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Deliverable 6.6

Requirements for new Sentinel missions and better communication and data transfer in the Arctic Ocean

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Table of Contents

1. Abstract

The report aims to provide an updated review of data requirements for new Sentinel missions and better communication and data transfer in the Arctic Ocean in the context of their relevance and applicability to the specific needs of operators and users of research icebreakers and ships of opportunity for their activities in the Arctic regions. The introductory part defines the scope of this study and used approach and presents a collection of reference documents that were used as a baseline for following review. General operational and scientific needs of the ARICE users are shortly discussed. The main part addresses separately the requirements for satellite Earth Observations (with a special focus in Copernicus Sentinel missions), satellite navigation, and satellite communications, first presenting a brief overview of the current status of each system, then going in detail through their specific limitations and future options for improvements. The main focus is on the needs and requirements of the ARICE community, i.e. users and operators of research icebreakers and ships of opportunity, operating in the high Arctic. Three case studies of using satellite-based support for field campaigns in the Arctic Ocean are presented to highlight the operational requirements for ice navigation and operations in ice-covered waters. Finally, the study shortly addresses the needs for data access and infrastructure and discusses the improved use of European space activities. Main conclusions are offered in the last section of D6.6.

2. Introduction

2.1 Document scope and structure

This report D6.6 “Requirements for new Sentinel missions and better communication and data transfer in the Arctic Ocean” ‘(D6.6) is a component of the ARICE WP6, the work package which aims in using the increased marine traffic in the Arctic to implement a “programme of ships and platforms of opportunity” in the Arctic Ocean and identifying key technologies that could lead to an improvement of ship-based and autonomous measurements in ice-covered seas. The deliverable D6.6 falls under Task 3.2 which is focused on identifying new technological solutions for environmental data collection. The main goal of this report is to address data requirements for new Sentinel missions and better communication and data transfer in the Arctic Ocean. This collaboration on technology and innovation for automatic data collection will lead to a more efficient use of the research icebreakers and the growing number of commercial vessels in the Arctic.

The ARICE deliverable D6.6 builds on, extends and updates two former reports by the EU PolarNet project, namely “Survey of existing use of space assets by European polar operators” and “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”, published in 2017 and 2018, respectively. The current report addresses more recent developments and adds new information on space technologies important for operations of research icebreakers and ships of opportunity in the Arctic regions. The existing uses of space assets by European polar operators are shortly reviewed with a focus on activities and components, most relevant for research icebreakers and ships of opportunity to increase efficiency of field operations and observational data provision in the Arctic. The limitations and gaps in space assets and technologies which the polar community requires or anticipates for support to science and operations in the Arctic regions are addressed for satellite Earth Observations, communication, and navigation. The future solutions and on-going developments, particularly within the Extension and Expansion of the Copernicus Space Component, but also relying on currently implemented or planned improvements to existing satellite systems for communication and navigation (or multi-purpose systems), are finally discussed and assessed in terms of fulfilling requirements from polar operators in the Arctic.

The primary focus of this report is on space assets which support polar operations, in particular field activities by research icebreakers and ships of opportunity that will likely play an increasing role in the future Arctic observing system due to the expected growth in commercial marine traffic in the Arctic Ocean. The multiplicity of direct use of space data in polar science is only addressed where it overlaps with the operational need or is directly linked to Arctic observations as provided with use of research icebreakers and ships of opportunity. 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 and has been a subject of many scientific reports and publications, exclusively devoted to the wide scope of scientific applications.

In summary the ARICE deliverable D6.6 has the following objectives:

- Briefly summarize current capabilities and limitations, relevant for efficient use of research icebreakers and ships of opportunity in the Arctic for each of the main space technologies, including satellite Earth Observations, communication and navigation.
- Highlight the gaps in current capabilities and review potential options to address these gaps for each of the main space technologies, according to requirements from users of research icebreakers and ships of opportunity, operating in the Arctic regions.
- Summarize the current and planned activities in the European Space programs and synergies with other to address specific polar needs.

It is important to note that design, developments and implementations of the space-based platforms and their missions require long periods (up to several years or even decades) and there is currently a significant effort from ESA and the EC to address polar requirements. While clearly defined plans have been established for extensions of the current Copernicus satellite missions and establishing new future Copernicus missions (expansion missions) the next decade, planning of multiple activities is currently multi-stranded and significant new developments or directions can be likely explored in the coming years. Therefore, 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 focused exclusively on identifying gaps in capabilities and the requirements to address these gaps. It is not the aim of this report to prioritize 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 implementation of new satellite missions.

The document contains the following sections:

Section 1: Presenting the executive summary.

Section 2: Summarizing the document scope, structure, and approach.

Section 3: Introducing different types of users' needs in the context of ARICE.

Section 4: Addressing status and requirements for satellite Earth Observation.

Section 5: Addressing status and requirements for satellite navigation.

Section 6: Addressing status and requirements for satellite communication.

Section 7: Addressing satellite vessel tracking and dual-purpose solutions.

Section 8: Presenting the case studies in the Arctic Ocean of (i) satellite-based support for ice navigation and research activities during the CAATEX and UAK expeditions and (ii) broad-band satellite communication during the MOSAiC campaign, and (iii) satellite-based support for improved situational awareness during the SODA cruises.

Section 9: Addressing requirements for data access and infrastructure.

Section 10: Addressing opportunities from improved synergies with European space activities.

Section 11: Summarizing the main conclusions.

2.2 Approach

In recent years a considerable amount of effort has been invested by space agencies and governmental organizations, and to determine the requirements for space assets for those who live and work 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 and/or complementary topics. Therefore, instead of initiating any new, the most likely duplicative, survey for user requirements in polar regions, the adopted approach has been based on detailed reviewing of existing policy documents, JRC Special Reports, including high-level user requirements studies (e.g., User Requirements for a Copernicus Polar Mission by PEG I (Duchossois et al., 2018a), II (Duchossois et al., 2018b)and III (Nordbeck et al., 2021), and the most recent report on the Europe's Earth Observations, Satellite Navigation and Communication Missions and Services for the benefits of the Arctic (Boniface et al., 2021)), white papers by the international expert groups and outputs from the international high-level fora (e.g., Arctic Observing Summit and OceanObs'19), detailed reports provided as deliverables from the relevant EU projects (e.g., EU PolarNet, KEPLER, and INTAROS), and the most recent materials, presented during the European Polar Science Week organized by ESA and EC at the end of 2020. The up-to-date information on on-going developments and new space-based initiatives has been also harvested from the relevant websites and digital sources.

When reviewing the aforementioned sources, the main focus was always on capabilities, gaps, requirements and future solutions of the space assets for the applications relevant for safe, efficient and innovative operations of research icebreakers and ships of opportunity in the Arctic waters. The list of the main documents is presented in the following section (Table 1) while other sources are referenced directly in the report text.

2.3 Reference documents used in this report

Table 1. List of reference documents and other materials (from the newest to oldest ones).

Regulation (EU) 2021/696 of the European Parliament and of the Council of 28 April 2021 establishing the Union Space Programme and the European Union Agency for the Space Programme and repealing Regulations (EU) No 912/2010, (EU) No 1285/2013 and (EU) No 377/2014 and Decision No 541/2014/EU	https://eur-lex.europa.eu/legal-content/BG/TXT/PDF/?uri=CELEX:32021R0696&from=EN
JRC Technical Report "Europe's Earth Observation, Satellite Navigation, and Satellite Communications Missions and Services for the benefit of the Arctic - Inventory of current and future capabilities, their synergies and their societal benefits" (2021)	https://op.europa.eu/en/publication-detail/-/publication/ef630f61-a6ff-11eb-9585-01aa75ed71a1/language-en
EU Special Report "EU space programmes Galileo and Copernicus" (2021)	https://www.eca.europa.eu/Lists/ECADocuments/SR21_07/SR_EUs-space-assets_EN.pdf
User Requirements for a Copernicus Polar Observing System – Phase 3 Report - Towards Operational Products and Services (2021)	https://www.copernicus.eu/sites/default/files/DEFIS_Copernicus_Polar_report_210414_HV-NC-29-144-EN-N.pdf
Proceedings of the 2021 conference on Big Data from Space (2021)	https://publications.jrc.ec.europa.eu/repository/handle/JRC125131
AEC Connectivity Working Group's Report on Arctic Connectivity and Sustainability (2021)	https://arcticeconomiccouncil.com/wp-content/uploads/2021/05/aec-cwg-report-050721-6.pdf
Materials from the 2020 European Polar Science Week available online (2020)	http://eo4polar.esa.int/programme
JRC Science for Policy Report "Europe's space capabilities for the benefit of the Arctic" (2020)	https://publications.jrc.ec.europa.eu/repository/handle/JRC118965
European GNSS Agency "GNSS User Technology Report" (2020)	https://www.gsa.europa.eu/sites/default/files/uploads/technology_report_2020.pdf
EU KEPLER deliverable D3.3 "Final report on research gaps of space-based Arctic monitoring" (2020)	https://kepler380449468.files.wordpress.com/2021/06/kepler-deliverable-report-3.3.pdf
EU KEPLER deliverable D3.4 "Report on research gaps in integration/assimilation of space-based and in-situ observations to improve Arctic monitoring and forecasting capabilities" (2020)	https://kepler380449468.files.wordpress.com/2021/06/kepler-deliverable-report-3.4-1.pdf
EU KEPLER deliverable D6.6 "Best practice guide for EO information use by research vessels and stations" (2020)	https://kepler380449468.files.wordpress.com/2021/07/kepler-deliverable-report-d6.6.pdf

EU KEPLER deliverable D4.1 "Harmonisation and improvement of sea ice mapping products" (2020)	https://kepler380449468.files.wordpress.com/2021/06/kepler-deliverable-report-4.1.pdf
Challenges in Arctic Navigation and Geospatial Data - User Perspective and Solutions Roadmap (2019)	https://julkaisut.valtioneuvosto.fi/bitstream/handle/10024/161989/LVM_2020_1.pdf
Report for EEA implementation of cross-cutting COPERNICUS activities 'Arctic In-situ Data Availability' (2019)	https://insitu.copernicus.eu/library/reports/CopernicusArcticDataReportFinalVersion2.1.pdf
EU Council Conclusions on "Council conclusions on Space solutions for a sustainable Arctic" (2019)	https://www.consilium.europa.eu/en/press/press-releases/2019/11/29/space-solutions-for-a-sustainable-arctic-council-adopts-conclusions/
OceanObs'19 Whitepaper "From Observation to Information and Users: The Copernicus Marine Service Perspective" (2019)	https://www.frontiersin.org/articles/10.3389/fmars.2019.00234/pdf
Arctic Council Task Force on Improved Connectivity in the Arctic Report "Improving Connectivity in the Arctic" (2019)	https://oaarchive.arctic-council.org/handle/11374/2369
IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. Chapter 3 Polar Regions (2019)	https://www.ipcc.ch/srocc/chapter/chapter-3-2/
EU KEPLER deliverable D1.1 "Stakeholder Needs: Maritime Sector Needs" (2019)	https://kepler380449468.files.wordpress.com/2021/06/kepler-deliverable-report-1.1.pdf
User Requirements for a Copernicus Polar Mission – Phase 2 Report – High-level mission requirements (2018)	https://publications.jrc.ec.europa.eu/repository/bitstream/JRC111068/2018.1802_src_polar_expert_group_-_phase_2_-_final_report_20180726final2.pdf
User Requirements for a Copernicus Polar Mission – Phase 1 Report – User Requirements and Priorities (2018)	https://www.copernicus.eu/sites/default/files/2018.1802_src_polar_expert_group_-_phase_1_-_final_report_20180726final.pdf
EU PolarNet deliverable D3.6 "Gap analysis highlighting the technical and operational requirements of the European Polar Research Programme for satellite applications" (2018)	https://eu-polarnet.eu/wp-content/uploads/2020/11/EU-PolarNet_D3.6_Gap_analysis_of_space_programmes_final.pdf
Mercator Ocean and CMEMS Report "CMEMS requirements for the evolution of the Copernicus Satellite Component" (2017)	https://marine.copernicus.eu/sites/default/files/media/pdf/2020-10/CMEMS-requirements-In_Situ.pdf
EU PolarNet deliverable D3.3 "Survey of existing use of space assets by European polar operators" (2017)	https://eu-polarnet.eu/wp-content/uploads/2020/11/D3_3_Survey_of_existing_use_of_space_assets.pdf
Arctic Council Task Force on Telecommunications Infrastructure in the Arctic Report	https://oaarchive.arctic-council.org/handle/11374/1924

"Telecommunications infrastructure in the Arctic: a circumpolar assessment" (2017)	
AOS2016 Whitepaper "Polaris: User Needs and High-Level Requirements for Next Generation Observing Systems for the Polar Regions" (2016)	https://www.arcticobserving.org/images/pdf/Board_meetings/2016_Fairbanks/14_Final-Summary-Report_2016-04-22.pdf
EU Joint Communication "An integrated European Union policy for the Arctic" (2016)	https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52016JC0021&from=EN

2.4 Acronyms and definitions

AIS	Automatic Identification System
CMEMS	Copernicus Marine Environment Monitoring Service
CIMR	Copernicus Imaging Microwave Radiometry mission
CMS	Copernicus Security Service – Maritime Surveillance
CSC	Copernicus Space Component
CSS	Copernicus Security Service
EEZ	Exclusive Economic Zone
EGNOS	European Geostationary Navigation Overlay System
EGNSS	European GNSS
EO	Earth Observation
EOL	End Of Life
ESA	European Space Agency
EUMESAT	European Organisation for the Exploitation of Meteorological Satellites
EUSPA	European Union Agency for the Space Programme
FOC	Full Operational Capacity
GEO	Geosynchronous Equatorial Orbit
GEO	Group on Earth Observations
GMDSS	Global Maritime Distress and Safety System
GNSS	Global Navigation Satellite System
HR	High Resolution
LEO	Low Earth Orbit
LRIT	Long Range Identification and Tracking
MEO	Medium Earth Orbit
METOP-SG	METOP Second Generation

ML	Machine Learning
MTG	Meteosat Third Generation
NWP	Numerical Weather Prediction
OS	Open Service
PEG	Polar Expert Group
PNT	Positioning, Navigation and Timing
SAF	Satellite Application Facility
SaR	Search-and-Rescue
SAR	Synthetic Aperture Radar
SAT-AIS	Satellite AIS (Automatic Identification System)
SGC	SAR Galileo Coverage
SGSC	SAR/Galileo Service Centre
SIC	Sea Ice Concentration
SIGINT	Signals Intelligence
SLSTR	Sea and Land Surface Temperature Radiometer
VDES	VHF Data Exchange System
VHR	Very High Resolution
VMS	Vessel Monitoring System
VTS	Vessel Traffic Services

3. Users' needs in the context of the ARICE

The relevance of the EU space-based capabilities, related to satellite Earth observation, navigation, and communication for users in the Arctic extends from the maritime sector applications to disaster risk management, monitoring essential climate variables and regulatory compliance, search and rescue services, communication, and satellite service disruptions. The satellite sensors provide a unique source of information for monitoring and analyzing various geophysical parameters related to the climate, environment, safety, operations planning, and for sustainable development goals. Different satellite programs are essential tools to provide continuous observations both for reliable operational services and for climate- and environmental assessment, modelling, and forecasting. In the context of ARICE, which focuses on extended and optimized use of research icebreakers and ships of opportunity for collecting in situ observations in the Arctic Ocean, two main aspects of users' needs can be identified. Operational needs are directly related to field applications and include requirements for safe and cost-efficient maritime operations in ice-infested waters, relying on PNT (Positioning, Navigation and Timing) information and a timely provision of environmental information (e.g., weather forecasts, sea ice maps and iceberg positions). According to the operational needs, the Arctic satellite communications system should provide broadcasting, broadband, backhaul, distress and safety services. Science-related needs are aligned more directly with collection of in situ Earth observations by research icebreakers and potential ships of opportunity to be used in synergy with remote sensing products for monitoring, assessing, and predicting the effects of climate change and environmental impacts in the Arctic and their global feedbacks.

3.1 Operational needs

Operational service products including service products for ice-charting, short-term ice prediction and metocean forecasting are pivotal for safe and efficient operations in Arctic waters. Critical information on sea ice characteristics (not only sea ice concentration but also ice thickness, type, deformation and drift) and iceberg detection (including size and distribution) derived from satellite imagery is needed to help protect vessels in the Arctic from ice collision, optimize ship routing and field operations in ice-covered waters, and meet the requirements of the Polar Code. Real-time reports and short-term forecasts of ice, weather, and sea conditions are needed to guide journeys and ensure safety of research icebreakers and ships of opportunity in the Arctic. In addition to sea ice cover and thickness, important information includes tracking of free-floating ice and icebergs, intensity and direction of wind, waves, and ocean currents, air and water temperatures, and visibility (due to snow or fog). Long-term projections of ice conditions are needed for designating Arctic shipping routes. Reliable positioning based on GNSS is instrumental for safe navigation in Arctic waters. Highly accurate DGPS techniques are often crucial for advanced research icebreaker operations, including installation and retrieval of in situ observing platforms, targeted sampling, coring and drilling activities, and operating remote or autonomous underwater, surface or airborne vehicles. The functional requirements from the Polar Code for ship communication include two-way voice/data communication available in all points along the operating routes, means for two-way communication for search and rescue purposes (including aeronautics), and appropriate communication means to enable tele medical assistance. In case of research icebreakers and ships of opportunity, maritime broadband connection is required for enabling access to high-resolution satellite products, supporting navigation and operations in ice-covered waters and for satellite transmission of observational data in the near-real time (NRT). Maritime broadband connections are used for vessel operations, internet, and email access for marine and science crews on icebreakers and ships of opportunity.

3.2 Science-related needs

Science-related needs in the context of ARICE activities by research icebreakers and potential ships of opportunity are largely focused on monitoring, understanding, and predicting climate change and environmental impacts in the Arctic as well as its feedbacks with global climate. Continuous monitoring of polar regions, both for scientific environmental research and provision of operational services and products, relies largely on the combined use of Earth Observation satellite data and of in situ observations collected by a variety of platforms. In the Arctic Ocean the continuous and year-round provision of in situ observations, with an emphasis on winter observations, require support from icebreakers (both research vessels and ships of opportunity). When used in a synergy, space-based and in situ observations in the Arctic Ocean allow for constraining (via assimilation) and validation of numerical models, applied for near-real-time analyses, forecasting, climate and environmental predictions, and atmospheric and ocean reanalyses. They contribute to addressing a majority of the European Polar Research Priorities and key research questions, identified by the EU-PolarNet Report (D2.1, 2016), in particular to (i) Polar Climate Systems, (ii) Cryosphere, (iii) Polar Biology, Ecology and Biodiversity and (iv) Human Impacts. Priority space-based parameters defined by the PEG I Report User Requirements and Priorities for a Copernicus Polar Mission (Duchossois et al., 2018) include a wide scope of variables, relevant for the ARICE users' needs: floating ice parameters (sea ice thickness – thin and thick, ice freeboard, concentration/extent, drift, snow depth on ice, iceberg detection and drift, ice surface temperature), and ocean parameters (sea level anomaly, mean dynamical topography, sea surface temperature, surface albedo).

