadal, ''Current situation and future innovations in Arctic communications,'' in *Proc. IEEE 82nd Veh. Technol. Conf. (VTC-Fall)*, Sep. 2015, pp. 1–7.
[4] L. Leppala, S. Honkala, G. Ferrara, M. Kirkko-Jaakkola, H. Kuusniemi, and S. Miettinen-Bellevergue, ''Challenges in Arctic navigation: The user perspective,'' in *Proc. Eur. Navigat. Conf. (ENC)*, Apr. 2019, pp. 1–8.
[5] M. Kirkko-Jaakkola, L. Leppälä, G. Ferrara, S. Honkala, M. Mäkelä, H. Kuusniemi, and S. Miettinen-Bellevergue. (Jan. 2020). *Challenges in Arctic Navigation and Geospatial Gata: User Perspective and Solutions Roadmap*. [Online]. Available: http://urn.fi/URN:ISBN:978-952-243-576-7
[6] D. Wang, X. Luo, J. Wang, J. Gao, T. Zhang, Z. Wu, C. Yang, and Z. Wu, ''Global ionospheric model accuracy analysis using shipborne kinematic GPS data in the Arctic circle,'' *Remote Sens.*, vol. 11, no. 17, p. 2062, Sep. 2019.
[7] J. V. Escusol, J. Aaltonen, and K. T. Koskinen, ''Kategoria: Autonomous and collaborative offshore robotics,'' Teknologiateollisuuden 100-vuotissäätiö, Helsinki, Finland, Tech. Rep., 2017.
[8] A. Felski and K. Zwolak, ''The ocean-going autonomous ship—Challenges and threats,'' *J. Mar. Sci. Eng.*, vol. 8, no. 1, p. 41, Jan. 2020.
[9] J.-X. Zhang and G.-H. Yang, ''Fault-tolerant fixed-time trajectory tracking control of autonomous surface vessels with specified accuracy,'' *IEEE Trans. Ind. Electron.*, vol. 67, no. 6, pp. 4889–4899, Jun. 2020.
[10] *Feasibility Study on Maritime Communication Services over 3GPP System (Release 16)*, document 3GPP TR 22.819 V16.2.0, Dec. 2018.
[11] *Study on Positioning Use Cases, Stage 1 (Release 16)*, document 3GPP TR 22.872 V16.1.0, Sep. 2018.
[12] (2020). *Convention on the International Regulations for Preventing Collisions at Sea, 1972 (COLREGs)*. [Online]. Available: https://www.imo.org/en/About/Conventions/Pages/COLREG.aspx
[13] J. G. Grimes, ''Global positioning system standard. Positioning service performance standard, Version GPS SPS PS-5,'' Dept. Defense, Global Positioning Syst., Washington, DC, USA, Tech. Rep., Sep. 2008.
[14] ESA Navipedia. (2018). *GLONASS General Introduction*. [Online]. Available: https://gssc.esa.int/navipedia/index.php/GLONASS_General_Introduction
[15] European Global Navigation Satellite Systems Agency. (2018). *Galileo Services*. [Online]. Available: https://www.gsa.europa.eu/galileo/services
[16] M. Hoffmann, P. Kryszkiewicz, and G. P. Koudouridis, ''Modeling of real time kinematics localization error for use in 5G networks,'' *EURASIP J. Wireless Commun. Netw.*, vol. 2020, p. 31, Dec. 2020.
[17] N. Joubert, T. G. R. Reid, and F. Noble, ''Developments in modern GNSS and its impact on autonomous vehicle architectures,'' 2020, *arXiv:2002.00339*. [Online]. Available: http://arxiv.org/abs/2002.00339
[18] K. de Jong, M. Goode, X. Liu, and M. Stone, ''Precise GNSS positioning in Arctic regions,'' in *Proc. All Days*, Feb. 2014, pp. 1–10.
[19] (2011). *Differential GNSS*. [Online]. Available: https://gssc.esa.int/navipedia/index.php/Differential_GNSS
[20] K. Su, S. Jin, and M. Hoque, ''Evaluation of ionospheric delay effects on multi-GNSS positioning performance,'' *Remote Sens.*, vol. 11, no. 2, p. 171, Jan. 2019.
