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GNSS AND SBAS SYSTEM OF SYSTEMS: CONCIDERATIONS FOR APPLICATIONS IN THE ARCTIC

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Youth for GNSS (YGNSS) is a team created by the Space Generation Advisory Council on GNSS and the International Committee on GNSS (ICG). Composed of students and young professionals, Youth for GNSS aims to recognize and promote the ways in which Global Navigation Satellite Systems (GNSS) and Satellite Based Augmentation Systems (SBAS) can benefit society. With the future and health of our planet and its citizens a primary concern, YGNSS aims to secure and optimize how GNSS -based applications and technology will benefit society by promoting compatibility and interoperability of GNSS through a network of systems. In addition to the development and improvement of technology, applications, education, and outreach in regions where GNSS is already established, it is the goal of YGNSS to analyze and promote the importance and impact of GNSS technology in areas with less developed infrastructure, such as in developing countries and in the Arctic. In this paper, drivers of change in the Arctic are discussed based on the impact of GNSS as tools for scientific applications and for strengthening and promoting interoperability of navigation, positioning, and timing systems. Topics such as surveying, mapping, engineering and construction, aviation, maritime and space weather monitoring are discussed. Due to the high ecological sensitivity and extreme weather conditions in Arctic regions, accidents there could cause great environmental damage and also threaten human lives. Navigation integrity is therefore of particular importance in this region.

I. SGAC, THE YGNSS PROJECT TEAM, AND THE INTERNATIONAL COMMITTEE ON GNSS

The Space Generation Advisory Council (SGAC) is a global non-governmental organization (NGO) and network that aims to represent university students and young space professionals to the United Nations, space agencies, industry, and academia.

One of the ongoing activities within SGAC is the YGNSS working group: Youth promoting cooperation and education in GNSS. In cooperation with the ICG and the United Nations Office for Outer Space Affairs (UNOOSA), the purpose is to help bring the maximum benefits of GNSS to society by encouraging consultations among its members, and promoting communication with relevant groups such as the International Civil Aviation Organization (ICAO), the International Maritime Organization (IMO), and the International Telecommunications Union (ITU).

This paper is a State-of-the-Art literature study on GNSS and SBAS, with special consideration for applications in the Arctic region.

II. BACKGROUND AND MOTIVATION

"There are two kinds of Arctic problems, the imaginary and the real. Of the two, the imaginary are the most real."

-Vilhjalmur Stefansson, The Arctic in Fact and Fable

Over the next several decades, or even years, the region defined by the Arctic circle above 66° latitude, by the tree line, or by the 10° Celsius isotherm (see Figure 1), will experience extraordinary economic and environmental change as it holds a great potential for exploitation of useful resources. According to estimates from the U.S Geological Survey (USGS), the Arctic holds approximately 13% of the world's undiscovered

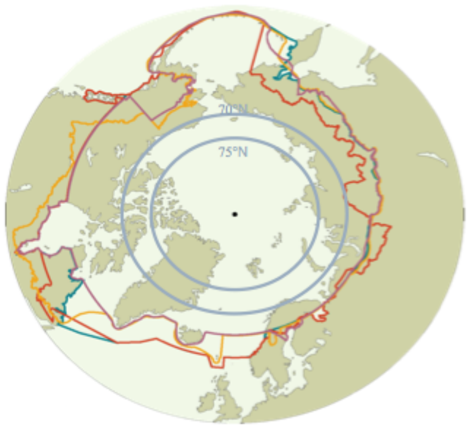


Figure 1: The Arctic is defined as the region above the latitude 66 degrees Arctic circle, the tree line, or the 10 degrees Celsius isotherm. Courtesy of Polar View.

oil reserves, 20% of its undiscovered LPG (Liquefied Petroleum Gas) reserves, and 30% of undiscovered gas reserves and approximately 84 % of these resources are estimated to be located offshore (U. S. Geological Survey 2008). The future undoubtedly holds promises of significantly increased activity in drilling for oil, gas, and natural minerals in this region as these natural resources are becoming available for extraction. In addition to increased drilling for oil and gas, both shipping and ecotourism is on the rise as new shipping routes are being created. The reason for this increase in Arctic marine traffic is that as polar icecaps recede, more waterways are becoming available. In fact, the polar ice cap was 40 % smaller in 2005 than it was in 1979 (Roach 2005), and during the summer of 2007 alone 1 million square miles of ice beyond the average melted. September of 2011 marked the lowest levels of sea ice extent ever recorded in the Arctic (H. A. Conley 2012), and Figure 2 illustrates the results of a study at NASA Goddard, estimating that the perennial ice extent is schrinking by 12.2% per decade.

