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D3.6 Gap analysis highlighting the technical and operational requirements of the European Polar Research Programme for satellite applications

Submission of Deliverable

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1. INTRODUCTION

1.1. Document Scope

This report (D3.6) is a component of EU-PolarNet work package 3, which encompasses Infrastructures, Facilities and Data, and falls under task 3.2. The task objective is to consider joint programming of infrastructure to enable bigger and more complex science projects.
Task 3.2 provides two formal deliverables as described in the EU PolarNet project proposal.

Table 1: Deliverables from EU-PolarNet Task 3.2

Task 3.2 Satellites, communication and remote sensing	
D3.3	Survey of existing use of space assets by European polar operators, including recommendations for improved coordination
D3.6	Gap analysis highlighting the technical and operational requirements of the European Polar Research Programme for satellite applications and identifying opportunities for improved linkages to ESA and other space agencies

Deliverable 3.6 considers gaps in current space technologies as part of the facilities, infrastructure and operations of European nations in the Polar Regions. This report follows directly from deliverable D3.3 which described the existing uses of space assets by European polar operators. A brief summary of these applications is provided in the first part of each section addressing satellite communications, navigation and remote sensing.
The primary focus of task 3.2 is space assets which support polar operations. The multiplicity of direct use of space data in polar science is only addressed where it overlaps with the operational need. Direct use of science data derived from in-orbit platforms should be considered separately as part of the wider consideration of polar science and related data requirements.
Having assessed the current uses of space technology (in D3.3), this report summarises the gaps in space assets and technologies which the polar community requires or anticipates for support to science and operations in the Polar Regions.
In summary this second deliverable (D3.6) has the following objectives:

- For each of the main space technologies, highlight the gaps in current capabilities and summarise requirements from the polar community.
- For each space technology, summarise potential options to address identified gaps.
- Summarise the current activities in the European Space programs to address specific polar needs.

It is important to note that space segment developments often take many years to conceive and implement, and there is currently significant effort from ESA and the EC to address polar requirements. Planning is currently multi-stranded and in a state of flux. This report should be considered a snapshot of the current situation at the date of publication.
It is also important to note that this report is purely concerned with identifying gaps in capabilities and the requirements that justify them. It is not the aim of this report to prioritise the need for these developments or to consider the relative benefits of any solutions and the associated costs. Ongoing activities are in place to define and assess the feasibility and implement new satellite missions.

1.2. Approach

In recent years a considerable amount of effort has been invested by space agencies and governmental organisations to determine the requirements for space assets for those living and working in the Polar Regions, especially the Arctic. At the time of writing this report, a number of relevant studies have been concluded or are still in progress. These studies frequently include user requirements and gap analysis, often addressing overlapping topics.

In the context of this report for EU-PolarNet, it makes no sense to repeat these efforts to complete another requirements and gap analysis involving direct consultation with users. Instead we have chosen to collate and summarise the outputs of several recent studies and present an up to date synopsis of the current situation. This covers the status of ongoing studies working towards potential new missions and infrastructure which might be built in the coming years.

1.3. Layout of the Document

The document contains the following sections.
Section 1: Document scope, approach and reference information
Section 2: Addressing satellite communications
Section 3: Addressing satellite navigation
Section 4: Addressing satellite Earth observation
Section 5: Addressing other space technologies
Section 6: Highlighting opportunities for improved linkages with European space activities
Section 7: Conclusions

1.4. Reference Documents

Table 2: List of publications referenced in Deliverable D3.6

EU Joint Communication "An integrated European Union policy for the Arctic"	http://eeas.europa.eu/archives/docs/arcticregion/docs/160427joint-communication-an-integrated-european-union-policy-for-the-arcticen.pdf
ESA Polaris Study	http://www.arcticobserving.org/images/pdf/Boardmeetings/2016Fairbanks/14Final-Summary-Report2016-04-22.pdf
Arctic Council Task Force - Telecommunications infrastructure in the Arctic: a circumpolar assessment	Arctic Council Task Force on Telecommunications Infrastructure in the Arctic, 2017, Telecommunications infrastructure in the Arctic: a circumpolar assessment. Arctic Council Task Force on Telecommunications Infrastructure in the Arctic (TFTIA). 90 pp. https://oaarchive.arctic-council.org/bitstream/handle/11374/1924/2017-04-28-ACSTelecomsREPORTWEB-2.pdf?sequence=1
COMNAP Antarctic Roadmap Challenges report	Council of Managers of National Antarctic Programs (COMANP) ARC report https://www.comnap.aq/Projects/SiteAssets/SitePages/ARC/AntarcticRoadmapChallengesBook2016.pdf
GNSS Integrity in the Arctic	Reid, Tyler & Walter, Todd & Blanch, Juan & Enge, Per. (2015). GNSS Integrity in the Arctic https://www.researchgate.net/publication/282663098_GNSS_Integrity_in_the_Arctic
Challenges in Arctic Navigation workshop	Challenges in Arctic Navigation workshop, April 2018, Olos, Lapland https://arkki-project.org/wp-content/uploads/2018/04/guyader.pdf and https://www.gsa.europa.eu/newsroom/news/gnss-addressing-challenges-arctic-navigation

User Requirements for a Copernicus Polar Mission - Phase 1 Report	User Requirements for a Copernicus Polar Mission - Phase 1 Report, EUR 29144 EN, Publications Office of the European Union, Luxembourg (2018) https://ec.europa.eu/jrc/en/publication/user-requirements-copernicus-polarmission-0
User Requirements for a Copernicus Polar Mission - Phase 2 Report	User Requirements for a Copernicus Polar Mission - Phase 2 Report EUR 29144 EN, Publications Office of the European Union, Luxembourg (2018). https://ec.europa.eu/jrc/en/publication/user-requirements-copernicus-polarmission

1.5. Acronyms

Table 3: List of acronyms used in this document.

ADS-B	Automatic Dependent Surveillance – Broadcast
AIS	Automatic Identification System
ARAIM	Advanced Receiver Autonomous Integrity Monitoring
COMNAP	Council of Managers of National Antarctic Programs
CDF	Concurrent Design Facility
CMEMS	Copernicus Marine Environment Monitoring Service
DPTD	Discovery, Preparation, and Technology Development
EC	European Commission
ECMWF	European Centre for Medium-Range Weather Forecasts
EGNOS	European Geostationary Navigation Overlay Service
EGSA	European Global Navigation Satellite Systems Agency
EMSA	European Maritime Safety Agency
EO	Earth Observation
ESA	European Space Agency
ESCP-P	Enhanced Satellite Communication Project
EU	European Union
GBAS	Ground-Based Augmentation Systems
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GSA	European **G**lobal Navigation **S**atellite System **A**gency
HDOP	Horizontal Dilution of Precision
HEO	Highly Elliptical Orbit
ICAO	International Civil Aviation Organization
ILS	Instrument Landing System
IMO	International Maritime Organisation
LEO	Low Earth Orbit
NWP	Numerical weather prediction

PB-NAV	Programme Board on Satellite Navigation
PMW	Passive Microwave
PSTG	Polar Space Task Group
RCC	Rescue Coordination Center
RIMS	Range and Integrity Monitoring Station
RTD	Research Innovation Directorate-General
S-AIS	Satellite Automatic Identification System
SBAS	Space Based Augmentation Systems
SAR	Search and Rescue
SART	Search and Rescue Transponder
TEP	Thematic Exploitation Platform
VAL	Vertical Alert Limit
VDOP	Vertical Dilution of Precision
VDES	VHS Data Exchange System
WAAS -	Wide Area Augmentation System

2. SATELLITE COMMUNICATIONS

2.1. CURRENT USES OF SATELLITE COMMUNICATIONS

The current uses of satellite communications in the Polar Regions is discussed in greater detail in the preceding EU-PolarNet report D3.3. A succinct list of the main applications for polar operations is given below for reference.

- Transmission of science data
- Field party safety
- Satellite data relay
- Shipping & maritime
- Aeronautical
- Search & rescue
- Remote polar stations & temporary field camps
- Emergency telemedicine

2.2. LIMITATIONS OF CURRENT SATELLITE COMMUINCATIONS IN THE POLAR REGIONS

There is a lack of satellite communications in the Polar Regions in terms of geographic coverage, bandwidth, quality of service and affordability.

The Arctic Council[1] Task Force report on Telecommunications Infrastructure in the Arctic provides a comprehensive assessment of telecommunication needs and a gap analysis of the currently available technologies. The Arctic Council Task Force focuses on the northern hemisphere, so information from the COMNAP[2] (Council of Managers of National Antarctic Programs) Antarctic Road Map is also included to cover requirements from the Antarctic.

Inadequate communications links are an established limitation in the Arctic in the context of growing economic activity and connectivity of indigenous populations. The same limitations exist in the Antarctic, affecting maritime and field logistics, plus science projects requiring year-round affordable connectivity to instrument networks and field operations.

The following section will summarise the limitations in satellite telecommunications capabilities. However, it is important to note that no single telecommunications technology will meet all requirements and a mixture of interoperable solutions (satellite, fixed lines, wireless, radio networks) will be used for the foreseeable future.

Reduced visibility of geostationary satellites

In both Polar Regions geostationary satellites are used for many connectivity requirements, but physical limitations associated with visibility of these satellites at higher latitudes undermine their viability.

Geostationary (GEO) satellites orbit at an altitude of 35,800 kilometers directly above the equator (Figure 1), where they remain in a fixed orbital location. GEO satellite provide communication services including network connections, bulk capacity, and direct to-home services. Local mobile services in remote areas rely on GEO satellites (few exceptions where fibre cables or terrestrial microwave towers are used) for connectivity back to the core network.

[1] https://arctic-council.org/index.php/en/

[2] https://www.comnap.aq/

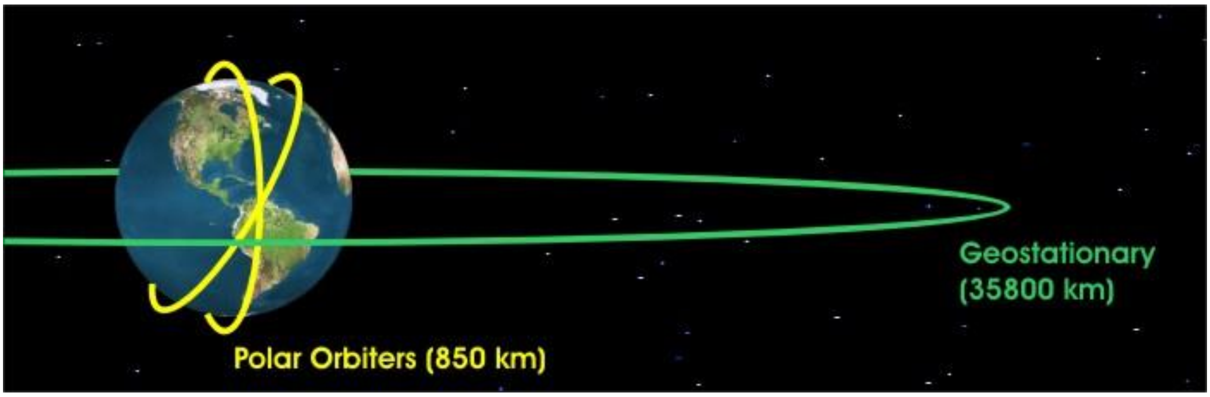

Figure 1: Orbital differences of geostationary and polar orbiting satellites drawn to scale.
(Graphic credit David Babb)

Where latitudes do allow, GEO satellites are well-suited to support many users in the Polar Regions, especially shipping activity, given the need for mobility and the absence of land upon which to deploy terrestrial communications infrastructure. These communication gaps are therefore particularly relevant to the Polar Regions, where users often require near real-time delivery of information to ensure safety of life and efficient operations.

