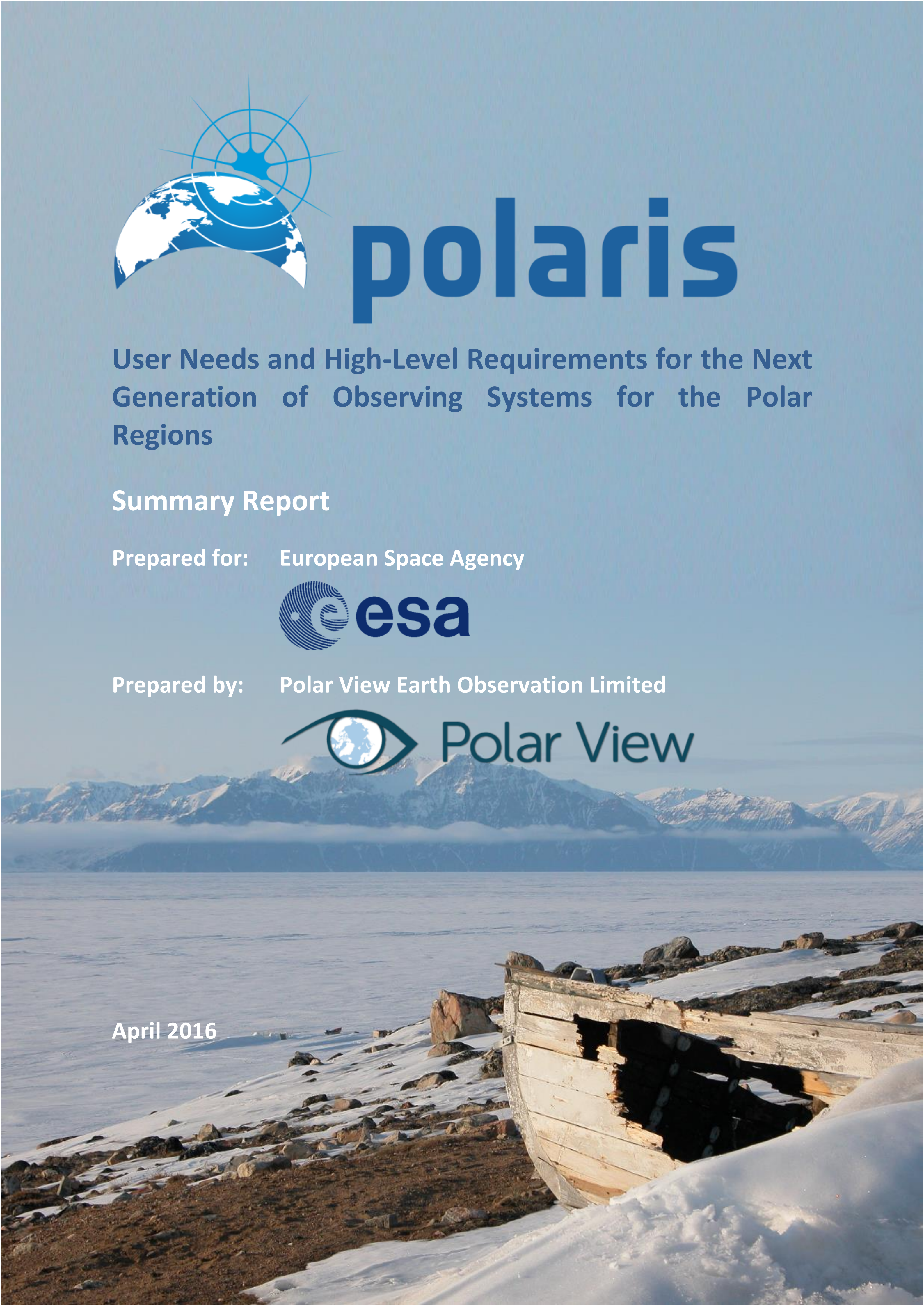

polaris

User Needs and High-Level Requirements for the Next Generation of Observing Systems for the Polar Regions

Summary Report

Prepared for: European Space Agency

Prepared by: Polar View Earth Observation Limited

April 2016

EXECUTIVE SUMMARY

The attention of the European Space Agency (ESA) member states, the European Union (EU), and indeed the world, is increasingly turning to the polar regions for a variety of reasons, including the opportunities for economic development, concerns about the impact of climate change, and the geo-political strategic importance of the regions, especially the Arctic.

Environmental information about the polar regions is required to support a broad range of scientific and operational activities. Researchers are involved in a host of studies on changes taking place across many domains, including climate, oceans, atmosphere, and ecosystems, which have significant impacts in the regions and through complex earth system connections worldwide. The drivers include both national and international science policies, strategies and programmes that contribute to an understanding of the changes taking place and shape policy responses. Operations in the polar regions take place in some of the most difficult conditions on Earth. Those involved in these operations, such as shipping and fisheries companies, offshore oil and gas operators, research organizations, and coast guards, require access to reliable and often near real-time information to plan and undertake their activities. Drivers of information requirements include a range of regulations, standards, and policies (such as the new Polar Code[1]) aimed at ensuring safety of life and mitigating negative environmental impacts.

Given the remote and inhospitable nature of the vast polar regions, earth observation and other space-based technologies can provide information that is detailed, comprehensive, cost effective, and not available from any other source. This information can support monitoring and analysis of issues relating to the environment, safety, and sustainable development.

The objective of the ESA Polaris Initiative is to respond to the evolving demands for space-based monitoring of the polar regions by:

- Developing the next generation of space infrastructure and exploring new sensors, orbital parameters, constellations and integrated platforms.
- Developing novel concepts for integrated information services.
- Reaching out to new user communities, and developing new partnerships and joint initiatives.

This study is the first of a number of activities planned as part of the Polaris Initiative. It has reviewed user requirements for polar environmental information, considered current and proposed sources of such information from space-based and in-situ sensors, evaluated the information gaps and the impact of filling those gaps with new integrated products and services, and provided a preliminary discussion of the considerations that will shape new satellite missions to fill the gaps.

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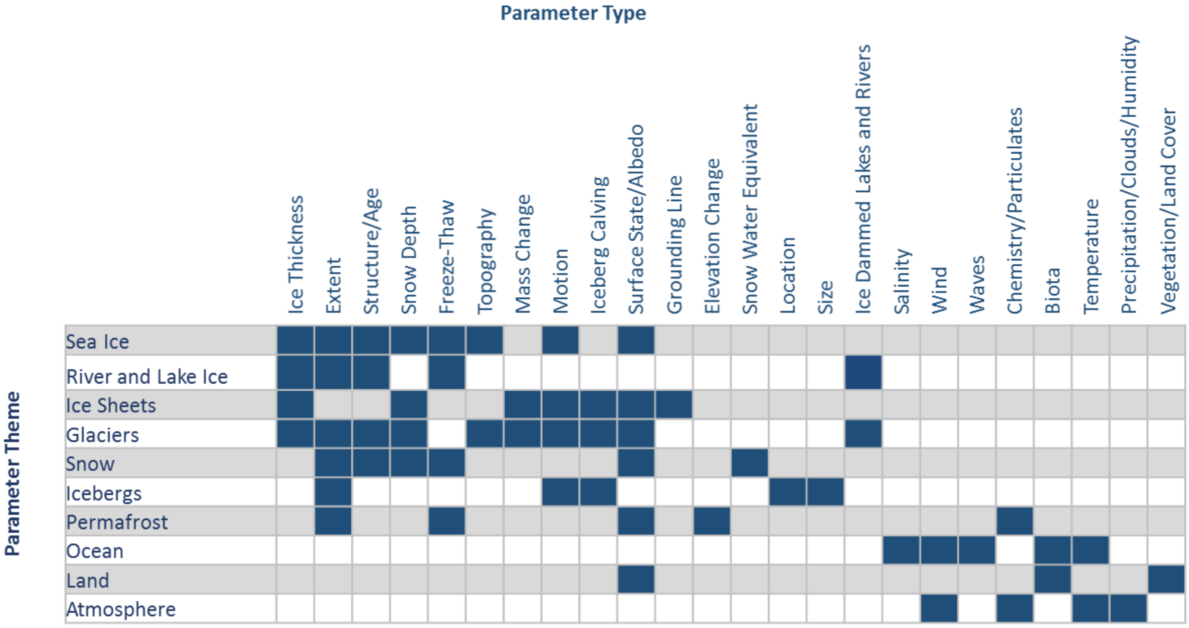
[1] To help address the risks of operating in the polar regions, the International Maritime Organization (IMO) Marine Environment Protection Committee approved the “Draft International Code for Ships Operating in Polar Waters” (known as the Polar Code) on 21 January, 2015. It will take effect on 1 January, 2017.

The study findings are based on a literature review, a review of polar data web portals, stakeholder consultations, and a stakeholder workshop. At each step in the process, the project team's work was reviewed by a steering committee of expert advisors that were chosen to reflect the interests of different polar information communities.

The study reviewed over 250 information parameters that are used by the polar stakeholder communities. While most of these are adequately provided by current space-based and in-situ sensor networks, a number of important parameters have deficiencies in availability, technical capability, or the services that provide the information.

