GLOBAL SATELLITE OBSERVATION REQUIREMENTS FOR FLOATING ICE

FOCUSING ON SYNTHETIC APERTURE RADAR

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EXECUTIVE SUMMARY

This report outlines the requirements for satellite observations of global sea ice, icebergs and freshwater ice on inland water bodies with a focus on Synthetic Aperture Radar (SAR). The objective is to identify the required set of satellite measurements to address key science questions relevant to the assessment of the impacts of climate change in the polar regions. It is not the purpose to iterate observational requirements of routine operations. Rather, the intention here is to identify the observations needed to support scientific investigations aimed at improving our ability to monitor and model the floating ice environment, including climate analysis and modeling, numerical weather prediction, coupled ocean-ice-atmosphere modeling and operational ice charting.

Reducing Arctic sea ice has been a widely publicized and visible indicator of climate change while significant changes are also occurring in the Antarctic. The ice covers on northern lakes and rivers show similar indications of the impacts of a changing climate. Climate feedback mechanisms involving sea ice and lake ice have important implications for the future progression of climate change. Icebergs present a significant hazard to marine operations and are an important factor in the transport of freshwater and nutrients. In a changing climate scenario, there is concern that iceberg distribution patterns and iceberg characteristics themselves may be changing. There is a need to monitor all of these changes and to model their behaviour in order to develop adaptation responses to deal with the inevitable impacts.

There are pressing science questions about all aspects of floating ice and priorities vary greatly depending on the user and the application. However, the overall consensus is that, because of their importance in the climate system and the state of current observational limitations, the following areas are most in need of investment to improve our measurement capability:

- Sea ice thickness and thickness distribution – both the operational and modeling communities generally rate sea ice thickness distribution as the most important variable to understand better.
- Snow cover on sea ice – characterizing the snow cover distribution, in terms of its depth, density and how it evolves in time, across broad areas, is a close second in importance.
- Sea ice deformation – opinions in the research communities are less convergent but ice deformation associated with ice motion ranks high in importance for a number of reasons.

Other areas of observational importance include:

- The timing of freeze-up and break-up of northern lakes and rivers
- Concentration of sea, lake and river ice
- Classification of sea, lake and river ice
- Ice motion / drift
- Melt and freeze onset of sea ice
- Melt pond formation and evolution on sea ice
- Leads and polynyas in sea ice
- Sea ice floe size distribution
- Landfast ice
- Iceberg distribution patterns
- Behaviour of icebergs, particularly their drift and deterioration

The general expectation in the ice community is that multiple SAR frequencies, polarizations and incidence angles, together with a higher frequency of repeat observations, will lead to greater understanding of the physical processes involved, better manual and automated interpretation of SAR images and improved model performance.

There is a broad range of observational requirements for the study of floating ice. Overall, the following can be noted:

- The most common requirement for multi-frequency observations is to couple L-band with either C- or X-band. There is little demand for C- and X-band together except to increase temporal resolution. For the most important and challenging science questions, there is a need to obtain observations from all SAR frequencies available, ideally simultaneously.
- The science community needs a finer temporal resolution as it becomes clear that diurnal and tidal effects have an impact on both SAR observation and floating ice properties. Observations at approximately 6-hourly intervals are needed to resolve these effects.
- The swath width requirement is generally to be as large as possible while meeting the requirements for resolution, polarization and interferometry.
- The minimum polarization requirement for science is HH+HV and HH+VV. Quad-polarization and full polarimetry are needed to advance understanding and algorithm and model development for most floating ice variables. Further research is required with compact polarimetry to validate its information content.
- While a broad range of incidence angles is required to study most floating ice variables, there is in increased interest in assessing steeper angles than have historically been used (<20°).
- When using different satellites to provide multi-frequency observation, it is essential to keep the time difference as short as possible and incidence angle differences as small as possible.
- Noise is an issue with SAR backscatter from ice, particularly at steep incidence angles and with cross-polarization. Effective noise floors need to be kept as low as possible, preferably less than -35dB.
- It is necessary to understand the impact of footprint size and shape when integrating observations from multiple instruments.

A broad strategy for SAR acquisitions to address the science requirements is presented. The general philosophy of this strategy is to:

- Aim for a complete coverage of the Northern and Southern Hemisphere ice regions on a daily basis, year-round, at C-band by integrating the baseline acquisition plans of the primary C-band satellites (RADARSAT-2, Sentinel-1, and RADARSAT Constellation Mission).
- Use additional acquisitions by the primaries (RADARSAT-2, Sentinel-1, RCM) to provide higher temporal resolution at C-band over particular target areas.
- Use acquisitions by other missions, especially X-band, to complement the primaries in order to increase spatial and temporal resolution.
- Overlap acquisitions by non-C-band missions with the primaries to provide multi-frequency observations.

- Take advantage of the high revisit time afforded by some satellite constellations (such as Cosmo-SkyMed) to provide specific datasets for individual science projects requiring high temporal resolution.
- Acquire SAR data in several frequencies and polarizations for the purpose of comparing with PMR and AMS for cross-assessment and validation.
- Undertake specific experiments to investigate the utility of SAR interferometry for measuring floating ice variables and to develop the necessary algorithms to exploit this capability in future.
- Design acquisition campaigns over targeted areas to investigate the potential of high-resolution quad-pol, compact polarimetry and fully polarimetric data.
- Coordinate acquisitions with known field campaigns - surface and/or aircraft - where possible.
- Target geographic areas that not only feature the ice characteristics of interest but are also synergistic with surface and airborne research campaigns and commercial activity (assuming that information-sharing agreements can be reached).

Satellite SAR missions are rapidly progressing from the purely scientific domain to the commercial realm. A significant concern of the scientific community is that the need to acquire data for commercial activities will reduce the quantity and variety of data available for research. The data providers have legitimate concerns that making commitments to supply data for science will hurt their business cases. It is a hope and a recommendation that the SAR data providers recognize the benefits of working together and seek ways to maximize the collaboration between the commercial and scientific communities.

Scientific advancement in the use of SAR data could benefit from closer collaboration between operational ice services and research institutes dealing with floating ice. The cost and availability of satellite SAR data remain major obstacles for some researchers while the operational centres have access to large quantities of data. Operational centres can also contribute ancillary information and analysis expertise to the research effort.

Field data, while challenging to acquire, are an essential component of remote sensing research, not least in terms of calibration and validation of satellite data-derived products. International collaboration is of great benefit in these efforts but needs continuing attention and support.

Closer coordination of data acquisition and distribution among satellite operators and data providers would be highly beneficial to the scientific community. Use of a central portal for access to data in common formats should be encouraged.

Now, and over the next few years, we will see more satellites with a wider range of sensors for floating ice than ever before in history. The general expectation in the scientific community is that this will allow greater diversity in the way ice is observed. Together with a higher frequency of repeat observations, this will lead to greater understanding of the cryosphere allowing us to better monitor, predict and adapt to our changing environment.

Contents

Global Satellite Observation Requirements for Floating Ice

Focusing on Synthetic Aperture Radar

1 Introduction

1.1 Purpose

This report outlines the requirements for satellite observations of global sea ice, icebergs and freshwater ice on inland water bodies with a focus on Synthetic Aperture Radar (SAR). The objective of the report is to identify the required set of satellite measurements to address key science questions relevant to the assessment of the impacts of climate change in the polar regions.

The reducing Arctic sea ice pack has been a widely publicized and visible indicator of climate change and the ice covers on northern lakes and rivers show similar indications of the impacts of a changing climate. Significant changes are also occurring in the Antarctic (Stammerjohn, Massom, Rind, & Martinson, 2012). Changing sea ice conditions and iceberg distribution are impacting marine activities including global navigation and resource development in the Arctic. Sea ice exerts a major influence on the marine ecosystem by controlling the heat and light that reach the ocean and providing habitat for a wide range of organisms.

Climate feedback mechanisms involving sea ice and lake ice have important implications for the future progression of climate change. Sea ice, as characterized by its extent, type, concentration, thickness, motion, melt stage, surface characteristics and seasonality of coverage, is recognized as an Essential Climate Variable by the World Meteorological Organization (WMO) and the United Nations Framework Convention on Climate Change (UNFCCC). The timing of freeze-up and break-up and the duration of the ice cover on northern lakes are strong indicators of climate change (EEA, 2012) (EPA).

While optical sensors are important and useful tools for visualizing the ice and snow surface, microwave sensors have become the norm for measuring and monitoring floating ice because they are largely impervious to clouds and darkness. This is especially important in the polar regions that are dark for long periods in winter and where the exposure of open water to a cold atmosphere generates extensive cloud cover in the melt seasons.

From a remote sensing perspective, sea ice is an incredibly complex medium, especially in the microwave region. The interaction of microwaves with a sea ice cover depends not only on the properties of the sea ice itself (temperature and salinity profiles, density and size of air bubbles, brine inclusions and other impurities) but also on the nature of the overlying snow pack (temperature profile, liquid water content, density, size and shape of snow grains). The interfaces – atmosphere-snow, snow-ice, ice-water – are particularly important to microwave remote sensing and, in a complication of real-world physics, there can be multiple snow-ice and ice-water interfaces as a result of recurring freeze-thaw cycles. Freshwater ice is no-less challenging. Although there are no complications due to salt, turbulent flow and bottom effects in shallow water create unique challenges.

The workhorse for high-resolution monitoring of floating ice is space-borne SAR. With resolutions routinely measured in metres, SAR is useful for monitoring not only the details of sea ice but also icebergs and lake ice. SAR signatures of sea ice are extremely complex, dependent not just on the vagaries of the surfaces but also on an intricate inter-relationship of frequency, polarization, incidence angle, noise level and spatial resolution (Dierking, 2013). These complexities have long been known (Drinkwater, et al., 1992) but it is only recently that significant volumes of varying types of SAR data have become available to support widespread study of these effects. As a result, there has been a rapid growth in research to explore and understand these complexities (e.g. Moen, et al., 2013).

1.2 Scope

The scope of this study is to assemble the science requirements for floating ice observations that can be made from space with a focus on SAR. It is not the purpose of this document to iterate observational requirements of routine operations. Rather, the intention here is to identify the observation requirements to support scientific investigations aimed at improving our ability to monitor and model the floating ice environment, including climate analysis and modeling, numerical weather prediction (NWP), coupled ocean-ice-atmosphere modeling and operational ice charting.

The purpose of this report is to: i) identify the properties of sea ice, icebergs and freshwater ice that are of greatest scientific interest with respect to the impacts of climate change; and ii) to recommend strategies to monitor and measure these properties with SAR from space.

While the primary focus of this report is on SAR, consideration of other measurements has been noted where appropriate.

1.3 Methodology

This study was conducted between December 2013 and March 2014. A review of previous requirements studies was undertaken along with a review of recent literature on floating ice research activities. The main source of input was a broad interaction, primarily by e-mail, with the ice and remote sensing scientific community. Over 150 scientists were contacted individually or in small groups to seek input on the observational needs of science and on the type of satellite SAR observations of floating ice that would be most useful. This group was asked for their opinions on the importance of floating ice characteristics and, considering the SAR satellite missions that will be flying over the next 5-10 years, to comment on the parameters that would be most useful to advance the scientific study of sea ice, lake ice, river ice and icebergs. A draft document outlining the broad science questions as well as an identification of SAR missions that could potentially be used was provided to help focus thinking.

Responses were received from 60 individuals from 43 different agencies and institutions.

2 Previous Work

The need to monitor floating ice has been noted in many previous publications, conferences and workshops, most recently:

- IGOS Cryosphere Theme Report (IGOS, 2007)
- IICWG Socio-Economic Benefits and Earth Observation Requirements, 2007 Update (IICWG, 2007)

- GCOS 2011 Update on Systematic Observation Requirements for Satellite-Based Data Products for Climate (Global Climate Observing System, 2011)
- SEN4SCI - The Science Needs for Cryosphere Sentinel 1-2-3 products (ESA, 2012)
- ESA Sea Ice Climate Change Initiative User Requirements Document (Sandven S. , 2012)
- WWRP Polar Prediction Project Implementation Plan (Jung, Gordon, & Klebe, 2013)
- 9th Session of the CliC Scientific Steering Group (WCRP, 2013)
- CliC Sea Ice Modeling and Observing Workshop (Wagner, 2013)
- 5th Symposium on the Impacts of an Ice-Diminishing Arctic on Naval and Maritime Operations (NOAA, 2013)
- 14th Meeting of the International Ice Charting Working Group (Falkingham, 2013)

The first five documents listed above contain various science requirements for cryospheric variables. These are summarized in Appendix B for information and comparison with the present.

