GNSS Augmentation using the VHF Data Exchange System (VDES)

Jan Šafář, George Shaw & Alan Grant, *General Lighthouse Authorities of the UK & Ireland*
Hans Christian Haugli & Lars Løge, *Space Norway*
Stig Erik Christiansen, *Kongsberg Seatex*
Nader Alagha, *European Space Agency*

BIOGRAPHIES

Dr Jan Šafář is an R&D Engineer with the Research and Radionavigation Directorate of the General Lighthouse Authorities of the United Kingdom and Ireland. His areas of expertise include GNSS and complementary technologies for providing resilient positioning, navigation and timing at sea, such as eLoran and enhanced radar positioning. In recent years Jan has been closely involved with the development and international standardisation of the VHF Data Exchange System (VDES) – one of the potential key elements of e-navigation. Jan holds Masters and PhD degrees in radio engineering from the Czech Technical University, Prague, and is a member of the Royal Institute of Navigation and the U.S. Institute of Navigation.

Mr George Shaw is a Principal Development Engineer working for the Research and Radionavigation Directorate of the General Lighthouse Authorities of the United Kingdom and Ireland. He is responsible for strategy and systems studies that inform the future direction of maritime Aids-to-Navigation and resilient Position, Navigation and Timing (PNT) as part of future maritime e-navigation. He is a Chartered Engineer with wide experience of the systems' analysis of robust GNSS-based solutions for navigation across air, land and sea applications, both civil and military. He is responsible for the business case and strategic evolution of eLoran in the United Kingdom, and leads the engagement of European maritime stakeholders in Resilient PNT solutions.

Dr Alan Grant is a Principal Development Engineer for the Research and Radionavigation Directorate of the General Lighthouse Authorities of the United Kingdom and Ireland, where he leads the GNSS and e-navigation project team. He chairs the PNT Working Group of the IALA Engineering Committee, is a member of Council for the Royal Institute of Navigation and is a member of several RTCM special committees. He is a Fellow of the Royal Institute of Navigation, a member of US Institute of Navigation and a Chartered Physicist.

Hans- Christian Haugli is head of Innovation and Development at Space Norway who owns the VDE-SAT payload on NorSat-2 launched last year. Hans has lead two ESA activities measuring channel performance and demonstrated live broadcasting of ice charts and ship position reporting using VDES technology in the Arctic. Hans has designed and deployed mobile satcom systems for Space Norway, Vistar (now Orbcomm), Inmarsat and the European Space Agency. He has been granted 12 patents mainly relating to satcom.

Stig Erik Christiansen is Product Manager for the space activities in the R&D department at Kongsberg Seatex. This includes projects related to provision of EGNOS and Galileo ground infrastructure as well as Space Based AIS and VDES payloads. Stig Erik is active in maritime standardisation bodies and is a member of RTCM Sub-Committee 104 and the IALA ENAV committee. He holds a M.Sc. degree in Geodesy from the Norwegian University of Science and Technology (NTNU) and is a member of ION and the Nordic Institute of Navigation.

Lars Løge is Lead System Engineer at Statsat, which is in charge of operations, continuation and enhancement of the Norwegian AIS satellite constellation. He also holds a position in Space Norway, supporting their ESA funded VDE-SAT activities. Since early 2015 he has been following the work in IALA and ITU on VDES and contributed to Recommendation ITU-R M.2092 as well as coordinated the input from IALA to the current draft version of Report ITU-R M.[VDES-SAT]. In January 2018 he was appointed to the role as CEPT Coordinator for WRC-19 Agenda Item 1.9.2 (VDE-SAT) by CEPT CPG.

Nader Alagha is with the Technical Directorate at the European Space Agency Research and Technology Centre (ESTEC) in The Netherlands. He has been the technical lead of several R&D projects related to broadband satellite systems as well as space based VHF maritime communications including SAT-AIS and VDES. He has participated in several standardization technical groups including DVB, IALA and ITU. He has contributed to the definition of satellite component of VDES and the Recommendation ITU-R M.2092-0.

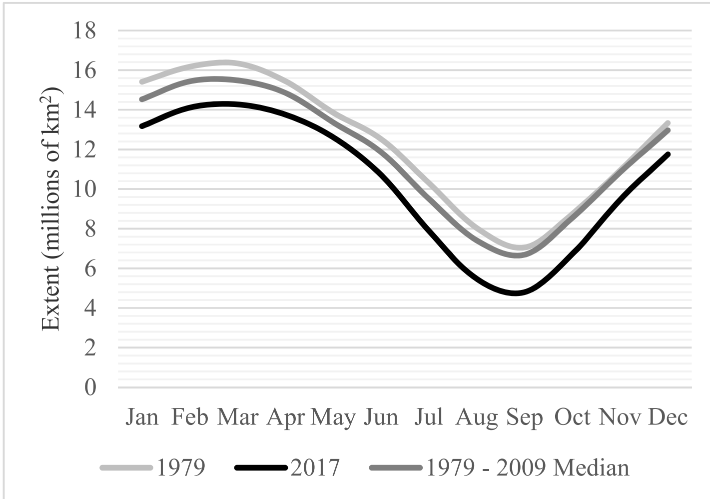

Figure 1: Arctic sea ice extent (area of ocean with at least 15% sea ice).

ABSTRACT

There is an observed trend for the extent of sea ice in the Arctic to recede over recent years. Research by the Arctic Council and the Arctic Monitoring and Assessment Programme suggests that the Arctic Ocean could be largely free of sea ice in summer by earlier than mid-century, possibly as early as the late 2030s. Given these predictions, GNSS could be increasingly required to support maritime navigation for a growing number of ships over diverse Arctic regions.

The safety of maritime navigation relies on the accuracy, integrity, availability and continuity of the navigation solution. At present, ground-based navigation augmentation systems are used to provide integrity and enhance the accuracy of GNSS-based positioning in major coastal and port areas of shipping around the world. Additionally, the provision of wide area maritime navigation augmentation services via Satellite-Based Augmentation Systems (SBAS) is gradually being developed. However, the geosynchronous satellites deployed by most existing SBAS are not visible at the high latitudes of the Arctic. The satellite component of the VHF Data Exchange System (VDES), currently being defined by the International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA) and endorsed by the International Telecommunication Union (ITU) offers the potential to provide a data link capability for an Arctic GNSS augmentation system based on a number of possible satellite configuration options.

This paper provides an overview of current and future GNSS and their augmentation systems and discusses their applicability to Arctic maritime navigation. Key technical characteristics of VDES are then described and two alternative navigation augmentation system architectures using VDES are proposed, each optimised for a different type of service: (i) an SBAS-type service providing near real-time integrity and correction data to maritime users in the Arctic; (ii) a store-and-forward type of service to deliver Integrity Support Messages (ISM) to users equipped with ARAIM (Advanced Receiver Autonomous Integrity Monitoring) enabled GNSS receivers. The system could also allow other data or messages to be conveyed, such as Maritime Safety Information, Virtual Aids to Navigation or ice charts.

The availability of navigation augmentation services for Arctic waters could have significant economic impact for shipping and global trade, especially as the North Eastern Passage (including the Northern Sea Route over Russia) may become navigable all year round within a few decades. The proposed ARAIM ISM service also has the potential to benefit users in other parts of the world as the ISM data has global applicability.

INTRODUCTION

There is an observed trend for the extent of sea ice in the Arctic to recede over recent years. Figure 1, based on data from the National Snow & Ice Data Centre (NSIDC) [1], part of the Cooperative Institute for Research in Environmental Sciences at the University of Colorado Boulder, illustrates the recent dramatic change in sea ice coverage since the median area of coverage in 1979 – 2009. There is a similar trend in the thickness of the ice cover.

The Arctic Council's Arctic Marine Shipping Assessment (AMSA) 2009 report [2] links future Arctic marine activity to how 'potentially accelerating Arctic sea ice retreat improves marine access throughout the Arctic Ocean'. Key findings are that coastal Arctic regions will be 'increasingly ice-free for longer summer and autumn seasons, and there is a possibility of a completely ice-free Arctic Ocean for a short period of time in summer by earlier than mid-century'. The more recent SWIPA (Snow, Water, Ice and Permafrost in the Arctic) 2017 report by the Arctic Monitoring and Assessment Programme, an Arctic Council Working Group [3], observes an increase in the rate of ice recession, with a key finding that: 'The Arctic Ocean could be largely free of sea ice in summer as early as the late 2030s, only two decades from now'.

Given the predictions for change in Arctic sea ice, GNSS could be increasingly required to support maritime navigation for a growing number of ships over diverse Arctic regions.

