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Challenges in Arctic Navigation and Geospatial Data

User Perspective and Solutions Roadmap

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Description sheet

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Abstract

Navigation and location-based applications, including business such as transport, tourism, and mining, in Arctic areas face a variety of specific challenges. In fact, these challenges concern not only the Arctic Circle but certain other areas as well, such as the Gulf of Bothnia. This report provides a review on these challengs which concern a variety of technologies ranging from satellite navigation to telecommunications and mapping.

In order to find out end-users' views on the significance of Arctic challenges, an online survey was conducted. The 77 respondents representing all Arctic countries, the majority being from Finland, highlighted the challenges in telecommunications as well as accuracy concerns for emerging applications dealing with precise navigation.

This report provides a review of possible technologies for addressing the Arctic challenges, based on which a road map for solving them is developed. The road map also uses the results of expert working groups from the *Challenges in Arctic Navigation* workshop arranged in April 2018 in Olos, Muonio, Finland.

This report was produced within the ARKKI project. It was funded by the Finnish Ministry of Foreign Affairs under the Baltic Sea, Barents and Arctic cooperation programme, and implemented by the Finnish Geospatial Research Institute in collaboration with the Finnish Ministry of Transport and Communications.

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Tiivistelmä

Navigointi ja paikkatietoperusteiset sovellukset, ml. liikenne, matkailu ja kaivostoiminta, kohtaavat erityisiä haasteita arktisella alueella ja mm. Pohjanlahdella. Tässä raportissa luodaan katsaus näihin haasteisiin, jotka liittyvät moniin teknologian aloihin, kuten satelliittipaikannukseen, tietoliikenteeseen ja kartoitukseen.

Kartoittaaksemme loppukäyttäjien näkemyksiä näiden haasteiden merkittävyydestä järjestimme verkkokyselyn. Kyselyyn saatiin 77 vastausta, jotka edustivat kaikkia arktisia maita, enemmistön vastaajista ollessa suomalaisia. Vastauksissa korostuivat erityisesti tietoliikenteen haasteet sekä erittäin tarkkaa navigointia tarvitsevat uudet sovellukset.

Tässä raportissa selvitetään erilaisia teknisiä ratkaisuja arktisen alueen paikkatiedon haasteisiin, minkä pohjalta annetaan toimenpidesuosituksia merkittävimpien haasteiden ratkaisemiseksi. Toimenpidesuositusten pohjana käytetään myös asiantuntijatyöryhmien mietintöjä, jotka tuotettiin *Challenges in Arctic Navigation* –työpajassa Oloksella huhtikuussa 2018.

Tämä raportti tuotettiin *Selvitys ja toimenpidesuunnitelma arktisen navigoinnin haasteista ja ratkaisuvaihtoehdoista (ARKKI)* -hankkeessa, jonka rahoitti ulkoministeriö Itämeren, Barentsin ja arktisen alueen yhteistyön määrärahalla (IBA). Hankkeen toteutti Maanmittauslaitoksen Paikkatietokeskus yhteistyössä liikenne- ja viestintäministeriön kanssa.

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Referat

Navigation och applikationer för geodata, inklusive transport, turism och gruvdrift, ställs inför särskilda utmaningar i den arktiska regionen och bl.a. i Bottniska viken. I denna rapport ges en översikt av dessa utmaningar som anknyter till ett stort antal teknikområden, såsom satellitpositionering, telekommunikation och kartering.

För att kartlägga slutanvändarnas åsikter om betydelsen av dessa utmaningar ordnades en webbenkät. Enkäten samlade in 77 svar från alla arktiska länder. Majoriteten av respondenterna var finländare. I svaren betonades särskilt utmaningarna inom telekommunikationen samt de nya applikationer som kräver mycket exakt navigation.

I denna rapport utreds olika tekniska lösningar på utmaningarna i fråga om geodata om den arktiska regionen. Utifrån dessa ges rekommendationer till åtgärder för att lösa de största utmaningarna. Som grund för rekommendationerna används också olika expertarbetsgruppers betänkanden från workshoppen *Challenges in Arctic Navigation* i Olos i april 2018.

Rapporten utarbetades som en del av projektet *Utredning och åtgärdsplan i fråga om utmaningarna inom arktisk navigation och lösningsalternativ (ARKKI)*, som finansierades av utrikesministeriet med anslaget för samarbete i Östersjöregionen, Barentsregionen och den arktiska regionen. Projektet genomfördes av Geodatacentralen vid Lantmäteriverket i samarbete med kommunikationsministeriet.

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Contents

1 Introduction

The Arctic region offers an immense potential for growth in business such as transport, mining, and tourism. However, the wide range of applications face a variety of challenges that are specific to the Arctic. For instance, maritime navigation requires up-to-date awareness of the ice conditions, aviation suffers from degraded coverage of satellite navigation augmentation systems at high latitudes, and atmospheric phenomena (those that cause, e.g., the Aurora Borealis) degrade the general accuracy and availability of satellite positioning. Moreover, visibility is often poor, telecommunications connectivity is not always available, and the quality of maps and nautical charts can be suboptimal, which is a challenge especially for autonomous vessels and vehicles. These challenges concern not only the Arctic Circle but certain other areas as well, such as the Gulf of Bothnia.

This document reports the results and findings of the ARKKI project. The goal of the project was twofold: First, the most significant challenges faced in navigation and geospatial information-based applications in Arctic areas were identified. Second, different technologies to address the challenges were studied, and a roadmap was developed to recommend pan-Arctic solutions. The ARKKI project was funded by the Finnish Ministry of Foreign Affairs under the Baltic Sea, Barents and Arctic cooperation programme, and it was implemented by the Finnish Geospatial Research Institute (FGI) in collaboration with the Finnish Ministry of Transport and Communications.

A highlight of the ARKKI project was the pan-Arctic “Challenges in Arctic Navigation” workshop organized in Olos, Finnish Lapland, on April 16–18, 2018. The workshop collected together 73 participants representing various Arctic stakeholder groups, ranging from navigation end-users and scientists to authorities and decision makers. The programme consisted of three main components: keynote presentations, panel discussions, and expert group work. The keynote presentations addressed various topics related to Arctic challenges, such as atmospheric phenomena and autonomous navigation. The three panel discussion sessions covered the future of Arctic navigation, the needs of different transport modes, and emerging Arctic business opportunities. The expert working groups discussed the challenges faced by different user groups and brainstormed a solution for one challenge of their choice. The results of the group work are summarized in Section 5.1 of this report.

The remainder of this document is organized as follows. The variety of challenges in Arctic navigation and location-based services is introduced in Chapter 2. Next, the results of the end-user survey about the significance of these challenges and their possible solutions are presented in Chapter 3. Possible technical solutions are presented in Chapter 4, and a roadmap for addressing the challenges is developed in Chapter 5. Finally, Chapter 6 concludes this report with a summary.

2 Challenges of the Arctic

When addressing the challenges in the Arctic, the first question is to define the Arctic region. Several alternative definitions can be used: for instance, with respect to the visibility of the midnight sun on the summer solstice, or as the area in the Northern hemisphere where the average temperature during the warmest month of the year is below 10 °C (dashed blue and solid red lines in Figure 2.1, respectively). The former definition is known as the geographical Arctic Circle.

Figure 2.1 Map of the Arctic region. Source: CIA World Factbook and Wikipedia.

The scope of this document is not strictly limited to any single definition of the Arctic. In principle, the focus in the ARKKI project is on challenges that are encountered within the Arctic Circle. Nevertheless, there exist places at lower latitudes where similar conditions apply: for instance, the Gulf of Bothnia and the White Sea suffer from ice and considerable darkness during winter time.

In the following sections, various challenges of navigation and other applications of geospatial data in the Arctic are discussed. The challenges are grouped in terms of technology, not applications; for instance, maritime transport encounters challenges in several categories.

2.1 Satellite Navigation

A common feature of mode smart devices, satellite navigation makes it possible to solve for the position of a receiver located anywhere on the Earth with an accuracy of a few meters in a matter of seconds, without need of any user equipment calibration. Because of these advantages, Global Navigation Satellite Systems (GNSS), i.e., GPS, GLONASS, Galileo, and BeiDou, are the cornerstone of modern positioning and navigation.

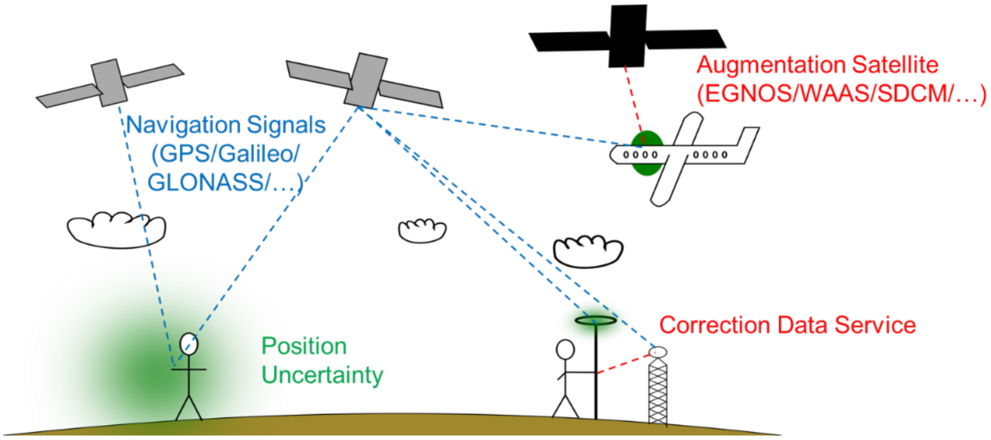

Figure 2.2 Different user needs for satellite navigation

The basic concept of satellite positioning is simple: by measuring the time of transmission from navigation signals transmitted by four or more satellites simultaneously, the receiver can solve for its three-dimensional position coordinates. As a side product, the receiver obtains very precise time information; in fact, some users are interested only in the time information which is a cost-efficient way of synchronizing networks such as power grids or telecommunications networks.

Different use cases of satellite navigation are illustrated in Figure 2.2. The basic user, such as a regular consumer driving a car with the help of a satellite navigation device, obtains a position accuracy in the order of 5–10 meters based on the navigation signals only. The uncertainty is caused by, e.g., signal propagation distortions in the atmosphere, errors in the estimates of satellite orbits, and the quality of the receiver. However, in some cases the position could be biased by dozens of meters, for example in cases where the signals are subject to reflections or if a satellite has failed; as a result, the user's navigation device could show the location of the user on a wrong street. Such a measurement blunder would, however, be unlikely to cause a safety hazard or significant economic loss; the user would be just annoyed if such a situation caused him or her to make a wrong turn.

Not all users can tolerate gross positioning errors. For instance, in the case of a satellite-guided aircraft landing, a positioning error of 100 m could have catastrophic consequences. In order to monitor the quality of their GNSS-based navigation information, aviation users use satellite navigation augmentation systems which transmit real-time correction and integrity data for the navigation signals transmitted by the GNSS satellites in order to prevent hazardously misleading information. For this reason, the uncertainty area around the aircraft in Figure 2.2 has a crisp boundary. Augmentation systems are always regional services; Europe is served by the European Geostationary Navigation Overlay Service (EGNOS), North America by the Wide Area Augmentation System (WAAS), and Russia by the System for Differential Correction and Monitoring (SDCM). Other systems exist at lower latitudes. Augmentation systems can be used free of charge, but certified receivers are required in safety critical applications.

The use of an augmentation system can provide an improvement to the accuracy of GNSS, but the uncertainty remains nevertheless larger than one meter. In many applications, the accuracy should be one or two orders of magnitude better: for instance, autonomous vehicles and surveying need centimeter-level position accuracies in practice. This can be achieved by using a correction data service together with a high-quality GNSS receiver. A correction data service consists of one or more base stations that are employed to estimate the systematic error components of GNSS measurements, such as atmospheric disturbances and satellite orbit prediction errors. These correction data are transmitted to the users, who consequently can have access to centimeter-level position solutions. Similarly to augmentation systems, correction data services are local or regional in nature, depending on the size of the base station network. Correction data services are typically offered for paying customers only.

2.1.1 GNSS Constellation Design

Each GNSS constellation consists of roughly 25–30 satellites in a medium Earth orbit (altitude in the order of 20 000 km above Earth)[1]. Their orbits are almost circular and inclined with respect to the equatorial plane. The choice of inclination angle has a direct consequence on the performance of the system at high latitudes: that angle, in degrees, corresponds to the highest latitude where the satellites can be observed in the zenith direction. When the receiver can observe satellites in high and low elevations and in different bearings, the geometric diversity is maximized, leading to a smaller positioning uncertainty.

Table 2.1 GNSS satellite inclinations

SYSTEM	GPS	GALILEO	GLONASS	BEIDOU
ORBITAL ALTITUDE [KM]	20 200	23 200	19 100	21 500
INCLINATION [DEGREES]	55	56	65	55

The orbital inclinations for different GNSS constellations are listed in Table 2.1. It can be seen that the GLONASS constellation has been designed to serve high latitudes better than the other three systems, but even GLONASS satellites don’t reach the zenith inside the Arctic Circle. The most immediate consequence of the degraded geometric diversity is a higher uncertainty in the vertical position coordinate.

2.1.2 Augmentation Systems and Correction Data Services

In order to improve the accuracy or integrity of satellite navigation from the nominal performance, external information needs to be input to the receiver. This gives rise to two challenges: first, sufficient local ground infrastructure must be deployed to produce the necessary data. Second, a telecommunications link is needed to relay the data to the receiver. In this section, we focus on the infrastructure aspect; telecommunications challenges will be addressed in Section 2.2.

The provision of GNSS augmentation or correction data hinges on the use of a network of base stations at known locations. This way, the accuracy and reliability of the navigation signals can be monitored in real time. Typically the navigation signal

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[1] As an exception, the Chinese BeiDou system also includes a handful of geosynchronous satellites (orbital altitude 35 768 km), intended to improve the service over China, in addition to medium Earth orbit satellites.

errors are divided into different types of corrections, such as slowly changing orbit corrections, rapidly changing satellite clock biases, and frequency dependent atmospheric disturbances. It is easy to understand that these error sources will have equal effects on different receivers located close to each other; therefore, users can take the base stations' estimates of errors and compensate their own measurements. However, especially the atmospheric disturbances are local in nature. Consequently, the denser the network, the more accurate corrections it can provide.

In addition to correction data intended to improve the positioning accuracy, augmentation systems such as EGNOS often broadcast integrity information with which the receiver can compute upper bounds for the expected position error. These error bounds, usually referred to as *protection levels*, are key quantities especially in aviation: if the protection level is too large, GNSS-based navigation cannot be utilized. The attainable protection level improves as more satellites with integrity information are used for position computation. However, the EGNOS ground monitoring station network does not include any base stations further East than Lappeenranta, Finland, on the Northern side of the Alps. Consequently, a receiver located in the North-East of Europe is likely to see many navigation satellites above Russia which are not monitored by EGNOS, resulting in a suboptimal protection level.

It is noteworthy that the integrity information must be timely: for instance, the EGNOS system has a specified time to alarm of six seconds in the case of a satellite failure [11]. Consequently, in safety critical applications, the augmentation data need to be continuously updated without interruptions, which is challenging in the Arctic from the telecommunications point of view (see Section 2.2). The navigation performance requirements vary depending on the flight phase, the most stringent requirements concerning approaches [11]. Similarly, vessels in port areas are subject to stricter navigation performance requirements than at open sea. Because of the challenges in telecommunications and the limitations of the EGNOS monitoring network, Arctic areas are often subject to degraded availability of safety-of-life GNSS services in comparison with, e.g., Central Europe.

2.1.3 Atmospheric Phenomena

GNSS signals are broadcast from space, and the propagation through the atmosphere causes disturbances in the signal travel time. The atmosphere consists of several layers, two of which affect the propagation of radio signals significantly: the ionosphere and the troposphere.

The ionosphere extends from approximately 50 km to 1000 km in altitude and contains free electrons which interfere with electromagnetic radio waves. Two kinds of effects can be observed. First, the signal is refracted, which causes a propagation delay with respect to the direct line-of-sight path. The magnitude of the refractive delay depends on the frequency of the signal: the lower the frequency, the higher the ionospheric error. Therefore, a receiver tracking the satellite at two different frequencies can compensate for the ionospheric error by examining the difference of measured travel times at the two frequencies. Single-frequency receivers must resort to the use of ionospheric corrections to compensate for the refractive delay; these corrections can be obtained from the navigation message modulated on the navigation signals themselves, from an augmentation system, or a correction data service. The ionospheric error can have a magnitude of dozens of meters, and the correction data provided in the navigation message is typically accurate to 50–70 %. Real-time corrections from augmentation or correction data services perform better, but the accuracy depends on the density of the monitoring network.