4. Satellite Earth Observations

4.1 Current capabilities of Satellite Earth Observations

Satellite observation systems have a unique role in the Arctic, 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 use of satellite remote sensing for Earth observations in the Polar Regions was discussed in greater detail in the EU-PolarNet Report (D3.3, 2018) and the JRC Technical Report "Europe's Earth Observation, Satellite Navigation, and Satellite Communications Missions and Services for the benefit of the Arctic - Inventory of current and future capabilities, their synergies and their societal benefits" (Boniface et al., 2021). For reference a quick list of the main applications for polar operations is given below.

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

Copernicus services, current Sentinel missions (as of June 2021) and their relevance to ARICE users

Copernicus operationally provides data and services to end users, based on satellite measurements complemented with non-space data. In Copernicus, the satellites component consists of satellites and their supporting ground stations. The satellites currently consist of two groups: the six Copernicus' own Sentinel satellites[1] and contributing (third party) missions of which there are about 30[2].

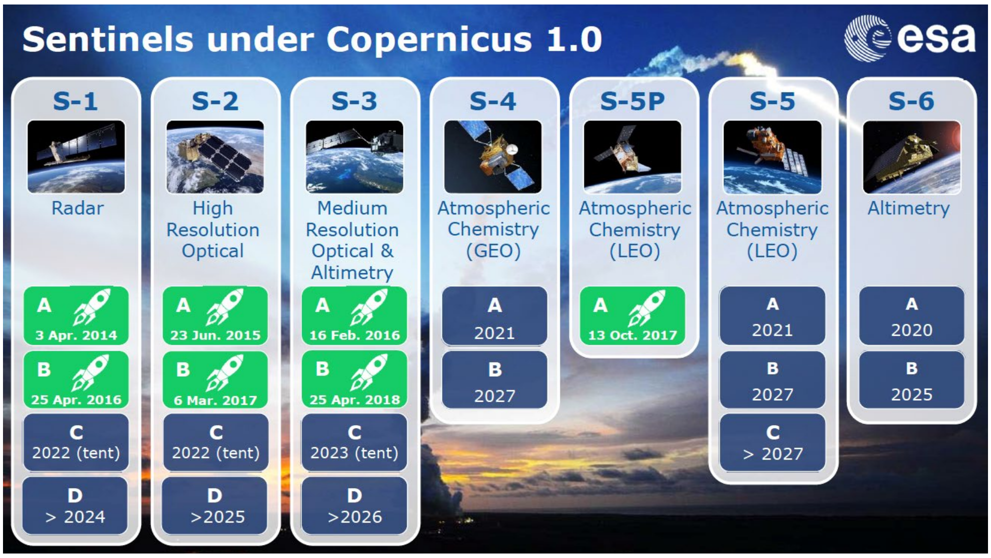
The Copernicus program offers six operational thematic services in the fields of atmosphere monitoring, marine environment monitoring, land monitoring, climate change, emergency management and security. All provide products relevant for the Arctic. The most relevant service for

[1] https://sentinels.copernicus.eu/web/sentinel/missions

[2] https://spacedata.copernicus.eu/web/cscda/data-offer/missions

the ARICE stakeholders is CMEMS (Copernicus Marine Environment Monitoring Service[3]), providing support for all marine applications, including support all marine applications, including marine safety, marine resources, coastal and marine environment, and weather, seasonal forecasting, and climate predictions. CMEMS main activity in the Arctic is the Arctic Monitoring Forecasting Centre[4] (ARC MFC) that provides the most accurate forecast and reanalysis products and information on sea ice, ocean, biology, and surface waves in the whole Arctic. The system is based on a numerical ocean model assimilating in situ and satellite data. The other relevant service is C3S (Copernicus Climate Change Service[5]) which integrates a dedicated service for Global Shipping based on reanalysis, seasonal forecast, or climate projections. Useful indicators provided by the service include a fuel consumption model, an arctic route availability model, and an iceberg drifting model, all of them of potential use for icebreaker operations. The CMS, Maritime Surveillance components of CSS[6] (Copernicus Security Service), albeit not publicly open (available only to authorized governmental users) may have applications relevant for icebreaker operations in the Arctic, e.g. in the field of maritime safety and security, and marine environment (pollution monitoring). The focus of the Copernicus services for the Polar Regions is put more particularly on continuous monitoring.

The Sentinels carry a range of technologies, such as radar and multi-spectral imaging instruments for land, ocean, and atmospheric monitoring. Their timelines are shown on Fig. 1 and the main features on Fig. 2. The polar-orbiting satellites have their orbits converge at the poles, so their revisit times at high latitudes are much shorter than over the equator, favoring Arctic monitoring. In addition, the Sentinel-1 and -2 satellites cannot collect data all the time due to capacity restrictions, so they have to select areas; Sentinel-1 always monitors the Arctic and Sentinel-2 always monitors part of it. The Sentinel missions and their data products relevant to the Arctic Ocean are shortly summarized below.



[3] https://marine.copernicus.eu/

[4] https://marine.copernicus.eu/about/producers/arctic-mfc

[5] https://climate.copernicus.eu/

[6] http://www.emsa.europa.eu/copernicus.html

Fig. 1. Timeline of current and Extension (NG) Sentinel missions
(from Copernicus 4. 0 Suppliers Industry Days Presentation, 26-27 Match 2019)

Mission	Sensor(s)	Resolution- Repeat - Revisit time[a]	Status (Nov 2019)	Key Features
Sentinel-1	C-band SAR	(5[b]) 21-50m 6 day repeat 3 day revisit at equator, <1 day in the Arctic	2 satellites in orbit	Polar-orbiting All-weather Day and night radar imaging
Sentinel-2	Optical Multi-spectral	10-60m 5 days repeat 5 day revisit at equator, <1 day in the Arctic	2 satellites in orbit	Polar-orbiting 13 spectral bands in optical and SWIR High resolution imaging
Sentinel-3	Optical multi-spectral (OLCI) + Infrared multi-spectral (SLSTR) + Radar altimeter + Microwave radiometer	300-1200m <1-2 day revisit at equator, <0.5 day in the Arctic	2 satellites in orbit	For surface colour, surface temperature and surface height
Sentinel-4	Similar to S-5		Launch late 2021	Geostationary, so not useful for Arctic
Sentinel-5p	Imaging spectrometer UV-Visible-SWIR	7-68km <1 day revisit in the Arctic	1 satellite in orbit	For atmospheric trace gasses
Sentinel-5	High-resolution spectrometer UV-Visible-SWIR	7.5-50km <1 day revisit in the Arctic	1[st] Launch in 2022	Payload for atmosphere chemistry on MetOp 2[nd] Generation
Sentinel-6	Altimeter	10 day revisit	1[st] Launch in Nov 2020	Radar altimeter to measure global sea surface height

Fig. 2. Sensors, resolution, and key features of current missions (from Boniface et al., 2021)

Sentinel 1 devoted for land and ocean monitoring, is composed of two polar-orbiting, all-weather, day-and-night satellites: Sentinel-1A and Sentinel-1B. As a constellation of satellites sharing the same orbital plane 180° apart, the Sentinel 1 carries a C-band Synthetic Aperture Radar (SAR). This advanced radar instrument that allows them to image the entire earth every 6 days. The constellation has a repeat frequency of 3 days at the equator, less than 1 day at the Arctic (Fig. 3). Data is transmitted to ground stations around the world as well as to the geostationary European Data Relay System (EDRS) for full-time, continual data delivery. The Sentinel-1 is used for a variety of purposes, among them the relevant for the Arctic Ocean: surveilling the marine environment (wind, waves, currents, fronts), forecasting sea ice conditions, monitoring icebergs, monitoring climate change, mapping oil spills, and detecting sea vessels. The SAR sensor is always switched on over the Arctic, but with different image modes and polarisations over different areas. Over the Arctic, the usual image modes are EW, giving 50 m resolution and 400 km wide images, and IW, giving 21 m resolution and 250 km wide images.

Sentinel-1 products relevant for ARICE users: ocean wind field, ocean swell spectra, surface radial velocity, sea ice concentration, drift, and type.

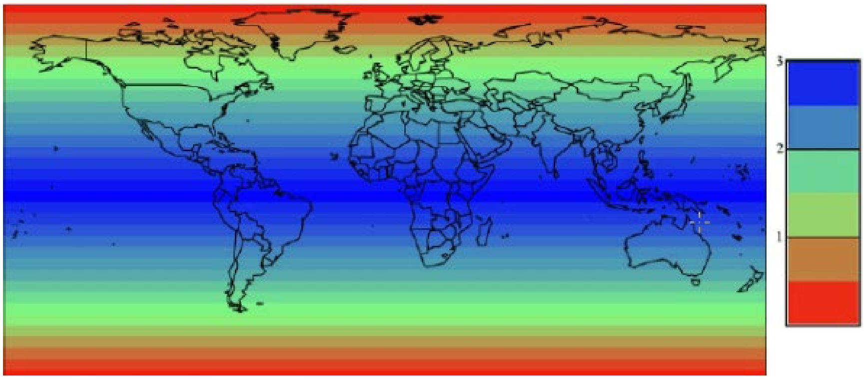


Fig. 3. Revisit Frequency for Sentinel-1A and Sentinel-1B in Days per Revisit[7] (two satellites in 12 day orbit, repeat frequency 6 days, revisit frequency (asc/desc & overlap) of <1 day at high latitudes)

Sentinel-2 is a land-monitoring constellation of two identical polar-orbiting satellites—Sentinel-2A and Sentinel 2B—phased at 180° to each other. It is equipped with a state-of-the-art high-resolution multispectral imager (MSI) instrument, which provides a 290 km swath width and covers all of Earth's land surfaces, large islands, and inland and coastal waters every five days. Geographical coverage in the Arctic Ocean is currently limited to 84°N and areas around islands. Sentinel-2 allows mapping of land cover, vegetation, soil and water cover, inland waterways and coastal areas. It can also deliver information for emergency and crisis response services. It can detect targets at sea and monitor infrastructures on land for security applications.

Less relevant for ARICE users (albeit some applications, e.g. for atmospheric correction over Arctic sea ice; Koenig et al., 2019).

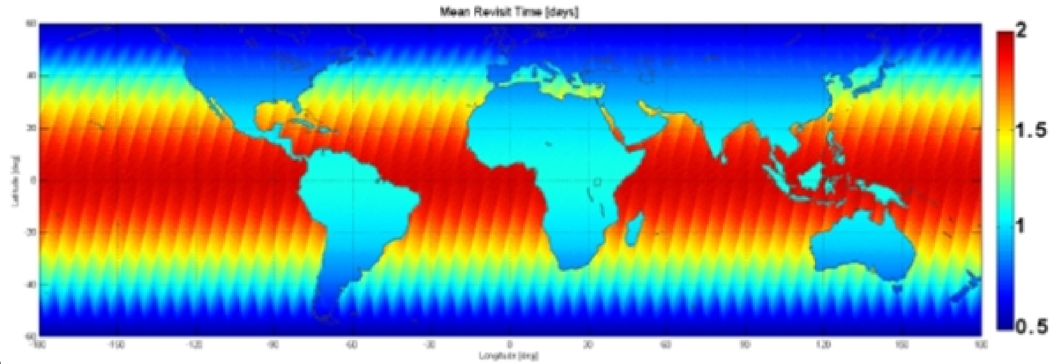
Sentinel-3 is a constellation of two identical satellites: Sentinel-3A and Sentinel-3B. Its main objective is to systematically measure the Earth's oceans, land, ice, and atmosphere for ocean, environmental, and climate forecasting. To achieve this, it is equipped with multiple instruments: Sea and Land Surface Temperature Radiometer (SLSTR, Fig. 4b), Ocean and Land Colour Instrument (OLCI, Fig. 4a), Synthetic Aperture Radar Altimeter (SRAL), Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS), and Microwave Radiometer (MWR). They measure sea surface topography (including significant wave height), sea and land surface temperature, and ocean and land surface color and provide various parameters critical for the Arctic region such as sea ice extent, sea ice thickness and albedo. Due to the orbit constraint, data contains an 1860 km-wide "hole" at northernmost latitude (coverage only to 81.5°N) and Arctic sea ice monitoring is reduced at the northernmost latitudes.

Sentinel-3 products relevant for the Arctic Ocean and ARICE users:

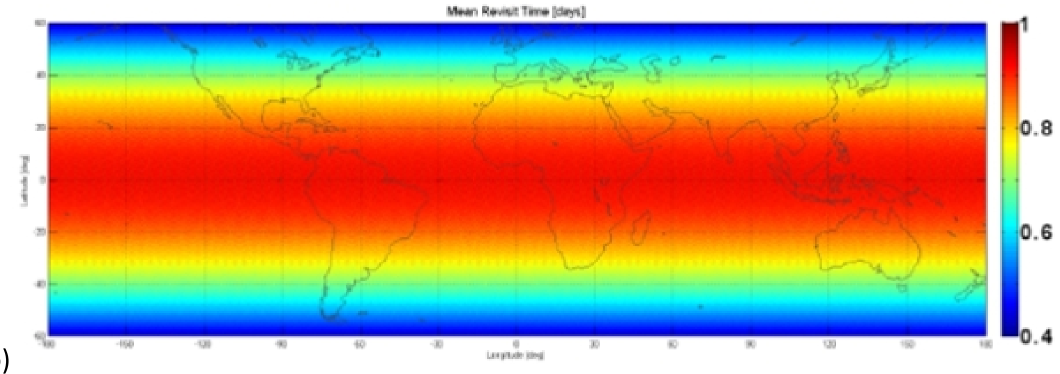
– Surface Topography Mission (SRAL) products: Surface Backscatter, Sea Surface Height, Significant Wave Height, Ocean Depth, Tides Height, Sea Ice Concentration, Sea Ice Freeboard, Sea Surface Wind Speed, Rain Rate.
– Ocean and Land Colour (OCLI) products: Water Surface Directional Reflectance, Algal Pigment Concentration, Total Suspended Matter Concentration, Diffused Attenuation Coefficient, Coloured Dissolved Matter Absorption, Photosynthetically Active Radiation, Aerosol Load over Water, Integrated Water Vapour.

[7] Source: https://sentinels.copernicus.eu/web/sentinel/user-guides/sentinel-1-sar/revisit-and-coverage

– Sea and Land Surface Temperature Radiometer (SLSTR) products: Sea Surface Temperature.



a)



b)

Fig. 4. Sentinel-3 instruments (a) OLCI[8] and (b) SLSTR[9] mean revisit time with a two-satellite configuration.

Sentinel-4 and **Sentinel-5** are not yet operational. Sentinel-5 (carried on EUMETSAT's Metop Second Generation satellite MetOp-SG A to be launched in 2021) will provide data for atmospheric composition monitoring from polar orbit whereas Sentinel-4 will provide similar data but on a geostationary orbit (carried on EUMETSAT's Meteosat Third Generation Sounder MTG-S satellite to be launched in late 2022). Geostationary Sentinel-4 will cover Europe, parts of North Africa, and parts of the Atlantic from 30°N to 65°N in latitude and 30°W to 45°E in longitude[10] therefore its use over the Arctic will be limited. Sentinel-5 provides a wide swath of about 2670km on earth and thus almost globally allows for daily coverage of the earth surface[11]. The Sentinel-5 mission will be to perform atmospheric measurements, with high spatiotemporal resolution, relating to air quality, climate forcing, ozone and UV radiation (key atmospheric constituents such as ozone, nitrogen dioxide, sulphur dioxide, carbon monoxide, methane, formaldehyde, and aerosol properties) and providing a daily global coverage.

Partially relevant for ARICE science users interested in the atmospheric research.

[8] Source: https://sentinels.copernicus.eu/web/sentinel/user-guides/sentinel-3-olci/coverage

[9] Source: https://sentinels.copernicus.eu/web/sentinel/user-guides/sentinel-3-slstr/coverage

[10] Source: https://sentinels.copernicus.eu/web/sentinel/missions/Sentinel-4/satellite-description/geographical-coverage

[11] Source: https://sentinels.copernicus.eu/web/sentinel/missions/sentinel-5/satellite-description/geographical-coverage

Sentinel-5 Precursor (otherwise known as the Sentinel-5P) is the forerunner to the Sentinel-5 satellite and was launched in 2017 (first products available in 2018). The main objective of the Sentinel-5P is to measure the trace gases and aerosols in the troposphere that affect air quality and the climate[12]. It bridges the gap between Envisat (Sciamachy data in particular) and Sentinel-5. The satellite payload on-board Sentinel-5P is TROPOMI (Tropospheric Monitoring Instrument) with a global coverage every day (and more frequently in the Arctic). It can map ozone, formaldehyde, methane, NO2, SO2, CO and aerosols.

Partially relevant for ARICE science users interested in the atmospheric research.

Sentinel-6 involves two satellites: Sentinel-6A Michael Freilich, launched in November 2020 and Sentinel-6B set to launch in 2025. Its primary mission is to provide high-precision information on the global sea surface height primarily for operational oceanography and climate studies, while its secondary mission is radio occultation for climate change monitoring and weather forecasting (Donlon et al., 2021). For these purposes, the Sentinel-6 is equipped with a Synthetic Aperture Radar Altimeter (POSEIDON-4) and a GNSS-RO respectively. It also provides information on ocean currents, wind speed, and wave height. Sentinel-6 has the ability of mapping up to 95% of the Earth's ice-free oceans every 10 days, with the gathered information complementing the oceanic data from Sentinel-3. Geographical coverage in the northern hemisphere is limited to 66°N therefore Sentinel-6 products are *less/not relevant for the ARICE users*.

4.2 Limitations of current Satellite Earth Observations in the Arctic

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

Several 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 (I, II, and III), the ESA Space & Arctic Task Force, the ESA Arctic Mission System Study, and the specific studies under the EU projects EU-PolarNet and KEPLER. 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 of ARICE users (research vessels and ships of opportunity).

Limitations of existing EO systems

While existing or planned EO missions are generally applicable to most areas of current use, the POLARIS study of user requirements (concluded in 2016) 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 Fig. 5.