Furthermore, the National Oceanic and Atmospheric Administration (NOAA) has stated that as a result of temperature changes, the significant breeding areas of fish stocks connected to the Arctic Ocean are anticipated to move farther north (H. A. Conley 2012). The combination of an increasingly ice-free and hostile climatic environment demands a comprehensive regional and global readiness in Arctic economics and environmental security strategy; Border security and border protection, environmental remediation, natural- and man-made disaster response, and search and rescue activity becomes increasingly important. There are also potential threats of piracy and terrorism; however, one advantage of navigating on northern sea routes is the fact that piracy and terrorism activity is more difficult and demanding in these areas.

III. ARCTIC POLICIES

III.I The Arctic Council

The five Arctic coastal states: Canada, Denmark, Norway, Russia, and the United States, together with Sweden, Finland and Iceland, make up the total of eight current members of the Arctic Council, formally established by the Ottawa Declaration of 1996. The Arctic Council serves as "a high level intergovernmental forum to provide a means for promoting cooperation, coordination, and interaction among the Arctic States, with the involvement of the Arctic Indigenous communities and other Arctic inhabitants on common Arctic issues of sustainable development and environmental protection in the Arctic." (The Arctic Council 2012). In addition, the Asian beneficiaries of a future Northern Sea Route, in particular China, Japan, and South Korea, have announced their interest in the Arctic region by applying for permanent observer status in the Arctic Council. Interest in the future conditions of the Arctic region could potentially reduce transit time from Asia to Europe and North America by one third. Italy and the European Commission have also applied for permanent observer status (Aarmo 2012; H. A. Conley 2012).

Policy priorities are reflected in most relevant security strategy documents. Excerpts from policy documents of the eight members of the Arctic Council are listed in Table 1.

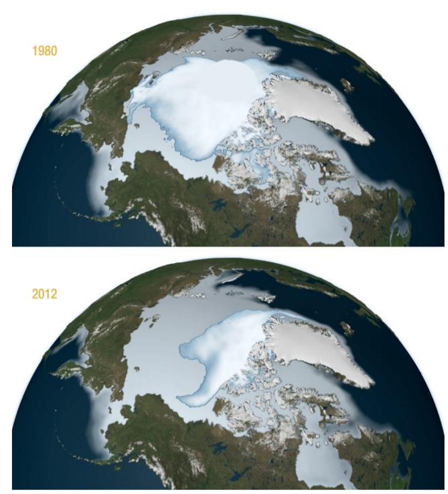
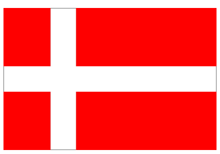
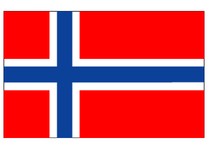
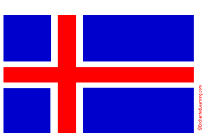
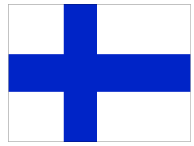
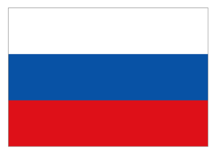
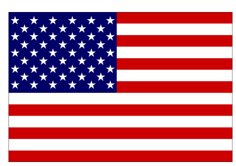
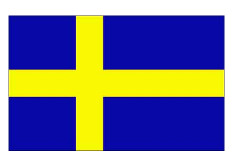


Figure 2: A study at NASA Goddard found that perennial ice extent is shrinking by 12.2% per decade (Consortium for Ocean Leadership 2012). This figure illustrates how perennial sea ice (seen as the white central mass) has declined from 1980 to 2012. Courtesy of NASA/Goddard.

Table 1: Excerpts from National Policy Documents of the eight members of the Arctic Council.

