European Commission

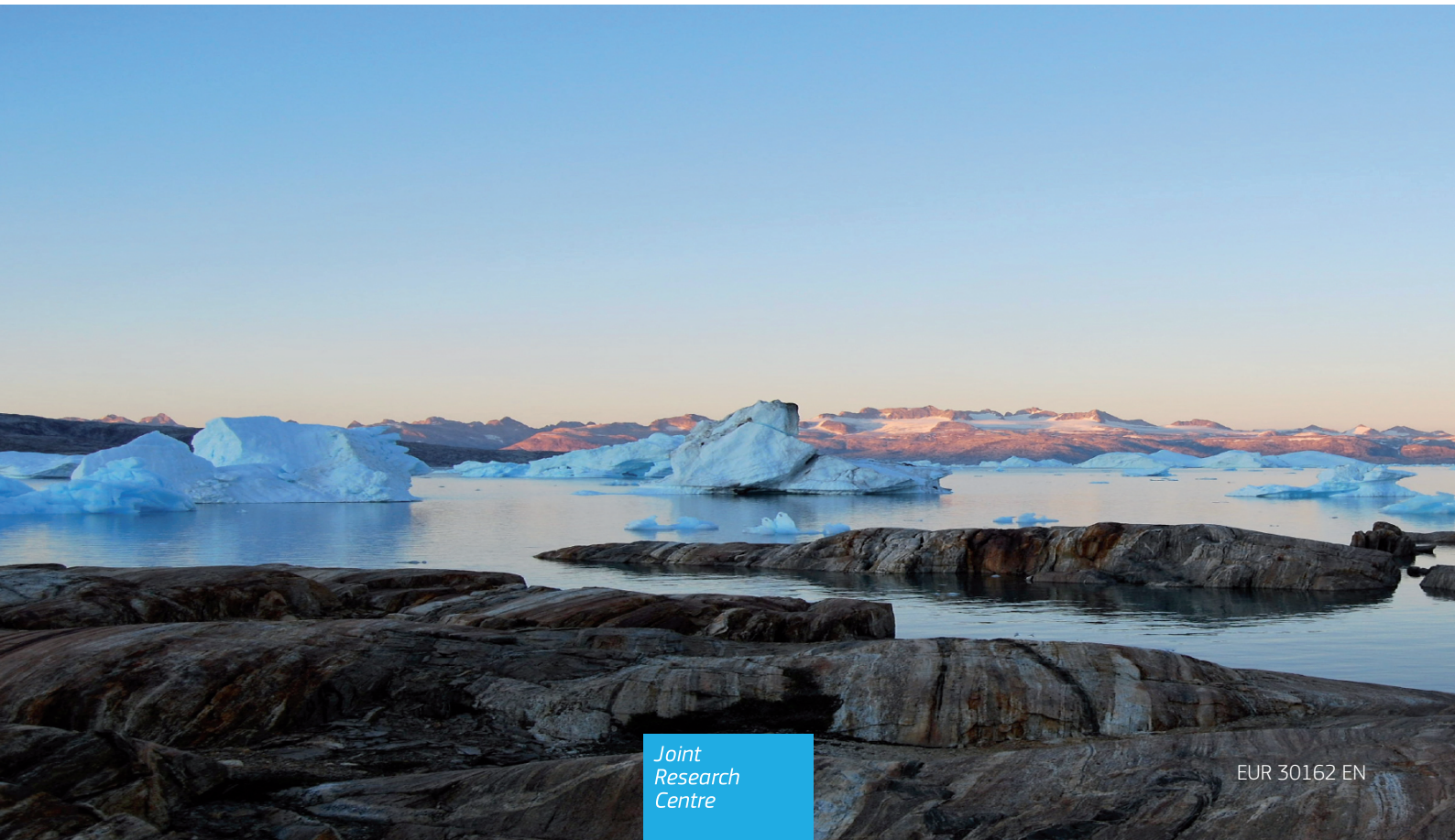
JRC SCIENCE FOR POLICY REPORT

Europe's space capabilities for the benefit of the Arctic

Key capabilities, synergies and societal benefits

Karen Boniface, Ciro Gioia, Luca Pozzoli,
Thomas Diehl, Srdjan Dobricic,
Joaquim Fortuny Guasch, Harm Greidanus,
Tomas Kliment, Jan Kucera,
Greet Janssens-Maenhout, Pierre Soille,
Peter Strobl and Julian Wilson

2020



Joint Research Centre

EUR 30162 EN

This publication is a Science for Policy report by the Joint Research Centre (JRC), the European Commission's science and knowledge service. It aims to provide evidence-based scientific support to the European policymaking process. The scientific output expressed does not imply a policy position of the European Commission. Neither the European Commission nor any person acting on behalf of the Commission is responsible for the use that might be made of this publication. For information on the methodology and quality underlying the data used in this publication for which the source is neither Eurostat nor other Commission services, users should contact the referenced source. The designations employed and the presentation of material on the maps do not imply the expression of any opinion whatsoever on the part of the European Union concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries.

Contact information
Name: **Karen Boniface**
Address: European Commission, Joint Research Centre, Directorate E: Space, Security and Migration
Email: karen.boniface@ec.europa.eu
Tel.: +39-0332-785295

EU Science Hub
https://ec.europa.eu/jrc

JRC118965

EUR 30162 EN

PDF	ISBN 978-92-76-17847-7	ISSN 1831-9424	doi:10.2760/43511
Print	ISBN 978-92-76-18118-7	ISSN 1018-5593	doi:10.2760/641049

Luxembourg: Publications Office of the European Union, 2020

© European Union, 2020

The reuse policy of the European Commission is implemented by the Commission Decision 2011/833/EU of 12 December 2011 on the reuse of Commission documents (OJ L 330, 14.12.2011, p. 39). Except otherwise noted, the reuse of this document is authorised under the Creative Commons Attribution 4.0 International (CC BY 4.0) licence (https://creativecommons.org/licenses/by/4.0/). This means that reuse is allowed provided appropriate credit is given and any changes are indicated. For any use or reproduction of photos or other material that is not owned by the EU, permission must be sought directly from the copyright holders.

All content © European Union, 2020, except: *Cover page, Jean-Christophe André. Source: www.pexels.com*

How to cite this report: Karen Boniface, Ciro Gioia, Luca Pozzoli, Thomas Diehl, Srdjan Dobricic, Joaquim Fortuny Guasch, Harm Greidanus, Tomas Kliment, Jan Kucera, Greet Janssens-Maenhout, Pierre Soille, Peter Strobl and Julian Wilson, *Europe's space capabilities for the benefit of the Arctic – Key capabilities, synergies and societal benefits*, EUR 30162 EN, Publications Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-17847-7, doi:10.2760/43511, JRC118965.

EUROPE'S SPACE CAPABILITIES FOR THE BENEFIT OF THE ARCTIC

Key capabilities, synergies and societal benefits

TABLE OF CONTENTS

Contents

Acknowledgements

Abstract

Executive summary

1 Introduction

2 Policy context

3 Users' needs

4 Earth Observation capabilities

5 EU satellite navigation capabilities

6 Satellite communications capabilities in the Arctic

7 Space situational awareness (SSA) capabilities

8 Synergistic uses of Earth observation, navigation and satellite communications in the Arctic

9 Societal Impact assessment

10 Conclusions

References

List of abbreviations

Annexes

Annex 1. Copernicus Sentinels missions

Annex 2. The Copernicus contributing missions

Annex 3. EU funded Arctic research and innovation H2020 projects

Annex 4. Societal Benefit Areas

Contents

Acknowledgements 7
Abstract 9
Executive summary 9

1. Introduction 13

2. Policy context 17
2.1. Arctic Policy 17
2.1.1. EU Arctic Policy 17
2.1.2. International context 18
2.2. EU Space policy 18

3. Users' needs 21
3.1. Science users 21
3.2. Operational users 22
3.3. Indigenous and local community users 23

4. Earth Observation capabilities 25
4.1. Copernicus programme 25
4.2. Overview of user-required functions versus Sentinels 25
4.3. Copernicus services 27
4.4. Other relevant Earth observation missions 27
4.5. EO support infrastructure 29
4.6. EO downstream services 29

5. EU satellite navigation capabilities 33
5.1. Galileo 33
5.2. EGNOS & Integrity 35

6. Satellite communications capabilities in the Arctic 39
6.1. Current SatCom systems 40
6.2. Low bit rate SatCom 40
6.2.1. ARGOS 40
6.2.2. ORBCOMM 41
6.3. EU GovSatCom 41
6.4. Future SatCom systems 41
6.4.1. Arctic Satellite Broadband Mission (ASBM) 41
6.4.2. LEO broadband mega constellations 42

7. Space situational awareness (SSA) capabilities 45

8. Synergistic uses of Earth observation, navigation and satellite communications in the Arctic 47
8.1. Service level 47
8.1.1. Synergistic applications 47
8.1.2. Innovative techniques 49
8.2. Infrastructure level 51

9. Societal Impact assessment 53

10. Conclusions 57

Annexes 61
Annex 1. **Copernicus Sentinels missions** 61
Annex 2. **The Copernicus contributing missions** 62
Annex 3. **EU funded Arctic research and innovation H2020 projects** 63
Annex 4. **Societal Benefit Areas** 65

References 67

List of abbreviations 71

Acknowledgements

The authors thank David Arthurs from the global organization Polarview, and Shridhar Jawak from the Svalbard Integrated Arctic Earth Observing System (SIOS) in Norway for the exchange of views and their valuable contributions to this study.

We are grateful to Solène Routaboul, Stephan Lauriol, and Mariana Childress from CLS France, for providing the latest updates and modernisation plans on the Argos system.

We thank our JRC colleagues Inès Joubert-Boitat and Jesus San-Miguel for the useful material provided on the Copernicus Emergency Service, and Pieter Beck for the Arctic vegetation aspects.

We are also thankful to Xavier Maufroid, Claude Cowe and Antonio Rolla, of the EU GNSS Programme Directorate of the European Commission, for sharing information on the status and planned evolution of the Galileo Search and Rescue Service.

We are grateful to these other colleagues from DG DEFIS for their constructive comments and remarks through the completion of the study: Tanja Zegers, Gilles Lequeux, Leo Guilfoyle, Eric Guyader and Ola Nordbeck.

Finally, we appreciate the thorough review and thoughtful recommendations provided by James Bishop, Frédéric Bastide and Carlos Santamaria.

Authors

Karen Boniface[1], Ciro Gioia[1], Luca Pozzoli[2], Thomas Diehl[3], Srdjan Dobricic[2], Joaquim Fortuny Guasch[1], Harm Greidanus[1], Tomas Kliment[4], Jan Kucera[1], Greet Janssens-Maenhout[3], Pierre Soille[5], Peter Strobl[3] and Julian Wilson[2].

[1] European Commission, Joint Research Centre, Directorate E, Space, Security and Migration, Italy.
[2] European Commission, Joint Research Centre, Directorate C, Energy, Transport and Climate, Italy.
[3] European Commission, Joint Research Centre, Directorate D, Sustainable Resources, Italy.
[4] Arhs Developments, Luxembourg.
[5] European Commission, Joint Research Centre, Directorate I, Competences, Italy.

0 ABSTRACT / EXECUTIVE SUMMARY

Abstract

Both the Arctic and Space are important policy topics for the EU, with recently defined strategies and programs. This report surveys the EU's space-based capabilities, related to Earth observation, navigation, communication and space monitoring, and assesses their current and potential future relevance for users in the Arctic. It discusses promising synergistic uses of space assets and applications, and presents a brief societal impact assessment.

Executive Summary

Policy context

In recent years, the environmental, social, economic and strategic importance of the Arctic has increased. As a consequence of global climate change, the Arctic ice is melting. This opens the Arctic to exploitation of its resources, which include not only fish, oil, gas, minerals and rare earths but also a natural environment that attracts tourism and provides shorter global shipping routes.

These natural and economic changes are strongly impacting the Arctic. Ecosystems are changing, affecting distributions of fauna. More people are present: in addition to the indigenous population, workers (in extraction, mining, transport) and cruise tourists come and go. Shipping, both local (supply, fishing) and global is increasing. On land, melting permafrost and coastal erosion undermine infrastructures. Indigenous ways of life are uprooted by changes in sea ice, snow, animal distributions, as well as by globalisation. With heightened geopolitical interest, military activities are increasing. As global warming is expected to continue for decades, we may expect these trends to continue.

In this context the present study aims to evaluate how the EU's space capabilities can benefit the Arctic. The study reviews key EU policy actions for the Arctic and for space; identifies Arctic users' needs; and surveys present and future space capabilities. It covers the four domains of the EU Space Programme – Earth observation, satellite navigation, satellite communications, and Space Situational Awareness – and treats various synergies across them. An additional objective of the study is a quantitative assessment of the societal impact of satellite and observation systems in the Arctic. The report can be of interest to policy makers at EU level and in EU Member States and to the space industry working on Arctic issues and seeking environmental, economic and societal solutions.

The Arctic hosts territories of eight states, three of which are in the EU, as well as High Seas beyond national jurisdiction. Many more countries (including EU states) have an avowed interest in the Arctic. This indicates the importance of an international approach and of a role for the EU. Indeed, in 2016 the EU set out an Arctic Policy aiming to balance economic growth with sustainability, environmental protection and social responsibility, taking a multilateral and international approach.

In spite of all the developments, the Arctic is and will remain a region of long distances and dangerous weather conditions, very sparsely populated, ill-charted and ill-surveyed. Measurement and long-term monitoring of changing Arctic conditions, activities and processes are needed. Areas for attention include: bathymetric mapping; monitoring of changing land surfaces and coastlines; monitoring of human activities on land and at sea; measurement and prediction of weather, sea, ice and snow conditions; and the establishment of adequate transport and communications connections.

Given its vast size, sparse population and lack of terrestrial infrastructure, the Arctic region can benefit greatly from space-based services. The Earth observation and global

satellite navigation programmes of the EU, Copernicus and Galileo, cover the region and provide an initial contribution to key environmental, safety and security needs. They are an implementation of the 2016 EU Space Strategy. The new EU Space Programme for the 2021-2027 budget will widen the scope of the space activities with the addition of the Satellite Communications and the Space Situational Awareness (SSA) domains. This creates opportunities for the exploitation of synergies to capitalise even more on the entire programme.

Key conclusions

Earth Observation (EO). Copernicus programme satellites provide large amounts of useful data over the Arctic, which is favoured with respect to other regions on Earth as most of the EO satellite orbits converge at the poles, increasing coverage there. The Copernicus Services transform satellite data into products like maps of vegetation, sea ice, air quality, shipping presence, and disaster risk and impact. These serve Arctic users, yet are sometimes falling short in specific information content, spatial resolution and timeliness.

Positioning and Navigation. The Galileo programme provides its services globally, covering the Arctic. The services comprise the Open Service, the Search and Rescue (SaR) service, and soon the Emergency Warning service. The Galileo Open Service caters to the positioning, navigation and timing needs of Arctic air, sea and land transport. The SaR Service under the Cospas-Sarsat system improves localisation of distress signals, which is important in the Arctic where SaR capacities are limited. The Galileo SaR service provides further enhancements for Cospas-Sarsat beacons thanks to a return link transmission, which broadcasts a confirmation of receipt to the sender of a distress message. In addition to Galileo, the EU has its own satellite based augmentation system, EGNOS that improves navigation accuracy (EGNOS Open Service) and provides integrity information (EGNOS Safety of Life). This service supports a great number of applications in the transport sector and renders safety-critical operations safer. Both services rely on geostationary satellites that are not visible above 72° North. Nevertheless, EGNOS is already used for GNSS-based landing procedures at a number of Arctic airfields below that latitude. Integrity information above 72° North remains a challenge for EGNOS, but this gap can be filled by a new service: Advanced Receiver Autonomous Integrity Monitoring (ARAIM), jointly developed by the EU and the US, which will start its initial service provision in 2025.

Satellite Communications (SatCom). These are essential in the Arctic for long-range communications as surface links are lacking. However, they are currently inadequate for broadband SatCom, as this is mostly offered via geostationary satellites that are not visible at high latitudes. Some commercial operators currently offer low-bandwidth communications from lower orbit satellites covering the poles. In the near future, the commercial offerings of broadband SatCom promise to increase, but the suppliers will mostly be U.S. companies. The EU is setting up the GovSatCom initiative initiative with a 'pull and share' access scheme providing governmental SatCom services. The EU's governmental SatCom capacity needed in the Arctic is expected to be an important driver influencing the future development of the EU GovSatCom initiative. As an alternative to SatCom, HF radio communications may be used but only at low bandwidths.

Space Situational Awareness (SSA). Monitoring of space weather is very important in the Arctic, where it influences the ionosphere, which in turn affects satellite radio navigation and communications signals as well as HF communications. Space weather can also seriously degrade the functioning of satellites and sensitive ground infrastructure, and pose a risk to air passengers. All of these effects are stronger in the Arctic.

The study identified synergies between these four components. The monitoring of space weather to warn against ionospheric disturbances impacting satellite radio navigation and communications systems has just been mentioned. Satellite navigation is used pervasively with EO, as all EO data must be geo-located. But observations of the reflection and occultation of satellite navigation signals have been found to provide means of measuring ocean wind, sea ice cover, ice thickness, atmospheric temperature and humidity profiles, as well as ionospheric disturbances.

Cross-applications still have growth potential in maritime surveillance – of high interest for fisheries control, law enforcement, environmental control, search & rescue and maritime security. For example, ship positions determined by satellites receiving ships' AIS messages can be corroborated with EO images to detect 'dark' ships (i.e. ships not sending AIS messages) which may be suspected of illegal fishing. The best synergy is obtained when the AIS receiver is co-located on the EO satellite to eliminate time delays between the two types of observation.

Strong synergies arise from integrating SatCom with EO operations. EO data are collected in space and transmitted to Earth for processing and enrichment. The resulting information then needs to be sent to the operational users in some remote Arctic location, e.g. on a ship. For users in rapidly changing circumstances (sea ice, ships nearby), this needs to be done in near-real-time; a capability that can only be provided by SatCom.

European space capabilities provide substantial societal benefits for the Arctic. This study used a methodology endorsed by the Arctic Council's Sustaining Arctic Observation Networks (SAON) Initiative to quantify benefits for the use cases of sea ice monitoring and Search & Rescue operations. A quantitative analysis of societal impact indicators based on key objectives and societal benefit areas shows the value and high impact of satellite and observing systems on society.

