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CLOSING THE ARCTIC INFRASTRUCTURE GAP: EXISTING AND EMERGING SPACE-BASED SOLUTIONS

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Summary

Since the acquisition of Alaska, the United States has been an Arctic country. Politically, governance in the Arctic comprises the "Arctic Five" or countries with Arctic coastal areas, including the United States, Russia, Canada, Norway, and Denmark (Greenland). As a country with territorial claims north of the Arctic Circle at 66.3˚ North, the United States has political, economic, national security, environmental, and cultural interests across the region. Protecting these interests while supporting international cooperation has become increasingly complicated as the retreat of sea ice and warmer temperatures have expanded human activity in the region. Previously unnavigable land and ocean surface routes and coastal harbors have become available for shipping, resource extraction, and industrial development. Increased activity in these extreme northern latitudes has fueled demand for communication, navigation, and surveillance infrastructures to serve commercial, civil, and military needs.

This paper provides an overview of U.S. Arctic policy and national interests and of the rapidly changing conditions in the region. It also describes how commercial satellite services can support Arctic stakeholders needs for faster and ubiquitous communications, timely domain awareness, and an improved means to accurately navigate and observe the region's rapidly changing conditions. By fully optimizing existing and future space-based infrastructure, using low Earth, geosynchronous, and highly elliptical orbits, the United States can work cooperatively with other Arctic nations to build situational awareness, enhance operations, and strengthen a common rule-based order.

Introduction

Approximately four million people live above the Arctic circle. While it is one of the most sparsely populated places on the planet and a remote region known for cold and harsh conditions, there is a growing demand for infrastructure in the Arctic. Facilities and services for space infrastructure in particular are not as available at parity as at lower latitudes. Closing this infrastructure gap will serve the United States on several strategic fronts, including national security, economic, environmental, cultural, and international cooperation.

Fortunately, the polar region is developing at a time when the space industry is moving from government-sponsored efforts to more commercial enterprises. The market momentum provided by commercial proliferated low Earth orbit (LEO) constellations, as well as geostationary equatorial orbit (GEO) and highly elliptical orbit (HEO) satellites, will contribute to closing this infrastructure gap. These capabilities are further enhanced through network convergence, data sharing and fusion, and greater situational awareness, whereby stakeholders gain a broader, more insightful picture of the region.

There is a growing sense of urgency as the changes in the Arctic are accelerating at a time when the United States needs to advance security interests, pursue responsible regional Arctic stewardship, and work closely with our international allies to protect the Arctic environment. The 20 million square kilometers around the North Pole are experiencing the effects of a warming climate even faster than the rest of the Earth. Surface air temperatures in the Arctic are rising at twice the rate relative to the rest of the planet, resulting in widespread permafrost melting.[1]

In the summer of 2019, the world experienced the first ever recorded opening of both potential Arctic Ocean routes. (see Figure 1). This has been possible because sea ice, which plays an important role in the Arctic system, is melting quickly. Since 1979, when data was first collected from passive microwave sensors onboard satellites, scientists have observed a steady decline in the extent of sea ice—approximately 12.8 percent decline per decade (measured during September).[2] Moreover, the quality of Arctic sea ice has declined; thick multi-year ice now accounts for only a small fraction of the summer ice coverage. Sea-ice loss models have predicted that the summer Arctic Ocean could be ice free as early as 2030.[3]

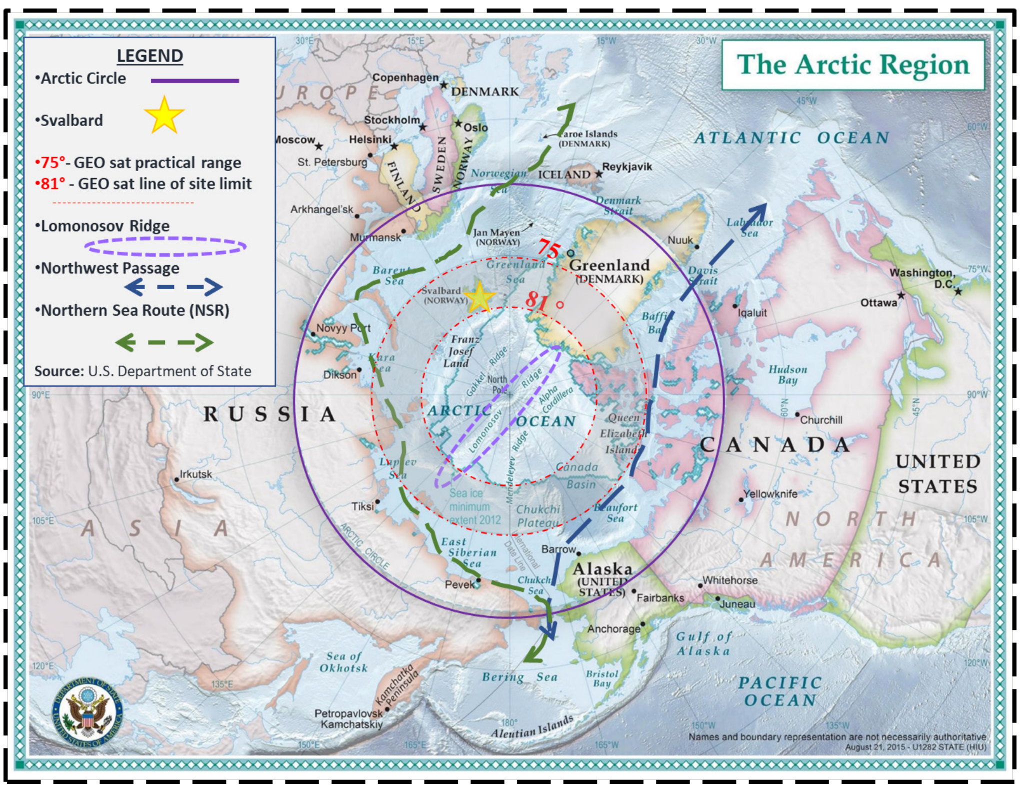

Figure 1: The Arctic Region. *The area north of the Arctic Circle (66.3° north latitude) includes vast expanses of ocean, ice, and some landmasses—including hundreds of major islands, thousands of minor islands, and the coastlines of five countries.*

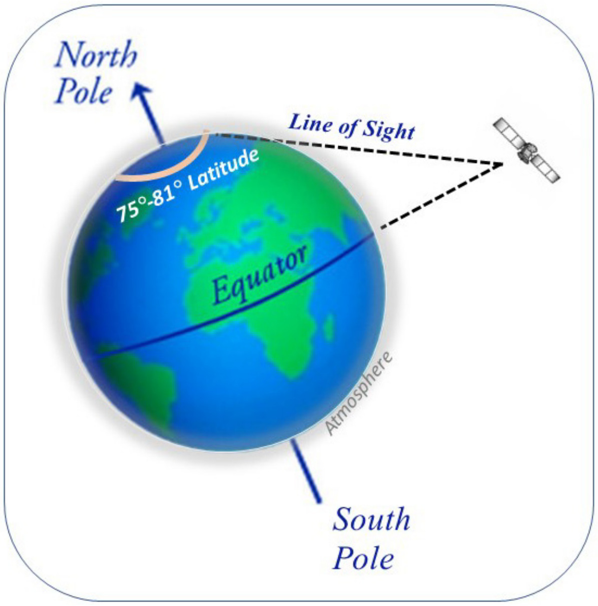

Figure 2: GEO Satellite Line of Sight. *Satellites in GEO cannot provide coverage beyond 81°3' maximum latitude; at this point a geostationary satellite is below the local horizon. At a practical level, a GEO satellite's operational limits are several degrees lower due to receiver noise from atmospheric refraction, frequency interference due to Earth's thermal emission, line-of-sight obstructions, and interference from signal reflections with ground structures.[5] While configurations of land-based antennas and the beam-steering capabilities on some GEO satellites can improve GEO performance between 60° and 80°, serious challenges exist for areas approaching 80° latitude.[6]*