Arctic Council Member National Policy Document	Policy Priorities (Excerpts)
Canada's Northern Strategy: Our North, Our Heritage, Our Future 	Increased military/law enforcement presence and capabilities, including search and rescue. Effective navigation ability in air, on land/ice and offshore. Canada seeks to extend national boundaries to the North Pole, i.e. to redefine national boundaries according to UNCLOS
Kingdom of Denmark Strategy for the Arctic 2011-2020 	Maritime safety including training and ship safety, and search and rescue, is a fundamental priority. High international safety standards for ships navigating in the Arctic are required. Denmark expects a large expansion of oil and gas extraction.
Norway: The High North – vision and means (Government White Paper) 	Norway bases its foreign policy with respect to a new industry era in the north, a pioneer era for integrated marine management, and the polar ocean's growing attraction. Main objectives are to secure peace and the entire eco-based management of the region, to strengthen international cooperation, and to strengthen value creation. In particular, Norway has a focus on oil spill prevention and clean up as navigation and drilling increases.
Iceland in the High North 	Safety issues concerned with transportation and accidents with ships. The environmental threat from oil exploitation and transportation is highlighted. The foundation of the Icelandic Arctic Policy is the sovereign right to sustainable utilization of natural resources and protection of the fragile environment.
Finland's Strategy for the Arctic Region 	Nuclear safety, especially on the Kola peninsula. Regards the increase in sea transportation the biggest threat to Arctic marine ecosystems, and concludes that the safety systems per today are inadequate. Finland seeks to strengthen its role as an expert on Arctic know how.
Fundamentals of State Policy of the Russian Federation in the Arctic in the Period up to 2020 and Beyond 	The main interest of Russia is usage of the Arctic resource base to improve the economic and social development in Russia. This requires a comprehensive ability for effective navigation in air, on land and ice, and offshore, and real-time navigation data streams. Russia seeks to expand hydrocarbon production in the Arctic Sea. For safety, Russia prioritizes the construction of maritime checkpoints to improve navigation monitoring, and assistance with cross pole air-borne navigation.
U.S. National Security Presidential Directive /NSPD – 66 concerning an Arctic Region Policy (2009) 	This document urges that the Senate consider immediately signing and ratifying the UNCLOS. The policy includes priorities related to security, research, continental shelf, environmental protection, and energy. Internationally, the overarching priority is maintenance of the freedom of the seas. In particular, the capability requirements seek effective navigation ability in air, on land and ice, and offshore. Vessel traffic monitoring, navigation, and timely navigational information is emphasized.
Sweden's Strategy for the Arctic Region 	Environment protection is a main objective for Sweden, climate change being paramount. Challenges to biodiversity connected to pollutants, oil and gas, and climate research is important.

IV. GNSS AND SBAS TECHNOLOGY: IMPACT AND UTILIZAITION IN THE ARCTIC

The requirements of GNSS –based applications and technology in the Arctic region are the same as for the rest of the world, however, the Arctic region holds no promise for mass market applications (Aarmo 2012).

The economic interests impose demands mainly on offshore applications, such as dynamic positioning for vessels and aviation requirements for integrity services in aircrafts, particularly helicopters and small airplanes (Aarmo 2012).

IV.I Marine Transportation

The facilitation of safe, secure and reliable navigation at sea is amongst the highest policy priority objectives of all sovereign states involved in Arctic development. The right of safe navigation at sea is most effectively governed and enforced by the United Nations Convention on the Law of the Sea (UNCLOS). According to the International Maritime Organization (IMO), all Safety-of-Life-at-Sea (SOLAS) vessels are required to carry a GNSS receiver; this has caused a general increase in the reliance of GNSS receivers for ship operations.

IV.II Environment and Safety Hazards

The Arctic region's ice infested waters, including sea ice, icebergs, and ice islands, impose a primary safety risk for marine transportation. As a result, GNSS technology is particularly critical in Arctic waters to ensure the safety of vessels and their crews. It is worth mentioning that GNSS technology is commonly supplemented with ECDIS (Electronic Chart Display and Information System) on the vessel bridge. The ECDIS system provides continuous position and navigational safety information, and may be enabled to generate audible and visual alarms should navigation hazards approach the vessel's proximity (Polar View 2012).

In general, maritime ship operations have experienced a shift of focus from accuracy to reliability in terms of integrity and continuity (Klepsvik 2011); Integrity is particularly important in the Arctic because of the sensitive environment. Vessel navigation and routing with GNSS is also the most accurate and efficient system for this application, and GNSS should therefore always be employed to reduce fuel consumption to a minimum. GNSS does, however, require aid from augmentation systems in order to meet integrity and continuity requirements for some GNSS applications, such as dynamic positioning.

IV.III Air Transportation

Similar to marine transportation, air transportation uses GNSS as its primary system for navigation, enabling all weather navigation capability. However, vertical guidance approaches require that GNSS is augmented by a ground- or space-based augmentation system to enhance GNSS performance in terms of availability of service by broadcasting integrity data and extra ranging signals via ground infrastructure or geostationary satellites (International Civil Aviation Organization 2005). Navigation performance using GNSS alone does not meet the safety requirements to support approaches with vertical guidance proposed by ICAO.

Air transportation is mentioned in only a few of the Arctic nations' policy documents; Canada's *Northern Strategy: Our North, Our Heritage, Our Future,* and Norway's *New Building Blocks in the North* are of the few that addresses air transportation specifically (Polar View 2012). Air transportation consequently appears to be of less significance than marine transportation from an Arctic policy perspective. However, air transportation services are more critical in the Arctic region due to bad weather and landing surface conditions, combined with a limited number of alternate reroute destinations (Polar View 2012).