These space capabilities are built on partnerships and projects covering science, operations, and Research and Development (R&D) activities, with a clear increase from commercial partners' involvement. Proper policy instruments (e.g. standardisation) are needed to facilitate synergies and cooperation between the public and private sectors, to maximise the benefits for Arctic users.

Today's satellites produce vast amounts of data, and that will only grow in future. Extraction of the information required for scientific and operational users requires significant computing power and reliable communications. In addition, the desiderata are often predictions; so full exploitation of the data and their synergies require predictive models on timescales ranging from hours or days (e.g. ship routing) to decades (climate).

1 INTRODUCTION

1 Introduction

Geographically, the Arctic is the region north of latitude 66.5°. Much of that area is sea. The Arctic territory comprises the sovereign territories of eight states (Canada, Denmark, Finland, Iceland, Norway, Russia, Sweden and the United States), gathering together over four million people including over 40 different indigenous communities.

The Arctic is currently receiving much attention as a consequence of climate change. Global warming is melting the sea ice that hitherto has made the Arctic inaccessible. This opens new opportunities for resource exploitation (such as fisheries, oil and gas extraction and mining) and for transport (both for access, and for transit along global shipping routes).

Arctic marine transport is expected to grow, with Arctic shipping routes becoming attractive as alternatives to the main shipping lanes via Suez and Panama. In the future, sea ice decline may even make the Central Arctic Ocean route navigable as ice-free conditions occur more frequently. Increased shipping, including cruise tourism, increases oil spill risks, and introduces new challenges such as the need for Arctic marine infrastructure for search and rescue, and emergency response, and the need for accurate and reliable navigation to deal with sea ice and icebergs.

The newly accessible wealth of the Arctic, in combination with the extraterritorial nature of most of the Arctic seas and their position right between the US and Russia lend a geopolitical consequence to the region. This has led to military build-up (notably by Russia) and an interest from new players (like China).

The presence of ice and permafrost makes the region particularly sensitive to warming induced by (non-local) anthropogenic greenhouse gas emissions and exacerbated by the (local) deposition of the atmospheric pollutant black carbon[1] on sea ice and land ice. This increases the absorption of solar radiation, which contributes to additional warming. The melting of ice causes additional radiation absorption by the darker ocean and land surfaces. The increasing warming thaws permafrost soils, releasing billions of tonnes of CO_2 and methane into the atmosphere. Together these processes form a strong positive feedback loop accelerating global warming. As melting Arctic land ice causes global sea levels to rise, the Arctic acts as a fulcrum in the global climate change process.

In addition to the territorial, geopolitical and global environmental complexities, the Arctic is also a unique local environment, home to several fragile ecosystems. The preservation of biodiversity and the viability of ecosystems in the Arctic is a global challenge.

Besides the aspects mentioned previously, the Arctic is the home of diverse local communities that are facing drastic changes. A transversal element that needs to be addressed through appropriate policies is the connectivity for the Arctic peoples. How can the EU support Arctic users in the future? How important is the digital infrastructure that exists today and what is missing to address the needs of the Indigenous population for e-learning, telemedicine and develop critical digital infrastructure in the region?

The eight Arctic states have set up the Arctic Council[2] as an intergovernmental forum to support better governance in this international domain. Three of the eight are EU states. Besides these eight full Members, the Arctic Council also has 38 Observers (countries and organisations), but the EU itself does not (yet) have this status even though it shares close historical, economical and geographical links with the Arctic region.

Considering all of the above, there is a strong need to reinforce a proper EU policy. Hence, given the important role of the Arctic as a regulator for the planet's climate, the EU has a duty to safeguard the Arctic environment and strengthen ecosystem resilience. The understanding and monitoring of the Arctic marine environment is also

[1] Black carbon is a material produced by the incomplete combustion of heavy petroleum products emitted notably from coal-fired power plants, gas and diesel engines.

[2] https://arctic-council.org

essential. The Arctic is an integral object of EU policy and confers to the EU a natural and important role to play in the region. EU activities and decisions are also having an impact on the region's sustainable development (European Commission 2016a). The relevance of the Arctic region for the EU was recently further highlighted in a strategic note of July 2019 summarizing the EU and non-EU actors positions (European Political Strategy Centre 2019).

Space-based services and infrastructures provide substantial benefits and can help to tackle many of these issues. Making an optimal use of the space-based capabilities requires having an up to date view of the current and future missions and services in Earth observation, satellite navigation, satellite communications, and space situational awareness (SSA). This report is written from the point of view of the European context and therefore a full insight into the benefits brought by the EU's operational programmes on Earth observation and satellite navigation (i.e. Copernicus and Galileo) is given. The study addresses the following three main objectives:

1. Identification of the **user needs in the Arctic** for space-enabled services and in particular their synergies, in the four domains of the EU Space Programme: Earth observation, satellite navigation, satellite communications and Space Situational Awareness (SSA), within a 10 years' time frame.

2. Provision of an inventory of the **current and planned future space services and infrastructures** in Europe relevant to the Arctic.

3. **Identification of the current and future synergies** both at the service and infrastructure levels, focusing on those in the EU Space Programme.

The document is organised as follows. It starts with an outline of the EU Arctic policy and the EU space policy in section 2. Section 3 presents the Users' needs according to science users, operational users, and indigenous and local community users. Then, the different elements of the EU Space Programme relevant for the Arctic region are presented: Copernicus in section 4.1, Galileo and EGNOS in section 5, GovSatCom in section 6, and the Space Weather component of the Space Situational Awareness (SSA) in section 7. Section 8 presents the synergistic uses of Earth Observation, navigation and satellite communications in the Arctic at service level and infrastructure level. Finally section 9 presents the societal impact assessment, highlighting, for a small number of case studies, the large impact of satellite and observing systems on Arctic society.

2

POLICY CONTEXT

2 Policy context

2.1 | Arctic Policy

A detailed presentation of the current policy framework of the Arctic can be found in the European Political Strategy Centre (EPSC) strategic note (European Political Strategy Centre 2019). Here only a few highlights are provided.

2.1.1 EU Arctic Policy

Three EU Member States – Denmark, Finland and Sweden – and some half a million EU citizens are involved in the Arctic. Even though the primary responsibility for Arctic policy remains with the Arctic states themselves, given the important role of Arctic as a regulator of the planetary climate, the EU is duty-bound to safeguard the Arctic environment and strengthen ecosystem resilience.

Furthermore, the Arctic is important in the context of EU strategic autonomy. For example Greenland has significant reserves of rare-earth elements which are crucial for advanced technologies promoted in the EU. Rare-earths are an indispensable part, for example, of wind turbines which generate renewable energy.

Following several initiatives[3], in 2016 a Joint Communication for 'An integrated European Policy for the Arctic' (European Commission 2016a) presented the three priority areas of the EU in the Arctic:

1. Climate Change and Safeguarding the Arctic Environment;

2. Sustainable Development in and around the Arctic with a focus on sustainable innovation, investment, space technology and maritime safety;

3. International Cooperation on Arctic Issues.

The actions undertaken by the EU within these three priority areas will be emphasized through research, science and innovation. These actions will be in line with other relevant global policies such as the United Nation's 2030 Sustainable Development Goals (SDG) (United Nations 2019).

The EU is a major contributor to research devoted to Arctic observation and monitoring programmes. It also supports research efforts through the EU-PolarNet initiative (22 research institutions across 17 European countries). The project supports an EU-wide consortium of expertise with the aim of optimising the use of infrastructures for polar research connecting science with society. The consortium is engaged in closer cooperation with International partners to prioritise science.

As regards the EU Arctic states, Finland like other EU countries is promoting regulatory frameworks on environmental sustainability, and highlighting in particular the importance of digital and physical connectivity. Denmark emphasizes the need to maintain peace, security, protection of the environment and to reinforce international cooperation. Sweden has also been active to reinforce the regulatory frameworks for environmental sustainability and respect of international norms and United Nations conventions. A number of EU states have a special interest in the Arctic. France, Germany, Italy, The Netherlands, Poland, Spain and UK have Observer status in the Arctic Council. Several have recently published Arctic policies or strategies.

[3] In particular, (COM/2008/0763 final), (JOIN (2012) 19 final) and (SWD(2012) 182 final) and (SWD(2012) 183 final).

2.1.2 International context

The Arctic is gaining international attention due to the increasing interests that emerge with the numerous developments affecting the region. The Arctic is also strongly affected by the current climate crisis. The international position of the main International actors is given hereafter:

— **Russia** considers the Northern Sea Route as an opportunity for national and regional developments. Two thirds of Russia's oil and gas is expected in its Exclusive Economic Zone off its Arctic coasts (Devyatkin 2018; Claes and Moe 2014). Hydrocarbon extraction in the Arctic is expensive, complex and not without environmental prejudice, therefore increasing the need of international cooperation. Western sanctions on Russia have complicated cooperation with Western companies. This partly explains why Moscow is creating a regulatory and administrative legal framework for foreign navigation. For example, foreign ships are required to pay for weather and ice reports (CNBC 2019), Russian pilots, and Russian icebreaking services while they are forbidden from transporting oil and gas extracted in Russia along the route (The Moscow Times 2018).

— **Norway** and **Iceland** emphasize the need to take economic advantage of their natural resources (energy, land and marine resources) while protecting the environment, climate and biodiversity.

— **Canada** aims to maintain its sovereign rights and follow up the growing interest of non-Arctic countries. The right of local communities and indigenous peoples are also emphasized in the Canadian Arctic policy (Government of Canada 2010).

— Following pressure from China and Russia, the **United States** is reinforcing its position. The Arctic is becoming a priority for the US with the growing ties between Russia and China. In August 2019, the diplomatic incident between Denmark and the US following the announcement of a possible purchase of Greenland by the US is a reminder that the Arctic is at the forefront of opportunity, abundance and geopolitical struggle. The current US administration has been retreating from international environmental governance, while it appears to remain committed to multilateral governance in the Arctic. A recent US Department of Defence Arctic Strategy highlights that the region is entering an "era of strategic competition" (Pompeo 2019).

— **China** gained observer status in the Arctic Council in 2013. It is involved in resource extraction in Greenland. China considers the Northern Sea Route to be of strategic importance to reduce its energy dependency. The current China Arctic policy includes the creation of a "Polar Silk Road" as part of its Belt and Road initiative (BRI). The Chinese shipping company COSCO plans to exploit the Northern Sea route during the summer season.

— **India** is also engaged in the Arctic region with the supply of liquefied natural gas (Ministry of External Affairs 2013) and is involved in Scientific Research in Svalbard (Norway).

2.2 | EU Space policy

The 2016 Space Strategy for Europe (European Commission 2016b) confirmed the Union's political commitment to an ambitious space policy in Europe to:

— maximise the socio-economic benefits, in particular by fostering the development of an innovative and competitive European upstream and downstream sectors, including small and medium-sized enterprises and start-ups

— foster a globally competitive and innovative European space sector;

— reinforce Europe's autonomy in accessing and using space in a secure and safe environment;

— strengthen Europe's role as a global actor and promoting international cooperation.

— meet existing and future needs and able to support the Union's political priorities and related evidence-based and independent decision making, inter alia for climate change, transport, and security;

The EU Space programme, proposed in June 2018, aims at ensuring investment continuity in EU space activities, encouraging scientific/technical progress, and supporting the competitiveness and innovation capacity of the European Space industry, and in particular small and medium-sized enterprises, start-ups and innovative businesses[4].

The space sector employs over 231 000 people and its value is estimated at 53-62 billion € in 2017, the second largest in the world. A third of the world's satellites are made in Europe.

Objectives of the new space programme

— **Guarantee the continuity and evolution** of the most advanced satellite positioning systems **Galileo/ EGNOS** and Earth Observation **Copernicus** systems; develop new security initiatives on **Governmental Satellite Communication** (GovSatCom) and **Space Situational Awareness** (SSA) component.
— **Support a strong and innovative space industry** by improving accessibility: to risk financing tools for emerging business models, to testing and processing facilities and promotion of certification and standardisation.
— **Maintain the EU's autonomous, reliable and cost-effective access to space** (e.g. optimization of launch services, innovative technology for reusable launchers)
— Create a unified and simplified system of governance with a **single Regulation** for simpler cooperation between all institutional actors.

An overall budget of 16.9 billion € for the EU Space programme has been proposed for the Multi-Annual Framework 2021-2027[5]. The main goals of each component of the programme are detailed in **Table 1** with the corresponding budget.

	Galileo, EGNOS	Copernicus	GovSatCom	SSA
Function	Global and Regional satellite navigation systems	Free and open EO data for land, atmosphere, sea, climate change, emergency management and security	Secure governmental satellite communications	Space hazards monitoring
Budget	€9,7 billion	€6 billion	€1,2 billion	
Objectives	Provide long-term, state-of-the-art and secure positioning, navigation and timing services whilst ensuring service continuity and robustness; Achieve a global, continuous, autonomous, high quality, service provision capacity;	Deliver accurate and reliable EO data, information and services integrating other data sources, supplied on a long-term sustainable basis; Improve the management of the environment, understand and mitigate the effects of climate change, and ensure civil security; Achieve a global, continuous, autonomous, high quality, wide range Earth observation capacity;	Develop GovSatCom through the pooling of resources from Member States; Establish an EU-level governance that can leverage SatCom services for all national and EU security actors; Support the activities of the EEAS and of the European Humanitarian Actors around the globe;	Further develop an operational capability towards the surveillance and tracking of space debris and near-Earth objects; Increase capability to protect space-based and terrestrial infrastructures against severe space weather events;

TABLE 1: EU SPACE PROGRAMME COMPONENTS WITH THEIR FUNCTION, BUDGET BREAKDOWN, AND OBJECTIVES.

[4] Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL establishing the space programme of the Union and the European Union Agency for the Space Programme and repealing Regulations (EU) No 912/2010, (EU) No 1285/2013, (EU) No 377/2014 and 2019.
[5] Briefing EU Legislation in Progress 2021-2027 MFF, EU space programme, European Parliamentary Research Service, PE 628.300, 15 May 2019.

3

USERS' NEEDS

3 Users' needs

Arctic users have been divided into three broad classes with similar needs: science users, operational users, and indigenous users.

3.1 | Science users

The EU is a major investor in Arctic research with 200 M€ already invested through Horizon 2020 (2014-2020). Annex 3 gives a summary of the different H2020 projects dedicated to the region while indicating their topic and objectives. Most of the Arctic science projects are related to environmental impact and climate change assessment.

Users' needs have been gathered by themes with the corresponding scientific activities and sectoral applications in **Table 2**. The geophysical themes relevant to the Arctic were taken from the Polar Expert Group report (Duchossois et al. 2018). The categories were devised by the experts to align with the different elements of the geosystem (atmosphere, hydrosphere, lithosphere and cryosphere division).

Themes	Needs	Sectoral Applications
1. Atmosphere, Climate and Weather	Assess the rate of climate change Increase knowledge of energy and water budgets to forecast local and global weather Trace gases and greenhouse gases quantification	Weather forecasting Energy Transport Ships emission
2. Ocean state and coastal zone	Sea level anomaly Sea Surface Temperature (SST) Ocean waves	Weather forecasts Navigation Tourism
3. Surface Fresh Water	Assess movement of fresh water Understanding Biogeochemical systems	Hydrology Natural and technical hazards Climate
4. Land Surface and Vegetation	Research on structural and functional characteristics of land use systems Impacts of human activities on land Global carbon cycle monitoring Global change monitoring Biodiversity changes	Energy Water management Food Territory management and hazards mitigation Forest management Food management, water and energy supplies
5. Permafrost and Soils	Assess the loss of permafrost on infrastructure, climate and people Understand and quantify the CO2 and methane release	Infrastructure management : transport, construction Weather and climate
6. Sea Ice, Icebergs, Ice shelves	Assess the changes in sea ice extent and mass balance Evaluate coastal stability	Ship routing, Navigation SaR, Weather and Climate change, Infrastructure (offshore, oil spill monitoring, coastal stability)
7. Ice sheets	Evaluate ice sheets	Water management Energy (hydropower) Weather and climate
8. Glaciers and Ice Caps	Glaciers evolution impact on sea level rise	Water management Energy (hydropower) Weather and climate
9. Snow	Monitor and assess snow cover changes and their role in climatology, hydrology, ecology and socioeconomics	Hydrology Water resources Reindeer farming

TABLE 2: USERS' NEEDS ARE EXPRESSED BY SCIENTIFIC ACTIVITIES WITH THE CORRESPONDING SECTORAL APPLICATIONS RELEVANT FOR THE ARCTIC REGION.

3.2 | Operational users

In addition to scientific and research needs in the Arctic, requirements for operational processes and sectoral applications have been identified and illustrate the various activities of interest in the region. The needs have been identified through various studies (Polar View Earth Observation Limited 2016; View et al. 2018) and using consultations from the Arctic Circle Assembly in Reykjavik in 2019.

The operational needs and their corresponding sectoral applications are summarized in **Table 3**.

Themes	Needs	Sectoral Applications
Resources exploration	Support of Integrated Operations (IO), broadband connections for sharing data and video surveillance of platforms	Oil and gas industry Mining
Navigation and operations	Surveillance systems on safe navigation, safety of new routes, new standards of marine environmental safety, crew training and education, integrity of the navigation solution	Transportation (marine, automotive industry)
Disaster and emergency management	Rapid mapping Permafrost variability monitoring	Rescue operations Civil protection
Transport	Two-way communications (voice/data) Tele medical assistance Air Traffic management communications, cabine communications	Maritime sector including off-shore installations, vessels Aviation
Safety	Collision avoidance system Route optimization Communications to issue distress calls	Aviation Maritime sector
Security	Real time communications for fast intervention Broad-band satellite communications systems	Border protection Law enforcement Inspections
Infrastructure	High-resolution mapping and monitoring of land and constructions	Construction and maintenance of roads, pipelines, ports, airports, settlements

TABLE 3: OPERATIONAL NEEDS AND THEIR SECTORIAL APPLICATIONS IN THE ARCTIC REGION GROUPED BY THEMATIC AREA.

Different users and scenarios have differing, quantitative requirements. Without going into the details, it is possible to identify requirements typical of the Arctic that can be addressed by space-based services.

Maritime activities are of foremost relevance and are expected to increase. Maritime navigation in the Arctic needs the following information:

- Weather – wind, temperature, humidity, precipitation, icing risk;
- Sea state – waves (height, frequency, direction, spectrum), currents, tides;
- Bathymetry – water depths, shallows, coastlines, intertidal differences;
- Sea ice – ice cover, ice edge, ice type, ice thickness, ice ridges, icebergs;
- Human activities – nearby ship traffic, aids to navigation, platforms, pipelines & cables, designated areas.