Background

Governance

The Arctic Ocean is largely governed by United Nations Convention on the Law of the Sea (UNCLOS), adopted in 1982. Politically, governance in the Arctic comprises the "Arctic Five" countries with Arctic coastal areas, including the United States, Russia, Canada, Norway, and Denmark (Greenland). UNCLOS specifies that these countries have claims in the Arctic Ocean up to a maximum of 200 nautical miles beyond their territorial baselines, known as the *exclusive economic zone* (EEZ). U.S. territorial waters and the exclusive economic zone account for approximately one million square miles.[4]

The addition of three other countries with land inside the Arctic circle but without Arctic Ocean coasts, Iceland, Sweden, and Finland, make up the "Arctic Eight." These eight countries are permanent Member States of the Arctic Council, which was established by the 1996 Ottawa Declaration to promote cooperation, coordination, and interaction. In addition to the permanent Member States, other countries (mid-latitude states), and notably China, are accorded Observer status and six Arctic indigenous communities have Permanent Participant status, which includes full consultation rights in connection with the council's negotiations and decisions. Approximately half of the Arctic population (two million) lives in Russia, which generates, depending on oil prices, between 24 and 30 percent of its gross national product (GNP) from its Arctic territory. By contrast, fewer than 68 thousand Americans live above the Arctic Circle—and Alaska generates only 0.3 percent of U.S. GNP annually.[7] Even though the direct stakes may seem comparatively low for the United States, the strategic importance of the Arctic cannot be underestimated. The polar region's biodiversity, increasing importance for shipping routes, and natural resource capacity are immense. Russia and China are proactive as they assert their interests in the region. Russia for instance has extended its continental shelf claim (see "Arctic Territorial Claims" sidebar) and has increased its military presence around the Arctic Ocean. Meanwhile China, a self-declared "Near-Arctic State," has ambitiously pursued plans for the "Polar Silk Road." Both Chinese ambitions and Russian territorial claims and strong military presence in the Arctic are even more concerning as these two countries collaborate, across diplomatic, economic, and security areas.[8] For example, Russia remains a top source for Chinese energy imports, and China has demonstrated a financial commitment to Russia's economy.

The pace of growth of human activity in the Arctic is astounding and the scramble to gain access to the

Arctic Territorial Claims

The United Nations Convention on the Law of the Sea (UNCLOS), or "the convention," establishes territorial seas extending 12 nautical miles from the "baseline" (coastal low tide), exclusive economic zones extending to 200 nautical miles, requirements for nations to work together to conserve high seas fisheries, and a legal regime for the creation of mineral property rights discovered beneath the ocean floor. Each of the Arctic nations has ratified the UNCLOS except for the United States. Some argue that joining the convention will serve national interests allowing the United States to exploit mineral and petroleum reserves and that the convention "improves access rights in the oceans for our armed forces, reducing operational burdens and helping avert conflict."[10] Others argue that ratifying the Convention offers few benefits and that the treaty's litigation exposure and impositions on U.S. sovereignty could outweigh any potential benefits.[11] Still others dismiss the debate completely by arguing that the United States abides by the principles of UNCLOS without ratification.

UNCLOS, Article 76, "Definition of Continental Shelf," allows signatory countries to establish the outer limits of their continental margins, which may in some cases go beyond the 200 nautical miles established for their EEZs. Article 76 opens the door to "interpretation" and potential bias as signatory countries are eager to claim more territory. Consequently, some Arctic states, including Russia, have been busy conducting bathymetric and geodetic surveys to define the outer limits of their continental shelf.

The region closest to the geographic pole, where the Lomonosov Ridge lies, is currently in dispute because of poorly mapped sea floor geography and the presence of unclaimed areas outside of the usual EEZs. The Lomonosov Ridge presents some difficulty because the actual dimensions and extent of the ocean floor contour of the ridge are unknown. In August 2007, two submersible vessels planted a Russian titanium "flag" on the seabed at the North Pole. Russia claims that the ridge extends continuously to the pole from Russian territory, which they believe justifies a territorial claim. This view is not agreed upon by all Arctic states, however. Improved bathymetric data and ocean floor mapping will be required to resolve the uncertainty.

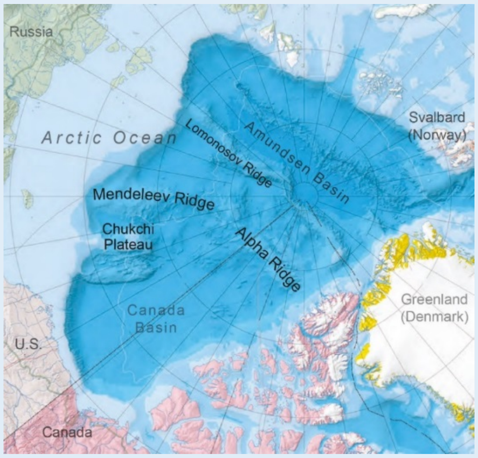

Figure 3: Arctic Ocean. *Base map from North Circumpolar Region (2008) (Source: Atlas of Canada, Natural Resources Canada)*

region's resources has reached a fevered pitch. Recently, during a May 2019 Arctic Council meeting, U.S. Secretary of State Mike Pompeo noted "We're entering a new age of strategic engagement in the Arctic, complete with new threats to the Arctic and its real estate, and to all of our interests in that region."[9]

Increasing Arctic Activities

A Wealth of Resources

"Rapid loss of Arctic sea ice and other changes will also bring new access to the Arctic's natural resources such as fossil fuels, minerals, and new fisheries, and this new access is already attracting international attention from industry and nations seeking new resources."[12]

The Arctic contains a wealth of natural resources that have avoided exploitation due to their remote geography and harsh conditions. Large areas of the Arctic's land and ocean are underlain by enormous mineral resources estimated to make up a large amount of the world's undiscovered hydrocarbons, including 16 percent oil, 30 percent gas, and 26 percent natural gas liquids.[13] Fisheries, fresh water, and excellent hydropower opportunities are also present. More recently, the consistently cool climate is attracting giant data centers to Arctic regions in Norway, Sweden, and Finland, where cold seawater is channeled to cool massive heat-generating server farms, saving millions in utility expenses.

Increased Maritime and Aviation Traffic

The Arctic is experiencing increased aviation and maritime cargo traffic, passenger ship and air traffic, adventure tourism traffic, oil and gas exploration, and research and scientific activities.[14] Shipping companies use well-established routes—the Northern Sea Route (NSR) and the Northwest Passage—which connect the North Atlantic to the North Pacific (see Figure 1). Until recently, these routes have been little used because of the presence of year-round sea ice. Theoretical time and fuel savings from cross-polar transportation provide significant economic and logistical incentives to commercial shipping; ships that cross the Arctic might use only two-thirds of the fuel of ships that use the Panama Canal.[3]

According to Business Index North, funded by the Norwegian Ministry of Foreign Affairs, shipping volume has increased dramatically along the NSR—more than doubling between 2017 (10 million tons) and 2018 (20.1 million tons). Most of the cargo consists of crude oil and liquefied natural gas (LNG).[15] Russia's Ministry of Transport forecasts that the NSR's cargo turnover will increase to 72 million tons by 2020 and that Russia will invest $11 billion to expand and improve ports, access roads, sea channels, and ice protection facilities.[16] Russia's NSR infrastructure expansion does not come without controversy. France's President Macron expressed concern over the impacts to the environment and natural ecosystems and has asked container lines to avoid using new Arctic shipping routes. The largest container line, A.P. Moller-Maersk A/S, completed a successful test run during September 2018; however, Maersk noted that the NSR is not currently commercially viable.[17] Regardless, if the ice continues to melt, the NSR may become the most expeditious path between Asia and Europe.

In addition to shipping traffic, air traffic has also increased as the aviation sector has grown more confident operating in Arctic airspace. Development of cross-polar routes began in the early 1990s when the Russian government worked with the international community on defined cross-polar routes. As a result, hundreds of flights now operate each week, in Russian airspace en route between North America and Asia, and they often save significant time and fuel compared to traditional lower latitude journeys.[18] Similar to the maritime sector, aeronautical activities need enhanced connectivity, including flight management tracking, search and rescue operations, and broadband data communications for crew and passengers.