GNSS has become the primary electronic position fixing system for maritime navigation. The safety of maritime navigation relies on adequate positioning performance in terms of accuracy, integrity, availability and continuity [4]. At present, local area augmentation systems are used to provide integrity and enhance the accuracy of GNSS-based positioning in major coastal and port areas of shipping around the world. These systems operate through terrestrial beacon infrastructure, broadcasting GNSS differential correction and integrity data to ships via Medium Frequency (MF) transmissions. The provision of wide area maritime navigation augmentation services via *Satellite-Based Augmentation Systems* (SBAS) is also gradually being developed, initially through the proposed introduction of EGNOS (European Geostationary Navigation Overlay Service) maritime services, with the potential for other SBAS providers to provide similar services in the future. However, the geosynchronous satellites deployed by most existing SBAS are not visible at the high latitudes of the Arctic. A further method contributing to integrity is *Receiver Autonomous Integrity Monitoring* (RAIM), which uses redundant signals and an overdetermined set of measurements obtained through visibility of many satellites at the user position [5].

In the long-term future, *Advanced RAIM* (ARAIM) based on a large number of satellites of multiple GNSS constellations may itself provide sufficient integrity. ARAIM relies on a ground infrastructure to provide regular updates on GNSS performance in the form of Integrity Support Messages (ISMs). Several ARAIM architectures have been proposed in the literature to support a wide range of applications, with required ISM update rates ranging from minutes to months. The ARAIM ISM dissemination channel is yet to be determined [6].

This paper examines the technical feasibility of using the satellite component of the *VHF Data Exchange System* (VDES), currently being defined by the International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA) and endorsed by the International Telecommunication Union (ITU), to provide a data link for an Arctic GNSS augmentation system.

The paper is structured as follows:

The Background Information section details the maritime performance requirements for position fixing systems, provides an overview of current and emerging GNSS and their augmentation systems and examines their applicability to Arctic maritime navigation. An overview of the VDES and the key technical characteristics of its satellite component is also provided. The following section introduces two candidate GNSS augmentation services for the Arctic proposed by the authors: (i) an SBAS-type service supporting wide-area augmentation through the near real-time dissemination of EGNOS-like correction and integrity data; and (ii) a store-and-forward type of service to deliver ISM data to users equipped with ARAIM-enabled GNSS receivers. The data link requirements of both services are estimated and two alternative augmentation system architectures using VDES are proposed, each optimised for one of the candidate services. The next section gives a brief overview of the ESA-funded AMNAS (Arctic Maritime Navigation Augmentation Service) project, which aims to further develop the concepts presented in this paper. The final section summarises the key findings and conclusions of this study.

BACKGROUND INFORMATION

Maritime Navigation Requirements

Global maritime use of GNSS by those ships governed by the Convention for the Safety of Life at Sea (SOLAS) is formally enabled by the International Maritime Organization (IMO)'s recognition of GNSS in the World Wide Radio Navigation System (WWRNS), as described in IMO Resolution A.1046(27) [7]. A second IMO Resolution, A.915(22), sets out maritime performance requirements for general navigation and a range of specialised maritime applications.

It should be noted that neither of these Resolutions were prepared with the express objective to capture all of the navigation requirements of today. Resolution A.915(22) was written many years ago with a view of capturing future GNSS requirements without defining the time frame or how the requirements are met. A.915 was reviewed by the IALA Aids to Navigation Requirements and Management (ARM) Committee in 2014, which concluded that the requirements should be retained with the exception of the continuity requirement which should be amended to reflect the 15 minute continuity time interval expressed in A.1046. As can be seen from Table 1 and Table 2, the two Resolutions also differ in terms of the accuracy requirements for general navigation in ocean waters, the applicability of the continuity requirement to coastal navigation and the required position update rate. Both Resolutions remain in force and reflect the best information available to-date. Therefore, the requirements identified by these two IMO Resolutions must be considered as the pertinent maritime navigation requirements.

Table 1: Performance requirements for recognition of radionavigation systems in the WWRNS; A.1046(27).

Voyage Phase	R95 Accuracy (m)	Integrity	Availability (%)	Continuity over 15 min (%)	Fix Interval (s)
Ocean waters	100	Integrity warning as soon as practicable by Maritime Safety Information (MSI) systems	99.8	N/A	2
Coastal waters, port approaches and entrances	10	Integrity warning within 10 s	99.8	99.97	2

Table 2: Performance requirements for future GNSS with respect to general maritime navigation; A.915(22) IALA rev.

Voyage Phase	Accuracy (interpreted as R95, m)	Integrity			Availability (%)	Continuity over 15 min (%)	Fix Interval (s)
		Horizontal Alert Limit (m)	Time to Alert (s)	Integrity Risk per 3 hrs			
Ocean and Coastal waters	10	25	10	10^{-5}	99.8	N/A	1
Port approaches, inland and restricted waters	10	25	10	10^{-5}	99.8	99.97	1
Port	1	2.5	10	10^{-5}	99.8	99.97	1

The IMO Resolutions apply globally, without distinction to the maritime area, including navigation of the Arctic. However, a recent study undertaken by the Stanford University [8] has proposed an additional set of performance requirements to specifically support navigation in the ice-covered waters of the Arctic. The study argues that as standards modernise and communication of ice conditions improves, vessels in the Arctic region will increasingly be required to find safe tracks on their own, without icebreaker assistance. In order to find and follow tracks previously carved by an icebreaker, vessels will need to be able to position themselves to within half the vessel's beam of the track. This is the rationale for the 10 m Horizontal Alert Limit (HAL) requirement (and consequentially 4 m accuracy requirement) in Table 3. It should be noted that this requirement is not a formal requirement of the IMO but is considered useful for this work; the figures used here are taken from the Stanford study [8].

Table 3: Proposed performance requirements for general navigation in ice-covered waters [8].

Voyage Phase	R95 Accuracy (m)	Integrity			Availability (%)	Continuity over 15 min (%)	Fix Interval (s)
		Horizontal Alert Limit (m)	Time to Alert (s)	Integrity Risk per 3 hrs			
Ice navigation	4	10	10	10^{-5}	99.8	99.97	1

It is noted that Resolution A.915(22) also defines requirements for navigation in ports and for a wide range of specialised maritime applications, with accuracy targets down to the 10 cm level. Such applications typically rely on the use of local Real-time Kinematic (RTK) correction systems and expert pilot knowledge and will not be considered in this paper.

A.1046 states that the performance requirements for recognition in the WWRNS may be met by individual radionavigation systems or by a combination of such systems. At present, four GNSS constellations are recognised within the WWRNS: GPS, GLONASS, BeiDou and Galileo. At IMO MSC 98 in June 2017, the EU proposed (in MSC 98-20-3) recognition of EGNOS under the WWRNS, but the proposal was not approved and it was agreed that IMO recognition of augmentation systems would not be needed.

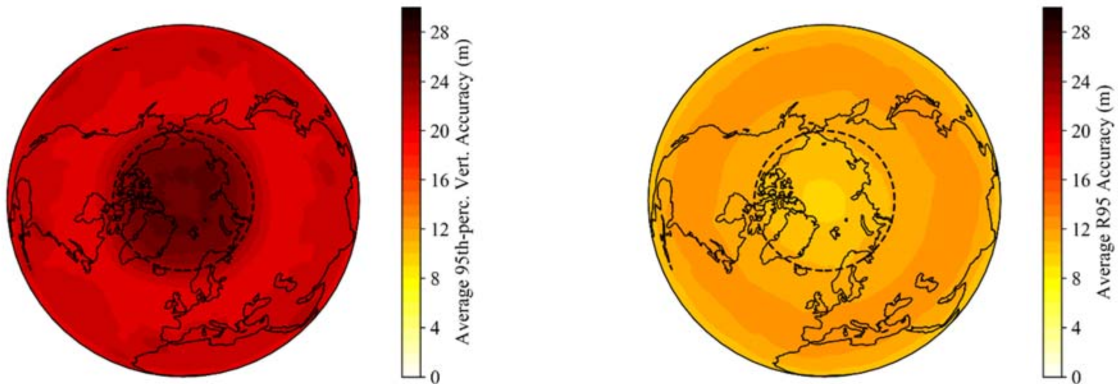

Figure 2: Single-frequency GPS vertical (left) vs. horizontal (right) accuracy in the Northern Hemisphere; dashed line shows the Arctic Cirle at 66⁰ 33' 47.2" N.

The IMO Resolution MSC.401(95), 'Performance Standards for Multi-System Shipborne Radionavigation Receivers' has established performance standards for a *Multi-System Receiver* (MSR). It recommends MSRs are installed on or after 31st December 2017, using civil access navigation signals of at least two independent GNSS recognized by the IMO as part of WWRNS. The Resolution requires the MSR to have the facilities to process augmentation data, in accordance with appropriate methods (including standards still to be developed in particular for SBAS adoption). The MSR should be capable of generating a new PVT solution at least once every 1 s for conventional vessels (and at least once every 0.5 s for high-speed craft, exceeding 70 knots). Type-approved MSRs are expected to be commercially available from 2019/20. For use on SOLAS vessels, ship's receivers using a future navigation augmentation service (potentially integrated within a MSR) will have to conform to the IMO MSR performance standard.