3 Need for Observations of Floating Ice

Floating ice covers a vast portion of the globe in both Northern and Southern Hemispheres with far-reaching environmental and socio-economic effects. The details of observational requirements are as varied as the range of scientific study. Different users, with different applications, have different needs for observations. For the purposes of this document, there are two general classes of use, as described in the following, under consideration.

3.1 Climatological, Meteorological and Numerical Modeling Applications

There are many models of floating ice ranging from one-dimensional thermodynamic models to 3-D coupled ocean-ice-atmosphere models. Models simulate virtually every ice characteristic from concentration and thickness distribution to ridge building to electromagnetic properties and span microscopic to global scales. Data requirements are very dependent on the intended use of any particular model and modeling systems have varying data assimilation capabilities. Detailed requirements can vary considerably. The accuracy of high-latitude climate forecasts and NWP is highly dependent on sea ice dynamics and thermodynamics as well as on the ice cover on northern lakes and rivers. Models need to account for physical, chemical, biological and biogeochemical influences on scales ranging from metres to kilometres.

In general, there are needs for (Massonet & Jahn, 2012):

- “process-scale” observations to develop new parameterizations or algorithms, typically at very small spatial scales with high temporal frequency (cm to metres, minutes to hours)
- “regional-scale” observations, usually with a somewhat larger spatial scale and with less frequency to initialize and validate ocean-ice-atmosphere predictive models (metres to 10’s of metres, hours to days)
- “climate-scale” observations to develop statistics over longer time frames and large spatial scales to validate global coupled models (kilometres to 10’s of kilometres, days to weeks)

The observational needs for modeling can be divided into two general categories:

- Observations to support model initialization, data assimilation and validation – these tend to be at the regional and climate scales
- Observations to support the development of new parameterization and algorithms in models – these tend to be at the process scale

For climate modeling, which depends on long historical time series of observations, an important requirement is to have data products that are as homogenous as possible over several decades for proper bias correction and calibration. Operational modeling systems have more stringent requirements with respect to observation latency and quality control.

Observations of ice concentration, thickness (ideally thickness distribution), and snow depth or water equivalent are needed to initialize models, although not all are currently available. For example, the Canadian seasonal prediction system uses only ice concentration in its initialization – ice thickness and snow depth on ice are treated as model variables because there are no operational inputs for these parameters[1]. All of these parameters affect the ice albedo, both spatially and spectrally, which is critically important for understanding the energy budget. Equally as important, they also affect the energy, moisture and chemical fluxes between the ocean and the atmosphere (Nghiem, et al., 2013).

Sea ice model validation requires comparisons with observations of the interrelated sea ice characteristics of concentration, thickness, snow, motion, strain, deformation, albedo and surface temperature – basically every physical quantity that is simulated by the model. Evaluation of modeled sea ice behavior, however, is limited by incomplete observational data across the scales that characterize sea ice growth, melt, motion, and deformation (Johnson, et al., 2012).

For climate models, a spatial resolution of 10's of kilometres with weekly or even monthly averages is often sufficient, although daily data are always useful. Spatial resolution on the order of kilometres on a daily basis is generally sufficient for validation of NWP models.

It should also be noted that, for present day model development, no single measurable parameter is sufficient. Rather, improvements will come from better understanding of the interaction of multiple parameters within the system. The biggest improvements to NWP will come from multi-parameter, sometimes multi-disciplinary, measurements that are specifically designed to understand the important processes in action.

Assimilation of ice concentration data from Visible/InfraRed (VIS/IR) sensors, Passive Microwave Radiometers (PMR) and Active Microwave Scatterometers (AMS) is much more advanced than from SAR data. Some progress is being made at assimilating ice vs. water information from HH and HV C-band SAR. However, noise in the cross-polarization channel makes it challenging to use this data in an automated system. Quad-polarization images could be used but are more limited in coverage.

The operational numerical modeling community is just beginning to think about ways to assimilate ice thickness information from spaceborne sensors. The most accurate thickness data comes from laser/radar altimeters but, for operational NWP, the latency of the current CryoSat and ICESat derived ice thickness observations is much too long[2].

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[1] Greg Flato, Environment Canada – personal communication

[2] Tom Carrieres, Environment Canada – personal communication

The scientific community is beginning to work on direct assimilation of satellite sensor radiances rather than retrieved parameters (Pedersen, 2013). Data assimilation techniques require sound estimates of observation and model uncertainties and, ideally, error covariances – how the error at one location is correlated with another location and how the error in one model field is correlated with other model fields (e.g. ice concentration and drift).

This document outlines the needs of modeling applications for floating ice observations and attempts to identify the areas were observations are available but need improvement and those areas where an extensive investment is needed to provide observations.

3.2 Ice Charting Applications

Ice charts depicting the distribution of sea ice, icebergs and freshwater ice on lakes and rivers are produced on an operational basis (i.e. routinely and regularly) by a number of national services. These charts are used by a host of parties including policy makers, regulators, climate scientists, hydrologists, flood prevention agencies, NWP organizations, emergency incident responders, fishers and ship and offshore platform operators. The overall purpose of ice charts is to provide a general awareness of ice distribution and to enhance the safety of marine navigation and offshore operations, to increase public safety, minimize property damage and aid ecosystem management. In addition, ice charts are produced operationally by ice information services, commercially and non-commercially, to support specific operations including individual ship voyages, offshore oil & gas operations and river ice jam management.

Ice charts are mainly produced by experienced human experts manually analyzing SAR (and other) images for ice concentration, type and floe size and occasionally identifying leads, ridges and rubble fields. It is a time-consuming, labour-intensive process subject to the varying skills of individuals working under the pressures of production deadlines. The objective of the majority of research for ice charting is directed at finding methods to analyze SAR data, and produce ice charts, automatically. To date, this research has met with only limited success. This document identifies the areas of investigation for operational ice charting where satellite SAR could be most useful.

4 Sea Ice Observational Requirements

Sea ice, frozen sea water, is a major component of the Earth's climate system. It effectively controls heat, moisture and chemical fluxes between the ocean and the atmosphere, dramatically alters the surface albedo and redistributes salt and freshwater in the ocean. It provides habitat for a wide range of organisms, from microbes to whales, that are specifically adapted to its presence and seasonal patterns. The seasonal sea-ice zones are highly productive biologically (IGOS, 2007).

Sea ice is both a hindrance and a help to human socio-economic activities. Shipping is a vital part of the world economy and is seriously hampered by sea ice. Development of the abundant natural resources in the Arctic is significantly impeded by sea ice. At the same time, northern peoples use sea ice as a transportation corridor and subsistence hunting platform (IICWG, 2007).

Sea ice in both polar regions progresses through a regular annual cycle of growth and decay. In the Arctic, the freezing season commences in September and progresses to a maximum extent in March that encompasses the Arctic Ocean and the sub-polar seas, in some areas as far south as 40N. Through the ensuing melt season, the Arctic sea ice retreats to a minimum that has been getting smaller and smaller for the past two decades. In the Southern Hemisphere, sea ice surrounds the Antarctic continent with an area extent that varies from about 3 million square kilometres at the minimum in February to around 19 million square kilometres in September (NSIDC, 2014). Unlike the Arctic, there has been a slight increase in overall Antarctic sea ice extent in recent decades.

Sea ice is a complicated medium that morphs as it grows and ages. It contains brine pockets, air bubbles and other impurities that leach out with time, especially if the ice survives a melt season. This has led to the distinction between seasonal or First Year Ice (FYI), and perennial or Multi-Year Ice (MYI), the latter being fresher and harder and a much greater hazard to ships and structures. Sea ice moves under the influence of ocean currents and winds, deforming into ridges and rubble fields under convergence and opening leads when divergent. Sea ice supports a snow cover that adds a further layer of complication to the medium.

The Arctic has been studied much more than the Antarctic but it is well known that the Antarctic sea ice regime is quite different from that of the Arctic. While the Arctic contains a mix of FYI and MYI (although the latter is rapidly declining), sea ice in the Antarctic is almost exclusively FYI that is subject to heavy snow loading, resultant surface flooding and the widespread formation of “snow ice”. The Arctic ice pack is largely constrained by land but, with no northward boundaries, the Antarctic sea ice is globally divergent, although there are local convergence zones. It should not be surprising that SAR signature responses from ice in the two polar regions can be different.

In general, for global climate model applications, surface albedo and atmosphere-ocean fluxes, as affected by ice concentration, ice thickness distribution, snow depth, melt stage, ponding and ice motion are most important. A spatial resolution of 10’s of kilometres is typically adequate on a daily basis. For regional climate models and NWP, these same variables are needed but at higher resolution. A spatial resolution on the order of 10’s of metres is needed to detect leads and thin ice that have important impacts on the atmospheric boundary layer. Frequent (at least once per day) global observations are desired.

While there are science questions about all aspects of sea ice, there is general consensus that the following three areas are most in need of investment to improve our measurement capability:

- **Sea ice thickness and thickness distribution** – both the operational and modeling communities generally rate sea ice thickness as the most important variable to get a better understanding of. Information about the thickness distribution over broad areas, ideally globally, is needed. There is an expectation that multi-frequency, multi-polarization SAR data, with increased repeat frequency and in conjunction with other sensors (VIS/IR, PMR, AMS, altimeters), can be used to refine the accuracy of the thickness estimate and extend the thickness distribution field spatially. More process research is needed to understand better how microwaves interact with the complex sea ice environment.
- **Snow cover on sea ice** – there is a general consensus from both communities that characterizing the snow cover distribution, in terms of its depth, density and how it evolves in time, across broad areas, is a close second in importance. Snow cover is closely related to ice thickness and degree of deformation in its role in the climate system and must be estimated accurately to derive ice thickness from the freeboard measurements of altimeters. Snow cover negatively impacts shipping due to increased friction. While this is a highly desired dataset by modelers, methods of measuring snow

depth on sea ice from space are in their infancy. Some success has been demonstrated with PMR data (Brucker & Markus, 2013) but the scientific community is not sure what is realistic to expect from SAR. Investigations with multi-frequency and multi-polarization together with frequent repeat across a range of incidence angles are needed.

- **Ice deformation** – opinions in the research communities are less convergent but ice deformation associated with ice motion ranks high in importance for a number of differing reasons. C-band SAR, which comprises the vast majority of satellite SAR data collected to date, is not too effective at quantifying ridges and rubble ice. As a result, the volume of ice contained in ridges is not well known, which compromises mass balance calculations. Ice ridges and rubble fields are significant hazards for marine transportation and offshore operations. Ridges and rubble fields also provide habitat for seals and polar bears in the Arctic. With the relative amount of FYI, which is rougher than MYI, increasing in the Arctic Ocean, deformed ice is likely becoming more prevalent but research is needed to validate this hypothesis. There is an expectation that multi-frequency, multi-polarization data together with frequent looks at different incidence angles within a short period of time will be useful in identifying deformed ice.

While the above represent the variables most frequently mentioned by those contacted for this study, virtually every sea ice variable was noted by more than one scientist. The relative importance of the variables is very dependent on the application in which they are being used and which hemisphere and region is involved.

In addition to the three noted above, all of the following were identified as needing further research:

- Ice Concentration
- Ice Classification / Type
- Ice Drift / Motion
- Melt and Freeze Onset
- Melt Pond Formation and Evolution
- Leads and Polynyas
- Floe Size Distribution
- Landfast Ice

It should also be obvious that all of these variables are intimately interconnected. Ice motion, melt and freeze-up affect, and are affected by, ice concentration, thickness, type and floe sizes. Ice motion creates leads and deformed ice which in turn impact drift and melt rates, ice growth and the thickness distribution. While recognizing these complexities, this report is structured along individual variable lines solely as a means of simplifying the discussion for the sake of clarity.