Polar information users also identified a number of anticipated changes in their future information requirements. For example, the activity of government vessels for icebreaking, fisheries surveillance, and search and rescue operations will grow as shipping and tourism traffic increases and the operational season extends. The commercial fisheries are migrating further north and south, with extended seasons in ice-infested waters. As ship traffic continues to grow, there are also expectations that responses to emergency situations (e.g. grounded vessels, oil and chemical spills) will increase in frequency.

The following table summarizes the gaps in existing information products and services derived from EO sensors. The gaps are broken down by parameter theme (along the left of the table) and parameter type (across the top of the table). Highlighted cells show where there is a shortcoming in the existing information.



Parameter Type

Parameter Theme	Ice Thickness	Extent	Structure/Age	Snow Depth	Freeze-Thaw	Topography	Mass Change	Motion	Iceberg Calving	Surface State/Albedo	Grounding Line	Elevation Change	Snow Water Equivalent	Location	Size	Ice Dammed Lakes and Rivers	Salinity	Wind	Waves	Chemistry/Particulates	Biota	Temperature	Precipitation/Clouds/Humidity	Vegetation/Land Cover
Sea Ice	■	■	■	■	■	■		■		■														
River and Lake Ice	■	■	■		■											■								
Ice Sheets	■			■			■	■	■	■	■													
Glaciers	■	■	■	■		■	■	■	■	■						■								
Snow		■	■	■	■					■			■											
Icebergs		■						■	■					■	■									
Permafrost		■			■					■		■								■				
Ocean																	■	■	■		■	■		
Land										■											■			■
Atmosphere																		■		■		■	■	

Information deficiencies can be addressed in two ways: i) by providing more capable earth observation technology (mission capabilities), and/or ii) by improving how well the overall information acquisition and delivery systems work (system capabilities).

The study examined seven main mission capabilities that were chosen to fill existing and future information deficiencies:

- Dual and Tri-Band Synthetic Aperture Radar (SAR) – Two or more SAR frequencies, if measured co-temporally, can be used to differentiate the boundary layers in snow and ice, providing significantly more information than can a single frequency by itself.
- InSAR – SAR interferometry achieved using a SAR satellite with a passive companion (bistatic SAR) can allow precise measurement of surface elevations and motion.
- Automatic Identification System (AIS) with SAR – AIS can help in differentiating between icebergs and ships in SAR imagery.
- Next-Generation Altimeter – There are a number of approaches to measuring topography, for example: passive Global Navigation Satellite System (GNSS) reflections receiver, stereo optical sensor, or SAR Interferometer Radar Altimeter (as in Cryosat).
- LEO Optical – Optical sensors in Low Earth Orbit (LEO), particularly multi-spectral[2] covering a range of frequencies, are of value for monitoring land use and vegetation. However, the use of optical sensors is constrained in the polar regions by the amount of cloud cover and darkness in the winter months.
- HEO Optical – An optical instrument in a highly elliptical orbit (HEO) can monitor the high latitudes not accessible to current geosynchronous weather satellites.

In addition, a gravity change mission was considered and discussed. This type of mission provides an integrated measurement of ice mass loss of ice sheets and larger ice caps, thus providing a direct estimate of sea level rise of global significance. Since gravity change missions are global in scope and not particularly aimed at the poles, albeit extremely useful for polar monitoring, this type of mission is not detailed in this report. Gravity missions in preparation or proposed include US and Chinese missions and the proposed ESA Next Generation Gravity Mission.

These mission capabilities were evaluated for contribution to each of five impact categories:

- Economy – increase in economic activity or decrease in operating costs.
- Safety – reduction in risk to life or property.
- Environment – protection of the environment and mitigation of the environmental impacts of human activity.
- Society – benefits to local, Indigenous, and other peoples in their quality of life and other considerations not captured elsewhere.
- Knowledge – increase in the understanding of natural processes.

In general, economic, safety, environmental and societal impacts come from operational uses, while knowledge impacts come from science uses. The relative potential impact of each mission capability for each impact category was assessed on a scale of 0 (no impact) to 5 (significant impact) by the project team. The degree of impact is a product of the breadth

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[2] Here, the use of the term ‘multi-spectral’ includes ‘hyper-spectral’.

of the impact (for example, the number of people impacted) and the magnitude of the impact (for example, how important the impact is to each person). The result of that exercise is shown in the following table:

Mission Capability	Economy	Safety	Environment	Society	Knowledge	Overall
Dual SAR	4.3	4.3	4.4	4.4	4.1	4.3
Tri SAR	5.0	5.0	5.0	5.0	5.0	5.0
InSAR	3.0	3.2	3.0	2.7	3.3	3.1
LEO Optical	3.7	3.1	4.3	3.6	3.8	3.7
Next Generation Altimeter	1.8	1.9	1.8	1.5	2.3	1.9
HEO Optical	1.4	1.0	1.7	1.4	1.1	1.3
AIS	0.1	0.1	0.1	0.1	0.0	0.1

Not surprisingly, a large number of polar user communities are interested in variations of frozen water (sea ice, river and lake ice, glaciers and ice sheets, icebergs, and snow). Because of the ability of SAR sensors to see through cloud and in darkness (both of which are common at high latitudes), and their ability to penetrate ice and snow to see below the surface, SAR is the best sensor for monitoring polar frozen water. Different SAR frequencies reveal different information, and therefore there are benefits to having more frequencies available. As a result, this analysis has found tri-frequency SAR to have the greatest impact of the mission capabilities examined, followed by dual-frequency SAR.

For observing things other than frozen water, optical sensors are superior to SAR, although they are obstructed by darkness and cloud. The results show multi-spectral optical to have its greatest impact in environmental applications involving monitoring of the atmosphere, land cover, vegetation, and ocean colour. The impact of multi-spectral optical was found to be below SAR, but above the other mission capabilities examined.

The ability to determine surface topography is important in a number of application areas. Although such information can be acquired in a number of ways, interferometric SAR offers the best combination of vertical resolution and wide-area coverage compared to alternative altimeter options.

However, even with excellent sensors in space, the data still needs to be appropriately processed, analyzed, and made available to polar stakeholders. The following points examine feedback from the polar community as to steps that can be taken to improve gaps in the overall information system for polar data:

- **Data Integration** – Non-specialist users want customized information developed by professionals who have the expertise to integrate data in the way that best meets user needs. Data has more value if it can be easily integrated with other data from multiple sources and of multiple types – time series, other parameters, other regions, other sensors, etc. Data integration is facilitated by data formats and access that adheres to recognized standards. The ESA Climate Change Initiative is a good example of such tailored data products for the climate modeling community.
- **Information Products** – Many end users are not in a position to work directly with earth observation data. Rather, they need information products and services that

provide the processed data in accessible formats. This is especially true for the inhabitants in the Arctic as they pursue their daily life in outdoor activities such as transportation, fishing and hunting.

- **Information Discovery** – Polar information is currently spread among a large number of sites and organisations. Better tools are needed to help discover this data, especially by non-specialists. Access to good metadata is an important component of the discovery process. Information on data quality and uncertainty needs to be part of the metadata.
- **Information Access** – Accessing information needs to be easy. Cost is a significant barrier to data access and use for many groups, as are bandwidth limitations faced by most northern communities and vessels.
- **Training** – Users need to be educated in how to use data properly so that it is not misinterpreted or used inappropriately, and to identify which information is applicable to their needs.
- **Data Platforms** – The solution to many of the identified gaps could be achieved through good data platforms that would store polar information and provide tools for information integration, discovery, access, and training. These platforms should use open web services that can be used by value-added partners in the development of applications and systems. They should provide processing capacity so that users do not need to download large volumes of EO data, but can instead manipulate the data ‘in the cloud’.

The choice of which missions to pursue will depend upon the potential impacts, analyzed in this study, but also critically on its costs. The mission design considerations and costs are being examined in a parallel study: “Future Mission Concepts for Polar Regions”.

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1.1 BACKGROUND

The objective of the Polaris Initiative is to respond to the evolving demands for space-based monitoring of the polar regions by:

- Developing the next generation of space infrastructure and exploring new sensors, orbital parameters, constellations and integrated platforms.
- Developing novel concepts for integrated information services.
- Reaching out to new user communities, and developing new partnerships and joint initiatives.