GNSS Coverage and Performance in the Arctic

GNSS have become the principal radionavigation aid for shipping globally, although currently only GPS and GLONASS are primarily used for maritime operations; the other two GNSS recognised within the WWRNS, Galileo and BeiDou, are currently being deployed. This section assesses the achievable coverage and performance of the existing and emerging GNSS constellations in the Arctic region against the requirements identified in the preceding section.

The coverage and performance of a GNSS is largely determined by the parameters of the satellite orbits and the availability of multi-frequency ranging signals. Multi-frequency operation greatly enhances accuracy by making it possible to estimate the additional signal propagation delay through the ionosphere, which is a major source of measurement error in GNSS. An overview of the key characteristics of the four GNSS constellations is provided below.

The nominal GPS constellation consists of 24 MEO (Medium Earth Orbit) satellites in 6 orbital planes, with the ascending nodes equally spaced about the equator. The nominal orbits are circular with a radius of 26,559.7 km and inclination to the equatorial plane of 55⁰ [9]. The GPS constellation is expandable and, for some time now, the system has been operating with more than the baseline number of satellites. At the time of writing, there were 31 operational GPS satellites, with 18 satellites providing civil multi-frequency ranging signals [10]. The GPS constellation is undergoing a modernisation and all newly launched satellites will be equipped for multi-frequency operation.

The nominal GLONASS constellation consists of 24 MEO satellites in 3 orbital planes, with the ascending nodes equally spaced about the equator. The nominal orbits are circular with an orbital altitude of 19,100 km and inclination of 64.8⁰ [5]. At the time of writing, there were 24 operational GLONASS satellites, all providing multi-frequency ranging signals [11].

Similarly to GLONASS, the nominal Galileo constellation consists of 24 MEO satellites in 3 orbital planes, equally spaced about the equator. The nominal orbits have a radius of 29,599.801 km and inclination of 56⁰ [12]. Galileo achieved its 'Initial Services' phase at the end of 2016 and at the time of writing, the constellation was nearing completion [13]. All Galileo satellites are designed to broadcast multi-frequency ranging signals.

BeiDou differs from the other three constellations in that it also contains satellites in geostationary (GEO) and inclined geosynchronous (IGSO) obits. The nominal constellation consists of 24 MEO, 5 GEO and 3 IGSO satellites. Similarly to GLONASS and Galileo, the MEO satellites are placed in 3 equally spaced orbital planes around the earth. The nominal orbits are at an altitude of 21,500 km, with an inclination of 55⁰. The GEO and IGSO satellites provide improved coverage in the Asia-Pacific region [5]. BeiDou has reached phase 2 of its deployment, providing continuous positioning, navigation and timing

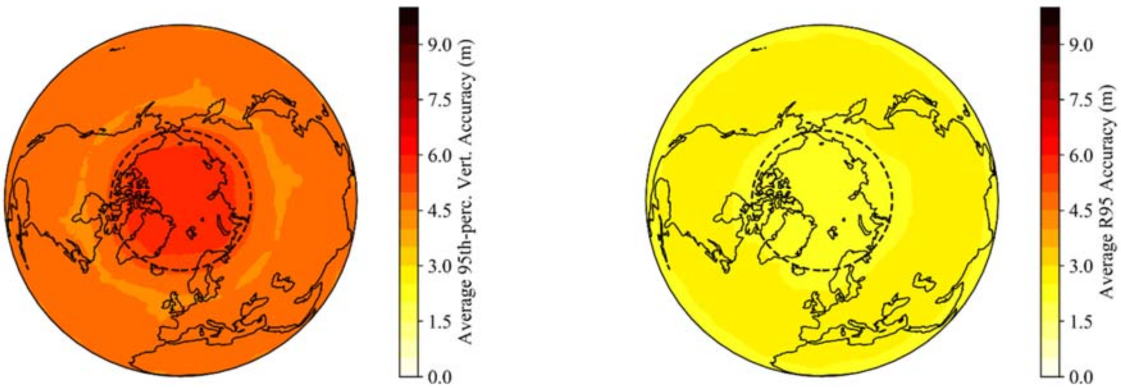

Figure 3: Dual-frequency GPS vertical (left) vs. horizontal (right) accuracy in the Northern Hemisphere.

services for China and most of the Asia-Pacific region. At the time of writing, there were 15 operational BeiDou-2 satellites (6 GEO, 6 IGSO and 3 MEO), all providing multi-frequency signals [14].

From the above it can be seen that the four GNSS constellations have very similar design parameters and are therefore expected to provide similar levels of performance. For a user in the Arctic, the GNSS satellites appear at relatively low elevation angles, as the inclination of the satellite orbits does not exceed 65^{o} (note that GLONASS has a slight advantage here over the other constellations). This creates satellite geometries that are poor for vertical positioning, but good for horizontal positioning (which is of primary interest to maritime users).

The effect is illustrated in Figure 2 which shows the estimated vertical and horizontal positioning accuracy for a user equipped with a single-frequency GPS receiver. The plots were generated assuming the nominal GPS constellation of 24 satellites and a satellite elevation mask of 5 degrees. A one-sigma User Equipment Error (UEE) of 2.3 m, ionospheric delay model error of 5.0 m and User Range Error (URE) of 4.0 m were assumed in line with [9], resulting in a User Equivalent Range Error (UERE) of 6.8 m (note that most of the error components in [9] are stated as 95-th percentile values and were converted to RMS values by dividing by a factor of 1.96). Figure 3 then shows the predicted accuracy for a user equipped with a dual-frequency GPS receiver, assuming a one-sigma UERE of 1.5 m [9]; the plot also assumes that all satellites in the baseline constellation have been upgraded to enable multi-frequency operation. Similar results can be obtained for the other three GNSS constellations.

From the plots it can be seen that a standalone single-frequency GNSS easily meets the WWRNS horizontal accuracy requirement of 100 m for navigation in ocean waters; however, the more stringent 10 m accuracy requirement set out in A.915 appears only to be met over a small portion of the Arctic, near the Pole. Meeting the 10 m accuracy target, and particularly the proposed 4 m target for navigation in ice-covered waters, therefore necessitates either the use of multi-frequency GNSS (as illustrated in Figure 3), or the use of an augmentation system providing near-real-time ionospheric corrections.

GNSS augmentation is also an important factor when it comes to integrity of the position solution. Integrity of navigation is fundamental to maritime safety, both at system level (rapidly alerting the mariner and user equipment to system faults such as a satellite malfunction) and at user level (raising an alert when the estimated position error in the operational environment exceeds a level deemed to be safe). Standalone GNSS have very low inherent integrity. Basic GNSS satellite health information is provided to users as part of the navigation message; however, this information is only relatively infrequently updated and cannot support the 10-second time to alarm requirement set out in A.1046 and A.915. Also, there is no inherent mechanism in GNSS to provide user-level integrity.

The following section provides an overview of existing augmentation systems and solutions that can be used to enhance both the accuracy and integrity of GNSS.

Existing GNSS Augmentation Systems and Solutions and their Applicability to Maritime Arctic Navigation

The *IALA Marine Beacon Differential GPS* (DGPS) system is a local area augmentation system relying on ground-based infrastructure to deliver DGPS correction and integrity data to ships in major coastal and port areas of shipping. Standards for marine beacon DGPS data transmitted in the MF frequency band (300 kHz) were developed by the Radio Technical Commission for Maritime Services (RTCM) Special Committee 104 and adopted by ITU-R, and marine beacon DGPS receivers are widely available. However, the IALA system has only limited coverage in the Arctic region and little potential for expansion due to the lack of landmasses where the necessary infrastructure could be installed. Marine beacon DGPS reference stations located in Faeroes, Scandinavia and Russia will offer some service to the Northeast Passage (combining the Northern Sea Route over

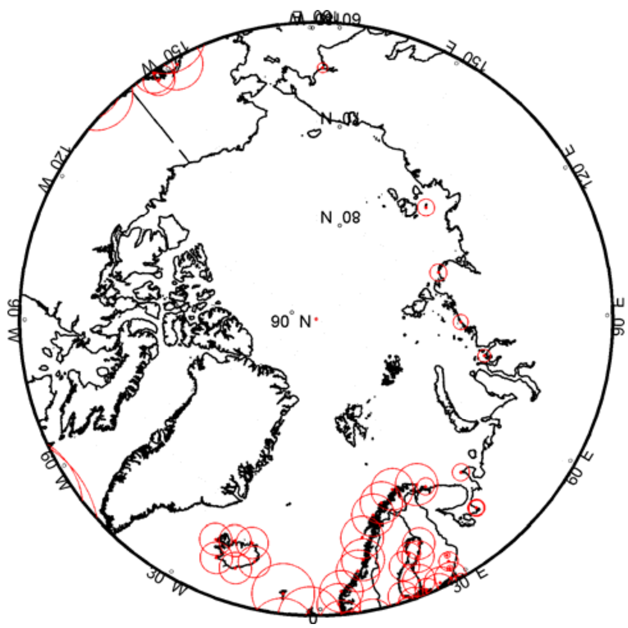

Figure 4: IALA Marine Beacon DGPS system coverage in the Arctic.