The ice aspects are specific for the Arctic, but weather and sea state – although needed everywhere on Earth for navigation – have a much bigger impact in the Arctic. Bathymetry is only very incompletely mapped, in the Arctic, and poses serious risks to shipping. Most of the information elements listed above are dynamic, and are needed for operations and planning (a) in the form of historical statistics, (b) in real-time and (c) as forecasts. They are needed with adequate spatial and temporal resolution, both locally around the ship and over wide areas for route planning. Much of the data on weather, ocean and ice conditions are collected by satellite or otherwise non-locally, and the processing (including running the forecasts) is done in distant data centres; yet the resulting information, that can be of high data volume, needs to reach the isolated users in the Arctic. Therefore,

high-bandwidth long distance communications are necessary in some scenarios.

Maritime operations, e.g. around platforms or in ports, have needs similar to navigation, plus high-accuracy and high-reliability positioning.

Inspection, law enforcement and security operations need high-quality maritime situational awareness / maritime domain awareness to know who is active at sea and what they are doing.

Together with search & rescue operations they need real-time communications, local as well as long distance.

Air operations – passengers and cargo transport, search & rescue, inspections, etc. – need:

- Accurate and reliable weather predictions as a function of altitude;
- High-accuracy and high-reliability positioning for instrument landing, often needed in bad Arctic weather conditions;
- Warning of increased solar activity that may lead to increased dangerous radiation at flight level in the Arctic;
- Situational awareness of other flight traffic;

Land and coastal infrastructures in the Arctic will expand (mining sites, ports, airports, oil storage facilities, pipelines, housing, roads), but are seriously and increasingly affected by permafrost thaw and coastal erosion. This creates needs for high-accuracy mapping and monitoring.

3.3 | Indigenous and local community users

Today digital connectivity has become a utility service, much like water or electricity, bringing numerous individual and social benefits. It supports education and social equality, and enhances democratic participation. Sufficient connectivity is needed to enable Arctic businesses to develop their potential without limitation.

In the next decade, the Arctic region is expected to experience a growth in human activities, and demand for telecommunications infrastructures providing the required connectivity will increase. Moreover, the geographic specificities of the Arctic region, which is composed mainly of ice and water, make the deployment of any terrestrial infrastructure extremely difficult and costly. As a result, satellite-based communications infrastructures are almost exclusively those able to satisfy the increasing demand for broadband connectivity in the Arctic.

Communities in the Arctic are located in remote areas and terrestrial infrastructure outside of communities is limited. Existing land based broadband infrastructures in the Arctic are mostly located in small communities. The harsh climate only allows a short construction season for deploying the physical infrastructure necessary for additional broadband technologies. Large amounts of snow and ice also complicate maintenance (Telecommunications Infrastructure Working Group 2016).

User needs originate not only from indigenous communities but also from workers on platforms, at remote mining sites or on fishing ships who may not be indigenous but are locals, and whose numbers are expected to grow.

Another significant growth area in the Arctic is cruise ship tourism. There will be cruise ships with thousands of passengers expecting luxury standards including broadband internet access on mobile devices. This is expected to be a strong driver of commercial broadband solutions in the Arctic.

Another category of needs that directly impact Arctic residents is related to food and water security. According to the recent Intergovernmental Panel on Climate Change (*IPCC)* food availability and water quality evaluation is needed. In particular, melting glaciers and thawing permafrost that release mercury need to be taken into account (Pörtner et al. 2019).

After having extracted and illustrated different Arctic user's needs, Sections 4 to Section 7 give, respectively, the inventory of the space assets in Earth observation, EU satellite navigation systems, satellite communications, and SSA.

4

EARTH OBSERVATION **CAPABILITIES**

4 Earth Observation capabilities

4.1 | Copernicus programme

Copernicus is managed and funded by the European Commission, the space component being implemented and co-funded by ESA. The data and information produced by Copernicus are free and openly available, for use by public and private users. The programme is shaped by user requirements.

The satellite constellations consist of two groups: Copernicus' six Sentinel satellites (Sensors and key features are detailed in Annex 1), and about 30 contributing (third party) missions (only missions relevant to the Arctic are summarized in Annex 2).

The Copernicus programme offers six operational thematic services in the fields of atmosphere monitoring, marine environment monitoring, land monitoring, climate change, emergency management and security. All thematic services are relevant for the Arctic region. Then specificities are given in section 4.3.

4.2 | Overview of user-required functions versus Sentinels

Table 4 links functions (functionalities) required by users in the Arctic (per line) with the ability of the Sentinel satellites to provide relevant information (per column). Entries: + means the satellite provides very limited information for the function, ++ moderate information, +++ very good information, and empty means no information or unknown.

The function refers to the measuring, detecting or mapping (as applicable) of the mentioned object or phenomenon. No separate entries are made for the capacity to measure changes. For example, damage assessment is not a separate function in the table but falls under "buildings".

The functions indicated in **Table 4** are a level more detailed than the themes identified in section 3.1 or other application domains such as "climate change", "maritime transport", "off-shore exploration", "border security", "emergency management", 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 does not show whether an actual user requirement is satisfied, because the requirement will have conditions on information details such as spatial scales, timeliness, update rate, usefulness for prediction, etc., which are not analysed here. Therefore, the table simply indicates which Sentinels may be used for which Arctic user-required functions.

As regards the third party missions listed in Annex 2, TerraSAR-X, Cosmo-Skymed and Radarsat-2 are radar imaging satellites like Sentinel-1 so have spatial characteristics, but with higher spatial resolution. Pleiades and Deimos are optical imaging satellites like Sentinel-2, so have similar spatial characteristics, but again with higher spatial resolution.

Satellite / Function	Sent-1	Sent-2	Sent-3	Sent-5/5p	Sent-6
Land					
Thematic mapping	+	++	++		
Terrain height (incl. ground displacement)	+++		++		
River and lake level, flooding	+++	++	+++		
River and lake ice	++				
Snow cover	+++	+++	++		
Snow thickness	++				
Snow melt	++				
Glacier and ice sheet height			+++		
Glacier runoff					
Permafrost	++				
Roads	+	+			
Buildings, urban	++	++	++		
Other infrastructure	++	+			
Vegetation	++	+++	+++		
Forest	++	+++	+++		
Carbon cycle			+++		
Biodiversity	++	++			
Prospecting	+		++		
Mining	++				
Surface contaminants[a]					
Land degradation	+		+		
Land and inland water oil pollution	+		++		
Land border permeability	+	+			
Land border crossing activities	+	+			
Terrain traffickability	+				
Land surface temperature			+++		
Fire	+		++		
Coastal					
Coastline, coastal erosion	+++	+++	+		
Ports, coastal infrastructure	++	+++			
Marine					
Ocean winds	+++		++		++
Ocean surface waves	++	+	+++		+++
Sea surface temperature			+++		
Ocean colour		++	+++		
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	+	+			

TABLE 4: USER REQUIRED FUNCTIONS IN THE ARCTIC AND CORRESPONDING INFORMATION PROVIDED BY THE COPERNICUS SENTINELS.
TABLE CONTINUES ON NEXT PAGE →

Satellite / Function	Sent-1	Sent-2	Sent-3	Sent-5/5p	Sent-6
Atmosphere					
Wind[(b)]					
Temperature					++
Precipitation					
Atmospheric water content			+++		+++
Cloud cover		++	++	++	
CO2					
Other GHG				+++	
Air pollution and trace gases				+++	
Aerosols			+++	+++	

TABLE 4: USER REQUIRED FUNCTIONS IN THE ARCTIC AND CORRESPONDING INFORMATION PROVIDED BY THE COPERNICUS SENTINELS.
(a): E.g., mercury released from melting glaciers and permafrost that poisons food and water.
(b): Except wind over the sea surface which is under marine.

4.3 | Copernicus services

An overview of the relevant Copernicus services with the key parameters involved and applications for the Arctic region is provided in **Table 5**.

Services	Key features	Applications
CLMS **Copernicus Land Monitoring Service**	Cryosphere parameters Global land cover Vegetation parameters Most products available to northern latitudes 70N-85N	Environmental monitoring Climate change Terrain stability Emergency response
CMEMS **Copernicus Marine Environment Monitoring Service**	Sea ice Ice chart products Sea level Ocean colour Waves	Navigation Climate change monitoring
CAMS **Copernicus Atmosphere Monitoring Service**	Atmospheric composition (global and regional at 10 km resolution)	Air quality monitoring Monitoring of wildfire emissions Pollution transport
C3S **Copernicus Climate Change Service**	Iceberg drifting model Seasonal forecast and reanalysis data of large range of variables	Decision making related to global shipping Arctic route optimization
CEMS **Copernicus Emergency Management Service**	Rapid mapping (incl. Iceberg monitoring[6]), risk and recovery assessment	Disaster mapping (floods, wildfires and droughts)
CSS **Copernicus Security Service**	Only for authorised governmental users CSS Maritime Surveillance Component	Support to EU External Action Maritime surveillance (fisheries control, maritime safety and security, pollution monitoring, customs activities)

TABLE 5: OVERVIEW OF THE COPERNICUS SERVICES RELEVANT IN THE ARCTIC WITH THEIR MAIN FEATURES AND APPLICATIONS.

4.4 | Other relevant Earth observation missions

Additional satellite capability in EO is brought by EUMETSAT with its Polar System (EPS) which is Europe's first series of polar-orbiting meteorological satellites. It consists of three Metop satellites (Metop-A, B and C).

[6] The Copernicus Emergency Management Service monitors an Iceberg in Greenland (https://emergency.copernicus.eu/mapping/ems/copernicus-emergency-management-service-monitors-iceberg-greenland).

ESA's Earth Explorers provide key satellite missions for Arctic monitoring, with SMOS for soil moisture and ocean salinity; Cryosat2 which provides Arctic sea ice thickness in near-real time; SWARM which measures the Earth's magnetic field; and Aeolus for measuring the Earth's wind profiles globally.

Several commercial missions like the first proof-of-concept Finnish ICEYE microsatellite mission with a SAR sensor and the Norwegian MicroSAR system are used to monitor ice conditions and oil spills. Planet operates the largest satellite constellation with over 200 Earth observation satellites. It permits imaging of the Earth's entire landmass. In particular for the Arctic, planet imagery is useful for monitoring permafrost melting. Finally, other international missions relevant to the Arctic are: the recent advanced Canadian Radarsat Constellation Mission (RCM), the American ICE-Sat2 contributing to polar ice observation, land topography and vegetation canopy and the Japanese ALOS-2 used for wildfire detection.

The inventory also assessed future missions relevant to the Arctic. Thus Copernicus 2.0 missions will ensure operational reliability and stability providing continuous monitoring of key variables. The recently approved CO2 Monitoring mission (CO2M) will monitor anthropogenic CO2 emissions with operational and internationally coordinated capabilities likely to be established by 2026. Three other Copernicus High Priority Candidate Missions are also included: CIMR (Copernicus Imaging Microwave Radiometer) (Donlon 2019) for monitoring sea ice with a full sub-daily coverage covering the Arctic Ocean; CRISTAL (Copernicus polaR Ice and Snow Topography Altimeter) (Kern 2019) for measuring sea ice thickness, land ice elevation, snow depth on ice, sea level anomaly, iceberg volume; and ROSE-L (L-band synthetic aperture Radar Observing System for Europe) (Davidson, M., et al. 2019) for monitoring ground movement and deformation, landslides, flooding, land use, forestry, soil moisture, sea ice concentration and motion, glacier surface velocity, snow water equivalent, wind, waves, surface currents, maritime traffic, oil spills, fisheries, icebergs.

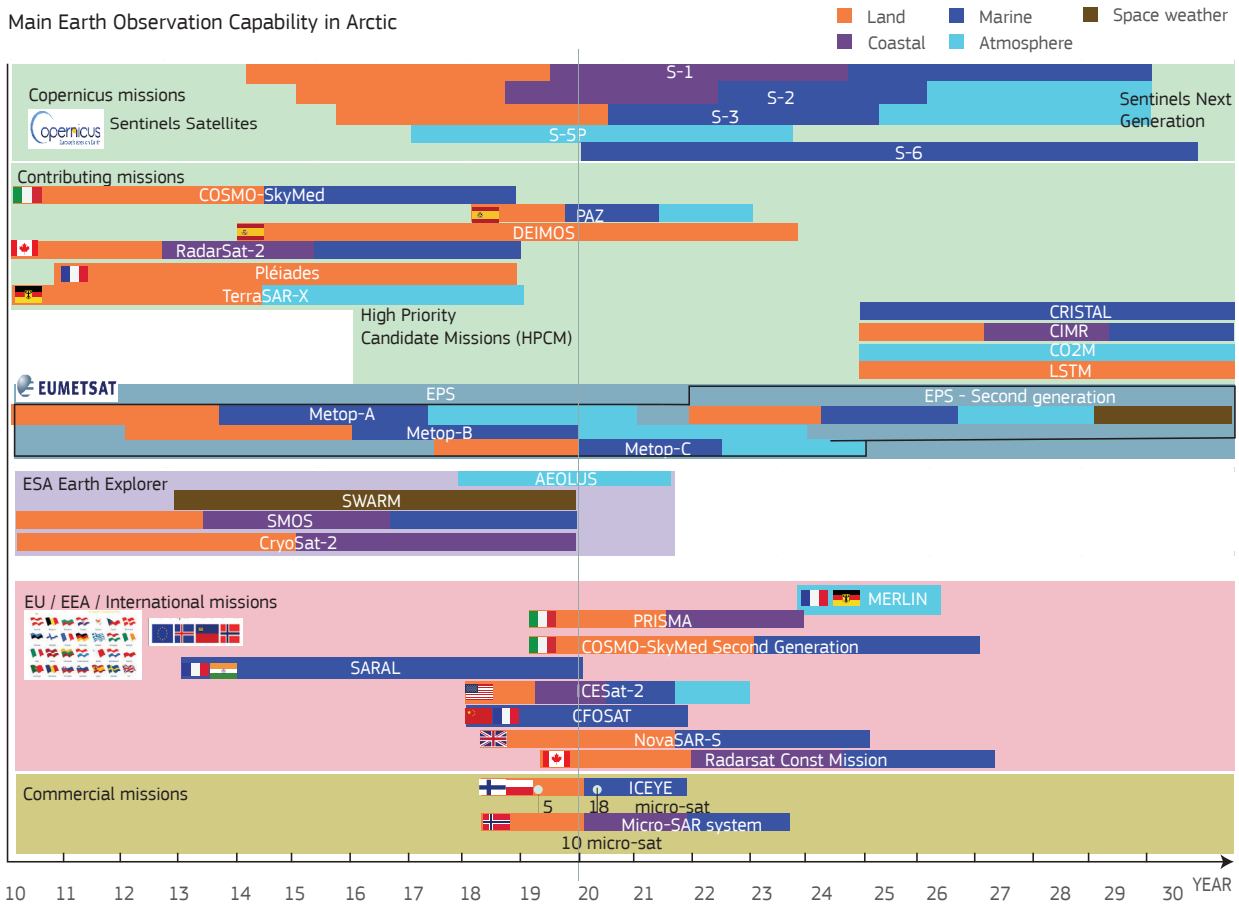


FIGURE 1: TIMELINE OF THE EARTH OBSERVATION MISSIONS WITH A RELEVANT ADDED-VALUE FOR THE ARCTIC REGION.

Future Member State missions include the Franco-German MERLIN (Methane Remote Sensing Mission) planned for 2021; and the COSMO-SkyMed Second generation (CSG) (Constellation of Small Satellites for Mediterranean basin Observation) to monitor ice formation and changes over the Arctic. Other international missions such as the American Joint Polar Satellite System (JPSS), and Earth Care (ESA, Japanese Space Agency JAXA) are also planned.

A summary with a timeframe of the main available and future satellite missions for Earth Observation applications is depicted in Figure 1.

4.5 | EO support infrastructure

EO satellite operations need ground infrastructure, in particular ground stations for telemetry, data reception and low-level processing. By far most Earth Observation (EO) satellites are in LEO (Low Earth Orbit), and most of the LEO satellites have polar orbits, which implies that they pass over the Arctic about once every 90 minutes. For polar orbiting missions, Arctic regions are therefore privileged with many more overpasses than equatorial regions. A ground station located in the Arctic is therefore much more efficient than one at lower latitudes. In the EU Arctic, this is exploited by the Ground station in Kiruna (Sweden), located at high latitude. It plays a primary role supporting ESA/EU low Earth orbiting satellites. It supports Cryosat, Swarm and Sentinel 1A satellites. The station hosts a Galileo Experimental Sensor Station (GESS) receiver and a Global Navigation Satellite System (GNSS) receiver, which deliver continuous data to ESOC (European Space Operations Centre).

In Norway, the Norwegian KSAT (Kongsberg Satellite Services) company operates ground stations in Tromsø just above the Arctic Circle and in Svalbard at 78° North. KSAT provides telemetry services for many satellites operates, as well as near real time Earth observation services for the detection of oil spill, vessels and ice monitoring. Satellite based oil and vessel detection services are provided to EMSA CSN (European Maritime Safety Agency Clean Sea Net).

EO satellites provide data, mainly images, and the services provide derived products, typically also of geospatial nature (such as maps of land cover, etc.). Yet all these are often just intermediate products for users with specific questions or needs. The outputs of the satellites and the services often need further processing, and combination with yet more data and information from other sources than satellites. The amount of data has become overwhelming ("big data"), so significant storage and processing capacities are needed.

Some applications such as climate change do not need results quickly, while operational applications such as navigation safety often need real-time (or near-real time) delivery. Therefore, fast processing capacity is also needed for a subset of collected data.

4.6 | EO downstream services

An overview of the main relevant supporting service and platforms used for Arctic Earth observation variables in that context is given below.

Services and data platforms specifically for the Arctic:

— **Polar Thematic Exploitation Platform (TEP-Polar)**
Developed for the European Space Agency, the TEP concept aims to provide a working environment where users can access algorithms and data remotely. The platform avoids the need to download and store large volumes of data and therefore encourages the exploitation of EO data. This digital platform service is under development.