In addition to refraction, ionospheric irregularities can also cause the signals to diffract, resulting in a phenomenon known as *scintillation* [49]. As a result, a receiver may be subject to severe short-term signal power fluctuations disturbing the signal tracking. Scintillation effects are most commonly observed in high-precision applications, such as surveying and geodesy, where errors exceeding 10 cm are rejected as outliers. However, this magnitude of position error is likely to be inadequate in the context of autonomous vehicles as well [44]. Moreover, strong scintillation can lead to loss of signal tracking and thus degraded availability of GNSS positioning for any receiver. Scintillation effects are mostly encountered at equatorial and polar latitudes; the phenomenon is less common at mid-latitudes.

The other atmospheric layer affecting the propagation of radio signals is the troposphere. Being the bottom layer of the atmosphere, the troposphere is where weather phenomena occur. Consequently, the troposphere contains gases and water vapor which slow down the propagation of electromagnetic radio waves. Most of the tropospheric delay is predictable and can be modeled accurately, but the contribution of water vapor is subject to fluctuations and causes an uncertainty in the order of decimeters. A correction data service can be utilized to compensate for this error. Unlike the ionosphere, the tropospheric delay is not a challenge particular to the Arctic per se.

2.2 Telecommunications

Modern societies are heavily dependent on telecommunications in numerous aspects; navigation is not an exception. Since the Arctic area is sparsely populated, infrastructure such as cellular networks are underdeveloped.

Satellite communications are often regarded as a solution for areas without proper cellular coverage. Telecommunications satellites are located in geostationary orbits (GEO). This orbit has an altitude of 35 768 km above the Earth and is not inclined with respect to the equator. At that altitude, the orbit period is 24 hours, therefore, the satellite appears to remain stationary when observed from the Earth. Unfortunately, this type of orbit is problematic for users located at polar latitudes, as illustrated in Figure 2.3: the higher the latitude, the closer to the horizon the satellite is seen; in other words, the satellite is seen at a low elevation angle. Consequently, environmental features such as buildings, trees, or mountains are likely to block the signal from a GEO satellite; at latitudes exceeding 82°, GEO satellites are below the local horizon.

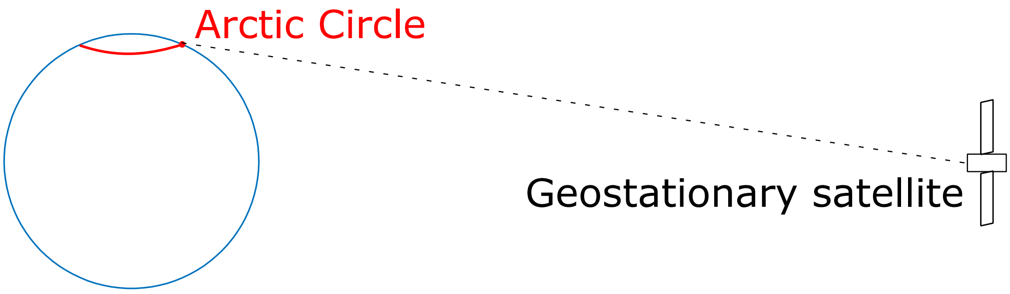

Figure 2.3 Geostationary telecommunications satellite link as seen from the Arctic

For maritime and aviation users, the low elevation angle of GEO satellites is a major challenge. Satellite navigation augmentation signals are broadcast from GEO satellites; when the aircraft banks, its wing can block the geostationary augmentation signal. The loss of augmentation signals, for any reason, can lead to the interruption of a precision approach. In maritime applications, a tall part of the vessel itself can block the visibility of geostationary satellites depending on the course; this phenomenon is referred to as the ”no internet heading” [31]. Since the course of a vessel can remain virtually unchanged for a long period of time, the lack of telecommuncations results in degraded situational awareness. Furthermore, vessels are required to send daily reports to authorities despite the challenges in telecommunications [31].

There exist satellite communications services that are not based on GEO satellites only; for instance, the Iridium constellation is based on 66 low Earth orbit satellites with a high orbital inclination, making it capable of covering polar regions as well [23]. In addition to the orbital geometry challenge, satellite communications is more expensive than, e.g., conventional cellular subscriptions, and the bandwidth is lower in general. On the other hand, satellite communications are not bound to national borders and roaming charges.

2.3 Maps and Nautical Charts

Arctic seaways suffer from a lacking quality of nautical charts: the soundings are often scarce and inaccurate, resulting in the presence of unknown shoals [31]. The risk they cause on navigation is evident.

Concerning road maps, the situation is not as bad for today’s requirements. However, in the era of autonomous vehicles, the availability of high-definition maps, having a resolution of 10 cm, is seen as an important factor [47]. Several companies offer high-definition maps, but it is unclear whether the service will cover the Arctic where the density of paying customers is low; in the end, gathering and maintaining high-definition map data is a very tedious undertaking.

2.4 Situational Awareness, Weather, and Road Maintenance

In any mode of transport, situational awareness including weather information is crucial for safety. In Arctic maritime navigation, an important component of situational awareness is ice information: a bad choice of route slows the vessel down, or in the worst case, the vessel has to wait for icebreaker assistance. Thus, route planning should be based on a forecast of ice conditions, which is not trivial: for instance, sea currents can be difficult to predict [31].

In addition to weather-related information, situational awareness should comprise information about accidents. Should an oil spill happen at sea, other vessels should avoid navigating in the vicinity of the spilled oil in order to avoid spreading the oil layer before cleanup actions take place. In road traffic, wildlife and lacking road maintenance can cause the likelihood of accidents to increase at a certain location.

During winter time, the Arctic region is subject to long periods of darkness. This makes it more challenging to navigate based on visual perception, and sometimes even impossible when the weather conditions are difficult. Particularly for aviation, such a situation calls for instrument flight rules, requiring type-certification and proper navigation equipment for the aircraft.

2.5 Other Radionavigation Systems

Although GNSS has superseded many means of radionavigation, it is well known to have certain vulnerabilities such as a low signal power. The shortcomings can be mitigated by using several sources of location information, which justifies the need for terrestrial backup systems, particularly for the purposes of safety or liability critical applications such as aviation and maritime navigation. Unfortunately, many suitable legacy radionavigation systems have been decommissioned in favor of GNSS, the maintenance costs being one of the driving factors [3].

Aviation uses distance measuring equipment (DME), very high frequency omnidirectional ranging (VOR), or an instrument landing system (ILS) as a backup for GNSS especially during approaches. However, satellite-based approaches are far more common [46]. The challenges in the visibility of satellite-based GNSS augmentation systems can be locally solved by deploying a ground-based augmentation system (GBAS) which broadcasts correction and integrity information on a very high frequency radio channel.

2.6 Indigenous People

The Arctic region is the home for various indigenous peoples who have long traditions in their way of life, including reindeer herding, hunting, and fishing. The purpose of the ARKKI project, or this document, is not to address the related possible social challenges. However, when developing technical solutions, the indigenous people must be taken into account: for instance, one should not deploy technical infrastructure at traditional hunting lands. Nevertheless, some challenges related to the local cultures can be addressed or at least mitigated by means of technology: for example, an online service has been established for collecting and distributing observations of wild reindeer [39], thus reducing the amount of road accidents involving them.

3 End-User Survey

The main target of the ARKKI survey was to find out the user’s views on the challenges in navigation and geospatial information based applications in the Arctic region. The results formed background material for the “Challenges in Arctic Navigation” workshop held in Olos, Finland, in April 2018. The survey consisted of questions that can be divided into four topics:

1. Background information and the activity in the Arctic
2. Encountered challenges related to navigation in the Arctic
3. Potential consequences of several navigation technologies and/or purposes in area
4. Feasibility of the already existing and upcoming solutions.

The survey mainly consisted of multiple choice questions with the possibility to leave open answers and further comments to each subtheme. In this report, the answers are grouped according to these themes and presented via charts and tables. The exact questions and answer possibilities can be found in the appendix of this document.

3.1 Background information and activity in the Arctic

3.1.1 Country

The total amount of completed surveys was 83 and the vast majority of the participants came from Finland, as shown in Figure 3.1. 89 % percent of answerers were from the Arctic council member countries where Iceland was the only country without a participant.

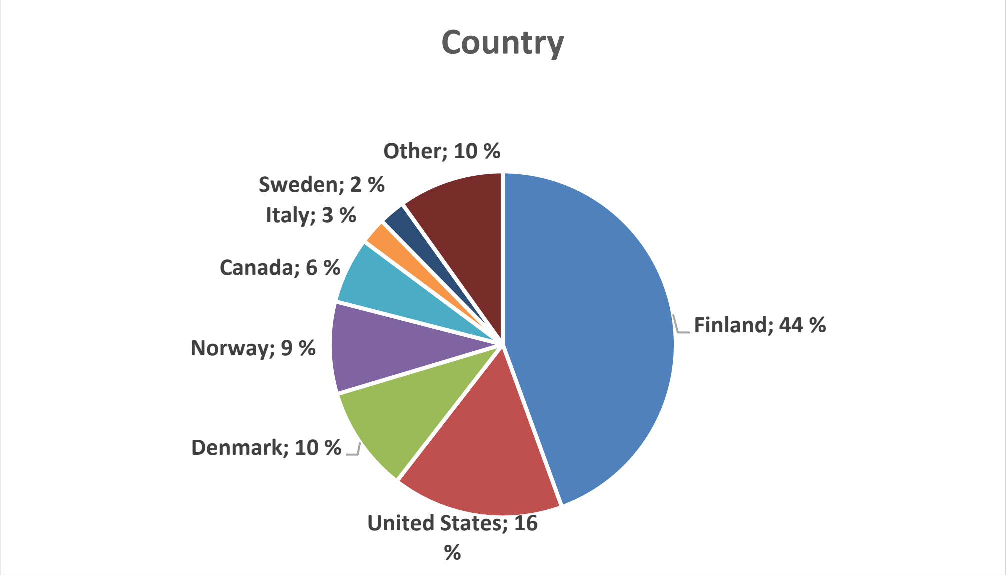

Figure 3.1 Survey respondents’ country of activity

Other countries included single respondents from Belgium, France, Greenland, Netherlands, Poland, Russia, Ukraine, and United Kingdom.

3.1.2 Activities taking place above the Arctic Circle

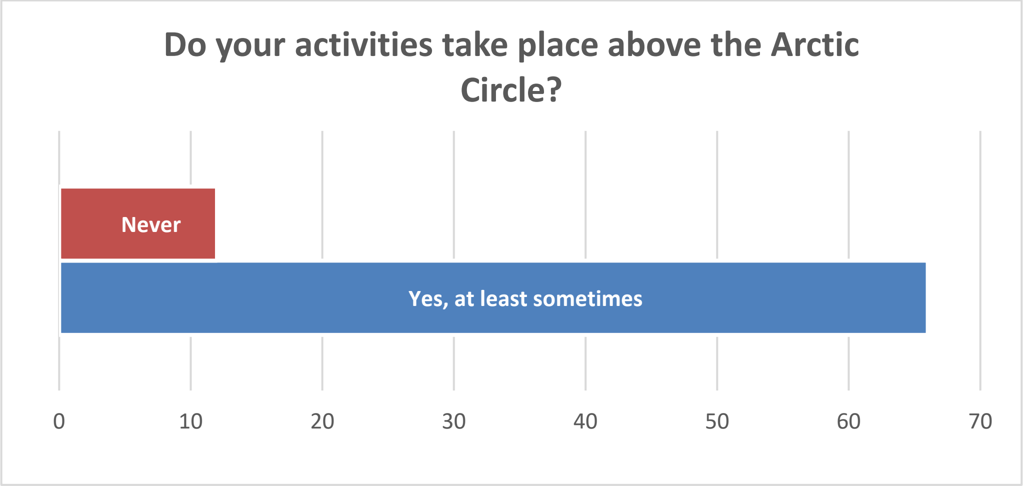

Figure 3.2 Proportion of respondents active above the Arctic Circle

As seen from Figure 3.2, the majority of the respondents operate at least sometimes in the Arctic area. From the 83 participants, 66 answered “yes”, 12 said “no” and five did not answer. Therefore, we can assume that the survey reached targeted experts and the evaluation of recognized challenges, potential consequences and feasibility of solutions is based on real-life experiences and scientific knowledge.

The activities taking place above the Arctic Circle varied slightly between the market segments. 90.6 % of the maritime segment, 87.5 % of the aviation segment, 80 % of the road segment, 77.8 % of the rail segment, and 79 % of the other market segment participants operate in the Arctic area.

3.1.3 Position in work

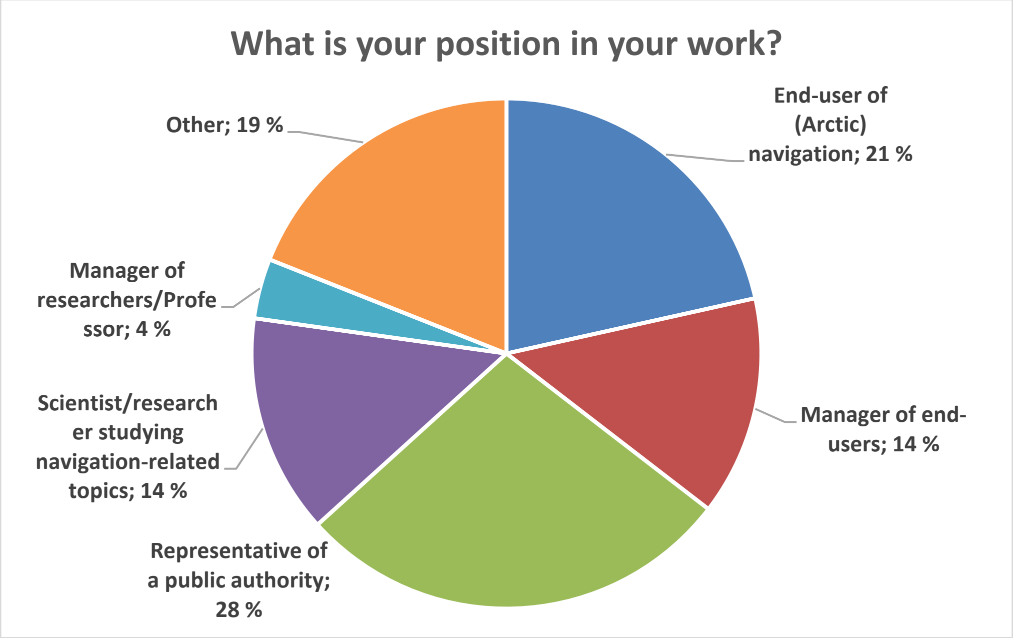

Figure 3.3 Survey respondents' work position

As seen from Figure 3.3, the biggest participant group were public authority representatives, which most probably also involves the defense sector as this was not asked separately. The participants who selected the "other" category work for example, as a GIS expert, design engineer on a private company, manager of a vessel traffic service, commanding officer, navigation officer, cruise industry representative, hydrographic expert, funding agency representative, and information officer.

3.1.4 Involvement in different market segments

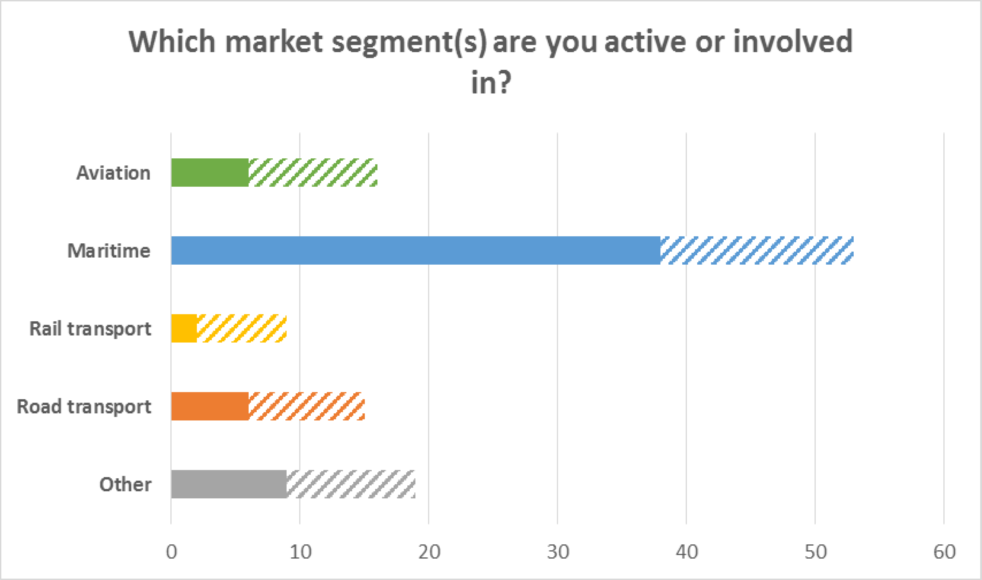

Figure 3.4 Market segments where the survey respondents are active; solid areas indicate respondents active exclusively in that segment while hatched areas correspond to respondents active in several segments.