Due to the location of GEO satellites directly above the equator and the curvature of the Earth, they have very low inclination 'look-angles' at high latitude parts of the globe. As a result, visibility of these satellites from the ground reduces to zero from latitude of approximately 70° to 79° (north and south). The rate of loss with latitude depends on weather, topography on the horizon, and the size of communication antennas. As an example, the footprints of geostationary Inmarsat satellites, are shown in Figure 2.

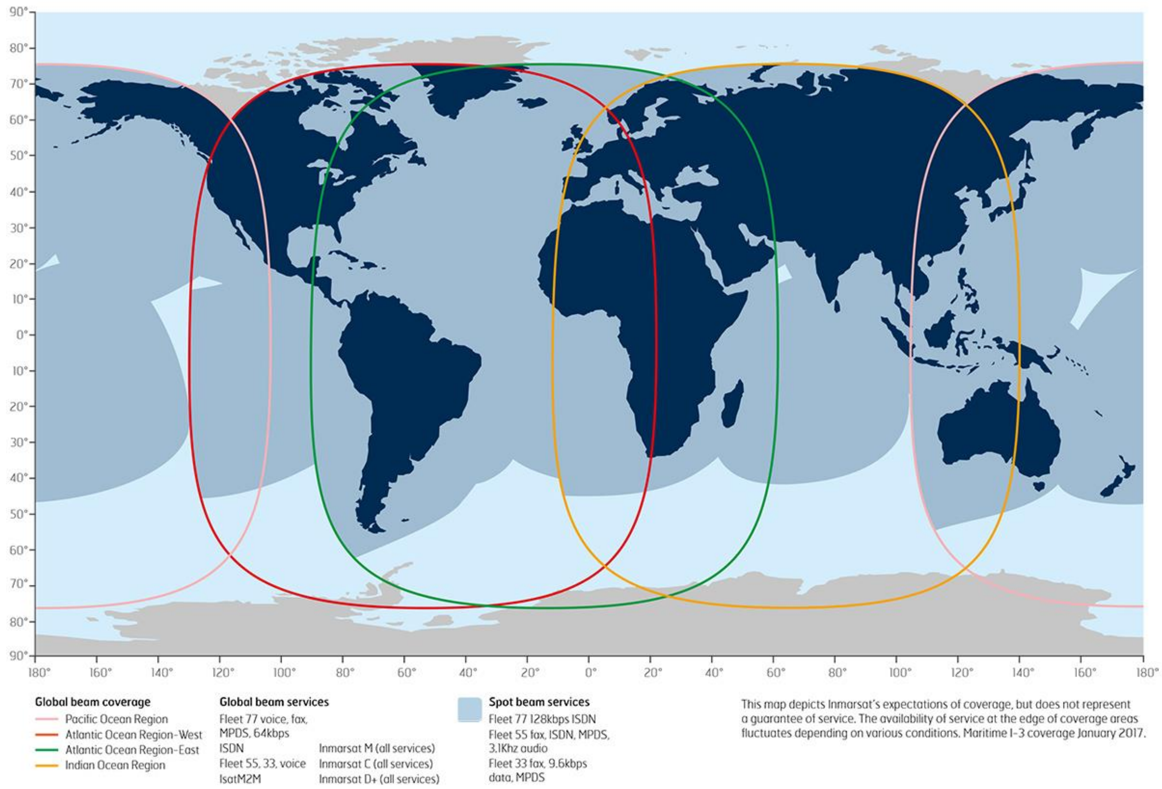

Figure 2: Footprints of Inmarsat[3] geostationary satellites showing the lack of coverage over the Arctic and Antarctic. (Graphic courtesy of Inmarsat)

[3] https://www.inmarsat.com/

Limited capacity of low-Earth orbit satellites
With such limited options available, the leading choice of connectivity in these high latitudes has been voice radios based on lower frequencies (where feasible) and satellite services on LEO satellites such as Iridium (Figure 3).
For higher latitudes with no GEO visibility, non-geostationary polar orbiting satellites are the only option Figure 1. These low-Earth orbit (LEO) satellite solutions mainly provide low-data-rate services and not the broadband connectivity available to users at latitudes lower than 70°.
As a result, maritime users accustomed to accessing large data sets over good broadband connections, are compromised in their ability to navigate safely at higher latitudes where communications are patchy and access to vital information is difficult.
The ability to use broadband services in the northernmost parts of the Arctic will depend on the successful development and deployment of new satellite systems (and improvement of existing systems) with sufficient bandwidth and quality of service. Until that happens, maritime and aeronautical communications in the Arctic will continue to rely on radios and low-data-rate satellite services.

2.3. Future Options to Address Satellite Communications Limitations

The challenge in the Polar Regions is finding telecommunications capacity that can serve the higher latitudes with sufficient bandwidth and quality of service to meet the evolving demands. Satellite technologies continue to advance, and it is likely that they will form part of the communications infrastructure in the future. The following options will be part of the future polar satellite communications infrastructure.

Mixture of interoperable solutions
As noted previously, satellite communications will be one of a mixture of interoperable solutions (satellite, fixed lines, wireless, radio networks) employed to solve the high-latitude communications gap. The Arctic Council Task Force report on Telecommunications Infrastructure includes details of national priorities and infrastructure of each of the Arctic States.

Improvement of geostationary coverage
The increase in shipping and other traffic in the Polar Regions means satellite communications providers have added coverage in these areas. This includes addition of targeted beams for these regions.
In addition, there is increasing provision of higher Ka[4] frequency with higher bandwidth, including satellites with Arctic Ka band coverage. Some of these options are likely to improve the communication options north of the reach of current GEO satellites and provide improved services for the maritime sector and other users in the Polar Regions.

Expansion of low Earth orbit constellations
Several companies seeking to deploy new constellations of low earth orbit satellites to provide expanded or ubiquitous mobile satellite service coverage of the Arctic.
Amongst the concepts that might prove their viability are low-Earth orbit constellations such as Iridium Next[5], LeoSat[6] and megaconstellations such as OneWeb[7] (Figure 3).

[4] https://en.wikipedia.org/wiki/Ka_band
[5] https://www.iridium.com/network/iridium-next
[6] http://leosat.com
[7] http://www.oneweb.world

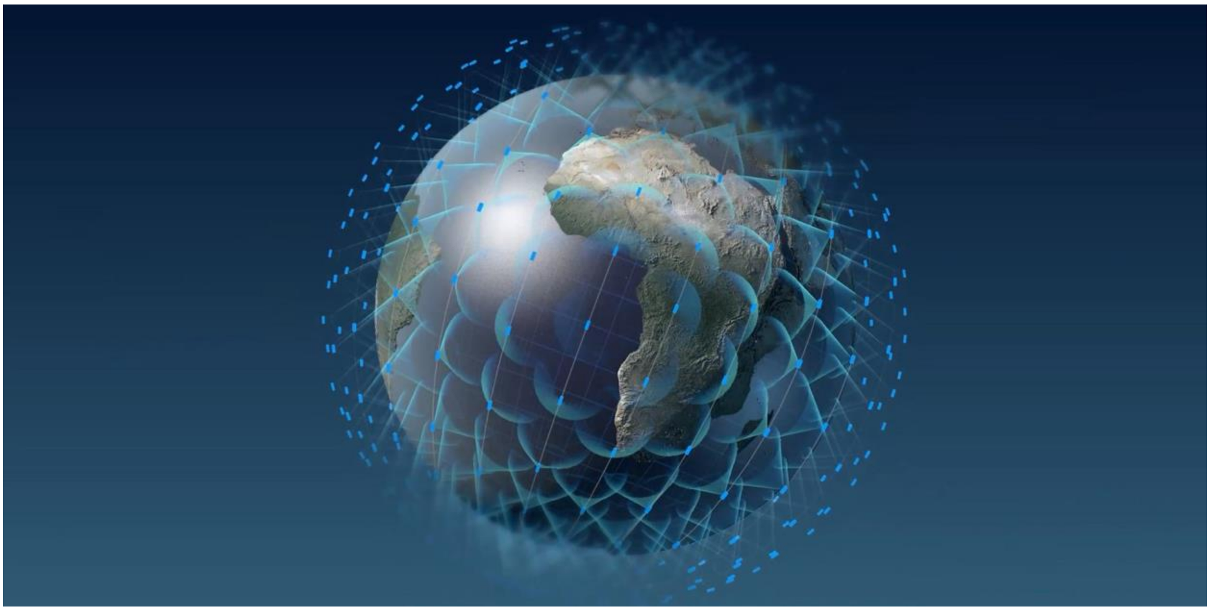

Figure 3: OneWeb constellation in low Earth orbit

Highly elliptical orbits

Highly elliptical orbits (HEO) are very elongated orbits which have the advantage of long dwell times over a point during the approach to, and descent from, apogee (furthest point from Earth). Satellites in these appear to move slowly and remain at high altitude over high-latitudes for long periods of time (Figure 4). These orbits are well suited to high-latitude regions not visible from GEO satellites and can be used for both communications and observation payloads.

Russian satellites in so-called Molniya[8] orbits have been used to provide coverage of high-latitude areas since the 1960s. More recently a number of other HEO missions have been proposed.

The Canadian Polar Communications and Weather (PCW) Project is designed to deliver satellite communications for mobile operations and meteorological observations. This project is led by the Canadian Department of National Defence and is currently limited to military use.

Norway is also studying HEO as a solution for satellite communications systems with capacity to serve maritime and aeronautical users in the Arctic[9]. Two satellites in HEO, to be in place by 2022 / 2023, would provide Ka and X band communication links and potential SBAS services, for areas north of 60°.