— **Polar View community ice service**

The Copernicus products are also provided through the **Polar View** organization. Polar View is an online downstream service useful to the general public in Greenland and also to professionals, for visualizing Copernicus ice-related data in Polar Regions (Satellite observation and Forecast Models). The Polar View consortium includes government agencies, research institutes, system developers, service providers and end users from 17 countries. Polar View uses the Copernicus Marine Service Satellite sea-ice products and ocean currents from the Arctic Ocean forecast model and provides a very simple user interface. Polar View helps, for example, shipping companies with the ship routing in ice covered areas. The proposed services integrate monitoring and forecasting services for sea ice, ice edge, snow monitoring, iceberg monitoring, lake ice and glacier services.

— **European Marine Observation and Data network (EMODnet)**

The main purpose of the European Marine Observation and Data Network (EMODnet) is to unlock fragmented and hidden marine data resources and to make these available to individuals and organisations (both public and private), and to facilitate investment in sustainable coastal and offshore activities through improved access to quality-assured, standardised and harmonised marine data which are interoperable and free of restrictions on use.

— **CleanSeaNet**

A European satellite-based oil spill and vessel detection service which offers, to participating States, assistance in identifying and tracing oil pollution on the sea surface; monitoring accidental pollution during emergencies; and contributes to the identification of polluters. The CleanSeaNet service is based on the regular ordering of Synthetic Aperture Radar (SAR) satellite images, providing night and day coverage of maritime areas independent of fog and cloud cover. The distributed network approach with regional service providers that acquire and process the satellite data create a **near real time service**. The northern latitudes centres are located in Svalbard and Tromsø.

— **SafeSeaNet**

A vessel traffic monitoring and information system, established to enhance: maritime safety; port and maritime security; marine environment protection; and efficiency of maritime traffic and maritime transport. It enables European Union Member States, Norway, and Iceland, to provide and receive information on ships, ship movements, and hazardous cargoes.

In parallel to these services and platforms, in Europe, the Commission has launched an initiative to set up commercially-run 'Data and Information Access Services' (DIAS), in particular to stimulate the uptake of Copernicus data. There are now 5 DIASes specialized on different datasets and applications: Onda, Sobloo, Creodias, WEkEO and Mundi (https://scihub.copernicus.eu/). This will facilitate data processing at the user level in the era of Big Data. Other facilities like the Svalbard Integrated Arctic Earth Observing Systems (SIOS)[7] is also engaged to encourage user uptake of Sentinel data through the so-called Copernicus Relay by providing information and training activities.

[7] SIOS is the northernmost Copernicus Relay and provides remote sensing service to the members. IOS is a consortium of 25 institutes from 10 nations with infrastructures in and around Svalbard. The observation facility database can be found on https://sios-svalbard.org/sios-ri-catalogue different sources of data are stored (e.g. land base station, sea station, aircraft, satellites and underwater platform).

5

EU SATELLITE NAVIGATION **CAPABILITIES**

5 EU satellite navigation capabilities

Galileo and EGNOS are the two EU satellite navigation systems; they provide fundamental services for land air and maritime navigation. The services and specific characteristics available in the Arctic region are described in the following subsections.

5.1 | Galileo

Galileo is the European GNSS, able to provide different all-weather services with global coverage. Since December 2016, following the initial service declaration, Galileo started to deliver two services free of charge: Galileo Open Service (European Union 2016), Galileo Search and Rescue (European Commission 2016c). In addition to the services already available, Galileo will provide the Emergency Warning Service, which will be fundamental in the Arctic region.

Galileo Open Service (OS) has been designed for **non-safety critical** purposes. The service provides positioning, navigation and timing synchronization worldwide in any weather condition. It is **freely available** for any user equipped with a Galileo enabled receiver (European GNSS Agency 2016). The average number of Galileo visible satellites in the Arctic region is similar to the values observed for other regions of the Earth. In particular, it emerges that the **average number of satellites varies between 5.9 and 6.8** (Figure 2).

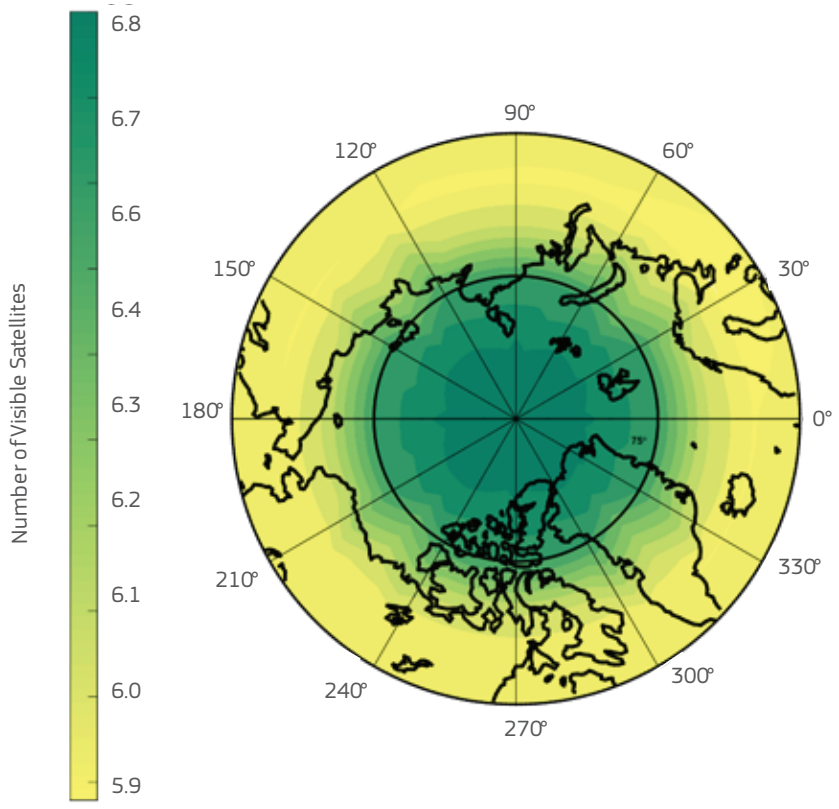


FIGURE 2: AVERAGE NUMBER OF GALILEO VISIBLE SATELLITES AS A FUNCTION OF THE USER LOCATION OVER THE ARCTIC.

Galileo Search-and-Rescue (SaR) supports Cospas-Sarsat for worldwide Search-and-Rescue operations. In this framework, **Galileo brings a net benefit in reducing significantly the time needed to detect a distress beacon after its activation,** bringing it down from one hour to 10 minutes. **Galileo SaR will also help localise the distress beacon more effectively**, reducing the uncertainty radius down to less than 5 km**.**

The Galileo SaR service complements the current LEOSAR (low orbit) and GEOSAR (geostationary) satellites of the Cospas-Sarsat system, mitigating their current limitations. SAR/Galileo European coverage area and ground facilities are depicted in (Figure 3). In addition, the service provides further enhancements for Cospas-Sarsat beacons thanks to **a return link transmission**. The return link broadcasts a confirmation to the user that the distress message has been received. The Galileo Return Link Service was declared operational on January, 21 2020. It is considered a major upgrade compared to the existing system, which provides no feedback to users.

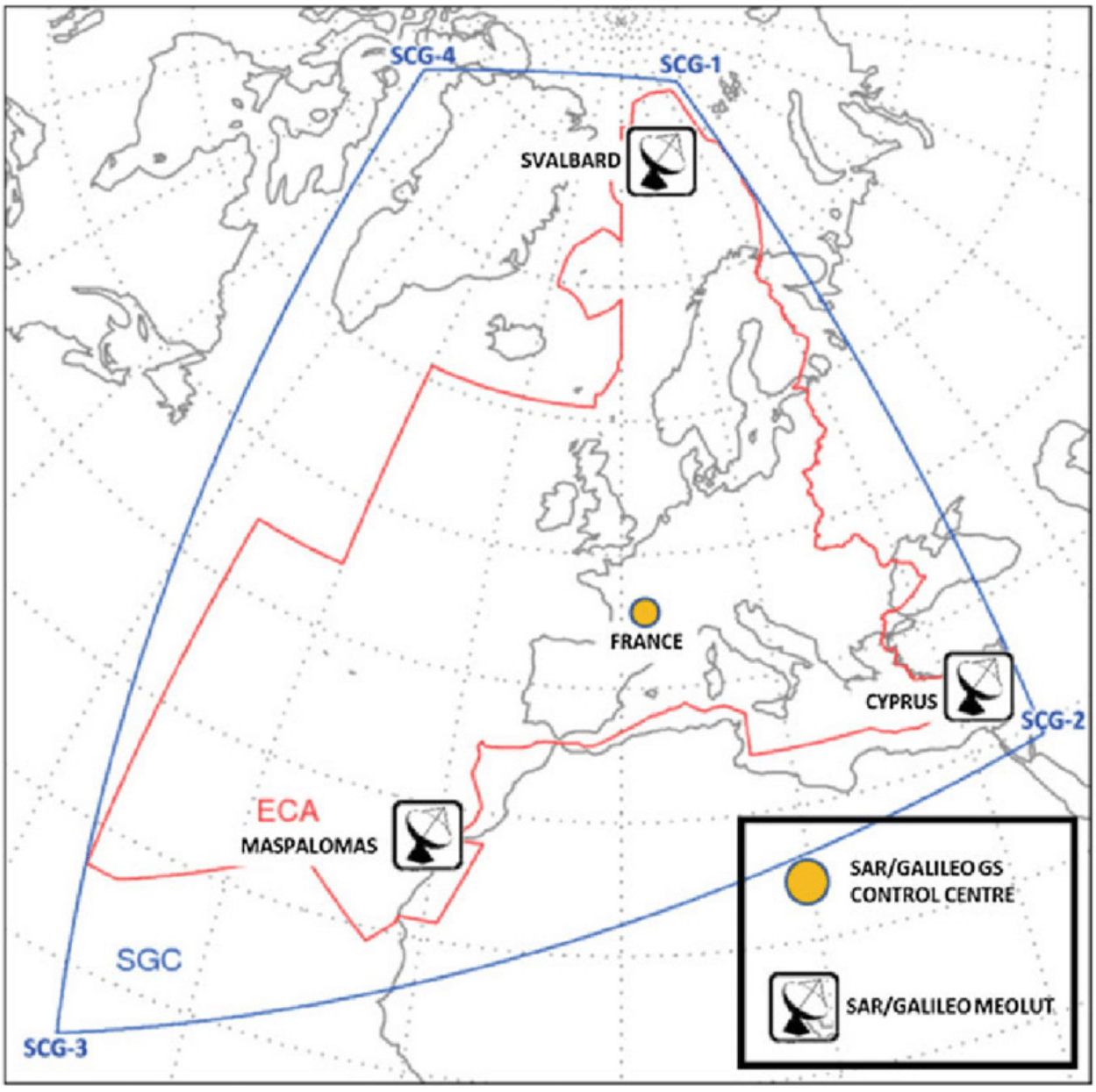


FIGURE 3: SAR/GALILEO EUROPEAN SERVICE COVERAGE AREA (IN BLUE) AND GROUND FACILITIES (DEDICATED MEOLUTS STATIONS IN RED).
The worldwide coverage is achieved through the COSPAS-SARSAT cooperation scheme.

Galileo-based Emergency Warning Service (Figure 4) provides a warning to the population in case of emergency related to events such as fire, floods, and storms. The warning contains the main information related to the event: Type of event, Location, Time and Basic guidance instruction.

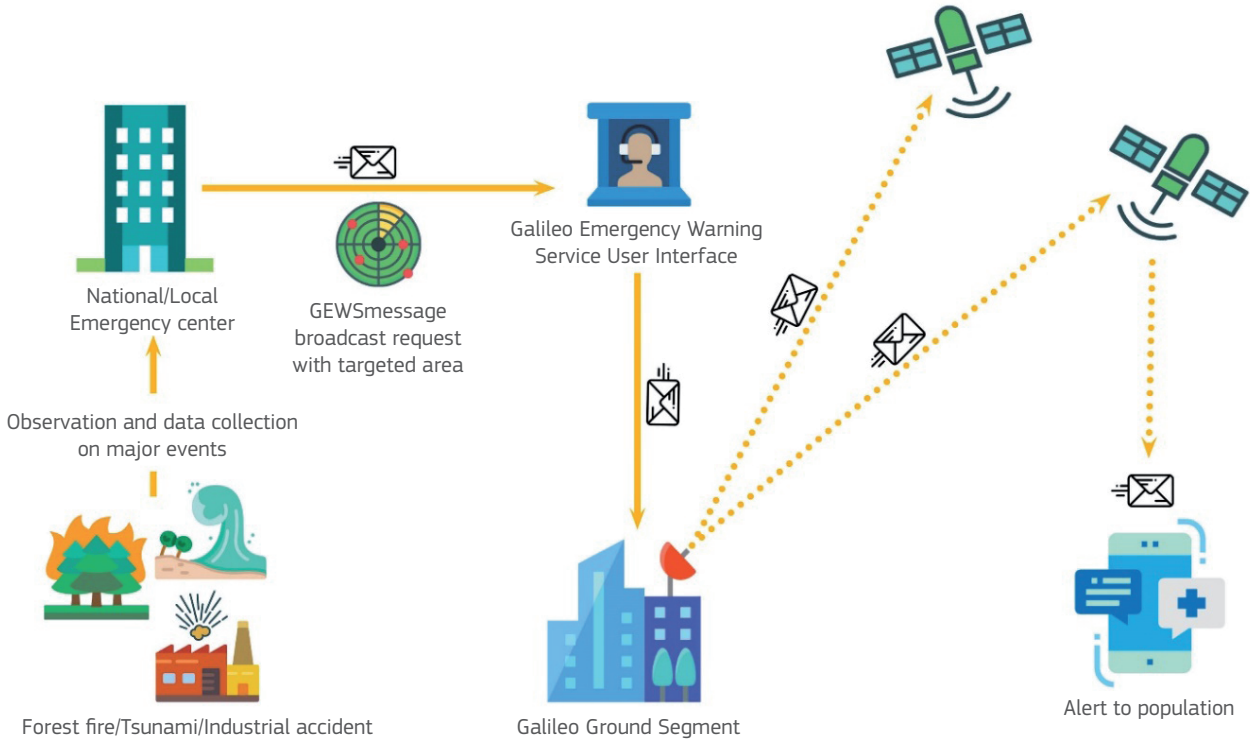


FIGURE 4: GALILEO EMERGENCY WARNING SERVICE.
Source: from the Galileo Reliable Automatic Low Latent Emergency Warning Service project.

5.2 | EGNOS & Integrity

EGNOS is the European **augmentation satellite system**, its current version (**EGNOS 2.4.2**) employs three **geostationary** satellites. EGNOS partially covers the Arctic region, reaching **up to 72 degrees North.** However, in mountainous regions shadowing may reduce visibility at lower latitudes. For the EU satellite navigation systems, this is the main gap identified for the Arctic region.

The most relevant EGNOS services for the Arctic region are:

EGNOS Open Service (OS) is accessible free-of-charge and improves positioning accuracy through broadcast corrections. The correction allows the user to reduce the error sources affecting GPS signals. In particular, the corrections mitigate the ranging error sources related to satellite clocks, satellite position and ionospheric effects.

In addition to enhanced accuracy, **EGNOS Safety of Life (SoL)**, 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. Currently, the service supports civil aviation operations down to Localizer Performance with Vertical Guidance (LPV) minima; the system is designed to be compliant with the ICAO Standard and Recommended Practices (SARPs) for SBAS. The EGNOS SoL Service has been available since 2 March 2011.

The yearly growing number of airports using EGNOS-based procedure is depicted in Figure 5. The figure considers only airports above 60 degrees North. Currently, Kirkenes Airport in Norway (69.72° North latitude) is the northernmost airport with active EGNOS-based procedures. New procedures will be set into operations in December 2020 for most of the airports in Norway between 70-72°N latitude (Hasvik, Berlevag, Båtsfjord, Vardo and Vadso).

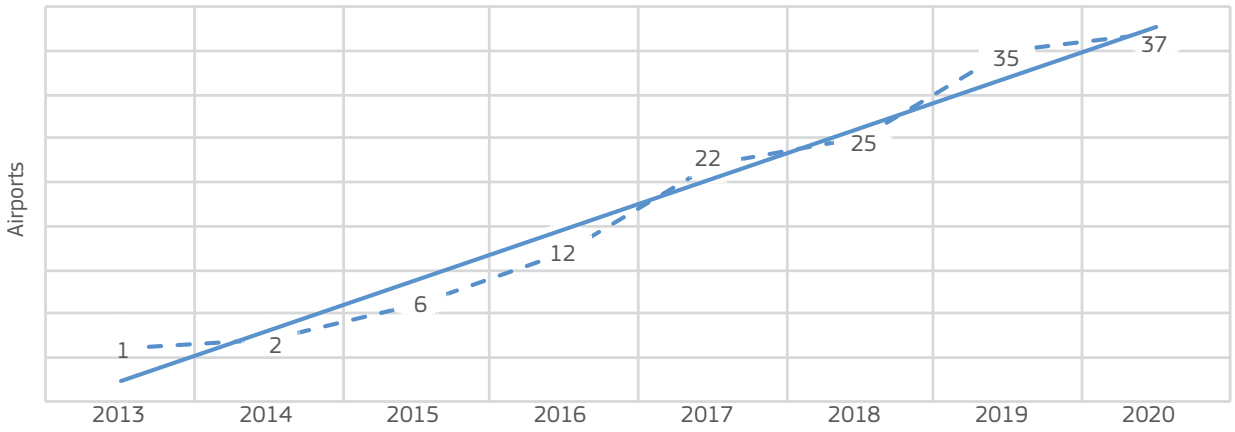


FIGURE 5: TIME EVOLUTION OF THE NUMBER OF AIRPORTS IN THE ARCTIC REGION WITH ACTIVE OR PLANNED EGNOS-BASED PROCEDURES.

To fill the EGNOS SoL coverage gaps in the Arctic region, integrity could be retrieved using algorithms implemented in the receiver, an approach referred to as **Receiver Autonomous Integrity Monitoring (RAIM)**. European Union (EU) and United States (US) of America are jointly developing SoL services based on GPS and Galileo (Working Group C-ARAIM Technical Subgroup. 2016), called **Advanced Receiver Autonomous Integrity Monitoring (ARAIM).** ARAIM has **global coverage** including Polar regions, different versions of the service have been designed: Horizontal-ARAIM and Vertical-ARAIM. The H-ARAIM will be available from 2025 and V-ARAIM from 2030.

A summary with a timeframe of the main available and future EU satellite navigation is depicted in Figure 6.