NOAA's Arctic Report Card notes that the Arctic climate is "no longer returning to the extensively frozen region of recent past."[19] Responding to the new Arctic condition, Russia has been investing heavily in the NSR, which they expect to be navigable year-round. The Russian military is also planning to replenish their communication constellation which provides continuous coverage of northern latitudes.[20] As Russia expands its activities and its presence in the Arctic, the United States should consider how best to assert and safeguard western interests in the region. U.S. Coast Guard Commandant Admiral Karl Schultz noted during a security conference in May 2019 that "We're championing increased capabilities in the Arctic, we're championing better communications, better domain awareness, we're talking about innovation, we're talking about resiliency, we're talking about rule-based order."[21]

Great Power Competition

Given Russia's significant and long-established stake in the region, it is no surprise that Russia has significantly increased shipping traffic through the NSR. Russia's Arctic activities are proportionate to its enormous territory and economic resources in the region. Still, concerns remain. In July 2019, Air Force Gen. Terrence O'Shaughnessy, commander of U.S. Northern Command, noted that "if you look at the northern approaches through the Arctic, that's a key avenue of approach that we have to be able to defend." He also identified cruise missiles by way of the Arctic "as one of the biggest threats that we face."[22] Russia is also ambitiously mapping the ocean floor, with the intent to extend its territorial claims based upon what they perceive as an extension of their continental shelf area (see the "Arctic Territorial Claims" sidebar).

Additionally, China's increasing prominence has caused many to worry about their longer-term intentions. China has declared itself a "near Arctic state," an informal self-designation but gained a formal designation as permanent observer at the Arctic Council in 2011.[23] As part of a larger strategy to increase access to global natural resources, China's President Xi Jinping expressed in January 2018 that China would encourage enterprises to build infrastructure and conduct commercial trial voyages, paving the way for Arctic shipping routes that would form a "Polar Silk Road."[24]

U.S. Policy Responses

Recognizing this changing environment and rising competition, the United States has defined its strategic and commercial interests in the Arctic through a series of laws and policies—each building upon previous policy strategies. In January 2009, near the end of President George W. Bush's second term, the White House issued the *National Security Presidential Directive 66/Homeland Security Presidential Directive 25* (NSPD 66/HSPD 25). This Arctic policy directive laid out six key objectives:

1. Meet national security and homeland security needs relevant to the Arctic region.

2. Protect the Arctic environment and conserve its biological resources.

3. Ensure that natural resource management and economic development in the region are environmentally sustainable.

4. Strengthen institutions for cooperation among the eight Arctic nations (the United States, Canada, Denmark, Finland, Iceland, Norway, the Russian Federation, and Sweden).

5. Involve the Arctic's indigenous communities in decisions that affect them.

6. Enhance scientific monitoring and research into local, regional, and global environmental issues.[25]

Four years later, the Obama administration released another directive, the *National Strategy for the Arctic Region* (May 2013),[26] which cites the earlier NSPD 66/HSPD 20 directive and notes that its objectives are "in furtherance" of the strategic priorities set forth by the previous administration. The Obama administration's directive was intended to position the United States to respond effectively to challenges as well as economic opportunities. The directive outlines three driving principles:

- **Advance U.S. Security Interests.** Enable vessels and aircraft to operate consistent with international law and through, under, and over Arctic airspace and waters. Support lawful commerce, achieve greater situational awareness of activity in the region, and intelligently evolve Arctic infrastructure and capabilities, including ice-capable platforms as needed.

- **Pursue Responsible Arctic Region Stewardship.** Protect the Arctic and conserve its resources, establish and institutionalize an integrated Arctic management framework, chart the Arctic region, and employ scientific research to increase understanding of the Arctic.

- **Strengthen International Cooperation.** Working through bilateral relationships and multilateral bodies, including the Arctic Council, pursue arrangements that advance collective interests, promote shared Arctic state prosperity, protect the Arctic environment, and enhance regional security.

While the current administration has not issued a presidential-level strategy or directive on the Arctic, expanding on prior Arctic-based presidential directives, the DOD recently described a "desired end-state for the Arctic"—a secure and stable region where U.S. national interests are safeguarded, the U.S. homeland is defended, and nations work cooperatively to address shared challenges."[27] The 2019 *Department of Defense Arctic Strategy* outlines three strategies to build Arctic awareness, enhance Arctic operations, and strengthen the rule-based order of the Arctic. Recognizing the evolution of these broad policies, Victoria Herrmann, president and managing director of the Arctic Institute (Washington, D.C.), notes that DOD's Arctic strategy is "almost a summary of what we have been talking about informally in D.C. and in the military community for a few years."[28]

Closing the Infrastructure Gap: The Role of Space Capabilities

The entire spectrum of increasing human activities in the Arctic—of which transportation and resource extraction are only a part—is spurring demand for connectivity, geolocation, and situational awareness applications. In light of the policy direction to intelligently evolve Arctic infrastructure and capabilities, space-based infrastructure will be critical to advancing the United States' communications and domain awareness in the region. This section examines existing challenges and needs across three main satellite applications: communications; positioning, navigation and timing (PNT); and Earth observation (EO).

Satellite Communications and Connectivity—Existing and New Services

Communication satellites provide critically needed broadband data connectivity in remote locations where terrestrial fiber optic infrastructure is scarce or nonexistent. They relay important scientific data for modeling interactions within the natural Arctic environment, provide critical search and rescue functions, deliver telemedicine and educational connectivity to remote communities, and help close the digital divide for Arctic residents.

As discussed in the previous section, increased aviation and maritime traffic will fuel demand for connectivity. The fastest growing segment of the maritime market is luxury cruise ships, carrying thousands of passengers and crew, many with expectations for onboard broadband capacity similar to their land-based experience. In addition to broadband connectivity, increased maritime activity in all segments will spur demand for search and rescue services and mobile communications.

Projected Capacity Growth

The range of available space-based connectivity solutions is expanding globally, including new options for the polar region. Euroconsult, a space industry consulting firm, found that global capacity supply is projected to grow eight-fold between 2017 and 2022. However, that report focused on a belt between 50° north and south latitudes and did not address the Arctic region. The projected growth in satellite communications globally is largely due to new low-cost capacity from very high throughput satellite (VHTS) systems and emerging constellations providing nongeostationary orbit (NGSO) broadband, referred to as proliferated LEOs (pLEOs).[29]

Many of the pLEO constellations are intended for polar orbit or high inclination orbits, which makes it possible for the polar region to gain coverage and service availability should these planned constellations become operational. This means that strategically located ground stations in both the north and south poles will play pivotal roles for satellite control and data connectivity. Svalsat, for instance, operated by Kongsberg Satellite Services (KSAT), is the largest ground station in the world. SvalSat is located on an island in the Norwegian archipelago known as Svalbard. (see Figure 1). This enormous ground station, comprising over 100 antennas, is ideally situated at a high enough latitude to see every polar orbiting satellite from all 14 daily transits of polar-orbiting satellites (altitudes usually range from 700 to 800 km, with orbital periods of 98 to 102 minutes).

Existing Satellite Communication Services

How will the growth in satellite numbers and capacity impact the Arctic region? Existing constellations in LEO are already serving some needs in the Arctic region, albeit with limited bandwidth and speeds (see Appendix A), although there is currently no true two-way, high-speed, low-latency broadband satellite-based service available above 81 degrees. This will change as new pLEO operators, such as OneWeb, Telesat, and SpaceX "Starlink," enter the market and introduce satellites in polar or near polar orbits (see Appendix B).

The summary below provides an overview of existing satellite services that offer various types of connectivity to address a diverse range of fixed and mobile user needs.

Existing Fixed Satellite Services

Various end-to-end service providers manage multi-technology network portfolios for C, Ku, Ka, and L-band GEO connectivity. These service providers optimize antenna installations to accommodate a high view angle to extend GEO coverage to northern latitudes. At this point, there is still no true polar coverage and most GEOs cease to operate well below the line-of-sight limit of 81°3' latitude. Broadcasting is typically available from one or more GEO satellites up to around 75° north. These fixed satellite services can benefit from strategically positioned parabolic dishes on buildings and poles to overcome obstructions from a low angle field of view.

Very small aperture terminals (VSAT) systems (two-way satellite ground stations with a dish antenna) have coverage similar to broadcast services. Fixed users might be able to access service up to around 80° north for broadband coverage, but VSAT systems typically do not allow coverage above 75° north. The VSAT market is very competitive. Providers must differentiate themselves based upon data speeds, capacity, technological features of products and services, ability to customize networks, and customer service. VSAT providers include companies like: Echostar (Colorado), Gilat Satellite Networks Ltd (Israel), ViaSat (California), Newtec (Belgium), and VT Systems (Virginia).