[8] https://en.wikipedia.org/wiki/Molniya_orbit

[9] https://www.sciencedirect.com/science/article/pii/S2468896716300568

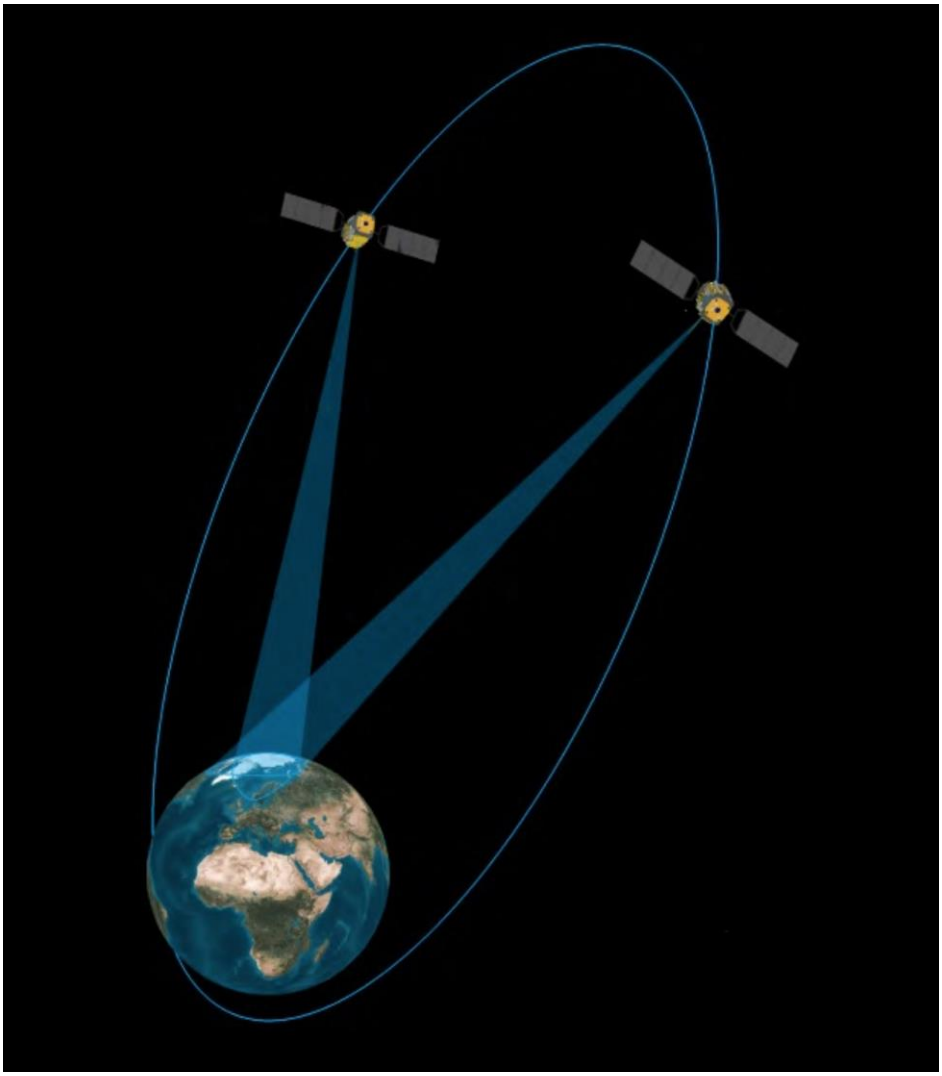

Figure 4: Highly-Elliptical Orbit option for Arctic communications and observations (graphic courtesy of Norwegian Space Center)

VHS Data Exchange System

VDES is a two-way VHF ship communications system for global use and small VDES LEO satellites may provide affordable two-way maritime communications in the future.

ESA is using the Norwegian NorSat-2 satellite (Figure 5) to test this new technology[10], sending data such as sea ice maps, emergency messages and possible GNSS augmentation service information over the existing VHF-based AIS system that already exists onboard vessels.

10 https://www.esa.int/Our_Activities/Space_Engineering_Technology/From_satellites_to_the_sea_VDES_offers_global_link_for_ships

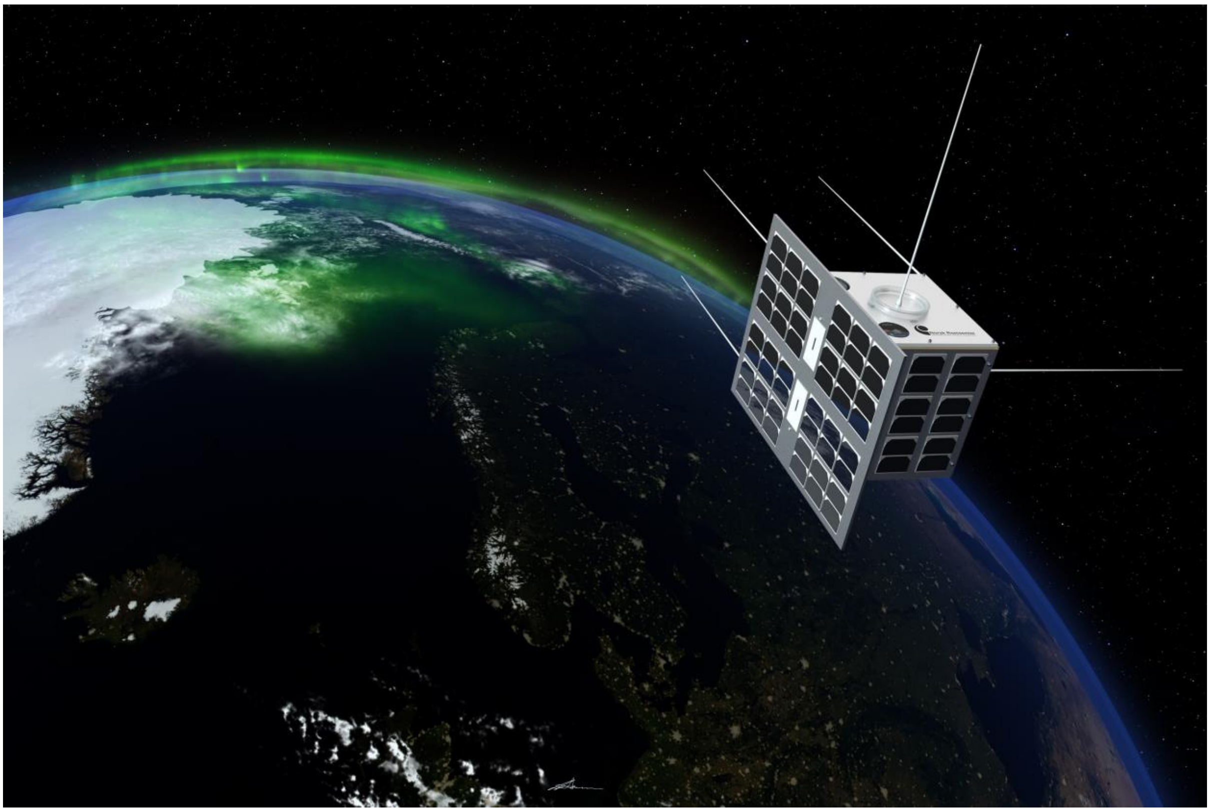

Figure 5: Norwegian Norsat-2 satellite used to test the VDES capability.

Shared public-private investment

Funding of development of telecommunications infrastructure in the Arctic should consider public-private partnerships funding models in addition to purely commercial or government solutions. These mixed models can entail cooperation among national and regional levels of government, the private sector, non-profit organizations, and between Arctic states. The plans and priorities of many Arctic nations explicitly address improvement of telecommunications services both on land and at sea, pointing to benefits for education, employment, interpersonal connection and access to services. A focus on the same technical issues, relatively small market and overlapping geographic coverage provide good motivation for cooperation on this topic.

3. SATELLITE NAVIGATION

3.1. CURRENT USES OF GNSS

The current uses of Global Navigation Satellite Systems (GNSS) are discussed in greater detail in the preceding EU-PolarNet report D3.3. For reference a quick list of the main applications for polar operations is given below.

- General navigation & position
- Timing information
- Sensor data for EO validation
- GNSS reflectometry

3.2. LIMITATIONS OF CURRENT GNSS IN THE POLAR REGIONS

GNSS are comprehensively used in the Polar Regions, as they are elsewhere. For many polar applications the available accuracy is sufficient, but some limitations exist for users at higher latitudes. Issues related to GNSS refer generically to all constellations including GPS[11] (US), Galileo[12] (Europe – Figure 6), GLONASS[13] (Russia) and BeiDou[14] (China). Issues and developments specific to a specific constellation will refer to it by name.

While the accuracy of positioning with GNSS and space-based augmentation systems[15] (SBAS) at higher latitudes is lower, it appears to be sufficient for applications involving integration of GNSS with EO. The most evident gap is in the geographical coverage of the two primary SBAS – WAAS[16] and EGNOS[17] – but no evidence has been found that this gap is of significant concern to the scientific and operational user communities.

[11] https://www.gps.gov/
[12] http://galileognss.eu/
[13] https://www.glonass-iac.ru/en/
[14] http://en.beidou.gov.cn/
[15] https://www.gsa.europa.eu/european-gnss/what-gnss/what-sbas
[16] https://www.faa.gov/about/office_org/headquarters_offices/ato/service_units/techops/navservices/gnss/waas/
[17] https://ec.europa.eu/growth/sectors/space/egnos_en

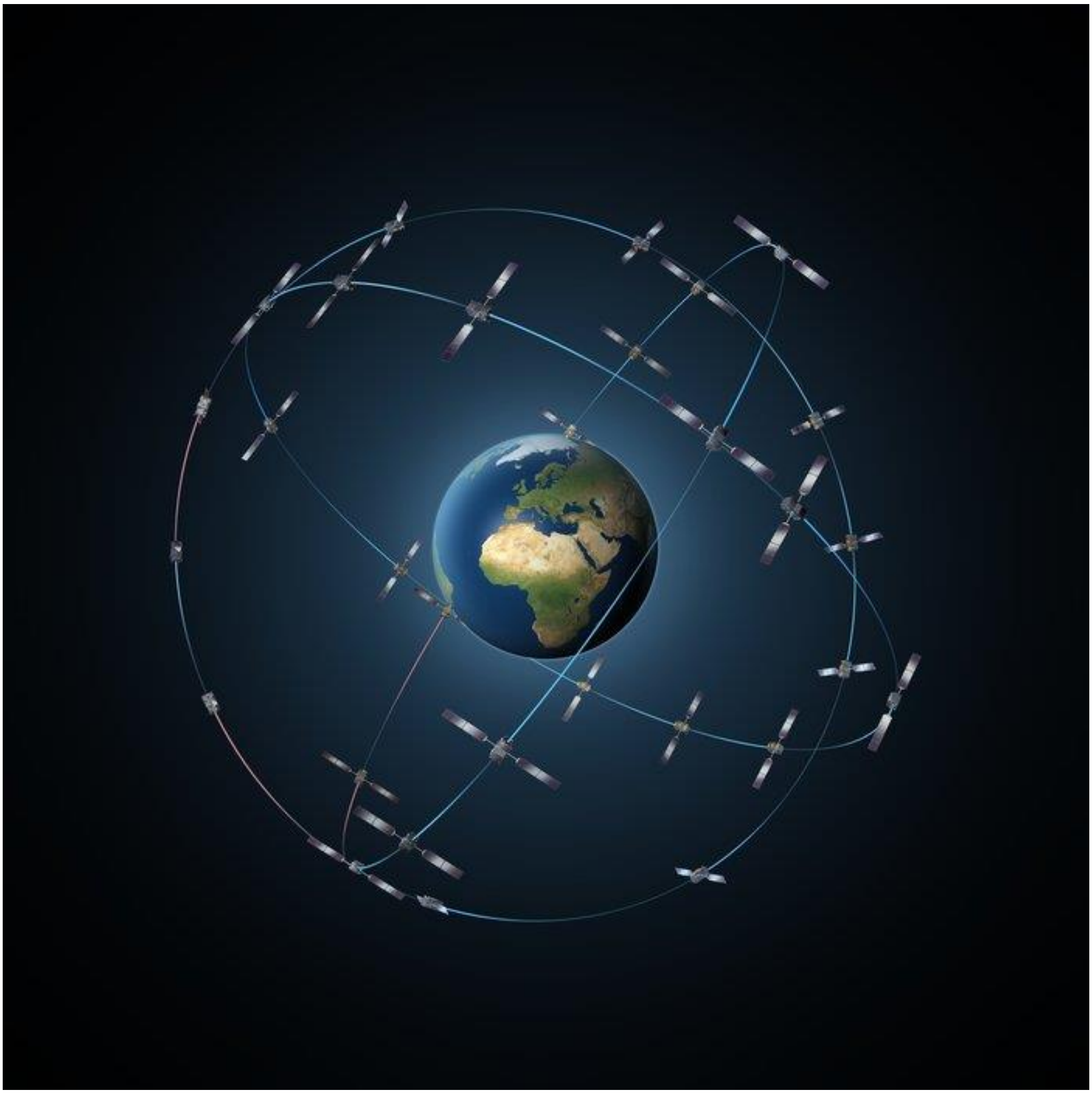

Figure 6: The complete Galileo constellation consisting of 24 satellites in 3 orbital planes.