[21] K. Guo, M. H. O. Aquino, S. Vadakke Veettil, C. Hill, and B. Weaver, ''Tracking jitter maps-a new product to mitigate ionospheric scintillation effects on GNSS positioning,'' in *Proc. AGU Fall Meeting Abstracts (AGUFM)*, 2019, pp. G13A–02.
[22] (2020). *Satellite—Automatic Identification System (SAT-AIS) Overview*. [Online]. Available: https://artes.esa.int/sat-ais/overview
[23] *European Maritime Safety Agency*. Accessed: 2020. [Online]. Available: http://www.emsa.europa.eu/
[24] *ESAIL Maritime Satellite Ready for Launch*. Accessed: 2020. [Online]. Available: https://www.esa.int/Applications/Telecommunications_Integrated_Applications/ESAIL_maritime_satellite_ready_for_launch
[25] *ESAIL Maritime Microsatellite*. Accessed: 2018. [Online]. Available: https://directory.eoportal.org/web/eoportal/satellite-missions/e/esail
[26] *Asitech Access to Intelligent Space Technologies*. Accessed: 2020. [Online]. Available: https://www.aistechspace.com/
[27] *The IoT Network for the Planet*. Accessed: 2020. [Online]. Available: https://www.astrocast.com
[28] *Copernicus Services*. Accessed: 2020. [Online]. Available: https://www.copernicus.eu/en
[29] *Copernicus Marine Service*. Accessed: 2019. [Online]. Available: https://marine.copernicus.eu/
[30] *The Copernicus Atmosphere Monitoring Service (CAMS) Radiation Service in a Nutshell*. Accessed: 2019. [Online]. Available: https://atmosphere.copernicus.eu/sites/default/files/2019-03/Copernicus_radiation_service_in_nutshell_v10.pdf
[31] *Copernicus Services Information and Sentinel Products for the Arctic Region*. Accessed: 2020. [Online]. Available: https://www.copernicus.eu/en/copernicus-services-information-and-sentinel-products-arctic-region
[32] *Sea Ice*. Accessed: 2018. [Online]. Available: https://climate.copernicus.eu/sea-Ice
[33] *Using Artificial Intelligence to Automate Sea-Ice Charting*. Accessed: 2019. [Online]. Available: http://www.esa.int/Applications/Observing_the_Earth/Using_artificial_intelligence_to_automate_sea-ice_charting
[34] *INTAROS: Integrated Arctic Observation System*. Accessed: 2016. [Online]. Available: https://www.nersc.no/project/intaros
[35] B. M. Howe, B. K. Arbic, J. Aucan, C. R. Barnes, N. Bayliff, N. Becker, R. Butler, L. Doyle, S. Elipot, G. C. Johnson, and F. Landerer, ''SMART cables for observing the global ocean: Science and implementation,'' *Frontiers Mar. Sci.*, vol. 6, p. 424, Aug. 2019.
[36] S. Sandven, H. Sagen, A. Beszczynska-Möller, P. Vo, M. N. Houssais, M. Sørensen, M. K. Sejr, M. DziecIuch, P. Worcester, E. Storheim, and F. Geyer, ''Implementation of a multipurpose Arctic ocean observing system,'' in *Proc. EGU Gen. Assem. Conf. Abstr.*, 2020, p. 20347.
[37] *SGP: Space Geodesy Project*. Accessed: 2012. [Online]. Available: https://space-geodesy.nasa.gov/
[38] M.-J. Vinas. (2017). *NASA, Norway to Develop Arctic Laser-Ranging Station*. [Online]. Available: https://www.nasa.gov/feature/goddard/2017/nasa-and-norway-to-develop-arctic-station
[39] Y. Dobrev, M. Vossiek, M. Christmann, I. Bilous, and P. Gulden, ''Steady delivery: Wireless local positioning systems for tracking and autonomous navigation of transport vehicles and mobile robots,'' *IEEE Microw. Mag.*, vol. 18, no. 6, pp. 26–37, Sep. 2017.
[40] M. Mukhtar, ''GPS based advanced vehicle tracking and vehicle control system,'' *Int. J. Intell. Syst. Appl.*, vol. 7, no. 3, pp. 1–12, Feb. 2015.