The Polaris Initiative is motivated by the rapidly increasing interest in the polar regions and the need to provide integrated information to support the research and operations of a growing range of user communities, including science, industry, government, and northern communities. As illustrated in Figure 1, a number of political, environmental, social, and technological trends are fueling this interest and activity in the polar regions, including:

Figure 1: Polar Trends

- Political and Policy Trends – The interest of governments around the world in the polar regions is driven by the perceived opportunities for economic development, more efficient shipping routes, and the regions' geo-political strategic and sovereignty importance. With these opportunities come concerns over their environmental impact and risks to life and property in a hostile environment where governments have a duty to mitigate through emergency response and search and rescue operations. The opportunities are also motivating countries to try to expand their jurisdictions and to better protect their borders.
- Economic Trends – Economic development opportunities include development of renewable resources such as fisheries and forests; non-renewable resources such as fossil energy resources and minerals; and other activities such as shipping and tourism. Closely associated with these opportunities is the need for related infrastructure development, such as offshore platforms, ice class ships, pipelines, railways, roads, sea ports, airports, and housing. There is also the potential for increased pollution and environmental accidents.
- Social and Cultural Trends – Concern about the impact of climate change is growing around the world and it is becoming evident that the impact is greatest in the polar regions. Of particular social relevance in the Arctic are the changes that are being imposed on Indigenous Peoples by climate change and increased economic activity. Such changes include impacts on hunting and fishing practices, impacts on infrastructure caused by coastal erosion and the melting of permafrost, impacts from

glacier and ice sheet melts (e.g. on hydropower and fjord changes), and impacts on culture and social cohesion.
- Technological Trends – The space technologies of most relevance in the polar regions are earth observation, telecommunications, global navigation satellite systems (GNSS), and automatic identification systems (AIS). Each has a role to play in monitoring the vast and harsh polar regions and each is undergoing significant improvements in capabilities.

1.2 OVERVIEW

This study is the first of a number of activities planned as part of the Polaris Initiative. The results of this study will help in the development of new space mission concepts for the polar regions that address evolving scientific and operational information needs. Three other technical reports support this summary document:

- The *Environmental Information Requirements Report* identifies, reviews, and consolidates user community environmental information requirements for the polar regions.
- The *Gaps and Impact Analysis Report* identifies information gaps considering existing and planned earth observation (EO) and integrated (navigation/ telecommunications/ surveillance) satellite systems, and terrestrial in-situ monitoring systems.
- The *Preliminary Observation Requirements Report* establishes a set of high-level mission requirements reflecting the identified information gaps and performs a preliminary assessment of the high-level operations requirements for supplying future integrated services[3].

The study findings are based on four lines of enquiry: a literature review, a review of polar data web portals, stakeholder consultations, and a stakeholder workshop. The study team reviewed approximately 150 reference documents and web resources on user needs and drivers of environmental information requirements in the polar regions. Telephone interviews were conducted with representatives of over 50 polar organizations (see Appendix 3). The information collected from the literature review and consultations was consolidated and discussed during a workshop attended by 20 polar stakeholder representatives. At each step in the process, the project team's work was reviewed by a steering committee of expert advisors that were chosen to reflect the interests of different polar information communities (see Appendix 2).

The following chapter looks at user requirements for polar environmental information. Chapter 3 then examines current information sources for EO-based information, other space-based information, non-space information, and the integration of information sources. Chapter 4 considers the gaps in the current information and Chapter 5 evaluates the impacts

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[3] An integrated service takes information from an earth observation data source, combines it with data from other sources as required, and processes and interprets the combined data to produce an information product that is of value to a user community.

of filling those gaps with new integrated products and services. Finally, Chapter 6 provides a preliminary discussion of the considerations that will shape new satellite missions to fill the gaps.

2 USER REQUIREMENTS FOR ENVIRONMENTAL INFORMATION

The requirements for environmental information in the polar regions are being driven by a broad range of scientific, operational, and societal imperatives. Researchers are involved in a host of studies on changes taking place across many domains, including climate, oceans, atmosphere, and ecosystems, which have significant impacts in the regions and, through complex earth system connections, worldwide. The drivers include both national and international science policies, strategies and programmes that contribute to an understanding of the changes taking place in the polar regions and shape policy responses. Examples of polar science activities are contained in Table 1.

Operations in the polar regions take place in some of the most difficult conditions on Earth. Those involved in these operations, such as shipping and fisheries companies, offshore oil and gas operators, research organizations, coast guards, and local communities, require access to reliable and often near real-time information to plan and undertake their activities. Drivers of information requirements include a range of regulations, standards, and policies (such as the new Polar Code[4]) aimed at ensuring safety of life and mitigating negative environmental impacts. Examples of polar operational activities are contained in Table 2.

The current information needs cover a broad spectrum of environmental parameters, with more than 250 different environmental parameters being of interest to the science and operations user communities working in the polar regions – a significant number of which are of common interest to the majority of users in both communities.

Table 1: Examples of Polar Scientific Activities that Drive Information Requirements

Theme	Examples of Types of Activities
Atmosphere, Climate and Weather Change Research	▪ Research on how interactions between the atmosphere, ocean and ice control the rate of climate change ▪ Increasing knowledge of how lake ice cover affects energy and water budgets to improve ability to forecast northern weather ▪ Research on landfast sea ice distribution as a sensitive indicator of climate variability and change, especially in Antarctica
Land Surface and Use Change Research	▪ Research on structural and functional characteristics of land use systems to manage sustainably food, water and energy supplies ▪ Research on the impacts of human activities on the land in the Arctic
Ocean State and Coastal Zone Change Research	▪ Study of the role of the ocean in the stability of the Antarctic and Greenland ice sheets and its contribution to sea-level rise ▪ Monitoring and understanding extremes such as coastal sea level surges and ocean waves ▪ Study of how the melting of landfast sea ice and advancing permafrost

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[4] To help address the risks of operating in the polar regions, the International Maritime Organization (IMO) Marine Environment Protection Committee approved the "Draft International Code for Ships Operating in Polar Waters" (known as the Polar Code) on 21 January, 2015. It will take effect on 1 January, 2017.

	thawing is causing increasing coastal erosion that is impacting coastal infrastructure and local populations
Ecosystem and Organism Change Research	▪ Understanding the impact on ecosystems of reduced sea ice thickness and extent ▪ Research on how the thawing of permafrost is affecting wetlands and food security ▪ Research on how the reduction of ice cover on rivers and lakes is affecting animal and plant communities and subsistence activities
Sea Ice Change Research	▪ Research on the nature of changes in sea ice distribution and mass balance in response to climate change and variability ▪ Improving understanding of the impacts of a changing sea ice regime on coastal stability and communities ▪ Improving understanding of how a thinner and weaker ice cover responds to wind and precipitation
River and Lake Ice Change Research	▪ Research on the influence of river and lake ice on atmospheric circulation and composition ▪ Understanding hydrological processes involved in ice-jam break-up and flooding
Snow Change Research	▪ Understanding the role snow cover plays in the climatological, hydrological, ecological, and socio-economic systems of the polar regions ▪ Establishing the variability of snow regimes, and the trends over space and time
Ice Sheet and Glacier Change Research	▪ Establishing the net mass loss or gain from ice sheets and glaciers, and their contribution to sea level rise ▪ Predicting the impact of glacier retreat on water supplies for drinking water, irrigation, hydropower and industrial uses
Permafrost Change Research	▪ Research on the impact of rising temperatures on the extent and depth of permafrost ▪ Understanding the impact of the loss of permafrost on infrastructure, ecosystems, climate, and people

Table 2: Examples of Polar Operational Activities that Drive Information Requirements

Theme	Examples of Types of Activities
Environmental Impact Assessment	▪ Supporting the responsible development of major infrastructure or resource development projects ▪ Assessing and mitigating the operation of such projects
Engineering Design	▪ Design of buildings and structures for installation in changing permafrost conditions ▪ Design of offshore drilling and production platforms for safe and effective deployment in ice-covered waters
Safe Navigation and Operations	▪ Navigation of vessels through hazardous ice-covered waters ▪ Avoiding collisions with icebergs in operation of offshore oil and gas exploration and production platforms ▪ Navigation to and along the sea ice edge for traditional hunting and fishing
Risk Management	▪ Assessing the risks of subsidence around buildings, pipelines and structures in permafrost areas ▪ Assessing and mitigating the risks of flooding due to ice-jammed rivers
Emergency Response	▪ Developing and maintaining a common operating picture (COP) between response organizations ▪ Expeditious movement of responders and their equipment from bases of operation to the emergency site
Weather Forecasting	▪ Observing and modelling weather patterns to improve short-term weather predictions in support of operations in the polar regions
Climate Change Adaptation	▪ Establishing new regulations and standards, investing in new infrastructure, and enhancing operational capabilities in reaction to changes in the polar climate and its impact on southern latitudes

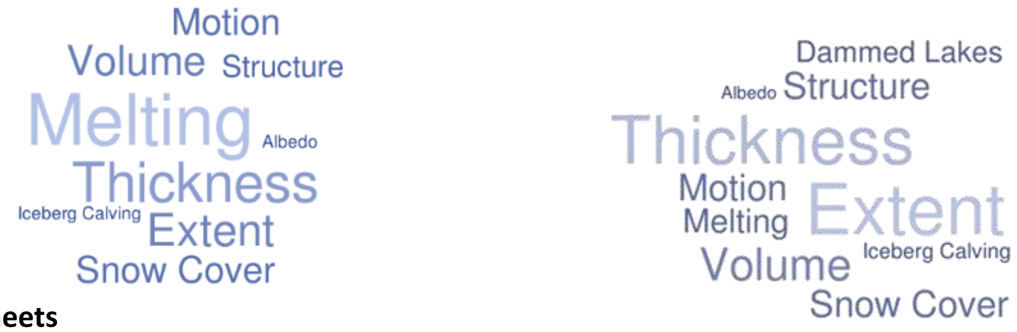
2.1 CURRENT INFORMATION REQUIREMENTS

To demonstrate the range of requirements and the importance of specific information parameters, Figure 2 illustrates (by size of the word) the relative frequency with which the key parameters in each of the major categories of environmental information were referenced in the study research. The analysis highlights that many of the parameters are common across multiple categories.