The bar areas which are colored with a solid color, signal the number of participants that operate only on that particular segment. The hatched part indicates those participants who are operating in other market segment(s) as well. As seen from Figure 3.4, almost half of the participants are active in maritime segment whereas the other market segments are seemingly smaller. In addition, 19 of the participants reported that they are operating in more than one segment (the hatched areas). Other market segments included, for example, surveying and/or monitoring, seafloor mapping, hydrographic surveys, people flow solutions, geodesy, indoor navigation, weather services, inland water transport and subsistence hunting and fishing/observational reporting.

Because of the high amount of participants from the maritime segment, we have settled a specific emphasis to analyze the answers of this group. In some cases, the survey results seemed to be slightly skewed due to the major appearance of the maritime segment. These results are discussed separately.

3.1.5 Challenges related to navigation in the Arctic

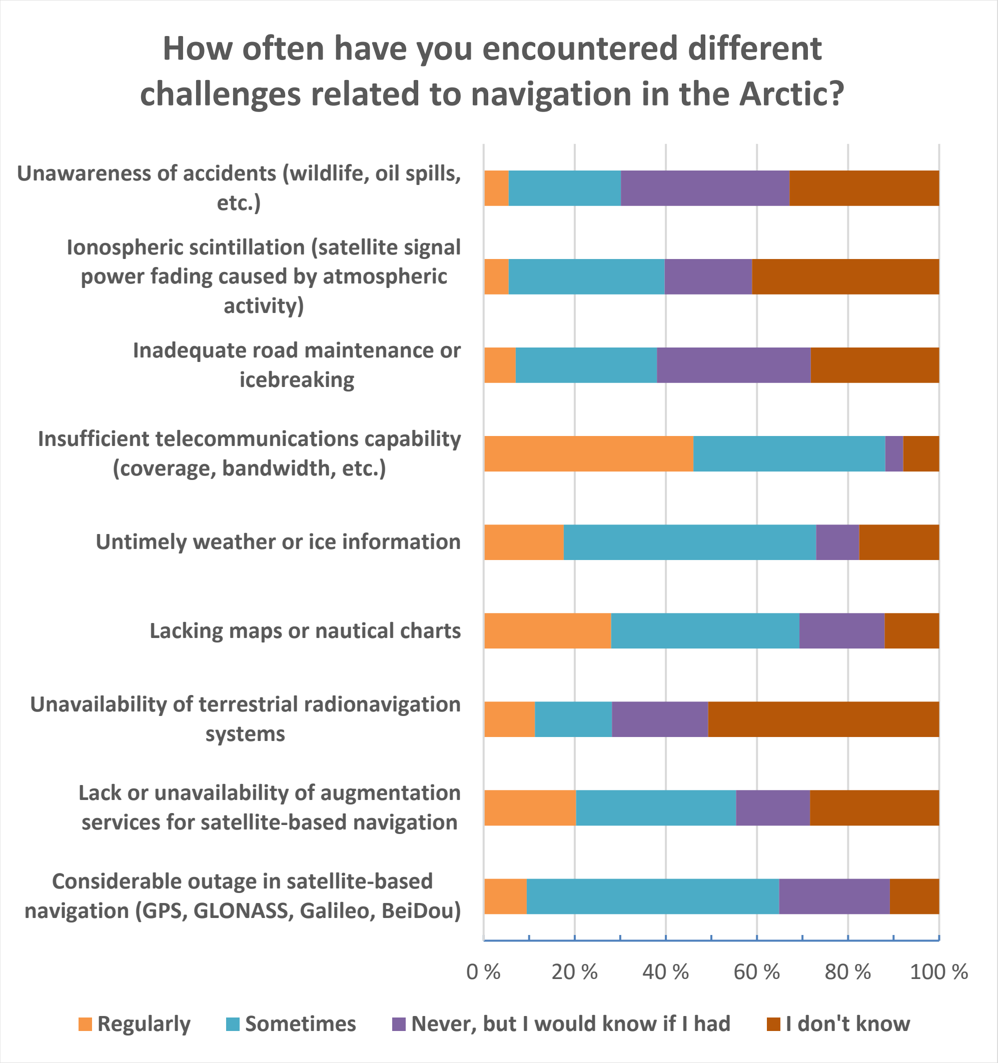

Figure 3.5 Challenges encountered by the respondents

The respondents’ experiences on different challenges in the Arctic are shown in Figure 3.5 To sum up, almost 90 % of participants had experienced “regularly” or “sometimes” insufficiency in telecommunications, e.g. issues with coverage or bandwidth. This option stands clearly out from the others and stated that lacking telecommunication capability affects every market segment. Over half of the participants had confronted untimely weather or ice information, lack of maps and nautical charts, outages in satellite-based navigation as well as unavailability of augmentation services. Unavailability of terrestrial radio navigation, unawareness of accidents, ionospheric scintillation and inadequate road maintenance or icebreaking were among the rarest occasions since under 50 % of participants had encountered these issues or is affected by them.

In addition to the questions illustrated in Figure 3.5, it was also asked whether participants had encountered challenges related to lacking physical infrastructure (ports, roads, and airports) or telecommunication functionality. One partaker had regularly encountered the challenge where bandwidth is theoretically available, but not actually functional or available.

When comparing the answers given by the operators from different market segments, a few differences were found. For example, maritime users had encountered fewer considerable outages in augmentation services for satellite-based navigation than others. They had also encountered lacking nautical charts and/or maps (regularly + sometimes 86.4 %) and untimely weather or ice information more often than other groups.

Regarding the aviation segment, the most encountered challenges are considerable outages in satellite-based navigation, untimely weather information, lack or unavailability of SBAS, and insufficient telecommunications capability which over 75 % of the aviation segment had confronted regularly or sometimes. Participants from aviation segment had also faced lack or unavailability of SBAS more often than maritime.

Lacking maps/nautical charts was reported to be rather wide problem among the road segment since 11.1 % had encountered these issues regularly and 66.7 % sometimes. In comparison, rail segment representatives had faced maps/nautical charts 14.3 % had encountered regularly and 42.9 % sometimes whereas inadequate road (rail) maintenance was encountered sometimes by three (42.9 %) or never by four (57.1 %) participants. All rail segment participants had been affected by insufficient telecommunications capability regularly or sometimes, 85.7 % had encountered considerable outages in satellite-based navigation sometimes. Majority did not know whether they had encountered unavailability in terrestrial navigation or not.

According to the survey, lacking maps or nautical charts was not that severe problem within other segments as it was with maritime, aviation, road, or rail segments.

Overall, unavailability of terrestrial navigation and ionospheric scintillation gained most “empty” or “I don’t know” answers. These slightly skewed results may be due to the high representation of maritime actors.

Some users' comments related to the most encountered challenges:

- Up-to-date ice information and the serious lack of suitable communications we see daily when operating there. Ice services have improved this year, but we hope it continues. (maritime)
- Quality of nautical charts are bad, even in coastal areas are not to be trusted and luck has too much to do with success. (maritime)
- Lack of SBAS/EGNOS coverage around Iceland, delaying development of LPV approaches.
- Insufficient coverage of standard aviation functionality (LPV, B2, B3) due to European systems based on GEO satellites (EGNOS, Iris). (multiple segments)
- Enough cannot be said about the problems caused by lack of Internet/mobile coverage in the Alaskan Arctic. (other segments)
- EGNOS coverage in Finland (aviation)
- Inmarsat Fleet Broadband covers the whole area but is expensive whereas the cheaper satellite navigation solutions have blind spots. (maritime)
- Lack of reliable communications in the high latitudes (i.e. above 75N). (maritime)
- Inadequate maps (maritime)
- Accuracy, reliability and positioning frequency of GNSS aren't good enough for autonomous vehicles. (road)
- Lack of ENC Charts for navigation. Bad V-SAT coverage on the higher latitudes. (maritime)
- Around the east side of Spitsbergen area, charts are only available in large scale not suitable for navigation. (maritime)
- Lack of connectivity (maritime)
- Main challenges in 100 aerial and terrestrial survey missions in the Nordic area have been related to limited satellite coverage in the north. This has caused problems in positioning in canyons and on the north side of larger buildings and structure. (other segments)
- Outages of emergency tracking/beacon devices (SPOT). (multiple segments)

3.2 Potential consequences

The survey also examined the user’s impression of the potential impact of several challenges, including

1. Snow, ice, and situational awareness
2. Telecommunications
3. Satellite-based navigation
4. Other radio navigation than satellite-based
5. Maps and nautical charts.

The scale of severity is defined as follows:

- **Catastrophic**: Incident may lead to persons being killed or severely injured, severe damage to property and significant economic impact.
- **Critical**: Incident may cause severe damage to property and significant economic impact. Small chance that a person gets killed, still a reasonable chance of injuries.
- **Major**: Incident may cause damage to property and economic impact. Reasonable chance that people may panic or get distressed. A small chance that people get injured.
- **Minor**: Incident causes mainly economic loss. There is a small chance of damage to property. May cause minor distress.
- **Negligible:** People may be alerted and feel uncomfortable. A possibility of damage to people, property, or business is very unlikely.

In most questions, the basic response trend followed the normal distribution where the response options in center gained most answers. For example, issues were more often voted to have minor or major impact than catastrophic or negligible impact.

3.2.1 Snow, ice, and situational awareness

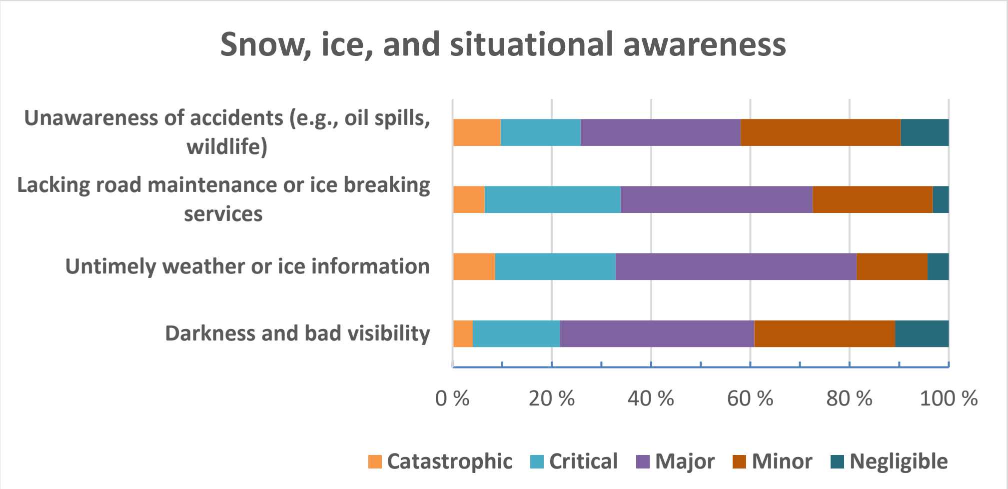

Figure 3.6 Potential consequences of snow, ice, and situational awareness related challenges

Regarding the different aspects of weather conditions, there was no significant variation between priorities and majority of the participants stated that each of these weather-related issues has at least major effect.

According to maritime segment, consequences with maps and nautical charts were severe since the vast majority of participants voted for them to be major, critical or catastrophic.

For the road sector, the most critical or catastrophic issues were related to untimely weather information, lacking road maintenance where unawareness of accidents, issues with telecommunications were seen as major challenges. Otherwise, satellite-navigation as well as other radio navigation than satellite-based related issues were reported to have major or minor influence.

All of the participants from rail segment reported that untimely weather or ice information as well as unawareness of accidents have at least major effects.

Further comments related to snow, ice, and situational awareness:

- Darkness, bad visibility and lack of ice information can create a catastrophic situation especially in areas with polar ice. E.g. cruise ships in polar waters. (maritime)
- If communications with somewhere like Gambell -- or similar communities -- are down during an earthquake-related tsunami event, residents could be completely wiped off the island. (other segments)
- Darkness and bad visibility mainly causes delay and waiting resulting economic loss. Snow makes identification of ice type even more challenging. (maritime)
- For low level (0-10000 ft.) flights (helicopters, HEMS) good weather information is very important. (aviation)
- Due to the political decisions, vehicles and fleet are not up-to-date (other segments)
- Currently, the weather and climate conditions are biggest factors causing productive losses in rail transport. The possible future scenarios of autonomous traffic, also on rails, these factors create more severe challenges. (rail)
- Information about ice, its sort and movements is always considered to be progressive, but receiving the overall information with a minimal delay is most useful. With it, we can evade risks and optimize the routes. (maritime)
- Transport is occasionally very risky due to the icy roads and whirling snow. The main factor is insufficient road maintenance. (road)
- Lacking ice breaking services (maritime)
- (Service providers viewpoint) We produce weather information for road transport 120 000 times per year and the system updates once per every hour. Emphasis is on rapid changes but the accuracy of the location references on maps cause challenges. (road)

3.2.2 Telecommunications

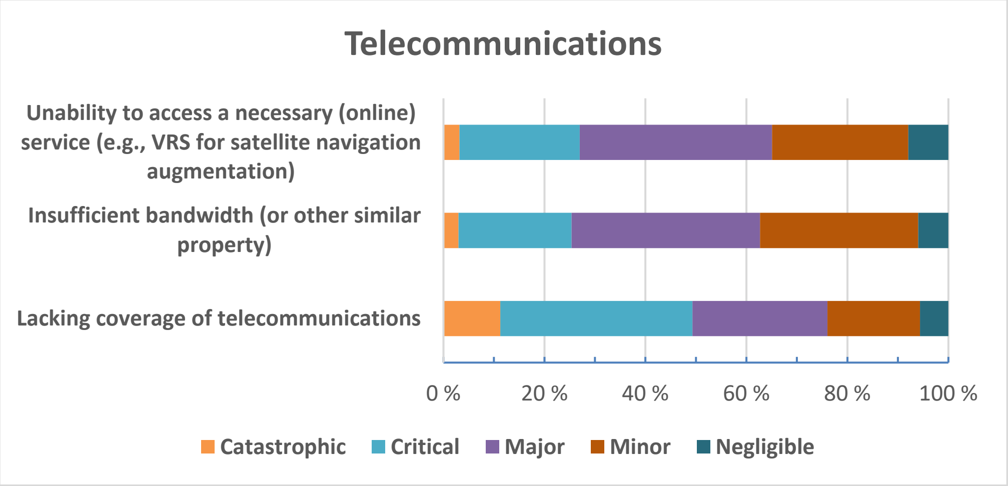

Figure 3.7 Potential consequences of telecommunications related challenges

All telecommunication issues were considered to be comparably severe as over 60 % of participants classified these matters as catastrophic, critical, or major.

Regarding telecommunication consequences from the aviation segments’ viewpoint, lacking coverage was seen to have most severe effects: 15.4 % said it would be catastrophic, 15.4 % answered critical, and 30.8 % expected major consequences. In comparison, lacking coverage of telecommunications was classified to be major, critical or catastrophic by all rail segment participants.

Further comments related to telecommunications:

- Lack of communications is a significant operational hurdle to overcome and adds a layer of complexity (and cost) to everything. (multiple segments)
- Products have to be stripped too much less information because of bandwidth limitations. As a provider it is difficult to estimate how much this affects the activities themselves. (multiple segments)
- Members of communities on St. Lawrence Island (Alaska) have attempted to use SAT phones while subsistence hunting and fishing, and occasionally been connected to Russian operators, who don’t speak English. If it is a distress call, this could be extremely dangerous. (other segments)

- Some lower accuracy geostatic satellite services can make up for possible lack of more precise VRS services, but in the Nordic region availability of these is limited to only areas, where there is a good visibility to the southern sky. Otherwise geostationary correction satellites in the equator are not visible in the arctic region. (other segments)
- Connections in Northwest and West-north Passages are poor or nonexistent. (maritime)
- The biggest challenge with terrestrial networks is related to the disparities of different networks and the reliability of data transfer between operators. (road)

3.2.3 Satellite-based navigation

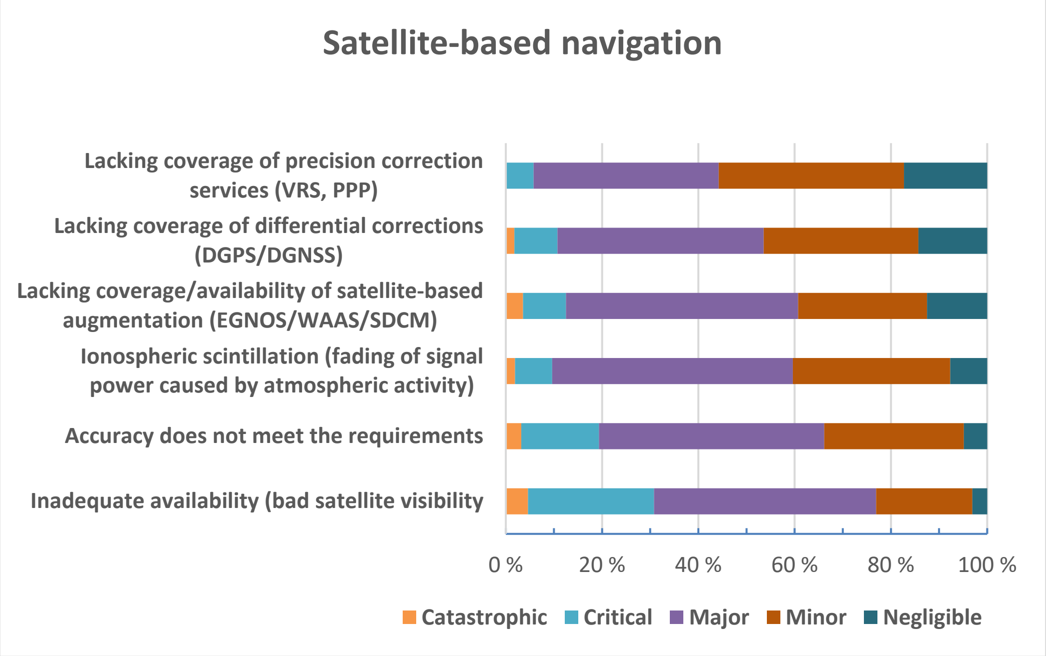

Figure 3.8 Potential consequences of satellite navigation related challenges

As seen from Figure 3.8, the major effect was the most common answer to every question. The amount of consequence that was experienced to be “catastrophic” or “critical” varied, dropping from the 30 % to ca. 5 %. The underlining trend appears to be that the more detailed and technology related the question was, the more it gained either “empty” or “no opinion” answers.