[41] T. Suzuki, M. Kitamura, Y. Amano, and T. Hashizume, ''High-accuracy GPS and GLONASS positioning by multipath mitigation using omnidirectional infrared camera,'' in *Proc. IEEE Int. Conf. Robot. Autom.*, May 2011, pp. 311–316.
[42] A. Yastrebova, M. Höyhtyä, and M. Majanen, ''Mega-constellations as enabler of autonomous shipping,'' in *Proc. AIAA Int. Commun. Satell. Syst. Conf. (ICSSC)*, Oct. 2019, pp. 1–7.
[43] E. Jokioinen, J. Poikonen, R. Jalonen, and J. Saarni. (Jun. 2016). *Remote and Autonomous Ships–The Next Steps*. [Online]. Available: https://www.rolls-royce.com/~/media/Files/R/Rolls-Royce/documents/customers/marine/ship-intel/aawa-whitepaper-210616.pdf
[44] C. Castillo, A. Pyattaev, J. Villa, P. Masek, D. Moltchanov, and A. Ometov, ''Autonomous UAV landing on a moving vessel: Localization challenges and implementation framework,'' in *Proc. Internet Things, Smart Spaces, Next Gener. Netw. Syst.* Cham, Switzerland: Springer, Aug. 2019, pp. 342–354.
[45] S. Kavuri, D. Moltchanov, A. Ometov, S. Andreev, and Y. Koucheryavy, ''Performance analysis of onshore NB-IoT for container tracking during Near-the-Shore vessel navigation,'' *IEEE Internet Things J.*, vol. 7, no. 4, pp. 2928–2943, Apr. 2020.
[46] M. Kiviranta, I. Moilanen, and J. Roivainen, ''5G radar: Scenarios, numerology and simulations,'' in *Proc. Int. Conf. Mil. Commun. Inf. Syst. (ICMCIS)*, May 2019, pp. 1–6.
[47] V. Ilci and C. Toth, ''High definition 3D map creation using GNSS/IMU/LiDAR sensor integration to support autonomous vehicle navigation,'' *Sensors*, vol. 20, no. 3, p. 899, Feb. 2020.
[48] J. Kang, M. Jin, J. Park, and D. Park, ''A study on application of sensor fusion to collision avoidance system for ships,'' in *Proc. Int. Conf. Control, Autom. Syst. (ICCAS)*, Oct. 2010, pp. 1741–1744.
[49] *Sustaining Arctic Observing Networks Strategy: 2018-2028*. Accessed: 2018. [Online]. Available: https://www.arcticobserving.org/images/pdf/Strategy_and_Implementation/SAON_Strategy_2018-2028_version_16MAY2018.pdf
[50] *EU-PolarNet—Connecting Science With Societyg*. Accessed: 2020. [Online]. Available: https://www.eu-polarnet.eu/about-eu-polarnet/
[51] *The ARKKI Project*. Accessed: 2017. [Online]. Available: https://arkki-project.org/

[52] GRAD. (2020). *Driving Innovation for Safer Maritime Navigation*. [Online]. Available: https://www.gla-rad.org/projects/amnas/
[53] ESA. (Feb. 2019). *NARWHALS—Navigation in ARctic With GNSS High Accuracy Low power Solution*. [Online]. Available: https://business.esa.int/projects/narwhals
[54] *ESA ARTICOM*. Accessed: 2011. [Online]. Available: https://artes.esa.int/projects/arcticom
[55] University of Helsinki. (2020). *5G-Assisted Ground-Based Galileo-GPS Receiver Group With Inertial and Visual Enhancement*. [Online]. Available: https://researchportal.helsinki.fi/en/projects/5g-assisted-ground-based-galileo-gps-receiver-group-with-inertial
[56] T. Reid, T. Walter, J. Blanch, and P. Enge, "GNSS integrity in the Arctic," *Navigation*, vol. 63, no. 4, pp. 469–492, Dec. 2016.
[57] N. Linty, R. Romero, C. Cristodaro, F. Dovis, M. Bavaro, J. T. Curran, J. Fortuny-Guasch, J. Ward, G. Lamprecht, P. Riley, P. Cilliers, E. Correia, and L. Alfonsi, "Ionospheric scintillation threats to GNSS in polar regions: The DemoGRAPE case study in Antarctica," in *Proc. Eur. Navigat. Conf. (ENC)*, May 2016, pp. 1–7.