Russia with passage via the Barents Sea and over Norway). From available data, there is no expected marine beacon coverage currently serving the Northwest Passage (along the northern coast of North America) as Canadian stations are limited to the east and west coastlines. This is illustrated in Figure 4, which shows the nominal ranges of all beacons in the Arctic region listed in the IALA list of DGPS radiobeacons [15].

SBAS systems currently provide wide area augmentation services for single-frequency GPS only: EGNOS in Europe, WAAS (Wide Area Augmentation System) in North America, MSAS (Multi-functional Satellite Augmentation System) in Japan and GAGAN (GPS-Aided GEO Augmented Navigation) in India. Some systems provide augmentation services for GLONASS, but this is not very common and limited to a few local areas world-wide. Other signals from GPS and GLONASS are not covered by the existing systems, while Galileo and BeiDou are not covered at all. SBAS is widely used by mariners on non-SOLAS vessels; however, there is no recognised maritime SBAS service for SOLAS vessels. SOLAS users of SBAS require type-approved receivers which are now under development and are expected to become available around 2019 [16]. No existing SBAS provides adequate Arctic coverage from their GEO satellites, which have a practical coverage cut off at approximately 72°N. Extending the coverage area of existing SBAS further north would necessitate the use of non-GEO communication satellites, as discussed further in this paper. New SBAS reference stations may also need to be deployed in the high latitudes of the Arctic, as has been demonstrated by the Arctic Test Bed project [17].

GNSS can also be augmented by RAIM – a technique developed to determine integrity of the position solution based on an overdetermined set of measurement equations. Basic RAIM using a single constellation (GPS) and single-frequency signals is a mature technology, but it requires the visibility of a sufficient number of satellites to provide a redundancy of signals and satellite measurements. A minimum of five satellites is required to detect a fault and at least six satellites are required to detect a fault and exclude the faulted satellite. Traditional RAIM provides integrity for horizontal navigation only. RAIM is not mandated for inclusion within current maritime receivers and some do not use it. Where RAIM is included, the algorithms used may vary in performance, as they are not required to satisfy a performance standard. RAIM can also be used as a complement with SBAS, hence using the SBAS error model within RAIM algorithms. Use of SBAS allows RAIM to determine a smaller error bound in the receiver. In combination, RAIM could be used when SBAS is not available, hence increasing availability.

Advanced RAIM techniques based on a large number of satellites of multiple GNSS constellations are currently being developed and will be discussed further in this paper.

Need for Extended GNSS Augmentation Coverage and New Augmentation Services

Two key conclusions can be drawn from the discussion above. Firstly, neither the IALA Marine Beacon DGPS system nor the existing SBAS have adequate coverage in the Arctic. Due to the lack of landmasses, the only way to cover the entire Arctic region is through space-based solutions, making use of non-GEO satellites.

Secondly, there is an emerging need for new augmentation services supporting multi-frequency, multi-constellation operation and new integrity concepts, such as ARAIM. As discussed above, the existing SBAS provide augmentation for GPS single frequency (L1) only. Europe is planning to include Galileo in their next EGNOS version 3 (i.e. the European SBAS), and similar SBAS upgrades are planned in other regions to support dual-system GNSS. It is not planned to include augmentation data for all four GNSS from any of the existing systems.

In addition, there is a need to cryptographically secure the data to prevent spoofing (i.e. transmitting of fake augmentation data by an attacker seeking to disrupt maritime navigation).

The following section introduces the VDES communication system and provides details of its satellite component, which could be used to convey GNSS augmentation data to users in the Arctic. The next two major sections then define two new GNSS augmentation services to support SBAS and ARAIM operation, and propose two architectures for an Arctic GNSS augmentation system using the VDES.

The VHF Data Exchange System (VDES)

The VDES is a new maritime radio communication system being developed by IALA and ITU, supported by IMO, with the principal objectives, to: (i) safeguard existing *Automatic Identification System* (AIS) core functions, such as ship-to-shore and ship-to-ship position reporting, preventing future AIS overload; and (ii) enhance maritime communication applications, based on robust and efficient digital data transmission with wider bandwidth than the AIS. VDES could become a key supporting element of the IMO concept of e-navigation, aiming to enhance berth-to-berth navigation and related services for safety and security at sea, protection of the marine environment and efficiency of maritime trade, as described in the 'e-Navigation Strategy Implementation Plan' (SIP) [18]. VDES also has the potential to contribute to the modernisation of the IMO's Global Maritime Distress and Safety System (GMDSS) and convey cryptographically signed messages which can help secure safety-related information.

Being a development of the AIS, the VDES naturally has a *terrestrial component*. However, due to the propagation characteristics of VHF signals, terrestrial VDES stations can only provide coverage to around 60 km from the shore (depending on antenna heights, transmit power and receiver and environment characteristics). In order to extend the communication range beyond the shore coverage a *satellite VDES component* is also being implemented. With polar orbiting satellites, the entire globe can be covered, including the Arctic and Antarctic regions that cannot be served by traditional geostationary communication satellites. The satellite VDES communications functions (ship-to-satellite and satellite-to-ship) are intended to be fully integrated with the terrestrial communications functions (ship-to-ship, ship-to-shore and shore-to-ship) in the shipborne VDES equipment. Shipborne terminals will preferably use one combined transmitting/receiving VDES antenna system, although the final design remains open at this stage.

The VDES operates on AIS, *Application Specific Message* (ASM) and *VHF Data Exchange* (VDE) channels in the Maritime Mobile VHF band. These radio channels are not exclusive to maritime users. Compatibility between the satellite VDES downlink and land-based radio systems operating in the same frequency band is ensured by means of a Power Flux Density (PFD) mask. The PFD mask is a way of limiting emissions from the VDES satellites so that receivers of the land-based systems are not interfered with. The detailed frequency arrangements and PFD mask for satellite VDE (VDE-SAT) are currently under discussion at ITU and are expected to be finalised at the World Radiocommunication Conference in 2019. For the purpose of this study, it is assumed that the PFD mask defined in Recommendation ITU-R M.2090-0 [19] will be used.

The VDES uses a TDMA (Time-Division Multiple Access) scheme to access the radio channels. The scheme is based on the concept of a *frame*, established in Recommendation ITU-R M.1371 on the Technical Characteristics of the AIS. Each frame lasts 60 seconds, starts on the UTC minute (as in AIS), and is divided into 2 250 *time slots*. A time slot therefore lasts approximately 26.67 milliseconds and is the shortest addressable interval of time in VDES.

The allocation of VDES time (and frequency) resources is controlled using the *Bulletin Board*. The current VDE-SAT specification assumes that the Bulletin Board information is transmitted within the first 90 slots (or 2.4 seconds) of each frame (i.e. at each 1-minute UTC epoch). The Bulletin Board defines a repeating sequence of 12 *logical channels*. A logical channel is defined by its centre frequency, channel bandwidth, start time slot and duration. Each logical channel is assigned a specific function (such as Announcement Signaling Channel, Downlink User Data Channel, Uplink User Data Channel or Random Access Channel) and *physical layer frame format* (determining the modulation and coding scheme and thereby the effective information rate).

The VDES maximizes spectrum efficiency by using *adaptive modulation and coding*, selecting the most appropriate physical layer frame format based on real-time link quality measurements. The specifications for the VDE-SAT downlink formats are summarized in Table 4.

Initial system access is typically done using a combination of spread spectrum (see 'BPSK/CDMA' in Table 4), low bitrate and powerful forward error correction (FEC). Estimated carrier-power-to-noise-density ratio thresholds for an Additive White Gaussian Noise (AWGN) channel, C/N_0, are also included in Table 4.

Table 4: VDE-SAT downlink physical layer frame formats.

Physical layer frame format #	1	2	3	4	5	6	7
Channel bandwidth (kHz)	50	50	50	100	150	300	500
Occupied bandwidth (kHz)	42	42	42	90	141	291	492
CDMA chip rate (kcps)	33.6	N/A	N/A	72.0	112.8	232.8	393.6
Symbol rate (ksps)	4.2	33.6	33.6	18.0	28.2	58.2	98.4
Burst length (time slots)	90	90	90	90	90	90	90
Modulation	BPSK/CDMA	π/4 QPSK	8PSK	BPSK/CDMA			
FEC rate	½	¼	½	½	½	½	½
Number of bits per burst post FEC	4,728	40,144	120,448	20,392	33,648	69,472	117,480
Net data rate (kbps)	2.0	16.7	50.2	8.5	14.0	29.0	49.0
Estimated threshold E_s/N_0 for an AWGN channel and PER=10^{-2} (dB)	-2.0	-2.4	5.0	-2.0	-2.0	-2.0	-2.0
Estimated required C/N_0 (dBHz)	34.2	42.9	50.3	40.6	42.5	45.6	47.9

PROPOSED GNSS AUGMENTATION SERVICES

Two new services are proposed here to address the growing need for GNSS augmentation in the Arctic. One enables the extension of the coverage of existing SBAS' into the Arctic region; the other is designed to provide ARAIM integrity data to users in the Arctic. The latter also has the potential to become a worldwide service as the ARAIM data has global applicability.