The standard for sea ice monitoring for almost two decades has been C-band SAR, initially with single polarization and more recently with dual polarization. ERS-1 and -2, Envisat-ASAR and RADARSAT-1 and -2 have been the workhorses, although only the last remains in operation. In the near future, Sentinel-1 will assume this role as well. Wide swaths (for SAR), providing relatively frequent coverage over broad areas with adequate resolution for most needs, are the principal reasons that these have become the sensors of choice.

The general expectation in the ice community is that multiple SAR frequencies, polarizations and incidence angles, together with a higher frequency of repeat observations and field validation, will lead to greater understanding of the physical processes involved, better manual and automated interpretation of SAR images and improved model performance.

4.1 Sea Ice Cover / Extent / Concentration

The WMO identifies "Sea-ice cover" as an important variable for a range of applications from climate modeling to nowcasting. The WMO definition (WMO-OSCAR) of sea-ice cover ("fraction of an ocean area where ice is present") is analogous to the more commonly used "sea ice concentration".

"Sea ice extent" is defined by the National Snow and Ice Data Center (NSIDC) as "the total area covered by some amount of ice, including open water between ice floes" and has been used for over a decade as an indicator of the gross changes in sea ice conditions (NSIDC, 2014) for climate monitoring. However, as it conveys nothing about the ice cover properties, sea ice extent alone is no longer a useful variable for most modeling or charting applications.

Ice concentration is probably the single most important variable for climate modeling and NWP because it largely determines the surface heat fluxes to and from the atmosphere. Monitoring sea ice extent and concentration at large, climate scales with satellite PMR systems (SMMR, SSM/I, AMSR) is a mature science with recognized limitations: coarse spatial resolution (10's of km); difficulties near coastlines, during the melt season and with new ice; inability to detect sea ice in low concentrations (<15-20%) and a practical accuracy limit of around 5%. Recent advancements with AMSR2 PMR data have improved the resolution to a few kilometres but with increased inaccuracy caused by atmospheric contamination effects (Integrated Climate Data Center, 2014a). Satellite AMS data have also been shown to consistently determine sea ice extent under various wind speed and surface melt conditions (Nghiem, Hall, Rigor, Li, & Neumann, 2014) and are used in the automated, pre-operational global sea ice analysis products of the EUMETSAT Ocean and Sea Ice Satellite Application Facility (OSISAF, 2014).

Satellite SAR effectively complements PMR and AMS in monitoring ice extent and concentration by virtue of its higher spatial resolution and minimum coastal and weather effects. Despite its own limitations including a narrow swath, incidence angle dependencies and surface moisture effects, for ice charting and research into the processes governing ocean-ice-atmosphere transfers, satellite SAR is the "go-to" sensor.

A promising area of research is to use SAR data to validate and tune algorithms that extract ice concentration (and other parameters) from PMR data. SAR data has been used to identify areas of high concentration thin ice and to measure ice drift to find areas of convergence where the PMR data quality can be assessed[3]. To validate PMR data with SAR requires fairly large areal coverage. A swath width of at least 100 kilometres and daily repeat coverage are required to cope with the drift of the ice. Target areas should be spread across several seas in both the Arctic and Antarctic.

Determining ice concentration is essentially a problem of separating ice from open water. With SAR, this problem has largely been solved using dual co- and cross-polarization data (HH+HV at steep incidence angles, HH+VV at shallow angles) which effectively discriminates ice from open water. While C-band has been used most widely, the frequency is not too critical for

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[3] Leif Toudal Pedersen, Danish Meteorological Institute – personal communication

determining concentration. SAR does have some trouble detecting grease ice and very new ice but this is not generally deemed a high priority for research.

Another area where SAR data can be used in parallel with PMR for numerical model ice concentration is to overcome the difficulties of “land contamination” in PMR data. In areas such as the Canadian Arctic Archipelago, where ice is found in the many narrow channels, PMRs do not provide accurate ice concentration retrievals (Agnew & Howell, 2003). SAR data could be used effectively in such specifically targeted areas to provide an ice concentration field for numerical models.

Generally, higher resolution is better for analyzing any ice variable. However, since this always comes as a trade-off with coverage (swath width), many of the sea ice concentration questions can be addressed with a spatial resolution of about 25m allowing greater areal coverage. At this resolution, the most important individual floes and leads can be detected.

Incidence angles in the range of 20° to 50° have historically been used. There is no general call for changes to this practice (for ice concentration), although caution against using very shallow incidence angles (>60°) was expressed.

Repeat coverage requirements depend greatly on location and intended use. In the centre of the ice pack, where concentrations are high and ice mobility is relatively low, daily coverage is deemed sufficient. Near the marginal ice zone where ice mobility is high and where socio-economic activity is most likely to occur, coverage every six hours is needed to capture diurnal and tidal effects. In some cases, even more frequent coverage is needed to resolve small-scale, high frequency events.

Table 4-1: General Observation Requirements for Sea Ice Concentration

Target Geographic Location	• Spread across seas in the Arctic and Antarctic for PMR/AMS validation • Targeted coastal areas; especially Canadian Arctic Archipelago
Repeat Cycle	• At least daily • Every 6 hours to capture diurnal and tidal effects • < 6 hours in cases to capture small scale events
Resolution	• <25m
Frequency	• C most common but not critical
Polarization	• HH+HV; HH+VV at shallow incidence angles
Incidence Angle	• 20-50°
Seasonality	• Year-round
Complementary Sensors	• VIS/IR, PMR, AMS

4.2 Ice Classification / Type

Classifying sea ice into different “types” or “stages of development” related to thickness can provide a proxy not only for thickness but for other important ice attributes such as salinity, roughness and strength (and possibly snow thickness) that are correlated with albedo, air- and water drag coefficients and heat flux through the ice. In particular, the separation of FYI and MYI is important for navigation as well as for monitoring the impacts of climate change. It has been determined that the Arctic ice pack contains much less and much younger MYI than in the recent past and is becoming a more seasonal ice cover in response to sustained warming (Maslanik, Stroeve, Fowler, & Emery, 2011). As the seasonal cycle of Arctic ice growth and retreat changes, the historical relationships between ice type and other attributes are becoming questionable.

Another key distinction is between pack ice and landfast (fast) ice. While pack ice is, by definition, in constant motion under the influence of wind, ocean currents and internal ice stresses, fast ice forms a stationary cover along the coastal margins of both the Arctic and Antarctic. In certain locations around Antarctica, it can attain thicknesses of tens of metres and be perennial.

As noted earlier, the interaction of SAR with sea ice is a complex phenomenon that depends on radar parameters (frequency, polarization, incidence angle), ice characteristics (salinity, roughness, thickness, density, orientation, inclusions) and properties of the overlying snow cover (moisture content, grain size, density, thickness). This makes ice classification by SAR very much an “art” practised by human experts in a labour-intensive manner. Development of robust, automated ice classification techniques using multi-polarization and multi-frequency SAR, as well as multi-sensor, techniques is an area of continuing research.

Satellite AMS systems (QuikSCAT, ASCAT, Oceansat-2, -3) have been used to map sea ice types, primarily FYI vs MYI across the Arctic on a daily basis. However, because these products have relatively coarse resolution and are restricted to seasons without surface melt, they fall short of the needs of NWP. There is potential to use SAR, AMS and PMR together to provide frequent global mapping of sea ice types by extending the detailed information content of the SAR into the broad swaths of AMS and PMR.

Dual polarization (HH and HV) has become the standard for operational ice classification. Moving forward will require experimentation with quad-pol and full polarimetry (Fernández-Prieto, et al., 2012). With full polarimetric capability, a SAR system enables distinction of different scattering mechanisms - essential to improving the understanding of the underlying physics. Backscatter models based on polarimetric parameters with a clear physical interpretation and statistical distribution need to be further advanced. Currently available polarimetric SAR suffers from a narrow swath width which limits coverage. However, current research will improve the exploitation of the emerging compact polarimetry mode implemented on future satellites like ALOS-2 and the RADARSAT Constellation Mission (RCM) (Moen, et al., 2013). Polarimetric features are not expected to be invariant through seasonal changes and so a large spectrum of images must be acquired spanning all seasons and geographic areas.

Automated classification is not independent of incidence angle and the variations in backscatter for different ice types across a range of incidence angles are not well understood for all frequencies and polarizations. Incidence angle variation offers a mechanism to study and exploit the scattering mechanisms related to physical processes. A range of incidence angles is needed to exploit the variation in incidence angle dependences of scattering on moisture content, surface roughness, and freeze/thaw state of sea ice and its snow cover.

The separation of different classes of sea ice is partly based on macroscopic ice structures, such as ridges, leads and floes, with scales on the order of several metres. Achieving a robust (automated) classification system will require sufficient resolution to resolve these features (Dierking, 2013).

Concerning frequency, C-band and X-band do not differ appreciably in ability to identify ice types, although the higher resolution of current X-band systems provides an advantage at discriminating ice types. L-band microwaves penetrate deeper into the surface and have been shown to be effective at identifying rough ice (Eriksson, et al., 2010). L-band is also less sensitive than C-band to a snow cover and to frost flowers that form on new ice (C-CORE, 2012). L-band may also help with classification once melt is underway, when C-band loses the ability to differentiate between FYI and MYI. L-band provides complementary information to C- and X-band so the most effective frequency combination is expected to be L-band and C- or X-band. A future Ku-band would be a welcome addition to the L-, C- and X-band combination.

A major challenge is that there is no single satellite with dual-frequency capability. There are time gaps and incidence angle differences between observations from different satellites. In designing SAR data acquisitions from different satellites, it is important to try to minimize these differences as much as possible.

A general requirement is for increased frequency of observation. For ice classification, this is important because of rapid changes in dielectric properties of the snow and ice layers. The current operational use of SAR provides repeat coverage of an area at about the same time every day, which neglects diurnal variations in temperature and tidal motions of the ocean. Multiple satellite acquisitions are needed to obtain enhanced temporal sampling to detect these key dynamics.

Table 4-2: General Observation Requirements for Sea Ice Classification

Target Geographic Location	• Global polar and sub-polar sea ice areas
Repeat Cycle	• At least daily • Every 6 hours in cases to capture diurnal and tidal effects
Resolution	• <10m
Frequency	• C+L or X+L • Future Ku
Polarization	• HH+HV and HH+VV for routine monitoring • Quad-pol, full polarimetry for research advancements • Compact polarimetry in future
Incidence Angle	• Research across 10-60° to study incidence angle effects at new polarizations and frequencies • Narrow range for individual datasets to limit unwanted incidence angle effects
Seasonality	• Year-round

Complementary Sensors	• VIS/IR, PMR, AMS
Comments	• When using different satellites to provide multi-frequency observation, it is essential to keep the time difference as short as possible and incidence angle differences as small as possible

4.3 Sea Ice Thickness

Ice thickness distribution is currently the most important, under-sampled and inaccurate sea ice parameter according to a large majority of the scientific community. While concentration is relatively easy to monitor from space, ice thickness poses a special challenge and is an area of intense scientific scrutiny at the current time. Together with concentration, thickness is needed to compute the ice volume. Ice volume itself is an important indicator of changing climate and is needed to compute ice mass exchanges with the ocean, to understand the changes in surface fresh water, the export of freshwater (in the form of ice) from the Arctic Ocean and how it is balanced with freshwater input from precipitation, ice sheet melt and river discharge.

Knowledge of ice thickness is needed to plan ship and offshore operations in areas affected by ice. Along with concentration and pressure, ice thickness is a major direct factor influencing ice forcing on structures and operations in ice areas. For offshore construction, the drift and thickness of ice are key parameters in the calculation of ice loading (Sandven, et al., 2009). Accurate ice thickness is required not only for pack ice but also for fast ice regions.

For climate modeling and NWP, a complete ice thickness distribution across the model domain is needed to initialize and to validate numerical models of the ocean, ice and atmosphere. The thickness of the ice is a major determinant of its strength and is correlated with the roughness of both the upper and lower surfaces. Ice thickness is important in determining the transfer of energy through the ice via transmission and conduction.

Space- and airborne altimeters, such as CryoSat-2, ICESat-2 (launch in 2016) and Operation IceBridge (airborne), are currently the most effective instruments to remotely collect ice thickness data at high resolution. However, these instruments are limited to measuring ice freeboard along a narrow line below the craft, requiring many days of observations to build the thickness distribution over a significant area. In addition, measurements are very sensitive to assumptions about snow cover thickness and density and sea ice density, also subjects of much scientific study. Another challenge in Antarctica is that the sea ice freeboard is generally close to the waterline and surface flooding is extensive. There are significant ice freeboard and thickness discrepancies between laser and radar altimetry records, and current research is underway on the use of consistent physical assumptions in the retrieval algorithms[4]. Robust validation is needed.