Figure 2: Key Parameter Frequency

Sea Ice

River and Lake Ice



Ice Sheets

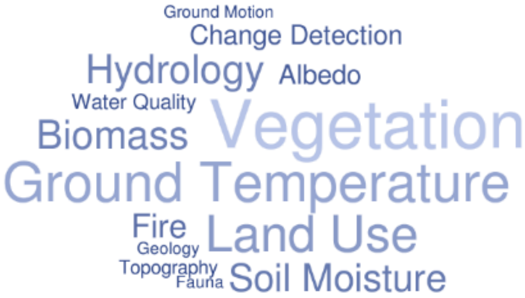
Glaciers

Icebergs

Snow

Permafrost

Oceans



Land

Atmosphere

2.2 FUTURE INFORMATION REQUIREMENTS

Polar information users identified a number of anticipated changes in their future information requirements. There is a universal expectation of increased demand for environmental information in the polar regions, driven by multiple pressures. The activity of government vessels for icebreaking, fisheries surveillance, and search and rescue operations will grow as shipping and tourism traffic increases and the operational season extends. The commercial fisheries are migrating further north and south, with extended seasons in ice-infested waters[5].

The Fishing Vessel Saputi Lists after being Holed by Ice (Ludvig Siegstad)

Ship-based tourism is also increasing. The International Association of Antarctica Tour Operators reports that the number of ship-borne tourists increased by 430 percent between 1993 and 2007 and of land-based tourists by 757 percent from 1997 to 2007[6]. As ship traffic

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[5] For example, the fishing vessel Saputi was recently holed by ice off Nuuk, Greenland, and required assistance by Canadian and Danish rescue resources. See: http://www.thetelegram.com/News/Local/2016-02-24/article-4446451/MV-Saputi-makes-it-safely-to-Greenland/1

[6] GRID-Arendal. (2008). Tourism in the Polar Regions. Retrieved 08 12, 2015, from http://www.grida.no/publications/tourism-polar/page/1421.aspx

continues to grow, there are also expectations that responses to emergency situations (e.g. grounded vessels, oil and chemical spills) will increase in frequency. Overall, despite significant year-to-year variability, activity in the polar regions is on a growth trajectory.

Near real-time applications, requiring more frequent satellite imaging for production of ice and iceberg information services, are expected to increase to support higher levels of shipping traffic and fisheries resource management.

An important driver of the future demand for information will be the new Polar Code, which comes into effect in 2017. Among other things, the Polar Code specifies a range of information that ships travelling in polar waters will be required to access for planning and operations. The information is to be used for:

- Risk analysis and determination of safe operating regions,
- Application of operating procedures and risk mitigation,
- Determination of permissible areas for garbage disposal and sewage discharge,
- Avoidance of marine mammals, protected areas, and culturally sensitive areas, and
- Emergency planning for places of refuge, fuel depots, and search and rescue.

Finally, demands for simultaneous collection of different types of data and for integration of data collected by satellite, airborne and in-situ sensors are expected to grow, in particular to provide answers to some of the most complex scientific questions in the polar regions that require data integration.

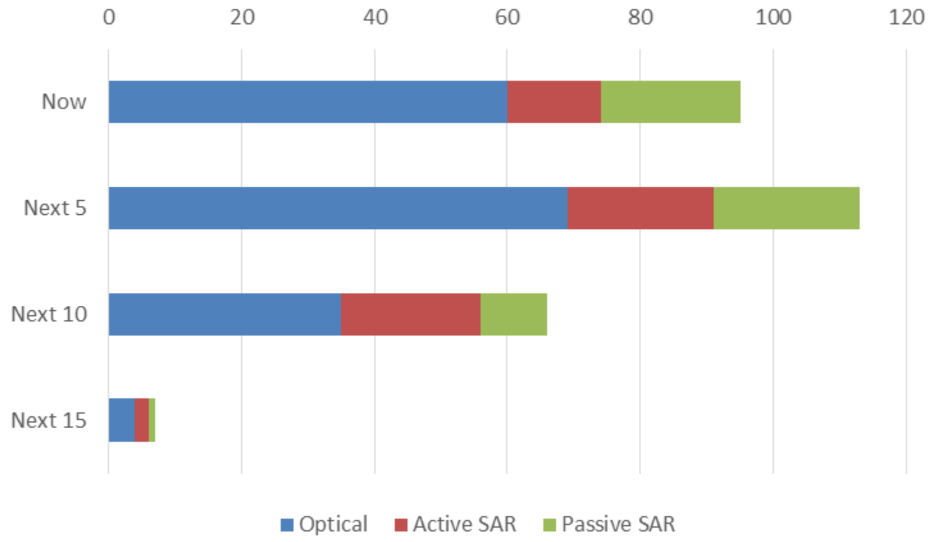
3 CURRENT INFORMATION SOURCES

While some of the user requirements for environmental information in the polar regions can be addressed with products and services based on EO data, assimilation of EO with other space and non-space data is often necessary to fully address needs. This chapter discusses the availability of EO, other space and non-space data, and the importance of data integration to meet the information requirements of users.

3.1 EO-BASED INFORMATION PRODUCT SOURCES

Numerous EO missions currently exist or are planned. Figure 3 shows the number of current and planned EO missions over the next 15 years, broken down by the type of sensor: optical, active SAR, and passive SAR.

Figure 3: Current and Planned EO Missions



The majority of sensors covering the polar regions (63 percent) are optical, while the sensors of most importance to cryospheric parameters (active and passive SAR) are in the minority. This is not surprising, since there are widespread optical sensor applications outside the regions that drive most of the demand for these sensors. Data continuity is a concern for all sensor types beyond 10 years, highlighting the importance of long-term mission planning and execution.

Users in the polar regions can discover and access relevant EO-based information products that match many of their requirements at a range of portals and information services on the web. Unmet requirements tend to result from deficiencies in the available EO-based products due to the lack of integrated services or inadequate spatial resolution, temporal resolution or integration of EO with other data, as discussed in Chapter 4.

3.2 OTHER SPACE INFORMATION SOURCES

Space-based systems that are of value for integration with EO data include: global navigation satellite systems (GNSS) and their associated satellite-based augmentation systems, satellite automatic identification systems (S-AIS), and satellite telecommunication systems.

Use of GNSS has become ubiquitous, with receivers built into cars, vessels, airplanes, cell phones and other mobile devices, emergency locators, and a large variety of in-situ sensors that provide earth measurements and associated geolocation. GNSS has recognized limitations in higher latitudes (e.g. inadequate augmentation coverage and ionospheric disturbances that reduce positioning and navigation accuracies). Despite these limitations, GNSS is an integral part of most scientific, operational, and community activities in the polar regions.

AIS was conceived mainly as a collision avoidance system and is based on the transmission of messages containing information about a ship's identity, position, speed and course. Placing an AIS receiver on a satellite is a means of addressing wide area surveillance requirements and in recent years, a number of government and commercial entities have deployed AIS receivers in this way. Combining AIS data with EO data can enhance surveillance capabilities and help in differentiating ships from icebergs.

Robust, accessible and cost-effective telecommunications is essential to access EO-based information and services when operating in the polar regions. However, geo-stationary satellite-based telecommunication systems do not operate reliably in regions at greater than 75° north or south, and current low earth orbit systems have limited capacity and low data rates. Several initiatives are proposed that could facilitate better and more cost-effective telecommunications solutions in the polar regions. These solutions utilize either satellite constellations, for example, Iridium NEXT and Thor 7, or highly elliptical orbits, for example the Polar Communications and Weather (PCW) satellite.

3.3 NON-SPACE INFORMATION SOURCES

The spatial and temporal resolutions of atmospheric, land, ocean and other in-situ sensors may fill information needs that cannot be met by space-borne EO systems. Data from in-situ sensors can be used for geospatial ground-truthing and rectification, model calibration, research on environmental and social processes, and supporting regulatory compliance.