Future alternative space based solutions, other than the already operable geostationary SBAS systems, are discussed below.

IV.IV Infrastructure; Engineering and Construction

Development of infrastructure in general is in demand of several GNSS applications. Power generation facilities, for example, utilize the precise timing capability of GNSS for synchronizing of frequencies in power networks. In addition, in the featureless landscape of the Arctic navigation data is of utmost importance for guidance to infrastructure sites such as for construction-, maintenance-, and repair-work (Polar View 2012). One proposed method to increase SBAS coverage is to increase the number and extent of reference stations with known locations. Reference stations of the Russian System of Differential Correction and Monitoring (SDCM) and the Japanese geostationary MTSAT Satellite Based Augmentation System (MSAS) could also be included. Moreover, the current lack of land- and naval infrastructure in the Arctic region in addition to the fact that the region is difficult to access and is sparsely populated makes it well suited for space-based infrastructure (Aarmo 2012).

IV.V Sovereignty

Most of the Arctic nations' policies reflect an interest for clear definition and protection of their respective national boundaries (Polar View 2012). The United Nations Convention on the Law of the Sea (UNCLOS) governs this territorial definition, and GNSS technology is often used to measure and determine the borders within which a country is territorially sovereign. Within these borders it is in the interest of all states to manage the access of people and goods moving by sea, air, and over land. GNSS technology is therefore widely used for navigation of aircraft, vehicles, and border control vessels in order to protect a state's security and maintain its integrity. There is also the possibility of accidental incidents potentially causing disputes, in which case GNSS technology could be used to determine in which restricted area or jurisdiction the incident has occurred (Polar View 2012).

IV.VI Disaster Management and Search and Rescue

In addition to the necessary military border protection- and control, search and rescue is related to a high priority policy in GNSS technology, as it is necessary for GNSS position information to be incorporated into distress signals. This enables search and rescue operations to systematically navigate the areas from which distress signals were broadcast. Search and Rescue operations are currently most widely used in response to fishing activity (Polar View 2012). GNSS technology is also used for military training exercises and disaster response. The disaster response phase is the phase of disaster management for which GNSS technology is most commonly employed; Data collection and mapping applications, and real-time and post-disaster monitoring for planning and implementation of disaster recovery work utilize GNSS technology to optimize their efficiency. Military organizations also often support civil organizations in disaster preparedness, response, and recovery; the military typically has access to more accurate navigation data than civilian users.

There is currently ongoing research for very precise geodynamic measurements using GNSS technology, which may be used in the future to produce early warnings of imminent disasters such as tsunamis and earthquakes (Polar View 2012).

V. CHALLENGES OF GNSS AND SBAS AT HIGH LATITUDES

The Arctic landscape is featureless and lacks established routes, and is therefore very difficult to navigate without the aid of GNSS. The region is also without sun for half of the year and is characterized by rough weather and climate. There are, however, some challenges with activities that require GNSS availability in these extreme climatic operating conditions. For example, the most widely used GNSS system, the U.S. Global Positioning System (GPS), does not meet the integrity requirements for certain navigation applications in Arctic regions. GPS satellites are found in orbital planes that are inclined at 55 degrees with respect to the equator and can thus be seen only at low elevation angles in the sky in Arctic regions. The geometry is such that you can see many GPS satellites in the sky at once, more so than at lower latitudes, though you will only see them at low elevation angles, never overhead. This results in good horizontal positioning geometry but the vertical positioning geometry is reduced for Arctic applications (G. X. Gao et al. 2011). This will also be the case for the future European GNSS Galileo system which is in a 56° inclination orbit. The integrity limitations on these systems in Arctic applications are due in part to the inclination of these constellations but also to increased ionospheric activity at these high latitudes. The Russian GLONASS system was designed to support high latitude positioning due mainly to the Russian high latitude geography. The Russian GNSS Global'naya Navigatsionnaya Sputnikovaya Sistema (GLONASS), inclined at 64.8 degrees to the equator, is able to provide some Arctic coverage with the precision needed for high integrity activity such as dynamic positioning, vertical guidance approaches, search and rescue, and weapons targeting technology. GLONASS may therefore in the near future, until alternative systems become operable, "well become the only GNSS option in the Arctic." (Schrivastava 2011).

Although issues with GNSS technology do arise above approximately 70 degrees north latitude basic satellite navigation does work in the Arctic (Aarmo 2012). The main issue is that the Arctic region is in the periphery of the signals broadcast from the geostationary Space Based Augmentation Systems (SBAS). The limit of geostationary communication coverage limitation theoretically goes up to 80 degrees north, but problems, such as large errors in the position solution, have been registered to occur down to 72 degrees latitude (Aarmo 2012). Above this threshold there is also an increase in magnetic and solar phenomena that generally impose limitations on all communications equipment (H. A. Conley 2012).