Existing Mobile Satellite Services (MSS)

Although not a true broadband provider due to lower data rates than conventional providers, IridiumNEXT's LEO constellation is the only current MSS provider with true polar coverage. Inmarsat's GEO bent pipe[30] reaches impressive latitudes. Through Inmarsat's five GEOs in the L-band network, Inmarsat provides Global Xpress availability up to 76° north, at a 5° look angle. Inmarsat provides data rates up to 432 kbit/s through its FleetBroadband service, which serves passenger ships in polar regions.

Existing LEO Connectivity Services

Existing LEOs are now providing limited data and connectivity services in the Arctic region. Appendix A lists four existing LEO providers in polar or near-polar orbit. For instance, if users can tolerate data latency, they may find that Kepler Communication's two-CubeSat constellation might work well, providing high bandwidth data speeds at high latitudes, but each satellite offers windows of connectivity only every 90 minutes, during a short time when the CubeSat flies over the polar region.

New Entrants (GEOs, LEOs, pLEOs and HEOs)—Closing the Gap

Due to the increased interest and activity from commercial communications and connectivity providers, both terrestrial and satellite based, Arctic stakeholders can benefit from the existing commercial market forces at play and the diversity of new providers entering the Arctic market.

New Players—GEO for Niche Markets

A GEO satellite keeping orbital station over the equator is not the first solution that comes to mind when considering far-Northern Arctic communications. However, a GEO with appropriate longitudinal alignment can offer impressive reaches to northern latitudes. Pacific Dataport (Alaska), as an example, plans to address the underserved Alaskan market, including the Aleutian Islands, as well as portions of the Arctic up to 75° north latitude by providing broadband Internet capacity with a GEO Ka-band high throughput satellite (HTS) system. Pacific Dataport plans to launch two small GEO (300 kg) satellites in optimal orbit locations to achieve the requisite capacity, diversity, and redundancy for its target markets. The first of these satellites is under construction and scheduled to be launched in Q4 2020. This may represent a new trend toward smaller, less expensive GEOs, which can target niche sectors and regions. Pacific Dataport plans to launch a much higher capacity satellite with complementary coverage in Q4 2022.

New Players—pLEOs and HEOs

There are a number of new LEO, medium Earth orbit (MEO), or HEO systems in various stages of planning and implementation, collectively forecasted to account for a significant portion of the global satellite capacity and of equipment unit shipments to broadband satellite sites, platforms, and subscribers. The commercial space industry has proposed approximately 20,000 satellites, mostly in LEO orbit. However, they face various challenges as they design, fund, build, obtain permits, coordinate launch, and successfully deploy and operate such constellations. While it is reasonable to assume that not all proposed satellites and satellite constellations will make it to orbit, most industry analysts still agree that satellite capacity will increase dramatically over the next few years as some of the proposed systems become operational.

While the Arctic region stands to benefit from this surge of new space activity, most non-GEO satellite constellations are focused on geographic markets at mid-latitudes, where higher population concentrations exist (see Figure 4). Out of the five LEO constellations listed in Appendix B, OneWeb and SpaceX Starlink have already started to launch and deploy satellites. OneWeb expects to offer high-speed, low-latency Internet service in the Arctic region during 2020 as it plans to deliver 375 Gbps of capacity above the 60th parallel North.

Starlink's initial deployment of 1600 satellites will orbit at 53° inclination and will not cover the Arctic.[31] Later deployment phases will include high-inclination orbits (70°, 74°, and 81°). Appendix B does not include other proposed constellations that do not provide line-of-sight (LOS) coverage for the Arctic region (e.g., O3B's Mpower system or Amazon's planned pLEO).

Inmarsat (UK), a global mobile satellite communications provider that operates 13 GEO satellites, intends to introduce two new satellite payloads in partnership with Space Norway in 2022 that will be dedicated to the Arctic region.[32] These payloads will provide high-speed mobile broadband services in the Arctic for its Global Express (GX) customers—primarily serving merchant fleets, fishing vessels, commercial airlines, the energy sector, and government customers for tactical and strategic communications. The new GX Arctic payloads (GX10A and 10B) will be placed into highly elliptical orbits (HEO) to provide continuous coverage above 65° north and will have the ability to direct capacity in realtime to the areas of highest demand. Inmarsat has indicated that these payloads are scheduled to launch during 2022.

With growing communication needs of the northern region, Russia is also planning to replenish its next

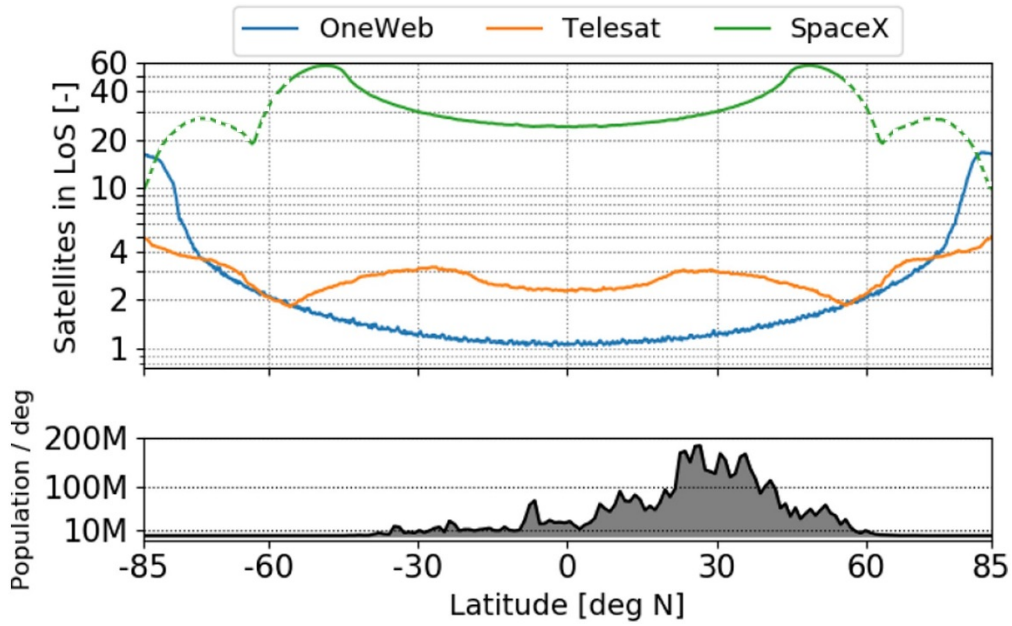

Figure 4: Satellites in Line of Sight (LOS) – Latitudes and Populations: *There are great differences between future planned pLEO constellation providers regarding the number of satellites within LOS for different latitudes. SpaceX's initial deployment of 1,600 satellites will not provide polar coverage (solid green line). Later deployment will include high inclination orbits which will provide polar coverage (dotted green line). Source: Adapted from del Portillo, I., Cameron, B.G. and Crawley, E.F., 2019. "A technical comparison of three low earth orbit satellite constellation systems to provide global broadband"; Acta Astronautica, 159, pp. 123-135*

generation military communication satellites operating in a HEO Molniya orbit.[33] This constellation, comprising Meridian communication satellites, is optimized for the northern hemisphere, including covering Russia's northern landmass and the Arctic Ocean.

Positioning, Navigation, and Timing (PNT)

Global Navigation Satellite System (GNSS) services of the type pioneered by the U.S. Global Position System (GPS) constellation have become indispensable to navigation, tracking, and communication infrastructure in the modern global economy. South of the Arctic circle, GNSS infrastructure provides precision (PNT) services with high accuracy, availability, continuity, and integrity. However, in the Arctic region, GNSS service suffers from decreased performance, which inhibits safe sea and air navigation.

While the Arctic user population is small, it includes both permanent and transient inhabitants that require access to PNT services. The transient population (in particular, cross-polar aviation, sea shipping companies, and cruise ships) require high integrity navigation. Precision PNT is also vital for accurate surveying, mapping (see "Territorial Claims and Land Disputes" sidebar), and scientific research.