Coverage of current GNSS constellations

The orbit inclination of the GPS and Galileo satellite constellations is 55º, and a higher orbit inclination of 65º for GLONASS (Figure 7). Therefore, GNSS satellites are visible at low elevation angles from the Polar Regions.

This geometry results in good horizontal position accuracy (HDOP[18]) since there is visibility of more orbital planes at once. The same geometry also raises the risk of crayoning effects in areas of steep terrain. Conversely this geometry also results in reduced vertical position accuracy (VDOP[19]).

Another consequence is a higher noise level in observations from larger ionospheric effects due to longer path length at lower elevation angles. These positional and noise effects are reduced for the higher inclination GLONASS system which was designed to better support the high latitude regions of Russia.

[18] https://gssc.esa.int/navipedia/index.php/Positioning_Error

[19] https://gssc.esa.int/navipedia/index.php/Positioning_Error

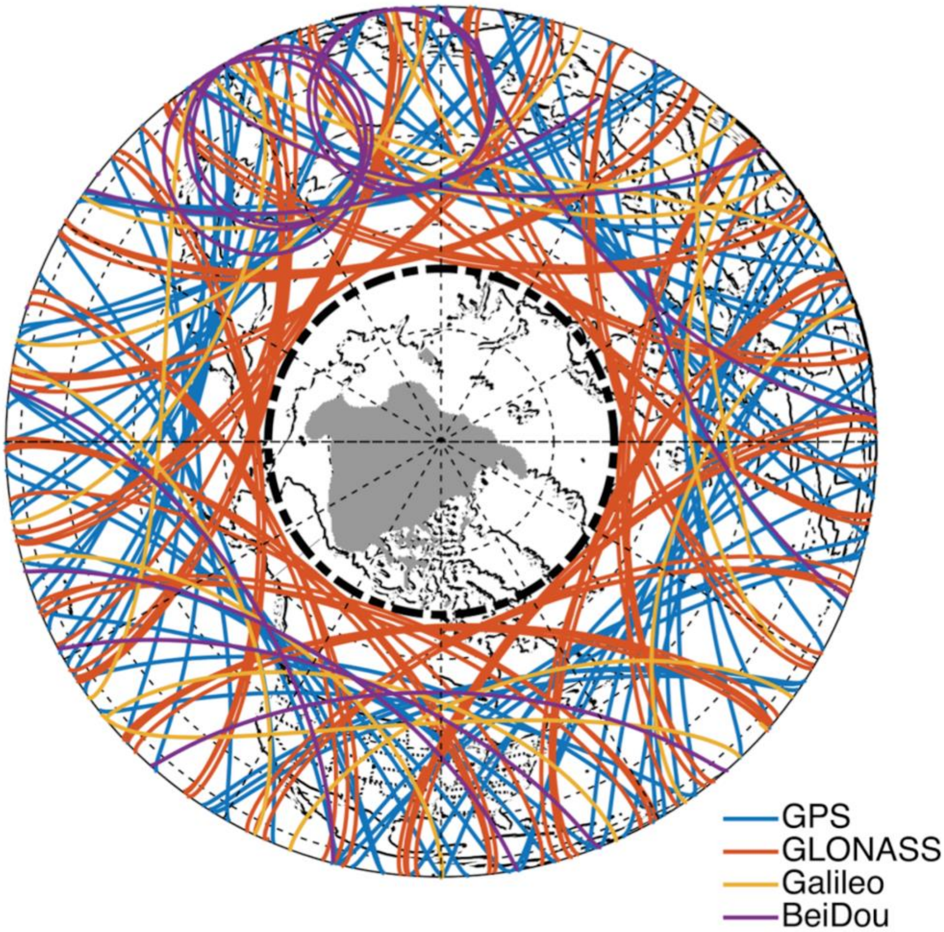

Figure 7: Ground tracks of all GNSS core constellations (Graphic from 'GNSS Integrity in the Arctic', Reid et al, 2015)

Maritime navigation requirements are strict for horizontal positioning given the vertical position is known to be sea level. The integrity bound, known as the Horizontal Alert Limit[20] (HAL), is 25 metres for open water operations. Precision applications, such as drilling and mapping, require an order of magnitude better accuracy at 2.5 – 5 metres. These limits have been agreed upon by the International Maritime Organization[21] (IMO).

Aviation navigation, specifically for GNSS-based precision approach in the Arctic requires an integrity bound known as the Vertical Alert Limit (VAL) of 35 meters. Due to the aforementioned orbit inclination issue, there is a fundamental difficulty with vertical guidance using GNSS navigation.

Augmentation services

The performance of GNSS is improved by regional Satellite-based Augmentation Systems (SBAS – Figure 8). This includes the European Geostationary Overlay Service[22] (EGNOS). SBAS improves the accuracy and reliability of GNSS information by correcting signal measurement errors and by providing information about the accuracy, integrity, continuity and availability of its signals.

For safety of life applications, the integrity of the GNSS signal must be assured. Integrity provides a measure of trust which can be placed in the correctness of the information supplied by a navigation

[20] https://gssc.esa.int/navipedia/index.php/Integrity

[21] http://www.imo.org

[22] https://www.gsa.europa.eu/egnos/what-egnos

system. SBAS information includes an integrity message, informing users in the event of signal problems.

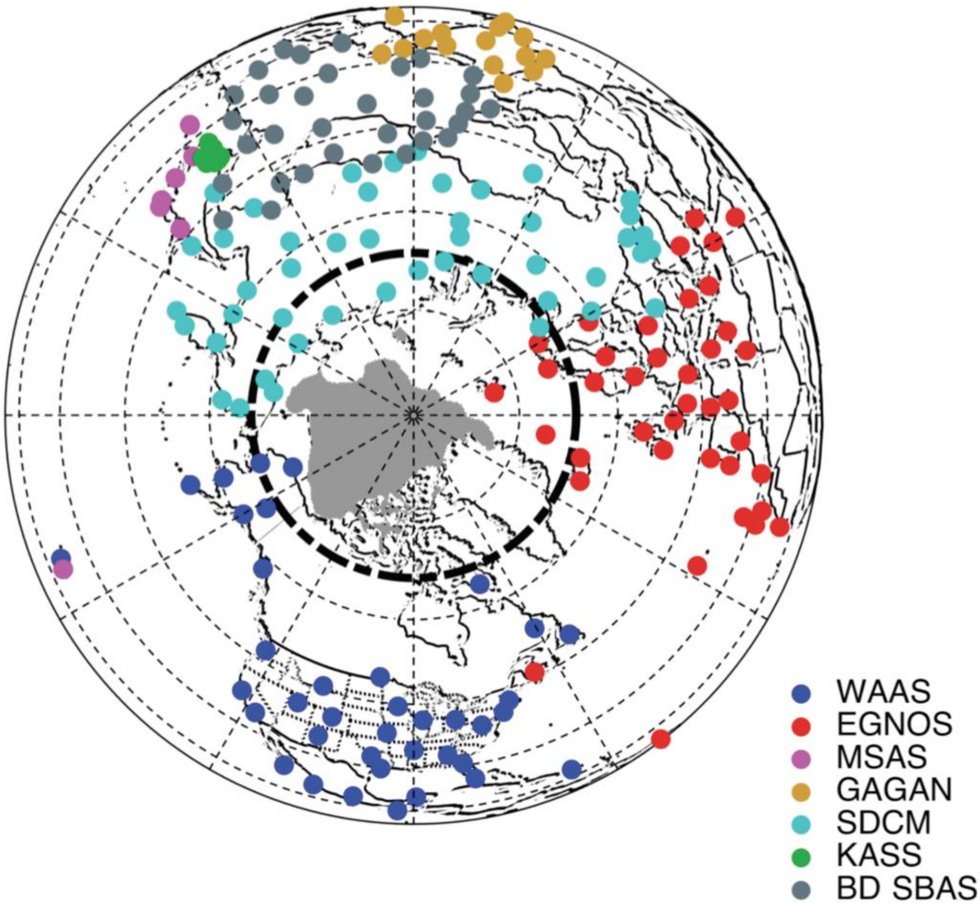

Figure 8: SBAS ground segment reference stations for current and future systems (Graphic from 'GNSS Integrity in the Arctic', Reid et al, 2015)

SBAS consists of ground-based ranging and integrity monitoring stations[23] (RIMS) (Figure 8), plus space-based geostationary satellites to deliver the information to users. The extent of RIMS coverage at high latitudes and the poor visibility of GEO satellites present a significant obstacle to the expansion of SBAS-based navigation in the Polar Regions (Figure 9). This currently limits the opportunities and applications supported by EGNOS and other SBAS networks.