SBAS Extension Service

The 'SBAS Extension' service is based on existing SBAS', such as WAAS or EGNOS, which were introduced earlier in the paper. The aim is to extend the coverage of these systems into the Arctic region by broadcasting SBAS messages through non-GEO satellites.

The standard SBAS messages are 250 bits in size, and a new message is transmitted every second. Fresh augmentation data must be generated, delivered to the user and processed within 10 seconds of a GNSS integrity event occurring (see the IMO requirements in Table 2). This places a stringent requirement on the latency of the satellite communications link used to convey the SBAS messages to users. It is expected that, in order to meet the 10-second time to alert limit set out by the IMO, the link latency must be less than 1 second.

The service area shall be defined as the part of NAVAREA XIX north of 70º N latitude. NAVAREAs are geographical areas established for the purpose of coordinating the transmission of radio navigational warnings. NAVAREA XIX is bounded approximately by 65º N on the south, 90º N on the north, 20º W on the west and 30º E on the east. It is assumed here that existing GNSS augmentation solutions, such as EGNOS and IALA DGPS beacons, provide adequate service coverage at latitudes below 70º N [15], [20].

The satellite communications link requirements for this service are summarised in Table 5. Note that while the existing SBAS services provide augmentation data for single-frequency, single-constellation operation only, future versions may include additional data to support multi-frequency, multi-constellation SBAS solutions.

ARAIM Support Service

ARAIM (Advanced RAIM) is a development of the traditional RAIM approach introduced earlier in this paper. It adds four main elements: support for multiple GNSS constellations; use of multi-frequency measurements; a deeper threat analysis, and the possibility to update the parameters of the receiver integrity algorithm via ISM (Integrity Support Message) broadcasts.

Two approaches to ARAIM have been studied in the literature, differing in the way the ISM is generated and disseminated: (i) Offline ARAIM uses a quasi-static ISM, which is manually produced and only rarely updated, primarily to reflect changes in GNSS constellations or to reduce conservatism of prior ISM values; (ii) Online ARAIM uses a dynamic ISM, which is automatically generated and updated every 15 minutes or so.

The information carried by the Offline ARAIM ISM includes a mask indicating whether a GNSS satellite is valid for ARAIM; constellation and satellite fault probabilities; and nominal signal-in-space error statistics. In Online ARAIM, the ISM also includes corrections to the broadcast GNSS ephemeris data. This results in improved ranging accuracy and reduced fault probabilities, ultimately leading to tighter integrity bounds.

ARAIM is capable of providing integrity for both vertical and horizontal guidance, meeting the navigation requirements of the aviation sector. For maritime users, a horizontal ARAIM solution (H-ARAIM) may be sufficient.

Unlike SBAS data, which is specific to a geographical region, the ARAIM data is applicable globally. Therefore, the ARAIM Support service could be provided worldwide, assuming the ISM latency / update interval requirements can be satisfied by the chosen communications solution.

The ARAIM concept is still under development; the design is not finalised and user equipment is not yet available. However, the latest report of the EU-U.S. ARAIM working group [21] provides sufficient detail to enable the requirements on the ARAIM communications link to be estimated.

Two message types for Offline ARAIM (Type 1A and Type 1B) and one for Online ARAIM (Type 2) were proposed in the report [21]. The Type 1A ISM contains all ISM content in a single message, whereas Type 1B contains only the ISM content for a single GNSS constellation and provides more flexibility if there is a need to apply different parameter values to different satellites within each constellation. The estimated communications link requirements for both message types, including provisions for cryptographic authentication of the messages (proposed by the authors), are shown in Table 6.

The Type 2 ISM to support Online ARAIM carries ISM data for only a single GNSS satellite. The estimated communications link requirements for this ARAIM approach are shown in Table 7.

The following section explores the possibility of implementing the services proposed here within a system architecture using the VDES satellite component as the carrier of the augmentation data.

Table 5: Satellite communications link requirements for the proposed SBAS Extension service.

Parameter	Value	Unit	Comments
Data size	250	bit	Standard WAAS/EGNOS SBAS messages for single-frequency, single-constellation GNSS positioning as defined in RTCA DO-229 [22]
Latency	< 1	s	New augmentation data must be delivered and processed within the IMO-required 10-second time to alert. It is assumed that the processing and communication delays in other parts of the augmentation system are such that the overall 10-second time-to-alert requirement is met.
Update interval	1	s	One 250-bit message is sent every second (see RTCA DO-229 [22]).
Coverage	NAVAREA XIX, bounded on the south by 70º N	-	NAVAREA XIX is a geographical area bounded approximately by 65º N on the south, 90º N on the north, 20º W on the west and 30º E on the east, established as part of the World-Wide Navigational Warning Service. In Europe, the area south of 70º N is covered by EGNOS and DGPS beacons.

Table 6: Satellite communications link requirements for the Offline ARAIM Support service.

Parameter	Value	Unit	Comments
Data size	755 (signed Message Type 1A) or 1,380 (signed Message Type 1B)	bit	Augmentation data [21]: - ARAIM Message Type 1A: 211 bit for four GNSS'; - ARAIM Message Type 1B (allows different ARAIM parameter values for different groups of satellites within a constellation): 209 bit per GNSS, i.e. 836 bit for four GNSS; Authentication: - Signature (Elliptic Curve Digital Signature Algorithm with 256-bit keys): 512 bit; - Timestamp (to prevent replay attacks): 32 bit (a shorter timestamp may be sufficient if used in combination with the time data in the message header); - Assume signature is included with each augmentation message.
Latency	~(1- 10)	day	ARAIM relies on measurement consistency checks performed by the positioning receiver to determine integrity, therefore the augmentation data does not need to be disseminated within the IMO-required 10-second time-to-alert; In Offline ARAIM, there is no urgency to broadcast the augmentation data, as prior values will have been chosen to remain safe for the very long term [21].
Update interval	~(1-24)	hour	New augmentation data is generated only very rarely, perhaps once a month; however, the data may be broadcast more frequently to ensure a sufficiently low time-to-first-operations.
Coverage	NAVAREA XIX, bounded on the south by 70º N	-	

Table 7: Satellite communications link requirements for the Online ARAIM Support service.

Parameter	Value	Unit	Comments
Data size	6,944	bit	Augmentation data [21]: - ARAIM Message Type 2: 100 bit per GNSS satellite; - Assume augmentation data for 2 GNSS constellations is broadcast; - Assume 32 satellites per constellation, i.e. 64 satellites in total (equivalently, 4 GNSS constellations and 50% satellite visibility could be assumed); Authentication: - Signature (Elliptic Curve Digital Signature Algorithm with 256-bit keys): 512 bit; - Timestamp (to prevent replay attacks): 32-bit (a shorter timestamp may be sufficient if used in combination with the time data in the message header); - Assume the complete set of messages for all 64 satellites is signed rather than each individual message separately.
Latency / update interval	~15	min	ARAIM relies on measurement consistency checks performed by the positioning receiver to determine integrity, therefore the augmentation data does not need to be disseminated within the IMO-required 10-second time-to-alert; In Online ARAIM, the augmentation data is expected to be updated every 12-15 minutes and refreshed within this time [21].
Coverage	NAVAREA XIX, bounded on the south by 70º N	-	