[12] https://sentinels.copernicus.eu/web/sentinel/missions/sentinel-5p/satellite-description

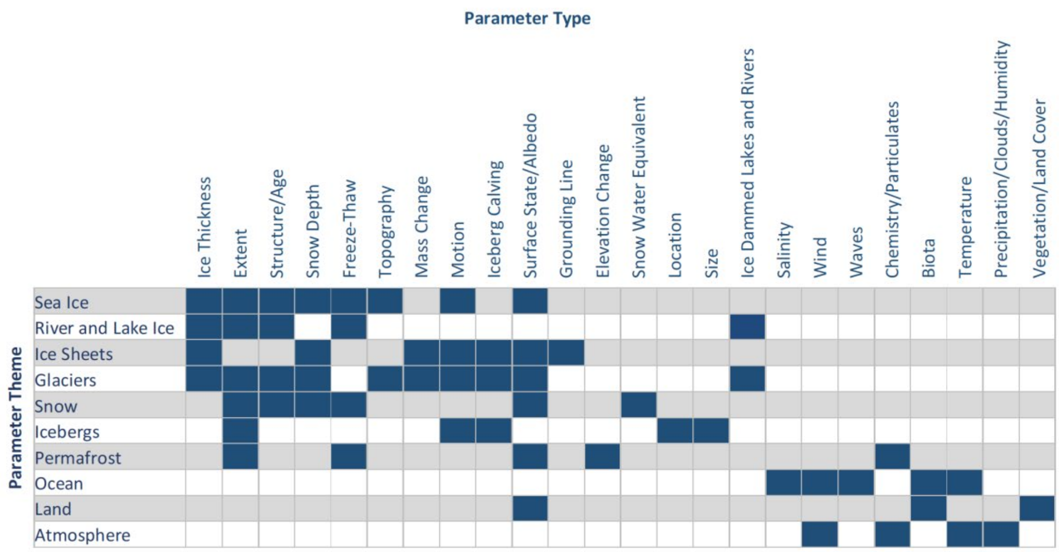


Fig. 5. Polar information gaps identified by the ESA POLARIS requirements study (Gråbak et al, 2016)

Improved sea ice and iceberg information recommended by POLARIS (2016)

The POLARIS study identified dominant information gaps for polar operations as the need to have improved sea ice 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 research icebreakers and ships of opportunity operations in the Arctic Ocean.

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.

KEPLER recommendations (2020) to improve the Copernicus services for Polar monitoring from satellite remote sensing data – sea ice and ocean (relevant to the Arctic Ocean and ARICE users)

The gap analysis of the remote sensing parameters, the analysis of new parameters derived by the potential future missions, and the feasible synergies was employed to make a list of more detailed recommendations:

- **Increase in situ observations (high impact)** ⟹ acquisition and archiving of more extensive in situ data set for better quality assessment and improving the algorithms.
- **Reduce polar observation hole (mid impact)** ⟹ considering twilight acquisition, and more generally polar data coverage, when designing future missions.

- **Enable low timeliness of Copernicus polar mission data flow (high impact)** ⟾ ensure near-real-time (<1h) or better for critical operational missions (e.g. ROSE-L, CIMR).
- **Snow depth on sea ice (high impact)** ⟾ assess possible synergies, new HPCMs (CIMR, CRISTAL and ROSE-L) will contribute to improve the retrieval.
- **Near-real-time high resolution ice analysis (high impact)** ⟾ enhanced automation of high resolution (sub km) ice chart production to handle increased satellite data volumes.
- **Improved sea ice concentration for forecasting (high impact)** ⟾ Fully operational missions with long-term continuity are needed. Synergy with SAR and/or optical
- **Multi-sensor sea-ice drift analyzes (mod impact)** ⟾ develop and implement operational multisensor sea-ice drift analyses.
- **Summer sea ice concentration (high impact)** ⟾ improve accuracy and generate melt-pond fraction data products from visible/infrared imagers.
- **Sea ice thickness (high impact)** ⟾ Supplement microwave remote sensed data sources with optical satellite and in situ data.
- **Surface ocean biogeochemical compounds (high impact)** ⟾ Merging satellite data, promoting CHIME for poral regions.
- **Sea surface salinity** ⟾ promote CIMS mission since it also carries onboard an L-band radiometer
- **Wind speed (mid impact)** ⟾ add Doppler capability to future scatterometers, allows for simultaneous measurements of surface winds and currents and improves directional accuracy.

User-required functions versus Sentinels for the marine domain (Boniface et al., 2021)

Functionalities (“functions”) required by users in the Arctic can be linked with Copernicus Sentinel EO satellites that provide information relevant to the specific function for the specific domain. The function refers to the measuring, detecting, or mapping (as applicable) of the mentioned object or phenomenon. No separate entries were made for the capacity to measure changes. The functions are a level more detailed than application domains such as “climate change”, “maritime transport”, “offshore exploration”, etc. Each of these application domains will have (somewhat different) requirements in a number of the listed functions. The level of aggregation of the functions in the table still does not show whether an actual user requirement is satisfied and additional parameters such as the spatial scales or temporal availability are not analyzed. Table 2 only gives indications about which Sentinel satellites may be used for which Arctic user-required functions in the coastal, maritime and atmosphere domains, relevant for the ARICE users operating in the Arctic region.

Table 2. Summary table of the Arctic user-required functions in the coastal and marine domains for the Sentinels satellites. Entries: + satellite provides very limited information, ++ moderate information, +++ very good information, and empty means no information or unknown (modified from Boniface et al., 2021). Functions most relevant to the ARICE users are marked with gray shading.

Function	Sentinel-1	Sentinel-2	Sentinel-3	Sentinel-5/5p	Sentinel-6
Coastal					
Coastline, coastal erosion	+++	+++	+		
Ports, coastal infrastructure	++	+++			
Maritime					
Ocean winds	+++		++		++
Ocean surface waves	++	+	+++		+++
Ocean surface temperature			+++		
Ocean color		++	+++		

Internal waves	++				
Sea level, sea surface height	+	+	+++		+++
Currents, circulation, and fronts	++	+	+++		+++
Bathymetry	+	+			
Sea ice cover and edge	+++	++	++		
Sea ice concentration			+++		
Sea ice type	++		+		
Sea ice thickness			++		
Sea ice ridges	+		++		
Sea ice surface temperature			+++		
Icebergs	++	++			
Offshore structures	++	++			
Fisheries, fishing ships	++	++			
Merchant ships	++	++			
Small boats and other marine targets	+	+	+		
Marine oil pollution	+++	+			
Sea border crossing activities	+	+			
Atmosphere					
Wind over land					
Temperature					++
Precipitation					
Atmospheric water content			+++		+++
Cloud cover		++	++	++	
CO2					
Other GHG				+++	
Air pollution and trace gases				+++	
Aerosols			+++	+++	

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. Europe's Meteosat geostationary satellites[13] positioned 36 000 km above the equator return images every 15 minutes over the full Earth and every five minutes over Europe, they have no visibility of higher latitudes, closer to the poles, and so cannot be used for Arctic weather forecasting.

The EUMETSAT Polar System (EPS) consists of three of polar-orbiting meteorological satellites (Metop-A, B and C)[14]. Their primary objective is to support Numerical Weather Prediction (NWP) including nowcasting at high latitudes which is not covered by the geostationary Meteosat program. Metop C, the last flight unit that is operational since 2018 contributes to operational meteorology and brings a substantial contribution to ocean and ice monitoring, climate monitoring and atmospheric chemistry. Metop and other polar orbiting meteorological satellites provide regular weather observations, but less frequently than geostationary satellites such as Meteosat which do not have visibility of higher latitudes. EUMETSAT is managing eight Satellite Application Facilities (SAF). All facilities are relevant for the Arctic, in particular the OSI (Ocean and Sea Ice) SAF that provides sea ice, SST, wind and radiative flux products in the near-real time. While the Metop satellites do return data over the poles

[13] https://www.eumetsat.int/our-satellites/meteosat-series

[14] https://www.eumetsat.int/our-satellites/metop-series

as they a circle Earth from pole to pole in a lower orbit, they need up to 24 hours to achieve global coverage.

There is an urgent need for more frequent weather data over the Arctic, particularly data on water vapor, which can change rapidly. A requirement exists to fill this gap and provide satellite observations with a temporal repeat of 1 hour or better.

4.3 Future options and requirements to address gaps and limitations of Satellite Earth Observations

Evolution 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.

The Copernicus Space Component (CSC) [15] currently consists of six series of dedicated Earth Observation space-based missions either operational or under development, Sentinels -1 to -6, each series including two to four units to be launched in order to provide data continuity at least through to the mid-2030s. In September 2020, ESA presented "The next phase of Copernicus - Copernicus Space Component (CSC) Long Term Scenario" (ESA LTS) providing a preliminary schematic overview of the CSC evolution (Nordbeck et al., 2021). This evolution, on the one hand, aims at providing stability and continuity of current Sentinels with the preparation of the Next Generation (Sentinel NG) missions to be launched in the 2030s and, on the other hand, aims at responding to emerging and urgent user needs with the so-called Copernicus High Priority Candidate Missions (HPCMs). The fleet of Sentinels is also expanding and is expected to eventually increase from eight Sentinels today to possibly 20 Sentinels in orbit in 10 years (Fig. 6).

Sentinel extension missions (Sentinel NG)

Microwave family of Sentinel missions

C-BAND SAR: The ESA LTS foresees launches of Sentinel-1C and Sentinel-1D in 2023 and during the period 2024-2027, respectively. Launches of Sentinel-1 NG-A and NG-B would then take place in the first half of the 2030's.

Topography family of Sentinel missions

According to the ESA LTS (September 2020), Sentinel-3C and Sentinel-3D are planned to be launched in 2024 and during the period 2025-2028, respectively, while Sentinel-3A NG TOPO and Sentinel-3B NG TOPO are planned to be launched in the first half of the 2030's. Sentinel-6B is planned to be launched in the 2025/2026 timeframe. Similarly, to the above NG families, the ESA LTS foresees launches of Sentinel-6A NG and Sentinel-6B NG in the first half of the 2030's.

[15] https://www.esa.int/Applications/Observing_the_Earth/Copernicus/Space_Component

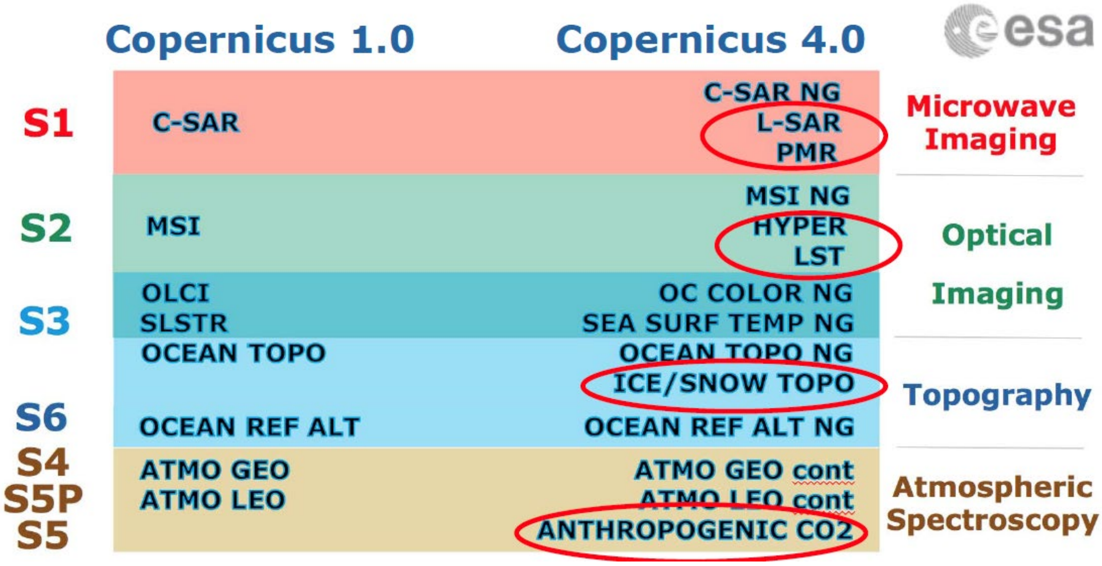


Fig. 6. Evolution of current Copernicus 1.0 Sentinel Families to Copernicus 4.0 (from Copernicus 4. 0 Suppliers Industry Days Presentation, 26-27 Match 2019)

Sentinel expansion mission (HPCM)

In addition to extension of the current and NG Sentinel missions, the Copernicus Space Component will evolve to fill gaps not addressed by current satellites. The initial requirements were specified by the EC and the Copernicus Polar Expert Group and summarized in User Requirements for a Copernicus Polar Mission - Phase 1 & 2 reports that recommended following microwave instrumentation to best complement the existing Sentinels and to meet the user requirements:

- An Imaging Passive Microwave Multi-frequency Radiometer (PMR) 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.
- An advanced SAR Interferometric altimeter (SARIn): A follow-on mission to CryoSat-2, specialized in nadir altimetry in the polar regions.
- A Single Pass Interferometric Synthetic Aperture Radar (SP-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.

The six High Priority Candidate Missions (HPCM), also known as the Sentinel Expansion missions, are identified as new potential candidates with planned launches over the period 2025 to 2030.

Three Copernicus HPCMs focused on microwave instrumentation, with day-and-night, and near-all-weather observation capability, have been identified as most relevant to monitor polar regions.

- **CIMR - the Copernicus Imaging Microwave Radiometer mission**

  CIMR (Donlon, 2019) will provide sea ice concentration, sea surface temperature, thin sea-ice thickness, sea surface salinity and wind over the ocean (amongst others) and serve operational systems in almost all-weather conditions, day and night. Multi-frequency (L-, C-, X-, Ku- and Ka-band) microwave radiometer imaging measurements will ensure with high-spatial resolution and sub-daily revisit in the polar regions. The mission will focus on pan-Arctic and adjacent seas

(>58°N), Greenland and Antarctica regions. Primary products include improved continuity of almost all-weather sea-ice concentration products with high revisit and accuracy (in particular near the ice edges). It will also provide measurement of Sea Surface Temperature and a range of other parameter including thin sea ice thickness, ice extent and ice drift ice type, sea surface salinity, wind over the ocean and the potential for a variety of other parameters over global ocean and land surfaces. The mission will ensure improved continuity of AMSR- and SMAP/SMOS L-band type capability for Europe. The ESA LTS (September 2020) foresees a launch of CIMR-A in 2029 and of CIMR-B in 2031.

CIMR information relevant for the Arctic Ocean and ARICE users (Fig. 8):

– User required products for marine and climate applications (with spatial resolution): sea ice concentration (<5 km), sea ice extent (<5 km), sea surface temperature (<15 km), thin sea ice thickness (<60 km), sea ice edge (<5 km), sea ice drift (<25 km), ice stage of development/type (<15 km), snow depth on sea ice (<15 km), sea surface salinity (<60 km), ocean surface wind vector (<40 km), precipitation rate (<15 km), liquid water path (<15 km), and total column water vapor (<15 km).
– For sea ice parameters and sea surface temperature (all weather) – subdaily temporal resolution, for the remaining parameters - daily temporal resolution.
– Specific products (sea ice concentration, extent, type, edge, snow depth on ice, sea ice surface temperature, ocean surface wind) to be provided with timeliness of NRT1H (Near-Real Time 1 hour) in support of Arctic navigation and safety systems and the other products with NRT3H.
– ~95% global coverage every day, meaning 6-hourly revisit in Arctic areas, no hole at the pole.

- **CRISTAL - the Copernicus Polar Ice and Snow Topography Altimeter mission**

CRISTAL (Kern et al., 2020) will provide enhanced land ice elevation and sea-ice thickness measurements, implementing higher spatial resolution for improved lead detection and additional capability to determine snow loading on sea ice. Improved on-board tracking systems for operation in rough terrain and addition of radiometer for all-round oceanographic use and coastal altimetry may also be considered.

The ESA LTS foresees launches of CRISTAL-A and CRISTAL-B in 2028 and 2030, respectively.

CRISTAL information relevant for the Arctic Ocean and ARICE users (Fig.8):

– User required products for marine applications: sea ice thickness and snow depth, sea level anomaly and geostrophic ocean currents in polar oceans, significant wave height in polar oceans, global sea level and global sea surface wind and waves.
– User required products for climate application: ice sheet topography, sea ice thickness and volumes, global sea level, and snow depth over sea ice.
– Vertical resolution of ~30 cm with enhanced freeboard measurements accuracy.
– For sea ice thickness and freeboard, very high along-track resolution sea ice thickness products (<=80 m) and vertical uncertainty of ice thickness of 0.15 m in winter and meaningful measurements in summer.
– For ice sheets, glaciers, and ice caps, high spatial resolution (<=100 m), ice surface elevation uncertainty of 2 m, temporal sampling of 30 days or less.
– Fulfils the needs for continual altimetric monitoring of the Arctic Ocean north of 81.5°N.

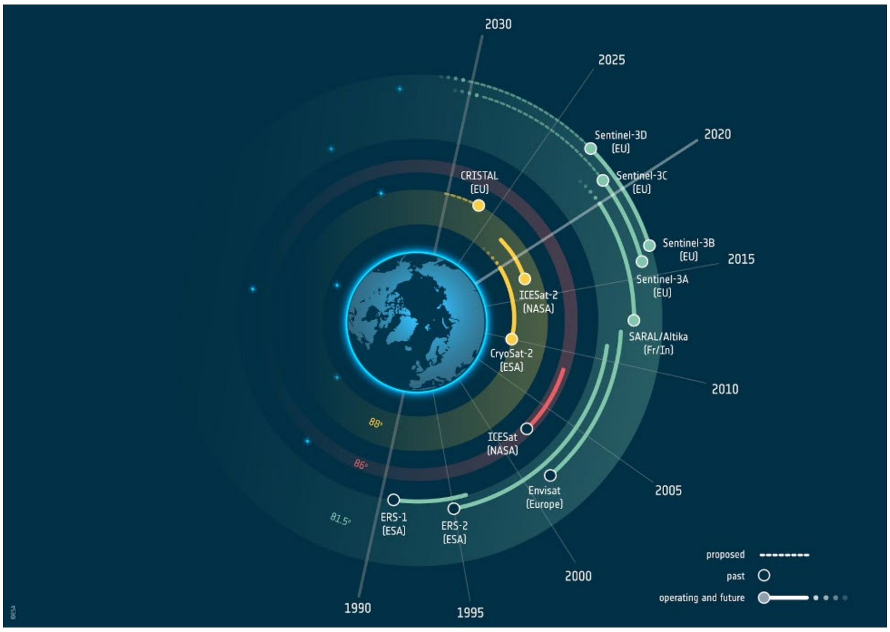


Fig. 7. Past, current, and future altimetric missions showing high latitude coverage: in the mid 2020s CRISTAL is the only altimetric mission covering the high latitudes above 81.5°N[16]

- **ROSE-L - Radar Observing System for Europe at L-band mission**

ROSE-L (Davidson et al., 2019) will provide enhanced observations for applications as soil moisture, land cover mapping, crop type and status discrimination, forest type/forest cover (in support to biomass estimation), food security and precision farming, maritime surveillance, and natural and anthropogenic hazards. In addition, the mission will contribute to the operational monitoring of the cryosphere and polar regions including sea ice mapping and land ice monitoring and complement the European maritime situational awareness.