[23] https://gssc.esa.int/navipedia/index.php/EGNOS_Ground_Segment

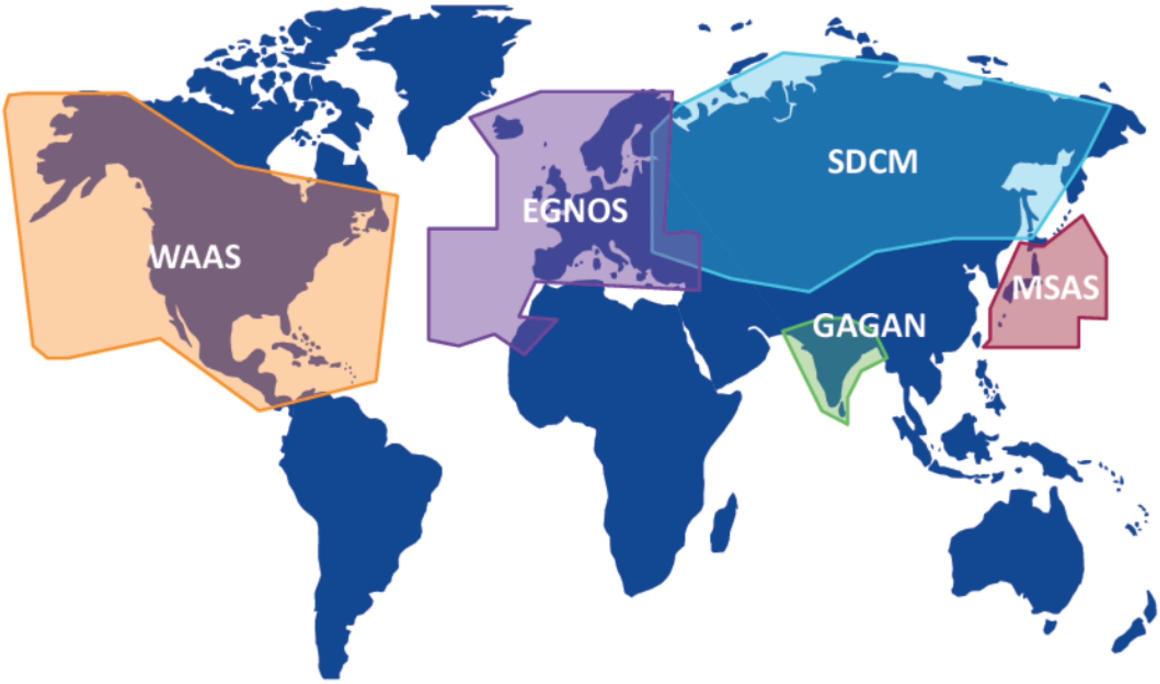

Figure 9: EGNOS & other national SBAS coverage (courtesy GSA)

For example, it is not possible to use the EGNOS LPV[24] (Local Performance with Vertical guidance) 200 service. This provides lateral and angular vertical guidance on aircraft landing approach without the need for visual contact with the ground until an aircraft is 200 feet above the runway. GNSS-based precision approach may be especially relevant to small airports in the Arctic as they typically are not equipped with ground infrastructure for instrument landing.

Ionospheric corrections

GNSS radio signals travel from the satellite to the receiver on the ground, passing through the Earth's ionosphere. Ionospheric scintillation introduces errors to GNSS signals, with the magnitude dependent on the number of electrons encountered. The size of delay is dependent on several factors including GNSS signal frequency and time of day but ranging errors of 1 to 15 metres are typical. Correction of these errors is handled by ionospheric models and combinations of observations from different signal frequencies. During space weather events, the modelled corrections are no longer accurate, and the receivers are unable to calculate an accurate position based on the satellites overhead.

Some consider the space weather effect an important issue in the Polar Regions, especially in the auroral zone (Figure 10) where the errors are largest. However, the auroral zone is relatively far south of most of the Arctic and so the effects are limited geographically.

[24] https://www.gsa.europa.eu/news/egnos-lpv-200-enables-safer-aircraft-landings

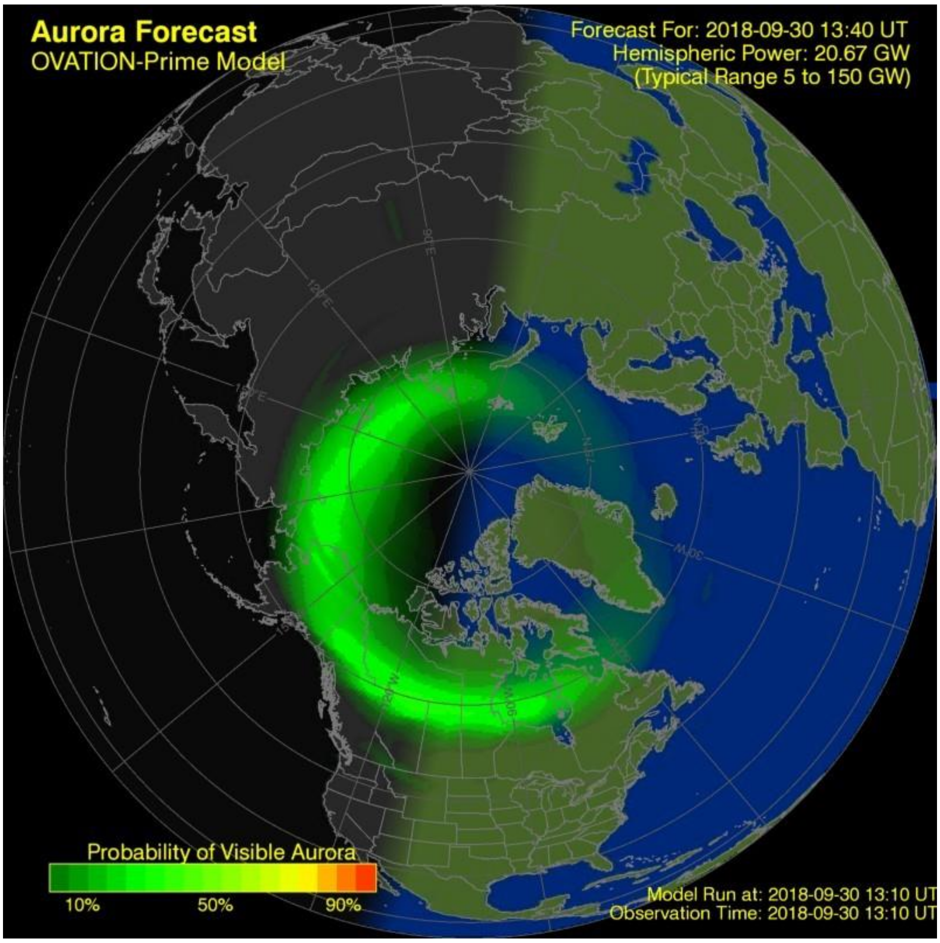

Figure 10: Aurora ionosphere forecast (Graphic from NOAA Space Weather Prediction Center[25])

3.3. Future Options to Address GNSS Limitations

The challenge for use of GNSS in the Polar Regions is expansion of available augmentation services to ensure accuracy and integrity of the signal. The following options will be part of future GNSS use in the Polar Regions.

Expanded augmentation services

Expansion of SBAS services to cover the Polar Regions will allow expanded use of GNSS services, including for safety-of-life applications. It is the stated aim to expand SBAS services to the Arctic. For example, the EGNOS Safety of Life Service Implementation Roadmap[26] includes extension of the commitment areas for key service levels up to 72ºN in Norway and Finland is planned for 2018.

In part expansion of SBAS will be reliant on improved communications links given the inadequate coverage of geostationary communications satellites. Options are described in section 2.3, and include alternative non-GEO solutions such as LEO, SatAIS and HEO if they carry an SBAS payload. If plans for extending communication links in the Arctic and Antarctic are pursued, delivery of augmentation services would be an additional benefit and may remove the need for additional local infrastructure (e.g. airport ILS[27] or GBAS[28]) in some cases. Consideration of the cost relative to benefit of new ground-based infrastructure compared to the cost of a space component will be necessary.

[25] https://www.swpc.noaa.gov/products/aurora-30-minute-forecast
[26] https://egnos-user-support.essp-sas.eu/new_egnos_ops/documents/egnos-safety-life-service-roadmap
[27] https://en.wikipedia.org/wiki/Instrument_landing_system
[28] https://gssc.esa.int/navipedia/index.php/GBAS_Systems

SBAS expansion will also require new ground infrastructure such as expanded geographic coverage of ranging and integrity monitoring stations (RIMS).

GNSS system modernisation

GNSS and associated augmentation systems will continue to develop and deliver an improved level of service.

For example, the European Commission has been developing modernisation plans for Galileo to ensure that the system responds to new challenges. The EC's stated approach is to capture the strategic priorities of its Member States, including in the Arctic, ensuring that the needs of high latitude areas are included. Communicating the specific challenges posed by the Arctic region will be through open dialogue with countries in the region, plus ESA, GSA and industry to establish priorities.

Specific aspects of Galileo modernisation include:

- plans for Advanced Receiver Autonomous Integrity Monitoring (ARAIM) for safety of life navigation in the Arctic (see below)
- an ionosphere forecast service (launched 2018), which will make it possible to quickly react to sudden signal degradation[29]

Dual-frequency and multi-constellation receivers

Use of dual frequency in modern receivers addresses issues with vertical and horizontal accuracy. The Galileo constellation is a key enabler of the required E1/E5 dual frequency.

Receivers capable of receiving signals from multiple constellations, including GLONASS, will also improve horizontal and vertical positional accuracy due to the higher orbital inclination suited to the Polar Regions.

Advanced RAIM Receiver Autonomous Integrity Monitoring

SBAS is ultimately limited in service area by the reference stations shown in Figure 8. ARAIM (Advanced RAIM Receiver Autonomous Integrity Monitoring)[30] requires no such infrastructure and has the added benefit of delivering the same level of service in both the northern and southern hemisphere.

RAIM methods make use of redundancy in available GNSS signals to check the relative consistency among them and in case of detection, isolate and remove the source of the error. Advanced RAIM extends this service to support the required vertical integrity to support air navigation. ARAIM provides an additional source of GNSS integrity information, independent of SBAS.

ARAIM is a key part of the GALILEO modernisation plans.

[29] https://www.gsa.europa.eu/newsroom/news/new-ec-service-monitors-ionosphere-gnss-users

[30] https://gssc.esa.int/navipedia/index.php/ARAIM

4. SATELLITE EARTH OBSERVATION

4.1. CURRENT USES OF SATELLITE EARTH OBSERVATION

Satellite observation systems have a unique role in the Polar Regions, providing the only option for regular, year-round, wide-area, repeatable, consistent measurements of many parameters required to study and operate in the Polar Regions. The current uses of satellite remote sensing in the Polar Regions is discussed in greater detail in the preceding EU-PolarNet report D3.3. For reference a quick list of the main applications for polar operations is given below.

- Environmental impact assessment
- Monitoring human impact
- Engineering design
- Overland travel
- Ship navigation & operations
- Risk management
- Emergency response
- Weather forecasting
- Climate change adaptations

4.2. LIMITATIONS OF CURRENT SATELLITE EARTH OBSERVATION IN THE POLAR REGIONS

Limitations of current EO data in the Polar Regions are either lack of in-orbit instruments to collect required geophysical measurements or limitations with existing systems in terms of spatial resolution, accuracy, revisit frequency, continuity of observations etc.

A number of recent and ongoing European activities have investigated the user requirements for satellite observing systems in the Polar Regions. These include the ESA POLARIS study, Copernicus Polar Experts Group, the ESA Space & Arctic Task Force and the ESA Arctic Mission System Study. A summary of the main areas of current requirements from these studies is provided below. The full detail of each study is not provided exhaustively in this section, but only the main topic areas which emerged from these studies and maintaining a focus on those related to polar operational needs.

<u>Limitations of existing EO systems</u>

While existing or planned EO missions are generally applicable to most areas of current use, the POLARIS study identified a number of deficiencies resulting from inadequate spatial resolution, temporal resolution and inability to combine data from different sensors. The gaps in existing information products and services derived from EO sensors to meet user requirements are shown in Figure 11.