[58] H. Xi, H. Jiang, J. An, Z. Wang, X. Xu, H. Yan, and C. Feng, "Spatial and temporal variations of polar ionospheric total electron content over nearly thirteen years," *Sensors*, vol. 20, no. 2, p. 540, Jan. 2020.
[59] PennState. (2020). *The Ionospheric Effect*. [Online]. Available: https://www.e-education.psu.edu/geog862/node/1715
[60] PennState. (2020). *The Tropospheric Effect*. [Online]. Available: https://www.e-education.psu.edu/geog862/node/1719
[61] S. Mahato, A. Santra, S. Dan, P. Verma, P. Banerjee, and A. Bose, "Visibility anomaly of GNSS satellite and support from regional systems," *Current Sci.*, vol. 119, no. 11, 2020, Art. no. 00113891.
[62] Netherlands Regulatory Framework (NeRF). (2002). *Revised Maritime Policy and Requirements for a Future GNSS*. [Online]. Available: https://puc.overheid.nl/nsi/doc/PUC_1412_14/1/
[63] (2020). *COLREGs Course, Rule 7*. [Online]. Available: https://www.ecolregs.com/index.php?option=com_k2&view=item&layout=item&id=50&Itemid=382&lang=en
[64] R. G. Wright, "Intelligent autonomous ship navigation using multi-sensor modalities," *TransNav, Int. J. Mar. Navigat. Saf. Sea Transp.*, vol. 13, no. 3, pp. 503–510, 2019.
[65] IASC. (2020). *Sustaining Arctic Observing Networks (SAON)*. [Online]. Available: https://arctic-council.org/en/projects/saon/
[66] U. M. Bohlmann and V. F. Koller, "ESA and the Arctic—The European space agency's contributions to a sustainable Arctic," *Acta Astronautica*, vol. 176, pp. 33–39, Nov. 2020.
[67] G. Jiao, S. Song, Y. Ge, K. Su, and Y. Liu, "Assessment of BeiDou-3 and multi-GNSS precise point positioning performance," *Sensors*, vol. 19, no. 11, p. 2496, May 2019.
[68] J. Nurmi, E. S. Lohan, Sand, and H. Hurskainen, *GALILEO Positioning Technology*, vol. 176. Heidelberg, Germany: Springer, 2015.
[69] L. Pan, X. Zhang, X. Li, X. Li, C. Lu, J. Liu, and Q. Wang, "Satellite availability and point positioning accuracy evaluation on a global scale for integration of GPS, GLONASS, BeiDou and Galileo," *Adv. Space Res.*, vol. 63, no. 9, pp. 2696–2710, May 2019.
[70] National Coordination Office for Space-Based Positioning, Navigation, and Timing. (2020). *Official US Government Information About the Global Positioning System (GPS) and Related Topics*. [Online]. Available: https://www.gps.gov/systems/gps/space/
[71] *GPS General Introduction*. Accessed: 2011. [Online]. Available: https://gssc.esa.int/navipedia/index.php/GPS_General_Introduction
[72] E. D. Kaplan and C. J. Hegarty, Eds., *Understanding GPS: Principles and Applications*, 2nd ed. Norwood, MA, USA: Artech House, 2006.
[73] S. Dawoud, "GNSS principles and comparison," IT Syst. Eng. Comput. Sci., Potsdam Univ., Potsdam, Germany, Tech. Rep. WS1112, 2012.
[74] R. Wu, W. Wang, D. Lu, L. Wang, and Q. Jia, "Principles of satellite navigation system," in *Adaptive Interference Mitigation in GNSS*. Singapore: Springer, Oct. 2018, pp. 1–29.
[75] (2011). *Galileo Navigation Message*. [Online]. Available: https://gssc.esa.int/navipedia/index.php/Galileo_Navigation_Message
[76] Z. Nie, P. Zhou, F. Liu, Z. Wang, and Y. Gao, "Evaluation of orbit, clock and ionospheric corrections from five currently available SBAS L1 services: Methodology and analysis," *Remote Sens.*, vol. 11, no. 4, p. 411, 2019.