The ESA LTS from September 2020 foresees a launch of ROSE-L A in 2028 and of ROSE-L B in 2030.

ROSE-L information relevant for the Arctic Ocean and ARICE users (Fig. 8):

– User required products including floating ice (sea ice types; iceberg detection; ice extent, fraction, and concentration; sea ice/iceberg drift; sea ice thickness), glaciers and ice caps (surface velocity), ice sheets (grounding line, surface velocity), and snow-water equivalent at high resolution (e.g. 100 m).
– Daily tactical information for Arctic shipping and infrastructure hazards.
– High-resolution information on hazardous sea ice and iceberg conditions.
– Enhanced monitoring of ice sheets in areas not accessible to Sentinel-1.
– Enhanced accuracy in sea ice type classification and sea ice motion estimation.

[16] https://futureearth.org/publications/explainers/plans-for-a-new-wave-of-european-sentinel-satellites/

CRISTAL	CIMR	ROSE-L
• Sea ice thickness • Snow depth on sea ice • Ice sheets and glaciers • Icebergs • Polar oceans	• Sea surface temperature • Sea surface salinity • Sea ice concentration • Sea ice thickness • Snow depth on sea ice • Snow cover	• Surface deformation and geohazards (earthquakes, volcanoes, flodings) • Forestry monitoring • Soil moisture, water availability • Sea ice types • Detection of icebergs

Fig. 8. Comparison of main geophysical parameters for three HPCM with relevance to the polar areas

The three other missions may also be relevant to observe parameters in the polar regions:

- **CO2M - Copernicus Anthropogenic CO2 Monitoring** - this set of satellites will detect the spectral absorption signals of carbon dioxide in infrared sunlight reflected off Earth's surface to retrieve concentrations of carbon dioxide in the atmosphere with high-precision. Additional instruments will detect nitrogen dioxides emitted from burning fossil fuels at high temperature, which will help locate carbon dioxide plumes produced by humans and distinguish them from carbon dioxide coming from natural sources. The satellites will also have sensors to detect clouds and aerosols to improve carbon dioxide measurement accuracy. *Less relevant to ARICE users*.
- **LSTM - Copernicus Land Surface Temperature Monitoring** - would carry a high spatial-temporal resolution thermal infrared sensor to monitor land surface temperature and rates of evapotranspiration in unprecedented detail (every 1-3 days at the resolution of 50 m). This mission is focused on addressing the priority requirements of the agricultural user community. LSTM will also apply to sea and lake surface temperature monitoring due to its high spatial resolution, particularly useful for tracking small features such as lakes in the Arctic, coastal zones, rivers, coral reefs, ocean upwellings and structures such as oceanic eddies that influence vertical transport of nutrients, crucial for ocean productivity. *Less relevant to ARICE users*.
- **CHIME - Copernicus Hyperspectral Imaging Mission for the Environment** – will provide routine hyperspectral observations for the management of natural resources. This includes biodiversity on land, forestry, inland and coastal waters, environmental degradation and hazards, hydrology and cryosphere. Benefits expected from the mission are a higher temporal resolution to monitor snow properties, detailed knowledge of snow albedo, accurate snow-covered area and snow water equivalent. CHIME would bring key observation to assess environmental degradation and hazards, permafrost change, water availability and serve as early warning capacity for avalanche risk for the Arctic region. *Less relevant to ARICE users*.

In 2020 ESA signed contracts with Thales Alenia Space in France and in Italy, and Airbus Defence and Space in Spain to build the new high-priority Copernicus satellite missions: CRISTAL (in September) CHIME, CIMR and LSTM (in November), and ROSE-L (in December). While these contracts are for the development of three new missions, full implementation relies on further agreements. This includes an agreement between ESA and the European Commission, including a joint positive decision by the Commission and ESA and their Member States to go from Phase B2 to Phase C/D for the prototype missions and to procure the recurrent satellite units. This decision point is planned in the second half of 2021. The strengths of the Polar HPCM are not only their uniqueness, but more importantly their complementarity to one another and with the existing and future Sentinels.

Arctic Weather Satellite Mission

The Arctic Weather Satellite (AWS) mission[17] will provide frequent coverage of Earth for improved nowcasting and numerical weather prediction. Carrying a 19-channel cross-track scanning microwave radiometer, the Arctic Weather Satellite mission will provide measurements of atmospheric humidity and temperature. In March 2021 ESA has signed a contract with OHB Sweden to a build prototype satellite for AWS as the precursor to a potential satellite constellation that would provide a near-constant stream of temperature and humidity data from anywhere on Earth. This would make very short-term weather forecasts – known as "nowcasting" – in the Arctic possible for the first time and would allow to better predict storms or extreme weather conditions. The launch of the prototype satellite weighting about 120 kilograms is planned to take place in 2024. The now ordered prototype is planned to be followed-up by a constellation of 16 AWS satellites. The polar-orbiting AWS mission complements the data of existing satellites systems such as MetOp or its US counterpart, the Joint Polar Satellite System (JPSS).

Improved very-short range weather forecast in the Arctic will be of critical importance for the ARICE users and icebreaker and ships of opportunity operations in the Arctic Ocean.

In February 2021 Russia launched the satellite Arktika-M1 on a mission to monitor the climate and environment in the Arctic. With its highly elliptical orbit (a Molniya-type orbit) the Arktika-M1 spacecraft will take about 12 hours to complete one lap around the planet. The satellite’s orbit has an inclination of about 63.3 degrees, meaning Arktika-M 1 will provide its instruments a view of Arctic weather patterns for multiple hours on each orbit. Russia plans to send up a second satellite in 2023 and, combined, the two will offer round-the-clock, all-weather monitoring of the Arctic Ocean.

5. Satellite navigation and positioning

5.1 Current use of satellite navigation

The current uses of Global Navigation Satellite Systems (GNSS) are discussed in greater detail in the EU-PolarNet Report (D3.3, 2018) and the JRC Technical Report “Europe’s Earth Observation, Satellite Navigation, and Satellite Communications Missions and Services for the benefit of the Arctic - Inventory of current and future capabilities, their synergies and their societal benefits” (Boniface et al., 2021). The results of the ARKKI project[18], which identified the most significant challenges in navigation and geospatial information-based applications in Arctic areas and proposed a roadmap to recommend pan-Arctic solutions, and the pan-Arctic “Challenges in Arctic Navigation” workshop[19] organized in Olos, Finnish Lapland in 2018 are summarized by Leppälä et al. (2019) and Kirkko-Jaakkola et al. (2020). A comprehensive overview “Navigation in the Arctic” is provided by Reid et al. (2021). For reference a quick list of the main applications for polar operations is given below.

- General navigation and positioning of ships.

[17] https://www.esa.int/Applications/Observing_the_Earth/Meteorological_missions/Arctic_Weather_Satellite/Contract_signed_to_build_Arctic_weather_satellite

[18] https://arkki-project.org/

[19] https://arkki-project.org/seminar/

- Navigation and positioning of autonomous surface and subsurface vehicles, drifting ice-based platforms, and unmanned airborne systems.
- Precise timing information for vessels and research infrastructure.
- Sensor data for EO validation.
- GNSS reflectometry.

5.2 Limitations of satellite navigation in the polar regions

GNSS are comprehensively used in the polar regions, as they are elsewhere. Each GNSS constellation consists of roughly 25–30 satellites in a medium Earth orbit (MEO). Their orbits are almost circular and inclined with respect to the equatorial plane. The choice of inclination angle has a direct consequence on the performance of the system at high latitudes: that angle, in degrees, corresponds to the highest latitude where the satellites can be observed. For many polar applications the available accuracy is sufficient, but some limitations exist for users at higher latitudes. Poor sea chart quality is the first challenge to navigation in polar regions due to sparse soundings and persistent errors. This problem is compounded with challenges in positioning where navigational aids such as the magnetic and gyrocompass experience degradation at high latitudes, and GNSS also faces difficulties at high latitudes (Reid et al., 2021). Satellites are low on the horizon, leading to problems with tracking and geometry; ice buildup can affect antenna performance; and integrity through SBAS is limited or unavailable. These limitations lead to obstacles with offshore dynamic positioning. All these issues can be critical for maritime mission planning and operation in ice conditions. Ice information from a variety of sources is key including statistical information in the planning stages all the way to satellite radar imagery (see Section 4) and ship-based sensors for use in real-time planning. GNSS integrity in the Arctic regions is crucial for ice management, in particular when automated route optimization becomes practical in avoiding dangerous ice and to perhaps minimize the impact on the Arctic ecosystem (Reid et al., 2021).

Issues related to GNSS refer generically to all constellations including GPS[20] (US), Galileo[21] (Europe), GLONASS[22] (Russia) and BeiDou[23] (China). Operational satellites are shown on Fig. 10. Issues and developments specific to a specific constellation will refer to it by name.

While the accuracy of positioning[24] with GNSS at higher latitudes is lower, it appears to be sufficient for most of the applications involving integration of GNSS with EO. Even at the North Pole, Horizontal Dilution of Precision (HDOP) is satisfactory for most of maritime applications, except those that require very high positioning precision (among others hydrographic surveys, drilling, offshore operations based on Dynamic Positioning systems). GNSS challenges at high latitudes are more severe to aviation applications due to lower elevation angles of satellites, giving rise to higher Vertical Dilution of Precision (VDOP). Space-based augmentation systems (SBAS[25]) which gives GNSS integrity, is limited by both ground- and space-based infrastructure. The geostationary (GEO) space segment placed at the

[20] https://www.gps.gov/

[21] https://www.gsc-europa.eu/

[22] https://www.glonass-iac.ru/en/GLONASS/

[23] http://en.beidou.gov.cn/

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

[25] https://www.euspa.europa.eu/european-space/eu-space-programme/what-sbas

equator has significantly degraded signals above latitudes of 70°N and is completely and lost above 75°N. Ground reference stations (Fig. 11), which monitor GNSS signals, are currently placed to support activities at lower latitudes. As a result, they will not see the same satellites as a vessel in polar seas, and corrections can therefore not be provided for all satellites in view (Reid et al., 2016). The most evident gap is in the geographical coverage of the three regional SBAS relevant to the northern high latitudes – European EGNOS[26], US WAAS[27] and SDCM[28] being developed in the Russian Federation.

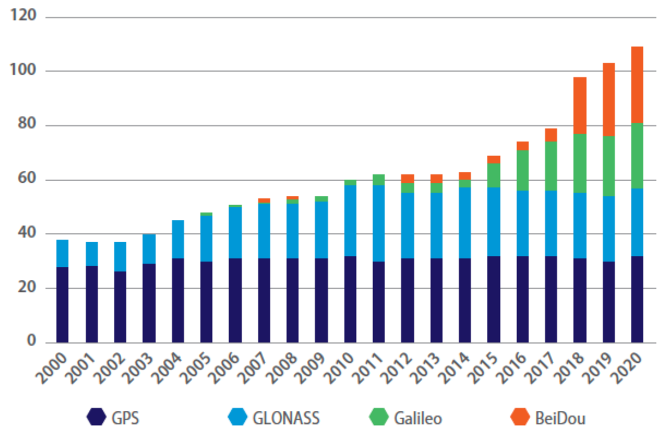


Fig. 10. Operational GNSS satellites with global coverage (MEO), excluding test satellites as of October 2020 (from 3rd GNSS User Technology Report[29])

While the accuracy of positioning[30] with GNSS at higher latitudes is lower, it appears to be sufficient for most of the applications involving integration of GNSS with EO. Even at the North Pole, Horizontal Dilution of Precision (HDOP) is satisfactory for most of maritime applications, except those that require very high positioning precision (among others hydrographic surveys, drilling, offshore operations based on Dynamic Positioning systems). GNSS challenges at high latitudes are more severe to aviation applications due to lower elevation angles of satellites, giving rise to higher Vertical Dilution of Precision (VDOP). Space-based augmentation systems (SBAS[31]) which gives GNSS integrity, is limited by both ground- and space-based infrastructure. The geostationary (GEO) space segment placed at the equator has significantly degraded signals above latitudes of 70°N and is completely and lost above 75°N. Ground reference stations (Fig. 11), which monitor GNSS signals, are currently placed to support activities at lower latitudes. As a result, they do not see the same satellites as a vessel in polar seas, and corrections can therefore not be provided for all satellites in view (Reid et al., 2016). The most evident gap is in the geographical coverage of the three regional SBAS relevant to the northern high latitudes – European EGNOS[32], US WAAS[33] and SDCM[34] being developed in the Russian Federation.

[26] https://www.euspa.europa.eu/european-space/egnos/what-egnos

[27] https://www.faa.gov/about/office_org/headquarters_offices/ato/service_units/techops/navservices/gnss/waas/

[28] https://gssc.esa.int/navipedia/index.php/SDCM

[29] https://www.euspa.europa.eu/european-space/euspace-market/gnss-market/gnss-user-technology-report

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

[31] https://www.euspa.europa.eu/european-space/eu-space-programme/what-sbas

[32] https://www.euspa.europa.eu/european-space/egnos/what-egnos

[33] https://www.faa.gov/about/office_org/headquarters_offices/ato/service_units/techops/navservices/gnss/waas/

[34] https://gssc.esa.int/navipedia/index.php/SDCM

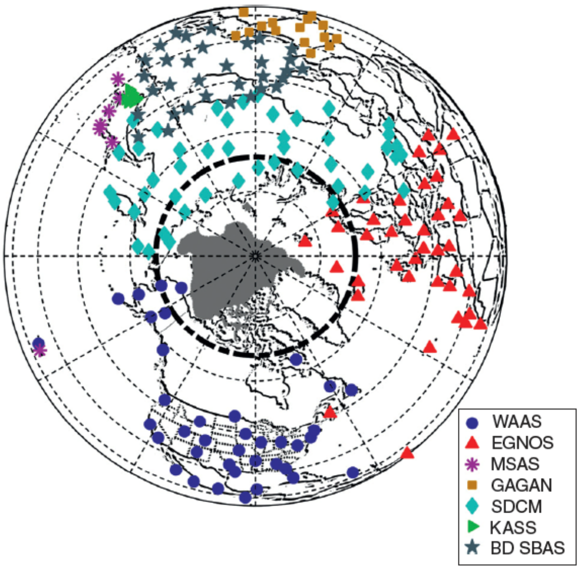


Fig. 11. SBAS ground segment: Reference stations of all current systems and those under construction (from Reid et al., 2021).

Coverage of current GNSS constellations

The orbit inclination of the GPS and Galileo satellite constellations is 55°, and a higher orbit inclination of 65° for GLONASS. Therefore, GNSS satellites are visible at low elevation angles from the Polar Regions. Fig. 12 shows the ground tracks of the GPS constellation, which reach a maximum latitude of 55°N and improvement with the addition of GLONASS, Galileo, and BeiDou. This improvement comes from GLONASS as it was designed to support the high-latitude regions of Russia.

This geometry results in good horizontal position accuracy (HDOP) 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). 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.

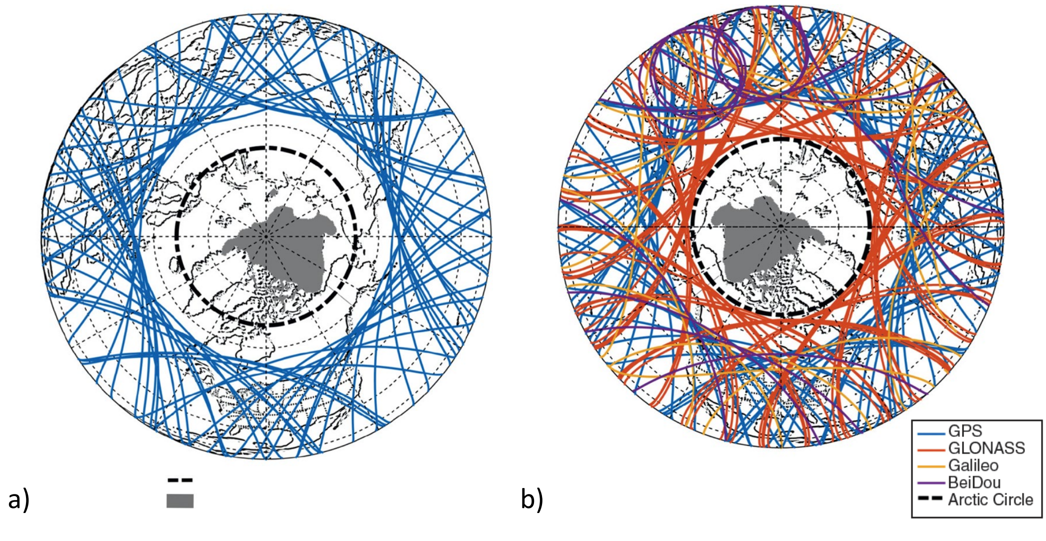


Fig. 12. Ground tracks of (a) GPS and (b) combined GPS, GLONASS, Galileo, and BeiDou (from Reid et al., 2016).

Maritime navigation requirements given in Table 3 are strict for horizontal positioning given the vertical position is known to be sea level. The integrity bound, known as the Horizontal Alert Limit (HAL), is 25 m for open water operations. Precision applications, such as drilling and mapping, require an order of magnitude better accuracy at 2.5-5 m. These limits have been agreed upon by the International Maritime Organization (IMO).

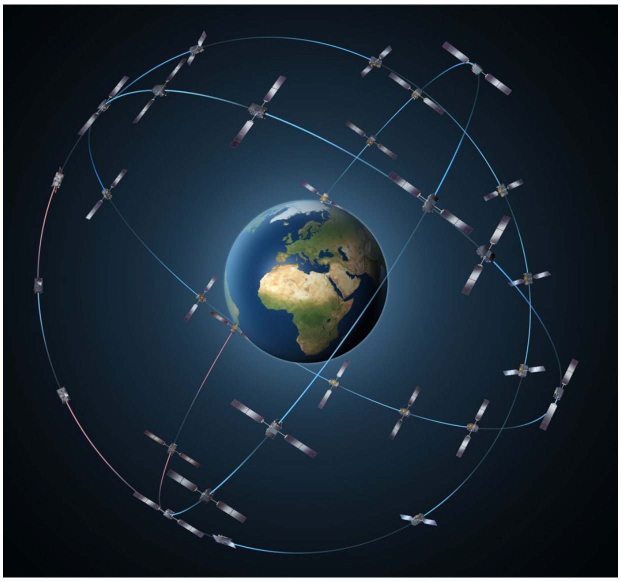
Table 3. Maritime navigation requirements (from Reid et al., 2016 and IMO, 2002)

	Horizontal alert limit (HAL) [m]	Time to alarm [sec]	Continuity (per 3 h)	Integrity risk (per 3 h)
Ocean	25	10	N/A	10^{-5}
Coastal				
Ice navigation	10-12	10	99.97%	10^{-5}
Hydrography	2.5-5	10	99.97%	10^{-5}
Port/Drilling Exploration	2.5	10	99.97%	10^{-5}

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

EGNSS (European GNSS): Galileo, EGNOS and services available in the Arctic regions

Galileo is the European GNSS[35], able to provide different all-weather services with global coverage. The nominal space segment of Galileo is composed of 24 plus 3 spares Medium Earth Orbit (MEO) satellites placed on 3 orbital planes and this constellation covers the Arctic region (Fig. 13). The average number of visible satellites in the Arctic region is similar to the values observed for other regions of the Earth and the average number of satellites varies between 5.9 and 6.8 (Boniface et al., 2020).