Maritime users had more often “no opinion” answers in the consequences of satellite-based navigation than other groups.

Further comments related to satellite-based navigation:

- We are used to navigate near coastal and inshore by radar navigation and we do not depend too much on satellite navigation. (maritime)
- As nautical charts are so bad, knowing exactly where you are is not as important as you wouldn’t know where that is. (maritime)
- Maps/charts are not WGS (maritime)
- The positioning accuracy is not sufficient for UAVs (road)
- Multi GNSS with more frequencies is better than GPS L1 only to cover for ionospheric scintillation. (multiple segments)
- Northern railways are mainly single rails where adequate position accuracy can be reached with current technologies. However, the situation on rail yards is different and for example, DGPS alone provides defective accuracy. (rail)
- Geographic information is moderate for civil navigation but poor for accuracy measurements. (maritime)

3.2.4 Other radio navigation than satellite-based (e.g., eLORAN, Distance Measuring Equipment)

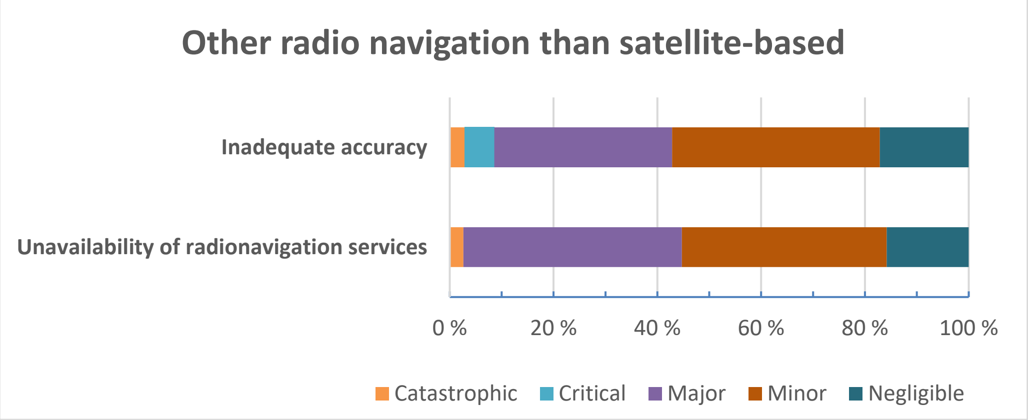

Figure 3.9 Potential consequences of challenges in other radio navigation technologies

Further comments related to other radio navigation than satellite-based (e.g., eLORAN, Distance Measuring Equipment):

- There should be a reasonably accurate backup for GPS. (multiple segments)
- Lack of LORAN in western ALASKA makes maritime navigation wholly reliant on GPS due to poorly charted and shifting shorelines and little to no visual markers, often obscured by poor visibility. (maritime)
- DME back up. eLoran no longer an alternative. Better use other radio sources if available more intelligent combined with GNSS. (multiple segments)
- If DGPS is supported by Dead Reckoning appliances they will together achieve exact rail locations. If the production relies on exact navigation, malfunction of either of the technologies can cause severe financial losses. (rail)

3.2.5 Maps and nautical charts

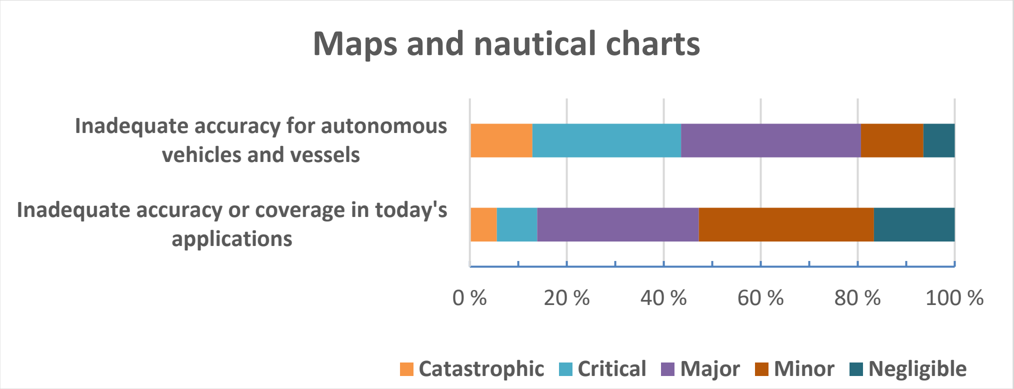

Figure 3.10 Potential consequences of challenges with maps and nautical charts

The answers (Figure 3.10) show clearly that the future prospects of autonomous traffic raise concerns about the adequate navigation accuracy. In current applications, we can still supplement inadequate map and nautical chart accuracy with other technologies and operations. According to maritime segment, consequences with maps and nautical charts were severe since the vast majority of participants voted for them to be major, critical or catastrophic.

Further comments related to maps and nautical charts:

- The Alaskan Arctic is full of communities who are very active in subsistence hunting and fishing. This means they are out on the water, often in bad weather, in very small vessels (open skiff, in the 20'/6 meter range). Inaccuracies in navigation by autonomous vessels could absolutely put people at substantial risk. (other segments)
- Chart data in Arctic is ancient and entirely insufficient for modern precision navigation. Significant effort and investment is needed. (multiple segments)
- Only few maps are new and ENC is very few (maritime)
- The maps from the Arctic area are very old and because probing etc. have been done before satellite navigation era, reliability is not even close to the norms. (maritime)
- The traffic policy in Finland is against EU's strategy since Finland is developing only four types of transport. Inland waterway transport is clearly missing out. (other segments)
- Poor charts at Spitsbergen (maritime)

3.3 Feasibility of solutions

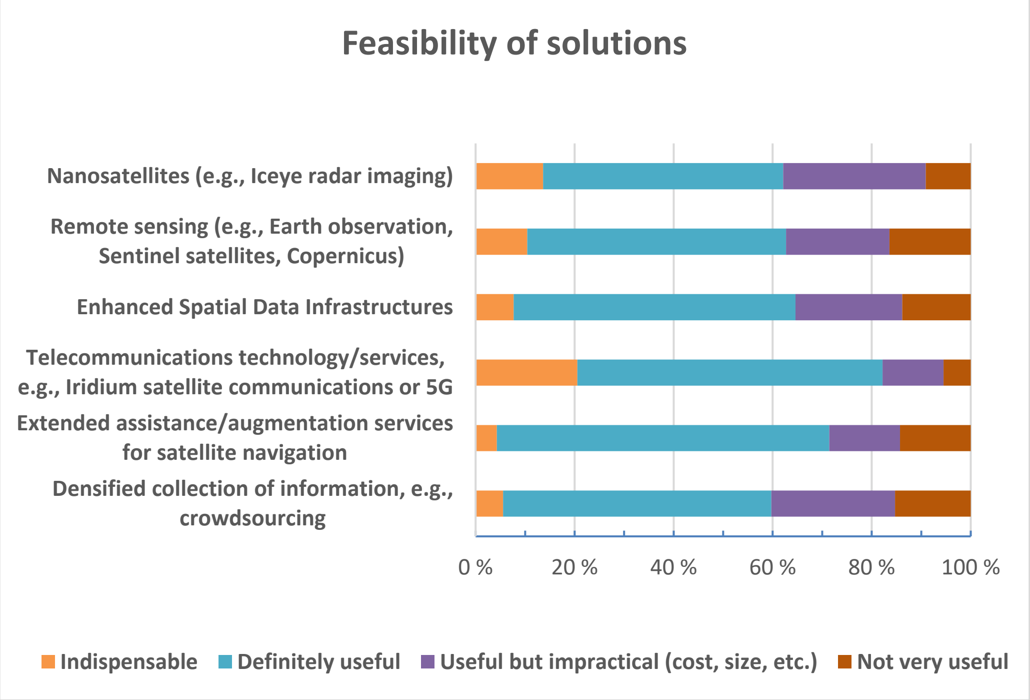

Figure 3.11 Feasibility of different solutions as seen by the respondents

When looking Figure 3.11 and at the answers in the ”definitely useful” and ”indispensable” categories, it seems that the most important, or needed, solutions according to users’ opinion are:

- Telecommunications technology/services
- Extended assistance/augmentation services for satellite navigation
- Remote sensing

When comparing the feasibility of solutions by market segment, few interpretations can be made.

Telecommunications technology/services were rated to be the most feasible solution while 87.8 % of the maritime users admitted these would be definitely useful or indispensable.

Remote sensing was seen as the most feasible and important solution among the aviation segment: 63.6 % said it would be definitely useful and 18.2 % classified the importance indispensable. Other important solutions were telecommunications technology/services (38.5 % definitely useful; 38.5 % indispensable) and extended assistance/SBAS (61.5 % definitely useful; 7.7 % indispensable). Nanosatellites were seen to be either definitely useful or useful but impractical.

According to the road segment representatives, remote sensing services, such as Copernicus, were seen definitely useful or indispensable (100 % of the responses were in these categories).

Among the rail sector, extended assistance/augmentation services for satellite navigation was seen as the most useful (88.9 % saying it would be definitely useful or indispensable) whereas 77.8 % of the rail segment participants rated the improvements of telecommunications capability to be either definitely useful or indispensable.

Participants representing the other market segments were comparably optimistic about the feasibility of solutions: only nanosatellites and remote sensing received one vote saying that these solutions are not very feasible while otherwise all were classified to be at least useful. Extended assistance/augmentation services for satellite navigation was seen as the most useful (93.8 % saying it would be definitely useful or indispensable).

Further comments related to feasibility of solutions:

- Improved connectivity/communication services are only helpful if they are affordable. We’ve run research projects utilizing both sat phones and Inreach units, but they are not at all affordable for general use in the communities. (other segments)
- Crowdsourcing would be useful if it is intelligent crowd sourcing (multiple segments)
- Iridium has not been reliable option and has worked poorly when other communication equipment have malfunctioned. (maritime)
- Common operational pictures, like NOAA’s Arctic ERMA exist for the Arctic Council for sharing geospatial data and products. (maritime)
- Positional accuracy must be developed to be exact enough. Because technology is developing rapidly and different market segments are having different needs, there is no need to set restrictions for what level is exact enough. (rail)
- Providing modern standards of bandwidth to the Arctic would enable many other technologies to flourish. Furthermore, utilizing crowdsourcing data to help set priorities will leverage resources in this expensive and difficult environment. (multiple segments)

3.4 Summary of the survey results

The foreseen revolution of both autonomous vehicles and vessels as well as unmanned aerial vehicles (UAV) reflected in the answers. Particularly, the issues of insufficient maps and nautical charts were mentioned as a part of larger reliability challenge. From the technology perspective, the survey participants underline that the current accuracy of any navigation application along with the insufficiency in telecommunication coverage will cause severe issues in precise positioning and close-proximity navigation.

Insufficiency in telecommunications is a widely recognized and encountered problem as nearly 90 % of the participants had been affected by lacking telecommunication services or inadequate bandwidth. These issues are familiar to all, but affect the navigation operations and accuracy especially in the Arctic.

The more detailed and technical the question was, the more it gained “empty” or “no opinion” answers. This trend can be seen especially in potential consequence questions, where satellite and radio navigation-related questions received more “empty” and “no opinion” answers than others. All answer options included some examples of related technologies.

As 44 % of the participants were from Finland (see Figure 3.1), we compared the English and Finnish versions to find out if there are significant differences. Of course, this method can only give indicative results since some Finnish participants answered in English. Nevertheless, few interesting observations were made when especially the answers from maritime segment were compared. Firstly, Finnish participants tended to select the stronger options. For example, in the series of questions asking the consequences, “minor” was chosen over “negligible” whereas “critical” gained more answers than “major”. Secondly, very few Finnish maritime participants selected the “no opinion” or “I don’t know” options. Lastly, the questions related to remoteness and extreme weather conditions were seen to have more severe and wider consequences and confronted more often among Finnish participants than in the international group.

In other market segments, the number of “no opinion” or “I don’t know answers” was typically higher in the Finnish survey than in the international group. However, generalizing the answers to reflect the experiences and opposed challenges of the whole market segment would be misleading since the sample size in other market segments varies between 2–6 participants where six participants reported to operate on road, while aviation, rail and other segments each had two participants, respectively.

Overall, the survey pointed out some problems and insufficiencies that affect very specific areas, applications, or technologies. Some of these are related to political decisions but are similarly crucial to the operators who are dealing with these matters regularly.

4 Technical Solutions and Their Feasibility in the Arctic

In this chapter, several technical solutions to the identified challenges in Arctic navigation and geospatial data are discussed. Most of the technologies addressed in this chapter are related to GNSS, but some of them are applicable to telecommunications and situational awareness as well. These technologies will be referred to in the roadmap developed in Chapter 5.

4.1 Multi-Frequency and Multi-Constellation GNSS

Global navigation satellite systems (GNSS) are used in the Arctic as the preferred method of navigation for transportation and a variety of other positioning and timing applications. However, GNSS have some limitations at high latitudes. The maximum elevation angle with which a GNSS satellite can be seen from a location on earth is determined by the satellite orbital plane. If the latitude of the location is less than the orbital inclination, the maximum elevation is 90°, but for latitudes greater than such inclination, maximum elevation will be less. Therefore, coverage of GNSS constellations in the Arctic regions is not optimal, as the satellites do not reach high elevation angles and no GNSS satellites are overhead in the Arctic. This creates weak geometries to support vertical positioning, and also the horizontal accuracy is in many cases reduced because of a higher noise level in the observations, caused by the large number of more noisy low elevation satellite signals.

The world of satellite navigation is experiencing an era of big changes as the GNSS community is growing. Besides the two existing systems, the United States' GPS and Russia's GLONASS, two more constellations are currently under development: the Chinese BeiDou and the European Galileo. When their full operational capability will be reached, the number of GNSS satellites will be higher than 100. GPS satellites' orbital planes are inclined at 55° with respect to the equator and can therefore be seen only at low elevation angles in the Arctic regions. This is also the case for the European system, Galileo, whose orbital planes have a slightly higher inclination of 56°. The Russian GLONASS has higher orbit inclination, namely 64.8°, and it is then capable to provide better Arctic coverage.

The use of multiple GNSS constellations will significantly increase the number of observed satellites and improve the satellite-user spatial geometry and consequently the continuity and reliability of positioning. The satellite-user spatial geometry influences the positioning accuracy. Such impact is normally described by the Geometric Dilution of Precision (GDOP), which indicates how errors in the measurements from the satellites in view will affect the final position estimate. The more the satellites are spread above the horizon, the smaller is the GDOP, and consequently, the better is the expected positioning accuracy. A thorough analysis of the GDOP in the presence of four GNSS constellations is conducted in [15]. Through the use of complete constellations simulated data, results showed a large improvement in the satellite-user spatial geometry across the earth, including the Arctic regions, when going from single-GNSS to multi-GNSS case.

In particular, the joint utilization of four systems will improve the Vertical Dilution Of Precision (VDOP) and thus reduce vertical positioning errors in the Arctic. An analysis of the significant VDOP improvement in the Arctic obtained by using two or more constellations is provided in [17]. It is shown that VDOP values reduce to below 1.3 with the help of multiple constellations. If using only two systems, adding GLONASS to GPS is the most helpful combination. The VDOP improvement in the Arctic is more significant using three or even all four constellations.