While SBAS services provide crucial integrity data and improved accuracy for a variety of GNSS-based applications, it has now been outlined that these signals are unavailable in the Arctic due to a lack of communication and an inadequate number of reference stations, and the main challenges thus arise due to the consequent degradation of SBAS coverage and performance.

Figure 3 illustrates the current combined SBAS service coverage given by the three certified SBAS operational worldwide today: The European Geostationary Navigation Overlay Service (EGNOS), the U.S. Wide Area Augmentation System (WAAS), and the Japanese Multi-functional Satellite Augmentation System (MSAS).

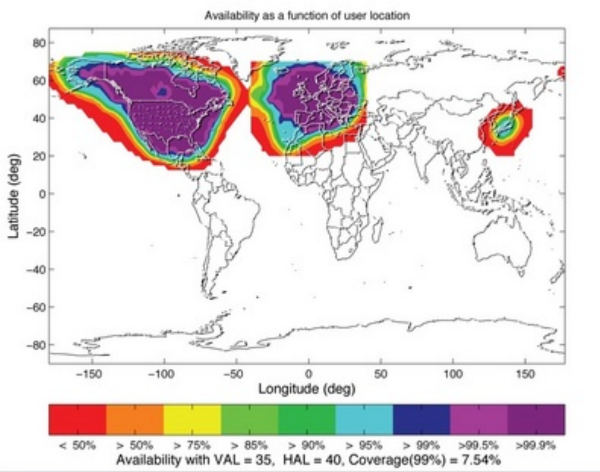


Figure 3: Current combined SBAS service coverage, showing availability as a function of user location. Courtesy of the European Space Agency.

Because the current systems do not provide coverage to meet the need for high integrity navigation in the Arctic as of today, future systems and services are currently being defined to solve these issues.

V.I Dual-Frequency

Additional SBAS systems, which are currently under development, offer to further improve the availability map shown in the above Figure 3. Future SBAS systems such as the Russian System for Differential Correction and Monitoring (SDCM) and Indian GPS Aided Geo Augmented Navigation (GAGAN) are currently under development and will come with them many more ground based reference stations in these geographic regions. In addition, GNSS systems of the future will broadcast on two separate frequencies, which further increases availability. These dual frequency systems are capable of protecting against ionspheric effects as well as offer protection against radio interference. The largest benefit of these dual frequency systems is that their availability can extend much farther away from the reference station network. An availability map that utilizes dual frequency GNSS as well the aforementioned 5 SBAS systems is shown in the figure 4 (T. Walter et al. 2010).

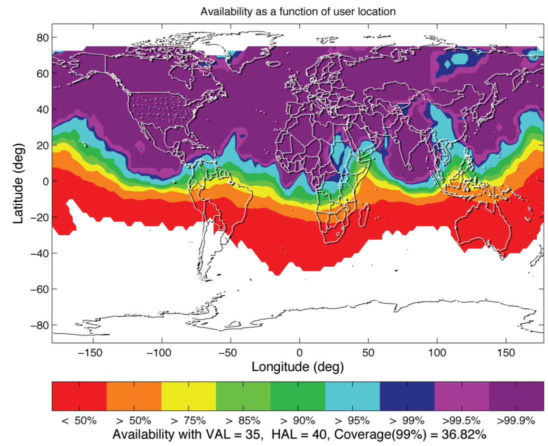


Figure 4: Future integrity availability service coverage including making use of dual frequency and WAAS, EGNOS, MSAS, GAGAN, and SDCM systems. Courtesy of the European Space Agency.

Although these improvements offer great potential for Arctic regions, there is still the problem of obtaining integrity data. As previously mentioned, geostationary satellites are not capable of broadcasting this data to arctic regions. It has been proposed that the existing Iridium constellation, a communcations satellite network consisting of 66 low Earth orbiting spacecraft in polar orbits, could be a sutable candidate to fulfill this role. As these spacecraft are in polar orbits, the geometry is such that there will always be several satellites in view at a given time in the Arctic circle. In addition, if the Iridium constellation had the capability of broadcasting ranging signals for navigation purposes, there would be better navigation geometry in the Arctic as this would add several satellites at higher elevation angles which would give rise to better vertical positioning geometry (G. X. Gao et al. 2011). The Iridium constellation is illustrated in Figure 5.