While space-borne remote sensing data collection programs are typically well documented and have accessible, long-term data archiving and dissemination mechanisms in place, this is often not the case for in-situ sensors, with many sensors being deployed for specific, time-limited scientific or operational purposes. What currently exists is a partial network that includes key initiatives at a number of geographical and organizational scales, including international, regional and national. Examples of initiatives include:

- International level: Global Biodiversity Information Facility, Global Cryosphere Watch, International Council for the Exploration of the Sea, and World Climate Research Programme;

- Regional level: Sustaining Arctic Observing Networks, International Network for Terrestrial Research and Monitoring in the Arctic, AMAP Trends and Effects Monitoring Programme, Circumpolar Biodiversity Monitoring Program and Southern Ocean Observing System;
- National and local levels: Polar Portal (Denmark, including data from the national Greenland ice sheet monitoring programme), Alaska Ocean Observing System, and Norwegian Polar Institute

Although an integrated polar in-situ sensor system does not yet exist, significant effort has been made over the past decade towards developing a sustained, global in-situ observing system in both polar regions. In the Arctic, for example, efforts are being coordinated by the Arctic Monitoring and Assessment Programme, Conservation of Arctic Flora and Fauna, the International Arctic Science Committee (IASC) and the Sustaining Arctic Observing Networks (SAON) program, and in the Antarctic by bodies such as the Standing Committee on Antarctic Research (SCAR) and the Southern Ocean Observing System (SOOS).

3.4 INTEGRATED PRODUCTS AND SERVICES

New integrated information products and services can be developed that combine data from various EO sensors with data from the global navigation satellite system (GNSS), the space-based automatic identification system (S-AIS) that transmits ships' positions and identification, and a wide array of ground, marine and airborne in-situ sensors, for delivery using improved satellite telecommunications systems. Table 3 provides examples of the kinds of applications that can be supported by the integration of EO data with other data sources.

Table 3: Examples of Integrated Products and Services

Application	Integrated Product / Service
Navigation Through Ice	GNSS can be used to locate a vessel's position within an EO image of ice conditions to help avoid hazardous situations.
EO Validation	In-situ or mobile sensors combined with GNSS receivers allow real-time feedback of ground information that can be used to validate remotely sensed information in a satellite image.
Drift Forecasting	GNSS-equipped in-situ sensors, such as ocean buoys, can provide real-time information on currents, winds and sea surface temperatures (SSTs) to fuse with satellite derived SSTs, winds and surveillance data, along with ocean models to allow for drift forecasting. The fusion of these data can be used to forecast drifted positions of icebergs or search and rescue targets.
Dark Target and Spoof Detection	EO data can be fused with S-AIS data for identification of suspicious marine vessels that do not transmit an AIS signal or that alter their AIS-reported position to appear to be in a different location.
Oil Slick Surveillance	S-AIS data can be used to confirm and track vessels responsible for oil slicks detected in EO data.

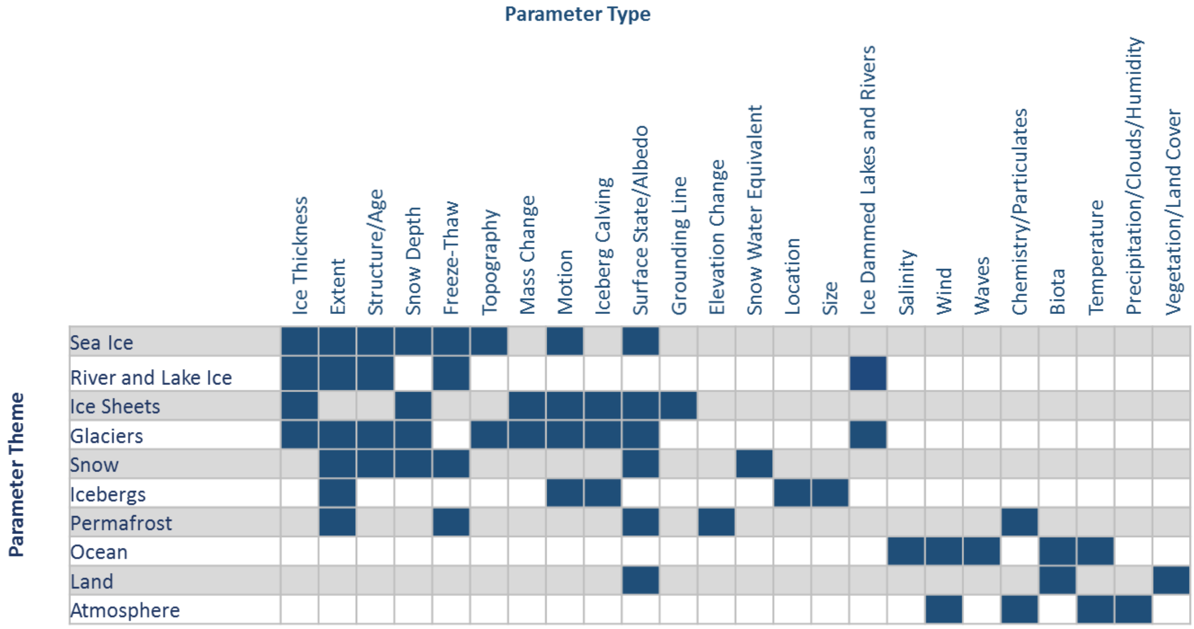
4 CURRENT INFORMATION GAPS

Where products and services are not available to meet user requirements, this can be attributed to two kinds of gaps: i) gaps in data availability from current or planned EO missions and other space or non-space sources; and ii) gaps in the integrated information products and services derived from those data. This chapter discusses these gaps, identifies new integrated products and services to address the gaps and assesses their impacts.

4.1 EO INFORMATION GAPS

While existing or planned EO missions are generally applicable to all the different information themes, our consultations with users and EO experts identified a number of deficiencies resulting from inadequate spatial resolution, temporal resolution and ability to combine data from different sensors. The gaps in existing information products and services derived from EO sensors to meet user requirements are identified in Table 4. The gaps are broken down by parameter theme (along the left of the table) and parameter type (across the top of the table). Highlighted cells show where there is a shortcoming in the existing information (for example, in terms of spatial or temporal resolution), or where there are concerns about data continuity or coverage.

Table 4: Polar Information Gaps



Parameter Type

Parameter Theme	Ice Thickness	Extent	Structure/Age	Snow Depth	Freeze-Thaw	Topography	Mass Change	Motion	Iceberg Calving	Surface State/Albedo	Grounding Line	Elevation Change	Snow Water Equivalent	Location	Size	Ice Dammed Lakes and Rivers	Salinity	Wind	Waves	Chemistry/Particulates	Biota	Temperature	Precipitation/Clouds/Humidity	Vegetation/Land Cover
Sea Ice	■	■	■	■	■	■		■		■														
River and Lake Ice	■	■	■		■											■								
Ice Sheets	■			■			■	■	■	■	■													
Glaciers	■	■	■	■		■	■	■	■	■						■								
Snow		■	■	■	■					■			■											
Icebergs		■						■	■					■	■									
Permafrost		■			■					■		■								■				
Ocean																	■	■	■		■	■		
Land										■											■			■
Atmosphere																		■		■		■	■	

4.1.1 *Environmental Information Gaps for Polar Sciences*

Despite considerable progress in understanding the polar regions over the last decade, many gaps remain in observational capabilities and scientific knowledge. These gaps limit the present ability to understand and interpret on-going processes, prediction capabilities and forecasting in the polar regions, thereby hampering evidence-based decision-making. Sea ice and ice sheet mass balances were identified as key information gaps, both hampered by the difficulty in estimating varying snow cover and snow properties. Sea ice thickness influences the heat flux between the atmosphere and the ocean surface and ice sheet (in particular Antarctica) mass balance measurements are key to understanding and predicting sea level fluctuations. More precise measurements of phase changes from solid to liquid in sea ice and covering snow are important to climate studies and research on the physics of ice. The requirements for improving the knowledge of terrestrial snow (particularly snow water equivalent and snow depth), lake and river ice dynamics, and biodiversity were also highlighted.

4.1.2 Environmental Information Gaps for Polar Operations

The dominant information gaps are mainly driven by the need to have improved sea ice and iceberg information for tactical operations. This will require more detailed sea ice and iceberg classification products at a higher temporal resolution than is currently available. Sea ice thickness, stage of development, structure, motion, extent, and topography were identified as parameters where significant gaps exist. In addition, having more accurate information about snow on sea ice will be required to reliably establish these information parameters. The ability to identify icebergs within sea ice and forecast iceberg motion are other capacities which are key to the communities carrying out polar operations, and linked to this is the issue of improved polar weather predictions (especially wind). Latency or timeliness of sea ice and iceberg product availability (i.e. the amount of delay between the data collection and its accessibility for subsequent use) and lack of satellite coverage of some areas and times of interest were also identified as significant weaknesses in information provision for operations.

4.1.3 Information System Gaps

Information deficiencies can be addressed in two ways: i) by providing more capable earth observation technology (mission concepts), and/or ii) by improving how well the overall information acquisition and delivery systems work (system concepts). The following points examine steps that can be taken to improve gaps in the overall information system for polar data:

- **Data Integration** – Non-specialist users want customized information developed by professionals who have the expertise to integrate data in the way that best meets user needs. Data has more value if it can be easily integrated with other data from multiple sources and of multiple types – time series, other parameters, other regions, other sensors, etc. Data integration is facilitated by data formats and access that adhere to recognized standards.
- **Information Products** – Many end users are not in a position to work directly with earth observation data. Rather, they need information products and services that provide the processed data in the form they require.
- **Information Discovery** – Polar information is currently spread among a large number of sites and organisations. Better tools are needed to help in discovering this data, especially by non-specialists. Access to good metadata is an important component of

the discovery process. Information on data quality and uncertainty needs to be part of the metadata.