[35] https://galileognss.eu/

Fig. 13. The complete Galileo constellation, consisting of 30 satellites, 24 satellites used along three orbital planes, plus two spare satellites per orbit (picture courtesy of ESA[36]).

Since December 2016, Galileo started to deliver two services free of charge: **Galileo Open Service** (Galileo OS[37]) and **Galileo Search and Rescue** (Galileo SaR[38]). Galileo OS has been designed for non-safety critical purposes, provides ranging signals and data broadcast from the Galileo constellation, and allows positioning, navigation and timing synchronization worldwide in any weather condition free of charge for any user equipped with a Galileo enabled receiver. Galileo OS allows reaching a horizontal and vertical positioning error of respectively about 30cm and 40cm using single point positioning (considering Signal in Space errors only) for the Arctic region (similar accuracy to the midlatitude regions). In the future, the Galileo OS will also provide Navigation Message Authentication, which will allow the computation of the user position using authenticated data extracted from the navigation message. Galileo SaR service covers the Arctic up to 85°N and allows to significantly reduce the real time detection and localization of distress signals (decreasing radius area size from 8km to 2km and time detection from 4 minutes instead of 4 hours). A fundamental element of the Galileo SaR service is the return link feature (available since January 2020) which enables confirmation to the user that the distress message has been received.

These Galileo services are of key importance for the ARICE users and the icebreakers and ships of opportunity operations in the Arctic.

The performance of GNSS is improved by regional Satellite-based Augmentation Systems (SBAS) that improve 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. This includes the European augmentation satellite system **European Geostationary Navigation Overlay Service (EGNOS)**. The current version of EGNOS (EGNOS 2.4.2) employs three geostationary satellites and partially covers the Arctic region, reaching up to 72°N (Fig. 14).

[36] https://www.esa.int/ESA_Multimedia/Images/2014/07/Galileo_constellation

[37] https://www.euspa.europa.eu/galileo/services

[38] https://www.gsc-europa.eu/galileo/services/search-and-rescue-sar-galileo-service

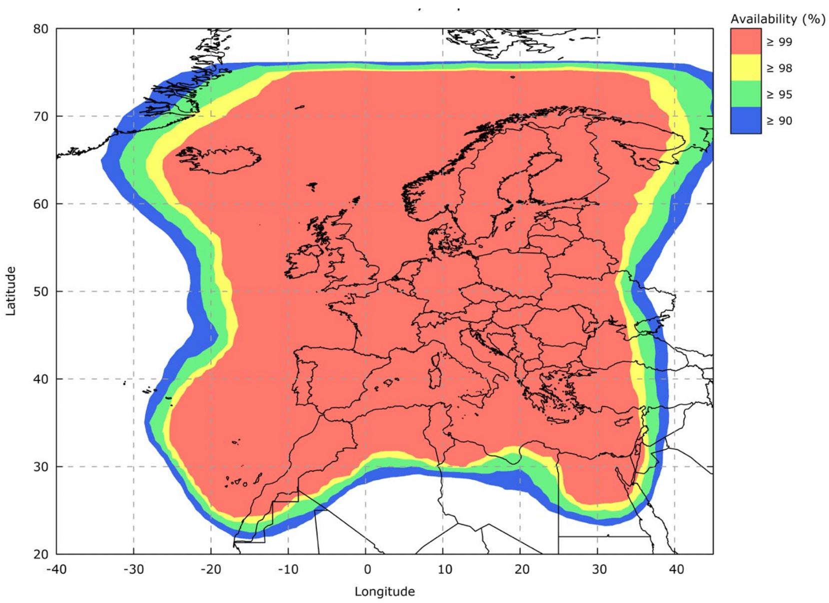


Fig. 14. EGNOS OS availability map (from EGNOS OS Service Definition Document[39])

SBAS consists of ground-based ranging and integrated monitoring stations (RIMS), 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 presents a significant obstacle to the expansion of SBAS-based navigation in the polar regions. This currently limits the opportunities and applications supported by EGNOS and other SBAS networks. For the EU satellite navigation systems, this is the main gap identified for the Arctic region.

The integrity information provided by SBAS must be timely: for instance, the EGNOS system has a specified time to alarm of six seconds in the case of a satellite failure. Consequently, in safety critical applications, the augmentation data need to be continuously updated without interruptions, which is challenging in the Arctic from the telecommunications point of view (see Section 6).

EGNOS provides corrections and integrity information for GPS signals over Europe as two services. EGNOS Open Service broadcasts two type of corrections (slow and fast corrections) to improve the positioning accuracy. The corrections transmitted mitigate the ranging error sources related to satellite clocks, satellite position and ionospheric effects. EGNOS Safety of Life (SoL) service in addition to the enhanced accuracy EGNOS provides integrity information. The integrity is the measure of the trust that can be placed in the correctness of the information provided by a navigation system. EGNOS SoL mainly supports civil aviation operations but also has applications in a wide range of other domains such as maritime domain.

Ionospheric corrections and Galileo Ionosphere Prediction Service

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 m are typical. Correction of these

[39] https://www.gsa.europa.eu/sites/default/files/brochure_os_2017_v6.pdf

errors is handled by ionospheric models and combinations of observations from different signal frequencies.

The signals from the predominantly low-elevation satellites available in the Arctic travel longer distances through the ionosphere and troposphere. Problems have been reported with auroral activity and ionospheric scintillation of GNSS signals due to space weather and in addition, dense fog in the troposphere has been known to cause problems (Reid et al., 2021).

Galileo Ionosphere Prediction Service[40] (IPS) monitors ionospheric activity and informs GNSS users in good time of an upcoming event that could disrupt GNSS signals and applications. The IPS monitors and forecasts solar and ionospheric activity and predicts its effect on GNSS signals and on the final performance of user applications. The IPS predictions are delivered for ionosphere-related parameters and GNSS performance in three time scales (nowcast, 30 minutes and 24 hours ahead), the alerts are sent to registered users when the IPS predictions exceed predefined thresholds.

5.3 Future options and requirements to address limitations of satellite navigation

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. GNSS and associated augmentation systems will continue to develop and deliver an improved level of service. Overview of GNSS and SBA developments is the coming years is provided by the Third GNSS User Technology Report[41], published in October 2020.

GNSS system modernization towards multi-GNSS with a multi-frequency dimension

The four GNSS – GPS (USA), GLONASS (RU), BeiDou (PRC) and Galileo (EU) – will continue to provide navigation services with global coverage for the foreseeable future, with more than 100 GNSS satellites in Medium Earth Orbit (MEO). BeiDou reached full development in 2020 with 30 satellites that transmit in three frequencies. Galileo already has capability to broadcast multi-frequency (E1, E6, E5) signal components on all operational satellites. GPS and GLONASS currently undergo modernization that will allow them to broadcast multi-frequency signals. GPS already broadcasts the new L1C signal with 24 operational satellites broadcasting L2C available by 2020, and the corresponding ground segment capability enabling transition to L2C available by 2023. The latest generation of GLONASS-K satellites will in future broadcast on 3 frequencies (L1 and L2 in addition to currently used L3) and carry a SAR transponder.

Through 2020 the Galileo Programme developed improvements to Galileo First Generation ground and space system infrastructure for increased robustness and new service capabilities and launched a full modernization program aiming in the future at Galileo Second Generation. The Galileo system is expanding its infrastructure capabilities such that, once fully operational, it will offer additional services worldwide, including:

[40] https://galileognss.eu/galileo-ionosphere-prediction-service/#more-3833

[41] https://www.euspa.europa.eu/european-space/euspace-market/gnss-market/gnss-user-technology-report

- Public Regulated Service (PRS) restricted to government-authorized users for sensitive applications that require a high level of service continuity,
- Open Service INAV message improvements on Galileo E1-B (under implementation) for improved robustness in terms of navigation data retrieval in challenging environments,
- Open Service Navigation Message Authentication (OS-NMA) providing the free authentication of the Galileo OS for geolocation information through the Navigation Message (I/NAV),
- Commercial Authentication Service (CAS), complementing the OS, providing a ranging authentication function,
- High Accuracy Service (HAS) complementing OS by delivering free access high accuracy data and providing better ranging accuracy, enabling users to achieve sub-meter level positioning accuracy,
- Support to Safety of Life (SoL) Services through Dual Frequency Multi-Constellation (DFMC) SBAS and supporting the provision of integrity through the concept of H-ARAIM.

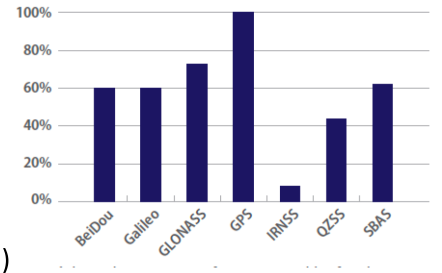
The Galileo Ground Segment is being upgraded implementing ground segment virtualization technologies. The production of 12 additional Batch 3 Galileo first generation satellites is proceeding, aiming at readiness for launch from mid 2021 onward. With Batch 3 satellites, Galileo will reach its full constellation capability, including a number of in-orbit spares. Galileo Batch 3 satellites will be progressively launched with the new Ariane 62 launcher vehicle.

The Galileo Programme is fully engaged in the process of developing Galileo 2nd Generation (G2G). Procurement activities for system, satellite and ground segment have been initiated in 2020 with the goal of starting deployment of the new infrastructure in 2024. G2G Service Portfolio and High-Level Mission Objectives include service evolution for increased performance and reduced complexity and power consumption at the user receiver level, time to first-fix, accuracy, authentication and other service attributes, PRS evolutions, advanced timing services, enhanced integration with terrestrial systems (5G/6G), complementarity with external sensors (such as inertial sensors, barometer, lidar) and application environments (such as low power devices and internet of things), SAR service evolution, Emergency Warning services, Space Service Volume and Ionosphere Prediction Service.

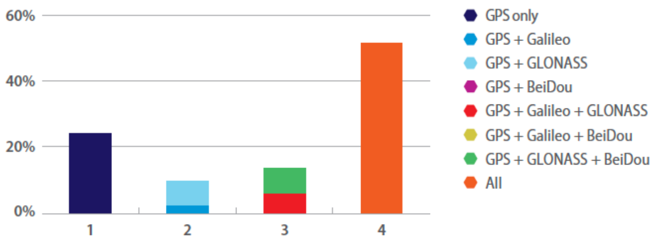
High accuracy services are no longer the exclusive preserve of commercial services providers but are also proposed by core GNSS (e.g. the free Galileo HAS and the QZSS CLAS) and in the plans of several SBAS service providers. The introduction of these multi-frequency GNSS devices and the increased use of corrections services actively support the democratization of high accuracy that combined with low-cost solutions will benefit all sectors, including maritime.

Multi-frequency and multi-constellation receivers

GNSS users operating in the Arctic can therefore benefit from the already partially existing multi-constellation, multi-frequency scenario by using receivers capable of processing signals from different constellations and at different frequencies. The vast majority (76%) of current receivers are multi-constellation, and the most popular way to provide multi-constellation support is to cover all constellations, which represents 52% of receivers (Fig. 15). 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.



a)



b)

Fig. 15. (a) Constellation capability and (b) supported constellations' combinations of GNSS receivers as of October 2020 (from 3rd GNSS User Technology Report[42])

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. Besides coverage, limitations in the Arctic are also due to the increased ionospheric activity at these high latitudes. However, dual-frequency GNSS offers a possible solution, as it would allow users to directly estimate ionospheric delay.

Advanced RAIM Receiver Autonomous Integrity Monitoring

SBAS is ultimately limited in service area by the reference stations. In order to fill this gap a possible solution is the adoption of algorithm implemented at receiver level. The ARAIM (Advanced RAIM Receiver Autonomous Integrity Monitoring) concept is based on the fact, that the future multi-constellation and multi-frequency signals will offer the possibility to reduce the dependency from the ground infrastructure and consequently reduce further the deployment and operation. This integrity data is contained in the Integrity Support Message (ISM) that is computed on the ground and provided to the users. An important advantage of ARAIM is that it has the potential to provide better coverage in the Arctic compared to SBAS, because it does not need the geostationary satellites. ISM dissemination requires only a modest data rate which could be accommodated within the GNSS navigation messages capacities.

For integrity information ARAIM will extend the coverage of the EGNOS SoL service (limited to 72°N) and has a global coverage including the polar regions. Three modes of operations for ARAIM have been defined: H-ARAIM (Horizontal ARAIM), which will be available from 2025, and two for vertical navigation (offline and online V-ARAIM, operational in 2029). ARAIM allows to compute the Horizontal Protection Level (HPL) and Vertical Protection Level (VPL). The protection level provides a bound on the position error with a confidence level derived from the integrity risk requirement.

Expanded augmentation services

International coordination between GNSS, RNSS, and SBAS providers has led to the adoption of open signals of compatible frequency plans, and common multiple access and modulation. This facilitates the design of multi-constellation GNSS chipsets and receivers. Furthermore, all GNSS constellations broadcast open signals in common multiple frequency bands, and SBAS will emulate them with plans to upgrade services to multiple frequencies and multiple constellations in the coming years.

Expansion of SBAS services (Fig. 16) will also cover the Polar Regions to allow expanded use of GNSS services, including for safety-of-life applications. It is the stated aim to expand SBAS services towards

[42] https://www.euspa.europa.eu/european-space/euspace-market/gnss-market/gnss-user-technology-report

the Arctic. For example, the EGNOS Safety of Life Service Implementation Roadmap includes extension of the commitment areas for key service levels up to 72°N in Norway and Finland is planned for 2018.

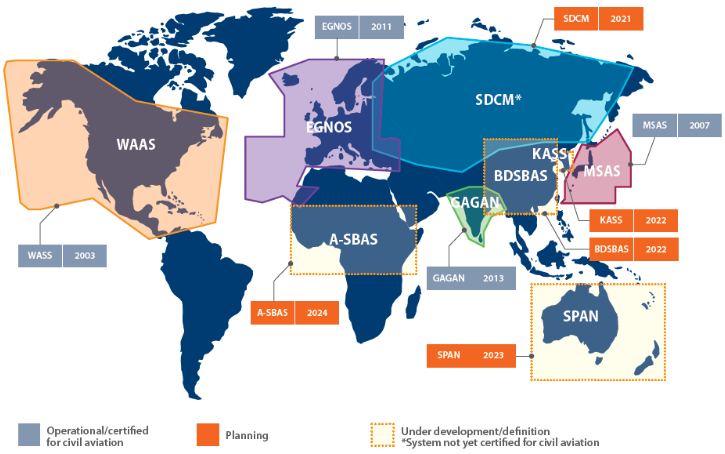


Fig. 16. SBAS indicative service areas as of October 2020 (from 3rd GNSS User Technology Report[43])

Whilst the first generation of SBAS systems offers augmentation services to GPS L1, the second generation intends to support both dual- (L1 and E5) and single- frequency (L1) operations, along with supporting correction data for signals originating from multiple GNSS constellations.

EGNOS V3 is the new generation of EGNOS, which will replace the current version 2 in operation since 2011 (Fig. 17). EGNOS V3 is currently under development and is foreseen to enter into service in 2024. V3 system architecture will be modular and upgradeable in time in order to progressively accommodate and support a very wide span of brand new GNSS services for various user communities. After the completion of the transition to V3, the V2 system will be decommissioned. Two versions of EGNOS V3 are foreseen:

– V3.1 expected to ensure continuity of EGNOS augmentation of GPS L1 and improved ionospheric corrections,
– V3.2 providing additional SBAS service capabilities through a new SBAS channel on L5 and including augmentation of dual frequency GPS-Galileo. This version of the service will exploit the advantages of in-operation Galileo signals as well as new frequencies from an improved class of GPS satellites. Moreover, the exploitation of the L5 lead to the improvement of the service robustness against errors and propagation delays caused by the ionosphere.

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 6, 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 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.

[43] https://www.euspa.europa.eu/european-space/euspace-market/gnss-market/gnss-user-technology-report

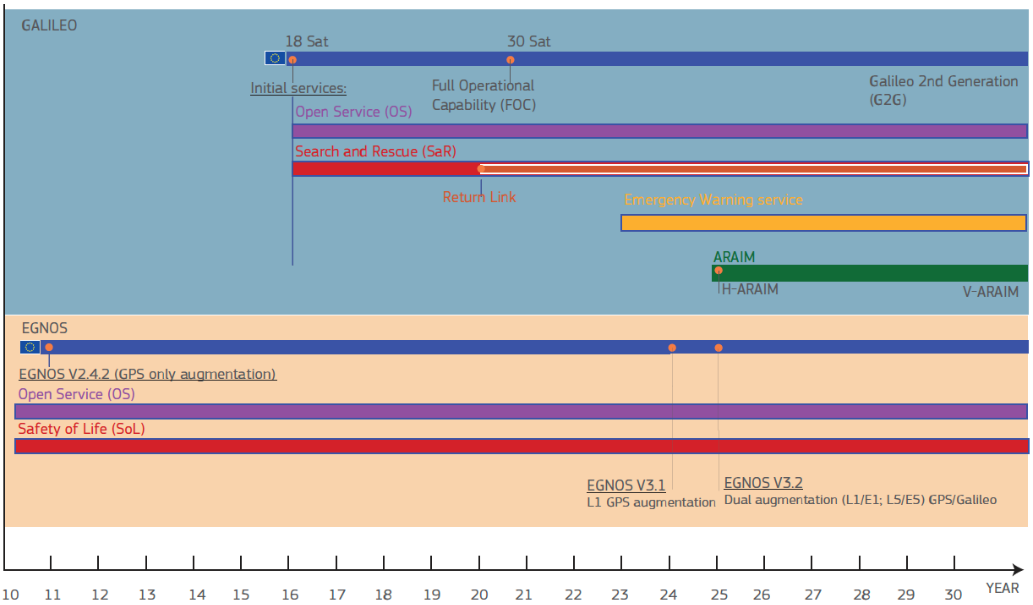


Fig. 17. Timeline EU Satellite Navigation services under Galileo and EGNOS programs, relevant for the Arctic regions (from Boniface et al., 2020)

Impact of the multi-constellation and multi-frequency systems and additional SBAS on the Arctic satellite navigation

Safe navigation both at sea and in the air can be achieved in the Arctic through GNSS integrity systems. Reid et al. (2016) examined both SBAS and ARAIM for maritime and aviation applications in the Arctic (Fig. 18). Dual frequency multi-constellation SBAS as it is intended for 2026 can meet many of the aviation and maritime navigation needs. Autonomous ice navigation requirements can be attained at sea, but it will require a reliable communication link to the Arctic. This is impossible with the SBAS GEOs in service today which have a latitude limit of 72°N. The next generation of SBAS standards allow for other, more suitable orbits to be considered for the Arctic (e.g. HEO orbits that fill much of the gap left by GEOs and will be available in the future). Addition of dual frequency to SBAS will also enable maritime operations, as this extends coverage over the oceans. The planned 2026 configuration enables ice navigation in most of the Arctic Circle and all areas not permanently covered by ice. These enable ice navigation requirements for finding tracks previously carved by icebreakers. Adding an additional core constellation to each system further allows for some restricted operations at sea and adding two additional core constellations enables hydrography and mapping. These results do not require the simultaneous use or sharing of reference stations, just the ability to switch between individual SBAS systems (Reid et al., 2021).