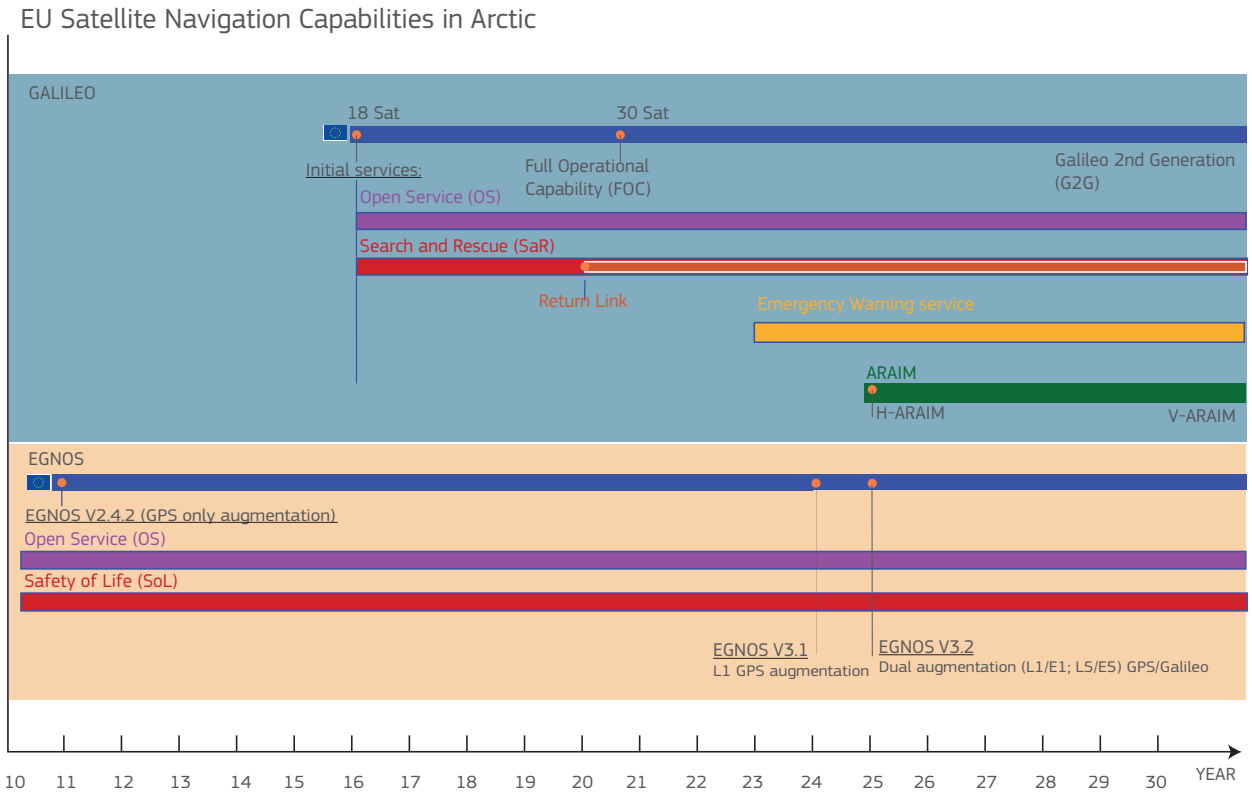


FIGURE 6: TIMELINE EU SATELLITE NAVIGATION SERVICES UNDER THE GALILEO AND EGNOS PROGRAMMES WITH A RELEVANT ADDED-VALUE IN THE ARCTIC.

6

SATELLITE COMMUNICATIONS CAPABILITIES **IN THE ARCTIC**

6 Satellite communications capabilities in the Arctic

Satellite communications (SatCom) include transmission and reception of radio telecommunication signals from/to the Earth via satellite. SatCom is used for voice, text and data (including internet).

SatCom is a key enabler for civil and military communication in remote and harsh environments where land-based communication is limited due to the lack of adequate infrastructure.

The majority of SatCom satellites used for voice, text and high volume data transmission are placed in the geosynchronous (GEO) orbits and are ideal for making connections over a fixed geographical area (within a given range of longitude). However, as GEO satellites are located above the equator areas beyond 72 degrees North and South are not well covered (see Figure 7). Consequently, this crucial lack of adequate, autonomous, secure and cost effective means of electronic communications is particularly challenging in the Arctic region. In addition to limitations of GEO orbits geometry, ground-based telecommunication infrastructure in Arctic region is limited or not sufficiently reliable.

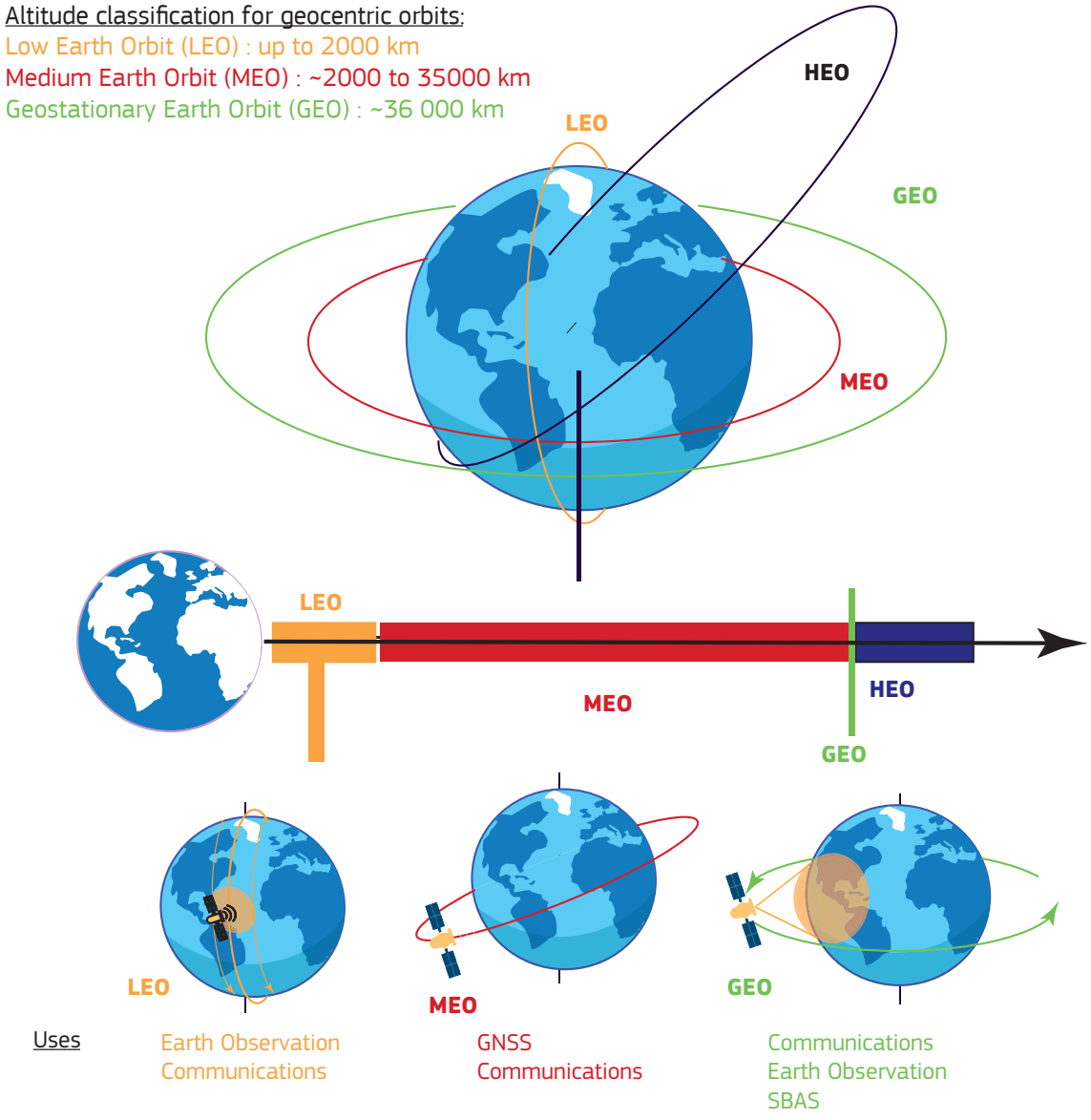


FIGURE 7: ORBIT CONFIGURATION AND LIMITATIONS OVER POLAR AREAS.

To overcome the limitations of GEO satellites, the alternative orbits Medium Earth Orbits (MEO) and Low Earth Orbits (LEO) are being increasingly used for SatCom in Arctic.

In addition to SatCom for voice, and high volume data transmission, there are systems using SatCom for short, low volume data and text messages. They are often used to monitor fixed or moving objects equipped with specific transmitters which automatically send data related to the object's status or position. They typically use LEO and MEO satellites. Argos (section 6.2.1) is one such system.

Beyond line-of-sight communications can work using HF radio, avoiding the use of satellites. However, HF communications are susceptible to variations of the ionosphere; so Arctic HF communications are the least reliable, as the ionosphere is at its most variable over the polar regions.

6.1 | Current SatCom systems

As previously highlighted, the current GEO satellites are of limited use in Arctic. Only the Iridium Next system can cover the Arctic region with SatCom capabilities. This system uses both MEO and LEO orbits to provide L-band voice and data coverage to satellite phones, pagers and integrated transceivers. It provides midband internet with the speed ranging from 22Kbps to 352 Kbps. Such limited bandwidth is sufficient for simple, applications (like email text messages etc).

6.2 | Low bit rate SatCom

While high bandwidth SatCom with the main GEO satellites is difficult in the Arctic, lower orbit satellites passing over the poles provide capacity for low bandwidth (short message) communication.

6.2.1 ARGOS

Argos is a SatCom system for transmission of short and low data volume messages. It was co-founded by the French space agency CNES, and the services are provided by the French company CLS.

The Argos system is a Satellite Data Collection System with global coverage, allowing collection of in-situ data from "platforms" equipped with a GNSS receiver and an Argos transmitter. Argos transmitters upload short duration data messages (including position) to Argos receivers on satellites which are then transmitted to regional stations (there are around 60 ground stations worldwide in the Argos System) and retransmitted to the processing centres and users. Platforms can be placed, for example, on buoys (ocean monitoring), fixed ground stations (meteorology, glaciology) and moving targets (wildlife monitoring).

There are seven operational polar-orbiting satellites with an Argos payload. In the Arctic region, the typical revisit time is therefore around 15 minutes on average, which supports a wide range of applications. There are 724 operational platforms with an Argos transmitter in the Arctic. They include gliders, ice buoys, drifting or moored buoys, sensors on animals and ships. The following sectors use Argos platforms (number of platforms is in brackets): oceanography (53), meteorology/hydrology (20), sustainable management of fisheries (17) and wildlife monitoring (634).

The most important future development of the Argos system is the launch of the dedicated Kinéis Constellation with 25 nanosatellites, fully compatible with the current Argos system, allowing near real time coverage of the Arctic region. Furthermore, the ability of platforms to operate in a harsh environment will be further reinforced with the future Argos-4 satellite segment, which will include fast processing and low energy consumption algorithms, on-board processing capacity, and include a dedicated bandwidth for very low power transmitters.

6.2.2 ORBCOMM

This US company runs a constellation of satellites in different orbits, some passing over the poles. It offers M2M (machine-to-machine) communications as a part of the IoT (Internet of Things). Messaging is two-way, at VHF frequency, and operation is similar to that of ARGOS using a network of ground-based gateway stations. It is e.g. used for fleet monitoring (of trucks, ships, etc.).

6.3 | EU GovSatCom

The objective of the EU's GovSatCom programme is to ensure reliable, secure and cost-effective civil and military satellite communication services for public authorities in the EU and in Member States managing critical security missions and operations. The goal is also to enhance European autonomy and overcome fragmentation of demand through the use of affordable and innovative solutions in synergy with industrial players (EDA 2019).

According to a recent study (PwC 2018), the main GovSatCom use-case families in the Arctic include surveillance (border and maritime surveillance and control), crisis management (maritime emergencies, police interventions, civil protection, humanitarian aid, military interventions) and protection of key infrastructures (infrastructure for institutional communication, for transport, for space management and for Europol communication).

Out of the inventory of available systems, only the Iridium constellation on MEO and LEO orbits can currently provide seamless satellite communications in the Arctic region. The systems based on GEO orbits are still very important to cover areas below 70 degrees and should be used whenever appropriate.

The GovSatCom programme should also explore how to incorporate future systems for SatCom in the Arctic, especially satellites on Highly Elliptical Orbits (HEO) and broadband constellations in Low Earth Orbits (LEO).

6.4 | Future SatCom systems

Advances in telecommunication technologies, satellite manufacturing and launching capabilities allow employment of systems which will tremendously improve high volume data SatCom in the Arctic. These include SatCom satellites on HEO and broadband constellations on LEO orbits, discussed below. In addition, new antennas are being developed especially for use in the Arctic to extend operational access to GEO satellites northwards.

6.4.1 Arctic Satellite Broadband Mission (ASBM)

Two HEOSAT satellites will be launched in late 2022 to HEO orbits (section 6.2.1) with the aim of becoming operational in 2023. The satellites will be operated by Space Norway HEOSAT ASBM (subsidiary of Space Norway owned by Norwegian Government) in cooperation with Inmarsat, the Norwegian Ministry of Defence and Kongsberg Satellites Services (KSAT, Tromsøo). The satellites will provide full mobile broadband coverage to civilian and military users in the Arctic. The system is scheduled to be operational for at least 15 years with the possibility of using geostationary satellites (where available). The satellites will include military payloads for the US Defence Departments and the Norwegian Ministry of Defence and commercial capacity for Space Norway. The two satellites will be incorporated into Inmarsat's Global Xpress (GX) geostationary constellation which is being built.

The constellation will have a user throughput of 50 Mbit/s downlink and 5 Mbit/s uplink. The main customers using the system are/will be defence governmental users, aviation, maritime, energy and enterprise.

For the Government sector, the new Inmarsat's GX payloads will provide continuous, assured communications to tactical and strategic government users operating in the Arctic region, including customers in the USA, Canada, Scandinavia and other Arctic regions.

6.4.2 LEO broadband mega constellations

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 (from approx. 500 to 1000 km). 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 Region). The signal from a user terminal will go via satellite (or even more satellites connected with optical link) into ground-based "gateways" connected with the terrestrial internet.

With the satellites in LEO orbits, signal latency is very low (less than 100 ms). The broadband connection will have a capacity of at least 50 Mbit/s.

The first services from a LEO constellation should be available from 2020-2021. However, one of the main players that were planning to have their service available in the Arctic in 2020, have gone bankrupt just at time of writing following the COVID-19 outbreak. Delays to establishing Arctic coverage may be expected.

Satellite communications capabilities in the Arctic for broadband communications and low bit rate SatCom are summarized in Figure 8. (OneWeb is still included).

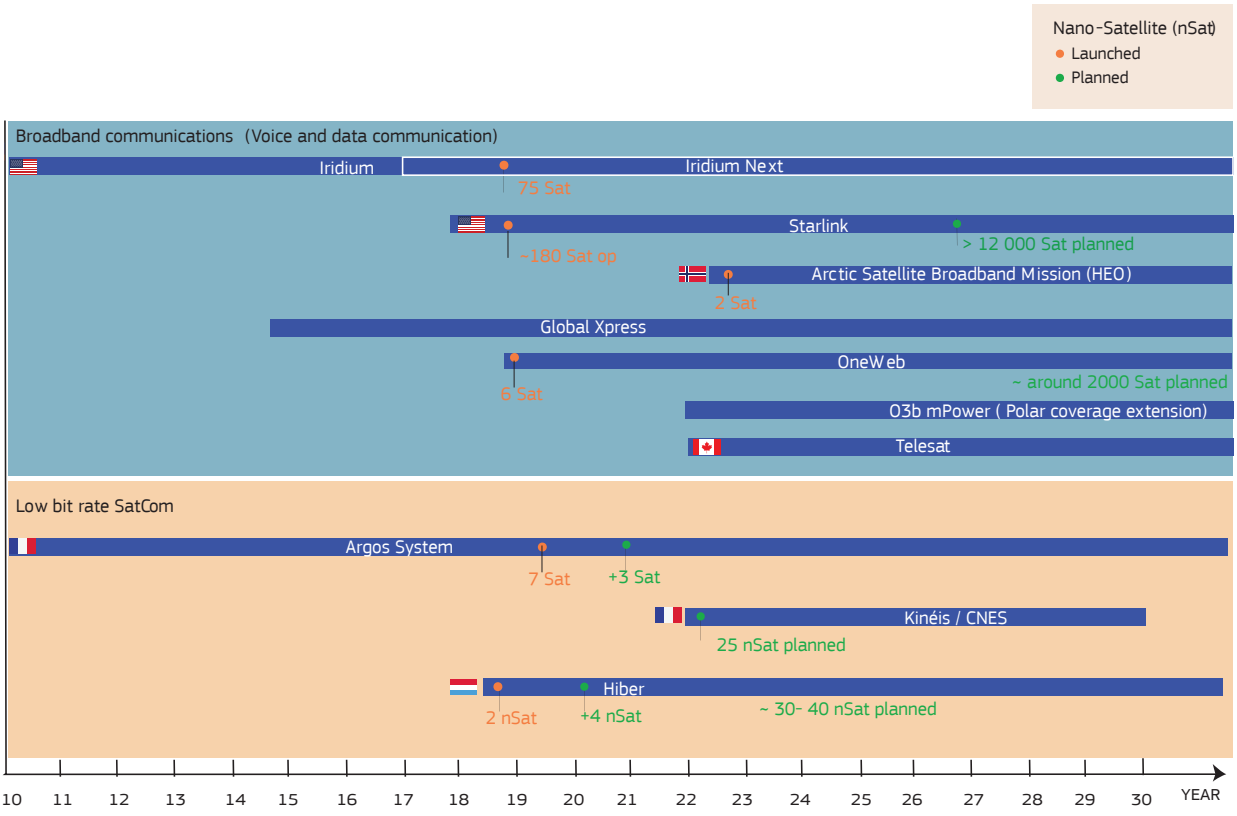


FIGURE 8: TIMELINE OF THE MAIN SATCOM SYSTEMS WITH ARCTIC COVERAGE.

7

SPACE SITUATIONAL AWARENESS (SSA) **CAPABILITIES**

7 Space situational awareness (SSA) capabilities

Ionospheric effects can be a major source of disruption for GNSS signals. Prediction of such effects is crucial when high accuracy positioning is needed for the aviation or maritime sectors.