Existing PNT Limitations

GNSS – High Latitude Limitations

Following GPS, three other agencies have deployed global GNSS constellations including Galileo (EU), GLONASS (Russia), and BeiDou (China). GNSS satellite visibility for these global constellations is poor at high latitudes due to their orbital plane inclinations (55°, 56°, and 65° for GPS, Galileo, and GLONASS, respectively). For Arctic users, GNSS satellites appear well distributed in azimuth but

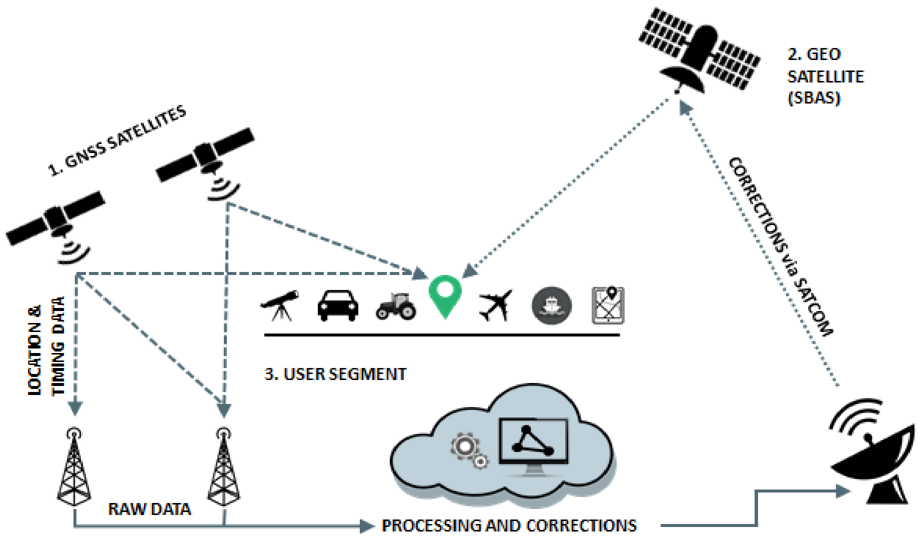

Figure 5: GNSS Infrastructure: *The GNSS infrastructure includes (1) global navigation satellite systems (GNSS), such as GPS (United States), global navigation satellite system (GLONASS, Russia), Galileo (EU), and BeiDou (China) in MEO; (2) aerial, ground, and/or satellite-based augmentation systems (SBAS) in GEO; and (3) the user segment, made up of signal receivers, which analyze and utilize data from navigation satellites and augmentation systems. Source: Image adapted from Geoscience Australia, a government agency under the Australian Department of Industry, Innovation, and Science (http://www.nav18.com/documents/Session4/SESSION-4-a-John-Dawson-SBAS-test.pdf)*

never appear overhead, near the user's zenith. The geometry of this configuration results in acceptable horizontal position accuracy but poor vertical accuracy, which makes high precision position determination difficult.[34]

Satellite-Based Augmentation Systems

Much of the effort to improve PNT in the Arctic focuses on improving satellite-based augmentation systems (SBAS) to overcome both northern latitude satellite visibility, satellite signal corrections, and the effects of atmospheric variability. SBAS provides correction signals that improve the accuracy, reliability, and availability of GNSS systems by adding external information (e.g., ionospheric conditions, map corrections, and clock drift) so that precise PNT can be calculated. Sub-Arctic GNSS users obtain PNT information with sufficient (centimeter) accuracy and availability (0.999) to support common functions such as airport approach and landing, deep water ship rendezvous, and hydrocarbon extraction by receiving signals from both GNSS and geosynchronous SBAS satellites.

GNSS—Arctic Atmosphere and Topography Challenges

Beyond GNSS coverage constraints at high latitudes, the Arctic's environment itself also weakens the precision of PNT services. For example, in the Arctic (and Antarctic) the flow of charged particles along terrestrial magnetic field lines intersects the atmosphere during unpredictable magnetic storms, causing aurora and large ionospheric disturbances.[19] Ionospheric ripples and waves cause GNSS signals to refract and diffract, as if by a mirror or through a lens, causing signal distortions known as scintillation. Additional topography challenges include the lack of landmass within the Arctic. While many high altitude SBAS ground stations exist—such as wide-area augmentation system (WAAS, United States), European Geostationary Navigation Overlay

System (EGNOS, European Space Agency [ESA]), MTSAT Satellite Augmentation System (MSAS, Japan), and satellite design and cost model (SDCM, Russia)—they have reached maximum coverage. Lack of landmass limits the usefulness of adding more ground stations to improve PNT coverage.

Precision PNT—Closing the Gap

Because GNSS infrastructure is not designed for operations above the Arctic circle, significant PNT capability gaps exist for Arctic users. However, both new space systems and new uses of existing systems show promise.[35] Arctic stakeholders and policymakers should encourage improved location determination capabilities to close the PNT infrastructure gap and consider SBAS hosted payloads on HEOs, GEOs, LEOs, and high-altitude platforms to augment and improve positioning and navigation capabilities. In addition to the space and airborne augmentation systems listed below, there are also emerging methods to improve GNSS receiver accuracy (e.g., receiver autonomous integrity systems, or RAIM).

HEOs/Irregular Orbits

Adding HEO satellites in Molniya or tundra orbits to current GNSS systems can help bridge gaps in Arctic coverage. Other irregular orbits such as quasi-zenith orbits are also possible. An example of this is Japan's four-satellite regional constellation, Quasi-Zenith Satellite System (QZSS), whose main function is to provide near zenith GNSS signals for Japan from 43° inclination geosynchronous orbits. While serving its main function, QZSS signals have demonstrated the usefulness of this orbit across portions of the Arctic by providing both primary and SBAS signals beyond the reach of equatorial SBAS satellites. However, deploying new HEOs/irregular orbit satellites with the narrow function of supporting current GNSS systems could be a costly solution.

GEO

Beam-shaping and selecting optimal GEO longitude has the potential to improve GEO SBAS to reach target markets.[36] For example, development teams in the defense and space industries have demonstrated increasing the reach of the GEO SBAS segment to within 1º of the pole for specific test situations involving airborne platforms.[37]

Commercial Global LEO in Near Polar Orbits

It is possible to utilize LEO satellites to broadcast the SBAS augmentation signals to Arctic users. However, there are many limitations to this approach, including the complexity and expense of satellite-to-ground connectivity, signal distribution to end users, and satellite operation and control at high latitudes.[38]

High-Altitude Balloons or Platforms

In the interim, it is also possible to take incremental steps to extend the reach of GEO SBAS by using high-altitude balloons or unmanned aircraft with receivers. These would extend the reach of SBAS GEO signals to ground users via a bent pipe. However, complicated air operations in the Arctic are difficult and the concept has not yet been proven.

Potential Policy Steps

Policy guidance for commercial, military, and civil spaceflight can play a key role in guiding the development of systems to close the GNSS infrastructure gap. In the past, the U.S. government has adopted a wide range of incentives and mandates to encourage extending critical services to under-served areas, especially in the area of telecommunications. An analogous model could be applied to encourage the extension of GNSS services to the far north. Effective policies should include guidelines to encourage high-latitude primary PNT signals and expanded Arctic GNSS augmentation systems. Both space and ground segment system requirements should be normalized and coordinated so that new systems are able to support Arctic PNT to the greatest extent possible beginning with the design phase, prior to manufacture and deployment. Examples include the following:

- During Arctic transits, pLEO satellites may shut down radio and optical transmissions in order to conserve power and increase lifetime. Such a duty cycle would limit application as a near-zenith primary or augmentation signal source. Policies and guidelines could bring awareness of Arctic consumer needs and encourage methods for new commercial new entrants to design "Arctic positive" capabilities into new systems.

- Cooperative agreements could help guide the various GNSS systems and commercial providers of user receivers to combine signals from the various global GNSS systems with simple interoperability to increase accuracy and integrity in the next generation of commercial equipment. This would require the cooperation of stakeholders of the various national GNSS systems to coordinate signal frequencies and data structures.