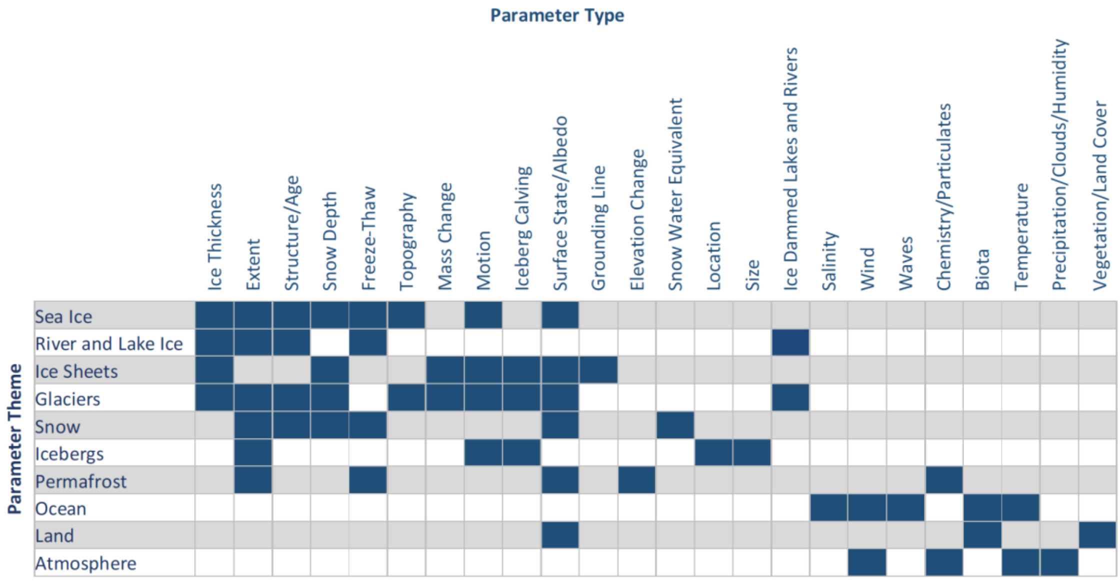

Figure 11: Polar information gaps identified by the ESA POLARIS requirements study[31].

Improved sea ice and iceberg information

The POLARIS study identified dominant information gaps for polar operations as the need to have improved sea ice (Figure 12) and iceberg information for applications such as maritime operations. This will require more detailed sea ice and iceberg products at a higher temporal resolution than is currently available.

Sea ice thickness, stage of development, structure, motion, extent, and topography were identified as parameters where significant gaps exist. Ensuring this information is timely and reducing current latency is critical. In addition, having more accurate information about snow on sea ice will be required to reliably establish these information parameters.

The ability to identify icebergs within sea ice and forecast iceberg motion are other capacities which are key to the communities involved in polar ship operations.

[31] https://www.arcticobserving.org/images/pdf/Board_meetings/2016_Fairbanks/14_Final-Summary-Report_2016-04-22.pdf

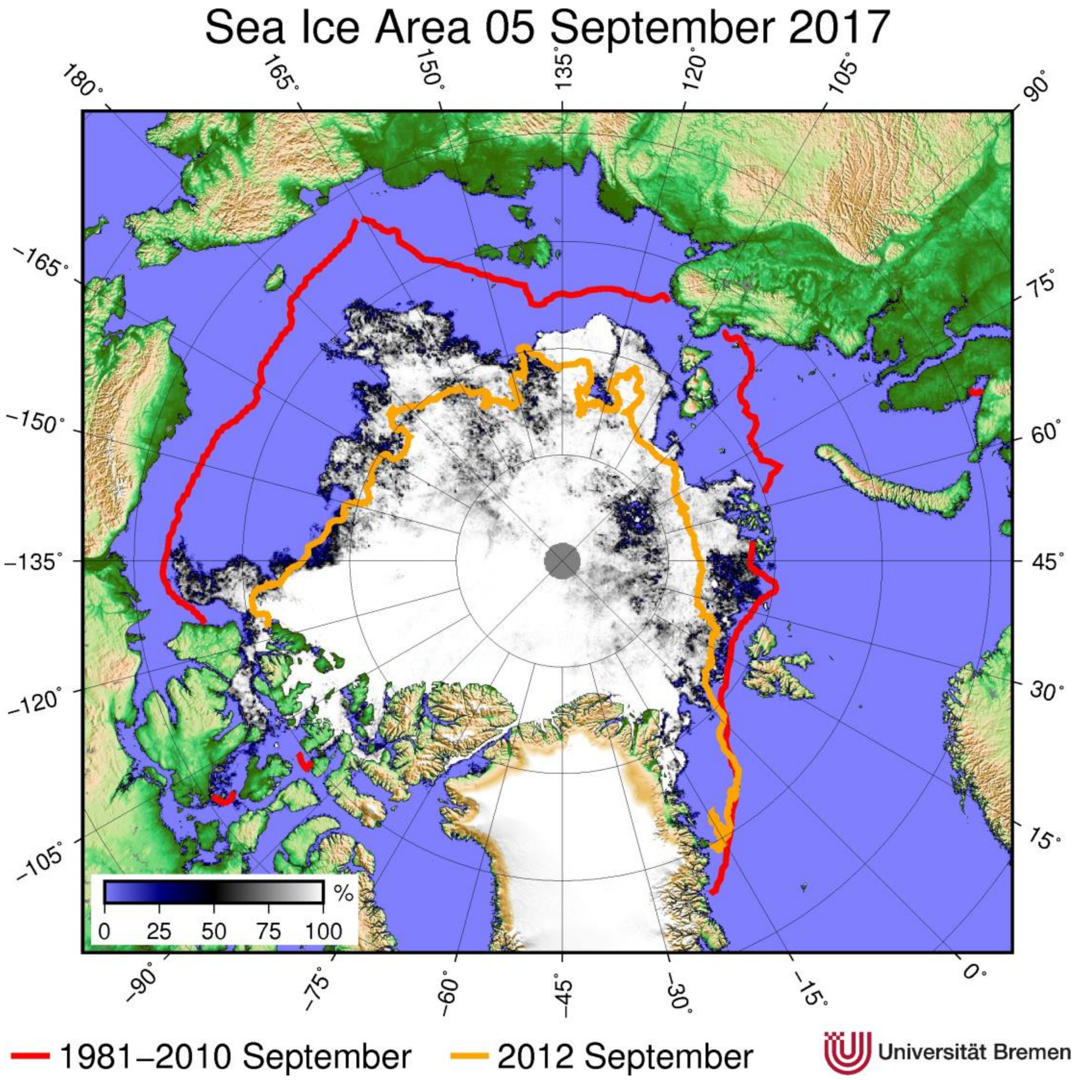

Figure 12: Sea ice concentration compared to previous years derived from AMSR-2 microwave radiometer (Graphic courtesy of University of Bremen)

The requirements for a Copernicus Polar Mission also identified floating ice parameters (including sea ice extent / concentration / thickness / type / drift velocity / thin sea-ice distribution / iceberg detection/volume change & drift) as a top priority.

Polar meteorology

Current and forecast weather information are a vital part of support to polar operations. Satellite imagery is a key input and regular overpasses of meteorological satellites provide vital observational data as inputs to forecasts and NWP (numerical weather prediction) models.

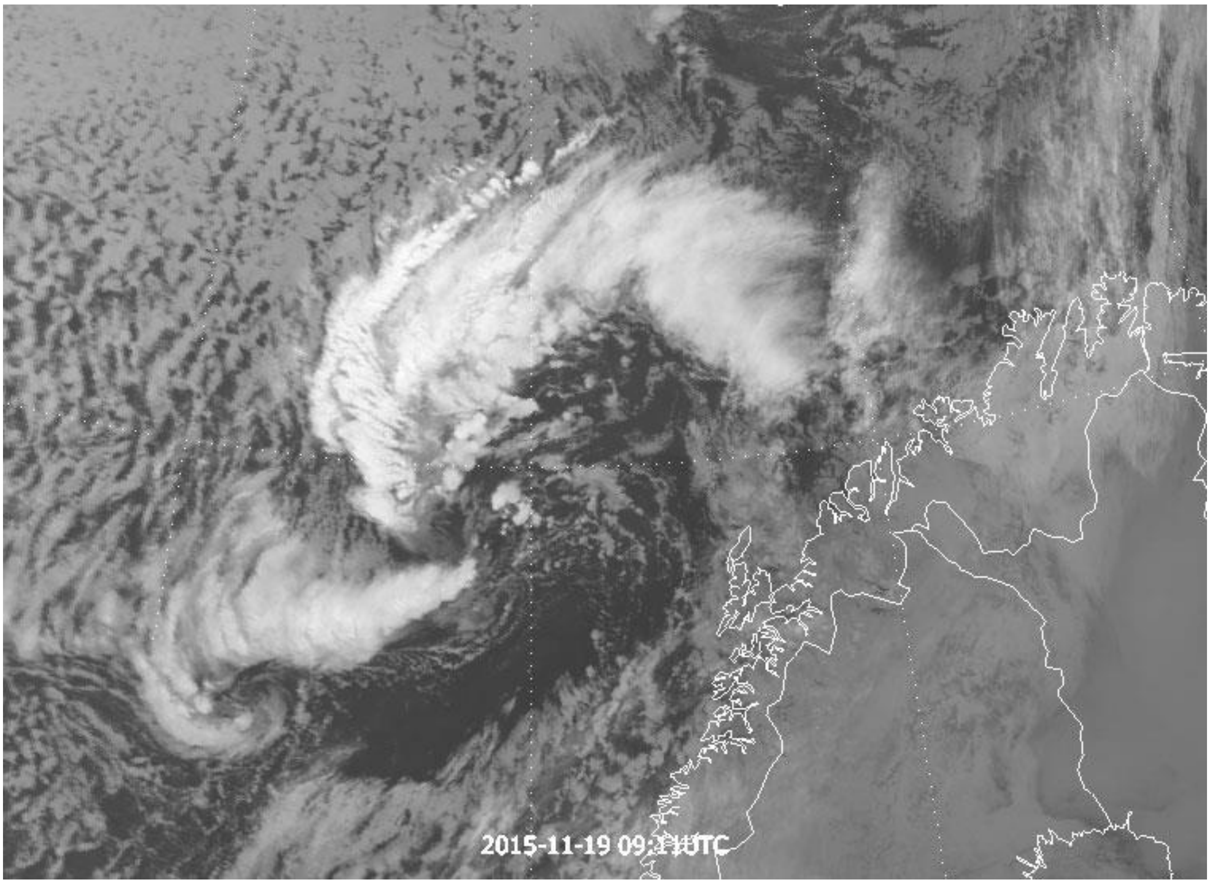

Figure 13: Metop-B satellite image showing a polar low off the coast of Norway (Graphic courtesy Norwegian Meteorological Institute).

Metop[32] and other polar orbiting meteorological satellites provide regular weather observations (Figure 13), but less frequently than geostationary satellites such as Meteosat[33] which do not have visibility of higher latitudes. A requirement exists to fill this gap and provide satellite observations with a temporal repeat of 1 hour or better.

4.3. Future Options to Address Satellite Earth Observation Limitations

The following options are currently in development to address some of the identified limitations and requirements for improvement.

Improvement of existing EO satellite capabilities

Current EO missions are frequently part of a series of satellites which evolve over time. For example, the eighth Landsat satellite is currently in orbit, delivering optical imagery with improved spatial and spectral resolution compared to previous versions.

Satellite remote sensing capabilities will continue to be launched with expanded and improved sensors, coverage, and availability that can provide integrated, synoptic region-wide measurements and that can capture diverse types of data.