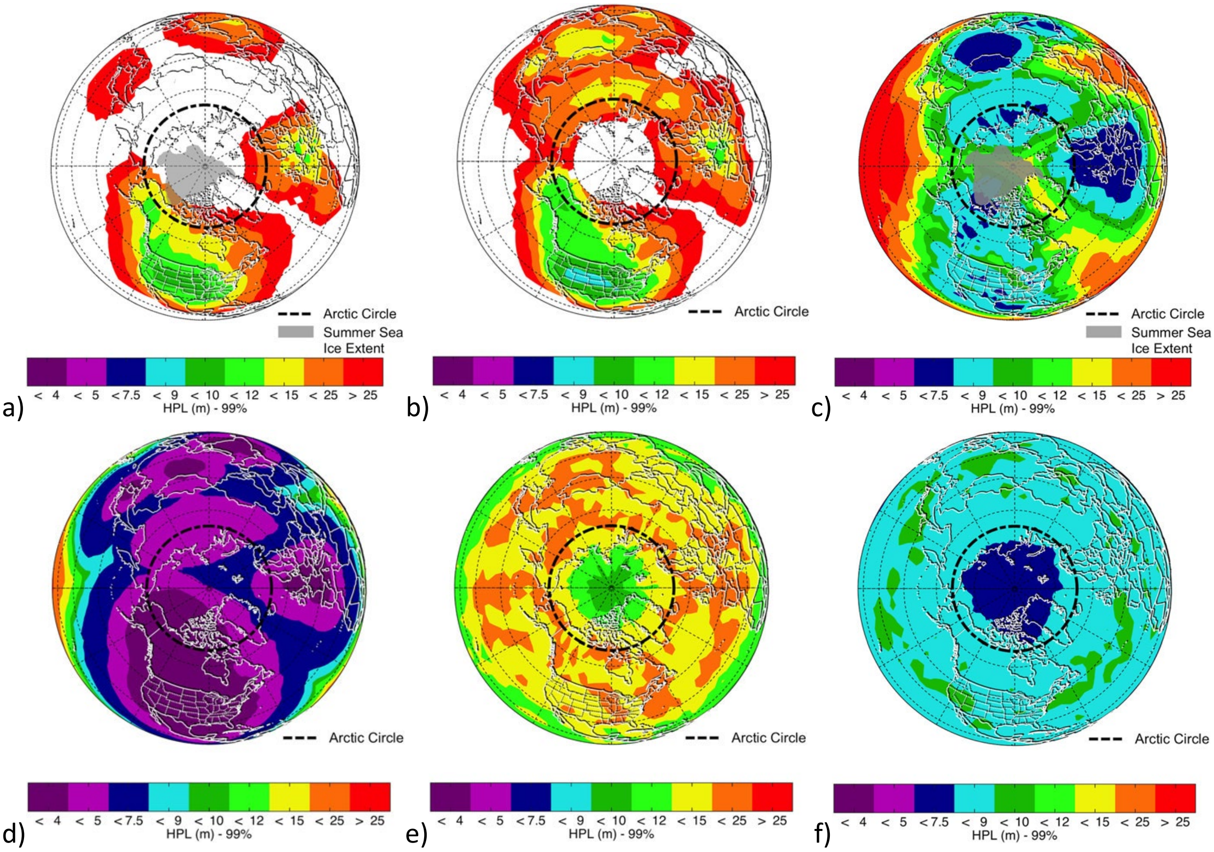


Fig. 18. Horizontal protection level (HPL) for (a) single frequency GPS-only four SBAS as in 2015, (b) single frequency GPS-only seven SBAS as in 2021, (c) dual frequency multi-constellation SBAS (2026) with an Arctic communications link, (d) dual frequency multi-constellation SBAS (2026) with an Arctic communication link plus two additional constellations being used by each system, (e) for dual frequency GPS + Galileo ARAIM (2029), and (f) dual frequency GPS + Galileo + GLONASS ARAIM (2029). (Adapted from Reid et al., 2016).

Future options and requirements most relevant to the ARICE users

For the research icebreakers operations in the ice-covered Arctic waters, the ability to georeferenced data precisely and with integrity in the key requirement. Therefore, all abovementioned future solutions that aim in improving satellite navigation and positioning in the Arctic through multi-GNSS and multi-frequency capabilities as well as augmentation services are aligned with the ARICE users' requirements. Moreover, significant number of research and monitoring in situ measurements or operations related to research infrastructure, or precision applications such as drilling, mapping, and piloting ROVs or AUVs require an order of magnitude better precision on the order of meters that can only be foreseen for future systems, utilizing dual-frequency, multi-constellation SBAS.

Some operations with research icebreakers or ships of opportunity require absolute or relative station keeping and rely on Dynamic Positioning (DP) systems. Depending on DP class, they require two or three independent position reference systems (PRSs) that typically consist of Differential GNSS (DGNSS), a Hydro-acoustic Position Reference (HPR), and a short-range laser or Microwave (MW) system measuring the range and bearing to a fixed point. In polar waters all PRS have limitations but likely the best solution is two independent DGNSS systems to act as required PRS. The design could consist of a DGPS receiver along with a secondary DGNSS receiver each obtaining corrections from different service providers via independent communication links (Reid et al., 2021).

The requirements for augmented or autonomous ice routing or ice management for field operations have yet to be strictly defined. As standards modernize, allowing for better communication of ice conditions, ships will be required to find safe tracks on their own without icebreaker assistance (Reid et al., 2021). In order to find and follow tracks previously carved out by icebreaker, ships need to find them to within half a boat width and hence 10–12 m.

The sea charts are still a main problem in remote Arctic areas where measurement density is low or non-existing or based on soundings taken before the modern technology era. E.g., in 2016 only 23% of areas around Svalbard have been surveyed by modern methods (even with a high intensity of research surveys in Svalbard waters). In areas with little or no bathymetric data commercial systems are commonly used nowadays to take soundings in situ (when the vessel is led by a small craft providing data in real time or equipped with long-range forward-looking sonar). Such measurements require precise position and orientation that can be provided by DGNSS system. Data collected by ships of opportunity, including research icebreakers, can be used as crowd-sourced bathymetric data, given that IHO requirements for horizontal accuracy are fulfilled. This could allow for building new or improved bathymetric maps in the remote Arctic areas (Reid et al., 2021).

A promising solution for applications requiring high-precision positioning is integration of multi-constellation GNSS with Inertial Navigation System (INS). GNSS provides absolute position fixing (available outdoor) and has superior long-term stability while INS provides orientation and relative positioning and has superior short-term stability (available everywhere). The GNSS/IMU (inertial motion unit) integration gives rise to a reliable system that provides flexible centimetre-level static positioning, GNSS-based heading information, centimetre-level continuous mobile positioning, plus three-axis precision orientation. Such integrated receivers are currently available, e.g. from Trimble. GNSS-Inertial receivers support GPS, Galileo, GLONASS, BeiDou, QZSS and NavIC constellations plus Trimble correction services with Integrity Monitoring delivering reliable, high-accuracy positioning without the constraints of a local base station (3rd GNSS User Technology Report, 2020).

6. Satellite communication

6.1 Current use of satellite communication

The current uses of satellite communications in the Polar Regions are discussed in greater detail in the EU-PolarNet Report (D3.3, 2018) and the JRC Technical Report “Europe’s Earth Observation, Satellite Navigation, and Satellite Communications Missions and Services for the benefit of the Arctic - Inventory of current and future capabilities, their synergies and their societal benefits” (Boniface et al., 2021). A succinct list of the main applications for polar operations related to the research icebreakers and ships of opportunity activities is given below for reference.

- Transmission of science data
- Field party safety
- Satellite data relay
- Shipping & maritime (including satellite support for navigation and ice routing)
- Aeronautical
- Search & rescue

- Remote polar stations & temporary field camps
- Emergency telemedicine

6.2 Limitations of current satellite communication 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 Task Force on Telecommunications Infrastructure in the Arctic report (TFTIA, 2017) provided a comprehensive assessment of telecommunication assets and available services in the Arctic, including gaps and user requirements, while the following report by the Arctic Council Task Force on Improved Connectivity in the Arctic (TFICA, 2019) focused more specifically on industry evolution, collaborations and emerging technologies and services that can serve the Arctic users. Both reports were used as the baseline documents in the section.

	System	Characteristics	Polar (> 80°N)	Sub-polar (70°N - 80°N)
Terrestrial systems	HF (500 kHz)	NAVTEX (safety related messages)	Unsuitable for digital communications (<0.1 kbps)	
	HF (500 kHz)	NAVDAT (safety related messages)	Currently unavailable; NAVTEX architecture for narrowband data (10-20 kbps)	
	HF, MF	Safety related messages and voice only	Unsuitable for digital communications	Unsuitable for digital communications
	VHF, Digital VHF	Line-of-sight voice and narrowband data	No base stations	Few base stations
	GSM, 3G	Line-of-sight voice and narrowband data	No base stations	Very few base stations
	LTE/4G, WiMAX	Line-of-sight voice and broadband data	No base stations	Insignificant deployment
SatCom systems	GEO (Inmarsat, VSAT)	Medium capacity - low to moderate latency	Unavailable	Limited availability and quality
	LEO (Iridium)	Narrowband data communications – high and variable latency	Potential problems with capability/ quality	Potential problems with capability/quality
	HEO	Properties comparable with GEO	Currently unavailable, but expected to provide good coverage and properties comparable to GEO systems at lower altitudes (< 60°N).	

Fig. 19. Arctic communications coverage limitations (from Plass et al., 2015).

The following section will summarize the limitations in currently available satellite telecommunications capabilities (as of August 2021). However, it is important to note that no single telecommunications technology will meet all requirements in the Arctic regions and a mixture of interoperable solutions (satellite, fixed lines, wireless, radio networks) will be used in the foreseeable future. For the ARICE users and research icebreakers and ships of opportunity operations in the high Arctic (often above 80°N), satellite communication capabilities are the most critical requirement, not only in the context of communication and data transfer, but also safe and efficient navigation and operations in ice.

Reduced visibility of geostationary (GEO) satellites

In the Arctic region 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 35786 km directly above the equator (Fig. 20), 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 fiber cables or terrestrial microwave towers are used) for connectivity back to the core network.

Where latitudes do allow, GEO satellites are well-suited to support many users in the Arctic 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.

Orbit		Altitude [km]	
		Apogeum	Perigeum
LEO: Low Earth Orbit		200 – 2 000; normally: 600-1 000	
MEO: Medium Earth Orbit		2 000-GEO; normally: 10 000-20 000	
GEO: Geostationary Orbit		35.786	
HEO: High Elliptical Orbit	Molniya (12 hr)	~500	~40 000
	Tundra (24 hr)	~24 000	~48 000

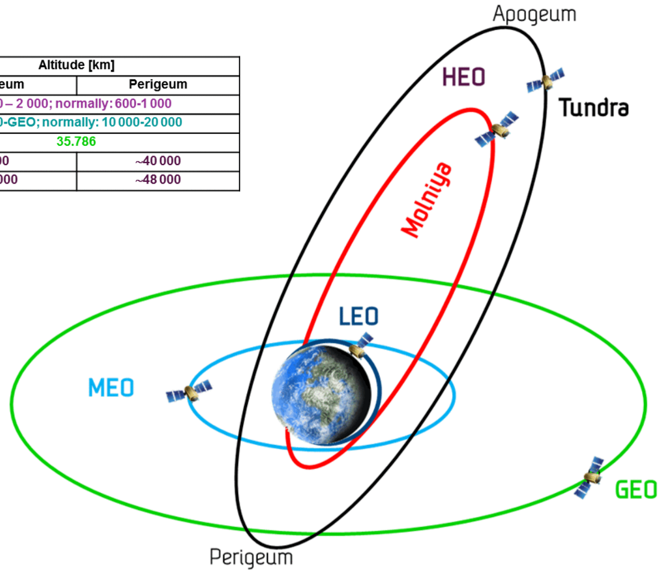


Fig. 20. Satellite orbits and major orbital characteristics (modified from Bekkadal, 2014).

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 and their Line-of-Sight (LoS) is obscured. As a result, visibility of these satellites from the ground reduces to zero from latitude of approximately 72° to 79°N. The rate of loss with latitude depends on weather, topography on the horizon, and the size of communication antennas. The efforts have been made in specialized antenna design for enhancing narrowband satellite communications systems using geosynchronous constellations and prototypes have been successfully tested[44] but this development is still ongoing.

VSAT (Very Small Aperture Terminals) technology is used for two-way satellite communications for Internet, data and telephony. VSAT services historically have operated using GEO satellites at Ku-band and C-band for the commercial market, and modern systems use also Ka-band on HTS (High Troughput Satellites). Due to the location of the satellites in combination with the movement of vessels, stabilised antennas with tracking are required for Maritime VSAT (MVSAT). Maritime VSAT is currently offered by multiple providers and data rates typically range from 64 Kbps up to 8 Mbps (lower and higher data rates are also available). However, the maximum northward extent of MVSAT is not more than 76-80°N. **Inmarsat** currently operates five GEOs in the Ka-band network and provides Global Xpress (GX) availability up to 76°N with data rates up to 4 Mbps through its FleetXpress service (by adding 2 new HEO satellites, GX-10a and GX-10b in 2022, Inmarsat GX will provide coverage in the central Arctic (see Fig. 21 and the next subsection). **Telenor Anker** provides a regional Ka-band VSAT service to maritime users over THOR 7 satellite from 1°West orbital location up to 30 Mbps (and recently, with the Newtec

[44] https://www.mitre.org/publications/project-stories/navigating-the-arctics-communications-challenges

platform, up to 50 Mbps in the Norwegian Sea up to about 79-80°N). However, above 80°N there is no broadband coverage by any GEO-based system.

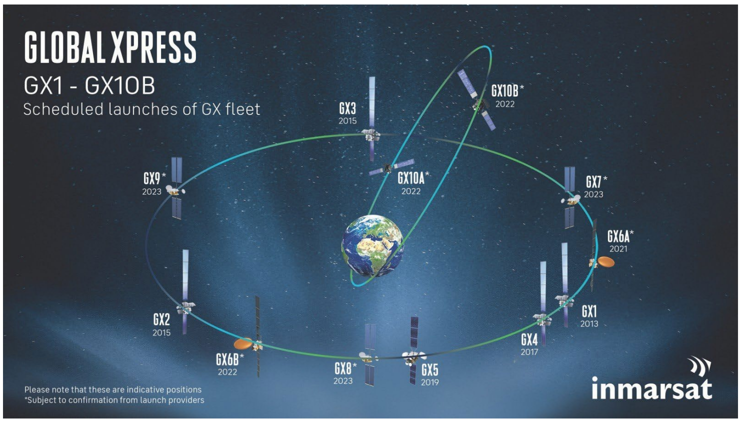


Fig. 21. Scheduled launches of Inmarsat Global Xpress fleet on GEO and HEO orbits[45].

Limited capacity of Low Earth Orbit (LEO) satellites

For higher latitudes with no GEO visibility, non-geostationary polar orbiting satellites are the only option. These low-Earth orbit (LEO, Fig. 20) 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. As by August 2021, four polar (or near polar) orbit LEO communications Satellites with Arctic coverage are operational: Argos (France/US), Gonets (Russia), IridiumNEXT (US), and Kepler (Canada).

Argos, a Satellite Data Collection System with global coverage (low data rate of 4.8 kbps), additionally used for tracking, transmission monitoring, sensor alert, surface and subsurface beacon monitoring. Allows GNSS-free positioning with an accuracy of up to 250 m (but GNSS position can also be transmitted via Argos). Argos payloads (two Argos-2 and five bidirectional Argos-3) are currently hosted on seven satellites, resulting in the typical revisit time of about 15 minutes over the Arctic. New generation Argos-4 payload (8 times more bandwidth, enhanced new modulations & protocols) will be launched on two satellites late in 2021 and on board EUMESAT satellite in 2024. Additionally, in 2023 Kinéis will launch a constellation of 25 dedicated nanosatellites, fully compatible with Argos. The first Argos nanosatellite prototype, ANGELS, was already launched in 2019. When complete, the new Argos constellation will provide a near-real time coverage of the Arctic region.

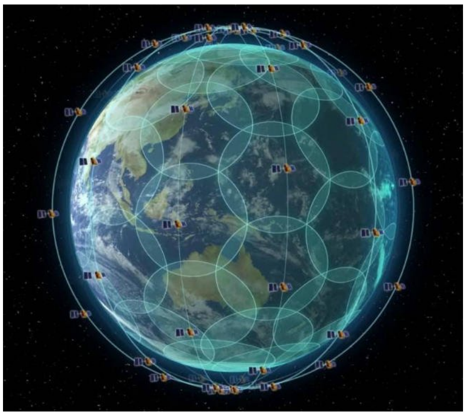
Argos system is highly relevant to the ARICE users in relation with their research activities in the Arctic region (in particular, moorings and buoys deployments, marine wildlife tracking, or Argo floats deployments)

IridiumNEXT (follower of Iridium) is currently the only provider of satellite L-band mid- and broadband data and voice solutions with truly global coverage, including full Arctic. After last launch in 2019, the Iridium LEO constellation consists of 66 satellites in 6 orbital planes (Fig. 22a) with 9 in-orbit and 6 ground spares. Satellite crosslinks create a mesh with low-latency (0.5 s) and high-quality

[45] https://www.inmarsat.com/en/about/technology/satellites.html

connections. Iridium Certus is a multi-service platform enabling products and services (Fig. 22b) on the IridiumNEXT constellation. As of August 2021, the maximum broadband offered by Iridium Certus is 704 Kbps (in addition to narrow- and midband services). The IridiumNEXT network can support data rate sup to 1408 Kbps and development of this service will depend on demand. These data rates do not truly represent broadband connection (defined as 25 Mbps) as provided by HTS GEO satellites but Iridium Certus is currently the fastest L-band connections available in the Arctic. From the beginning of 2021, Iridium is also authorized to provide GMDSS service.