Besides coverage, limitations in the Arctic are also due to the increased ionospheric activity at these high latitudes. However, dual-frequency GNSS offers a possible solution, as it would allow users to directly estimate ionospheric delay. All the four systems will implement multi-frequency transmission, including the already fully operational GPS and GLONASS, which are going through a modernization phase foreseeing the generation of signals on other frequencies in addition to the legacy ones. An overview of the four systems and their (current and planned) transmission frequencies is given in Table 4.1.

Table 4.1. GNSS frequencies

	BAND	CENTER FREQUENCY (MHZ)
GPS	L1	1575.42
	L2	1227.6
	L5	1176.45
GLONASS	L1	1602
	L2	1246
	L3	1202.025
GALILEO	E1	1575.42
	E6	1278.75
	E5a	1176.45
	E5b	1207.14
BEIDOU	B1	1561.098
	B2	1207.14
	B3	1268.52

GNSS users operating in the Arctic can therefore benefit from the upcoming (partially already existing) multi-constellation, multi-frequency scenario by using receivers capable of processing signals from different constellations and at different frequencies. According to [18], the vast majority of current receivers already implement multi-constellation support, and the most popular way to provide multi-constellation support is to cover all constellations, which represents over 30 % of receivers. Moreover, simultaneously, multi-frequency receivers have been launched for the mass market, with the most common multi-frequency combination being L1/E1+L2. This has resulted in a drop of nearly 10 % in the production of receivers that are single-frequency only, over the last two years. The dual-frequency support has even entered the smartphone market: on 31st of May 2018, the world's first dual-frequency (E1/L1+E5/L5) GNSS smartphone was launched.

4.2 GNSS Signal Processing Techniques

The low elevation of SBAS satellites limits coverage of GNSS landing guidance at airports north of the Arctic Circle. Low elevation of core GNSS satellites leads to more outages due to obstructions (mountains, canyons, buildings), and more errors from multipath. GPS-only terrestrial devices, such as animal trackers and S&R modules, can be more frequently blocked by high obstacles, but using multi-constellation GNSS receivers (at least GPS+GLONASS) provides better availability of satellites. At present, about two thirds of all GNSS receivers on the market support at least two constellations [18].

The precise positioning GNSS services, which are used in marine dynamic positioning (DP) systems, often get their corrections from satellite broadcasts, which limits availability to latitudes below 75 degrees. Better tracking of low-elevation satellites in high latitudes up to 80 degrees can be achieved by specialized antenna designs (e.g. from Fugro) [9].

GNSS can be vulnerable to space weather and ionospheric scintillation. Scintillation refers to signal amplitude and phase perturbations caused by ionospheric activity, most common near the equator and in the polar zones. The impact is most severe on precise positioning [37]. Most ionospheric effects can be mitigated by using dual-frequency signals, but strong scintillation can still degrade positioning [50]. In the polar zones, scintillation is associated with the aurora borealis and with ionospheric disturbances, which can be used as indicators to help in assessing its impact [16],[33]. Where problems are demonstrated in use, the next step would be to develop mitigation solutions. These would include signal processing methods taking advantage of modernized multi-frequency signals [54] and sensor fusion methods, using non-GNSS sensors to bridge the gaps and detect errors.

The potential threat of GNSS jamming is clear, with the availability of small, portable GNSS jammers on one hand, and on the other, reported cases of wide-area jamming related to military exercise activities in the Arctic. To mitigate any associated risks to navigation, it is important to first, to detect the interference and to notify affected users.

The state-of-the-art in detection today comprises monitoring of abnormal GNSS performance by both spectrum management authorities and following reports from users. Detection is followed by an official notification, such as a Notice to Airmen (NOTAM) in the case of aviation.

Furthermore, actions can be taken, if possible, to locate and remove the interference source. In the future, smartphones may be used for crowdsourced interference detection and localization [51].

The second approach in mitigating interference would be to develop and deploy either interference-resistant GNSS receivers or less GNSS-dependent navigation solutions, again incorporating other sensors. For example, as a countermeasure to GNSS interference, AIS-radar fusion has been suggested to aid maritime situational awareness and tracking [48]. For navigation, backup methods are always available, such as radar, or visual means of navigation, and modernized versions thereof are in development, such as e-Navigation and the electronic pelorus [6].

4.3 Receiver-Level Integrity Monitoring

Due to the high ecological sensitivity and extreme weather conditions, accidents in the Arctic regions could cause great environmental damage and also threaten human lives. Therefore, the growing activity in the Arctic calls also for high integrity navigation in this region. Integrity is a measure of trust that can be placed in the correctness of the information that the system is providing to the user. Moreover, integrity includes also the ability of a system to provide users with warnings within a specified time interval when the system should not be used for the intended operation. Given the harsh and remote environment, space-based architecture, such as GNSS, is ideal to attain high levels of safety both at sea and in the air. GNSS integrity can be achieved via Satellite Based Augmentation Systems (SBAS) as well as Advanced Receiver Autonomous Integrity Monitoring (ARAIM). While SBAS requires both ground-based and space-based infrastructure, ARAIM is more self-contained and achieves integrity algorithmically by exploiting the multitude of GNSS constellations and signals coming in the near future. The ARAIM concept is based on the fact that the future multi-constellation and multi-frequency signals will offer the possibility to reduce the dependency from the ground infrastructure and consequently reduce further the deployment and operation costs.

ARAIM is scheduled to become operational by 2029 to support air navigation worldwide. Specifically, ARAIM should support enroute and terminal area flight, and it should also support lateral and vertical guidance during airport approach operations. ARAIM is an advanced version of RAIM which has been known to the aviation community since the late 1980s. RAIM detects faults by examining the consistency of the measurements used in the position estimate (inconsistent measurements may be indicative of a fault). The original version of RAIM was based on a set of fixed parameters regarding the nominal performance and fault rates of GPS. In contrast, ARAIM allows a ground system to provide updates regarding the nominal performance and fault rates of the multiplicity of contributing constellations, allowing for flexibility to adapt to changing environmental conditions. This integrity data is contained in the Integrity Support Message (ISM) that is computed on the ground and provided to the users.

An important advantage of ARAIM is that it has the potential to provide better coverage in the Arctic compared to SBAS, because it does not need the geostationary satellites given that the ISM can be provided by the GNSS core constellations themselves. An analysis of SBAS and ARAIM performance for air navigation in the Arctic can be found in [42]. The main objective of ARAIM concept is to provide the aviation users with vertical guidance up to precision approach. The target operational levels are LPV and LPV-200, where LPV stands for Localizer Performance with Vertical Guidance. The requirements for these modern aviation instrument approach procedures are specified in the International Civil Aviation Organization (ICAO) Standards And Recommended Practices (SARPs). To achieve precision approach, a Vertical Protection Level (VPL) smaller than a Vertical Alert Limit (VAL) of 50 m is required, whereas to bring the aircraft down to a decision height of 200 feet (61 meters) (LPV-200), the VPL must be below 35 m. The protection level provides a bound on the position error with a confidence level derived from the integrity risk requirement. The integrity risk is the probability that, at any moment, the position error exceeds the alert limit, which, in turn, is the maximum allowable position error beyond which the system should be declared unavailable for the intended application. Simulation results showed that dual frequency GPS + Galileo ARAIM gives precision approach in all the Arctic, and that LPV-200 can be achieved if GPS + Galileo + GLONASS are used. In [42], the performance of ARAIM was also evaluated for maritime navigation in the Arctic. Differently than in aviation, maritime navigation requirements are strict for horizontal positioning due to the ship’s knowledge of being at sea level. These requirements vary according to the application and have been agreed upon by the International Maritime Organization (IMO). For open water operations, for example, the integrity bound, known as Horizontal Alert Limit (HAL), is 25 m, while for precision applications such as drilling and mapping it is 2.5-5 m, and for ice navigation is 10-12 m. Simulation results showed that dual frequency GPS + Galileo ARAIM meets the open water requirements in the entire Arctic region, and the ice navigation requirements only near the pole. By adding GLONASS, it was shown that the ice navigation requirements are met in all the Arctic.

Furthermore, the implementation of ARAIM requires almost no additional infrastructure. The ISM will be built up using a ground reference network which can be very much like that of the International GNSS Service (IGS) or the ground segments of the GNSS. This network does not need to be devoted or real time like that of SBAS. As such, the implementation of ARAIM requires no additional infrastructure than is planned to operate in the Arctic, and it has the added benefit of delivering the same level of service in both the northern and southern hemisphere.

The U.S.–EU Agreement on GPS-Galileo Cooperation signed in 2004 foresaw a working group to promote cooperation on the design and development of the next generation of civil satellite-based navigation and timing systems: Working Group C (WG-C). Within WG-C, a Technical Subgroup (ARAIM TSG) was specifically created to develop the ARAIM concept. As described in [13], the ARAIM TSG developed the following architectures to support air navigation based on GNSS:

- Horizontal ARAIM to support horizontal navigation based on occasional ISM from the ground
- Offline ARAIM to support horizontal and vertical navigation based on a monthly ISM from the ground
- Online ARAIM to support horizontal and vertical navigation based on an hourly ISM from the ground

In all cases, ISM dissemination requires only a modest data rate which could be accommodated within the GNSS navigation messages capacities. The ISM dissemination strategy is still under discussion, and potential approaches are reported in [13]:

- Core constellation navigation data bits
- Geosynchronous (GEO) satellite datalink (like SBAS)
- Ground VHF Data Broadcast (VDB) from terminal airport.

In the case of VDB, there would need to be a ground transmitter near every airport, while the GEO option would not cover the high latitudes of the Arctic. Acceptable method(s) of dissemination would need consensus from all stakeholders, including air navigation service providers (ANSPs) and avionics/aircraft manufacturers. Ultimately, it is possible that different dissemination methods could be implemented by different ANSPs.

Ideally, the ISM would be global. However, States may wish to alternatively use a regional or national ISM in particular when supporting approach operations. Having multiple ISMs would increase the cost and complexity of the system. The receiver, which introduces the content of ISM into its internal processing, would have to be able to switch between ISM regions, and there would be the risk of availability loss due to incorrect or missing ISM. Therefore, it is preferred to develop ARAIM with a single, global ISM.

The ISM drives how a constellation is weighted by the ARAIM algorithm. Of course a State (or group of States) operating a GNSS constellation will want to determine their ISM values, but this situation may create a conflict of interest for other States. As long as it can be assured that the values provided to the satellite operator will not be changed, the ISM provider can be a separate entity from the constellation operator. Using the example of the United States, the Federal Aviation Administration (FAA) could become the ISM provider and then furnish the ISM values for GPS not only to the GPS system operator but also to the other GNSS operators (each system will broadcast values for all the GNSS). In Europe, a suitable organization similar to the ESSP (European Satellite Services Provider) could be created. It is considered advised that an organization with close ties to the GNSS constellation operator would become the ISM provider. However, to ensure that the ISM values can be accepted globally, a sufficient level of transparency needs to be ensured. This need for transparency suggests that the methods to determine ISM values should be standardized. Furthermore, if another State disagreed with published ISM values based on observation or analysis, some type of an appeal procedure would need to be in place.

In summary, in view of the implications on safety and interoperability, the goal of a global harmonized and accepted ISM for supporting ARAIM operations should be pursued. If individual States choose to disallow the use of specific constellations or insist on determining their own ISM values, significant additional operational functionality will be required, which will negatively impact the feasibility and benefits that can be obtained through multi-constellation GNSS. Such a global ISM must be generated and maintained using a transparent and standardized methodology, building on the already existing processes and frameworks.

A potential path for implementation of ARAIM is outlined in [14]. The ARAIM TSG concluded that ARAIM services should be implemented incrementally. It should begin with horizontal only service, H-ARAIM, to support near-term multi-constellation applications. A global vertical service, V-ARAIM, can be implemented once sufficient data is collected and experience is gained to establish safe operations. This trust will be built up slowly based on Constellation Service Provider (CSP) performance commitments and observed actual performance. GPS L1 has more than 20 years of consistency with RAIM assumption. GPS L5, Galileo, GLONASS and BeiDou have yet to establish similar levels of performance and consistency.

4.4 New Space-Based Solutions

Earth observation (EO) satellites are monitoring the Arctic, providing useful data (e.g. on weather and sea ice). However, current EO systems, such as Sentinel 1, have revisit times longer than 1 day. If this information were available continuously, better situational awareness would be possible. This would require more timely information being available.

There is currently a lack of communications infrastructure in the Arctic area. Maritime users operating in re-mote seas have relied on satellite communications, which are provided from geostationary orbit (GEO) satel-lites above the equator. Coverage is nearly global, however in high latitudes, the satellites are seen at such a low angle above the horizon, that often a ship's own structures can block the satellite antenna's reception; this situation is known to mariners as "no internet heading". GEO satellites also transmit the satellite-based GNSS augmentation services such as EGNOS, and similar signal coverage limitations are experienced with them. A challenge in airline operations in the Arctic is the ICAO's requirement for all aircraft to be tracked at intervals of 15 minutes. Under this requirement, the lack of communications infrastructure in the polar zone renders transpolar flights impractical.

GNSS interference is a threat which has already been observed in the Arctic [34]. All modes of transportation are increasingly relying on, or benefiting from GNSS. Another phe-nomenon affecting GNSS in the Arctic is space weather, which is more active in the polar zones. Activity in the ionosphere can disturb GNSS signals and degrade positioning quality.

4.4.1 Small satellites

Several companies have initiated plans to develop new large low Earth orbit (LEO) constellations of small satellites. Since the (LEO) smallsat constellations are planned to have near-polar orbits, the Arctic will likely have very good service coverage from such constellations. If good polar communication service is offered, cross-polar flights would become more feasible. Furthermore, the small LEO satellites could be possible platforms for a new navigation signal similar to current GNSS [43]. Such a system would be less susceptible to interference, thanks to higher received signal power.

The new commercial constellations of small satellites can further benefit the Arctic by offering better situational awareness. Out of six upcoming commercial smallsat constellations, all will include Automatic identification system (AIS) receivers, and four will also have Automatic dependent surveillance—broadcast (ADS-B) receivers [45]. Vessels and aircraft respectively can be tracked globally by these services.

ICEYE synthetic aperture radar (SAR) microsatellites could be used for monitoring of traffic, navigation in icy waters, sea state and current monitoring, or detection of oil spills. SAR technology works also through clouds and in darkness. A constellation of many small satellites in LEO provides short revisit times down to a few hours.

While some efforts are being directed towards developing interference detection networks, these would require infrastructure investments on the ground which may not be feasible in the sparsely populated Arctic. According to initial simulations, it is possible to detect and localize RF interference from space [7]. A specialized payload, featuring directional antennas, could locate even signals as weak as 20 dBm low power GNSS jammers from an altitude of 700 km.

Each of the Galileo GNSS satellites includes a distress signal repeater and as such will also improve search-and-rescue (SAR) coverage as part of the MEOSAR system, and enable localization of distress beacons. The newspace startup HawkEye 360 plans to use its commercial satellite constellation to monitor a broad spectrum of radio frequency (RF) signals. The constellation of LEO satellites 600 km from the surface could be used to identify and locate emergency beacons, monitor transportation activities, and identify RF interference.

4.4.2 HEO satellites

Space Norway, a Norwegian state-owned company, is planning to launch two high elliptic orbit (HEO) satel-lites which would cover the Northern latitudes above 65 degrees 24 hours a day to provide broadband communications to the Arctic area. The company has been offered a conditional NOK 1 billion equity capital by the Norwegian government, on the condition that additional private investment will be secured. Launches are planned for 2022 [20]. These satellites would be another step towards improved communications infrastructure in the Arctic. Enabling highly reliable and high-speed maritime internet connectivity would be likely to increase safety and efficiency in operations. In principle, there is a possibility of adding EGNOS transmitters on the HEO satellites, which would also eliminate the EGNOS signal visibility problems in the Arctic. However, augmentation signals are currently required to be transmitted from GEO satellites, making this option more complicated to implement.

4.5 GNSS Augmentation Systems

Augmentation and correction data services to enhance the accuracy, integrity, or other performance metrics of navigation hinge on a monitoring network. Currently existing reference stations deployed for EGNOS, WAAS, and SDCM as well as the network of International GNSS Service (IGS) stations is shown in Figure 4.1. It is important to understand that the figure does not attempt to show all existing GNSS reference stations; for instance, commercial networks are excluded from it.