It has been shown that VIS/IR data can be used to estimate ice thickness with reasonable accuracy across a broad range (Wang, Key, & Liu, 2010). The technique is affected by cloud cover as well as uncertainties in albedo, solar radiation and snow depth but can resolve regional and seasonal variations in ice thickness and is useful for climatological analysis.

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[4] Pablo Clemente-Colón, National Ice Center - personal communication

Satellite low-frequency PMR (e.g. SMOS, SMAP) can be used to estimate the thickness of thin sea ice (<50cm) across the Arctic on a daily basis (Integrated Climate Data Center, 2014b). While adequate for climate modeling with further validation, the coarse spatial resolution of 12.5 kilometres falls short of the needs of both NWP and ice charting.

Significant advancements in sea ice classification and retrieval of ice thickness information using multi-polarization and fully polarimetric SAR data are anticipated by the community. To obtain ice thickness from SAR, multi-frequency and multi-polarization will almost certainly be required. This is the subject of much recent and current research. Multi-polarization C-band SAR has been used to estimate the thickness of sea ice in Antarctica based on empirical relationships between ice thickness and the co-polarization backscatter ratio (Nakamura, Wakabayashi, Uto, Ushio, & Nishio, 2009). and some success has been demonstrated on flat, thin ice (<30 cm) (Zhang, Zhang, Meng, & Su, 2013) (Kim, Kim, & Hwang, 2012). A combination of L-band with either C- or X-band is most promising. S-band should also be investigated if possible.

Satellite SAR could potentially be used in conjunction with other sensors, particularly altimeters and PMR, to extend the thickness field across a much broader area, but the techniques have not yet been proven to be robust.

While the swath width of fully polarimetric data is too limited for most charting and modeling work, it is useful for localized monitoring and for research into the physical processes of microwave interaction with ice of varying thickness.

Lagrangian analysis of sea ice motion coupled with a thermodynamic model, such as in the RADARSAT Geophysical Processor System (Kwok, Cunningham, & Hibler, 2003), could be used to develop ice thickness distribution estimates across the Arctic and Antarctic. The planned baseline operation of Sentinel-1 (ESA Earth Observations Programme Board, 2013) together with the RADARSAT Constellation Mission (Canadian Space Agency, 2011) could support this. The technique has been demonstrated on a smaller scale in the Gulf of St Lawrence (Karvonen, Cheng, Vihma, Arkett, & Carrieres, 2012). A scale cascade approach has also been developed and tested in the Beaufort Sea (Thomas, Kambhamettu, & Geiger, 2011). Lagrangian analysis requires at least daily repeat frequency – a major challenge in the Antarctic, in particular.

The commonly used 20-50 degree incidence angles work quite well, but a somewhat steeper incidence angle (i.e. down to 10 or 15 degrees) may prove advantageous in measuring ice thickness, although this would require a low noise floor (-35 dB) to minimize the noise in the SAR data at high incidence angles for low-backscatter features such as smooth ice[5].

In the middle of a stable ice pack, the repeat frequency of observations can be relaxed somewhat but in the marginal ice zone, at least daily observations are needed. For climate models, spatial resolution on the order of 10’s of kilometres on a daily basis is sufficient. For NWP, a spatial resolution of 10’s of metres is needed on a daily basis. Finer scale ice models for tactical support to ships and offshore structures, as well as process research, require spatial resolution on the order of metres with a temporal frequency measured in hours.

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[5] Matt Arkett, Canadian Ice Service – personal communication

Much less is known about Antarctic sea ice thickness distribution than in the Arctic. Flooded ice and snow ice are common owing to high snow loading. The relative contributions of ice growth from above and below are still unknown. This is a high priority area for the science community.

Table 4-3: General Observation Requirements for Sea Ice Thickness

Target Geographic Location	• Global polar and sub-polar sea ice areas • Arctic Ocean ice export gateways (Fram Strait, Kane Basin, Northwest Passage) • Antarctic regions around bases and experimental sites
Repeat Cycle	• At least daily • Every 6 hours in cases to capture diurnal and tidal effects
Resolution	• 10's of km for climate models • 10's of m for NWP • <10m for tactical support and process research
Frequency	• C+L or X+L • Investigate S
Polarization	• Multi-polarization (HH, VV, HV, VH) • Research with full polarimetry
Incidence Angle	• 10-50°
Seasonality	• Year-round
Complementary Sensors	• Altimeters, Low frequency PMR, VIS/IR

4.4 Snow Cover on Sea Ice - Depth and Evolution

Snow on ice affects the albedo, the formation and size of melt ponds and the growth/melt rates and properties of the underlying ice. It contributes to the formation of snow ice through flooding and refreezing of sea water and of super-imposed ice from refreezing of meltwater. It can impact navigation of ice-capable vessels due to friction and is a critical component in the ecology of certain ice-dependent species. The presence of a snow cover affects the availability and spectral characteristics of light for primary biological production both within and under the sea ice cover. Primary production below the ice begins when the first light returns in the spring and is almost totally controlled by the thickness of the snow cover[6].

Snow affects the rate of heat transfer between the ice and the atmosphere and thus the air-ice-ocean interactions. Measurements of the characteristics of snow on sea ice, including snow thickness and its distribution, fractional snow coverage, snow density, and snow conductivity would be very useful in models, in part because of the complex role that the overlying snow cover has on ice thermodynamics and the potential for an anomalously thin snow cover to hasten

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[6] David Barber, University of Manitoba – personal communication

ice melt in the spring-summer. The latter effect may become increasingly important in a climatically warming Arctic. Improving our understanding of snow depth on sea ice is seen as a high priority by modelers.

The depth and density of the snow cover impact greatly on the freeboard of the ice, essential for computing ice thickness from satellite altimeter data. Depth and density of the snow cover is one of the major distinctions between Arctic and Antarctic sea ice. While Arctic snow is mostly dry and transparent to radar, heavy, wet and saline snow loadings are very common in the Antarctic (also in the Sea of Okhotsk). This snow can depress the ice below sea level resulting in complex slush and re-frozen ice layers at and above the snow-ice boundary. Snow flooding is not handled well in models.

Methods to estimate snow depth on sea ice from PMR data have been known for some time (Markus & Cavalieri, 1998). The techniques are limited to snow depths less than 50 centimetres, suffer inaccuracies due to atmospheric effects and repeated freeze/thaw cycles and are not effective on MYI (Markus, Cavalieri, & Ivanoff, 2011). The snow thickness distribution field has lower spatial and temporal resolutions than demanded for operational activities, process studies and NWP.

While the NASA Operation IceBridge has been collecting snow depth profiles since 2006 (Cavalieri, et al., 2012), there are still large gaps in our knowledge of the overall thickness distribution and impacts of snow on sea ice across both polar regions. The Russian and European sectors of the Arctic are under-sampled as is much of the Southern Ocean. In particular, the ice growth processes of snow-covered sea ice in the Antarctic are not well understood.

In addition, the evolution of the snow cover on sea ice is not well understood. Multi-temporal observations are needed to model how the snow changes over time (e.g. in terms of its grain-size distribution and density). As with ice thickness, an accurate snow depth field is needed for modeling applications – not just transects or point measurements.

Some success has been demonstrated in measuring snow depth on sea ice with PMR data (Brucker & Markus, 2013) although there are limitations caused by rough ice and melt conditions (Melsheimer, 2013). SMOS data may have the potential to provide snow thickness information on thick sea ice but this needs further validation (Fernández-Prieto, et al., 2012). Current research is investigating the potential of using multi-frequency, multi-polarization SAR data to estimate snow thickness and other properties (Firoozy, Mojabi, & Barber, 2014). A correlation between snow thickness on land and polarimetric phase difference has been shown (Leinß & Hajnsek, 2013) but it has not been demonstrated to work on sea ice. There may be potential to use multiple incidence angles in the range 10-50°, observed within a short time window, to estimate the thickness of the snow cover. Multiple X- and Ku-band frequencies, similar to the CoreH2O technique proposed for snow thickness on land should be explored when available.

It has been suggested that repeat pass interferometry could be used to detect changes in snow depth over a stable (i.e. landfast) ice cover. This remains a research question. Finally, full polarimetry may provide clues to the microwave interactions with a snow cover on sea ice with further research.

For the development of snow thickness methods, rapid revisit (at least daily) would be beneficial to capture new snowfall events and the metamorphosis of the snow cover.

Table 4-4: General Observation Requirements for Snow Cover on Sea Ice

Target Geographic Location	• Global polar and sub-polar sea ice areas • Priority to Antarctic (as the least understood area)
Repeat Cycle	• At least daily • Every 6 hours in cases to capture diurnal and tidal effects
Resolution	• <10m for process research to develop algorithms
Frequency	• Combinations of all bands (C, X, L, S, Ku) needed to develop algorithms
Polarization	• Multi-polarization (HH, VV, HV, VH) • Research with full polarimetry
Incidence Angle	• 10-50°
Seasonality	• Winter, spring months
Complementary Sensors	• Altimeters, Low frequency PMR, VIS/IR
Comments	• Interferometry potential

4.5 Ice Drift / Motion

The drift of sea ice, in response to both atmospheric and ocean forcing operating at different temporal and spatial scales, is closely related to the concentration, thickness, roughness and floe size distribution of the ice and is an essential component in the calculation of ice volume fluxes. On a global scale, the macro volume flux of sea ice through gateways is important for climate change research (ice mass balance). On regional and local scales, ice drift is important to identify areas of convergence and divergence - both situations that are of primary concern for navigation, offshore operations and numerical modeling. Convergence causes ice deformation – rafting and ridging – significantly increasing the local ice thickness. This is important for navigation and offshore facilities and as well as in computing the global sea ice mass balance. Divergence causes leads to open in the ice with important effects such as new ice formation during the winter, enhanced melting in summer and non-linear interactions with inertial and tidal forcing (Geiger & Drinkwater, 2005).

Sea ice drift and deformation data are crucial for climate model and NWP optimization and validation. At the second annual Sea Ice Climate Change Initiative Review Meeting, it was agreed to recommend to ESA that sea ice drift be included as a 3rd component (in addition to concentration and thickness) of the sea ice Essential Climate Variable.[7] Ice drift velocity is affected by the roughness of the top and bottom ice surfaces. Knowledge of the ice roughness is important for modeling ice motion. Current sea ice models do not faithfully reproduce the observed ice motions, especially shear and divergence. High-precision ice drift data are required

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[7] Leif Toudal Pedersen, DMI - personal communication

for process studies related to sea ice rheology (the relationship between ice stress and deformation)[8].

While ice drift products are produced using PMR and AMS data, the resolution is too low for tactical support, for process studies or for understanding deformation except on very large scales. Such products cannot be produced within 10-20 kilometres of coastlines where, in many cases, they are most needed.

The techniques to determine ice motion from sequences of SAR images are well-known and, with the important exception of highly dynamic marginal ice zones, are quite robust. The basic problem involves identifying spatial patterns of radar intensity between subsequent images in a time-series and tracking their movement (Heygster, et al., 2012). Ice deformation and surface melt can rapidly alter the patterns of radar backscatter and complicate re-identification. The most important radar parameter is the temporal resolution – the closer together the images are in time, the greater is the likelihood of identifying and being able to track the common patterns.

Recurrent opening and closing of the ice on short time scales (<1 day) during freezing conditions can account for significant ice growth, especially in tidally rich areas (Geiger & Drinkwater, 2005). While this has been demonstrated at very high latitudes (Kwok, Cunningham, & Hibler, 2003), current datasets do not have a sufficiently high sampling frequency at lower latitudes and for higher drift speeds and intense deformation (de-correlation between images). This is especially problematic in the Antarctic.

In the Arctic under freezing conditions, C-band or X-band are preferable because of their ability to differentiate MYI from FYI and use the MYI patterns as “features” to track. However, in melting conditions or in areas that are predominantly FYI, L-band is preferable because of its better ability to delineate deformation structures which can be used as the patterns (Eriksson, et al., 2010). More work is required to determine optimal sensor combinations in the Antarctic, given the different ice-cover characteristics there.