[77] *Current WAAS Vertical Navigation Service Snapshot Display*. Accessed: 2020. [Online]. Available: https://www.nstb.tc.faa.gov/RT_VerticalProtectionLevel.htm
[78] *EGNOS Extension to Eastern European Neighbourhood Partner Countries*. Accessed: 2020. [Online]. Available: https://www.gsa.europa.eu/sites/default/files/uploads/egnos_for_enp_east.pdf
[79] K. Boniface *et al.*, "Europe's space capabilities for the benefit of the Arctic," Publications Office Eur. Union, Luxembourg, Tech. Rep. EUR 30162 EN, 2020
[80] *Galileo Return Link Service Declared at European Space Conference*. Accessed: 2020. [Online]. Available: https://bit.ly/3rblT0m
[81] T. Morley and G. Lachapelle, "GPS augmentation with pseudolites for navigation in constricted waterways," *Navigation*, vol. 44, no. 3, pp. 359–372, Sep. 1997.
[82] T. G. Morley, *Augmentation of GPS With Pseudolites in a Marine Environment*. Calgary, AB, Canada: Univ. of Calgary, 1997.
[83] X. Li, M. Ge, X. Dai, X. Ren, M. Fritsche, J. Wickert, and H. Schuh, "Accuracy and reliability of multi-GNSS real-time precise positioning: GPS, GLONASS, BeiDou, and Galileo," *J. Geodesy*, vol. 89, no. 6, pp. 607–635, Jun. 2015.
[84] Q. Zhang, Z. Chen, Y. Cui, X. Zheng, F. Rong, Y. Sun, and L. Gao, "A refined metric for multi-GNSS constellation availability assessment in polar regions," *Adv. Space Res.*, vol. 66, no. 3, pp. 655–670, Aug. 2020.
[85] P. Defraigne, E. Pinat, and B. Bertrand, "Impact of Galileo-to-GPS-time-offset accuracy on multi-GNSS positioning and timing," *GPS Solutions*, vol. 25, no. 2, pp. 1–15, Apr. 2021.
[86] O. Montenbruck, P. Steigenberger, L. Prange, Z. Deng, Q. Zhao, F. Perosanz, I. Romero, C. Noll, A. Stürze, G. Weber, R. Schmid, K. MacLeod, and S. Schaer, "The multi-GNSS experiment (MGEX) of the international GNSS service (IGS)–achievements, prospects and challenges," *Adv. Space Res.*, vol. 59, no. 7, pp. 1671–1697, Apr. 2017.
[87] X. Yao, M. Chen, J. Wang, and R. Chen, "Quality analysis of GNSS data in polar region," in *Proc. China Satell. Navigat. Conf.* Singapore: Springer, 2019, pp. 376–388.
[88] A. Grant, P. Williams, G. Shaw, M. De Voy, and N. Ward, "Understanding GNSS availability and how it impacts maritime safety," in *Proc. Int. Tech. Meeting Inst. Navigat.*, 2011, pp. 687–695.
[89] *Satellite—Automatic Identification System (SAT-AIS) Overview*. Accessed: 2020. [Online]. Available: https://artes.esa.int/sat-ais/overview
[90] S. Kosiak. (Oct. 2019). *Small Satellites in the Emerging Space Environment: Implications for U.S. National Security–Related Space Plans and Programs*. [Online]. Available: https://s3.us-east-1.amazonaws.com/files.cnas.org/documents/CNAS-Report-Small-Satellites-final-1-min-1.pdf
[91] U. Kanjir, H. Greidanus, and K. Ostir, "Vessel detection and classification from spaceborne optical images: A literature survey," *Remote Sens. Environ.*, vol. 207, pp. 1–26, Mar. 2018.