Europe already foresees the continuity of the Copernicus missions, including extensions of the current missions, with enhanced capabilities and delivering wider coverage (Figure 14). This long-term evolution of EO satellite series will answer a number of the current EO limitations in the Polar Regions

[32] https://www.esa.int/Our_Activities/Observing_the_Earth/MetOp
[33] https://www.eumetsat.int/website/home/Satellites/CurrentSatellites/Meteosat/index.html

by extending and enhancing current missions, expanding the range of missions and developing a long-term plan for the next generation of satellites.

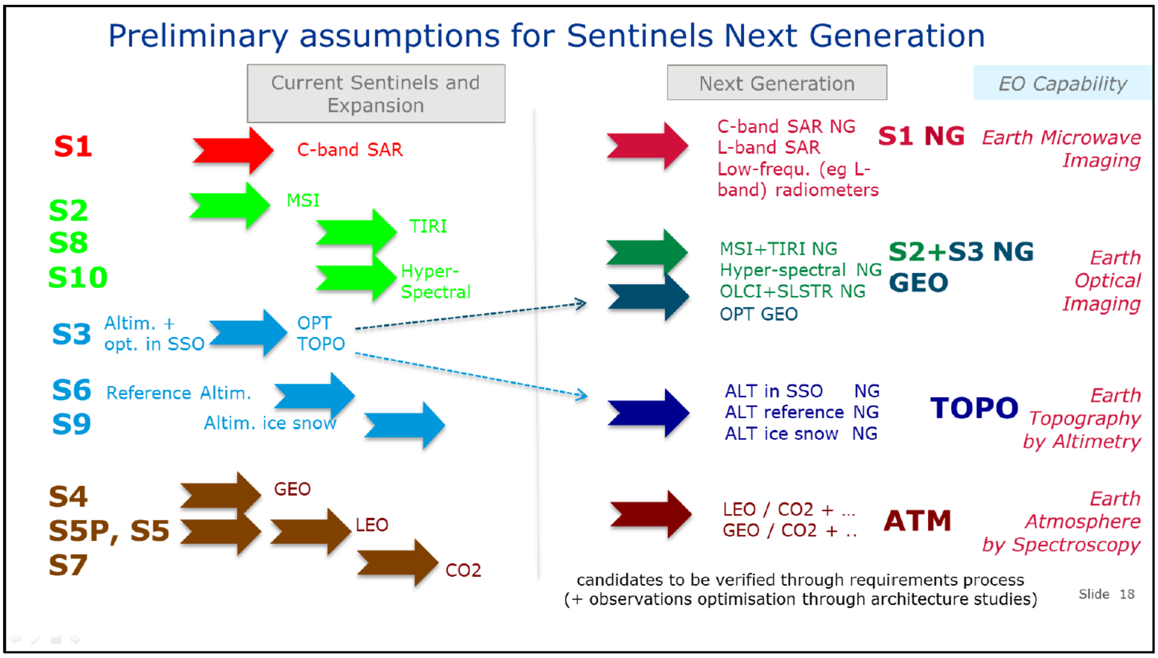

Figure 14: Planned evolution of Copernicus missions (Graphic courtesy of EC)

Sentinel expansion mission

In addition to extension of the current Sentinel missions, the Copernicus Space Component will evolve to fill gaps not addressed by current satellites. A dedicated Polar and Snow Sentinel satellite expansion mission is being considered. The geographic focus is on the Arctic, but observations over the Antarctic area have not been omitted and are considered as much as possible.

The initial requirements are specified by the EC and the Copernicus Polar Expert Group, summarised in User Requirements for a Copernicus Polar Mission - Phase 1 & 2 reports[34]. A number of possible mission concepts which meet the specified parameter performance have been identified. These are briefly summarised below.

- Imaging PMR: A Passive Microwave Imaging Multi-Spectral Radiometer with ~10km resolution and spectral channels for sea ice concentration and sea surface temperature retrievals and a swath width that offers at least daily revisits in the Polar Regions.
- SARIn altimeter: A follow-on mission to CryoSat-2, specialised in nadir altimetry in Polar Regions.
- Single Pass-InSAR: A Synthetic Aperture Radar imager that includes single pass interferometric capabilities as demonstrated with Tandem-X. Such capability could be implemented as a passive bistatic follower with Sentinel-1.

Feasibility and preliminary definition studies for three polar mission concepts listed below started in 2018.

- Copernicus Imaging Microwave Radiometer
- Copernicus Polar Ice and Snow Topographic Mission
- L-band SAR Mission

[34]https://cimr.eu/sites/cimr.met.no/files/documents/EU_PolarExpertsGroup_Report_P1.pdf and https://cimr.eu/sites/cimr.met.no/files/documents/EU_PolarExpertsGroup_Report_P2.pdf

The Sentinel expansion missions are envisaged for launch in the mid-2020s and will be operated in parallel with the current Sentinel constellation. Accordingly, they will be based on a monitoring approach with a stable operation plan, provision of operational products and services including cal/val[35] activities.

ESA Arctic framework

ESA are currently investigating options to address the specific needs of the Arctic region. A set of activities, led by the ESA Arctic Task Force, includes an Arctic Mission System Study. Depending on requirements, this may lead to development of new observing mission for the Arctic. More details of this activity are provided in section 6.3.

Private sector investments

Continued commercial investment in space infrastructure will provide new observation capabilities for the Polar Regions. Commercial satellite operators (e.g. DigitalGlobe[36]) already provide high-resolution sub-metre optical imagery for the globe, including the Arctic and Antarctic.

More recently IcEye[37] is developing a constellation of 18 microsatellites (Figure 15) equipped with SAR instruments which aims to deliver frequent repeat imagery. A key target market for IceEye will be maritime users in the Arctic.

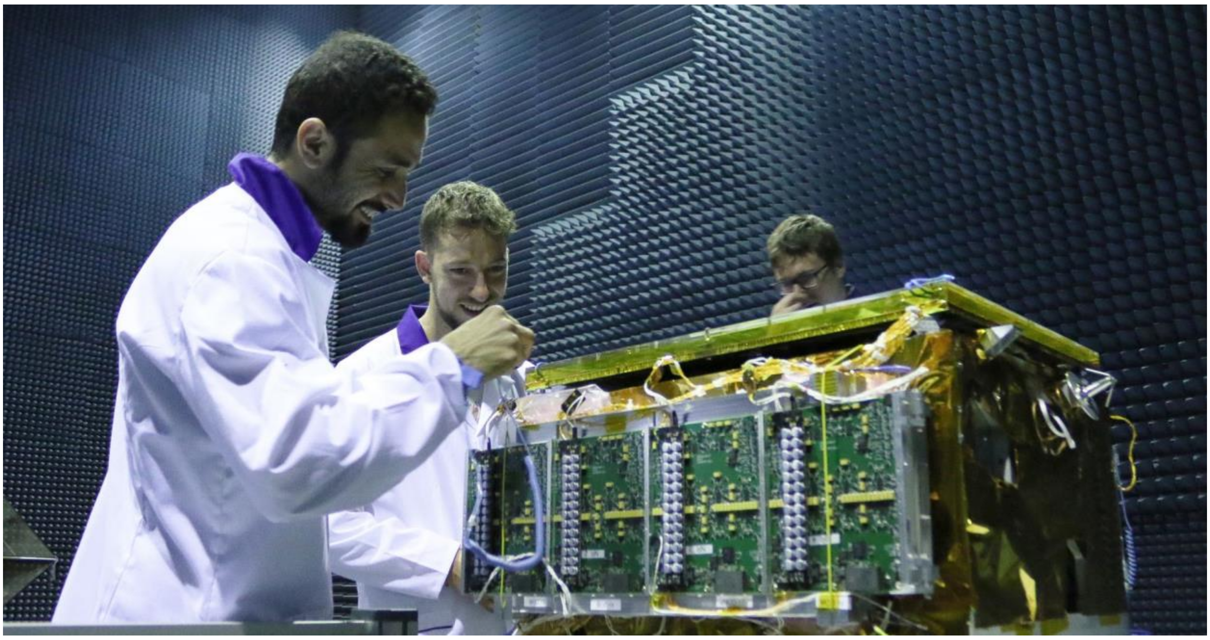

Figure 15: The ICEYE X1 satellite during testing (Image courtesy of ICEYE).

Given the growth in small and micro-satellite developments, it is likely that other commercial organisations will invest in space segment capabilities which may address current gaps in polar observations if there is resulting revenue to support them.

[35] https://earth.esa.int/web/sppa/home
[36] www.digitalglobe.com/
[37] www.iceye.com

5. OTHER SPACE TECHNOLOGIES

A number of other space technologies with current or potential application to polar operations were mentioned in the preceding D3.3 report. Gaps in these technologies and options for improvement are briefly described below.

5.1. SPACE BASED VESSEL TRACKING

Satellite AIS (Automatic Identification System) allows the extension of AIS vessel tracking from areas in range of terrestrial receivers to the open ocean and remote areas such as the Arctic and Antarctic. There are a number of beneficial applications in the Polar Regions for integrated EO and AIS information, including vessel tracking and as part of iceberg detection services.
Norway operate the AISSat[38] satellites (Figure 16) which monitor maritime traffic in near-real-time by detecting AIS from ships to provide information about their position, speed and direction.

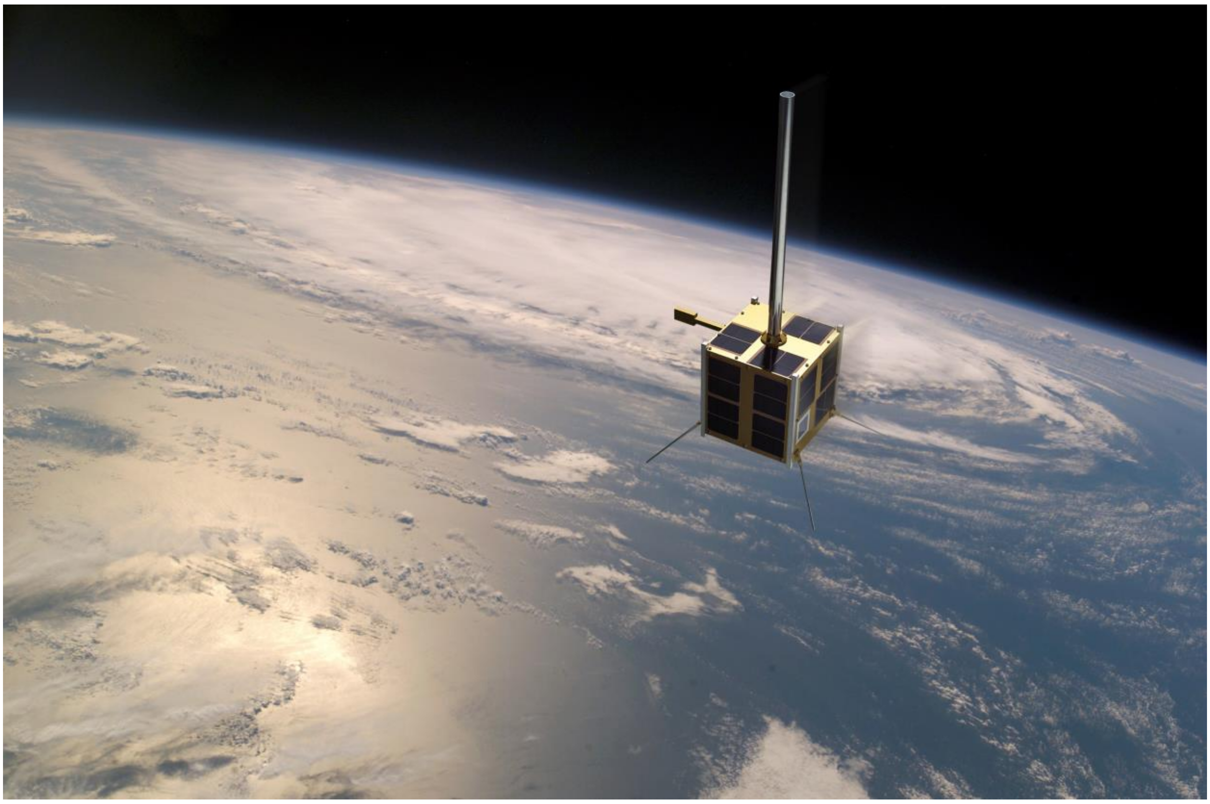

Figure 16: The Norwegian satellite AISSat-1 in orbit (Graphic from NRS/FFI/NASA/Nyhetsgrafikk.no)

There are suggestions to develop dual purpose AIS / EO missions, but also a growing number of third-party satellites which include the relatively low-cost AIS capability as an additional payload. For example, the Iridium NEXT constellation will carry hosted SatAIS payloads to deliver a real-time vessel tracking solution.