- Science and research communities can encourage increased Arctic space weather data collection, analysis, and distribution. The research and commercial sectors can be encouraged to develop consumer-level receivers to mitigate high-latitude ionospheric phenomena. Researchers and scientists can provide commercial receiver providers with data and analysis pathways to electronic and internal logic designs to mitigate Arctic-specific ionospheric phenomena.

Earth Observation (EO)

Commercial, civil, and military activities, human safety, and the protection of the environment in the Arctic depends on accurate and reliable Earth observation (EO) data collected from remote sensing and space-based weather systems.

Support to Navigation

As the Arctic continues to lose large amounts of ice, the conditions and movement of remaining ice grow increasingly difficult to predict. Remote sensing technologies such as synthetic aperture radar data, microwave radiometers, and multispectral optical sensors help measure sea ice drifts, track icebergs, and help ensure that shipping passages are clear and safe for navigation. Safe navigation in the Arctic also requires monitoring ocean currents and wind speed, both of which require the use of microwave radiometers. Because the weather in the Arctic is highly variable, it is critical that these instruments can capture accurate, timely, consistent, and reliable data.[39]

Historically, inadequate iceberg and sea ice drift tracking has resulted in numerous shipping collisions—often in dangerously remote areas where search and rescue operations require more time. Ice can also render ship routes impassable. For example, last year, heavy pack ice conditions created an impassible Northwest Passage for cruise ships, despite warming temperatures.[40] Finally, improved sea ice tracking can prevent environmental catastrophes, such as oil spills, by providing timely sea ice reports to ships transporting oil and other products.

Observing and Measuring the Cryosphere

The unique nature of the Arctic cryosphere makes it especially sensitive to a warming climate and a good indicator for global climate patterns. Data captured from EO satellites over a period of time can be used to measure trends in thinning ice and related rising sea levels.

Permafrost and its related degradation over time is another significant cryosphere feature that requires monitoring. Permafrost measurements over time provide a picture of the freeze-thaw cycle, and, with the drastic changes in climate, permafrost affects the terrestrial ecosystem of the Arctic, including human settlements, agriculture and forestry, and land animal habitats.[41] Measuring permafrost requires continuity of data, and its subsurface location requires the use of more sophisticated technologies. Synthetic aperture radar (SAR) sensors have been helpful in measuring and mapping this data. However, these instruments are constrained by their narrow swath; dependence on vegetation cover and surface roughness; and out-of-phase radar wave interference (known as speckle noise), which can render images as noisy or inaccurate.[42]

Existing Satellites and Data Limitations

Currently, there are several large-scale governmental satellite missions in polar orbit that capture EO data over the Arctic, such as the NOAA–NASA Joint Polar Satellite System (JPSS), the U.S. Geological Survey's Landsat satellites, and the European Space Agency's Sentinel satellites. These polar-orbiting satellites can capture Arctic EO data, with 14 to 15 flyovers each day.[43] These satellites utilize a variety of remote sensing sensor types: microwave radiometers and sounders; solar energy sensors; ozone spectrometers; electro-optical imagers, including multi-spectral and near infrared/hyperspectral imagers; and synthetic aperture radar sensors.[44]

Technical Capacity

Polar-orbiting space systems are constrained by swath width (some imaging instruments only capture narrow coverage areas) and the number of satellites in the constellation (the lower the number of satellites, the lower the revisit rate) as well as their technical capabilities (lower electro-optical resolutions cannot capture complex or subsurface details). Despite the limitations of polar-orbiting satellites, they are better suited to capturing Arctic EO data than geostationary satellites, which, as stated previously, are better situated to capture mid-latitude data.[45]

Data Continuity

Continuity of data remains a challenge for focused remote sensing initiatives, such as NASA's Icesat and Cloudsat missions and ESA's Cryosat and soil moisture and ocean salinity (SMOS) missions, which are wholly dedicated to addressing Arctic concerns. These satellites, launched during the early 2000s, are past their operational system lifecycle. For example, NASA operated Icesat 1 (carrying a laser altimeter and atmospheric light detection and ranging [LIDAR]) from 2003 to 2010 but just recently launched Icesat 2 (carrying a single instrument, an Advanced Topographic Laser Altimeter System, or ATLAS) in 2018.[46] Between the end of life for Icesat 1 and the beginning of Icesat 2, NASA introduced "Ice Bridge," a series of airborne surveys over the Arctic and Southern oceans to provide continuity between these two space missions.

Communication Integration

Finally, remote sensing systems work in conjunction with space and ground communications segments to provide reliable and continuously sensed Earth imagery and data. As discussed in the prior section, commercial sector capital infusion will support significant new capacity provided by GEOs, LEOs, and HEOs to provide reliable data—both for immediate realtime use and for subsequent analysis.

New EO Satellite Technologies—Closing the Gap

A wide range of EO data exists that may help bridge the remote sensing gaps in the Arctic. This section examines some EO applications and the current and emerging technologies that could support them. Appendix C describes a range of observable Arctic phenomena and the types of sensors needed to capture measurements, along with key remote sensing challenges for each phenomenology. For more information, the World Meteorological Organization (WMO) has developed an interactive tool that aligns user needs to sensor solutions, called Observing Systems Capability Analysis and Review (OSCAR), which includes an archive of current satellite sensors in space.[47]

HEO Applications

As the need for consistent, continuous, and reliable remote sensing data becomes even more urgent for the Arctic, it is likely that a combination of commercial and governmental solutions will aid in providing that coverage. One option is launching remote sensing HEO satellites to resolve some issues with the larger geostationary and polar orbiting satellites. Russia is known for launching HEO satellites, specifically in Molniya orbit, and has historically launched many communications and surveillance satellites in this orbit. In fact, the Russian space agency, Roscosmos, plans to launch its first-ever dedicated weather and climate satellite, Arktika, in mid-2020s.[48] The Arktika satellites would collect multi-scale images from various angles in regions that have been difficult to observe, specifically the atmosphere above and climate in the North and South poles.[49]

pLEO Constellation Applications

There is a greater likelihood that the much-needed combination of new remote sensing technologies, such as synthetic aperture radar, LIDAR, microwave radiometers, wide swath instruments, and constellations with higher revisit rates will be developed within the commercial sector in the form of LEO CubeSats. Even now, companies like Planet, which has been consistently launching small satellites in LEO since 2014, offer the potential to provide continuous regional coverage using polar orbits.[50]

SAR Applications

Prior to 2016, commercial SAR satellites were cost prohibitive, and it was challenging to develop a routine collection strategy. After 2017, when the ESA made available Sentinel-1's SAR-based data products free of charge to all data users, the market experienced a dramatic increase. This was primarily due to Sentinel-1's open data-sharing policy, which removed financial barriers. While moderate resolution SAR is freely available, new space entrants are beginning to fill the gap for higher spatial resolution needs for some civil and commercial applications. Commercial satellite companies, such as Capella Space or XPressSAR, are now introducing SAR constellations with high revisit rates.[51] ICEYE, a Finnish company, just recently launched two SAR satellites in 2019, with the goal of launching an 18-satellite constellation by 2020. As the first SAR mission provider to provide better than 1-meter resolution, it also hopes to provide a service level where any location on Earth can be reliably imaged every 1 to 3 hours.[52]

Vessel Tracking Applications

Vessel tracking has historically utilized radio frequency (RF) collections with geolocation capabilities, the most common of which is the maritime Automatic Identification System (AIS). While these are not technically remote sensing technologies, they are often used in tandem with remote sensing sensors to monitor maritime traffic, detect distress signals for search and rescue efforts and conduct scientific and observation studies of animal habitats. Companies such as Argos, Spire, and exactEarth have launched constellations dedicated to vessel tracking. New entrants have begun to find additional ways to track illicit and large-scale shipping activity, such as HawkEye 360, which launched its first three-cluster satellites into space in December 2018.[53] Likewise, the Defense Research and Development Canada (DRDC) Canadian Safety Security Program (CSSP) is testing a system to enable rapid cueing of an imaging satellite. The project "Maritime Cueing of Optical Satellites (MarCOS) is gathering high-resolution images of vessels of interest (VOIs). This system will be able to address "dark vessel" scenarios (e.g., those vessels that do not self-identify using AIS). Moreover, the applicability of cuing is much broader than dark vessel identification and allows government authorities to investigate and categorize a range of threats, suspicious activity, and detected anomalies.[54]

This influx of commercial remote sensing companies entering the market with constellations offering better resolution, more innovative imaging capabilities, and higher revisit rates over the Arctic will make it possible to track data over time and verify variable data across multiple sources.