- **Information Access** – Accessing information needs to be easy. Cost is a significant barrier to data access and use for many groups. The bandwidth limitations faced by most northern communities and vessels is an impediment to data access and use.
- **Training** – Users need to be educated in how to use data properly so that it is not misinterpreted or used inappropriately, and to identify which information is applicable to their needs.
- **Data Platforms** – The solution to many of the previous gaps could be achieved through good data platforms that would store polar information and provide tools for information integration, discovery, access, and training. These platforms should use open web services that can be used by value added partners in the development of applications and systems. They should provide processing capacity so that users do not need to download large volumes of EO data, but rather can manipulate the data 'in the cloud'.

4.2 OTHER SPACE CAPABILITY GAPS

The use of global navigation satellite systems (GNSS) is ubiquitous in the polar regions, as it is elsewhere. While the accuracy of positioning with GNSS and satellite-based augmentation systems (SBAS) in the higher latitudes at both poles is lower, it appears to be sufficient for applications involving integration of GNSS with EO. The most evident gap is in the coverage of the two primary SBAS (i.e. WAAS and EGNOS) but no evidence has been found that this gap is of significant concern to the scientific and operational user communities.

Although there are a few S-AIS limitations (e.g. signal collisions and time latency), steps are being taken to reduce these limitations and they are being addressed in the design of new space missions covering the polar regions. A new ESA mission that involves such applications could leverage the value contained in third party AIS missions for enhanced data products.

Information from satellite telecommunications systems is not combined with earth observation information into integrated products and services per se, but these systems provide the essential infrastructure for the delivery of such products and services to users. Infrastructure gaps are a particularly important concern for operational users and communities, who often require near real-time delivery of information to ensure safety of life and efficient production. The proposed telecommunications systems appear to be designed to address future operational user requirements in the polar regions. However, it is clear that the systems in place today meet neither present nor future demands. To date, none of the new satellites has been launched and many are still under study or development. There is also the limitation from the lack of telecommunications ground infrastructure in the polar regions. There is a need for an intermediate solution and backup plan for higher bandwidth telecommunications for polar users.

4.3 NON-SPACE INFORMATION GAPS

The optimal system of sensors and sensor networks would be persistent, well-documented and with the resulting data being easily discoverable and broadly available and interoperable with EO systems. Unlike space-borne EO missions, which are typically designed by a single agency or at most a small number of well-connected agencies, in-situ sensors and networks are designed, coordinated, deployed and managed by a large number of (often nested) actors ranging from a single researcher to small Arctic communities to government agencies and international networks. All of these actors are contributing to the broader polar observing system, but they are not yet connected in an optimal way.

The integration of, and synergies between, space-based EO data and data collected with airborne and ground-based, or in-situ, sensors and networks are well established. However, in-situ ground and airborne data collection is fragmented, sensor networks are not well distributed geographically, and there are large temporal gaps in coverage, primarily because many sensors are deployed for specific project-related, time-limited scientific or operational purposes. For example, the systematic measurement over large areas of snow depth and sea ice thickness would address an important gap in in-situ data that can be usefully integrated with space-based EO data to support operations in the polar regions.

5 IMPACTS OF NEW INTEGRATED PRODUCTS AND SERVICES

Investments in satellite EO systems provide benefits to:

- Industry – Companies working to increase economic prosperity.
- Governments – Nations or regions acting on behalf of the common interests of their citizens.
- Citizens – Individual members of society in pursuit of their personal aims, rather than as part of a company or a nation.
- Society – Where the beneficiary cannot be individually identified, benefits are attributed to society in general.

Of course, these beneficiaries are all inter-related and a benefit to one may be a benefit to all. They each may benefit from EO-derived information in a number of possible ways:

- Increase in economic activity – Better information allows economic activity to proceed where it might otherwise be too costly or dangerous.
- Reduction of operating costs – Better information increases efficiency or decreases the cost of economic activity.
- Reduction of risk to life and property – Better information allows better decisions to be made that reduce the likelihood of accidents and disasters.
- Protection of the environment – Better information allows the impact of human activities on the environment to be understood and mitigated.
- Contribution to knowledge – Better information increases knowledge of the physical and ecological sciences.
- Improvement in quality of life – Better information reduces obstacles to people pursuing activities of their choosing.
- Contributions to sovereignty and enforcement – Better information helps protect national borders and enforce laws.

Some of these benefits can be measured in economic terms, but the most significant are qualitative and intangible – safety of life and property, protection of the environment, quality of life, contribution to knowledge, and sovereignty and enforcement – which cannot be easily measured in monetary units.

Many benefits are inter-related, and in a sense cascade from one to the next. For example, a National Ice Service is publicly funded primarily to reduce risk to life and property for industry (i.e. for the safety of marine transport). The benefits from this single application justify the resources necessary to maintain the services. However, further benefits cascade from there. The ice information permits economic activity where it might not otherwise be possible, reduces operating costs, provides information for monitoring the environment, increases human knowledge, and facilitates a host of activities. All of these subsequent benefits come at a very small marginal cost once the ice information is produced.

Impacts from EO information result from activities at all points along the value chain:

1. Construction and launching of the satellite system (space and ground segments) by the system integrator and component manufacturers, and subsequent operation of the satellite system and sale of the data (if applicable) by the system operator and licensed resellers;
2. Analysis of satellite data on behalf of end users by value-added geospatial companies, and
3. Use of satellite data by end users in different application communities.

The potential impacts from a new Polaris satellite and integrated services considered in this analysis are those that will be incremental to the base case of the benefits that would accrue in the absence of such a satellite. Therefore, some benefits do not need to be considered since they are not considered incremental. For example, construction and operation of the satellite, and subsequent analysis of the data by value-added companies, are not considered incremental, as they will occur for some other satellite, even if not a Polaris concept. Therefore, the focus here is on the incremental benefits to end users that would not accrue from other existing or proposed satellite systems.

No attempt has been made here to try to quantify the impact of the different scenarios for a number of reasons:

- Most of the benefits do not have applicable measurement units.
- There is no practical way to convert non-monetary benefits into monetary terms.
- Quantifying the economic benefits would be a task beyond the resources available in this study.

Instead, both the economic and non-economic benefits have been rated qualitatively.

5.1 MISSION CAPABILITIES

The impact analysis compares different possible mission capabilities. A mission capability defines the type of information that a mission can collect. A mission concept may integrate one or more mission capabilities, and consider other factors such as the type of orbit and the arrangement of multiple satellites in a constellation[7]. This analysis has reviewed the following seven mission capabilities:

- Dual and Tri-Band SAR – Two or more synthetic aperture radar (SAR) frequencies, if measured co-temporally, can be used to differentiate the boundary layers in snow and ice, providing significantly more information than can a single frequency by itself.
- InSAR – SAR interferometry achieved using a SAR satellite with a passive companion can allow precise measurement of surface elevations and motion.

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[7] Mission concepts are analyzed in the “Future Mission Concepts for Polar Regions” project.

- AIS with SAR – AIS can help in differentiating between icebergs and ships in SAR imagery.
- Next-Generation Altimeter – There are a number of approaches to measuring elevation in a next-generation altimeter, for example:
  - Passive GNSS reflections receiver
  - Stereo optical sensor
  - SAR Interferometer Radar Altimeter (as in CryoSat).
- LEO Optical – Optical sensors in low earth orbit (LEO), particularly multi-spectral[8] covering a range of frequencies, are of value for monitoring the atmosphere, land use and biodiversity. However, the use of optical sensors is constrained in the polar regions by the amount of cloud cover and darkness in the winter months.
- HEO Optical – An optical instrument in a highly elliptical orbit (HEO) to monitor the high latitudes not accessible to current geosynchronous weather satellites.

Table 5 shows the relevance of the mission capabilities to the parameters with EO information gaps identified in Section 4.1. The project team made the assessment based on a six-point scale that ranges from 0 (not applicable to the information gaps) to 5 (very applicable to the information gaps).

Table 5: Relative Ability of Mission Capabilities to Measure Environmental Parameters

Parameter	**Dual SAR**	**Tri SAR**	**InSAR**	**LEO Optical**	**Altimeter**	**HEO Optical**	**AIS**
Ice Thickness	1	1	5	1	4	0	0
Extent	5	5	0	2	0	0	0
Structure/Age	4	5	3	1	0	0	0
Snow Depth	2	4	0	0	3	0	0
Freeze-Thaw	5	5	2	0	0	0	0
Topography	2	3	5	2	4	0	0
Mass-Change	3	4	5	2	4	0	0
Motion	3	3	1	2	0	0	0
Iceberg Calving	4	5	5	2	3	0	0
Surface State/Albedo	0	0	0	5	0	0	0
Grounding Line	1	3	3	0	4	0	0
Elevation Change	3	4	5	2	5	0	0
Snow Water Equivalent	3	4	0	0	0	0	0
Location (icebergs)	5	5	5	2	3	0	3
Size	4	5	5	3	2	0	0
Ice Dammed Lakes and Rivers	3	4	5	2	4	0	0
Salinity	0	0	0	2	0	0	0
Wind	5	5	2	2	0	5	0
Waves	4	4	5	2	5	3	0
Chemistry/Particulates	0	0	0	4	0	0	0
Biota	0	0	0	5	0	0	0
Temperature	0	0	0	2	0	4	0
Precipitation/Clouds/Humidity	1	2	0	4	0	5	0
Vegetation/Land Cover	3	4	4	5	0	0	0

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[8] Here, the use of the term 'multi-spectral' includes 'hyper-spectral'.