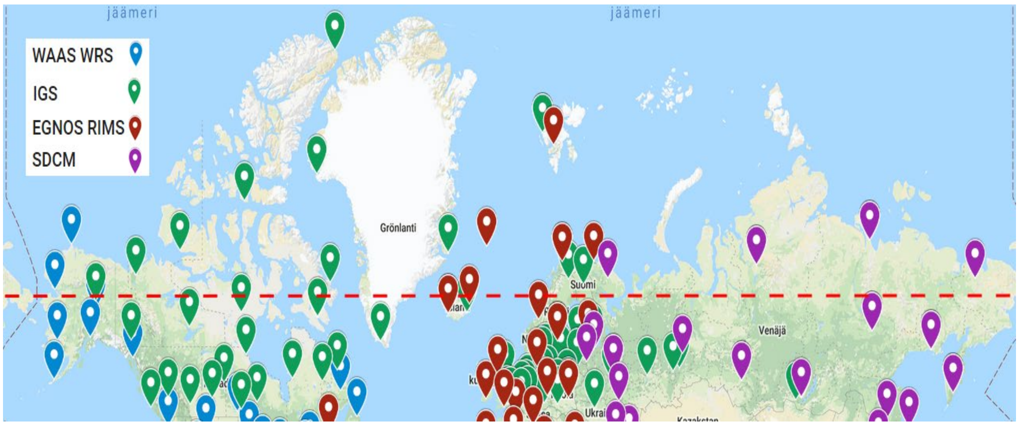

Figure 4.1 Locations of various existing GNSS reference stations. The dashed red line represents the geographic Arctic Circle. Map data ©2019 Google, INEGI

By looking at Figure 4.1 it is immediately evident that the density of reference stations in the Arctic is smaller than at moderate latitudes, as can be expected. Furthermore, Russian territory is much less densely covered than European and North American land areas.

4.6 Ionosphere Modeling

Satellite navigation signals need to pass through the atmosphere that consists of several different parts. In satellite navigation one part of the atmosphere, the *ionosphere* lying between 60 to 1000 km in altitude [19], is one of the most significant error sources [25]. Radiation from the Sun affects the gas molecules in that region of the atmosphere such that the molecules turn into electrically charged, *ionized*, particles [19]. For this reason that particular region is called the ionosphere.

The GNSS receivers can measure the distance to the navigation satellites either based on the phase of the carrier signal or based on the phase of the PRN code modulation on the signal, however the carrier-phase range measurements usually require external aiding and thus the code-based ranging is more common especially in low-grade receivers [25]. When the signal from the navigation satellites, being electromagnetic radiation, traverses the ionosphere it is either delayed or advanced. More specifically, the phase of the signal is advanced, whereas the code modulation is delayed [25]. For this reason the phase-based range measurements appear shorter than the actual distance between the receiver and the satellite, and similarly the code-based range measurements appear longer. The magnitude of the error in the range measurement due to the ionosphere is the same for carrier-phase and code measurements, but has opposite sign for both cases [25]. In the following we will refer to this advance/delay as *ionospheric delay*, even though for carrier-phase measurements the delay is in fact actually negative. Furthermore, the ionosphere is a *dispersive medium*, so the magnitude of the advance or delay of the signal is different for signals with different carrier frequencies.

The magnitude of the ionospheric effect on the range measurements is characterized by *Total Electron Content* (TEC) along the path the signal traverses. TEC is the number of free electrons along the signal path, expressed in electrons/m^2 or in TEC units (TECu) (1 TECu is 10^{16} electrons/m^2) [25]. If the TEC along the signal path is known, the ionospheric delay can be computed using the following equation [25]:

$$\Delta s = \frac{40.3}{f^2} TEC$$

In the above equation Δs is in meters and *f* is the carrier frequency of the signal in Hertz.

The TEC in the ionosphere is not constant, but varies for several reasons. There is daily and seasonal variation, apparently depending on the relative orientation of the Earth and the Sun. Solar activity level, having an eleven-year cycle, has also a significant effect on TEC. In addition, sunspots, solar flares and solar wind affect the TEC in the ionosphere. Furthermore, Earth's magnetic field and geomagnetic storms affect the TEC [19]. Irregularities in the ionosphere can cause the phase and amplitude of a GNSS signal to fluctuate. This is called scintillation [52]. At its worst scintillation can cause the GNSS receiver to lose lock, thus being unable to track satellites in visibility.

4.6.1 Ionospheric correction methods for single frequency receivers

A handful of different methods are currently used to mitigate the ionospheric effect for single frequency GNSS users. These methods will be discussed in the following sections. As the ionospheric delay depends on the carrier frequency of the signal [2], excluding the ionospheric effect for dual-frequency GNSS users is a straightforward process. The different single-frequency ionospheric correction methods are based on estimating the TEC in the ionosphere along the ray path from a navigation satellite to the user receiver. The TEC can then be converted into path delay using the formula presented above. The path delay estimates how much the measured distance appears to be longer than the true distance due to the ionosphere. This estimated delay can then be subtracted from the measured distance in order to mitigate the effect of the ionosphere.

4.6.1.1 Klobuchar

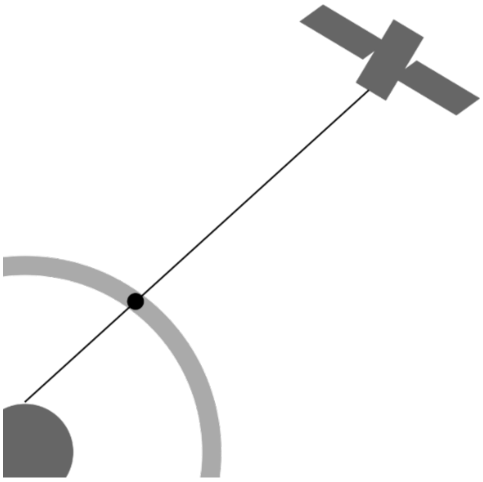

Figure 4.2 Illustration of the Klobuchar thin shell model.

The Klobuchar ionospheric correction model was developed for GPS satellites and has been in use since 1980s [26]. Klobuchar is an empirical model of the ionosphere and is a simplification of the Bent ionosphere model [30]. In the Klobuchar model the ionosphere is modeled as a thin shell at the height of 350 km [26], which is illustrated in Figure 4.2. In thin shell models it is assumed that the whole TEC in the ionosphere is concentrated on the shell.

The Klobuchar model estimates that the time delay caused by the ionosphere follows a positive cosine curve during daytime, reaching its maximum at 2 PM local time [26]. During nighttime the time delay is assumed to be a constant. In addition to the local time, also the geomagnetic latitude (which is different from the geodetic latitude) of the user has an effect on the estimated TEC.

The cosine curve and the nighttime constant TEC are characterized by eight coefficients that are included in the GPS satellites navigation message. The coefficients are updated at most once a day [32]. The Klobuchar model is able to correct approximately 50 % of the ionospheric error in the range measurements [26]. The model was designed to work best at the Contiguous United States (CONUS) region.

Since in the Klobuchar model the ionosphere is assumed to be concentrated on a thin shell at the height of 350 km, the user needs to compute the location of the Ionospheric Pierce Point (IPP) in order to estimate the ionospheric delay. IPP is the location where the signal transmitted from the navigation satellite pierces the ionospheric shell, and in general is different from the user location. This situation is illustrated in Figure 4.2. After that the user computes, based on the transmitted eight coefficients, the amplitude and phase of the cosine curve used in the Klobuchar model. During nighttime a time delay of 5 ns is assumed [26]. Then user estimates the geomagnetic latitude and local time based on the location of the IPP, and based on those finally obtains the vertical ionospheric delay at the IPP.

However, as the user is not usually directly below the satellite, the vertical ionospheric delay at the IPP is not sufficient. For this reason the vertical delay at the IPP needs to be multiplied by a slant factor that depends on the elevation angle of the navigation satellite. Now that the ionospheric time delay of the signal is estimated, it needs to be multiplied with speed of light in order to obtain the corresponding delay in meters. This value is then subtracted from the range measurement in order to mitigate the effect of the ionosphere on that measurement. This process needs to be repeated separately for each GPS satellite in vision as the ionospheric delay for each signal is unique.

4.6.1.2 NeQuick G

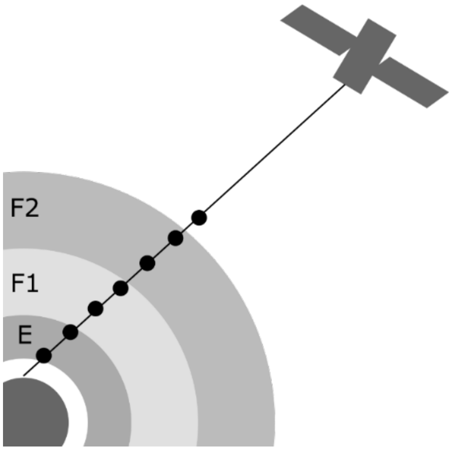

Figure 4.3 Illustration of the layers of the ionosphere and the NeQuick G ionosphere model. Layer D lies below layer E

The NeQuick G ionospheric delay model is based on an empirical climatological presentation of the ionosphere [22]. NeQuick G is a modification of the NeQuick model for Galileo single frequency users, and detailed implementation instructions can be found from [22]. Whereas the Klobuchar model is two-dimensional, assuming that the ionosphere is concentrated on a single height only, the NeQuick G is a three-dimensional model estimating TEC also at variable height. Excluding periods when the ionosphere is extremely disturbed (such as during geomagnetic storms), NeQuick G is designed to correct at least 70 % of the ionospheric error in all conditions [22].

The ionosphere can be divided into regions or layers D, E, F1 and F2, that each have slightly different properties [19]. The different layers are illustrated in Figure 4.3, noting that layer D lies below layer E. However, during nighttime the layer D disappears and layers F1 and F2 combine into one layer [38]. The heights of the different regions vary day to day, and depending on the season and on the solar activity. NeQuick G follows this structure of the physical ionosphere, but layer D is not included in the computations [22].

The Galileo satellites navigation message contains three coefficients that are used for estimating the TEC. Based on these coefficients and estimated user position, the user computes the effective ionization level, which represents the solar activity at the current time and place [22]. The user location is needed for determining Modified Dip Latitude (MODIP), which is related to the geomagnetic field at the user location. Based on the estimated location, time and previously computed effective ionization level the user computes some additional parameters describing solar activity, including Effective Sunspot Number, Solar Declination, Solar Zenith Angle and Effective Solar Zenith Angle [22].

Based on the solar zenith angle and the sunspot number it is possible to estimate the critical frequency for each layer [19]. Critical frequency is characteristic to each layer of the ionosphere, and it can be used to compute the maximum electron density within each layer [19].

The electron density is constructed in NeQuick G using two main components, the bottomside model and the topside model [22]. The bottomside model computes the electron density based on the critical frequencies, corresponding maximum electron densities and maximum electron density heights of each of the layers E, F1 and F2. These values are obtained using the solar activity parameters listed above [22]. The topside model estimates the electron density above the F2 layer maximum electron density height in a simplistic manner [22].

Based on these two models, the TEC along the satellite signals path is obtained by integrating the electron densities at different points on the path. Two different integration methods are suggested in [22], either the Gauss algorithm or Kronrod G_7-K_{15} adaptive quadrature method. Gauss algorithm is more accurate but is computationally heavier, and the final choice of the specific algorithm depends on the needed accuracy and available computational power.

4.6.1.3 Differential GNSS

Differential GNSS (DGNSS) methods provide corrections for single frequency GNSS users within some specific area [25]. DGNSS is based on the fact that many errors sources related to GNSS are correlated in space and time, which applies also to ionospheric errors. In DGNSS one or more reference stations with known locations make GNSS measurements usually using dual-frequency receivers, and based on those measurements provide corrections to range measurements for users via some kind of data link.

Ionosphere is a dispersive medium, which means that the delay caused by the ionosphere is different for different frequencies. Based on this fact it is possible to solve the ionospheric delay between the satellite and the reference station using dual-frequency measurements [25]. Similarly as in the Klobuchar model, in DGNSS the ionosphere is modeled as a thin shell at a height between 300 km and 400 km, specific height depending on the system [25]. Also the point where the signal from the navigation satellite to the reference station pierces the thin shell is called IPP.

If the user would be at the exactly same location as the reference station, the user could apply the ionospheric delay derived from the dual frequency measurement directly. However, this is not usually the case and there is some distance between the reference station and the user. This results also in difference between elevation angles viewed either from the reference station or from the user’s location to the same satellite. In addition the IPP for the reference station and the actual IPP for the user are separated by some distance. For this reason the ionospheric delay derived by the reference station needs to be converted for the users location based on the distance between the reference station and the user, and the different elevation angles.

In DGNSS the error in the ionospheric correction caused by different elevation angles is relatively small, being in order of few centimeters even for 100 km distance between the reference station and the user [25]. However, the distance between IPPs causes a larger error. If the ionosphere is not disturbed (i.e. due to geomagnetic storms), the error in the vertical delay caused by a 100 km separation is of the order of few tens of centimeters [25]. On the other hand, if the ionosphere is disturbed the error in the vertical delay can be several meters [25]. The change in the vertical delay, including the change in elevation angle and the changes in the ionosphere itself, ranges from few centimeters per minute to few tens of centimeters per minute depending on the area, the largest change rates observed in equatorial and polar regions [25].

4.6.1.4 Satellite Based Augmentation Systems

Satellite Based Augmentation Systems (SBAS), such as European Geostationary Navigation Overlay Service (EGNOS) in Europe, provide Wide-area DGNSS (WADGNSS) corrections for users within a large area [25]. In this work the focus is on EGNOS, but most of the presented details are applicable also to other SBAS.

EGNOS consists of Ground Segment, Space Segment and User Segment [40]. One essential part of the EGNOS Ground Segment are Ranging and Integrity Monitoring Stations (RIMS), that monitor navigation satellites and measure pseudoranges using dual-frequency measurements [40]. The RIMS are spread all over Europe and other parts of the world [10]. RIMS transmit the raw measurements to Central Processing Facilities (CPF), which generate differential corrections based on the measurements. The corrections are then transmitted to users via three geostationary satellites on L1 frequency band [11]. One important type of correction are ionospheric corrections that are included in SBAS messages of type 18 (locations of ionospheric grid points) and 26 (ionospheric delays and accuracy bounds for the delay estimates) [11].

SBASs provide ionospheric corrections and corresponding error estimates at predefined Ionospheric Grid Points (IGP) defined in message type 18. The locations of the IGPs serviced by EGNOS are shown in Figure 4.4, which was obtained from [12]. In most parts of the world the SBAS ionospheric corrections are available at a 5°×5° grid, but the grid is sparser around the North and South poles. The transmitted corrections are as such applicable only for L1 frequency users, but conversion for other frequencies is straightforward [25].

The EGNOS message type 26 provides Grid Ionospheric Vertical Delay (GIVD) values ranging from 0 m to 63.875 m, although GIVD of 63.875 is a flag for Do Not Use IGP status [53]. Also corresponding Grid Ionospheric Vertical Error Indicators (GIVEI), ranging from 0 to 15, are transmitted for each IGP. GIVEI from 0 to 14 indicate Grid Ionospheric Vertical Error (GIVE) ranging from 0.0084 m^2 to 187.0826 m^2 expressed as variance [53]. GIVEI 15 indicates IGP not monitored status [53]. Do Not Use status indicates that the ionospheric delay at that particular IGP is either larger than 63.875 m or that information regarding that IGP is inconsistent. IGP Not Monitored status indicates that the RIMS stations were not able to obtain sufficient dual frequency measurements around that IGP in order to compute the GIVD. This can happen especially near the edges of EGNOS coverage area. In Figure 4.4 the IGPs not monitored are marked in grey and located for example over Atlantic sea where there are no RIMS stations.

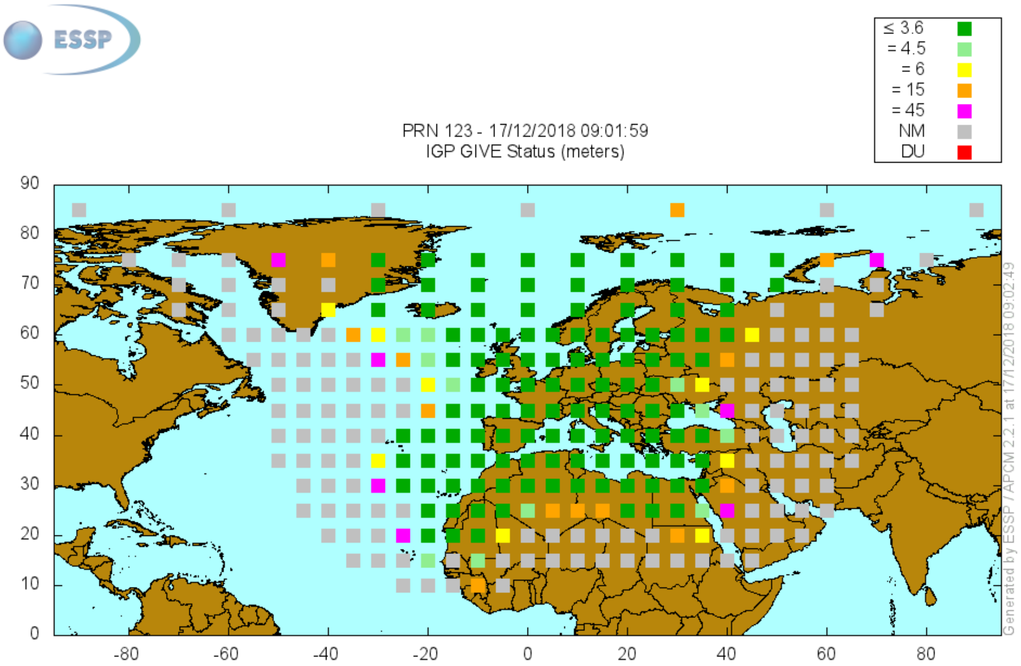

Figure 4.4: Locations of the IGPs for which EGNOS provides corrections. The grey IGPs are not monitored at the time instant of the figure. Figure source [12].