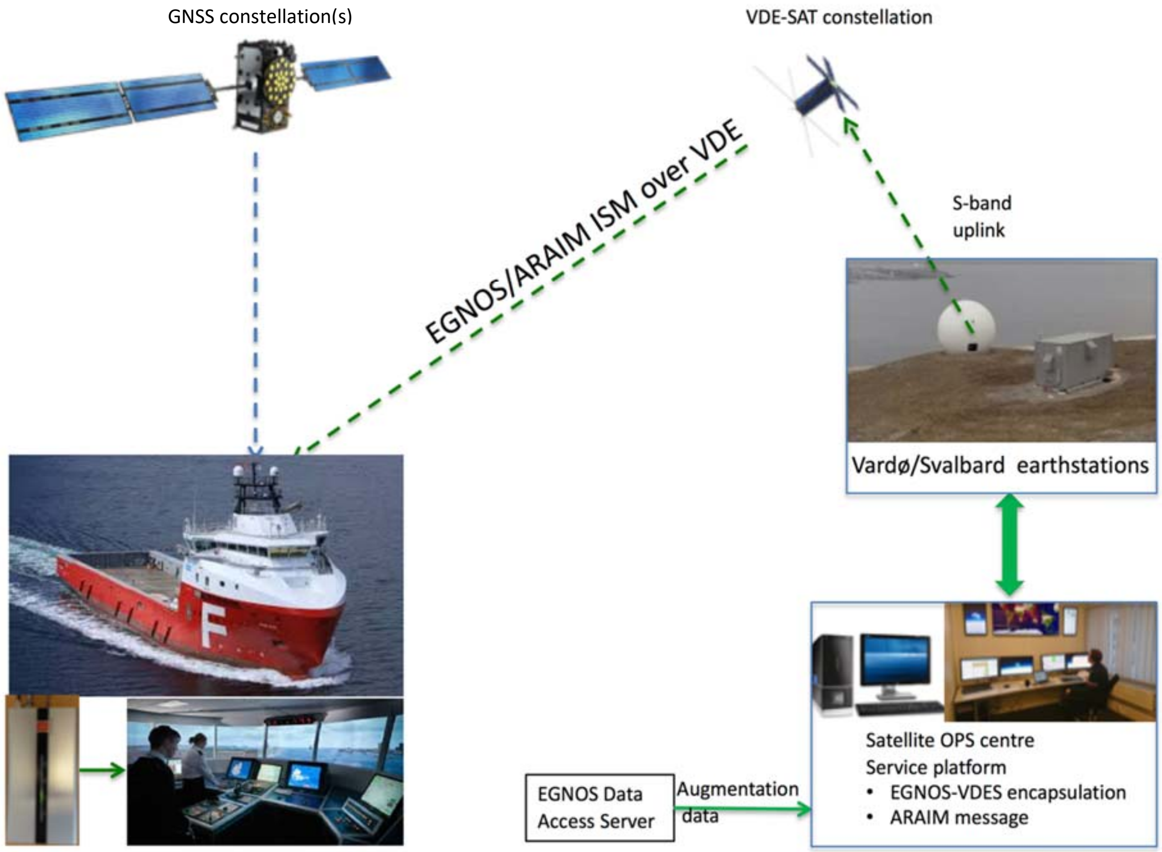

Figure 5: Proposed system architecture.

GNSS AUGMENTATION SYSTEM ARCHITECTURE USING VDE-SAT

Figure 5 shows a conceptual architecture for an Arctic GNSS augmentation system, implementing the augmentation services defined in the preceding section: A Satellite Operations Centre receives augmentation data from an Augmentation Data Provider (the generation of the augmentation data is considered out of the scope of the current work; for more information on potential sources of this data refer, for example, to the EGNOS Data Access Service, the Arctic Testbed project [17], and the work of the EU-U.S. ARAIM working group [21]). The augmentation data is converted into VDES messages and passed on to one or more VDES Satellite Earth Stations, which forward the messages via one or more VDES Satellites to maritime Users operating in the Arctic. The data is uploaded to the satellite(s) using an S-band link and broadcast to the Users via VHF, using suitable VDE-SAT waveforms. A standard ship-borne VDES Transceiver receives the VDE-SAT signals and outputs the received augmentation data to an on-board Navigation Receiver (such as the IMO MSR mentioned earlier).

The following two sections provide further detail for two system architectures optimised for the SBAS Extension service and the ARAIM Support service, respectively. The focus is on the VDE-SAT communications link as this represents the main innovative component of the system. Each section covers the following aspects of the satellite link in turn: satellite orbits; satellite earth station considerations; satellite characteristics; and VDE-SAT physical layer configuration.

Architecture Optimisations for the SBAS Extension Service

The SBAS Extension service requires a low-latency (near real-time) communications link that will provide essentially continuous availability (see Table 5). One way to ensure full-time coverage of the entire Arctic region is by placing VDES Satellites into a *Highly Elliptical Orbit* (HEO), such as Molnyia or Tundra. The key advantage of the HEO orbits is that they enable continuous Arctic coverage to be achieved with only two satellites. However, with an apogee altitude comparable to that of a geostationary orbit, the HEO option requires a relatively high satellite transmit power (an EIRP of around 200 W would be required, assuming a PFD limit of -149 dBW/m^2/4 kHz [19]) and results in long signal propagation delays (typically in low hundreds of milliseconds). In addition, the median satellite elevation angle for users in the Arctic is more than 45°. Existing omnidirectional

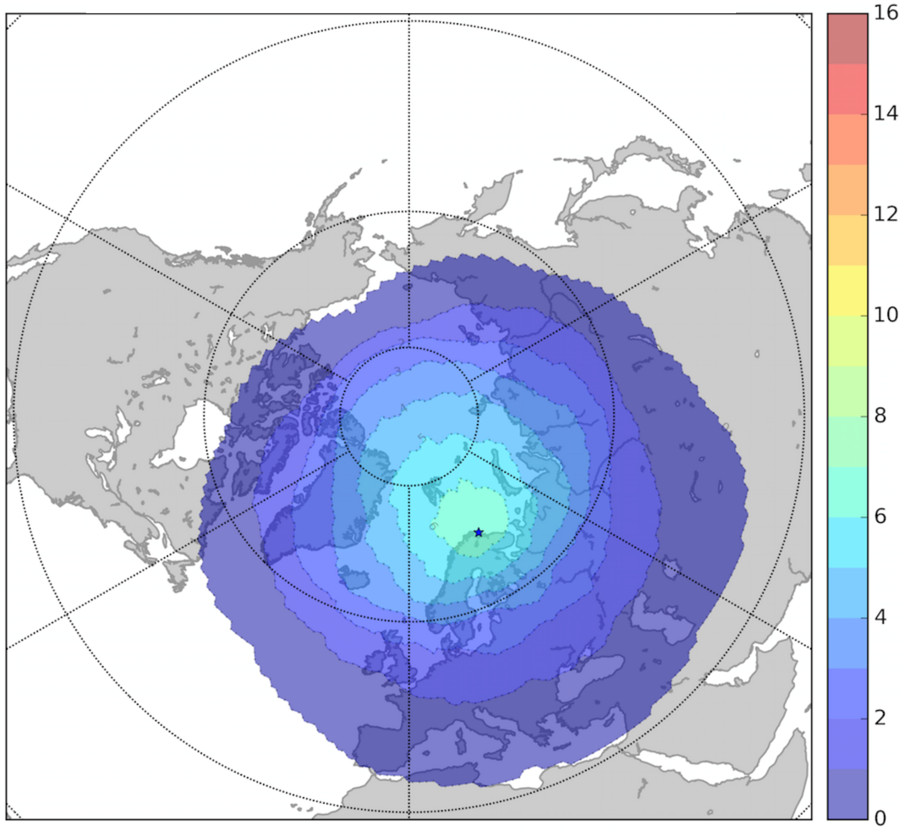

Figure 6: Simultaneous User and Vardø Satellite Earth Station visibility (satellite elevation above 3 degrees) as percentage of time for a LEO satellite at 600 km orbital altitude.

VHF ship antennas have poor performance at high elevation angles, which may negatively affect link availability and service quality for this option.

An alternative to HEO is to use a larger constellation of *Low-Earth Orbit* (LEO) satellites. Most LEOs are launched into Sun-synchronous polar orbits with an inclination of around 97.2º and orbital altitude of 600 km or so. These complement geostationary orbits by providing highest availability at high latitudes.

The near real-time character of the SBAS Extension service requires that the VDES Satellite can simultaneously be seen by both the Satellite Earth Station and the User. Figure 6 shows the percentage of time this condition is met for the Vardø Satellite Earth Station located at 71º N latitude and a LEO satellite with an orbital altitude of 600 km. It can be seen from the figure that the availability for a single satellite is at least 5% across most of the target service area, dropping to 4% towards the edges of the area. Therefore, it is expected that 20 to 25 perfectly phased LEO satellites would be required to ensure full-time coverage of this area. It would be desirable to launch all satellites into one plane, including any spares, and use small thrusters to maintain orbit phasing.

Assuming an average LEO satellite lifetime of 5 years, a constellation of 25 satellites would, on average, need to replace 5 satellites every year.

The increased number of satellites also increases requirements on the Satellite Earth Station. With the LEO option, the station would need to handle more than a 100 handovers per day (compared to only a few per day for a HEO constellation).

Despite the relatively high number of satellites required, a LEO constellation is an attractive solution, as the LEO satellites can be very small (the use of 4U CubeSats is being considered, i.e. satellites made up of four 10 cm x 10 cm x 10 cm units), require relatively low transmit power (an EIRP of less than 1 W is required, assuming the same PFD limit as before) and give shorter signal propagation delays (typically less than 20 ms). Assuming all satellites in the constellation are launched into one plane, orbit phasing could be achieved using a simple (1U size) propulsion system.