At European level, the EISCAT (European Incoherent Scatter Scientific Association) operates three incoherent scatter radar systems, at 224 MHz, 931 MHz in Northern Scandinavia and one at 500 MHz on Svalbard, to study interactions between the Sun and the Earth as revealed by disturbances in the ionosphere and the magnetosphere. The EISCAT radars are also used for continuous monitoring of LEO (Low Earth Orbit) debris. The radars are part of the European Space Agency's Space Situational Awareness Programme (SSA).

The European Commission-funded Galileo **Ionosphere Prediction Service (IPS)** aims to monitor ionospheric activity and inform GNSS users in good time of upcoming events that could disrupt GNSS signals and applications.

A prototype was delivered early 2019 to monitor and forecast ionospheric activity https://ips.telespazio.com/. The main prediction products include solar activity, Coronal Mass Ejection (CME), Total Electron Content (TEC) and scintillation. For operational users positioning error and loss of lock are provided. With regard to the Arctic region, developments are currently on-going at JRC to enhance the IPS and extend the availability of products in the Polar Regions.

JRC is investigating the possibility of using an analysis of the TEC available within Global Ionospheric Maps (GIM). In particular, the improvements of the IPS will include a now-casting product of the TEC. An example showing the monitoring of the vertical TEC (VTEC) is given in Figure 9.

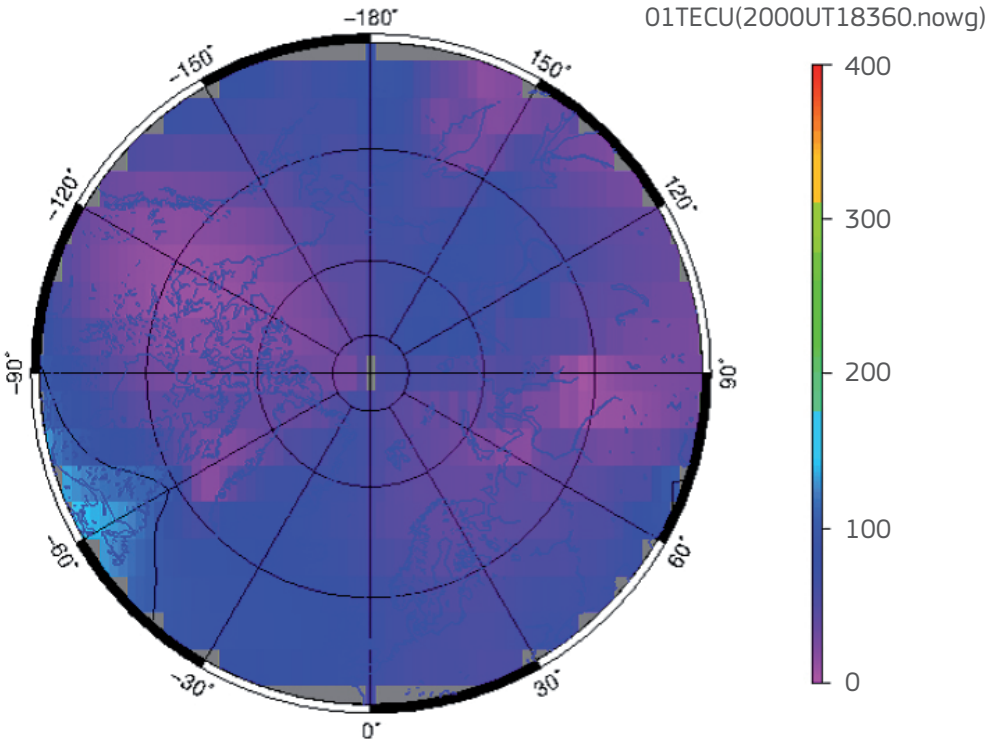


FIGURE 9: VTEC MONITORING AT 2000UT OF DAY 360 OF 2018 FOR THE NORTHERN POLE CAP.
Image generated in the framework of the European Commission Service Contract POLarGIMs.

8

SYNERGISTIC USES OF EARTH OBSERVATION, NAVIGATION AND SATELLITE COMMUNICATIONS **IN THE ARCTIC**

8 Synergistic uses of Earth observation, navigation and satellite communications in the Arctic

Having completed the inventory of the assets of each component of the EU Space Programme, relevant synergies are identified and discussed.

In particular they have been gathered at service and infrastructure level.

8.1 | Service level

8.1.1 Synergistic applications

Reanalysis products

Climate reanalysis combines past observations with models to generate consistent time series of multiple climate variables. Reanalyses are among the most-used datasets in geophysical sciences. They provide a comprehensive description of the observed climate as it has evolved during recent decades, on 3D grids at sub-daily intervals.

The ERA5 global reanalysis run by ECMWF is currently a good example of synergy, assimilating an increased number of satellite data, including GNSS-RO data and Copernicus products, to provide analysis of atmospheric states and improved surface state, snow and ice parametrisation, and sea state. The global and coarser ERA5 will be used as boundary forcing for the finer Copernicus Arctic Regional ReAnalysis (CARRA) that will cover the period from July 1997 to June 2021 (24 years) at 2.5 km horizontal mesh and three-hour update frequency (Dee et al. 2011).

Much of the needed information identified in section 3.2 is already being, collected with satellites (with subsequent processing and enrichment). Satellites play a key role, especially over the large expanses of the Arctic that have sparse local data collection structures. For example, national meteorological services provide weather and ocean forecasts using satellite data; and the Copernicus Marine Environment Monitoring Service provides ice forecasts. However, today's feedback from operators in the field indicates that the quality of the products is not yet adequate; e.g., higher resolutions are needed, more detailed information like ice thickness and ridges, and more timely delivery. It is by combining the observations from multiple types of satellite sensors that advances in the extraction of pertinent information may be expected; and in exploiting broadband satellite communications that near-real time delivery to users in the field can be realised.

Sectoral applications making use of various Space element programmes have been identified and are summarized in (Table 6). Almost all operational applications make use of position data at some point, while real-time applications need SatCom to deliver results to users.

For maritime surveillance, AIS (Automatic Identification System) tracks self-reporting ships, and the future VDES (VHF Data Exchange System) is a new technology that will enable a wider seamless data exchange for the maritime community. In combination with EO these technologies can provide a more complete maritime picture. AIS itself was designed as a ship-to-ship anti-collision system, and the reception of its signals from space could have been listed among the examples of the previous section as the novel use of a signal of opportunity.

FIGURE 10: THE TWO DOMAINS FOR THE REANALYSIS, A WESTERN DOMAIN (LABELLED "IGB") AND AN EASTERN DOMAIN (LABELLED "AROME-ARCTIC"). *Credit*: https://climate.copernicus.eu/.

Applications	EO	Navigation	SatCom
Ship routing	●	●	●
Ice extent mapping **Ice concentration**	●	● GNSS-R	
Meteorology **Climatology**	●	● GNSS-RO	
Maritime surveillance, including Fisheries control and Maritime security	●	●	● incl. AIS/VDES
Internet of Things	●	●	●
Precise Earth Imagery	●	● Precise Orbit Determination	

TABLE 6: EXAMPLES OF SYNERGIES AT SERVICE LEVEL BENEFITING FROM THE EARTH OBSERVATION, SATELLITE NAVIGATION SYSTEMS AND SATELLITE COMMUNICATIONS SYSTEMS.

Observations of solar and ionospheric activity, in the category of SSA that is not included in **Table 6**, contribute to risk assessment for GNSS reliability, space weather impacts on the ground, and air passenger radiation. Their timely communication to people and locations at risk again requires Satcom.

8.1.2 Innovative techniques

Several innovative technologies using signals of opportunity are highlighted below.

GNSS Radio Occultation (GNSS-RO)

The space-based GNSS-RO technique delivers vertical profiles of temperature and humidity at fine resolution (close to 300 meter in the troposphere). It does so by precisely measuring the delay between a GNSS transmitter and a GNSS receiver aboard a Low Earth Orbiter, when the former is setting below or rising above the horizon. The RO measurements significantly improve meteorological forecasting quality (Anthes et al. 2008; Cardinali 2009) and for atmospheric reanalyses products[8] (Poli, Healy, and Dee 2010; Simmons and Poli 2015) because they complement the usual 2D information from satellites with a vertical resolution.

For the Arctic, GNSS-RO data are a key asset for climate monitoring and for ionospheric research.

The on-going and future missions having a GNSS-RO payload relevant for the Arctic region are listed in **Table 7**.

Mission name	Institutions	GNSS RO Payload	Status
ROHPP-PAZ Radio Occultation and Heavy Precipitation with PAZ	CDTI, Astrium España, INTA, Hisdesat	ROHPP (GPSRO)	Operational since 2018
GRACE-FO	NASA, DLR	Tri-G (GPS, Galileo, Glonass)	Operational since 2018
Metop-C	ESA	GRAS (only GPS)	Operational since 2018
EPS-SG	ESA	RO-SG (GPS and Galileo)	From 2022
SPIRE	Commercial company	STRATOS GNSS science receiver	76 LEO 3U Cubesats in orbit since 2015 Only RO producer using Galileo signals

TABLE 7. MISSIONS HAVING GNSS-RO PAYLOAD RELEVANT FOR THE ARCTIC.

GNSS Reflectometry

Signals of Opportunity (SoOp) using existing navigation satellite systems are used to retrieve a large range of measurements: surface soil moisture (Chew et al. 2016), ocean surface winds (Clarizia et al. 2016; Foti et al. 2015; Ruf and Balasubramaniam 2018), sea ice thickness, altimetry (Cardellach et al. 2004; Cartwright, Banks, and Srokosz 2019; Clarizia et al. 2016) sea ice cover and wind speed over sea surface. All these measurements are relevant for the Arctic users.

The **UK Tech-Demosat 1** mission was designed by Surrey Satellite Technology Ltd. The satellite was launched in 2014. The specificity of the orbit of TechDemosat-1 with those of GPS satellites provided high spatio-temporal resolution and captured the dynamic of sea ice even close to the North Pole. **Spire** is also deploying a large commercial constellation of Cubesats with passive sensing payloads including GNSS reflectometry sensing capability, AIS for ship tracking and ADS-B aircraft tracking product,

[8] Reanalyses allow for producing the best estimate at any given time of a product using as many observations as possible, including satellites data from a long observation period (typically 30-50 years).

Surface characterization and distinction between open water (in blue) and sea ice (in red) is represented in Figure 11.

Recently the GNSS-R technique has also shown its capacity to provide wind field measurement with the NASA CYGNSS mission (equatorial only coverage) and studies are on-going to assess the benefits of GNSS-R data in weather forecasting models. GNSS-R data assimilation experiments have been conducted in the framework of the OSI SAF, the Eumetsat Satellite Application Facility on ocean and sea ice (http://www.osi-saf.org/?q=content/gnss-r-processing-and-nwp-assimilation).

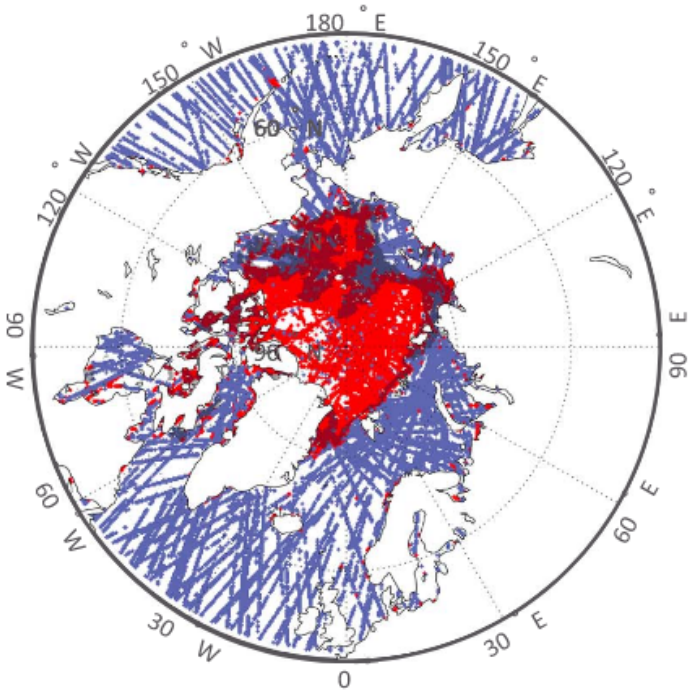


FIGURE 11: SURFACE CHARACTERIZATION FROM GNSS-REFLECTOMETRY (TECHDEMOSAT-1) OVER THE ARCTIC REGION FOR THE AUGUST AND MAXIMUM EXTENT IN 2016.
Red displays a sea ice assignment and blue an open water assignment. The black shaded area represents transition between sea ice and water during the month using the in the European Space Agency Climate Change Initiative product (Toudal Pedersen et al. 2017).
From (Cartwright, Banks, and Srokosz 2019).

Satellite GNSS positions

Another innovative technique of great interest for the Arctic region is the use of **GNSS data coming from space-borne receivers** for alternative applications. All the Sentinels have on board GNSS receivers that are intended for precise orbit determination; precise orbits being required for correct processing of raw EO data. Now, the Copernicus programme is releasing the Sentinel GNSS ("RINEX") data files and the other ancillary files to enable a number of other applications, namely:

- Ionosphere characterization through dual-frequency GPS measurements that provide TEC (Total Electron Content) data from the ionosphere
- Gravity Field modelling thanks to the evaluation of the time-variable part of the gravity field
- Geodesy in a broad sense since the inclusion of LEO measurements into global GNSS processing may improve global parameter determinations

The GNSS data are available on the Sentinels GNSS Rinex Hub (https://scihub.copernicus.eu/gnss/).

8.2 | Infrastructure level

Synergies at infrastructure level occur when hardware / infrastructure can be re-used for multiple purposes. This already happens when one satellite bus is used to carry multiple sensors, which is common practice. Nonetheless, it is useful to note several specific synergies that could be deployed to benefit the Arctic:

— While the fusion of AIS and EO was included above as a synergistic application at service level, the mounting of an AIS receiver on an EO satellite represents an infrastructure level synergy, that has the additional strong advantage that the signals from both sensors are collected simultaneously, obviating the need to interpolate / extrapolate the positions of moving ships;

— The Galileo **SaR** service (detailed in section 5.1) can be seen as an infrastructure synergy, as it is enabled by a low data rate SatCom facility on the GNSS satellites;

— The **European Data Relay Satellite System** (EDRS) is a GEO SatCom facility dedicated to downlink data from EO satellites when they are out of reach of a ground station, to reduce time delays in the transmission of large quantities of data;

— The **SIOS** infrastructure (section 4.6) that is used for a range of activities (Earth observation missions including the Copernicus satellites, Galileo satellite);

In future, satellites of the EU Space Programme may be using Quantum technologies that could also benefit Arctic users. Their different applications include Quantum Key Distribution (QKD) to encrypt systems and services, inertial navigation, gravity measurements, novel quantum magnetic sensors, quantum imaging and quantum radar.

A synthetic scheme with some example of synergies at service and infrastructure levels is shown in Figure 12 between the four elements of the European Space programme.

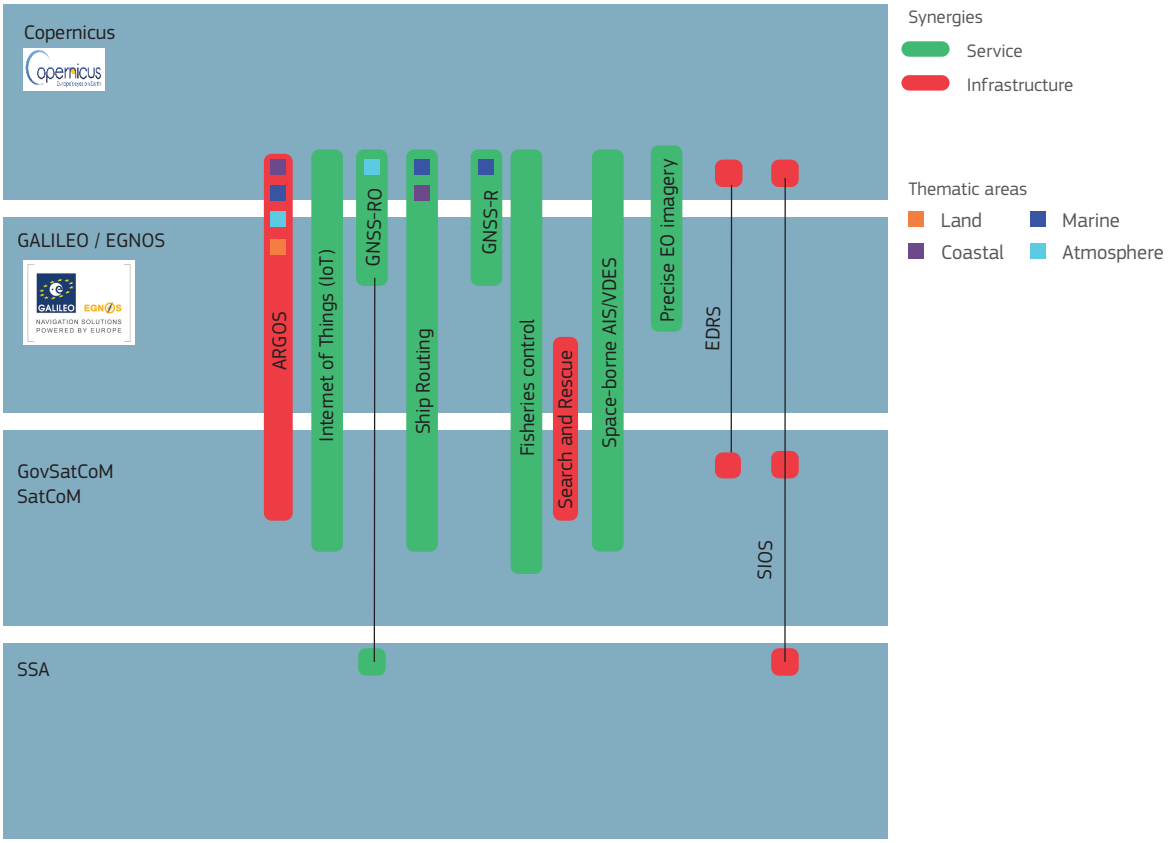


FIGURE 12: EXAMPLE OF SYNERGIES AT SERVICE AND INFRASTRUCTURE LEVEL BETWEEN THE DIFFERENT EU SPACE PROGRAMME'S ELEMENTS: COPERNICUS, GALILEO/EGNOS, GOVSATCOM AND SSA.
The main corresponding thematic areas of applications are also indicated.