IridiumNext (and the broadband capacity of Iridium Certus) is critically important for the ARICE users, including research icebreakers operators and scientific community, for all field activities above 80°N. It secures communication and data transfer required for ice routing and operations in ice as well as scientific data relay means (see Section 9 for examples).

a) 

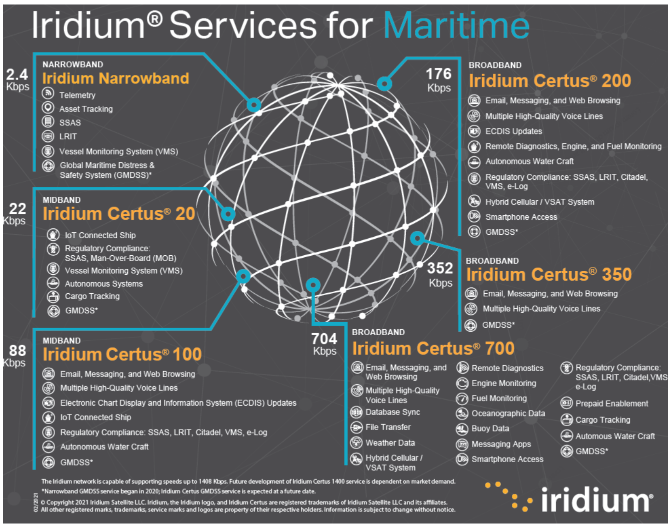
b) 

Fig. 22. (a) Global coverage of the IridiumNEXT and (b) Iridium Certus service classes for maritime[46] (from Iridium Certus Overview updated Q1 2021).

Kepler is the LEO constellation of nanosatellites, offering two primary communications services. The first is a global data transfer service that will securely relay gigabytes of data in a high-bandwidth store-and-forward solution via a Ku-band (also narrowband) communications system aboard each satellite. The second service will provide cellular-quality, standardized Internet of Things (IoT) connections. Kepler plans to launch 140 nanosatellites in 2020-2023, of which 15 has been already placed in orbit by March 2021. Using Ku-band which substantially higher than traditional nanosatellite frequencies, (often around 2 GHz for bi-directional communications), offers increased available bandwidth to support larger data applications. Data rates of 120 Mbps and 150 Mbps have been already achieved during field tests (See Section 9 and the Polarstern example).

Kepler develops fast and soon can be an important broadband service provider for the ARICE users in the high Arctic (in particular these with high bandwidth demands), provided that required hardware (antennas and terminals) will be available and robust. As provider specifically targeting IoT it can in future provide dedicated services for autonomous observing assets and unmanned systems.

[46] https://www.iridium.com/idr-file/302639

GONETS is the constellation of 12 satellites (6 of them recently renewed) on nearly polar LEO orbit with inclination 82.5°. The services include short burst direct communication with global coverage, telematics services and messaging. Only some of the satellites carry digital store & forward payloads. Maximum 9.6 Kbps data rate.

***GONETS** is not relevant for the ARICE users and research icebreakers other than Russian icebreakers.*

6.3 Future options and requirements to address limitations of satellite communication

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 (TFTIA, 2018) includes details of national priorities and infrastructure of each of the Arctic States.

Improvement of geostationary coverage and local hybrid solutions

The increase in shipping and other traffic in the Arctic 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-band 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. GEO with appropriate longitudinal alignment can offer impressive reaches to northern latitudes. Pacific Dataport[47] (Alaska), as an example, plans to provide broadband Internet capacity with a GEO Ka-band high throughput satellite (HTS) system to address the Alaska, including the Aleutian Islands, as well as portions of the Arctic up to 75°N. Pacific Dataport plans to launch two small GEO HTS satellites in optimal orbit locations to achieve the requisite capacity, diversity, and redundancy. The first of these satellites (Aurora 4A) is under construction but its launch has been delayed to 2022. The new Aurora GEO HTS network and new OneWeb LEO satellite constellation will be combined as a solution called "hybrid satellite middle mile".

Extended GEO and hybrid GEO/LEO networks can be beneficial for the ARICE users, operating locally in the regions when such coverage is provided.

Expansion of LEO mega constellations (also called proliferated LEO, pLEO)

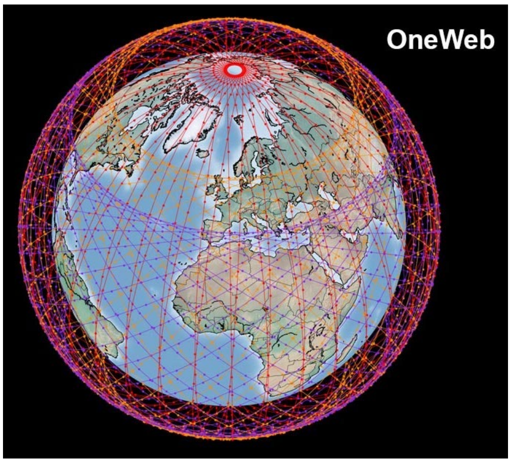
The concept of a LEO satellite mega constellation lies in placing a large number (from 100s to 1000s) of small satellites (150-200 kg) in LEO orbits (Fig. 20). A high number of satellites in one orbit and in combination with a high number of orbits (of different geometrical characteristics) will ensure satellite visibility from practically any spot in on the Earth (including the Arctic). With LEO orbit, the signal

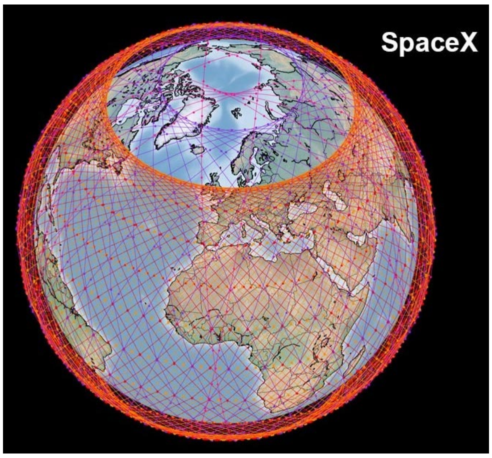
[47] https://www.auroraiv.com/

latency is very low and the broadband connection of at least 50 Mbps can be expected. The signal from user terminal will go via satellite (or even more satellites connected with optical link) into the ground-based gateway which will be connected with terrestrial internet. In order to maintain instant connection of the user terminal to internet, the gateway must be in Line of Sight (SoL) of a satellite (or satellites). This requirement is crucial especially for Arctic region where the network of gateways must be extended as far north as possible to be in SoL (Boniface et al., 2020). Several companies have been seeking to deploy new constellations of LEO satellites to provide expanded or ubiquitous mobile satellite service coverage of the Arctic. Two of them, OneWeb (UK) and Starlink (SpaceX, US) have already started deploying satellites in LEO orbits, but their services are not yet fully operational. The other two are Lightspeed (Telesat) that should be operational in 2023 and Kuiper (Amazon) that will not launch satellites earlier than in 2023.

The geometry of orbits and density of satellites of three of four candidate constellation (Fig. 23) allows visibility of satellites over the Arctic. The Amazon network will provide data coverage only between 56°N and 56°S thus it is not relevant for the Arctic regions and not described below.

OneWeb[48] started launching satellites in 2019 and after the launch in July 2021 reached the number of 254 satellites needed to provide high-speed connectivity from the North Pole to the 50°N, including the United Kingdom, Canada, Alaska and Arctic Region. Commercial service should start there at the end of 2021. The planned fleet of 648 LEO satellites for the initial phase that will deliver high-speed, low-latency global connectivity should be reached in June 2022. The complete constellation will have 6372 satellites. The orbital design already approved for OneWeb's constellation gives it an Arctic advantage as all the satellites cross over the polar region, so the highest concentration of their capacity is there. The next generation of OneWeb satellites will probably have optical links, which enables the satellites to talk to one another in space and reduces the need for ground stations in hard-to-reach areas in the Arctic. 24/7 Arctic coverage will be delivered by several commercial providers around January 2022. The OneWeb low-cost user terminals provided by Intellian[49] will be available in 2022.

a) 

b) 

[48] https://oneweb.net/

[49] https://www.intelliantech.com/news/newsroom/intellian-signs-73-million-contract-with-oneweb-for-user-terminals/#

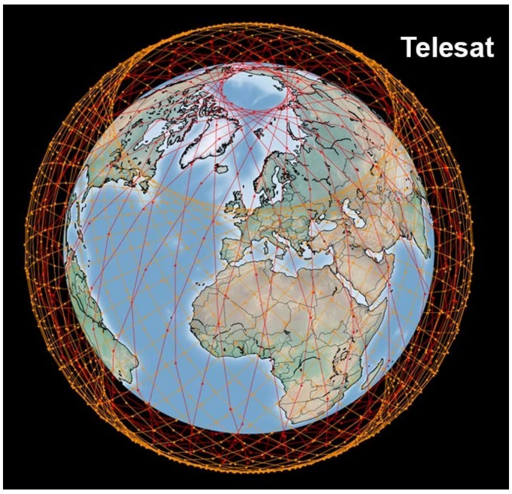
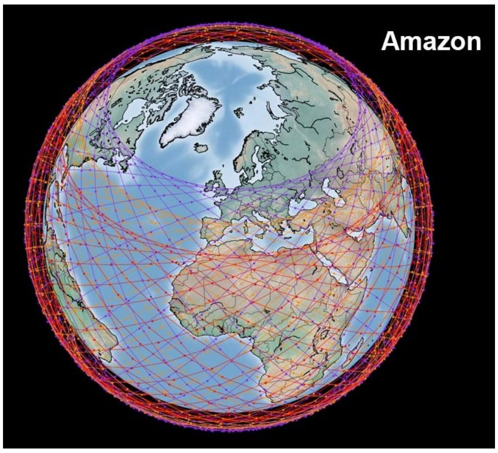
c)  d) 

Fig. 23. Orbits of mega constellations: (a) OneWeb, (b) Starlink, (c) Telesat, and (d) Amazon (from Pachler et al., 2021).

Starlink[50] (Xspace) started launching satellites in May 2019 and in May 2021 reached then number 1737 satellites, constituting "the first shell" which will allow to provide high-speed, low-latency internet services to lower latitudes up to 53°N. SpaceX has regulatory approval to eventually launch and operate up to 12,000 internet relay satellites. The early phases of SpaceX's Starlink network involves the launch of 4,408 satellites into five orbital shells in LEO. The first batch of 10 Starlink satellites was deployed in a polar orbital plane in January 2021 and about 500 are expected to be placed in polar orbits (over 100 in summer 2021) to provide service in high-latitude areas. The Starlink satellites deployed to polar orbit are equipped with laser crosslinks so no ground stations are needed over the poles.

Lightspeed[51] (Telesat) will comprise a fleet of 298 next-generation satellites (including 78 in polar orbit) integrated with an advanced ground network and about 1,200 high-capacity optical links. The first Lightspeed satellites are expected to be launched in approximately two years from now, with customer beta testing beginning shortly thereafter and commercial services commencing in the second half of 2023. A patent-pending architecture for the constellation of satellites, which features satellites operating in both polar and inclined orbital planes. This results in true pole-to-pole global coverage, concentrating capacity in areas where it is most needed to maximize network efficiency and achieve superior unit cost economics.

All three LEO mega constellations in near future will provide services of key importance for the operators and users of research icebreakers and ships of opportunity in the Arctic Ocean. All systems will provide coverage in Arctic regions but expected data rates is still difficult to estimate. Other important features will have to be considered, e.g. usability on moving vessel or surface vehicle, power consumption, data volumes, physical size of terminal and antenna, service cost, etc. The full evaluation of capabilities and performances of new networks and their services will be possible and only when commercial services are available on a regular basis.

50 https://www.starlink.com/

51 https://www.telesat.com/leo-satellites/

Highly elliptical orbits (HEO)

Highly elliptical orbits (HEO, Fig. 20) 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. 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 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.

As part of the Arctic Satellite Broadband Mission, Space Norway, owned by the Norwegian government, is cooperating with commercial satellite operator Inmarsat and the Norwegian Ministry of Defense to offer mobile broadband coverage to users in the Arctic. Both satellites will be launched in late 2022 on a SpaceX Falcon 9 rocket into HEO, which will provide full coverage from 65°N, which in practical terms is the area North of the Arctic Circle. The ground station will be established in Norway. Each of the two satellites will carry multiple payloads and the system is scheduled to be operational for at least 15 years, with users able to switch between current GEO satellites and the HEO satellites. The constellation will have user throughput of 50 Mbit/s downlink and 5 Mbit/s uplink. Two HEO satellites will be a part of the Immarsat Global Xpress geostationary constellation. To operate the system, users must have terminal (antenna) which will provide connection to internet via the Inmarsat network infrastructure and system will be fully compatible with current and future GX terminals.

7. Space-based vessel tracking and dual-purpose solutions

SAT-AIS systems

Satellite Automatic Identification System (SAT-AIS) 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 is a number of beneficial applications in the polar regions for integrated EO and AIS information, including vessel tracking, ice drift assessment (see Section 9) or as part of iceberg detection services. Norway operate the AISSat satellites which monitor maritime traffic in near-real-time by detecting AIS from ships to provide information about their position, speed, and direction. NorSat-1 was launched in 2017 it carries both, an AIS transponder and scientific instruments. The satellite allows investigating solar radiation, space weather and detecting ship traffic

VHS Data Exchange System

A second multi-payload satellite, NorSat-2, was launched together with NorSat-1. In addition to AIS, it carries a VHF Data Exchange System (VDES) transceiver. 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. VDES is based on AIS, with a common receiver and sender for both AIS and VDES. However, VDES may also be used for other types of digital messages between ships, with the communication going directly from ship to shop or via a station on land or satellite. ESA is using the Norwegian NorSat-2 satellite to test this new technology, 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. This new technology system will enable a wider seamless data exchange for the maritime community. The launch of Norsat-3 took place in April 2021

One of the satellites to use this in its payload is the new European satellite ESAIL, launched in September 2020. ESAIL is the ESA's first AIS satellite.

NorSat-4, currently in development, will also carry an AIS receiver, as well as an experimental camera from FFI. This camera is powerful enough to spot vessels larger than 30 meters in length, independently of light or weather conditions. A third generation of space AIS receiver, with increased performance and even smaller demands for power and payload volume, is currently in development. This receiver will be launched on a new Norwegian satellite in 2022, along with a second generation VDES receiver for space.

8. Examples of satellite-based support for navigation and communication of research icebreakers

8.1 Example of the satellite-based support for ice routing during the CAATEX and UAK cruises in the Arctic Ocean

Satellite-based support was provided for the ship routing and operations in ice covered waters in the Arctic Ocean during the CAATEX[52] (Coordinated Arctic Acoustic Thermometry Experiment) cruises to the North Pole in 2019[53], to the Beaufort Sea in 2020[54], and the UAK 2021 (Useful Arctic Knowledge[55]) summer school research cruise to the Nansen Basin with the Norwegian Coast Guard Icebreaker KV Svalbard (all cruises led by Hanne Sagen, NERSC). KV Svalbard incorporates a strengthened hull for ice-breaking missions and is the first Norwegian Naval vessel to receive the DNV Class notation, Icebreaker POLAR-10. KV Svalbard is a Double Acting Ship (DAS) type of ice-breaking vessel designed to operate in open waters and thin ice and equipped with real-time ice load monitoring system.

During the CAATEX 2019 cruise KV Svalbard has traversed the polar pack ice at speeds as high as 6 to 7 knots during much of the voyage through the ice to the North Pole[56]. Since ice conditions were more severe north of Svalbard, KV Svalbard selected a more easterly sailing route, starting north of Franz Josef Land. The decision was made based on detailed analysis of the ice conditions during the spring and summer during previous and this year. Daily updates satellite images from the Norwegian Ice Service in Tromsø and ice analysis provided onboard by Andreas Kjøl from the Norwegian Coastal Directorate were used to select a sailing route with less resistance from the pack ice[57]. Navigation in the lead made by the Russian nuclear icebreaker 50 Years of Victory could accordingly be done at speeds as high as up to 6-7 knots and only 3.5 days sailing through the pack ice north of Frans Josef

[52] https://caatex.nersc.no/

[53] https://caatex.nersc.no/node/27

[54] https://www.nersc.no/news/all-moorings-beaufort-sea-rescued-%E2%80%93-under-extreme-conditions

[55] https://www.nersc.no/project/uak

[56] https://www.nersc.no/news/norwegian-research-expedition-onboard-kv-svalbard-reached-north-pole

[57] https://www.kongsberg.com/kmagazine/2019/8/supported-historic-voyage-north-pole/

Land. KSAT supported the expedition through daily deliveries of satellite products, primarily detailed SAR images (e.g. a combination of Sentinel-1, RADARSAT-2, and COSMO-SkyMed imagery provided by CMEMS) showing the updated ice situation[58].

During the CAATEX 2020 Beaufort Sea expedition and the UAK 2021 summer school, the support for navigation in ice was provided onboard by Alistair Everett from the Norwegian Ice Service of MET Norway (personal comm., 2021). MET Norway provided access to an ftp server which was used to send data to the ship. Once downloaded the data was used in QGIS and the onboard navigation system. Data/internet connections were provided by VSAT and Iridium arranged by the Norwegian Coast Guard. VSAT coverage is limited to the area north of Svalbard and another area north of Alaska, but there was no limit on the amount of data which could be downloaded. Iridium covered the entire route but had a download limit. During the cruise around 4GB were used for downloading data on the ship via Iridium. Download speeds were significantly better when using Iridium than VSAT. Iridium typically gave download speeds ~90KiB/s, while VSAT was ~20KiB/s. In general Iridium was preferred due to better coverage and faster download speeds. Satellite images used during both cruises came from Sentinel-1, RADARSAT-2, both radar satellites, and were supplemented with an AMSR2 sea ice concentration derived from passive microwave images. Additionally, SMOS ice thickness product was used for ice thinner than 50 cm).