Combining Table 5 with the importance of each parameter to the different integrated services (Table 4 in Section 4.1), results in Table 6 that relates the mission capabilities to their potential impact on integrated service themes.

Table 6: Applicability of Different EO Sensors to Integrated Services for the Polar Regions

Integrated Service	SAR	Dual SAR	Tri SAR	InSAR	LEO Optical	Altimeter	HEO Optical	AIS
Sea Ice	1.9	4.2	5.0	3.1	2.9	2.1	0.8	0.0
Icebergs	3.3	4.6	5.0	3.5	2.4	1.7	0.0	0.7
River and Lake Ice	2.5	4.5	5.0	3.8	1.5	2.0	0.0	0.0
Ice Sheets	1.5	3.5	5.0	4.8	3.0	4.5	0.0	0.0
Glaciers	2.1	4.0	5.0	4.3	2.8	3.2	0.0	0.0
Snow	1.7	4.1	5.0	1.1	1.7	0.7	0.0	0.0
Permafrost	2.9	4.6	5.0	2.5	4.6	1.8	0.0	0.0
Land	0.7	1.0	1.3	1.3	5.0	0.0	0.0	0.0
Ocean	3.1	3.5	3.5	2.7	5.0	1.9	4.6	0.0
Atmosphere	1.4	2.1	2.5	0.7	4.3	0.0	5.0	0.0

5.2 IMPACT CATEGORIES

The following impact categories have been considered:

- Economy – increase in economic activity or decrease in operating costs.
- Safety – reduction in risk to life or property.
- Environment – protection of the environment and mitigation of the environmental impacts of human activity.
- Society – benefits to local, Indigenous, and other peoples in their quality of life and other considerations not captured elsewhere.
- Knowledge – increase in the understanding of natural processes.

In general, economic, safety, environmental and societal impacts come from operational uses, while knowledge impacts come from science uses. Typical uses include:

- Operational Users – Operational users need information to enable the conduct of their activities in a manner that is safer, more efficient, and with less of an environmental impact than would be possible otherwise. Examples of operational uses include weather forecasting, engineering design, operational planning, navigation, emergency response, and environmental impact analysis. In general, operational users require higher spatial and temporal resolution compared to science users. While they may use historical data for strategic planning and design, and forecasts for tactical planning, they often require current information as soon possible after it is acquired.
- Science Users – Science users need information to enable a better understanding of natural processes. Examples of scientific uses include research on climate change, weather, oceans, land, atmosphere, and ecosystems. In general, science users require data over larger areas and longer time-scales than operational users, although data requirements vary considerably depending on the subject of enquiry and the requirements of some science users are similar to operational users. Indigenous and traditional knowledge systems are included in this definition.

Of course, there is a transfer of impacts between these operational and science communities. While the impact of ice and snow figures prominently for both communities, other information is also of interest to each.

5.3 IMPACT ANALYSIS RESULTS

The relative potential impact of each integrated service for each impact category was assessed on a scale of 0 (no impact) to 5 (significant impact) by the project team. The degree of impact is a product of the breadth of the impact (for example, the number of people impacted) and the magnitude of the impact (for example, how important the impact is to each person).

The results were then normalized such that the highest score for each impact category across all mission capabilities received the highest score on a six-point scale, where:

- (0) None – the benefit is not applicable to the user community.
- (1) Minor – there is a benefit, but both size of the user community affected and the magnitude of the impact are small.
- (5) Major – there is a significant benefit to a large user community.

Table 7 contains the results.

Table 7: Mission Capability Impact Summary

Mission Capability	Economy	Safety	Environment	Society	Knowledge	Overall
Dual SAR	4.3	4.3	4.4	4.4	4.1	4.3
Tri SAR	5.0	5.0	5.0	5.0	5.0	5.0
InSAR	3.0	3.2	3.0	2.7	3.3	3.1
LEO Optical	3.7	3.1	4.3	3.6	3.8	3.7
Next Generation Altimeter	1.8	1.9	1.8	1.5	2.3	1.9
HEO Optical	1.4	1.0	1.7	1.4	1.1	1.3
AIS	0.1	0.1	0.1	0.1	0.0	0.1

A number of observations can be made about the results:

- **Multi-Frequency SAR** – Not surprisingly, a large number of polar user communities are interested in variations of frozen water (sea ice, river and lake ice, glaciers and ice sheets, icebergs, and snow). Because of the ability of SAR sensors to see through cloud and in darkness (both of which are common at the poles), and their ability at some frequencies to penetrate ice and snow to see below the surface, SAR is the best sensor for monitoring polar frozen water. Different SAR frequencies reveal different information, and therefore there are benefits to having more frequencies available. As a result, this analysis has found tri-frequency SAR to have the greatest impact of the mission capabilities examined, followed by dual-frequency SAR.
- **LEO Optical** – For observing things other than frozen water, optical sensors are superior to SAR, although they are obstructed by darkness and cloud. The results show multi-spectral optical to have its greatest impact in environmental applications involving monitoring of land cover, vegetation, and ocean colour. The impact of

multi-spectral optical was found to be below SAR, but above the other mission capabilities examined.

- **InSAR** – The ability to determine surface topography is important in a number of application areas. Such information can be acquired in a number of ways; however, interferometric SAR offers the best combination of vertical resolution and wide-area coverage compared to alternative altimeter options.
- **AIS** – The AIS mission capability does relatively poorly in the analysis here because it is only applicable to one environmental parameter – iceberg location. However, that is because the objective of this study is limited to the measurement of *environmental information*. While AIS does not measure environmental information, it is very valuable in other applications, such as ship safety and marine surveillance, the impacts of which have not been considered in this analysis.

6 PRELIMINARY MISSION CONSIDERATIONS

The gap analysis has outlined the high-level requirements of users for different information parameters. Here, the implications of meeting those requirements are expanded on in terms of the following mission characteristics:

- Sensor type
- Production process
- Orbital consideration (LEO, HEO)
- Configuration (constellations, single satellites, etc.)
- Launcher requirements
- High-level feasibility
- Cost

6.1 SENSOR TYPE

The choice here is clearly driven from the parameter type under observation. SAR instrumentation can fulfil large parts of the requirement in terms of ice sheets, iceberg, river/lake ice and snow, while various optical instruments uniquely cover some atmospheric and land parameters. Optical instrumentation is the only option available for HEO observations since active MW instruments do not have the available power to perform from HEO apogee altitudes (although they could from pedigree HEO altitudes).

While snow can be observed with optical instrumentation, it does not have the penetrating power of MW, does not operate in cloud-covered regions, and is limited to thermal infrared wavelengths during the months of polar darkness.

6.2 PRODUCTION PROCESS

The time between the acquisition and the data availability (e.g. for download) determines its usefulness for certain applications. Typically, operational applications have a stronger time criticality than science applications. The current state of the art for near real-time data is within 10 minutes. Timeliness dictates the downlink/space-to-ground architecture and strategy, such as the geographical distribution of ground stations. Very low latency (such as 10 minutes) tends to require downlink during acquisition (i.e. pass through mode) for the satellite architecture.

Modern data processing systems are trending towards automatic production; however, in some circumstances, skilled operator interaction is required. This may be to drive the processing or for quality control of the output. For these semi-automated production flows, consultation will be required with the data production community to ensure that any new satellite system can integrate efficiently with existing frameworks.

6.3 ORBITAL CONSIDERATIONS

High inclination orbits are clearly needed to meet the coverage requirements for polar missions. The observation region for polar missions is typically considered northward / southward of the ~ 60-65^{o} latitude marker. For optical instruments that are generally not power intensive, any inclination in the 70°+ region can cover various parts of the polar regions, with 90° clearly providing complete coverage, including over the poles. Lower inclinations within that region provide more payload mass since increasing the inclination requires significantly more launcher propellant than raising the altitude. For power intensive microwave SAR payloads, Sun-Synchronous-Orbits (SSO) are typically used due to the constant illumination, providing both consistent power and thermal loading to the platform and payload. Altitude impacts the power needed to attain a certain Signal-to-Noise Ratio (SNR) for the instrument, with lower (400-600 km) SSO's providing the best environment. However, the SSO inclination of ~98° does leave a certain region around the pole unobserved. Broadside viewing, a common feature of SAR instrument designs, can partially mitigate this.

For highly elliptical orbits (HEO) missions dedicated to communications and meteorology, variations of the critically inclined Molniya at 63° are often considered.