Single polarization HH data can be effectively used in freezing conditions although the addition of dual polarization data can improve the identification of lead and ridge patterns in the ice (Eriksson, et al., 2010).

Constraining the incidence angle range may improve the re-identification somewhat but with the serious drawback of decreasing the swath width and temporal resolution.

The spatial resolution required depends very much on both the ice regime and season. In the marginal ice zone and in summer where patterns may be small, diffuse and rapidly changing, a resolution down to 10 metres and a daily repeat may be required. For climate modeling and NWP, global coverage of the sea ice areas on a daily basis with spatial resolution on the order of 25-50 metres would be the optimum requirement. It may be possible to reduce the quantity of SAR data needed by combining them with PMR data (using the SAR for the difficult areas). Such a technique may reduce the need for SAR to as little as repeat coverage every three days[9].

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[8] Jennifer Hutchings, Oregon State University – personal communication

[9] Kjell Kloster, Nansen Environmental and Remote Sensing Centre – personal communication

Table 4-5: General Observation Requirements for Sea Ice Motion

Target Geographic Location	• Global polar and sub-polar sea ice areas • Arctic gateways - Fram Strait, Nares Strait, Parry Channel • Beaufort Sea–Canada Basin to better understand Arctic Ocean ice export • Kara Sea, Baltic Sea for regional studies • Antarctica, with intensive coverage at times of ship operations
Repeat Cycle	• Daily, every 3 days if combined with PMR • Every 6 hours in cases to capture diurnal and tidal effects
Resolution	• 10m in marginal ice zones • 25-50m elsewhere
Frequency	• C or X during freezing season • L during melting season
Polarization	• HH; HH+HV
Incidence Angle	• 20-50°
Seasonality	• Year round
Complementary Sensors	• VIS/IR, PMR, AMS

4.6 Ice Deformation - Ridges, Rafts, Rubble

Velocity convergence leading to deformation of the ice can dramatically and rapidly increase its thickness. This is of great importance to navigation and offshore activities. The production of thick ice by local rafting and ridging is important in determining the wide area thickness distribution. Deformation increases ice roughness and the macro ice rheology which are important factors in the transfer of atmospheric and oceanic momentum to the sea-ice which, in turn, largely determines the ice drift.

Ice deformation also occurs where mobile pack ice is forced against shorelines, coastal fast ice or offshore shoals. Sustained ridge building can create “stamukhi” or grounded ice ridges that are particularly hazardous to offshore and coastal structures including buried pipelines and cables. This is especially problematic to oil production operations on the Alaskan coast and in the Caspian Sea.

Ice divergence can increase open water areas during the freezing season, resulting in increased ice production/growth rates. The relatively thinner ice produced in leads is most prone to subsequent deformation. Changes in patterns of sea-ice convergence and divergence may become an important factor for wildlife in the Arctic. As the Arctic Ocean becomes predominantly FYI, which is rougher than MYI, there may be an increase in the available habitat for seals and polar bears, aiding their survival.

Ridge and rubble fields represent a complete ice classification that is critical to navigation and offshore operations but not well understood. The timescale for the consolidation of ridges and the impact of their mode of formation (shear or compression) is very much a mystery.

Deformation structures such as ridges, rafting, rubble, and brash ice can be better discriminated from smooth level ice at L-band than at C-band and higher frequencies. The contrast between smooth level ice and rough ice increases with incidence angle although additional research is needed to better understand the mechanisms involved (Dierking, 2013).

Imaging ridges and rubble fields at different incidence angles within very short time frames could provide information on surface roughness. At least multi-polarization and ideally, fully polarimetric, SAR is needed to advance our understanding of how microwaves interact with deformed ice.

Single pass interferometry, such as with TerraSAR-X/TanDEM-X, has been shown to have potential for identifying ice ridges and determining the ice thickness. Initial investigations have shown that this technique works best with relatively steep incidence angles (<30°) and interferometric baselines longer than 300 metres to detect sub-metre vertical features (Lang, Anderssohn, Lumsdon, & Partington, 2013). Acquisition of further test datasets with suitable baseline and ground observations would be very useful, particularly if simultaneous altimeter profiles were available to provide the sea level reference.

Very high resolution SAR, such as SpotLight modes, may reveal crucial details about the fine structure of sea ice, essential in ice deformation characterization.

Because ice deformation is a crucial question for offshore operations, research into improved observation of deformed ice may be an area of synergistic cooperation with commercial operators.

Table 4-6: General Observation Requirements for Sea Ice Deformation

Target Geographic Location	• Beaufort/Chukchi Seas, Baltic Sea, Sea of Okhotsk, Kara Sea, Caspian Sea • Other Arctic areas of economic activity for synergy with commercial operations • Antarctic
Repeat Cycle	• At least daily • Every 6 hours for weather coupling to ice convergence and to capture internal ice oscillations, diurnal and tidal effects • Hourly or better to capture ridge formation
Resolution	• 1-10m for process research to develop algorithms
Frequency	• L • Combination of all bands (C, X, L, S, Ku) needed to develop algorithms
Polarization	• Multi-polarization (HH, VV, HV, VH) • Research with full polarimetry

Incidence Angle	- 10-50°
Seasonality	- Year-round
Complementary Sensors	- Altimeters
Comments	- Interferometry potential

4.7 Floe Size Distribution

For navigation in ice-covered waters, floe size is an important variable that is a standard classification on ice charts. It has major implications for navigation and offshore structures and icebreaker captains and rig managers pay close attention to floe sizes in their operating areas. The floe size distribution affects the horizontal transmission of energy - vast/giant floes can transmit forces across long distances. The floe size distribution impacts melt rate - smaller floes have greater lateral ice melt than larger floes. This is important in regions of river discharge in the Arctic where warm river waters can enhance sea ice melt more effectively in a fragmented sea ice cover. Floe size affects heat and moisture fluxes and drift velocity.

There has been little research done on the impact of floe size on radar backscatter and on how a radar “sees” different floe sizes. Qualitatively, it is known that the delineation of ice floes in a radar image is often very different from what is seen visually. Older floes can often be embedded in younger ice and be completely masked visually by snow cover. The constant movement, freezing and re-freezing in a dynamic ice environment, and the presence of brash ice and slush between floes, makes this analysis extremely complex.

Observing the floe size distribution would require a spatial resolution on the order of metres and high temporal frequency – at least daily and preferably on the order of hours. It is expected that L-band is more sensitive to ice floe edges than C-band, particularly in windy conditions (C-CORE, 2012). However, there has been little research into the radar parameters that would be most effective to map the floe size distribution. It is an area ripe for research.

SAR interferometry has potential for ice floe analysis (Zakharov, Power, Bobby, & Randell, 2013). Individual floes have unique interferometric fringe patterns that may make it possible to accurately delineate them. Further research is needed but, despite the narrow swath width of interferometric SAR and the demanding signal processing requirements, this technique may prove beneficial.

There is current research underway to retrieve waves and ice properties in the marginal ice zone, where small ice floes are broken up by waves[10]. Dual polarization data and high resolution are required to separate ice floes from open water as well as to resolve the wavelengths of waves penetrating into the marginal ice zone.

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[10] Rick Danielson, NERSC - personal communication

Table 4-7: General Observation Requirements for Sea Ice Floe Size

Target Geographic Location	• Beaufort/Chukchi Seas, Fram Strait, Arctic Ocean • Marginal Ice Zones (e.g. Labrador Sea) • Antarctic
Repeat Cycle	• At least daily • Every 6 hours in cases to capture diurnal and tidal effects
Resolution	• 5-10m
Frequency	• C+L or X+L likely most promising
Polarization	• Multi-polarization (HH, VV, HV, VH) • Research with full polarimetry
Incidence Angle	• 10-50°
Seasonality	• Year round
Complementary Sensors	• VIS/IR
Comments	• Interferometry shows potential

4.8 Leads and Polynyas

Leads and polynyas dramatically affect the local albedo and the heat, moisture, salt and other chemical fluxes, as well as the momentum transfer, between the ocean and atmosphere. They affect the growth and melt rates of ice, lateral melting of ice floes and production of new ice through exposure of open water to freezing air temperatures.

Increased atmospheric boundary layer instability and low-level cloud formation associated with leads and polynyas have significant wide-ranging impacts on weather and climate. It has been postulated that frost flowers that grow rapidly on new leads could be a source of atmospheric salt. Very recent work has shown that leads can enhance the transfer of mercury and ozone from the atmosphere to the surface through boundary layer effects (Moore, et al., 2014).

From a practical point of view, leads and polynyas are important for marine transportation – both surface and submarine – as well as for on-ice travel. Recurrent polynyas are areas of important biological, economic and social activity.

VIS/IR sensors have been used to detect leads and polynyas but are subject to obscuration by low clouds associated with leads. PMR data has been shown to be somewhat effective for detecting leads at climate scales (>3km) (Röhrs & Kaleschke, 2012) and may be sufficient for climate models. However, for NWP, process studies and operational activities, satellite SAR is needed to reliably observe leads in all weather and light conditions.

Observing open water leads and polynyas with SAR is essentially the same problem as determining the ice concentration. As noted above, this has largely been solved using dual polarization (HH, HV) data provided the resolution is fine enough to resolve the leads. Generally, 25 metres is sufficient although finer resolution would be beneficial for research.

However, when leads have become frozen over with new ice, which can happen in less than an hour, the problem becomes more complex. Frost flowers forming on new ice produce a very strong backscatter, especially at C-band (less so at L-band). While human experts can fairly readily analyze this phenomenon, it is difficult to do automatically. A combination of C- and L-band (or perhaps X- and L-) would help to resolve this particular problem.

Because leads open and close with considerable frequency due to the motion of a mobile ice pack, frequent observation, at least daily, is needed to observe them. To better understand the diurnal and tidal forcings that open and close leads, multiple observations per day are needed.

Polynyas are larger and often quasi-permanent, or at least recurrent in the same locations, so the temporal resolution may be relaxed somewhat. However, the scientific question for long-lived polynyas becomes one of the ocean-atmosphere fluxes that are occurring over the open water or thin ice of the polynya.

Table 4-8: General Observation Requirements for Leads and Polynyas in Sea Ice

Target Geographic Location	• Arctic and Antarctic coastal areas • Central Arctic Ocean
Repeat Cycle	• At least daily • Every 6 hours in cases to capture diurnal and tidal effects
Resolution	• <25m
Frequency	• C+L or X+L
Polarization	• HH+HV; HH+VV at shallow incidence angles
Incidence Angle	• 10-50°
Seasonality	• Year round
Complementary Sensors	• PMR, AMS, VIS/IR

4.9 Melt/Freeze Onset / Melt Pond Formation and Evolution

The sea ice melting process is complex involving solar radiation, surface albedo, cloud cover, atmospheric temperature and ocean interactions (Nghiem & Neuman, 2007). The length of the melt and freeze seasons is an important parameter to monitor for climate change. The relative lengths of these seasons are major factors in determining the ensuing volume of sea ice with accompanying impacts on albedo, ocean temperature and salinity (ice melting/forming). The extent of the melt impacts the relative amounts of latent and sensible heat flux and the atmospheric dynamics (e.g., surface winds).

Sea ice melt pond fraction is a proxy for surface albedo and the amount of light transmittance across the ocean-sea ice-atmosphere interface in the Arctic (melt ponds are not common in the Antarctic). FYI typically has a greater extent of melt ponding than MYI – a factor that is becoming more important in the Arctic as the relative extent of FYI increases. Melt pond fraction is inadequately parameterized in sea ice climate models due to a lack of understanding through large-scale observations. The combined effect of melting snow/ice and variable wind-wave roughening on pond surfaces means radar backscatter from pond covered ice is poorly understood.

Melt progression and extent can be monitored at climate scales by PMR and AMS on a daily basis and, thus, the timing of melt onset and freeze-up across the polar regions can be inferred (Mortin, et al., 2014). However, the spatial resolution is too coarse (5-50km) for NWP, most charting applications and process research. Sequences of C-band SAR images with HH polarization have been used fairly effectively to detect melt and freeze onset in Arctic MYI because liquid water on the ice surface significantly reduces the backscatter. However, in FYI the situation is often reversed for reasons that are not completely understood but are likely related to the snow cover (Dierking, 2013). This is also an issue for Antarctic sea ice.