The Satellite Earth Station for the proposed system could be based on existing infrastructure at Svalbard or Vardø. In addition, Kongsberg Satellite Services (KSAT) has antenna farms at more than 20 locations around the globe. Satellite Telemetry, Tracking & Command (TT&C) is performed via an S-band link for most new LEO satellites, and the same link could be used for uploading the SBAS Extension service data. With a 50 W transmitter and a 3.7 m S-band antenna used at the Earth Station, data rates higher than 4.2 kbps can be achieved, even when the satellite is tumbling. To ensure continuous, full-time operation, two S-band antennas plus a spare would be required at the station.

The stringent latency and update interval requirements of the SBAS Extension service also present a number of challenges for the design of the VDES Satellite payload and the VDE-SAT waveform. The specifications for the existing VDE-SAT downlink waveforms / 'physical layer frame formats' were provided earlier in Table 4. It can be seen from the table that if VDE-SAT was configured exclusively for downlink, then the minimum data latency would be 2.4 seconds (90 time slots), except at the UTC minute epoch where the latency would be 4.8 seconds (as the start of the frame has to accommodate the Bulletin Board). Taking into consideration ground processing and communication delays, uplink latency, signal propagation delays and satellite signal processing, it is unlikely that the existing VDE-SAT waveforms would allow for the IMO 10-second time to alert requirement to be met.

The burst length of 2.4 seconds was originally chosen for VDE-SAT based on expected signal fading characteristics. However, recent channel sounding measurements performed using the NorSat-2 satellite [23] have shown that the fading is slower than originally expected; thus, the selected burst length results in a relatively long latency but provides minimal interleaving benefits.

To address this issue, a new VDE-SAT physical layer format is proposed here, with characteristics given in Table 8. The new format is a modification of the most robust VDE-SAT waveform (see physical layer format #1 in Table 4), with the burst length reduced from 90 to 15 time slots and FEC rate reduced from ½ to ¼. As a result, the minimum downlink latency is reduced to 0.4 seconds and the C/N_0 threshold is reduced from 34.2 dBHz to 31.6 dBHz. Based on VDE-SAT channel characteristics measured by the NorSat-2 mission, the reduced C/N_0 threshold is expected to result in an increase in link availability from 98% to 99.7%.

As can be seen from Table 8, the new physical layer format can deliver 312 information bits to the user every 0.4 second, which meets the data size and update rate requirements of the SBAS Extension service, as specified in Table 5.

Table 8: Proposed new VDE-SAT physical layer format optimised to the requirements of the SBAS Extension service.

Parameter	Value
Channel bandwidth (kHz)	50
Occupied bandwidth (kHz)	42.0
CDMA chip rate (kcps)	33.6
Symbol rate (ksps)	4.2
Burst length (time slots)	15
Modulation	BPSK/CDMA
FEC rate	¼
Number of bits per burst post FEC	312
Net data rate (bps)	780
Estimated threshold E_s/N_0 (dB) for an AWGN channel and PER=10^{-2}	-4.5
C/N_0 threshold (dBHz)	31.6

In order to keep the satellite communication latency to a minimum, a '*digital bent pipe*' architecture has been proposed for the VDES CubeSat payload, where the satellite acts as a virtually transparent digital repeater, passing SBAS data uploaded via the TT&C link (or a separate high-speed link, as is done with NorSat-2) to the user in near real-time. Some amount of buffering on-board the satellite will be required to handle path delay variations and enable ARQ (Automatic Repeat Query) on the uplink. However, it is expected that with the new VDE-SAT physical layer format, the total satellite latency will be less than 1 second.

The satellite would be equipped with a crossed 2-element Yagi VHF antenna. The antenna elements would be made of a metallic tape approximately 450 mm in length, deployed by a solenoid or a burn wire. The spacing between the radiator and the reflector would be approximately 350 mm and the antenna would provide a gain of around 6 dBi in Right Hand Circular Polarization. The coverage area corresponding to the 0 dBi contour would be approximately 2600 km by 2300 km in size, representing slightly less than ¼ of the satellite field of view.

The satellite would operate in an earth-limb pointing mode where the Yagi boresight is pointed at the earth horizon. The satellite body (and antenna boresight) would be rotated around the sub-satellite point to cover the required service area.

A satellite covering the portion of NAVAREA XIX between 70º N and 90º N latitude would be active for approximately 6% of the orbit period and would during the remaining 94% of the orbit point towards the sun for maximum charging. As shown earlier, the VDE-SAT downlink has sufficient capacity to operate at 50% or lower duty cycle, thus the charging time would be approximately 34-times the active transmit time. It should be noted that the same satellite could also be used to deliver other services in other geographical regions.

The rest of this section provides an example link budget for the proposed VDE-SAT downlink configuration.

Table 9 shows the noise breakdown for a VDE-SAT ship receiving system used on the Norwegian Coast Guard vessel Harstad during recent NorSat-2 trials in the Arctic Ocean. An example link budget for the proposed CubeSat architecture is then shown in Table 10.

The satellite antenna gain figures provided in Table 10 are based on a radiation pattern sourced from reference [24] and may need to be adjusted once the final antenna design is available. Based on these figures, and assuming output filtering and feed losses of 1.1 dB, the highest satellite transmit power that satisfies the VDE-SAT PFD mask [19] would be -5.1 dBW (or around 0.3 W). The gain characteristic for the ship antenna (Comrod AV7) shown in Table 10 is based on information provided by the antenna manufacturer.

It can be seen from Table 10 that the proposed VDE-SAT downlink configuration has a negative link margin for satellite elevation angles above about 75º. However, this is not expected to have a significant impact on the link availability, as LEO satellites appear at low elevation angles most of the time (for example, the elevation of the NorSat-2 satellite, as observed at 69º N latitude, is less than 65º for 99% of the time).

Table 9: Example ship receiving system noise breakdown.

Parameter	Value
Antenna noise temperature (K)	5,500
Feed loss (dB)	0.25
Feed noise temperature (K)	17.2
Receiver noise figure (dB)	9.0
Receiver noise temperature (K)	2013.6
System noise temperature (K)	7,650.0
Noise power spectral density at the input of an equivalent noise-less system, N_0 (dBm/Hz)	-159.8

Table 10: Example link budget for the VDE-SAT downlink using the proposed CubeSat architecture.

Satellite elevation angle (deg)	Range (km)	Satellite antenna gain (dBi)	Satellite EIRP (dBW)	Path loss (dB)	Polariz. loss (dB)	Ship antenna gain (dBi)	Signal level at ant. (dBm)	C/N_0 (dBHz)	Link Margin (dB)
0	2831	6.3	0.1	145.7	3.0	2.0	-116.6	43.2	11.6
15	1626	5.8	-0.4	140.9	3.0	-1.0	-115.3	44.5	12.9
30	1075	4.3	-1.9	137.3	3.0	-5.1	-117.3	42.5	10.9
45	815	1.3	-4.9	134.9	3.0	-1.8	-114.6	45.2	13.6
60	683	-3.7	-9.9	133.3	3.0	-2.2	-118.4	41.3	9.7
75	619	-8.7	-14.9	132.5	3.0	-6.8	-127.2	32.6	1.0
90	600	-23.7	-29.9	132.2	3.0	-26.6	-161.7	-1.9	-33.5

Architecture Optimisations for the ARAIM Support Service

Two variants of the ARAIM Support service, designed to support the Offline vs. Online ARAIM concepts, were introduced earlier in this paper. The online approach places more stringent requirements on the VDE-SAT link and will, therefore, drive the derivation of this system architecture option.

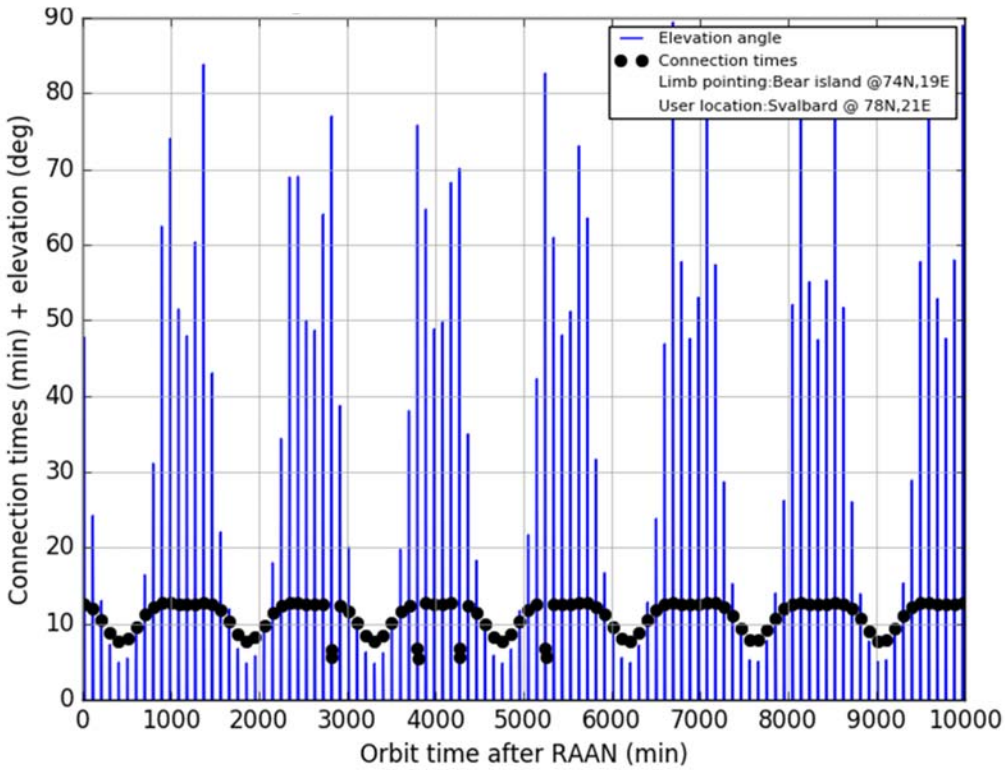

Figure 7: The maximum satellite elevation angle and connection time at 78º N latitude for a LEO satellite with an orbital altitude of 600 km (NorSat-2).