The satellite imagery and other products described below were used during the CAATEX 2020 Beaufort cruise (similar combination was also used on KV Svalbard during the UAK 2021 cruise):

Sentinel-1 images - accessed from a combination of three sources (cophub, scihub, and the Norwegian Ground Segment) were combined into mosaics before ftp upload. Initially, down-sampled low-resolution (500m resolution) mosaics were used, split into three relatively large areas covering the cruise route. The low-resolution images were useful for an overview of the ice situation and could be used to identify the ice edge; however, identifying ice types and small-scale navigation within the ice was extremely difficult using these images due to the loss of detail. The high-resolution Sentinel-1 mosaics were the primary source of detailed ice information during the cruise. The resolution was sufficient to identify ice types, leads, floes and other useful navigational features. It was also possible to recognize floes and features in the higher-resolution Sentinel-1 images (not possible at lower resolutions) which was useful to understand ice drift and any uncertainties in the image geolocation. High resolution mosaics were provided with a resolution of 40 m covering most of the ship route and an area of 50 km around each of the mooring positions. The delay in receiving Sentinel-1 images varied; typically, the images collected at 18:00 CET were not available until after midnight, therefore could not be used until early the next morning when they were already more than 12 hours old. This caused issues when downloading mosaics.

RADARSAT-2 images - provided by the Canadian Space Agency through agreements with the US National Ice Centre and KSAT and processed by the Norwegian Ice Service were primarily ordered by NOAA and delivered by MDA via an ftp server to MET Norway, where the images were processed and converted to 8-bit before being uploaded to the ftp server for the ship. A small number of images were also acquired through the Norwegian Joint Headquarters (NJHQ), these were delivered via KSAT to MET Norway. The images were an important component of the imagery received on board, particularly

[58] https://www.ksat.no/news/news-archive/2019/ksat-supports-historic-voyage-to-north-pole/

in the Laptev Sea where there is a gap in Sentinel-1 data, and also covering other regions in periods where there were gaps in the Sentinel-1 coverage. Additionally, it was valuable to have a higher frequency of images around the moorings as they could be used in drift tracking around the moorings.

AMSR2 sea ice concentration product - produced by the University of Bremen was used regularly during the cruise, mostly for route planning when travelling around the ice edge (with daily downloads) and to get an oversight of the ice extent over the whole arctic. It was not used in the ice, other than to monitor ice conditions around the ice edge for the return journey.

Ice chart products - mainly stage of development (SoD) charts provided by USNIC and AARI. SoD charts from AARI were provided weekly on their website covering the whole arctic, and in addition more detailed charts covering the Beaufort Sea region were ordered for travelling between the mooring points. Daily SoD charts were received from the USNIC while the icebreaker operated in the mooring area. Other ice charts were also received from USNIC, such as concentration and marginal ice zone; however, AMSR2 products were preferred for these purposes instead as these worked better in NORCCIS.

The critical information for ice routing was anything which could indicate ice thickness and therefore areas to avoid so that we could optimize fuel, distance and time when travelling in the ice. When navigating around the ice edge decisions were made on the short term, mostly using satellite images. This gave much more detail than ice charts and allowed for our own interpretation informed by conditions in the area. There were often differences between the analysis from different ice centers and also day-to-day analysis at the same ice center. The ice charts were thus used in combination with satellite imagery to get a second opinion on the ice type in the imagery and make a better-informed decision about the conditions we would encounter in different errors.

Sea ice forecast - experimental versions of a number of sea ice forecast models were used occasionally on board. Short-term forecasts were provided by the CMEMS/NERSC neXtSIM model and the US Navy GOFS3.1 model based on HYCOM and CICE. Long term and seasonal forecasts were provided by the US Navy ESPC model and SALIENSEAS ECMWF SEA5 models. The forecast products were only downloaded occasionally in the mooring operations area (for the ice thickness) and to give an overview of the general ice conditions. However, in all cases the model data was 'supplementary information' rather than a primary tool we used for decision making. The seasonal forecasts were used in advance of the cruise during the planning phase.

Weather information - provided as text forecasts from the Fleet Weather Centre, US, and through StormGeo's NAVI-Planner system. FWC provided very valuable along track forecasts which summarized relevant information over the following 48 hours. Forecasts from StormGeo were delivered as a data file (with charts of wind, pressure, air temperature, waves, and other parameters) via email which could be opened in the NaviPlanner software. The planned route was plotted and viewed alongside the charts, and then point forecasts could be extracted along the route ahead.

Winds were particularly important for interpreting ice drift speed and direction while navigating in sea ice. Wind and temperature were important for the mooring recoveries when the crew had to be on deck for extended periods of time and ice drift had to be estimated. Qualitatively, wind directions were generally good, wind speeds were less reliable. FWC point forecasts were generally better for winds.

Sea ice drift – critical during the mooring recovery operations and had to be known before ice management could begin so that the correct location to begin breaking ice could be calculated. Before arriving at the moorings drift calculations were made using satellite images to track the movement of the ice. These were a very coarse temporal resolution and often showed that the drift varied unpredictably from one day to the next. Ice drift was also estimated from data collected by AIS buoys deployed on ice floes in the operation area and the ad hoc written scripts and setup were used for automated processing and visualization. The previous hour of data was averaged over 10-minute time periods to identify trends in speed and direction more easily and this output proved very valuable for operations in ice. Some issues were encountered with a time stamp of AIS messages, showing that proper synchronization with UTC time is critical to obtain absolute positions from AIS.

Information presented above is a summary of the detailed analysis of support services for navigation and operations in the ice during the KV Svalbard research cruise to the Beaufort Sea, prepared by Alistair Everett from the Norwegian Ice Service of the MET Norway (alistaire@met.no).

8.2 Example of the satellite-based broadband communication during the MOSAiC campaign in the central Arctic

Kepler Delivers World's First Arctic High-Bandwidth Satellite Service For Largest Polar Expedition[59]

This example summarizes the press communication from Kepler Communications, a pioneer in nanosatellite telecommunication services, has demonstrated delivering over 100Mbps connectivity service in the Arctic region to the German icebreaker *Polarstern*. The vessel was located around 85^{o}N as the home to the MOSAiC[60] scientific expedition. The demonstration marks the first time in history that the central Arctic is successfully connected through a high-bandwidth satellite network.

Kepler's two polar-orbiting satellites were being used to transfer data for scientists taking part in MOSAiC, the most extensive research expedition ever to the North Pole. MOSAiC was an international expedition consisting of hundreds of scientists and operations crew, which will remain locked into the Arctic ice sheet to study the environment.

Thanks to Kepler, the *Polarstern* was equipped with the world's only high-bandwidth satellite data link delivered from low-Earth orbit (LEO) that is available in the Arctic. With the vessel operating well outside the range of traditional high-throughput satellites, Kepler was providing 100x higher data speeds, when the satellite passed the vessel than would be otherwise available to the ship. Due to this improved data transfer capability means scientists could share large data files between ship and shore, improving the ability to share, analyze, and disseminate information.

The Kepler Global Data Service provided a cost-effective means to transfer large data volumes gathered over the course of MOSAiC. Rather than only storing data locally and analyzing once physical storage could be sent back with supply vessels, scientists were able to continuously transfer test and housekeeping data sets over the Kepler LEO satellite network.

[59]Source: The Kepler press release from 7 November 2019 available from https://www.keplercommunications.com/kepler/news-view?id=57

[60] https://mosaic-expedition.org/

Kepler is the world's only provider of high-bandwidth satellite services in the poles. Aboard the *Polarstern*, Kepler demonstrated data rates of 38 Mbps downlink and 120 Mbps uplink to a 2.4m Ku-band VSAT (Very Small Aperture Terminal).

8.3 Example of the improved situational awareness during SODA campaigns in the Beaufort Sea

This example summarizes the study by Rainville et al. (2020) that addresses the near real-time situational awareness information regarding the weather, sea ice conditions, and oceanographic processes provided to the USCGC Healy in the Beaufort Sea during SODA (the ONR funder project 'Stratified Ocean Dynamics of the Arctic') field campaigns in 2019 (also to RV Sikuliaq in 2018). Seamless access to, and an understanding of, satellite images, model output, weather charts and other observational products, is essential to provide the situational awareness in the Arctic marine environment. Effective situational awareness must be achieved through the blending of several products and this approach requires identifying the suite of products needed, and familiarity with their visualization and interpretation. The most up-to-date products that have the maximum value and the time-window associated with situational awareness products is usually less than 24 h from the time of collection. Forecasts, such as weather predictions, are valuable out to about 5 days.

The products utilized aboard Healy included sea ice, weather, and model products:

Sea ice products - Synthetic Aperture Radar (SAR) satellite imagery (publicly available SAR imagery, e.g., Sentinel-1 as well as others specifically ordered to support the mission, e.g., RADARSAT-2, COSMOSkyMed, and TerraSAR-X), visible imagery (occasionally downloaded MODIS visual images directly from the tools provided in Worldview), Passive Microwave, and ice charts (United States National Ice Center ice charts detailing the ice types and position of the ice edge, both the standard ice charts and specialized products);

Weather products - weather charts provided by partners at the United States National Weather Services as targeted weather forecasts to the ship operators and scientists in the fields, complementing more broadly available tools displaying weather conditions and forecasts;

Model products – for variables not available in NRT, e.g. sea ice extent, thickness, and drift obtained from the Naval Research Laboratory's high resolution Global Ocean Forecasting System (GOFS) model, together with forecasts over the next 24–48 h, made available for the Chukchi and Beaufort Seas (the SODA operational area);

Other products - derived in near-real time from analysis of SAR and other remote sensing products, e.g. daily sea ice drifts based on a Maximum Cross Correlation technique from EUMESAT OSI SAF.

The Rainville et al. (2020) study provides detailed information about sources of all used products as well as the details of ordering and acquiring these products, operational sea ice analysis from USNIC, challenges with formatting and file size, data transmission systems to the ships, and data visualization techniques.

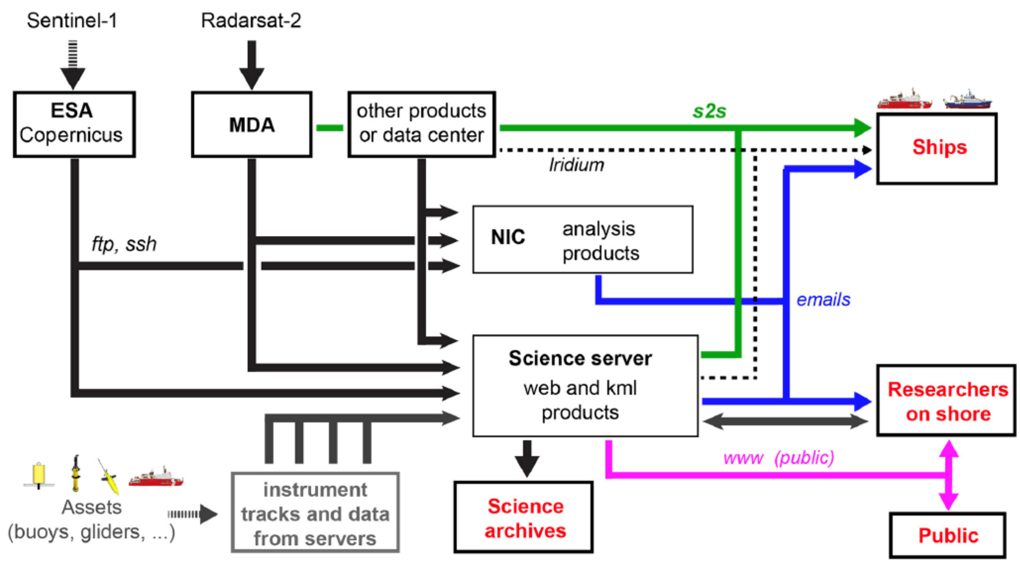


Fig. 24. Block diagram of the information flow related to situational awareness during the SODA field campaigns (from Rainville et al., 2020)

Regular communication and coordination between the SODA team, the USCG and the USNIC allowed to identify what situational awareness products were needed, and who could provide them. The next step was to develop the mechanisms to automatically obtain these products as soon as they became available from the providers, archive them on a data-server in a logical manner, and to provide the protocols to automatically 'push' these products to the field-team, or for the field-team to 'pull' the products from the server. A developed system is shown on Fig. 24. Rainville et al. (2020) study discusses some applications of the developed system for ship navigation, moorings deployments, upper ocean sampling, and floe selection for ice-based instruments. The study provides good overview of the dedicated system developed to overcome many of the challenges associated with obtaining timely situational awareness information in remote Arctic regions and can be used as a baseline for the planning and implementation of the large field campaigns with research icebreakers and ships of opportunity (and less extensive operations, using the selected components of the presented system).

9. Requirements for data access and infrastructure

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 or under development for the Arctic regions. This limits the ability of all operators to easily discover, access and exploit the data which is being acquired in the Arctic. The following limitations were 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 and user-friendly visualization tools.
- Information discovery – ability to easily discover information distributed over multiple sites and organizations, access to multiple information sources via a single hub.

- 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 (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 online community tools to support learning and new developments.

10. Improved use of 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 organizations, 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.

10.1 GALILEO and EGNOS

The European GNSS programme is funded and owned by the EU. Until recently, the European GNSS Agency [61] (GSA) had overall responsibility for the programme, managing and overseeing the implementation of all activities on behalf of the EU. In 2021, in line with the new EU Space Regulation and the growing role of space in supporting EU priorities in terms of growth, competitiveness, sustainability, and security, the EU decided to expand the scope of the former European GNSS Agency (GSA) to include new responsibilities. This resulted in the creation of the European Union Agency for the Space Programme[62] (EUSPA), which was officially launched in May 2021. EUSPA's mission is to be the user-oriented operational Agency of the EU Space Programme. EUSPA is responsible for Galileo and EGNOS positioning, navigation and timing services and cost-effective satellite communications services for GOVSATCOM.

The European Commission is developing modernization 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

[61] https://www.euspa.europa.eu/sites/default/files/summary_of_gsa_achievements_in_2020.pdf

[62] https://www.euspa.europa.eu/about/about-euspa

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[63] and at associated community events.

As an example of the engagement with specific GNSS issues in the Arctic, Finland organized the Challenges in Arctic Navigation workshop in April 2018. 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.

10.2 European Copernicus Programme

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[64] (ESA), the European Organisation for the Exploitation of Meteorological Satellites[65] (EUMETSAT), the European Centre for Medium-Range Weather Forecasts[66] (ECMWF), EU Agencies and Mercator Océan[67]. 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.

The requirements gathering for the planned polar mission was led in two rounds by a Polar Expert Group (PEG) established by the European Commission. The first report (PEG I, 2018) identified the critical variables to be observed in polar areas (i.e. floating ice, glaciers, caps and ice sheets, sea level, sea surface temperature, surface albedo, surface, fresh water, snow and permafrost). The second report (PEG II, 2018) indicated that it would not be possible to meet all observation requirements relying on a single Copernicus HPCM, operated together with the current Copernicus Sentinels (and Copernicus Contributing Missions). Consequently, PEG II focused on a smaller number of top-operational-priority objectives, including priority variables and recommended instrumentation.

In 2020, PEG supported by ESA, EUMESAT, EEA, and the H2020 Kepler project published the third report (PEG III, 2020) to complement the requirements according to development and new drivers in 2017-2020 (e.g. EU Council Conclusions on “Space solutions for a sustainable Arctic”, publishing IPCC SROCC, UN SDGs, evolution of Copernicus Services and Copernicus Space Component, or new H2020 projects). The PEG III requirements are mapped with corresponding EO space assets over time with the year 2020 as a baseline followed by the time period 2021-2027, the period beyond 2027 including the Copernicus HPCMs and the NG Sentinels. PEG III also describes potential synergies across satellite missions, potential gaps, and the needs for non-space assets (in-situ data).

[63] https://www.europeanpolarboard.org/

[64] https://www.esa.int/

[65] https://www.eumetsat.int/

[66] https://www.ecmwf.int/

[67] https://www.mercator-ocean.fr/en/

PEG has also proposed objectives to be considered for a future Polar Task Force starting in 2021 with a main focus on the Copernicus Services. The Task Force will also further elaborate on the linkages to the other components in the European Space Programme, meaning the Galileo navigation system and telecommunication systems coordinated by GOVSATCOM.

Consultations between the European Commission and the entrusted entities in charge of the Copernicus Space Component (CSC), i.e. ESA and EUMETSAT, have started to focus on the evolution of the CSC. In September 2020, ESA presented to its Programme Board for Earth Observation “The next phase of Copernicus - Copernicus Space Component (CSC) Long Term Scenario” providing a preliminary schematic overview of the CSC evolution. Ongoing engagement with these groups, member state delegates to both ESA and Copernicus, and related community events will communicate the ongoing need for evolution of the Copernicus programme, including the Sentinel and third-party space components, in situ observation elements and changes to the Copernicus services.

10.3 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. 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 DPTD52 (Discovery, Preparation, and Technology Development) Programme. Two parallel studies proposed potential mission architectures including space segment, ground segment, data management and downstream applications, based on consolidated user requirements. The output of this study, concluded in 2019, acted as inputs to a follow-on Phase A feasibility study.

The European Polar Science Week organized in October 2020 jointly by the European Space Agency and the European Commission (together with EASME and EU PolarNet) was intended to bring together the European Polar science community and reinforce European cooperation for Polar Science[68]. This online event (due to COVID-19) provided a valuable forum not only for scientific community but also for other stakeholders with interest in polar areas to discuss how Earth observation from space can help addressing the major challenges in Polar research and, more specifically (among other issues), what are requirements from different groups, including also the operators and users of research icebreakers in the Arctic.

11. Conclusions

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

The operators and users of research icebreaker and ships of opportunity in the Arctic use space technologies to support a large and growing part of their activities. Their requirements are related

[68] http://eo4polar.esa.int/#background

both to operational and scientific needs that are often aligned. 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.

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 high Arctic. Opportunities for developing new technologies to address this gap (including HEO and LEO satellite constellations) should be pursued either as European, national, commercial or partnership developments.

New opportunities for the broadband satellite communication are currently emerging at an unprecedented pace with new LEO mega constellations (and other systems as hybrid networks or HEO missions) going from the design phase to commercial installations. To assure that new services and platforms can be in future used for the maximum benefit of ship operators and scientists working in the Arctic regions, a dialog between established or expected providers and user community should be established in advance.

GNSS options are adequate for many applications in the Arctic regions, but limited access to augmentation services prevents their use for unmanned autonomous mobile systems, aviation, or 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 Arctic.

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. New capabilities in monitoring sea ice for maritime operations and improved observations for polar weather meteorology are high-priority options in this context. Requirements of the icebreakers and ships operators in the Arctic are to large degree aligned with the needs of scientific community in terms of observed variables related to sea ice, ocean state or weather, but resolution and latency of available products can be a limiting factor of better uptake.

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.

Future plans of the European Space Programme are developed with the input from representatives of EU and ESA member states. The requirements of polar operators and national activities in the Arctic should be coordinated and clearly communicated to national representatives to ensure they are included in future development plans where relevant.

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