9

SOCIETAL IMPACT **ASSESSMENT**

9 Societal Impact assessment

The links between satellite systems and the potential benefits to Arctic society have been identified, with a focus on synergies between the different elements of the EU Space Programme (including Earth observation, Communication, Navigation and SSA). This analysis builds on the well-established methodologies of Value Tree Analysis (VTA) and Intervention Logic (IL), and extensive knowledge collected in the context of the International Arctic Observations Assessment Framework (IDA-STPI and SAON 2017) and the IMOBAR study (Dobricic et al. 2018) on societal benefits of Arctic observing systems. These two studies relied on expert domain knowledge, collected through workshops, surveys and interviews. VTA provides a hierarchical description of the process leading to societal benefits. The bottom of the hierarchy contains observing systems and the top of the hierarchy wide areas of societal benefits that arise directly or indirectly from products and services based on the observing systems. Twelve Societal Benefit Areas (SBAs) were defined in the Arctic for four focus areas, People, Environment, Climate, and Economy (Annex 4). In a similar way the IL methodology builds a logical link between the problems that need to be tackled, the underlying drivers of the problem, and the action to address the problem and achieve the objective. While VTA provides a consistent approach for the evaluation of societal benefits across the 12 SBAs, IL further includes descriptions of other steps in the policy process (Figure 13).

FIGURE 13: SEQUENTIAL LOGICAL STEPS OF THE VTA AND IL METHODOLOGIES.

Information on societal benefits arising from observing systems in the Arctic was collected during structured workshops from experts representing the major providers of environmental information and important stakeholders in the Arctic (such as ESA, EU-Polarnet, ECMWF, WMO). Most of the organizations involved represent public entities or international organizations representing different stakeholders. Desk research and structured interviews with selected stakeholders provided additional information for the evaluation of links between services and SBAs defining the relative importance and strength of the relationships, and refined the selection of observing systems contributing to different case studies. In this report we focused on the **needs connected to the monitoring and forecast of sea-ice conditions** in the Arctic**. Several human activities require information about sea-ice, such as ship routing, search and rescue, offshore installations and oil spill detection**. The selected case studies met the criteria of relevance and sensitivity to environmental and societal issues in the Arctic, capacity of producing benefits, coverage of a wide spectrum of different satellite systems and their synergies. Taken together they produce benefits in all of the twelve Arctic SBAs.

It is shown in particular how the communication and GNSS, together with Earth Observation System (EOS), are fundamental to providing services needed by indigenous people, local population and economic actors in the Arctic. Declining sea-ice is affecting different activities in the Arctic, such as shipping, search and rescue and off-shore installations. New navigation routes may transit through the Arctic Ocean due to extended open water areas and summer navigability. Services for ship routing include real-time reports, short term forecasts and longer term predictions of ice, weather, sea conditions, iceberg tracking, and communication assistance, which all depend on satellites.

An example of existing synergies between different satellite programme elements is the GNSS RO technique that makes use of existing transmitted GNSS signals, originally designed for positioning and navigation, to improve estimates of tropospheric temperature and humidity profiles and thus improve weather prediction and climate monitoring.

A second example is the use of the ESA Soil Moisture and Ocean Salinity (SMOS) mission, which in combination with Cryosat data improved the measurement of sea-ice thickness. Synergies between different satellite programmes are fundamental in SaR operations, such as the Galileo SaR service. The Sentinel-1 satellite, for example, provides all-weather day-and-night measurements of sea ice. In addition, satellites are also used to detect AIS, which are tracking systems used on ships and vessel traffic services. These are very important in a SaR operation for establishing the location of particular vessel that could be in distress. Satellites may be very helpful to complement traditional knowledge in the rapidly changing environmental conditions of the Arctic. First of all, geo-localization and communication are of paramount importance in such remote areas. Second, some environmental information, such as sea-ice or snow cover and thickness, may also be used by indigenous people and local populations for their daily activities, such as hunting and moving on the sea-ice. A number of services, such as the Polar View Community Ice Service, have been developed mainly combining three elements: traditional knowledge; ice sensing, through satellite imagery but also in-situ measurements; and smart design.

The services based on sea-ice monitoring and forecast for ship routing, SaR, offshore installations and oil spills were connected to a total number of 92 key objectives distributed among 8 different Societal Benefit Areas (Figure 14 and Figure 15).

A qualitative score (low, medium and high) was assigned to each link according to the extent to which the product or service contributes to the specific key objective. Most of the benefits were found for disaster preparedness, including identification, mitigation, recovery, and protection. Three sub-areas were identified for planning, development, operations and maintenance of infrastructures. Other societal benefits were identification of drivers of environmental impacts, food security, human health, weather effects on economic productivity and on protection of lives and property. A larger number of societal benefits may be expected considering the wide spectrum of issues and activities of indigenous peoples, local population and economic actors in the Arctic, and extending the impacts of a changing Arctic in the lower latitudes. Indeed, the rapid changes happening in the Arctic impact the rest of the globe by changing the atmospheric and ocean circulation processes at a larger scale, such as the sea level rise from the glaciers melting in Greenland, or weather extremes affecting the societies at the mid-latitudes.

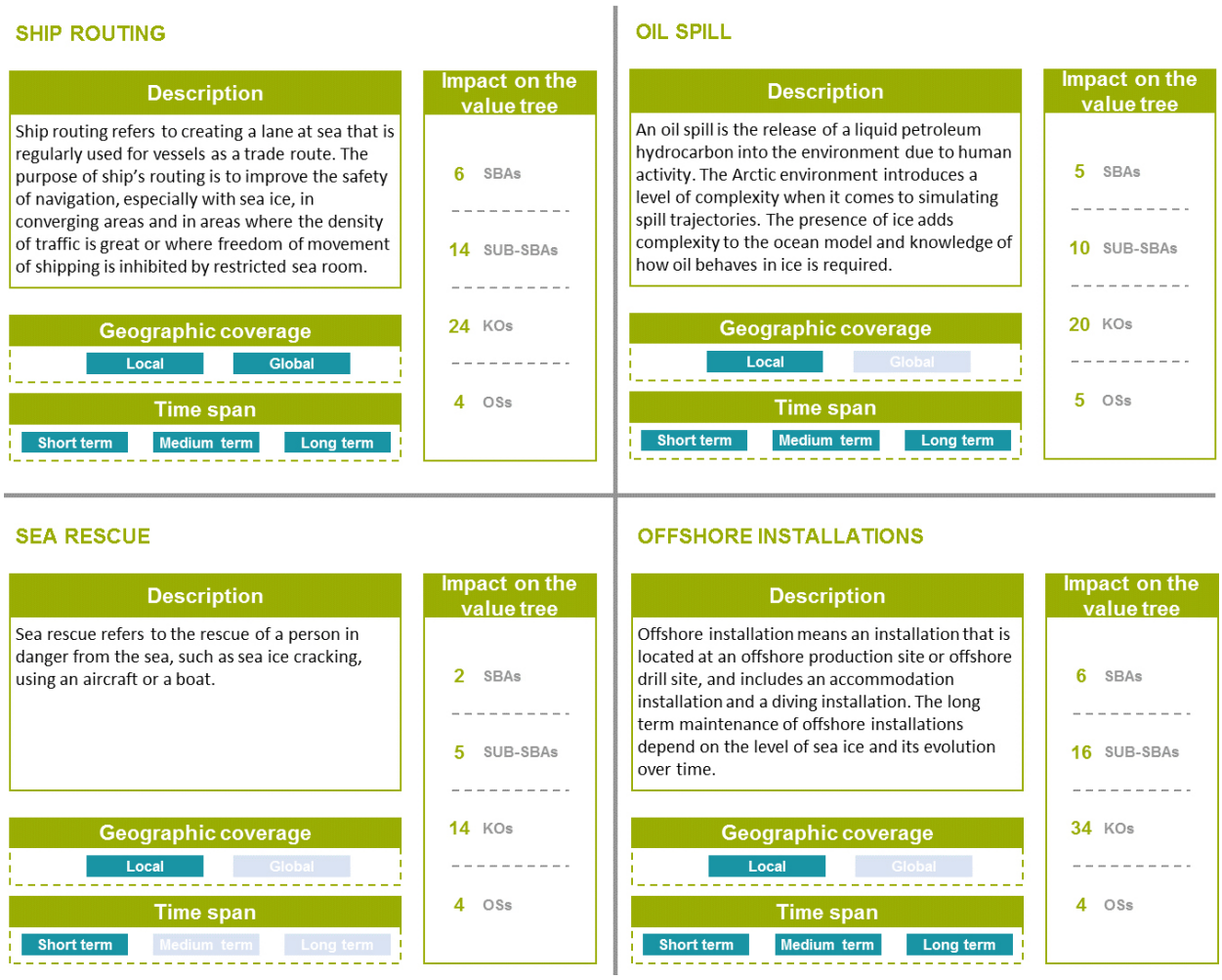
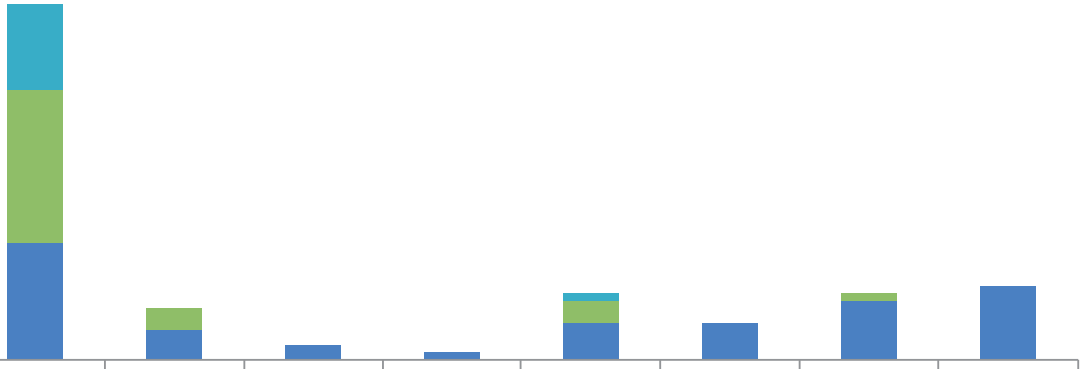


FIGURE 14: SHORT DESCRIPTION OF KEY PRODUCTS, SERVICES AND OUTCOMES (KPSO) ASSOCIATED TO SEA-ICE CONDITIONS. THE IMPACT ON THE VALUE TREE WAS ASSESSED BY EXPERTS IN TERMS OF NUMBER OF SBA AND SBA SUB-AREAS, AND KEY OBJECTIVES FOR EACH KPSO.
Source: Everis 2018; Dobricic et al. 2018.



	Disaster Preparedness	Environmental Quality	Food Security	Human Health	Infrastructure and Operations	Marine and Coastal Ecosystems and Processes	Natural Resource	Weather and Climate
Low	12	0	0	0	1	0	0	0
Medium	21	3	0	0	3	0	1	0
High	16	4	2	1	5	5	8	10

FIGURE 15: AGGREGATE CONNECTIONS BETWEEN ALL SEA-ICE KPSOS AND THE SBAS
Everis 2018; Dobricic *et al.* 2018.

10 CONCLUSIONS

10 Conclusions

The rapid environmental changes occurring in the Arctic are accompanied by an increasing presence of human activities and interests in the region which also calls for additional security applications. The needs of indigenous peoples, local population and economic actors in the Arctic require more and more the combined use of different satellite products to communicate, to move with navigation support, and to monitor and forecast environmental conditions.

It is in this context that this study identifies the specific user needs and the challenges of the Arctic region, and the available and foreseen Space assets with a focus on the European capacities.

Arctic Space solutions were sought through the four elements of the European Space programme – Earth observation, European Global Navigation Satellite Systems (EGNSS), Satellite Communications and Space Situational Awareness – inventorying current and future capabilities (10 year's timeframe).

The evaluation of the pertinence of each space asset was mapped according to the challenges identified using a cross-cutting approach. The study led to the identification of gaps in particular related to some products and existing services, with possible solution to improve them.

Regarding **Copernicus** for safe navigation in the Arctic, the Copernicus Marine Environment Monitoring Service (CMEMS) brings a clear benefit by delivering an array of sea ice products (including sea ice concentration, sea ice edge, sea ice type, sea ice thickness and sea ice drift, as well as iceberg concentration). However, operational users, both civilian and military, are still in need of more detailed and more timely provision of sea ice, bathymetry and iceberg information to adequately evaluate risk.

Improved service product portfolios and new products (e.g. redistribution of radar altimetry sea ice thickness) would be incorporated in next generation Copernicus missions, expected to improve safe operations and navigation in the maritime sector, and better covering of research needs. However, a clear gap remains between model-based forecast systems and polar end-users needs in terms of resolution. Continuous investments in the development of high-resolution forecast systems, observations and appropriate data assimilation techniques are required to generate more user-relevant services.

EGNSSs already cover the Arctic region; in particular, the Galileo Open Service (OS) is available for non-safety critical purposes for positioning, navigation and timing synchronization under all weather conditions. In addition, the **Galileo Search and Rescue** (SaR) service covers the Arctic up to 85° North latitude. The service brings a net benefit in reducing significantly the time needed for localization of users in distress. A fundamental element of the Galileo SaR service is the **return link feature** (available since January 2020)**.** This unique capability confirms the user that the distress message has been received.

The augmentation system EGNOS has a gap in its coverage of the Arctic. This gap is due to the GEO orbit of the EGNOS satellites, which makes them visible only up to 72° North (or lower in mountainous terrain). Although EGNOS only partially covers the Arctic, EGNOS services (OS and SoL) are already exploited in the area. EGNOS SoL service is particularly useful in aviation where the integrity information is fundamental. The study found that a growing number of airports implement EGNOS-based landing procedures. An alternative solution to the integrity information provided by EGNOS is **the future Advanced Receiver Autonomous Integrity Monitoring (ARAIM) service**, which will provide improved integrity, in particular for aviation and maritime sectors. The service will have a global coverage, also above 72°N, and horizontal ARAIM will be available by 2025.

An additional future capability of Galileo that is expected to be very valuable to the Arctic is **the Emergency Warning Service,** which will provide warnings to the population in case of emergencies related to events such as fire, floods, and storms. The service is designed to target the public and in some cases the emergency authorities.

Regarding **the Satellite Communications (SatCom)** component, the key issue is that most communications satellites are GEO, but only non-GEO satellites are able

to cover the Arctic region. Currently only Iridium Next (US-based Company) operating on MEO orbits covers the Arctic region entirely. Governmental Systems serve primarily for MILSATCOM, although some of them have a dual-use payload which would allow their usage for GovSatCom. However, all these governmental systems also employ GEO orbits, therefore their usage for northernmost regions is limited.

Future potential systems for GovSatCom have been investigated: HEO satellites – Global Xpress (by Inmarsat); LEO satellite mega constellations – OneWeb, Starlink and Telesat LEO. The new GX payloads will provide continuous, assured communications to tactical and strategic government users operating in the Arctic region. The satellite mega constellations for broadband internet are starting to put their first satellites in orbit and are testing the first connections to users.

Following this in-depth review of the different Space element programmes, **it was possible to identify a number of synergies. Remote sensing techniques can use GNSS signals as a signal of opportunity to retrieve geophysical parameters**: GNSS radio occultation for atmosphere and climate applications; GNSS-reflectometry to derive sea ice extent or snow depth; and signal delays from GNSS payloads on board satellites to derive ionospheric parameters.

The synergies between Earth observation, GNSS and SatCom are very strong for maritime applications including safe navigation and surveillance. Space-borne Automatic Identification System (AIS) receivers – that can be seen as a kind of SatCom system – are used to track reporting ships, while imaging satellites can detect non-reporting ships and map ice conditions; and the results can be transmitted to ship-board users in near-real-time with SatCom. The Internet Of Things (IoT) applications are growing and represent a nice example of synergy between GNSS, SatCom and Earth observation bringing new services with improved connectivity to the indigenous Arctic populations.

Under **the SSA component**, Space weather is monitored to warn against dangerous events that can impact electronics in space and on earth. But space weather also influences the ionosphere, leading to GNSS inaccuracies or outages, so we see a clear synergy in the support of GNSS by the SSA component.

An analysis based on expert opinions was conducted for a few case studies related to activities which depend on sea-ice forecast (ship routing, SaR, off-shore installation and oil spills). **Communication, positioning and Earth observation satellites and their synergies contribute to the definition of key products and services** concerning sea-ice in the Arctic which could be linked to 92 key objectives in 8 different societal benefit areas.

The evaluation of the benefits for Arctic people and operators was based on methodologies developed for policy evaluation such as Value Tree Analysis and Intervention Logic. In particular, this demonstrates that Arctic observing systems are linked to a wide range of societal benefits, even for the limited number of case studies considered here. The study focused mainly on local-to-regional benefits but the proposed analytical framework can be further developed to account for societal benefits of Arctic observing systems ranging from local to global scales.

To reinforce the efficiency of existing and future capabilities for the Arctic users and to improve connectivity, the exploitation of various synergies like those illustrated in this report are highly desirable at programmatic levels between in particular Galileo and Copernicus. A mention to the European Space programme should be referred in the future updated EU Arctic policy to give more evidence of the usefulness of the synergies for the benefits of the Arctic.

ANNEXES

- ANNEX 1. COPERNICUS SENTINELS MISSIONS
- ANNEX 2. THE COPERNICUS CONTRIBUTING MISSIONS
- ANNEX 3. EU FUNDED ARCTIC RESEARCH AND INNOVATION H2020 PROJECTS
- ANNEX 4. SOCIETAL BENEFIT AREAS

Annexes

Annexes 1 | Copernicus Sentinels missions

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	1st Launch in 2022	Payload for atmosphere chemistry on MetOp 2nd Generation
Sentinel-6	Altimeter	10 day revisit	1st Launch in Nov 2020	Radar altimeter to measure global sea surface height

(a) Repeat is the interval that image acquisitions of the same area can be repeated under exactly the same angle, following the repeating pattern of the satellite orbit. Revisit is the interval that a specific area can be imaged combining different imaging geometries and assuming the satellite is always collecting data. This is not the case, so quoted revisit times are therefore theoretical best times.
(b) Theoretical best resolution that is normally not available.
(c) The precise numbers are different for each of the four sensors.
Data from https://sentinels.copernicus.eu/web/sentinel/user-guides.