5.2. ADS-B

Automatic dependent surveillance—broadcast[39] (ADS–B) is a surveillance technology in which the Aircraft position from GNSS is broadcast, allowing the aircraft to be tracked. This has clear benefits for air traffic management and flight following for aircraft operators in the Polar Regions.

[38] https://www.romsenter.no/eng/Norway-in-Space/Norway-s-Satellites
[39] https://www.faa.gov/nextgen/programs/adsb/

This is again limited by availability of good near-real-time communication links in the Polar Regions. Wider application is therefore dependent on the same developments referred to in section 2 addressing satellite and other communications gaps.
Iridium is in the process to introduce ADS-B receivers as hosted payloads on Iridium NEXT, Iridium's next-generation constellation of LEO satellites which will enable a global aircraft surveillance service.

5.3. DATA ACCESS AND CYBERINFRASTRUCTURE

The increasing volume of satellite and other data covering the Polar Regions has wide-ranging implications. Ensuring optimal use of this data flow requires use of latest technologies in information management, interoperable communications, and computation.
The required cyberinfrastructure is currently lacking for the Polar Regions. This limits the ability of all operators to easily discover, access and exploit the data which is being acquired in the Arctic and Antarctic. The following limitations are highlighted by the POLARIS and other studies.

- Data integration – combining data from multiple sources and of multiple types
- Information products – access to derived information by non-expert users rather than raw satellite data
- Information discovery – ability to easily discover information distributed over multiple sites and organisations
- Information access – overcoming issues related to accessing data in the right format and over low-bandwidth connections
- Training – education in proper use of EO information products
- Access to high performance computing

The solution to many of the previous limitations of Data access and cyberinfrastructure could be supported through use of data platforms. These new cloud-based infrastructures provide integrated access to numerous sources of polar information and alongside tools for information discovery, access, processing and training.
The Polar Thematic Exploitation Platform[40] (Polar TEP) is one example of a developing platform targeted towards polar users. It provides online discovery and data access, options for processing data and accessing scalable compute resources, access to a virtual development environment allowing development of new processing routines, and an online community tools to support learning and new developments.

[40] https://portal.polar-tep.eo.esa.int

6. OPPORTUNITIES FOR IMPROVED LINKAGES WITH EUROPEAN SPACE ACTIVITIES

Operators in the Polar Regions make use of a wide range of space assets provided by multiple international agencies and commercial providers. Free and open data policies make access to information significantly easier for organisations, companies and multi-national projects operating in the Polar Regions.

The space programmes of the EU and ESA include important elements such as Galileo and Copernicus. Use of these assets is already significant and likely to grow as the range and uptake of applications increases. It is therefore important for the polar community to engage with the development of the space programmes and ensure polar needs are taken into consideration where relevant.

A number of options for linkages between European polar operators and the European space programmes are highlighted below.

6.1. Galileo & EGNOS

The European GNSS programme is funded and owned by the EU, with European Commission and the European GNSS Agency (GSA) having overall responsibility for the programme, managing and overseeing the implementation of all activities on behalf of the EU. The GSA governance structure includes representatives from all EU countries.

The European Commission is developing modernisation plans for Galileo, to ensure that the system responds to new challenges in the use of GNSS, including those in the Arctic. These developments are based on the strategic priorities of the member states; hence it is important that polar operators communicate requirements through GSA national representatives, collaborative European bodies such as the European Polar Board and at associated community events[41].

As an example of the engagement with specific GNSS issues in the Arctic, Finland organised the Challenges in Arctic Navigation workshop in April 2018[42] (Figure 17). This addressed how GNSS is a solution to some of the difficulties posed by navigation in the Arctic and how satellite navigation itself can be improved in the region.

[41] https://www.gsa.europa.eu/newsroom/events

[42] https://www.gsa.europa.eu/newsroom/news/gnss-addressing-challenges-arctic-navigation

Figure 17: Challenges in Arctic Navigation workshop (source European GNSS Agency)

6.2. COPERNICUS

The European Copernicus programme is coordinated and managed by the European Commission. It is implemented in partnership with the Member States, the European Space Agency (ESA), the European Organisation for the Exploitation of Meteorological Satellites[43] (EUMETSAT), the European Centre for Medium-Range Weather Forecasts[44] (ECMWF), EU Agencies and Mercator Océan[45]. In addition to the space component, Copernicus also includes the Copernicus services and an in-situ observations element.

ESA is responsible for the technical coordination of the Copernicus space component, defining the overall system architecture and its evolution on the basis of user requirements, coordinated by the Commission. This is the context for the current extension and expansion of the Sentinel satellite series described in section 4.3.

The requirements gathering for the planned polar mission was led by a Polar Expert Group established by DG GROW[46]. Inputs were received from the members, complemented by additional relevant documentation such as ESA Polaris study reports from Polar View (April 2016), IGOS Cryosphere 2007 report, Copernicus Maritime Surveillance Service User Workshop report by EMSA (December 2016), report of Polar Space Task Group (PSTG) on "Strategic Plan: 2015-2018" (November 2015), DG RTD/ESA

[43] https://www.eumetsat.int
[44] https://www.ecmwf.int/
[45] https://www.mercator-ocean.fr/en/
[46] http://ec.europa.eu/growth/

Climate Task Force report (November 2016) and CMEMS 2016 Position paper on Polar and snow cover applications.
Ongoing engagement with these groups, member state delegates to both ESA and Copernicus, and related community events[47] will communicate the ongoing need for evolution of the Copernicus programme, including the Sentinel[48] and third-party[49] space components, in situ observation elements[50] and changes to the Copernicus services[51].

6.3. European Space Agency Arctic Framework

The European Space Agency is responsible for development of Europe's space capability, based on the requirements of its member states. A resolution in 2016 outlined the need for ESA to address the needs of specific areas, including the Arctic.
As a result, an ESA Arctic Task Force has been established to develop a proposal for a programmatic framework related to activities specific to the Arctic. This includes representatives from all ESA Directorates, including Earth Observation. Initial work reviewed past and current activities supporting the Arctic region. A preliminary Concurrent Design Facility (CDF) Study for the Arctic was completed in 2017. The outcome of the CDF study and following consultations, an "Arctic Mission System Study" was started under the DPTD[52] (Discovery, Preparation, and Technology Development) Programme. Two parallel studies shall propose potential mission architectures including space segment, ground segment, data management and downstream applications, based on consolidated user requirements. The output of this study is anticipated to act as inputs to a follow-on Phase A feasibility study.

These industry studies will complete in 2019 and hence outputs for potential mission architectures that might fill some of the limitations in the Polar Regions are currently not known.

Some early indications point to a number of mission concepts emerging from the requirements assessment phase of these studies. These are listed below as an illustration but are not yet confirmed. It is likely that similar requirements emerge from these studies as have been summarised elsewhere in this report. It has already been noted that any following developments will need to avoid overlap with related polar national, commercial or Copernicus developments.

- Shipping and fisheries monitoring using SatAIS and multi-frequency SAR systems
- Polar weather monitoring system using a low-Earth or both optical constellations or highly-elliptical orbit concepts.
- Arctic Data Centre to provide integrated access to comprehensive data for the Arctic region.

[47] http://www.copernicus.eu/events
[48] http://www.copernicus.eu/main/sentinels
[49] http://www.copernicus.eu/main/contributing-missions
[50] http://www.copernicus.eu/main/insitu
[51] http://www.copernicus.eu/main/services
[52] https://www.esa.int/Our_Activities/Preparing_for_the_Future/Discovery_and_Preparation

7. CONCLUSIONS

A summary of the key conclusions from this document are provided below.

- Operators in the Polar Regions use space technologies to support a large and growing part of their activities. However, there are some key gaps in capabilities at higher latitudes. Communicating and addressing these limitations through the recognized channels to the responsible agencies should be coordinated by European Polar Board.
- A number of relevant future developments of space technologies will address the Polar Regions in the coming years. Due to the geographic proximity of the Arctic and representation in the EU from several Arctic states, current requirements are dominated by the agenda in the Arctic. The requirements of the Antarctic and Southern Ocean should be emphasized to ensure development of similar space assets where possible.
- Poor visibility of GEO satellites at high latitudes, combined with a lack of ground infrastructure, results in a significant gap in good communications links in the Polar Regions. Opportunities for developing new technologies to address this gap (including HEO and satellite constellations) should be pursued either as European, national, commercial or partnership developments.
- GNSS options are adequate for many applications in the Polar Regions, but limited access to augmentation services prevents use for aviation and other safety-of-life applications. The costs and benefits of expanding space or ground based augmentation services should be considered to widen use of GNSS in the Polar Regions.
- The Copernicus and ESA programmes are actively developing options for polar Earth observing missions. This is a very welcome development which should fill important gaps in current observations of the Arctic and Antarctic. New capabilities in monitoring sea ice for maritime operations and improved observations for polar weather meteorology are high-priority options in this context.
- The growing volume of data about the Polar Regions from multiple sources creates a problem concerning how to provide easy access and ensure exploitation by the widest possible user base. The development and use of new cloud-based data platforms and cyberinfrastructure will be a key part of national polar programmes and data management initiatives to achieve this.
- The future plans of the European Space Programme are developed with input from representatives of EU and ESA member states. The requirements of polar operators and national polar activities in both the Arctic and Antarctic should be coordinated and clearly communicated to national representatives to ensure they are included in future development plans where relevant.
- Currently there is no overarching strategy for polar space infrastructure. The European Polar Board is well positioned to coordinate and prioritise a strategy for polar space assets across satellite communications, navigation and observation. This would bring together the needs of operators, scientists, national interests, plus linked international programmes and space agencies.