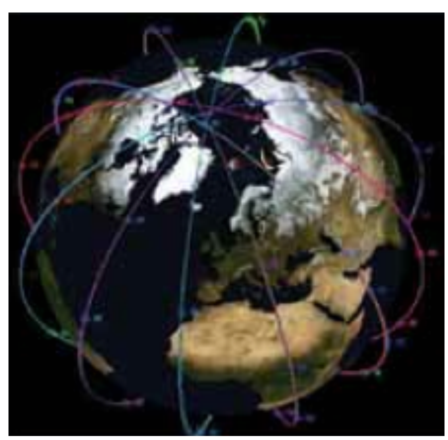


Figure 5: Constellation of Iridium satellites. Courtesy of Tyler Reid.

VI. SBAS STANDARDIZED SOLUTIONS

Finding a communication solution to the limitations on SBAS in the Arctic is critical, and it is important that such a system is standardized (Aarmo 2012). The SBAS Signal-In-Space Interface Control Document (ICD) (denoted RTCA/DO-229D) is responsible for the necessary documentation of the SBAS messages, and ICAO has adopted this standard as the aeronautical SBAS standard, which may readily be adopted by any state in the world. The main purpose of aeronautical SBAS is to provide near real-time GNSS integrity, differential corrections, ranging signals, and Safety-of-Life (SoL) service (J.L. Issler 2010).

VI.I Universal Space Based Augmentation System

(J.L. Issler et. al. 2010) proposed a generalized aeronautical GNSS Space Based Augmentation System in a worldwide multi-frequency, multi-modal future standard named Universal SBAS (U-SBAS), with the purpose to extend the current aeronautical SBAS such that it could be used in any region of the world and carry additional channels to enable services such as time authentication services, safety services, scientific application services, in addition to high precision positioning services.

VI.I.I U-SBAS Applications

The multi-frequency Universal SBAS standard would be applicable to a vast number of areas, including precise and robust positioning, timing, security, and science applications. In order to permanently cover the region for which the U-SBAS services are provided, geostationary orbits, inclined geostationary orbits, or highly elliptical orbits (HEO) are applicable. Satellite coverage using highly elliptical orbits is illustrated in Figure 6.

The Tundra Orbit first introduced by Russia is an interesting option in this context; The Tundra Orbit is a 24-hour period derivative of the 12-hour period Molniya orbit, meaning that it is capable of providing 24-hours coverage with a minimum of only two spacecraft (P. Fortescue 2011). In this context it is relevant to note that Canada is currently developing a Polar Communication and Weather (PCW) satellite system, which will achieve continuous Arctic coverage by operating two spacecraft in Molniya orbit (A. P. Trishchenko 2011). The system is planned to include an optional GNSS payload onboard. (J.L. Issler 2010). An SBAS system could piggyback on the launch of a mission such as the PCW.

Figure 6: A dedicated satellite constellation using Highly Elliptical Orbit (HEO) would take care of GNSS augmentation data broadcast as well as many other communications needs in the Arctic (A. B. O. Jensen 2010). Courtesy of the Canadian Space Agency (CSA).

V.II Compatibility and Interoperability

V.II.I Compatibility

The ICG (International Committee on Global Navigation Satellite Systems) Forum definition of compatibility is as follows: "Compatibility refers to the ability of global and regional navigation satellite systems and augmentations to be used separately or together without causing unacceptable interference and/or other harm to an individual system and/or service." This definition includes radiofrequency compatibility such as cross-correlation properties and affordable receiver noise floor, as well as spectral separation between authorized signals and other signals (International Committee on Global Navigation Satellite Systems 2011) (ESA 2011). Multi-GNSS compatibility is therefore a mandatory requirement to ensure the absence of harmful interference when the same frequencies are being shared, and there is a consensus amongst global and regional system providers that all GNSS signals must at the very least be compatible (Kaigisho 2011). In order to avoid modification of existing single frequency SBAS receivers, backward compatibility with current and validated L1 C/A SBAS aeronautical standards should be mandatory, and by ensuring automatic switching receivers, the cost of services could be greatly reduced (J.L. Issler 2010). A U-SBAS standard should be open and compatible with all GNSS systems potentially using L band, such as GPS/WAAS, Galileo/EGNOS, GLONASS/SDCM, COMPASS, and GAGAN, and services including robust governmental cryptography would be excluded (J.L. Issler 2010).