Similarly to the Klobuchar model, in EGNOS the ionosphere is approximated as a thin shell located at the height of 350 km [53]. Also similarly, for each satellite the user needs to first find an IPP. When the IPP is known, the user needs to find three or four suitable IGPs surrounding it, i.e. IGPs without Not Monitored or Do Not Use status. Preferably the user should find four IGPs forming a rectangle surrounding the IPP within 5 degrees [36]. If there are no such four IGPs, three IGPs within 5 degrees (forming a triangle) should be used. If there are no three suitable IGPs within 5 degrees, the user should try to find four suitable IGPs surrounding the IPP within 10 degrees, or if that is not possible, try to find three suitable IGPs within 10 degrees. If that is not possible, then no ionospheric correction is available for that IPP [36].

When the three or four suitable IGPs surrounding the IPP are found, the user computes the vertical ionospheric delay for the IPP using a weighted interpolation scheme [25]. Finally the obtained vertical delay is multiplied by an obliquity factor depending on the elevation angle of the satellite viewed from the users location [25]. This slant ionospheric delay is then subtracted from the pseudorange measurement.

4.6.2 Ionosphere and GNSS in the Arctic regions

The behavior of the ionosphere is different in different regions of the Earth. There are variations in the electron content for various reasons listed above. In Arctic regions, as well as in equatorial areas, there are some phenomena affecting the ionosphere that cause problems especially for satellite navigation. They are geomagnetic storms and scintillation [19].

The magnetic field of the Earth mainly prevents the Earth encountering solar wind and other energetic particles [19]. However, this is not the case around polar regions and particles may enter through polar cusps [19]. Polar cusp is a region between the sunward and tailward side of the magnetic field lines of the Earth that has nearly zero magnetic field magnitude [8]. Also the Interplanetary Magnetic Field (IMF) originating from solar magnetic field has a significant effect on the ionosphere at high latitudes [19].

Geomagnetic storms develop as a result of energy transferred from solar wind to the magnetosphere. Ionospheric storms develop as a response to the geomagnetic storms [19]. For example the aurora are a consequence of geomagnetic storms [19]. When the IMF is directed towards south and there is a high speed solar wind and sunspot activity, i.e. there is a magnetic storm, the ionization is driven towards polar regions due to subsequent disturbances in the magnetic field [19]. In fact, at high latitudes the magnetic activity has a larger effect on the ionosphere than the solar activity [19]. The auroral oval, where aurora are experienced, changes as a function of local time due to the fact that the geomagnetic poles are not located exactly at the geographic poles [19]. However, the occurrence of geomagnetic storms as such has no clear dependence of local time [52]. Prediction of geomagnetic storms is challenging, and empirical models such as NeQuick are not sufficient for it. Instead some physics-based model might yield better results [52].

Disturbed geomagnetic conditions result in dramatic growth in small-scale irregularities especially in high latitudes [19]. As a result of a geomagnetic storm the electron concentration in the ionosphere is first shortly increased, after which the electron content is largely diminished [19]. However, the ionospheric response to magnetic storms is not always same, and the effect can depend on the latitude and season [19]. Furthermore, all phenomena related to ionosphere, especially at high latitudes, are not yet fully understood [19].

Irregularities in the electron content of the ionosphere, that occur especially at equatorial and polar regions, are challenging in terms of satellite communications [19]. The location, density and size depend on various factors, such as solar and magnetic activity, time and geographical area. Small-scale inhomogeneities cause scintillation of radio signals from navigation satellites [19]. These inhomogeneities exist in all of the ionosphere but are more common at polar and equatorial regions. In arctic areas, increased geomagnetic activity significantly increases occurrence of these irregularities [19]. One interesting phenomena are ionospheric patches and blobs, that are discrete, isolated regions of increased electron density being of the scale of 100–1000 km horizontally. They occur especially at polar regions [19]. It has been suggested that these patches and blobs decompose into smaller structures, resulting in inhomogeneities in the ionosphere and subsequent scintillation events.

Scintillation is fluctuation in the phase and amplitude of the signal from the navigation satellite due to the temporal and spatial variations in the refractivity of the ionosphere. Twinkling of the stars is caused by the same phenomenon as scintillation, being irregularities in the ionosphere especially at F region heights around 200 km to 600 km [19]. The intensity of scintillation is related to magnetic activity and intensity of solar flux [19]. Scintillation is small during low solar flux [19]. Occurrence of scintillation has a diurnal variation, being more common during nighttime [19]. Scintillation at high latitudes is not as severe as in equatorial regions, but can occur for hours or days [52].

When scintillation occurs, the amplitude of the signal fluctuates and can fade even 15 dB or more [52]. Scintillation also causes the phase of the signal fluctuate [19], which is more common than amplitude fluctuation at high latitudes [52]. The result is loss of phase lock in the navigation receiver due to unexpected phase changes or fading of the signal [19],[52]. Scintillation also can cause cycle slips or navigation data bit errors in the receiver [52]. In any case scintillation results in degraded positioning performance. In [27] it was shown positioning error can be double in presence of scintillation compared to quiet ionospheric conditions. The severity of positioning error seems to depend on how many of the signals from different satellites are affected by scintillation.

Loss of lock can be mitigated to some extent by using certain types of phase lock loops (PLLs), for example a variable bandwidth PLL or a 3rd order PLL [52]. Frequency lock loops (FLL) are more robust in the presence of scintillation compared to PLL [52]. Also refraction of the satellite signal can occur due to scintillation, which is seen as code delay [52]. Furthermore, scintillation can diffract the satellite signal, which at its worst can appear as multipath or mutual interference of the signals at the navigation receiver [52]. Using dual frequency measurements reduces but does not completely eliminate the effect of scintillation on the receiver, and scintillation is the most significant problem in dual-frequency GNSS [19]. There is a need for developing tools for scintillation mitigation in the navigation receivers [52].

4.6.3 Ionospheric corrections in the Arctic regions

In principle there are no limitations in the area of use for the ionospheric correction methods for GNSS described above. Even in EGNOS there are IGPs defined near the North Pole. However, in practice the reliability and availability of the ionospheric corrections for single frequency users may not be sufficient in the Arctic regions. The phenomena described in Section 4.6.2 contribute significantly to the difficulties in predicting ionospheric behavior in the Arctic regions.

4.6.3.1 Performance of single frequency correction methods

The ionospheric models perform best at midlatitudes [19]. Significant TEC increases have been observed at signals that penetrate the polar cap. The available ionospheric models have not been able to predict these increases [19]. However, it seems that the performance of different single-frequency ionospheric correction methods in the Arctic regions has not been extensively studied and further investigations might be needed.

The Klobuchar model is able to correct about 50 % of ionospheric delay [26]. However, in the model there is no attempt to model the highly variable ionospheric delay in high latitudes [26]. In addition, the simplifications made in computing the IPP in the model result in large inaccuracies in latitudes above 75° [26]. Keeping in mind that the Klobuchar model is a compromise between the number of broadcast parameters, the computational complexity in user receiver, and the likely geographical area of the users at the time of the development in the 1980s [26], it is likely that the performance of the Klobuchar model in the Arctic regions is significantly poorer than in midlatitudes.

In [5] the Klobuchar model and different versions of NeQuick model are tested at various sites, the northernmost ones located in Tromso and Sodankylä. The data period discussed is year 2002, which had a high solar activity. It is concluded that the NeQuick models perform best at midlatitude Europe, whereas the worst performance is observed in high-latitude Europe due to underestimation of the vertical TEC [5]. The Klobuchar model performs best in northern America and worst in high-latitude Europe [5]. However, the NeQuick models perform better than the Klobuchar model in all cases.

In [1] similar results are obtained regarding the NeQuick model performing better than the Klobuchar model. The tests were done using data from several days with different geomagnetic activity from the years 2008-2010. The northernmost test site was in Holman in northern Canada. In contrast to the results obtained in [5], in the northernmost test site the NeQuick model performs the best. However, the performance at the test site in Holman is slightly worse during days with high geomagnetic activity compared to those with light or medium activity. The Root Mean Squared (RMS) error in the estimated ionospheric delay at the test site in Holman was 0.56 m for the NeQuick model and 1.63 m for Klobuchar model. For comparison, the corresponding RMS errors in delay were in Naples, Italy 0.83 m and 1.34 m.

The different conclusions in [1] and [5] regarding the performance of NeQuick in northern areas may be due to differences in solar activity. Based on the number of sunspots, 2002 had more solar activity than years 2008–2010 [21]. In addition, there were only one or two test sites in Arctic areas, so care must be taken in drawing definite conclusions from the discussed results.

Performance of SBASs can be severely degraded during geomagnetic storms. During the Halloween storm of 2003, Wide Area Augmentation System (WAAS) serving United States failed for several hours [19]. In [2] it is suggested that during scintillation events many of the EGNOS RIMS stations are unable to estimate the ionospheric delay, resulting in unmonitored IGPs and thus unavailable EGNOS ionospheric corrections. During geomagnetic storm, that took place 24th and 25th October 2011, EGNOS performance suffered clearly especially in Scandinavia [24]. EGNOS Approaches with Vertical Guidance (APV-I) availability was 85 % or less in most parts of Scandinavia in 25th of October 2011 [24]. In most parts of Finland the APV-I availability was around 70 % [24]. Even in central Europe the availability was 90 % or less during the same day [24]. In addition, Localizer Performance with Vertical Guidance (LPV-200) is not available at all in most parts of Finland and northern parts of Norway and Sweden [11]. APV-I and LPV-200 are related to SBAS accuracy requirements in aviation applications.

Geomagnetic storms disturb also DGNSS performance in general. During the geomagnetic storm mentioned above, most of the CPOS stations (national real-time kinematic (RTK) positioning service operated by the Norwegian Mapping Authority) were practically disabled for a period of couple of hours during the storm, failing to correct for the ionospheric activity [24]. In addition, more local disturbances in station performance were observed all over Norway during the two-day storm [24].

4.6.3.2 Generating ionospheric corrections

It is possible that the quality of the ionospheric corrections in the current models for single-frequency GNSS users is not sufficient in the Arctic regions. One solution to this problem might be to develop separate correction methods for the arctic areas.

In [29] a model estimating TEC based on spherical cap harmonics is proposed for Arctic regions. During a period of low solar activity in the beginning of 2007, the model has a comparable performance to other regional TEC mapping approaches. In [28] similar approach is studied over one solar cycle from 2000 to 2013 in the Arctic, showing best performance compared to other regional models. The model should also be capable to predict the TEC for some time into the future.

A modified Klobuchar model is proposed in [4] for polar regions. For example, the nighttime delay is modeled as linear function between minimum and maximum delay values instead of a single constant delay value in the traditional Klobuchar. The modified Klobuchar model is shown to result in smaller horizontal and especially vertical positioning error compared to the traditional one at several stations in northern latitudes.

In [41] phase scintillation occurrence maps are generated. It is suggested that these maps could be used in predicting the occurrence of scintillation and possibly used as input in GNSS receiver tracking in order to modify the tracking algorithm based on the level of scintillation.

5 Roadmap

Based on the end-user survey (Chapter 3) and the studied technical solutions (Chapter 4), a mapping between the most significant challenges and the most promising solutions is proposed in Table 5.1.

Table 5.1 Mapping between challenges and solutions

CHALLENGE	SOLUTIONS
TELECOMMUNICATION	HEO telecommunication satellites nano-satellites
MAPS AND CHARTS	enhanced spatial data infrastructure nano-satellite imaging crowdsourcing
GNSS AUGMENTATION AND INTEGRITY	ARAIM HEO telecommunication/augmentation satellites improved ionospheric modeling
SITUATIONAL AWARENESS	nano-satellite imaging crowdsourcing

In this chapter, we outline a roadmap for addressing the challenges. We start by summarizing the ideas and conclusions developed in expert working groups at the workshop in Olos, Lapland, in April 2018; note that these groups worked independently of the technical study presented in the previous chapter of this report. Then, we select a set of actions as a recommendation to tackle the most significant challenges. Finally, we discuss the challenges that would remain after implementing these recommendations.

5.1 Summary of Expert Working Groups at Olos Workshop

At the workshop, a total of nine working groups dedicated to five different sectors (aviation, maritime transport, land transport, search and rescue operations, and business) discussed Arctic challenges specific to the sector in question. Each group chose one challenge – not necessarily the most significant one – to work on and proposed a way to solve it. In this section, the challenges and solutions identified for each sector are presented.

5.1.1 Aviation

Two of the nine expert groups were assigned to work on aviation-related challenges. One of the groups chose to discuss the monitoring of GNSS interference; this challenge was seen as important because ICAO and SESAR (Single European Sky ATM Research) are expected to adopt GNSS as the primary means for navigation. In order to implement such monitoring throughout the large but sparsely populated Arctic region, the proposed solution was to collect as much detection data as possible from infrastructure deployed on the ground, aircraft, and nano-satellites; such data would be of interest for other purposes as well, e.g., meteorology and geodesy, possibly generating some revenue. Big data analysis would then be applied on the collected data to detect malicious interference; natural phenomena such as space weather should be separated from malicious sources but considered as well. Real-time interference detection would secure aviation contingency by reducing the risk of an interrupted approach due to lost GNSS signals. The group proposed a way of funding the development under a research framework programme: first, a coordination and support action should be initiated to build a suitable network of partners and to design a solution. Next, international frameworks should be activated for the definition of new standards and procedures in ICAO and SESAR. The system should be developed and tested with multi-source data and different analysis models under a research and innovation action, and procedures and protocols for sharing the data with all interested parties need to be established.

The other group addressed the challenge of degraded EGNOS availability at Arctic latitudes, which is not in line with the principle of offering equal services in all member states. To rectify the situation, the group proposes the use of HEO satellites and building new RIMS stations; the improvements would be expected to be ready at the launch of EGNOS version 3.2. First, possible new frequency spectrum allocations should be made, and especially Nordic ministries should align forces to lobby the initiative within the European Commission. Once enough stakeholder support is obtained, funding for the HEO system should be acquired.

5.1.2 Maritime Transport

Challenges in maritime transport were discussed by two expert groups. One of the groups worked on the lacking quality of maps, especially depth maps (bathymetry). This challenge is important for maritime safety as an inaccurate depth map could lead to vessel grounding. The envisaged solution consisted of two components: seabed surveys and information crowdsourcing by collecting depth soundings made by individual vessels. These pieces of information could be combined using a probabilistic approach to enhance the accuracy of Arctic depth maps. At least one company is already sharing crowdsourced data between users [35], which supports the feasibility of the solution. To reach the goal, the first step was considered to be presenting the idea at the Arctic Council in order to gain international support. Next, it is likely that public money needs to be acquired to carry out the seabed surveys. Finally, measurement and surveying standards need to be established for depth data crowdsourcing.

The other working group studied the lack of broadband connectivity in the Arctic, significant in light of increased activities in the Arctic (e.g., tourism and fishery) as well as digitalization in general; solving the problem would improve the navigation capabilities and possibly even open new business opportunities in the Arctic area. No single technology was seen as a silver bullet solution; instead, the group concluded that a combination of several methods is needed to meet the objective. These methods range from new satellite constellations to mesh cellular networks, VHF data exchange systems as well as unmanned aerial vehicles and even hot air balloons. The first step to reach the solution is to find a consensus about the solution among relevant stakeholders, at least coastal Arctic countries, the Arctic Council, and the Arctic Coast Guard Forum. Next, international organizations such as IMO and ITU should be involved in the process to consolidate the solution with existing standards and to create new ones where necessary. Finally, before the system can be created and deployed, political decisions and funding are needed, and one or more pilot projects need to be conducted.

5.1.3 Land Transport

Two working groups were assigned for land transport. The first group decided to address changing the attitude regarding earning models in the Arctic: at the moment, the importance of the Arctic area is not completely understood. The solution was seen to be pan-Arctic public-private partnership co-operation to develop new services, platforms, and technical solutions, such as HEO satellite communication systems. The first step to reach the solution is to get the stakeholders committed to this common goal; it was foreseen that a snowball effect should be created. Next, technical solutions should be defined, and their trade-offs analyzed in terms of, e.g., costs and benefits. Public partners should be attracted by means of both lobbying and participating in funding opportunities launched by, e.g., the European Commission and the European GNSS Agency.