Online ARAIM requires the transfer of approximately 7 kbits of data in 900 seconds (see Table 7). Using the same physical layer format as for the SBAS Extension service (Table 8) and a transmit duty cycle of 50%, the data could be transferred in 18 seconds; thus the satellite revisit time is the main design driver.

Figure 7 shows the satellite connection time and the maximum elevation angle for each pass of the NorSat-2 satellite visible at 78º N latitude, as recorded over the time span of one week (or 10 000 minutes). It can be seen from the figure that at 78º N latitude, all 14 or 15 passes in a day are visible, with an average connection time of around 10 minutes. As mentioned before, the VDE-SAT link has a negative margin at high elevation angles, which may cause connection interruptions of around 10 to 30 seconds; the effect can be seen in Figure 7 as two short connection times for a given elevation angle (e.g. at 5,200 minutes after passing through the ascending node).

Assuming an average connection time of 10 minutes, and a maximum tolerable latency of 15 minutes, a new satellite would need to appear above the horizon every 25 minutes in order to meet the requirements for Online ARAIM. With an orbital period of 98 minutes, approximately 4 satellites (plus a spare) would provide sufficient coverage for latitudes above 78º N, where all satellite passes for the intended orbit are visible. At 70º N, 1 or 2 additional satellites would be required, bringing the constellation size up to 7 satellites (including one in-orbit spare). The same system architecture could be used to disseminate Offline ARAIM messages.

If only Offline ARAIM support was required then as few as 1 or 2 (for redundancy) satellites would be sufficient.

The ARAIM Support service does not require full-time coverage, therefore only one antenna (plus a spare) would be required at the Satellite Earth Station.

The satellite payload for the ARAIM Support service could be based on the digital bent pipe concept discussed in the preceding section. Alternatively, a 'store-and-forward' architecture could be used, where the augmentation data would be stored on-board the satellite and updated only when fresh data becomes available.

AMNAS PROJECT AND FOLLOW-ON WORK

The use of the VDES system for augmentation data, as presented in this paper, has been studied in the AMNAS (Arctic Maritime Navigation Augmentation Service) project. This is a project financed by the European Space Agency (ESA) through the ESA General Studies. The project is conducted by Kongsberg Seatex AS, together with Space Norway AS and the General Lighthouse Authorities of the United Kingdom & Ireland (GLA). The project is scheduled to complete in Q4 2018. The preliminary results from the project have been followed up in the new ESA project VNADS (VDE-SAT Navigation Augmentation Data Service), where a GNSS augmentation service will be demonstrated using the NorSat-2 satellite.

CONCLUSIONS

This work has indicated that the VDES should be capable of supporting GNSS augmentation to users in the Arctic.

Two services have been proposed, to enable the extension of the coverage of exiting SBAS services to the Arctic region, and to support future ARAIM users. The SBAS Extension service has stringent latency and update rate requirements, but by using a modified VDES physical layer format, a near real-time service could be provided with a constellation of 20 to 25 satellites operating in a digital bent pipe manner. The ARAIM Support service is less demanding, requiring only 7 satellites, or possibly less if only Offline ARAIM support is required.

The satellites considered are 4U CubeSats, which are cheaper to build and launch than traditional communication satellites launched into GEO or HEO orbits.

The results of this project will be shared with the international standards bodies that are developing VDES to help shape the future of the satellite component of VDES.

ACKNOWLEDGMENTS

This work is partly funded by the European Space Agency, ESA-ESTEC, Noordwijk, The Netherlands, under contract no. 4000119199/16/NL/FE (Arctic Maritime Navigation Augmentation Service). Opinions, interpretations, recommendations and conclusions expressed herein are those of the authors and are not necessarily endorsed by the European Space Agency.

REFERENCES

[1] National Snow & Ice Data Centre (NSIDC), 'Arctic Sea Ice News & Analysis', *NSIDC Website*, Jun-2018. [Online]. Available: https://nsidc.org/arcticseaicenews/sea-ice-tools/.
[2] Arctic Council, 'Arctic Marine Shipping Assessment 2009 Report', 2009.
[3] Arctic Monitoring and Assessment Programme, 'Snow, Water, Ice and Permafrost in the Arctic 2017 Report', 2017.
[4] IMO, 'Resolution A.915(22) on Revised Maritime Policy and Requirements for a Future Global Navigation Satellite System (GNSS)', Nov. 2001.
[5] E. D. Kaplan and C. J. Hegarty, *Understanding GPS/GNSS - Principles and Applications*, Third Ed. Artech House, 2017.
[6] J. Blanch *et al.*, 'Architectures for Advanced RAIM: Offline and Online', in *Proc. 27th International Technical Meeting of the Satellite Division of the Institute of Navigation*, Tampa, Florida, 2014, pp. 787–804.
[7] IMO, 'Resolution A.1046(27), World Wide Radionavigation System', Dec. 2011.
[8] T. Reid, T. Walter, J. Blanch, and P. Enge, 'GNSS Integrity in the Arctic', *NAVIGATION: Journal of the Institute of Navigation*, vol. 63, no. 4, pp. 469–492, Winter 2016.
[9] U.S. Department of Defense, 'Global Positioning System Standard Positioning Service Performance Standard', 4th Edition, Sep. 2008.
[10] 'Space Segment', *GPS.gov*, Jun-2018. [Online]. Available: https://www.gps.gov/systems/gps/space/.
[11] 'GLONASS Status', *Website of the Information and Analysis Center for Positioning, Navigation and Timing*, Jun-2018. [Online]. Available: https://www.glonass-iac.ru/en/GLONASS/.
[12] 'European GNSS (Galileo) Initial Services - Open Service (OS) Service Definition Document', Issue 1.0, Dec. 2016.
[13] 'Constellation Information', *Website of the European GNSS Service Centre*, Jun-2018. [Online]. Available: https://www.gsc-europa.eu/system-status/Constellation-Information.
[14] 'BeiDou Constellation Status', *Website of the Information and Analysis Center for Positioning, Navigation and Timing*, Jun-2018. [Online]. Available: https://www.glonass-iac.ru/en/BEIDOU/.
[15] 'World DGNSS Stations List', *Website of the International Association of Marine Aids-to-Navigation and Lighthouse Authorities*, Jun-2018. [Online]. Available: http://www.iala-aism.org/products-projects/technical-area/world-dgnss-stations-list/.
[16] IMO, 'Performance Standards for Multi-system Shipborne Radionavigation Receivers', Resolution MSC.401(95), Jun. 2015.
[17] P. E. Kvam *et al.*, 'The Arctic Testbed - Experimentation Results on SBAS in the Arctic Region', in *Proc. 29th International Technical Meeting of the Satellite Division of the Institute of Navigation*, 2016, pp. 3228–3248.

[18] IMO, 'Report to the Maritime Safety Committee', NCSR 1/28, Jul. 2014.
[19] ITU, 'Technical Characteristics for a VHF Data Exchange System in the VHF Maritime Mobile Band', Geneva, Switzerland, Recommendation ITU-R M.2092-0, Oct. 2015.
[20] European GNSS Agency, 'EGNOS Safety of Life (SoL) Service Definition Document', Sep. 2016.
[21] GPS-Galileo Working Group C, ARAIM Technical Subgroup, 'Milestone 3 Report', Feb-2016. [Online]. Available: https://www.gps.gov/policy/cooperation/europe/2016/working-group-c/.
[22] RTCA, 'Minimum Operational Performance Standards for Global Positioning System/Satellite-Based Augmentation System Airborne Equipment', RTCA DO-229D, Dec. 2016.
[23] 'VDE-SAT Downlink Verification', ESA Contract 4000113274/15/NL/NR Final Report, Sep. 2018.
[24] '2 Elements Yagi', *dx-antennas.com*, Sep-2018. [Online]. Available: http://www.dx-antennas.com/Yagi2.htm.