The main idea of U-SBAS outlined by (J.L. Issler 2010) is to "encapsulate" the aeronautical SBAS standard, and to provide services not covered by the present SBAS frame. By minimizing of the number of standardized modulations per frequency, more robustness to unintentional interferences and multipath can be achieved. However, there are only four bands that can support the navigation-only component of both aeronautical and non-aeronautical Safety-of-Life services, in addition to the SoL and non-SoL services themselves. At least one of the Medium Earth Orbit GNSS constellations (GPS, Galileo, GLONASS, COMPASS), is occupying each of these only four Aeronautical Radio Navigation Service/Radio Navigation Satellite Service (ARNS/RNSS) bands, and therefore, to ease compatibility with signal processing receivers, it was suggested by (J.L. Issler 2010) that any universal SBAS overlay one or, preferably, 2 or 3 of the MEO systems, and that at least one of the selected bands of a U-SBAS system should be part of the ARNS bands of the corresponding GNSS MEO system. The aforementioned bands are located between 1164 - 1188 MHz, 1188 - 1215 MHz, 1559 - 1591 MHz, and 1591 – 1610 MHz, respectively.

V.II.II Interoperability

Interoperability is often separated into system interoperability and signal interoperability, both subject to the ICG Forum definition, which states that interoperability "refers to the ability of global and regional navigation satellite systems and augmentations and the services they provide to be used together to provide better capabilities at the user level than would be achieved by relying solely on the open signals of one system." (ESA 2011). I.e. at a system level, any GNSS receiver should be able to provide the same navigation solution, within the respective system accuracy, as any other GNSS receiver, whereas signal interoperability would allow GNSS receivers to use signals from other GNSS systems, demanding from all system providers that signals are similar enough in terms of time, geodetic reference frames, carrier frequency, and Signals-in-Space (SiS). At the Sixth Meeting of the ICG on 9 September 2011 in Tokyo, it was specifically recommended by WG-B (Working Group B) that navigation message content in the L5 signals should be optimized to achieve "the highest possible level of multi-GNSS interoperability", and one given example was the Federal Aviation Administration (FAA) inclusion of Advanced Receiver Autonomous Integrity Monitoring (ARAIM) Integrity Support Message parameters in SBAS L5 (Kaigisho 2011). Optimization of the L5 signal in the sense of navigation data messages could further be extended to include all new signals coming from GPS, Galileo, GLONASS, COMPASS, and other GNSS service providers.

During the same meeting, the benefits of interoperable multi-constellation GNSS for maritime applications were outlined by (Klepsvik 2011), based on the aforementioned fact that major oil and gas discoveries have recently been made in critical ecological areas in the Arctic. This poses several challenges due to the severe lack of ground infrastructure for navigation, communication, and surveillance in this environmentally sensitive region. In order to provide a safe and environmentally friendly exploitation and transport of oil and gas resources, it is crucial to be aware of the existing technology gaps which still remain to be filled (Klepsvik 2011). In 2010, the MarSafeNorth-project concluded that "GNSS will work fine in the Arctic areas most of the time", and that "some degradation due to ionospheric scintillations has to be expected." One solution to minimize this problem is to combine GPS, Galileo, and GLONASS in two, or multiple, frequency and orbit/clock solutions. It was also concluded that "Both public and commercial orbit/clock dGNSS (differential GNSS) corrections will apply to all Arctic areas, but availability of the correction signals is limited." (Klepsvik 2011). Figure 7 illustrates an example of GPS vs. GPS+GLONASS.

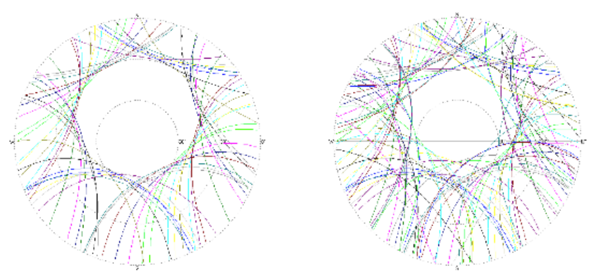


Figure 7: Example of satellite trajectories (groundtracks) at high latitude (75°N) using GPS only (left) vs. GPS+GLONASS (right).
Plots generated by use of GeoSky II (Fugro). Courtesy of (Klepsvik 2011)

VII. THE GNSS TECHNOLOGY EVOLUTION AND PREFERENCES

The technology evolution trend is toward highly digital and flexible GNSS receivers, and the current EGNOS signal has been validated in the same manner as the GPS and GLONASS Course/Acquisition (C/A) codes in the ICAO Standard and Recommended Practices for compatibility (J.L. Issler 2010). Russia promotes governmental users to be mandatorily equipped with GLONASS/GPS receivers, whereas the preferred solution for the Republic of China is COMPASS compatible GNSS receivers. Europe generally prefers GPS/Galileo compatibility, and the U.S. is expected to promote a symmetrical situation with GPS and Galileo (J.L. Issler 2010). Japan is currently planning to expand the bandwidth of their Multi-functional Satellite Augmentation System (MSAS) to include a Sub-meter class Augmentation with Integrity Function with compatibility with ICAO Standard And Recommended Practices (SARPs), and Japan will continue to keep the interoperability at a higher level for all user communities (Japanese Aerospace Exploration Agency (JAXA) 2010) In addition, both Malaysia and Korea are currently investigating the development of space-based augmentation systems (Polar View 2012).