Closing the Gap—Summary

Table 1: Bridging the Satellite Infrastructure Gap in the Arctic Region

Existing Challenges/Needs	Space-Based Solutions to Address Needs
Communications	
Limited access to mobile telephone, fixed broadband, and mobile broadband in sparsely populated areas in Alaska. Long-term ***affordable*** access to broadband and other connectivity needs.	Existing providers will strive to offer competitive services based on speed, capacity, technological features, ability to customize networks, and customer service. New commercial entrants (Appendix B) aim to close the Arctic "digital divide" including strategically positioned GEO over the Pacific to gain higher latitude broadband reach to Alaska, and commercial pLEOs orbiting at high inclinations (particularly OneWeb, Telesat, and SpaceX "Starlink").
Pointing, Position, and Navigation (PNT)	
Limited accuracy, availability, and integrity of space-based navigation and timing services due to orbit geometries and ionospheric disturbances. Lack of international standards and system requirements.	A range of satellite orbits and platforms can expand or improve PNT in the Arctic region, including commercial LEO entrants in polar or near polar orbits; satellites in HEO orbits, which spend most of their time over the northern latitudes; and high-altitude balloons or unmanned aerial systems. Arctic GNSS gap closure solutions will require coordination among GNSS national systems and commercial hosting of GNSS payloads.
Earth Observation	
Standard techniques used in lower latitudes are not always appropriate for the remote, harsh, and dynamic Arctic.	A wide range of existing sensors (Appendix C) are currently used to monitor and observe the Arctic Ocean, permafrost/land, cryosphere, and mobile vessels from space. Government and commercial entrants will improve data collection with new space-based technologies that fill gaps and combine data from ocean and ground-based assets. Data continuity and timeliness combined with the ability to integrate remote sensing data through reliable communication infrastructure is also critical.

What's Next? Smarter Infrastructure and Emerging Trends

The Arctic population, both transient and permanent, will seek the ubiquitous communication, connectivity, navigation, and observation capabilities that are increasingly taken for granted by inhabitants south of the Arctic Circle. Growing commercial momentum for remote sensing, navigation, broadband, and connectivity provisioning in the Arctic, combined with clear policy guidance and targeted government investment, can help to meet these needs.

The summary below lists solutions and trends to meet future needs across communication, positioning, and remote sensing.

Ubiquitous Networking Solutions for Satellite Communications

A range of new GEO and LEO commercial services will provide critical innovative networked capacity. There is an industry-wide discussion between the satellite sector and terrestrial providers regarding convergence of terrestrial mobile cellular (including 5G) systems and satellite systems. Over time, consumers will expect to see integration and unification of heterogenous technologies. Software-defined satellites working with flexible and compatible terrestrial networks will be able to transform communications into an efficient hybrid network. This will allow Arctic stakeholders to optimize connectivity, taking advantage of all available options including GEO, MEO, LEO, and terrestrial wireless. Over time, it is reasonable to expect that flexible plug-and-play architectures will emerge. These architectures will depend on gaining industry consensus interoperability standards for interfaces and communication protocols. Remote regions of the world, including the Arctic, will benefit from this convergence trend since they will be able to better optimize communication paths and existing available infrastructure.

In addition to network convergence, enterprise cloud connectivity for polar region customers (commercial, civil, and military users) will also drive efficiencies and allow remote Arctic business locations and operations to become more integrated and central. High north customers will have access to the same cloud hosted services that lower latitude counterparts have relied upon, including database services and storage; business analytics; and various enterprise solutions such as IoT applications, logistics, and supply chain applications

Data Sharing and Research Convergence

Sharing data between governmental agencies and nations will be a game changer as scientists continue to monitor global climate change. There are currently over 458 unclassified Earth observation satellites that have been successfully launched since the dawn of the space age. Yet there are still many gaps in our knowledge regarding climate change. Of the 458 Earth-observing satellites launched between 1957 and 2016, only 38 percent have made their data fully open to the public.[55] This has been attributed to the fact that programs get more funding for demonstrating a new technology than for facilitating broad access for existing data.[56] Arctic stakeholders would be well served by encouraging all Arctic nations to make their data freely available without restrictions.

In 2016, the National Science Foundation (NSF) unveiled "Navigating the New Arctic."[57] NSF seeks "innovations in Arctic observational networks." This initiative is part of NSF's larger efforts to spearhead "convergence research," which involves integrating knowledge, methods, and expertise from different disciplines to catalyze scientific discovery and innovation. For NSF's Arctic initiative, this will involve developing frameworks across social, natural, environmental, information sciences, and engineering to address the intersection of natural, social, and built systems."

Situational Awareness

Understanding the rate of change in the Arctic requires a multidisciplinary approach, fusing remote sensing, communications, and PNT data. Despite the number of polar-orbiting systems focused on capturing data and innovative small satellite solutions focused on satcom, PNT, and Earth observation, gaping voids and uneven coverage still exist in Arctic Ocean situational awareness as a whole, and uneven coverage of many observable characteristics within the Arctic. In the interim, emerging SAR (ICEYE, Capella, XPressSAR), LIDAR, and geolocation services (Argos, HawkEye 360) will aid in ocean and sea ice monitoring for shipping and navigation purposes.

Integral to situational awareness is improved data analytics and intelligence. The Arctic Domain Awareness Center (ADAC) is now leveraging the data provided by near-realtime and high-resolution satellite imagery and incorporating it into available models, sensors, web-based communications, and appropriate social networking feeds to gain domain awareness in support of operational decisionmaking. ADAC's goal is to improve situational awareness and crisis response capabilities related to maritime challenges posed by the dynamic Arctic environment.[58] The National Maritime Intelligence-Integration Office (NMIO) also supports information-sharing across the global maritime community and helps identify new solutions to "accelerate technology development to advance strategic, operational, and tactical decision making."[59]

Artificial intelligence (AI) and, particularly, machine learning (ML) have a strong future role to play in sifting through the zettabytes of remote sensing data and providing actionable intelligence.[60] This is happening now. The National Geospatial-Intelligence Agency (NGA) and other defense and intelligence organizations have many pilot projects underway to explore how best to insert AI/ML into GEOINT workflows.[61] The goal is to compress the time from data collection to actionable intelligence and free analysts from rote data review and analysis. Given the vast amount of data collected over the Arctic, ML and AI promise to deliver timely intelligence to industry, civil, and military stakeholders.

Conclusion—Closing the Gap

Through existing and future space systems, Arctic stakeholders can benefit from increased connectivity, accurate positioning, and persistent and pervasive remote sensing capabilities. These capabilities are further enhanced through network convergence, data sharing, and fusion, whereby stakeholders gain a broader, more insightful picture of the region. The integration of data from ground-based assets with space-derived sensor data can provide better actionable intelligence for navigation, tracking and shipping goods, natural resource management, economic development activities, search and rescue operations, environmental monitoring, telemedicine, and ensuring safety and security for all citizens. Arctic stakeholders will benefit from a range of partnership synergies among GEO, HEO, and LEO commercial service providers. Network capacity from these emerging partnerships will optimize coverage and performance, and cloud-based enterprise solutions.

The "New Arctic" is becoming center stage for observing the impacts of a changing climate. During this time of warming and increased accessibility, Russia, China, the United States, and NATO allies will assert their territorial, economic, and military interests. It is, therefore, a pivotal time to protect and respond to national and environmental security threats. For remote Arctic regions, space systems provide critical infrastructure, which supports long-term national security, civil, environmental, and economic goals. By fully leveraging existing and future space-based infrastructure, the United States can work cooperatively with other Arctic nations to build awareness, enhance operations, and strengthen a common rule-based order.

Appendix A. Existing Communication Polar or Near Polar Satellites

Existing Arctic Data Connectivity Options

As of the time of this publication, no true two-way near realtime (low-latency) broadband speed service (>25 Mbps) exists for the polar region above 81° latitude.