SAR can be useful for validating AMS and PMR estimates of melt extent. However, with an increased number of SAR satellite constellations providing greater temporal resolution in future, SAR could also be used on its own to generate global scale melt and freeze maps. In general, higher radar frequencies are preferred for monitoring melt/freeze because they are more sensitive to liquid water. The VV/HH ratio from dual polarization C-band at high incidence angles (>40°) has been shown to be useful for determining the ice melting state as well as the melt pond fraction on smooth Arctic sea ice. However, the technique is complicated by wet snow and re-freezing situations (Scharien, Hochheim, Landy, & Barber, 2014). Use of a lower frequency such as L-band will be needed to extend this to rougher ice categories.

Monitoring the processes of melt pond formation, evolution and distribution is still a challenge. Validation field campaigns are difficult and hazardous to undertake at the season boundaries. Frequent and focused melt and freeze observations during the early stages of the seasonal changes are particularly difficult to make but are most needed. For freeze/melt timing studies, a rapid revisit sufficient to capture diurnal effects is needed. To study the evolution of melt pond evolution, at least daily observation is required.

Use of SAR is complicated by the narrow swath widths and the fact that backscatter changes as a function of incidence angle. Research into the use of different polarization effects across a range of incidence angles is needed. However, recent work with several polarimetric parameters and decomposition techniques has shown that fully polarimetric data carry no more information on melt ponds than dual polarization data[11].

Table 4-9: General Observation Requirements for Freeze/Melt Onset and Melt Ponds

Target Geographic Location	• Arctic Ocean
Repeat Cycle	• Daily • Every 6 hours to capture diurnal and tidal effects
Resolution	• <25m
Frequency	• C or X
Polarization	• HH+VV • Research with quad-pol
Incidence Angle	• 35-50°

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[11] Randall Scharien, University of Manitoba – personal communication

Seasonality	- Autumn, late spring-early summer
Complementary Sensors	- PMR, AMS

4.10 Landfast (Fast) Ice

Landfast (fast) sea ice distribution is thought to be a sensitive indicator of climate variability and change, especially in Antarctica. Landfast ice plays an important role in polynya formation and thus in bottom water production. The breakout and melting of fast ice has a significant impact on freshwater and nutrient supply for generating phytoplankton blooms[12]. It forms a crucially important biological habitat as well as a surface transportation corridor. Moreover, the fast ice affects the drift rate of icebergs and is intimately associated with grounded icebergs.

Landfast ice is not well simulated in current sea ice models used for NWP. When the wind is offshore, models fail to allow for fast ice and predict leads to form at the coast – not at the leeward edge of the fast ice. This causes inaccuracies in ice thickness values and ice growth rates (Johnson, et al., 2012) and a large bias in the surface air-sea heat and moisture flux.

VIS/IR data are routinely used in operational centres to map fast ice. PMR and AMS are also useful at discriminating fast ice at lower resolution (Takeshi, et al., 2007).

Fast ice can be detected in time series of SAR images as sea ice that remains (relatively) stationary - as opposed to pack ice which is in constant motion. Current techniques largely use image cross-correlation methods, although there may be scope to also use interferometry to detect fast ice.

Multi Polarization (HH, VV, HV, VH) data in L- and C-bands is important to distinguish fast ice from open ocean, thin ice, pack ice and ice shelves.

As fast ice responds rapidly to storms, temporal resolution should be at least every 3 days and preferably daily. A routine monitoring of the fast ice coverage around Antarctica at a high spatial and temporal resolution would be very beneficial to understanding changes in ice sheet coastal dynamics. However, some scientists noted that spatial coverage is more important than resolution, and that even 500-1000 metres resolution could be acceptable.

There should be an emphasis on obtaining frequent high-resolution coverage around the Antarctic coastal polynya areas focusing on penguin colonies, Antarctic bases and experimental sites.

Table 4-10: General Observation Requirements for Landfast Sea Ice

Target Geographic Location	- Arctic and Antarctic coastal areas (priority in Antarctic)
Repeat Cycle	- Daily (although once every 2-3 days is acceptable)
Resolution	- 25 - 100m (secondary to coverage extent)
Frequency	- L, C

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[12] Kay Ohshima, Hokkaido University – personal communication

Polarization	Multi-polarization (HH, VV, HV, VH)
Incidence Angle	20-50°
Seasonality	Year round – winter months should be increased because other sensors are less effective
Complementary Sensors	PMR, AMS, VIS/IR
Comments	Interferometry shows potential

5 Iceberg Observational Requirements

Icebergs present a significant hazard to marine operations in those ocean areas where they occur. An iceberg collision with a ship or offshore structure can be a catastrophic event involving substantial damage to property and loss of life. In a changing climate scenario, there is concern that iceberg distribution patterns and iceberg characteristics themselves may be changing. For example, the rapid break-up of glaciers on Canada's Ellesmere Island and on Greenland in recent years has unleashed a large number of "ice islands" – massive tabular icebergs that have very large area extent and mass but a relatively limited draft, allowing them to drift into shallower waters than more conventionally shaped Arctic icebergs.

Icebergs are an important factor in the transport of freshwater and nutrients and play a key, though poorly understood, role in the biology of the polar seas. They are important in the study of the evolution and break-up of floating ice sheets and ice shelves. Icebergs can ground and form anchor points for the formation of landfast sea ice or create semi-permanent coastal polynyas that can last for several years.

There are two main science questions to be addressed with respect to icebergs. The first is to detect whether iceberg distribution patterns are changing and, if so, to determine the causes and predict future changes to reduce risk. For example, monitoring iceberg flux through gateways, such as Fram Strait and in key sectors of the Southern Ocean, would be useful for detecting changes in calving rates from the Greenland and Antarctic ice sheets and in patterns of ocean currents. The risk of ship collision can be reduced by avoiding areas where icebergs are drifting or, at least, avoiding areas where they may be difficult to detect from the ship. This requires accurate and frequent monitoring over broad areas together with predictions of iceberg drift and deterioration. Detecting large icebergs (>100m) with SAR is a maturing science although significant challenges remain relative to:

- Detecting small icebergs, bergy bits and growlers
- Detecting icebergs in sea ice
- Detecting icebergs in differing sea states
- Differentiating icebergs from small vessels

The second major science question is to better understand the behaviour of icebergs, particularly their drift and deterioration. This is critical to reduce the risk of operating in areas frequented by icebergs. For offshore structures such as oil and gas production platforms that are difficult to move, the main defence against collision is ice management – deflecting or towing icebergs away from the structure. This requires not only effective detection in all environmental conditions but also reliable predictions of individual iceberg drift and deterioration. The area of detection is limited but the required frequency of observation and the need for individual iceberg characteristics are greater.

These two questions require considerably different observational approaches. Detection of icebergs in open water and in sea ice generally places a priority on wider swaths to obtain greater geographic coverage. Observing the characteristics of individual icebergs generally sacrifices swath width in favour of other parameters.

5.1 Automated Iceberg Detection in Open Water

The major difficulty for iceberg detection in open water is separating the iceberg targets from the ocean backscatter. C-band HH polarization data can be effective in calm states but cross-polarized (HH+HV) data is preferred to reduce wind speed and incidence angle effects. At shallow incidence angles (>35°), HH polarization yields better detectability while HV is superior for steeper incidence angles (<35°). Higher spatial resolution provides better reliability of detection at the expense of reducing the ocean area that can be imaged. Operationally, a swath width of 100-200 kilometres with spatial resolution of 10-25 metres provides an optimum balance[13]. Even so, it is recognized that only icebergs larger than about 100 metres in length can be detected. With favourable environmental conditions, some information on iceberg size and shape can be obtained.

Once an iceberg has been detected, re-identification becomes easier. Tracking icebergs requires frequent imaging, preferably daily. Longer gaps between images can be overcome by predicting positions with iceberg drift models but, given the inaccuracies of the models, the longer the gap, the less likely it is to re-identify an iceberg. Depending on the dynamics of the area and the size of the iceberg, a gap of more than a few days is usually not acceptable.

A further complication of iceberg detection is in separating iceberg targets from small vessels. It is speculated that fully polarimetric data may be useful in this discrimination but practical investigation is needed. The narrow swath width available would limit the usefulness of this technique to specific applications.

It has been shown that clusters of icebergs can be detected effectively and automatically with space-based altimeters (Zakharov, et al., 2012). While the technique can be very useful for risk reduction by identifying areas where icebergs are likely to be found, it is limited to open water and does not provide information about individual icebergs. It can, however, be used to direct SAR acquisition.

Table 5-1: General Observation Requirements for Iceberg Detection in Open Water

Target Geographic Location	• Arctic Ocean • Atlantic Ocean north of 50N • Antarctic south of 50S • Target specific glacier fronts
Repeat Cycle	• 1-3 days

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[13] Michael Hicks, International Ice Patrol; Jørgen Buus-Hinkler, Danish Meteorological Institute; Stéphanie Tremblay-Thérrien, Canadian Ice Service – personal communication

Resolution	- 10-25m
Frequency	- C or X - Investigate L
Polarization	- HH + HV - Research full polarimetry
Incidence Angle	- 30-50°
Seasonality	- February – September in Northern Hemisphere - Year-round in Southern Hemisphere
Complementary Sensors	- Altimeters

5.2 Automated Iceberg Detection in Sea Ice

For icebergs in sea ice, the types of sea ice, the sea ice partial concentration, ablation state, local incidence angle, drift rate, iceberg size and iceberg shape are all important factors in detectability with SAR. For icebergs in drifting sea ice with a concentration greater than 90%, the probability of detection is relatively high because of open water tracks that icebergs make in the sea ice. If the sea ice concentration is less than 90% the detectability is very low (Babiker & Sandven, 2013).

VIS/IR data can be effectively used to detect icebergs in the absence of cloud cover when shadows on surrounding landfast ice or drift tracks through mobile sea ice are visible.

Dual polarization SAR (HH, HV) in both C- and X-band has been shown to detect even small icebergs in sea ice provided that the noise floor in HV is sufficiently low (Howell, Bobby, Power, Randell, & Parsons, 2012).

Fully polarimetric SAR data has potential for iceberg detection in sea ice. The correlation coefficient and phase difference of the like-polarized channels (HH, VV) delivers the most information about the dominant backscattering mechanisms and allow the best separation of icebergs from sea ice (Dierking & Wesche, 2014). However, the spatial patterns of the polarimetric parameters are not well understood and further research is needed. The additional disadvantage of currently available polarimetric SAR is the narrow swath width.

There has not been a lot of research in the use of frequencies other than C- and X-band for detecting icebergs. It is expected that L-band, especially in combination with C- or X-band, might improve detection owing to the greater penetration of radar waves at L-band. Further research with multiple frequencies and polarizations is needed.

In Antarctica, a full coverage of the iceberg area once every 4 or 5 days is deemed sufficient. In the Arctic, more frequent monitoring of specific high production glaciers at high resolution would be better.

For investigating SAR detection of icebergs in sea ice, the winter season is preferable because iceberg motion is less dynamic. However, for looking at iceberg production from glaciers, the summer season is better.

Table 5-2: General Observation Requirements for Iceberg Detection in Sea Ice

Target Geographic Location	• Arctic Ocean, Barents Sea, Baffin Bay, Fram Strait • Antarctic offshore waters • Target specific glaciers
Repeat Cycle	• 1-5 days
Resolution	• 10-25m
Frequency	• L, C, X
Polarization	• HH + HV • Research with full polarimetry
Incidence Angle	• 10-50°
Seasonality	• Year round
Complementary Sensors	• VIS/IR, Altimeters
Comments	• Interferometry shows potential

5.3 Observing Iceberg Characteristics

Besides location and drift velocity, the iceberg variables of interest are its dimensions, mass, calving rate and melt rate.

5.3.1 Iceberg Dimensions and Mass

Iceberg draft is needed to determine if it can ground in a particular area. Statistically, this is essential for seabed structures such as pipelines and production manifolds. Tactically, it can determine whether a particular iceberg is able to drift into a specific area without grounding.