[92] *SGP: Project Overview*. Accessed: 2018. [Online]. Available: https://space-geodesy.nasa.gov/
[93] *Efficient Deployment of Satellite Navigation Systems in Finland. Action plan 2017-2020*. Accessed: 2018. [Online]. Available: https://arkki-project.org/wp-content/uploads/2018/04/Efficient-deployment-of-satellite-systems-in-Finland_Action-plan-2017-2020_3.pdf
[94] Arctic Finland Portal to Finnish Arctic Policies, Research and Business. (2020). *VTT Technical Research Centre of Finland Ltd*. [Online]. Available: https://www.arcticfinland.fi/EN/Research/vtt
[95] Kongsberg. (Mar. 2019). *AMNAS Project. Challenges and Opportunities for Satellite Communications and Navigation Augmentation Systems in Maritime VHF Bands*. [Online]. Available: https://nebula.esa.int/sites/default/files/neb_study/2480/C4000119199ExS.pdf
[96] ESA. *Enhancing SATNAV for Arctic Voyagers*. Accessed: 2019. [Online]. Available: https://www.esa.int/Enabling_Support/Preparing_for_the_Future/Discoveryand_Preparation/Enhancing_satnav_for_Arctic_voyagers
[97] SPACEARTH Technology. (2019). *NARWHALS, an ESA Funded Project to Support the Maritime Navigation in Arctic*. [Online]. Available: http://www.spacearth.net/images/blog/2019_NARWHALS.pdf
[98] *SAON Implementation Plan*. Accessed: 2018. [Online]. Available: https://www.arcticobserving.org/images/pdf/Strategy_and_Implementation/SAON_Implementation_Plan_version_17JUL2018_Status_approved.pdf
[99] Analytical Graphics, Inc. (2020). *AGI's Ready-to-Use STK and ODTK Families of Products, Enterprise Software, and Developer Tools*. [Online]. Available: https://www.agi.com/products

[100] A. Afonin, E. Ol'Khovik, and A. Tezikov, "Study of ship speed regimes in the Arctic sea ice conditions," in *Proc. IOP Conf. Ser., Earth Environ. Sci.*, Nov. 2018, pp. 1–5.
[101] R. Dach, E. Brockmann, S. Schaer, G. Beutler, M. Meindl, L. Prange, H. Bock, A. Jäggi, and L. Ostini, "GNSS processing at CODE: Status report," *J. Geodesy*, vol. 83, nos. 3–4, pp. 353–365, Mar. 2009.
[102] S. Cakaj, B. Kamo, A. Lala, and A. Rakipi, "The coverage analysis for low Earth orbiting satellites at low elevation," *Int. J. Adv. Comput. Sci. Appl.*, vol. 5, no. 6, pp. 6–10, 2014.
[103] UBX-15030289-R03. *GNSS Antennas: RF Design Considerations for u-Blox GNSS Receivers*. [Online]. Available: https://www.u-blox.com/sites/default/files/products/documents/GNSS-Antennas_AppNote_%28UBX-15030289%29.pdf
[104] Analytical Graphics, Inc. (2016). *Measuring the Accuracy of a Navigation Solution*. [Online]. Available: https://help.agi.com/stk/11.0.1/Content/cov/fom-14.htm#NavAccSel
[105] Analytical Graphics, Inc. (2020). *Introduction to STK Coverage*. [Online]. Available: https://help.agi.com/stk/index.htm#cov/intro.htm
[106] *User Needs and High-Level Requirements for Next Generation Observing Systems for the Polar Regions*. Accessed: 2016. [Online]. Available: https://www.arcticobserving.org/images/pdf/Board_meetings/2016_Fairbanks/16_Final-Gaps-and-Impact-Report—2016-04-22.pdf
[107] *Challenges in Arctic Navigation and Geospatial. Data User Perspective and Solutions Roadmap*. Accessed: 2020. [Online]. Available: http://julkaisut.valtioneuvosto.fi/bitstream/handle/10024/161989/LVM_2020_1.pdf
[108] R. Birkeland and D. Palma, "Freely drifting small-satellite swarms for sensor networks in the Arctic," in *Proc. 3rd Int. Congr. Inf. Commun. Technol.* Singapore: Springer, 2019, pp. 175–190.
[109] D. Feng, "Review of quantum navigation," in *Proc. IOP Conf. Ser., Earth Environ. Sci.*, 2019, vol. 237, no. 3, Art. no. 032027.
[110] Z. Nie, F. Liu, and Y. Gao, "Real-time precise point positioning with a low-cost dual-frequency GNSS device," *GPS Solutions*, vol. 24, no. 1, pp. 1–11, Jan. 2020.

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