Polar or Near Polar Orbit LEO Communications Satellites – Operational		
Company (Location) *Year Established*	**Description**	**Target Market**
Argos (France/USA) ***1978***	♦ Hosted payload on **12 satellites** ♦ Unidirectional comm, store & forward (delay tolerant). ♦ Future constellation 25 CubeSats operational by 2022, 2-way comm, greater bandwidth, improved data timeliness due to a shorter revisit time (5–15 mins) ♦ 401.65 MHz, 480 bps	**Scientific community and governments.** Wildlife tracking, oceanography, environmental monitoring. French Space Agency and NASA partnership
Gonets (Russia) ***1996***	♦ **13 satellites,** including 12 2nd gen satellites. ♦ Short burst direct comm, global coverage. Telematics services and messaging. Only some of the satellites carry digital store & forward payloads. ♦ Orbit is not polar – approx. 82 degrees. ♦ Ultra high frequency – 259.5–1541.9 MHz; 2.4 Kbps uplink; 9.6 Kbps downlink.	**Civilian apps.** Logistics, industrial, environmental, meteorological, and emergency comm.
Iridium/Iridium NEXT (USA) ***2018***	♦ **75 satellites in orbit** – 66 + 9 spares ♦ Crosslink mesh architecture ♦ 2nd gen NEXT completed constellation replacement in 2018 ♦ L-band (1616–1626.5 MHz) mobile terminals – up to 128 Kbps; marine – up to 1.5 Mbps; fixed – up to 8 Mbps	**General consumer and vertical markets.** Works with large ecosystem of value-added resellers.
Kepler (Canada) ***2018***	♦ **2–3U CubeSats** ♦ Store & forward service "bulk data transfer"; high-capacity, high-throughput, and software-defined radio. ♦ Offers both wideband (Ku) & narrowband onboard a single CubeSat. ♦ Allows for up to 500 Mbps ♦ Future: 140 satellites – sunsynchronous orbit.	**Internet of things (IoT) market.** Remote businesses, shippers, research stations, mining, oil and gas, tourism, and defense.

LEGEND:

Delay Tolerant

Near Realtime

<500 Kbps

>500 Kbps
<25 Mbps

>25 Mpbs

Appendix B. Future Commercial Satellite Options for Arctic Region Coverage

Two constellations (green) are already in the deployment phase. Four constellations (yellow) are planned. Based upon FCC data.

Company	Future Constellations with Polar Region Coverage
OneWeb (Virginia)	***Market:*** Global broadband. ***Description:*** 720 LEO satellites, 10 polar planes, 1,200 km altitude; will deliver 375 Gbps capacity above the 60° North. ***Bent Pipe Architecture:*** Bent pipe, no crosslinks, user links Ku-band, gateway links Ka band. Future hybrid architecture working with Iridium LEOs. ***Schedule:*** Regional service in 2020 with approximately 300 satellites, global coverage in 2021 with approximately 600 satellites. ***Status:*** Deployment underway; 150 satellites in orbit by the end of 2019.
SpaceX "*Starlink*" (Washington)	***Market:*** Global broadband, developing world. ***Description:*** 4,425 LEO satellites total. Initial deployment – 1,600 satellites for 53° latitude orbits. Later deployment – 1,225 satellites at 70° and higher for arctic coverage. ***Cross Link Architecture:*** User links Ku-band, gateway Ka-band. Medium-size satellites (386 kg). Digital payload with beam steering & shaping. ***Schedule:*** In May 2019, launched 60 satellites; no polar coverage yet. ***Status:*** Deployment underway, begin service during 2020.
Telesat (Canada)	***Market:*** Global broadband – consumer and vertical markets, remote Canada. ***Description:*** 117 LEO satellites, 11 planes; 6 polar planes 12 satellites; 1,000 km @ 99.5°. ***Cross Link Architecture:*** User and gateway links in Ka-band. Optical cross links between satellites. Digital beamforming payload with steering & shaping capabilities. ***Schedule:*** Launch 2021; begin service 2022. ***Status:*** Planned; Canadian government (July 2019) agreed to invest $600 million for capacity to connect Canada's remote citizens.
LeoSat (Washington, D.C.)	***Market:*** Enterprise, telecoms and government communications. ***Description:*** 108 LEO satellites, at 1,400 km, 99° inclination. ***Cross Link Architecture:*** High-speed, space-based data networking. Ultra-low latency. Laser linked HTS will create optical backbone. ***Schedule:*** Uncertain. ***Status:*** Planned – pending regulatory approvals.
ViaSat (California)	***Market:*** United States and allied military forces. ***Description:*** 24 LEO satellites. ***Bent Pipe Architecture:*** Link 16-capable LEO satellites. Secure, high-speed resilient communications. Contract options for future cross links. ***Schedule:*** To be determined. ***Status:*** Planned; May 2019 contract awarded by the Air Force Research Laboratory (AFRL).
Inmarsat and Space Norway (UK)	***Market:*** Broadband for Global Express customers, vertical markets. ***Description:*** Two new hosted payloads on HEO satellites, continuous coverage above 65° North. Ability to direct capacity in realtime to areas of highest demand. ***Hybrid GEO-HEO Architecture:*** Space Norway HEOs with Inmarsat's 13 GEOs. ***Schedule:*** Launch in 2022. ***Status:*** Planned.

Appendix C. Earth Observation—Phenomena and Sensors in Polar Regions

This table aligns desired observables with associated sensors and key challenges to obtaining key EO data.[62]

	Phenomena	Sensors	Challenges
OCEAN	***Surface Currents and Waves***	GNSS-reflectometry, microwave radiometer, radar altimeter, SAR	Gaps in revisit time and speed accuracy, and delays/latency in data receipt; could use small platforms to fill this gap.
OCEAN	***Atmospheric Pressure***	Microwave sounder, cloud radar, microwave radiometer, infrared sounder/spectrometer	Gaps in revisit rate, gaps in weather observation data accumulation on large government satellites; can use CubeSats to compliment large satellites.
OCEAN	***Sea Surface Temperature***	Microwave radiometer, infrared sounder/spectrometer, microwave imager, multispectral radiometer	Need to be able to penetrate cloud coverage.
OCEAN	***Sea Floor and Ocean Depth***	Bathymetric surveys (multi-beam and single beam sounders, side-scan sonar and Doppler velocity loggers), LiDAR	About 70% of the Arctic has never been surveyed as there is difficulty mapping the sea floor, and much of it done via boat. However, new efforts integrate satellite-based surveying efforts such as LIDAR.
OCEAN	***Wind Speed***	GNSS-reflectometry, microwave radiometer, radar scatterometer, radar altimeter, SAR	Gaps in revisit time, speed accuracy, and time delays/latency in data receipt, interference from precipitation and sea surface roughness.
CRYOSPHERE	***Sea Ice Type***	Radar scatterometer, microwave imager, radar altimeter, SAR	Gaps in revisit rate and higher spatial resolution requirements
CRYOSPHERE	***Sea Ice Cover, Extent and Thickness***	GNSS-reflectometry, microwave radiometer, radar scatterometer, radar altimeter, SAR, multispectral radiometer, hyperspectral radiometer, infrared sounder/spectrometer, LIDAR	Gaps in revisit rate and higher spatial resolution requirements; higher spatial resolution requirements with wider swaths; LIDAR helps to determine ice thickness but has a narrow swath width and is costly.
CRYOSPHERE	***Iceberg Tracking***	Radar scatterometer, SAR, radar altimeter	Gaps in revisit rate and spatial resolution, uses technologies that have narrow swath widths, but need wider swath widths. It takes time to analyze this data.
CRYOSPHERE	***Sea Ice Drift***	Microwave radiometer, SAR, multispectral imagers, microwave scatterometer	Gaps in revisit rate and improve data latency.
LAND	***Surface Soil Moisture***	Microwave radiometer, thermal infrared imager, SAR, radar scatterometer	Narrow swath, vegetation cover, and surface roughness make images noisy. Need to improve accuracy of data – may require combining data from multiple sensor types.
LAND	***Permafrost***	Microwave radiometer, thermal infrared imager, SAR, LiDAR, microwave radiometer	Need sensors to penetrate ground surface.
VESSEL	***Vessel Tracking and Maritime Awareness***	AIS decoder, SAR, RF geolocator	Difficulty tracking high traffic amounts and illicit activity; combining AIS with SAR may help.

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