Annexes 2 | The Copernicus contributing missions

The missions are listed with the responsible country, the special features and applications relevant for the Arctic.

Mission name	Country	Features	Applications
Pléiades	France	Highly sensitive optical instrument	Biomass, land cover monitoring
TerraSar-X	Germany	X-band SAR Two GPS occultation receivers Constellation of 2 together with the identical Tandem-X	Land use, emergency response, environmental monitoring
Cosmo-SkyMed (CSM)	Italy	X-band SAR Civil-military dual use Constellation of 4	Dual Use (Civil / Military) Global Earth Observation Imagery for disaster and emergency management
PAZ	Spain	X-band SAR Polarimetric GNSS Radio-Occultation payload AIS receiver	Security and defense Precise Orbit determination
Deimos-1 **Deimos-2**	Spain	Multi-spectral imager	Land observation Ice shelf crack Disaster monitoring
RadarSat-2	Canada	C-band SAR Precise orbit determination	Arctic sea lines and territories Seasonal variations of glacier ice flow Sea ice monitoring

Annexes 3 | EU funded Arctic research and innovation H2020 projects

Project name	Themes and countries involved
EU-Polarnet 2015-2020	Generate new knowledge about the world's polar regions which are seen as indicators of our planet's health. Coordinator: Alfred Wegener Institut (Germany) Other countries: France, United Kingdom, Italy, Sweden, Portugal, Netherlands, Norway, Spain, Austria, Bulgaria, Denmark, Belgium, Finland, Poland, Estonia, Greenland
Intaros 2016-2021	Develop an integrated Arctic Observation System (iAOS) by extending, improving and unifying existing systems. It seeks to help address Arctic challenges and enable better-informed decision-making. Coordinator: Nansen Environmental and Remote Sensing Center, Norway Other countries: Sweden, Germany, Poland, Denmark, Finland, United Kingdom, Ireland, France, Germany, Belgium, Portugal, Spain, Italy, Greenland, Russia, United States, Canada, China
iCupe 2017-2020	Help establish and maintain long-term, coherent and coordinated polar observations and research activities. Its focus is on improving the integration of existing in-situ observational networks collecting data on pollutants, including aerosols and trace gases, as well as contaminants. It also seeks to harmonise quality control. Coordinator: University of Helsinki, Finland Other countries: Italy, Denmark, Germany, France, Estonia, Greece, Sweden, Switzerland
Interact 2016-2020	Build capacity for identifying, understanding, predicting and responding to diverse environmental changes in the Arctic. It offers scientists access to numerous research stations, giving them the chance to work in the field in often remote locations. Coordinator: Lund University, Sweden Other countries: United Kingdom, Denmark, Finland, Italy, Germany, Norway, Russia, Czech Republic, Greenland, Poland, Austria, Faroe Islands, Iceland, Canada, United States, Netherlands, Belgium
Arice 2018-2021	ARICE seeks to give polar scientists better access to ice-breakers and boost Europe's capacity for marine-based research in the ice-covered Arctic Ocean. It also aims to work with the maritime industry on a programme that involves commercial ships collecting oceanic and atmospheric data. Coordinator: Alfred-Wegener-Institut Helmholtz-Zentrum für Polar- und Meeresforschung, Germany Other countries: Sweden, Norway, Canada, United States, Iceland, Spain, Italy, United Kingdom, Poland, Finland, France, Denmark
Applicate 2016-2020	Address the need for trustworthy weather and climate predictions in the Arctic and beyond. APPLICATE's international team of experts are aiming to make significant improvements to current climate and weather models and help determine the influence of Arctic climate change on the Northern Hemisphere. Coordinator: Alfred-Wegener-Institut Helmholtz-Zentrum für Polar- und Meeresforschung, Germany Other countries: Spain, United Kingdom, Norway, Belgium, Sweden, France, Iceland, Russia
Blue action 2016-2021	Boost the ability to describe, model and predict Arctic climate change and its impact on the Northern Hemisphere. It seeks to do this by, for example, improving the uptake of relevant Earth observation satellite data and contributing to a forecasting framework. Coordinator: Danish Meteorological Institute, Denmark Other countries: Finland, Portugal, Italy, France, South Korea, Norway, Germany, Faroe Islands, China, Russia, Spain, Canada, Iceland, United States, Netherlands
Nunataryuk 2017-2022	Determine the impact of thawing land, coast and subsea permafrost on both the global climate and humans in the Arctic, and to develop targeted and co-designed adaptation and mitigation strategies. Coordinator: Alfred-Wegener-Institut Helmholz-Zentrum für Polar- und Meeresforschung, Germany Other countries: Sweden, Netherlands, France, Canada, Finland, Denmark, Iceland, Austria, Italy, Norway, Portugal, Belgium
GRACE 2016-2019	Focus on developing, comparing and evaluating the effectiveness and environmental impact of different oil-spill response methods in a cold climate. It is also developing a system for the real-time observation of underwater oil spills and a strategic tool for choosing oil-spill response methods. Coordinator: Suomen Ymparistokeskus, Finland Other countries: Denmark, Estonia, Germany, Spain, Norway, Greenland, Sweden, Canada
SEDNA 2017-2020	Develop an innovative and integrated risk-based approach to safe Arctic navigation, ship design and operation to enable European maritime interests to fully embrace the Arctic's significant and growing shipping opportunities while safeguarding its natural environment. Coordinator: BMT Group Ltd, United Kingdom Other countries: Sweden, Norway, Ireland, Finland, China

Project name	Themes and countries involved
ARCSAR 2018-2023	Monitor research and innovation projects and recommend the uptake and the industrialization of results, express common requirements as regards innovations that could fill in capability and other gaps and improve their performance in the future, and indicate priorities as regards common capabilities, or interfaces among capabilities, requiring more standardization. The project will look into the need for enhanced measures to respond to composite challenges including surveillance of and mobilization in case of threat situations, and emergency response capability related to search and rescue (SAR), environmental protection, firefighting, and actions against terror or other forms of destructive action. Coordinator: Hoverdredningssentralen, Norway Other countries: Iceland, Faroe islands, UK, USA, New Zealand, Germany, Finland, Ireland, Italy, Russia, Canada, Sweden
KEPLER 2019-2021	Multi-partner initiative, built around the operational European Ice Services and Copernicus information providers, to prepare a roadmap for Copernicus to deliver an improved European capacity for monitoring and forecasting the Polar Regions. Coordinator: Norwegian Meteorological Institute, Norway Other countries: Germany, Denmark, France, UK, Sweden, Finland, Spain

Annexes 4 | Societal Benefit Areas

Disaster Preparedness
Environmental Quality
Food Security
Fundamental Understanding of Arctic Systems
Human Health
Infrastructure and Operations
Marine and Coastal Ecosystems and Processes
Natural Resource
Resilient Communities
Sociocultural Services
Terrestrial and Freshwater Ecosystems and Processes
Weather and Climate

REFERENCES

References

Anthes, R. A., P. A. Bernhardt, Y. Chen, L. Cucurull, K. F. Dymond, D. Ector, S. B. Healy, et al. 2008. "The COSMIC/FORMOSAT-3 Mission: Early Results." *Bulletin of the American Meteorological Society* 89 (3): 313–34. https://doi.org/10.1175/BAMS-89-3-313.

Cardellach, E., C. O. Ao, M. de la Torre Juárez, and G. A. Hajj. 2004. "Carrier Phase Delay Altimetry with GPS-Reflection/Occultation Interferometry from Low Earth Orbiters." *Geophysical Research Letters* 31 (10): 4–7. https://doi.org/10.1029/2004GL019775.

Cardinali, C. 2009. "Monitoring the Observation Impact on the Short-Range Forecast." *Quarterly Journal of the Royal Meteorological Society* 135 (638): 239–50. https://doi.org/10.1002/qj.366.

Cartwright, J., C. J. Banks, and M. Srokosz. 2019. "Sea Ice Detection Using GNSS-R Data From TechDemoSat-1." *Journal of Geophysical Research: Oceans* 124 (8): 5801–10. https://doi.org/10.1029/2019JC015327.

Chew, C., R. Shah, C. Zuffada, G. Hajj, D. Masters, and A. J. Mannucci. 2016. "Demonstrating Soil Moisture Remote Sensing with Observations from the UK TechDemoSat-1 Satellite Mission." *Geophysical Research Letters* 43 (7): 3317–24. https://doi.org/10.1002/2016GL068189.

Claes, D. H., and A. Moe. 2014. *Arctic Petroleum Resources in a Regional and Global Perspective*. Edited by R Tamnes and K Offerdal. London: Geopolitics and Security in the Arctic: Regional Dynamics in a Global World.

Clarizia, M.-P., C. Ruf, P. Cipollini, and C. Zuffada. 2016. "First Spaceborne Observation of Sea Surface Height Using GPS-Reflectometry." *Geophysical Research Letters* 43 (2): 767–74. https://doi.org/10.1002/2015GL066624.

CNBC. 2019. "Russia Eyeing Arctic Future Launches Nuclear Icebreaker," 2019.

Davidson, M., et al. 2019. "Copernicus L-Band SAR Mission Requirements Document, Version 1.0." Noordwijk, The Netherlands.

Dee, D. P., S. M. Uppala, A. J. Simmons, P. Berrisford, P. Poli, S. Kobayashi, U. Andrae, et al. 2011. "The ERA-Interim Reanalysis: Configuration and Performance of the Data Assimilation System." *Quarterly Journal of the Royal Meteorological Society* 137 (656): 553–97. http://centaur.reading.ac.uk/24937/.

Devyatkin, P. 2018. "Russia's Arctic Strategy: Aimed at Conflict or Cooperation ?"

Dobricic, S., F. Monforti-Ferrario, L. Pozzoli, J. Wilson, A. Gambardella, and A. Tilche. 2018. "Impact Assessment Study on Societal Benefits of Arctic Observing Systems." https://doi.org/10.2760/713084.

Donlon, C.J. 2019. "Copernicus Imaging Microwave Radiometer (CIMR) Mission Requirements Document. Version 2.0; ESA-EOPSM-CIMR-MRD-3236." https://esamultimedia.esa.int/docs/EarthObservation/CIMR-MRD-v3.0-20190930_Issued.pdf.

Duchossois, G., P. Strobl, V. Toumazou, S. Antunes, A. Bartsch, T. Diehl, F. Dinessen, et al. 2018. "User Requirements for a Copernicus Polar Mission - Phase 2 Report." Luxembourg (Luxembourg): Publications Office of the European Union. https://doi.org/10.2760/44170.

European Commission. 2016a. "An Integrated European Union Policy for the Arctic," 1–17. http://www.eeas.europa.eu/arctic_region/docs/160427_joint-communication-an-integrated-european-union-policy-for-the-arctic_en.pdf.

European Commission. 2016b. "COM(2016) 705 Final, 26.10.2016."

European Commission. 2016c. "SAR/Galileo Service Definition Document."

European GNSS Agency. 2016. "EGNOS Open Service (OS) Service Definition Document."

European Political Strategy Centre, European Commmission. 2019. "Walking on Thin Ice : A Balanced Arctic Strategy for the EU."

European Union. 2016. "European GNSS (Galileo) Open Service Signal-in-Space Interface Control Document."

Everis. 2018. "Impact Assessment Study on Societal Benefits of Arctic Observing Systems. Final Report."

Foti, G., C. Gommenginger, P. Jales, M. Unwin, A. Shaw, C. Robertson, and J. Roselló. 2015. "Spaceborne GNSS Reflectometry for Ocean Winds: First Results from the UK TechDemoSat-1 Mission." *Geophysical Research Letters* 42 (13): 5435–41. https://doi.org/10.1002/2015GL064204.

Government of Canada. 2010. "Statement on Canada ' S Arctic." http://www.arctic-council.org/index.php/en/document-archive/category/12-arctic-strategies#.

IDA-STPI and SAON. 2017. *International Arctic Observations Assessment Framework. IDA Science and*

Technology Policy Institute, Washington, DC, USA, and Sustaining Arctic Observing Networks. Oslo, Norway.

Kern, M. 2019. "Copernicus PolaR Ice and Snow Topography Altimeter (CRISTAL) Mission Requirements Document, Version 2.0." Noordwijk, The Netherlands. http://esamultimedia.esa.int/docs/EarthObservation/Copernicus_CRISTAL_MRD_v2.0_Issued_20190228.pdf.

Ministry of External Affairs, Government of India. 2013. "India and the Arctic."

Polar View Earth Observation Limited. 2016. "User Needs and High-Level Requirements for the next Generation of Observing Systems for the Polar Regions."

Poli, P, S B Healy, and D P Dee. 2010. "Assimilation of Global Positioning System Radio Occultation Data in the ECMWF ERA–Interim Reanalysis." *Quarterly Journal of the Royal Meteorological Society* 136 (653): 1972–90. https://doi.org/10.1002/qj.722.

Pompeo, M. 2019. "Remarks at the Arctic Council Ministerial Meeting."

Pörtner, H.-O., D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, et al. 2019. "IPCC, 2019: Summary for Policymakers. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate."

Ruf, C. S, and R. Balasubramaniam. 2018. "Development of the CYGNSS Geophysical Model Function for Wind Speed." *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing* 12 (1): 66–77. https://doi.org/10.1109/JSTARS.2018.2833075.

Simmons, A. J., and P. Poli. 2015. "Arctic Warming in ERA-Interim and Other Analyses." *Quarterly Journal of the Royal Meteorological Society* 141 (689): 1147–62. https://doi.org/10.1002/qj.2422.

Telecommunications Infrastructure Working Group. 2016. "Arctic Broadband. Recommendations for an Interconnected Arctic."

The Moscow Times. 2018. "Russia Will Restrict Foreign Warships in Arctic Ocean," 2018.

Toudal Pedersen, L., G. Dybkjær, S. Eastwood, G. Heygster, N. Ivanova, S. Kern, T. Lavergne, et al. 2017. "ESA Sea Ice Climate Change Initiative (Sea_Ice_cci): Sea Ice Concentration Climate Data Record from the AMSR-E and AMSR-2 Instruments at 25km Grid Spacing, Version 2.1." *Centre for Environmental Data Analysis, 05 October 2017*.

United Nations. 2019. *The Sustainable Development Goals Report 2019*. https://doi.org/https://doi.org/https://doi.org/10.18356/55eb9109-en.

View, Polar, Earth Observation, Electron Building, Fermi Avenue, Harwell Oxford, and United Kingdom. 2018. "Environmental Scan on User Needs Assessment for the International Arctic Spatial Data Infrastructure," no. March.

Working Group C-ARAIM Technical Subgroup. 2016. "Milestone 3 Report."

LIST OF ABBREVIATIONS

List of abbreviations

ADS-B	Automatic Dependent Surveillance-Broadcast
Arctic ROOS	Arctic Regional Ocean Observing System
AIS	Automatic Identification System
BRI	Belt and Road initiative
CIMR	Copernicus Imaging Microwave Radiometry mission
CLS	Collecte Localisation Satellites
CME	Coronal Mass Ejection
CRISTAL	Copernicus polaR Ice and Snow Topography Altimeter
CSM	COSMO-SkyMed Constellation of Small Satellites for Mediterranean basin Observation
DIAS	Data and Information Access Services
ECMWF	European Centre for Medium-Range Weather Forecasts
ECV	Essential Climate Variables
EDRS	European Data Relay Satellite System
EGNOS	European Geostationary Navigation Overlay System
EGNSS	European Global Navigation Satellite Systems
EISCAT	European Incoherent Scatter Scientific Association
EMSA CSN	European Maritime Safety Agency Clean Sea Net
EO	Earth Observation
ESA	European Space Agency
EU	European Union
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
GEO	Geostationary Orbit
GEOSAR	Geostationary Search And Rescue Systems
GHG	Greenhouse Gas
GIM	Global Ionospheric Maps
GNSS	Global Navigation Satellite Systems
GNSS-R	Global Navigation Satellite Systems Reflectometry
GNSS-RO	Global Navigation Satellite Systems Radio Occultation
HEO	Highly Elliptical Orbit
ICAO	International Civil Aviation Organization
IL	Intervention Logic
IO	Integrated Operations
KPSO	Key Products, Services and Outcomes
LEO	Low Earth Orbit
LEOSAR	Low Earth Orbit Search And Rescue Systems
LPV	Localizer Performance with Vertical Guidance
MEO	Medium Earth Orbit
MERLIN	Methane Remote Sensing Mission
OS	Open Service
RO	Radio Occultation
ROSE-L	L-band synthetic aperture Radar Observing System for Europe
SaR	Search and Rescue
SAR	Synthetic Aperture Radar
SARP	Standard and Recommended Practices
SatCom	Satellite Communications
SBA	Societal Benefits Areas

SIOS	Svalbard Integrated Arctic Earth Observing Systems
SoL	Safety Of Life
SMOS	Soil Moisture and Ocean Salinity mission
SSA	Space Situational Awareness
SST	Sea Surface Temperature
TEC	Total Electron Content
TEP	Thematic Exploitation Platform
TSX	TerraSar-X
VDES	VHF Data Exchange Format
VTA	Value Tree Analysis
WMO	World Meteorological Organization

GETTING IN TOUCH WITH THE EU

In person

All over the European Union there are hundreds of Europe Direct information centres. You can find the address of the centre nearest you at: https://europa.eu/european-union/contact_en

On the phone or by email

Europe Direct is a service that answers your questions about the European Union. You can contact this service:

– by freephone: 00 800 6 7 8 9 10 11 (certain operators may charge for these calls),

– at the following standard number: +32 22999696, or

– by electronic mail via: https://europa.eu/european-union/contact_en

FINDING INFORMATION ABOUT THE EU

Online

Information about the European Union in all the official languages of the EU is available on the Europa website at: https://europa.eu/european-union/index_en

EU publications

You can download or order free and priced EU publications from EU Bookshop at: https://publications.europa.eu/en/publications.

Multiple copies of free publications may be obtained by contacting Europe Direct or your local information centre (see https://europa.eu/european-union/contact_en).

KJ-NA-30162-EN-N

The European Commission's science and knowledge service

Joint Research Centre

JRC Mission

As the science and knowledge service of the European Commission, the Joint Research Centre's mission is to support EU policies with independent evidence throughout the whole policy cycle.

EU Science Hub
ec.europa.eu/jrc

@EU_ScienceHub

EU Science Hub - Joint Research Centre

Joint Research Centre

EU Science Hub

Publications Office
of the European Union

doi:10.2760/43511

ISBN 978-92-76-17847-7