Iceberg mass is important for iceberg management (towing) and in determining whether a structure is able to withstand a collision. It is also the key to estimating mass loss from the ice sheets and freshwater input into the oceans. Iceberg mass can be estimated from its horizontal dimensions and its draft, although a complete topographical map (Digital Elevation Model - DEM) is needed to compute mass accurately. Success in generating a DEM of an iceberg has been shown using high resolution interferometric Tandem-X data (Zakharov, Power, Bobby, & Randell, 2013). Despite the narrow swath of the sensor, interferometry has potential for tactical situations where the locations of icebergs are well-known. For drifting icebergs, bistatic interferometry (TanDEM-X) is required to eliminate iceberg motion effects. For stationary (grounded) icebergs, repeat pass monostatic mode is acceptable provided there is no motion of the iceberg between passes.

5.3.2 Calving / Melt Rates

Small icebergs, bergy bits and growlers, 5-50 metres in length, with very low freeboard and often awash in the sea, are the most hazardous forms of floating glacier ice because they are very difficult to detect. Modeling iceberg deterioration, calving and melt rates has been the most effective method of predicting where these small masses are most likely to occur. While they are a significant marine hazard, there appears to be little potential in the near future to observe them from space.

Table 5-3: General Observation Requirements for Individual Iceberg Characteristics

Target Geographic Location	• Individual icebergs in the vicinity of offshore operations or research field campaigns (for synergy of observations)
Repeat Cycle	• At least daily for drifting icebergs • Weekly to monthly for immobile (grounded) icebergs
Resolution	• <5m
Frequency	• L, C, X
Polarization	• HH
Incidence Angle	• Research across 10-60°
Seasonality	• Winter season to map immobile icebergs • Summer season to capture drifting icebergs
Complementary Sensors	• Airborne stereo-photography
Comments	• Interferometry can be used to measure individual icebergs

6 Freshwater Ice Observational Requirements

Lakes and rivers in the Arctic and sub-Arctic represent a significant portion of Earth's hydrosphere and the ice cover that forms on these water bodies is important environmentally and socio-economically. (There are no significant lakes and rivers in the southern polar region except for those beneath the Antarctic Ice Sheet.) Ice controls the biological productivity of northern lakes and rivers, transportation modes (open water and on-ice), hydroelectricity production and the severity of spring floods (Duguay, Bernier, Gauthier, & Kouraev, In press).

As the climate changes in the North, there is evidence that patterns of ice formation, distribution and break-up are changing as a consequence (Surdu, Duguay, Brown, & Fernández-Prieto, 2014). There is a need to monitor these changes and to model their behaviour in order to develop adaptation responses to deal with the inevitable impacts.

From a science perspective, the major parameters related to freshwater ice are:

- The timing of freeze-up and break-up (ice phenology)
- Ice classification
- Ice concentration
- Ice and snow thickness

Other variables similar to those for sea ice including floe size, ice motion, ridging and rafting are of interest, especially on large lakes, but have not been identified as being a high priority for investigation at this time.

Scientifically, greater technical issues are expected in the southern reaches of the sub-Arctic because of on-going freeze/thaw cycles that have a large impact on microwave backscatter. This is less of an issue farther north.

6.1 Lake Ice

By acting as a shutter controlling heat, moisture and chemical fluxes between the surface and the atmosphere, and by dramatically and rapidly changing the surface albedo, ice cover on thousands of northern lakes across the Eurasian and North American Arctic and sub-Arctic has a large impact on weather and climate (Brown & Duguay, 2010). Our ability to forecast northern weather, climate and river flow patterns depends on knowledge of how the ice cover affects energy and water budgets.

Besides its influence on weather and climate, ice on inland water bodies can have major socio-economic impacts due to disruption of ship transportation, fishing activities and wildlife habitat (Leshkevich & Nghiem, 2013). The Great Lakes-St. Lawrence River system, the Great Slave Lake-Mackenzie River system, and the Yenissei, Ob and Lena river systems of Russia are all important transportation routes that are affected by ice.

6.1.1 Lake Ice Phenology - Freeze-up / Break-up

PMR and AMS data have been used to obtain freeze-up/break-up dates in automated systems (Kang, Duguay, & Howell, 2012). However, the coarse resolution limits this approach to large lakes. VIS/IR data at high resolution can be used but are limited by cloud cover and darkness. Satellite C-band SAR is used by the Canadian Ice Service to monitor lake freeze-up and lake ice break-up on an operational basis and can be considered a maturing application (van der Sanden, Geldsetzer, Short, & Brisco, 2012). Additional work to automate the analysis procedure is needed to improve efficiency.

C- and L-band SAR data have been used to map changes in lake ice cover. Generally, HH+HV polarization has been found to be best for ice break-up while HH+VV is better for freeze-up. C-band SAR single polarization data (either HH or VV) can differentiate between freshwater ice and open water but only at steep incidence angles (<30-35°). There is evidence that very steep incidence angles (10-15°) may provide better ice-water discrimination at all wind speeds[14]. A low noise floor (<-35 dB) is needed to ensure the usefulness of SAR data at high incidence angles. For larger incidence angles, dual polarization data (HH+VV) are required.

Fully polarimetric C-band SAR has been shown in one case to provide the best ice-water discrimination in all wind speeds and over the greatest range of incidence angles (Geldetzer & van der Sanden, 2013) but further validation is needed.

Many small northern lakes are very shallow and freeze completely to the bottom in winter. In a long time series, this can be used as an index of climate change and SAR data can be used effectively to monitor this phenomenon (Surdu, Duguay, Brown, & Fernández-Prieto, 2014). Use of C-band VV data has long been established as a good indicator of ice that has frozen to the bottom of a lake. Conversely, L-band does not work particularly well for this purpose (Engram, Anthony, Meyer, & Grosse, 2013).

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[14] Torsten Geldsetzer, Canada Centre for Remote Sensing – personal communication

Microwave monitoring of lake ice break-up is complicated by the presence of wet snow and liquid water on the ice surface. There may be multiple freeze-thaw cycles creating an intricate pattern of snow-ice and ice-water interfaces. On an operational basis, the Canadian Ice Service monitors the freeze-up and break-up of inland lakes by visually interpreting C-band SAR single-polarization (HH or HV) or dual-polarization (HH+HV or VV+VH) data. However, automated techniques have not been developed.

The most challenging aspect of ice phenology is to acquire data with sufficient repeat frequency. For lake ice phenology as well as input to NWP, daily observation is needed during the freeze-up and break-up seasons (to improve upon the weekly monitoring that is currently operational). To determine when shallow lakes freeze to the bottom, daily observations must be extended well into the winter. A spatial resolution of less than 25 metres is needed.

For scientific purposes, a combination of high and low frequencies would be very useful. X- or C-band together with L-band is preferred although investigation with Ku-band could also be fruitful.

Table 6-1: General Observation Requirements for Lake Ice Freeze-up / Break-up

Target Geographic Location	• Lake areas of North America and Eurasia north of 45N
Repeat Cycle	• Daily
Resolution	• <25m
Frequency	• L, C, X • Investigate L+C, L+X, Ku
Polarization	• HH, VV, HH+HV, VV+VH • Research with full polarimetry
Incidence Angle	• 10-50°
Seasonality	• Autumn freeze-up through winter to spring break-up
Complementary Sensors	• VIS/IR • PMR, AMS (large lakes)

6.1.2 Lake Ice Concentration and Classification

Determining the concentration and types of ice is most important on very large lakes, such as the Great Lakes which, in addition to having a strong influence on regional weather and climate, support year-round navigation and economic activity. Ice jams on the rivers connecting the Lakes can disrupt navigation and cause flooding with serious economic impacts. The North American Ice Service analyzes ice concentration and classification on the Great Lakes on an operational basis using VIS-IR and C-band HH+HV data. There has been little research on classifying ice types on smaller lakes (Duguay, Bernier, Gauthier, & Kouraev, In press).

As noted above, C-band SAR single polarization data can differentiate between freshwater ice and open water although multi-polarization data (HH, VV, HV) are required to minimize wind effects across a broad range of incidence angles. Besides discriminating between ice and water, dual polarization data can also be used to classify lake ice into categories such as brash ice or stratified ice (Nghiem & Leshkevich, 2007) (Leshkevich & Nghiem, 2007). Recent advancement in automated ice classification on the Great Lakes has been demonstrated using quad-pol and dual-pol C-band SAR (Leshkevich & Nghiem, 2013). However, there are issues with noise, particularly in the cross-polarization channels. Steep incidence angles with VV polarized data seem to work best but further research is needed. Additionally, X- and L- bands should be investigated for their information content.

Table 6-2: General Observation Requirements for Lake Ice Concentration and Classification

Target Geographic Location	• Large lakes of North America and Eurasia north of 45N; especially Great Lakes
Repeat Cycle	• Daily
Resolution	• <25m
Frequency	• C, X • Investigate C+L and X+L, Ku
Polarization	• HH, VV, HH+HV • Research with full polarimetry
Incidence Angle	• 10-50°
Seasonality	• Fall freeze-up through winter to spring break-up
Complementary Sensors	• VIS/IR • PMR, AMS (large lakes)

6.1.3 *Lake Ice and Snow Thickness*

Knowing the thickness of lake ice is important for estimating its load-bearing capacity for on-ice transportation, predicting ice melt and break-up, monitoring water quantity and quality, understanding eco-system impacts and estimating the heat and moisture exchanges with the atmosphere.

Some success has been achieved in measuring lake ice thickness with PMR data but the practice is limited to large lakes (Duguay, Bernier, Gauthier, & Kouraev, In press). VIS/IR data can also be used to estimate lake ice thickness (Wang, Key, & Liu, 2010). To date, there has been little success in measuring lake ice thickness with SAR, except in cases where ice forms to the bottom of a lake of known depth (Duguay & Lafleur, 2003). To advance the ability to directly measure lake ice thickness, research with the full breadth of multi-frequency, polarimetric and/or interferometric SAR data across a range of incidence angles is needed to better understand the microwave scattering mechanisms. L-band coupled with either C- or X-band is the most promising place to begin. Incidence angles in the 20-50° range are acceptable but, for lake ice, a somewhat steeper angle (10-15°) may prove useful. A low noise floor (<-35db) is needed especially at steep incidence angles. Resolution on the order of metres with re-visit at least weekly would be beneficial. Based on work with Ku-band radar altimeters (Kouraev, et al., 2007) and scatterometers (Howell, Brown, Kang, & Duguay, 2009) it may be profitable to investigate Ku-band SAR for the estimation of snow thickness on lake ice.

Repeat pass SAR interferometry has some potential for mapping ice thickness on lakes where ice motion is minimal, although further study is necessary. This approach requires a high temporal resolution, preferably daily, to keep the changes in the ice cover between image sequences manageable. A high sensitivity to height is essential because of the small values of ice thickness (relative to terrain height). The choice of radar frequency can be quite flexible (van der Sanden, Drouin, & Bian, 2013).

Table 6-3: General Observation Requirements for Lake Ice and Snow Thickness

Target Geographic Location	• Lake areas of North America and Eurasia north of 45N
Repeat Cycle	• Daily
Resolution	• <10m
Frequency	• C, X • Investigate C+L and X+L, Ku
Polarization	• Research with multi-polarization and full polarimetry
Incidence Angle	• 10-50°
Seasonality	• Fall freeze-up through winter to spring break-up
Complementary Sensors	• VIS/IR • PMR, AMS (for large lakes)
Comments	• Interferometry potential

6.2 River Ice

River-ice affects an extensive portion of the northern high-latitude hydrologic system (Interdisciplinary Centre on Climate Change). Ice jams on rivers disrupt navigation and are a major cause of flooding that can result in substantial economic loss and threats to human safety. Knowledge of river ice is needed to manage hydroelectric systems, build and maintain bridges, dams, ice-roads, water intakes and other river structures.

River ice generally has a more complex structure than lake ice due to the more turbulent environment in which it forms. Suspended air bubbles and sediments generated by the streamflow create multiple microwave scattering interfaces not present in ice formed on a calm lake.

The major science parameters related to river ice are:

- Freeze-up and break-up
- Ice classification
- Ice thickness

6.2.1 River Ice Phenology - Freeze-up / Break-up

The freeze-up and break-up of ice on northern rivers typically happens in a fairly short time interval (1-2 weeks at any given point) although the actual dates vary considerably from year to year. This places a premium on the ability to acquire satellite data on short notice to avoid over-monitoring.