6.4 SATELLITE CONFIGURATION

There are several concerns and associated trade-offs in defining the requirements of a Polaris mission. These are temporal resolution, timeliness, cost and functionality. Single satellites cover a given region once per orbit, and so are intrinsically limited in providing rapid temporal resolution less than ~90 minutes. In turn, since they are over ground stations only one or two times per orbit, there is a natural data latency in transmitting data to the ground, and hence the user. A constellation of satellites alleviates some of these issues, particularly if they relay data between their member satellites. However, this comes at a cost of building multiple platforms, and either the split of functionality between platforms (i.e. different payloads on different constellation members), or the duplication of functionality on each and every constellation member (i.e. three identical satellites). Conversely, a single satellite is generally less expensive to implement.

Acquisition approaches, such as multi-frequency SAR, which require close temporal collocation of measurements, may drive the satellite architecture (e.g. sensors/instruments located on the same platform, sensors on separate platforms flying in close formation, or sensors on separate platforms flying in different orbits).

6.5 LAUNCHER REQUIREMENTS

There is a drive to use the new ESA small launcher, VEGA, for most EO missions. The launch mass provision of VEGA to SSO 400-600 km altitude is around 1500 kg. Constellations of multiple satellites, unless rather small, can be challenging to fit into such a launcher, when nominal design margins are included. Clearly small platforms can have a direct impact on the payload functionality in terms of resolution etc.

Starting from ~2021, Ariane 62/64 will provide significantly (multiple factors of) more launch capacity, at a notably reduced cost over Ariane 5. This could provide a paradigm shift in the capability for ESA EO missions given the much smaller gap between the cost of VEGA and Ariane 62.

For any possible HEO provision of synergistic communications and meteorology, only the Ariane 62/64 (or Soyuz) can provide a European-sourced HEO launch.

6.6 HIGH-LEVEL FEASIBILITY

Most of the information parameters required by users have been observed from space previously, via one sensor type or another. There are few examples where new observation techniques and instruments would be required. This falls favourably in line with the Polaris mission requirements that the observation technique not be new, but rather of relatively proven heritage.

However, while SAR payloads now have a notable amount of design heritage, moving into the multi-frequency domain does involve instrument developments that, while not foreseen to be technically problematic, do involve cost implications.

Optical instruments focusing on meteorology have a large amount of heritage from previous EUMETSAT missions. The focus is to minimize mass and retain current performance (e.g. 1 - 4 km VIS/IR resolution), or improve upon it within the same mass envelope.

6.7 COST

While very hard to estimate at a high level, it is clear that cost increases with increasing complexity and decreasing heritage. The driver for cost is the specific implementation of the instrument, and whether it is deployed on a single satellite or in a constellation, and the knock-on effect to the launcher required. Constellations, if using identical platforms, can result in savings due to economies-of-scale and so are not necessarily a simple multiple of a baseline single satellite cost. Single satellites in turn, if using a rebuild platform, can also have significant savings.

Generally, whether constellation or single satellite, the best approach is to reuse as much technically as possible in order to limit design costs and, if possible, use a pre-existing design with as few changes to the payload and platform as possible. Even in the cases of moving to more complex implementations of existing technology (e.g., multi-frequency SAR), working from a baseline design can speed up development and reduce costs.

However, it should be noted that in general, there is not much ability to dramatically move away from the cost of a certain class of satellite. For example, the cost of a complex Sentinel-1 type platform and instrument to perform similar mission requirements (i.e. in terms of resolution, etc.) is unlikely to be brought down to a different class of satellite just through reliance on rebuild/heritage savings.

7 CONCLUSIONS

This study has consulted widely on the environmental information requirements of the polar science and operations communities, and the gaps that exist in fulfilling those requirements.

Those gaps are interfering with the ability of the communities to address important issues concerning the environment, the economy, safety, and society, both in the polar regions and in southern latitudes that are impacted by the polar regions.

Space-based assets, and in particular earth observation satellites, have the potential to fill many of the gaps, especially when the information they provide is properly integrated with information from in-situ sensors. Achieving that goal will require both improved earth observation missions and better systems to make data discoverable and accessible by user communities.

APPENDIX 1: ACRONYMS

AIS	Automatic Identification System
EGONS	European Geostationary Navigation Overlay Service
EO	Earth Observation
ESA	European Space Agency
EU	European Union
GNSS	Global Navigation Satellite System
HEO	Highly Elliptical Orbit
IASC	International Arctic Science Committee
InSAR	Interferometric SAR
LEO	Low Earth Orbit
MW	Microwave
PCW	Polar Communications and Weather satellite
S-AIS	Space-based AIS
SAON	Sustaining Arctic Observing Networks
SAR	Synthetic Aperture Radar
SBAS	Space-Based Augmentation System
SCAR	Scientific Committee on Antarctic Research
SNR	Signal to Noise Ratio
SSO	Sun-Synchronous Orbit
WAAS	Wide Area Augmentation System

APPENDIX 2: STEERING COMMITTEE MEMBERS

John Falkingham is Secretary of the International Ice Charting Working Group, an organization that brings together the national ice centres from around the world. As a result of 33 years spent with the Canadian Ice Service, he is an expert, not only in ice monitoring, forecasting and climatology, but also in how ice affects marine navigation, how weather and ice information is delivered to mariners and how they make use of it.

René Forsberg is Professor and Geodynamics Division Head at the Danish Technical University, and State Geodesist and Head of the Geodynamics Department at the National Space Institute of Denmark. He is a member of the scientific advisory board for the ESA CryoSAT mission, lead for the Greenland ice sheets component of the ESA Climate Change Initiative, and author or coauthor of more than 250 papers.

Peter Pulsifer is a Research Scientist with the National Snow and Ice Data Centre. Peter is the Principal Investigator of the Exchange for Local Observations and Knowledge of the Arctic (ELOKA) project and sits on the data committees of the International Arctic Science Committee, Sustaining Arctic Observing Networks, and the Scientific Committee on Antarctic Research.

Jan René Larsen is the Deputy Executive Secretary of the Arctic Monitoring and Assessment Programme (AMAP), one of the working groups of the Arctic Council, and Secretary at Sustaining Arctic Observing Networks (SAON), an organization initiated by the Arctic Council through AMAP and the International Arctic Science Committee to support and strengthen the development of multinational engagement for sustained and coordinated pan-Arctic observing and data sharing systems

Andrew Fleming is the Remote Sensing Manager for the British Antarctic Survey where he leads the application of remote sensing methods to science and operations projects. He is involved with the Council of Managers of National Antarctic Programmes (COMNAP), the Scientific Committee on Antarctic Research (SCAR), the U.S. Polar Geospatial Centre Science Operations Committee, and EU-PolarNet.

Tiina Kurvits is a Project Manager at GRID-Arendal, a centre supporting the United Nations Environment Programme (UNEP). She has worked on Arctic issues at the national and international level throughout her career with a particular focus on ecosystem management, climate change, and biodiversity. She coordinates the Many Strong Voices program and co-manages the UNEP/Global Environment Facility (GEF) Blue Forests project.

Captain David (Duke) Snider is Senior Vice President at The Nautical Institute and CEO of Martech Polar. Duke is a Master Mariner with 27 years at sea. He has served onboard naval, commercial and Coast Guard vessels in polar regions, the Baltic, Great Lakes and Eastern North American waters. He now provides global ice pilotage, navigation, and training services.

APPENDIX 3: ORGANIZATIONS CONSULTED

Aker Arctic Technology Inc.

Alfred Wegener Institute

Antarctic and Southern Ocean Coalition

Arctic and Antarctic Research Institute

Arctic Monitoring and Assessment Programme

Arctic Research Consortium of the United States

Arctic Science Partnership

ArcticNet

Asiaq Greenland Survey

Association of Arctic Expedition Cruise Operators

Association of Polar Early Career Scientists

Australian Antarctic Division

British Antarctic Survey

Canadian Coast Guard

Canadian Cryospheric Information Network

Canadian Shipping Company

C-CORE

Chevron Arctic Centre

Circumpolar Conservation Union

Coalition of Legal Toothfish Operators

Commission for the Conservation of Antarctic Marine Living Resources

Conservation of Arctic Flora and Fauna

Danish Energy Agency

Danish Meteorological Institute

Danish Technical University

European Fisheries Control Agency

European Maritime Safety Agency

Finnish Geospatial Research Institute

Finnish Ministry of Defence

International Association of Antarctica Tour Operators

International Ice Charting Working Group

International Network for Terrestrial Research and Monitoring in the Arctic

Inuit Circumpolar Council-Alaska

NASA Carbon Cycle and Ecosystems Office / SSAI

National Snow and Ice Data Center, University of Colorado

Norwegian Meteorological Institute

Norwegian Polar Institute

Polar Bears International

Polar Geospatial Center

Research Data Alliance

Royal Belgian Institute for Natural Sciences

Scientific Committee on Antarctic Research

Shell Global

Southern Ocean Observing System

Stockholm University

Sustaining Arctic Observing Networks

The Nautical Institute

UK Met Office

WCRP Climate and Cryosphere Project

ZAMG - Zentralanstalt für Meteorologie und Geodynamik

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