VII.I Scientific Applications

Another interesting aspect of a Tundra Orbit SBAS system is the potential it brings for scientific study of the ionosphere, operational ionospheric applications, and operational precise positioning and timing applications (J.L. Issler 2010)

As previously mentioned the Arctic region is similar to the Antarctic and Equatorial region as it is subject to large-scale ionospheric scintillations that degrade GNSS signals. Though it was argued in (Klepsvik 2011) that a combination of GPS, GLONASS, and Galileo signals would minimize the problem, there are some other innovative solutions currently being investigated (Polar View 2012).

Most science space missions primarily serve weather and climate change applications, and the application of GNSS in this context is usually limited to the positioning of in situ sensors that collect weather and climate data. A drawback in this context is that space-based weather observation platforms are usually geostationary in near-equatorial orbits, and therefore unable to provide data on the high-latitude atmospheric conditions of the northerly remote areas of Canada and Europe, as these areas consequently end up on the periphery of these satellites' field of view (Polar View 2012). However, it is possible to complement the already available signals from GNSS satellites in Medium Earth Orbits with spacecraft in Tundra Orbits which employ quasi-stationary multi-frequency SBAS signals in order to fine-monitor the low temporal variations of the ionosphere. In Arctic regions, ultraviolet auroral imaging could be used in conjunction with a triple –or multi-frequency GNSS payload onboard SBAS spacecraft in a Tundra Orbit to obtain accurate measurements of the second order terms of the ionosphere (J.L. Issler 2010). While first order terms can be used to produce TEC (Total Electron Count) maps revealing small structures in the ionosphere, second order terms can significantly enhance real-time information on the location of the ionospheric irregularities. These observations can be made available thanks to the sufficient "quasi-fix" terrestrial reference frame that Tundra orbits provide, and severe ionospheric irregularities can be uncovered; The large-scale scintillations causing these irregularities can be thousands of kilometers in extent in this region (J.L. Issler 2010).

Another phenomenon that can be investigated using multi-frequency links is the polarization of the signals received, and thereby the Faraday effect, inked to the terrestrial magnetic field (J.L. Issler 2010).

Not all scientific applications of GNSS are space based. For example, the now famous experiment conducted by the OPERA collaboration at the European Organization for Nuclear Research (CERN) on the French-Swiss border and at Italy's Gran Sasso National which had early results of neutrinos moving faster than the speed of light was made possible by the precise timing provided by the GPS constellation which was used to calculate their speed over the known distance between the two research centres. Although these results were incorrect, this was due to a faulty wire and not to the satellite constellation (A. Boyle 2012).

VIII. CONCLUSION AND FURTHER RECOMMENDATIONS

The current SBAS systems: EGNOS, WAAS, MSAS, and GAGAN operate in geostationary orbits, and may therefore experience reduced availability and continuity due to shadowing or the so-called urban canyon effect where tall buildings in major cities act as major obstacles for the transmitted signals in areas where the Geo satellites are seen as low in the horizon. Alternative solutions have been proposed to solve this challenge; The network of ground reference stations could be extended, and low-earth-orbit (LEO) systems such as Iridium could be utilized. Several independent studies have indicated that using a constellation of highly elliptical orbit satellites, in a Molniya or Tundra orbit, would be a much-preferred solution.

In order to maximize benefit to all GNSS users globally and in particular in developing regions, open signals and services should be interoperable to the maximum possible extent. Although the ICG is not binding on states, YGNSS sees the Arctic as a promising and interesting region in which the systems and infrastructure must develop by cooperation of states, as it is at a high altitude where compatibility and interoperability of systems is in demand to ensure the link between different systems to optimize user performances. The coverage area for the different SBAS systems meets in the Arctic, and it is therefore a must to ensure interoperability to facilitate seamless operations in these areas.

Furthermore, the needs and scope of applications must be defined on multilateral GNSS compatibility. Based on the recommendation of the International Committee on GNSS Working Group B, research on a consensus on the definition of broadcast parameters necessary to enable multi-constellation ARAIM is encouraged. In order to achieve the most benefit for GNSS and SBAS key user groups, as well as industry and system providers, any opportunities of spare capacity of the respective navigation messages should be identified. The Seventh Meeting of the International Committee on GNSS is scheduled for November 5 – 9 2012 at the Beijing International Convention Center (BICC), and is expected to bring GNSS and augmentation providers further together.

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