The second group discussed the need for extensive infrastructure for intelligent transport systems in order to ensure their reliability and safety. Such infrastructure is needed to support vehicles especially in the Arctic where white-outs and slush can temporarily block the use of on-board sensors. In order to be able to build the infrastructure, safety objectives and key performance indicators (KPIs) must be comprehensively defined, leading to harmonization, regulation, and standardization. To initialize this process, the European Commission, particularly its Directorate-General for Mobility and Transport (DG MOVE), is seen as a key actor; however, the principle of subsidiarity must be kept in mind. Together with the member states, DG MOVE would establish a working group as well as an ombudsman to carry out the work involved. The first task of the group would be to map existing standards, KPIs, etc. and identify missing pieces of the puzzle. Then, the working group should define the relevant safety objectives and KPIs, after which they could be adopted at least EU-wide.

5.1.4 Search and Rescue Operations

One of the working groups focused on search and rescue (SAR), choosing the challenge of missing instrument flight procedures for SAR helicopter operations as the topic. The rationale for this choice was the potential of faster and safer rescue flights in low-visibility conditions, thus contributing to safety of life. The envisaged solution was to implement GNSS-based instrument flight rules for transit routes as well as point in space (PINS) procedures to break out from clouds, both of these with state-level commitment. An implementation roadmap was sketched as follows. First, a feasibility study should be conducted, and national level goals should be defined. Next, the Arctic Coast Guard Forum is seen as a good forum for international discussions, surveys, and discussions on best practices etc. to establish a common opinion. More extensive discussions can be carried out afterwards, involving other authority groups as well. Finally, the financing and necessary technical solutions need to be agreed on, possibly involving the Arctic Council as well.

5.1.5 Arctic Business

Two working groups were dedicated for Arctic business. One of the groups discussed the need to understand the market opportunity, and its size, which determines the types of business solutions as well as the private/public division and any value propositions to be made. The group concluded that the goal should be the development of the Arctic as a commercial activity area, to enable the proliferation of new sustainable business and utilization of Arctic resources, and to provide the necessary facilities for business to take place. The goal could be met by first liaising with the Arctic Economic Council and boost ing its activities, followed by the involvement of other organizations such as ICAO, IMO, and the Nordic Council. Finally, the feasibility of a joint network innovation fund program should be studied, and additional funding could be acquired from Arctic states.

The other group discussed the increasing environmental risk that can be caused by the utilization of mineral and fossil resources in the fragile Arctic environment. These hazards can be monitored and mitigated by improved practices and systems for communications, Earth observation, and satellite positioning.

5.2 Recommended Actions

Based on the material presented above, the following actions are seen as the most important ones to address the challenges in Arctic navigation.

5.2.1 Adoption of ARAIM

Especially in sparsely populated areas such as the Arctic, a global integrity monitoring framework would be a cost-effective solution to the GNSS integrity monitoring challenges faced in aviation. ARAIM is currently the most promising solution that can be implemented without dense local infrastructure. As ARAIM is expected to become operational in 2029, the development towards a global ISM instead of different regional ISMs should be supported in order to avoid availability gaps across national borders.

5.2.2 Deployment of HEO telecommunication satellites

The lack of telecommunications coverage was seen as the most significant Arctic challenge in the end-user survey. HEO satellites would solve the problem of bad telecommunications satellite visibility without need for a massive constellation. Therefore, the development of HEO constellations should be supported, and the possibility of adding EGNOS or other satellite navigation augmentation transmitters on board should be promoted by adapting the relevant requirements where possible.

5.2.3 Crowdsourcing of Nautical Chart Data

Maps and especially nautical charts are difficult to be maintained up to date in the Arctic. A cost-efficient solution would be to harness crowdsourced information to update the nautical charts. This has been shown to be feasible [35], but a widespread adoption of crowdsourcing would require the measurement standards. This is related to the challenge of satellite navigation integrity in the Arctic: a faulty GNSS position estimate must not jeopardize the crowdsourced chart.

5.2.4 Nano-satellite constellations for imaging

The near-polar orbits of most nano-satellites give rise to opportunities in high-latitude regions. Deploying imaging or radar satellites in such orbits would be very beneficial for maritime situational awareness. Such technology is already under development and should be utilized for improved safety of life. Where possible, the satellites could carry also different payloads such as navigation-related transmitters, but obviously, nano-size satellites are very limited in payload capacity.

5.2.5 Deployment of new GNSS reference stations

In order to enhance the performance of satellite navigation in the Arctic in terms of accuracy and integrity, new reference stations are needed for the provision of the necessary augmentation/assistance products. From the perspective of shipping along the Northern Sea Route, the density of reference stations along the Russian North coast needs to be increased. These reference stations could then be used for integrity monitoring, differential GNSS, or other services.

From the North European aviation point of view, the availability of EGNOS should be increased by increasing the amount of reference stations in the Northeastern service area. Fortunately, such stations have already been planned, e.g., in Kuusamo, Finland. The future adoption of ARAIM can be expected to reduce the dependency on EGNOS, but it should be kept in mind that the shift from augmentation-based integrity to ARAIM would not happen overnight anyway. Thus, the availability of regional augmentation systems must be secured for the foreseeable future.

5.3 Remaining Challenges

The actions recommended above were intended to solve the most significant challenges as identified during the ARKKI project, particularly through the online survey. The following challenges are not addressed by these actions.

Atmospheric phenomena, in particular in the ionosphere, degrade the accuracy of single-frequency satellite navigation and the availability of high-precision satellite positioning (scintillation). Dual-frequency GNSS receivers are expected to become available in even the mass market in the near future, but it remains to be seen how long it takes until they are fully adopted by user communities such as civil aviation. Scintillation effects, on the other hand, are more difficult to overcome.

Untimely weather and road/sea route maintenance (icebreaking) information are not solved by deploying imaging satellites. A crowdsourcing based service such as [39] could be a feasible solution concerning the road maintenance information.

Finally, the inherent vulnerabilities of GNSS call for a back-up system, preferably a terrestrial one. Unfortunately, the large area and sparse population of the Arctic makes terrestrial navigation solutions excessively expensive to be implemented. A LEO constellation could work, but this needs further investigation.

6 Summary

Main motivation: During the recent years, the Arctic region has faced growing interest due to an immense potential for growth in business such as transport, mining, and tourism. However, the wide range of applications face a variety of challenges that are specific to the Arctic and certain other areas at high latitudes. Due to the harsh weather and darkness, visibility os often poor and during the winter season, ice conditions add complexity to maritime navigation. Coverage of satellite navigation augmentation systems is degraded at high latitudes and atmospheric phenomena deteriorates the general accuracy and availability of satellite positioning. Telecommunications connectivity is not always available, hampering all communication activities and endangering human safety.

Project basics: The ARKKI project had two main goals. First, to indentify the most significant challenges faced in navigation and geospatial information-based applications in the Arctic area. Second, to study different technologies addressing the challenges and to compose a roadmap recommending pan-Arctic solutions for further developments. The results and findings reported in this paper are based on the outcomes of identified challenges (Chapter 2), online user survey (Chapter 3), technical solutions study (Chapter 4), and the expert working group discussions held at the pan-Arctic workshop (Chapter 5).

Overall findings of the study and survey: Based on the user survey and technical study, the following topics were identified as most significant challenges: telecommunications, maps and nautical charts, GNSS augmentation and integrity, and situational awareness. Telecommunication issues were most widelyexperienced. Otherwise, the impact of each challenge varied slightly between the market segments (aviation, maritime, rail, road, other) the survey respondents and workshop participants represented.

Currently, GNSS is utilized as a preferred navigation method in the Arctic. However, due to the low elevation angles and absence of satellites overheading the Arctic, the coverage of GNSS constellations is suboptimal in the area. Despite the developments of multi-frequency and multi-constellation GNSS and entailed improvements in the continuity and reliability of positioning, the increased ionospheric activity sets some limitations at the high latitudes.

Furthermore, some advancing technologies, for instance autonomous road transport and maritime operations, are more prone to latency and interference in navigation and require improved accuracy. Due to developing means of transport, extreme weather conditions, and highly sensitive nature, current coverage, reliability, and integrity of satellite-based augmentation systems need to be improved to guarantee flawless navigation in the Arctic. In addition to the technical challenges affecting navigation in the Arctic areas, scarce infrastructure, economical and political situation are playing a central role.

Road map summary: As a result of the end-user survey, the study of technical solutions, and the expert working group discussions, a roadmap addressing the most significant challenges was formulated. The roadmap recommends a set of actions to tackle the challenges. Telecommunication operability can be improved by deploying HEO telecommunication satellites and nanosatellites. Updating maps and nautical charts could advance from the use of nanosatellite imaging and map data crowdsourcing. To improve GNSS augmentation and integrity, further adoption of ARAIM concept, deployment of HEO satellites and new GNSS reference stations as well as improving ionospheric corrections are suggested.

Next steps: Key proposals suggested in the roadmap target tackling the most significant challenges. Furthermore, the ongoing discussions now initiated regarding the challenges in Arctic navigation need to be actively maintained between the Arctic Council Member States and policymakers. The public-sector actors related to space-based activities are here in a crucial role (ESA/GSA/NASA/Roscosmos).

Appendix: End-user survey questions

Introduction

The purpose of this survey is to identify what are the most significant challenges in Arctic navigation as experienced from the users' perspective. The survey is part of a research project conducted by the Finnish Geospatial Research Institute.

Although we have chosen the word "navigation" to describe the activity of interest, we would like to emphasize that the scope of the survey comprises various applications that involve the use of geospatial information. Examples include

- Transport at road, rail, sea, or air
- Situational awareness
- Satellite positioning (GPS/GLONASS/Galileo/BeiDou/GNSS) and its applications, e.g., construction and mining (in addition to transport)

Also note that the scope is not strictly tied to "Arctic" in terms of the Arctic Circle: similar challenges are applicable to certain areas at lower latitudes, such as Iceland, and sharing such experience is warmly welcome.

The questionnaire is divided into four parts. First, we would like to know about your background. The second part asks about your experiences concerning "navigation" in the Arctic. Then, you are asked about your opinion on how severe these challenges are, i.e., what are their possible outcomes for human safety and business. Finally, we would like to know if you have opinions or suggestions on how the challenges could be solved most efficiently.

Answering the survey is expected to take ten minutes. We are grateful for your effort!

Background information

1) What is your position in your work?
( ) End-user of (Arctic) navigation
( ) Manager of end-users
( ) Scientist/researcher studying navigation-related topics
( ) Manager of researchers/Professor
( ) Representative of a public authority
( ) Other - please specify:
____*

2) In which country are you mainly located?
( ) Canada
( ) Denmark
( ) Finland
( ) Iceland
( ) Norway
( ) Russia
( ) Sweden
( ) United States
( ) Other - please specify:
____*

3) Do your activities take place above the Arctic Circle?
( ) Yes, at least sometimes
( ) Never

4) Which market segment(s) are you active or involved in?
[ ] Road transport
[ ] Rail transport
[ ] Maritime
[ ] Aviation
[ ] Other application (e.g., surveying, mining, mobile LBS) - please specify:
____*

Your experience on the challenges

On this page, we would like to know what Arctic-related challenges you actually have encountered in your professional activity. Note that the purpose of this page is not to ask if you find these challenges difficult or dangerous; you can tell your opinion about the potential impact of these challenges on the subsequent page.

5) How often have you encountered different challenges related to navigation in the Arctic?

	Regularly	Sometimes	Never, but I would know if I had	I don't know
Considerable outage in satellite-based navigation (GPS, GLONASS, Galileo, BeiDou)	( )	( )	( )	( )
Lack or unavailability of augmentation services for satellite-based navigation (e.g. SBAS/EGNOS/WAAS/SDCM, DGPS/DGNSS, VRS/PPP services)	( )	( )	( )	( )
Unavailability of terrestrial radionavigation systems (e.g., eLORAN, Distance Measuring Equipment)	( )	( )	( )	( )
Lacking maps or nautical charts	( )	( )	( )	( )
Untimely weather or ice information	( )	( )	( )	( )

Insufficient telecommunications capability (coverage, bandwidth, etc.)
( ) ( ) ( ) ( )

Inadequate road maintenance or icebreaking
( ) ( ) ( ) ( )

Ionospheric scintillation (satellite signal power fading caused by atmospheric activity)
( ) ( ) ( ) ( )

Unawareness of accidents (wildlife, oil spills, etc.)
( ) ( ) ( ) ( )

6) Further comments on how you have experienced challenges in Arctic navigation [optional]

____
____
____
____

Potential consequences of the challenges in Arctic navigation

Please give your impression on the potential impact of the following challenges. The scale of severity is defined as follows:

1. **Negligible:** People may be alerted and feel uncomfortable. Possibility of damage to people, property, or business is very unlikely.
2. **Minor:** Incident causes mainly economic loss. There is a small chance on damage to property. May cause minor distress.
3. **Major:** Incident may cause damage to property and economic impact. Reasonable chance that people may panic or get distressed. A small chance that people get injured.
4. **Critical:** Incident may cause severe damage to property and significant economic impact. Small chance that a person gets killed, still a reasonable chance of injuries.
5. **Catastrophic:** Incident may lead to persons being killed or severely injured, severe damage to property and significant economic impact.

In addition to rating the challenges mentioned in the survey, you can give comments to explain your answers or bring up challenges that were not mentioned in the questionnaire. Answers to these optional fields are highly appreciated.

7) Snow, ice, and situational awareness
Negligible Minor Major Critical Catastrophic No opinion

Darkness and bad visibility
( ) ( ) ( ) ( ) ( ) ( )

Untimely weather or ice information
( ) ( ) ( ) ( ) ( ) ( )

Lacking road maintenance or ice breaking services
( ) ( ) ( ) ( ) ( ) ( )

Unawareness of accidents (e.g., oil spills, wildlife)
( ) ( ) ( ) ( ) ( ) ( )

8) Further comments on snow, ice, and situational awareness related challenges [optional]

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____
____
____

9) Telecommunications
Negligible Minor Major Critical Catastrophic No opinion

Lacking coverage of telecommunications
( ) ( ) ( ) ( ) ( ) ( )

Insufficient bandwidth (or other similar property)
( ) ( ) ( ) ( ) ( ) ( )

Unability to access a necessary (online) service (e.g., VRS for satellite navigation augmentation)
( ) ( ) ( ) ( ) ( ) ( )

10) Further comments on communications [optional]

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____
____
____

11) Satellite-based navigation
Negligible Minor Major Critical Catastrophic No opinion

Inadequate availability (bad satellite visibility)
( ) ( ) ( ) ( ) ( ) ( )
Accuracy does not meet the requirements
( ) ( ) ( ) ( ) ( ) ( )
Ionospheric scintillation (fading of signal power caused by atmospheric activity)
( ) ( ) ( ) ( ) ( ) ( )
Lacking coverage/availability of satellite-based augmentation (EGNOS/WAAS/SDCM)
( ) ( ) ( ) ( ) ( ) ( )

Lacking coverage of differential corrections (DGPS/DGNSS)
( ) ( ) ( ) ( ) ( ) ( )
Lacking coverage of precision correction services (VRS, PPP)
( ) ( ) ( ) ( ) ( ) ( )

12) Further comments on satellite navigation [optional]

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____
____
____

13) Other radionavigation than satellite-based (e.g., eLORAN, Distance Measuring Equipment)
Negligible Minor Major Critical Catastrophic No opinion

Unavailability of radionavigation services
( ) ( ) ( ) ( ) ( ) ( )
Inadequate accuracy
( ) ( ) ( ) ( ) ( ) ( )

14) Further comments on radionavigation [optional]

____
____
____
____

15) Maps and nautical charts
Negligible Minor Major Critical Catastrophic No opinion

Inadequate accuracy or coverage in today's applications
( ) ( ) ( ) ( ) ( ) ( )

Inadequate accuracy for autonomous vehicles and vessels
( ) ( ) ( ) ( ) ( ) ( )

16) Further comments on maps and charts [optional]

____
____
____
____

17) Other challenges [optional]
Negligible Minor Major Critical Catastrophic No opinion

18) Any other comments? [optional]

____
____
____
____

Solutions to the challenges

Please share your views on what would be - or would not be - worthwhile solutions to the problems in Arctic navigation.

19) Feasibility of solutions
Not very useful Useful but impractical (cost, size, etc.) Definitely useful Indispensable

Densified collection of information, e.g., crowdsourcing
( ) ( ) ( ) ( )

Extended assistance/augmentation services for satellite navigation
( ) ( ) ( ) ( )

Telecommunications technology/services, e.g., Iridium satellite communications or 5G
( ) ( ) ( ) ( )

Enhanced Spatial Data Infrastructures (framework of geographic data, metadata, users and tools that are interactively connected in order to use spatial data)
( ) ( ) ( ) ( )

Remote sensing (e.g., Earth observation, Sentinel satellites, Copernicus)
( ) ( ) ( ) ( )
Nanosatellites (e.g., Iceye radar imaging)
( ) ( ) ( ) ( )

20) Comments, other solutions, etc.? [optional]
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