PMR capability to automatically determine the timing of river freeze-up and break-up have been demonstrated (Brakenridge, Nghiem, Anderson, & Mic, 2007). With multiple PMRs (AMSR2, SSMIS, WindSat/Coriolis, and GPM), excellent coverage in time and in space can be achieved. VIS/IR data have been used to monitor ice formation and break-up both visually and in an automated fashion although it is hampered by cloud cover. Radar altimeter data at Ku-band has also been shown to be reasonably accurate at detecting ice formation and break-up (Duguay, Bernier, Gauthier, & Kouraev, In press).

Both C- and X-band SAR provide excellent images to monitor ice freeze-up and break-up visually. There are multiple visual clues in the images, such as ice cracks, that experienced analysts can use to detect the presence or absence of ice. Automatic detection is difficult, however, owing to the complexity of the backscattering environment. A combination of high and low frequencies would be very useful. X- or C-band together with L-band is preferred although future investigation with Ku-band could also be fruitful.

There may be some potential for SAR interferometry using image sequences several days apart to detect freeze-up and break-up in rivers. In both C- and X-band SAR, a loss of coherence between sequential images indicates a change in the environment that could be due to ice growth or melt (van der Sanden, Drouin, & Bian, 2013). However, there are unexplained changes that must be due to other causes. Further research is needed in this area. Generally, for this method to work, the time lag between images in an interferometric pair must be a day or two at most.

Frequent observation, preferably daily, is needed to monitor the changes in river ice during the freeze-up and break-up seasons. Break-up is the time when changes happen most rapidly and when the greatest impacts can occur. However, it is known that the break-up process is affected by how the ice cover initially forms on a river making freeze-up monitoring important. Changes in the ice that will affect break-up can also happen throughout the winter requiring continued observations, preferably daily but at least every few days.

At a minimum, HH+HV polarization is needed to monitor break-up. HH+VV polarization is better for freeze-up[15]. Resolution on the order of metres is needed to capture the detail of river ice processes. Full polarimetry needs further study to determine its utility.

Table 6-4: General Observation Requirements for River Ice Freeze-up / Break-up

Target Geographic Location	• Rivers in North America and Eurasia north of 45N
Repeat Cycle	• Daily • Hourly during dynamic break-up incidents
Resolution	• <10m
Frequency	• C, X • Investigate C+L and X+L, Ku

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[15] Joost van der Sanden, Canada Centre for Remote Sensing – personal communication

Polarization	• HH, VV, HH+HV • Research with full polarimetry
Incidence Angle	• 10-50°
Seasonality	• Fall freeze-up through winter to spring break-up
Complementary Sensors	• PMR, VIS/IR
Comments	• Interferometry potential

6.2.2 *River Ice Classification*

C-band HH and HV data have been used to discriminate several classes of river ice in an automated system with excellent results (Jasek, Gauthier, Poulin, & Bernier, 2013). X-band multi-polarized SAR (HH+VV) has also been used to classify several river ice types with slightly inferior results (Mermoz, et al., 2009). L-band has been found less suitable at classifying river ice than C-band, although multi-frequency combinations may provide additional information.

Fully polarimetric SAR has some potential capabilities but further study is needed to better understand the microwave-ice interaction process.

Frequent repeat is essential to capture events in the dynamic river environment.

Table 6-5: General Observation Requirements for River Ice Classification

Target Geographic Location	• Rivers in North America and Eurasia north of 45N
Repeat Cycle	• Daily
Resolution	• <10m
Frequency	• C, X • Investigate C+L and X+L, Ku
Polarization	• HH+HV • Research with full polarimetry
Incidence Angle	• 10-50°
Seasonality	• Fall freeze-up through winter to spring break-up
Complementary Sensors	• VIS/IR
Comments	• Interferometry potential

6.2.3 *River Ice Thickness*

Satellite SAR data has been investigated for its potential to measure river ice thickness without much success to date. The complex ice structure, ice deformation and inclusions in the ice and snow cover all contribute to the difficulty. C- and L-band SAR appear to offer similar, rather limited, potential for the estimation of the thickness of non-consolidated ice covers (van der Sanden & Drouin, 2011).

Some success in estimating the thickness of smooth river ice has been demonstrated using C-band fully polarimetric data (Mermoz, et al., 2013). However, this is an area requiring further research with a variety of SAR parameters.

As with lake ice, SAR interferometry has potential for mapping river ice thickness although further study is necessary. This approach requires a high temporal resolution, preferably daily, to keep the changes in the ice cover between image sequences manageable. A high sensitivity to height is essential because of the small values of ice thickness (relative to terrain height). The choice of radar frequency can be quite flexible (van der Sanden, Drouin, & Bian, 2013).

Resolution on the order of metres is needed to capture the detail of river ice processes.

Table 6-6: General Observation Requirements for River Ice Thickness

Target Geographic Location	• Rivers in North America and Eurasia north of 45N
Repeat Cycle	• Daily
Resolution	• <10m
Frequency	• C, X • Investigate C+L and X+L, Ku
Polarization	• Multi-polarization (HH, VV, HV, VH) • Research with full polarimetry
Incidence Angle	• 10-50°
Seasonality	• Fall freeze-up through winter to spring break-up
Complementary Sensors	• VIS/IR
Comments	• Interferometry potential

7 Suborbital and Spaceborne Mission Development and Cal/Val Science Requirements

As noted in previous sections, there is great expectation throughout the scientific community that multi-mission SAR data with high spatial and high temporal resolution will provide many more answers about floating ice and its role in the climate system. At the same time, there is considerable uncertainty about exactly what the information content of these new datasets will be. Focused investigation into the complementarity of multi-mission data, accompanied by field validation is needed.

An overall requirement that has come across explicitly from many scientists is the need for stable, calibrated data over long periods of time and across changes in individual instruments. For both climate prediction and model evaluation, it is very important to have a data record measured in decades. There is also a need for specific information on the accuracy of derived datasets.

There are many permutations of inter-mission studies possible but, from the floating ice scientific community, the following come out as the most important:

- Correlating the backscatter from floating ice across multiple frequencies and a broad range of incidence angles. L-, C- and X-band are of greatest interest but S- and Ku-bands are also mentioned. Incidence angles should range from 10° to 60°. This could perhaps be best accomplished by selecting a small number of specific project sites, containing a known variety of ice types, to be imaged multiple times with a varied array of SAR parameters from satellite and/or airborne platforms. This must be done within a short time span (days) to minimize the effect of environmental changes.
- Better understanding of the capabilities of full polarimetry at multiple frequencies. Just as the use of dual-pol SAR led to significant breakthroughs in automated ice classification, it is expected that full polarimetry will yield equally beneficial results. This would likely require the acquisition of fully polarimetric datasets across a wide range of ice types, including sea ice, lake and river ice and icebergs. Further investigation with compact polarimetry is also needed to assess the information content of this new data.
- Determining the potential of SAR interferometry, in both single-pass and repeat-pass modes, particularly for characterizing ice thickness, snow cover and deformation (the variables of greatest interest to the scientific community). This would necessitate acquiring field validated datasets across a range of targets.
- Investigating the synergistic use of SAR with other satellite Earth observation instruments, especially PMR, AMS and VIS/IR. There is considerable interest and potential benefit to be gained from the broad coverage capabilities of the latter combined with the high resolution of SAR.
- Understanding the impact of footprint size and shape from multiple instruments. Sea ice motion is subject to temporal aliasing due to low revisit times (Geiger & Drinkwater, 2005). Spatial aliasing is emerging as an issue in the integration of sea ice thickness measurements because sea ice thickness has very low roughness at length scales above 100 metres but very high roughness below 100 metres[16].

8 Summary of Observational Requirements

It is obvious from the previous sections that the study of floating ice has a broad range of observational requirements. A summary of the requirements for each floating ice variable is presented in Table 8-1. Overall, the following can be noted:

- The most common requirement for multi-frequency observations is to couple L-band with either C- or X-band. There is little demand for C- and X-band together except to increase temporal resolution. For the most important and challenging science questions, there is a need to obtain observations from all SAR frequencies available, ideally simultaneously.
- The science community needs a finer temporal resolution as it becomes clear that diurnal and tidal effects have an impact on both SAR observation and floating ice properties. Observations at approximately 6-hourly intervals are needed to resolve these effects.
- Spatial resolution requirements for scientific investigation are typically an order of magnitude finer than the requirements for operational use. Whereas 50-100 metres is

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[16] Cathleen Geiger, University of Delaware – personal communication

common for operational ice charting or NWP, 5-10 metres is more typical of the requirement for research into advancements in these areas.

- The swath width requirement is common for all variables to be as large as possible while meeting the requirements for resolution, polarization and interferometry.
- The minimum polarization requirement for science is HH+HV and HH+VV. Quad-polarization and full polarimetry are needed to advance understanding and algorithm and model development for most floating ice variables. Further research is required with compact polarimetry to validate its information content.
- While a broad range of incidence angles is required to study most floating ice variables, there is in increased interest in assessing steeper angles than have historically been used (<20°).
- When using different satellites to provide multi-frequency observation, it is essential to keep the time difference as short as possible and incidence angle differences as small as possible.
- Noise is an issue with SAR backscatter from ice, particularly at steep incidence angles and with cross-polarization. Effective noise floors need to be kept as low as possible, preferably less than -35dB.

The variables deemed most important to make observing investments in – sea ice thickness, snow cover on sea ice, and sea ice deformation – are bolded in Table 8-1.

Table 8-1: Summary of Observation Requirements

Variable	Frequency Band	Target Locations	Repeat	Resolution	Polarization	Incidence Angle	Seasonality	Complementary Sensors
Sea Ice Thickness	**C+L or X+L; Investigate S**	**Global polar and sub-polar sea ice areas; Arctic ocean ice export gateways; Antarctic around bases and experimental sites**	**Daily; every 6 hours**	**<10m to 10's of km**	**Multi-polarization; research with full polarimetry**	**10 – 50°**	**Year-round**	**Altimeter, Low Freq PMR, VIS/IR**
Snow Cover on Sea Ice	**Combination of all bands (Potential for interferometry)**	**Global polar and sub-polar sea ice areas; priority Antarctic**	**Daily; every 6 hours**	**<10m**	**Multi-polarization; research with full polarimetry**	**10 – 50°**	**Winter, spring**	**Altimeter, Low Freq PMR, VIS/IR**
Sea Ice Deformation	**L; Combination of all bands (Potential for interferometry)**	**Beaufort, Chukchi, Baltic, Kara, Caspian Seas; Sea of Okhotsk, Other Arctic areas of economic activity; Antarctic**	**Hourly to Daily**	**<1-10m**	**Multi-polarization; research with full polarimetry**	**10 – 50°**	**Year-round**	**Altimeter**
Sea Ice Concentration	C	Arctic and Antarctic seas; targeted coastal areas; Canadian Arctic Archipelago	Daily; every 6 hours	<25m	HH+HV; HH+VV	20 – 50°	Year-round	VIS/IR, PMR, AMS
Sea Ice Classification	C+L or X+L; Future Ku	Global polar and sub-polar sea ice areas	Daily; every 6 hours	<10m	HH+HV; HH+VV; research with quad-pol, full polarimetry, compact pol	10 – 60°	Year-round	VIS/IR, PMR, AMS
Sea Ice Motion	C or X in freezing season; L in melting season	Global polar and sub-polar sea ice areas; Arctic gateways; Beaufort, Kara, Baltic Seas; Antarctic	1-3 days; every 6 hours	10-50m	HH; HH+HV	20 – 50°	Year-round	VIS/IR, PMR, AMS
Sea Ice Melt/Freeze Onset, Melt Ponds	C or X	Arctic Ocean	Daily; every 6 hours	<25m	HH+VV; research with quad-pol	35 – 50°	Autumn, late spring-early summer	PMR, AMS
Sea Ice Leads and Polynyas	C+L or X+L	Arctic and Antarctic coastal areas; central Arctic Ocean	Daily; every 6 hours	<25m	HH+HV; HH+VV	10 – 50°	Year-round	VIS/IR, PMR, AMS
Sea Ice Floe Size Distribution	C+L or X+L (Potential for interferometry)	Beaufort/Chukchi Seas; Fram Strait; Arctic Ocean; marginal ice zones; Antarctic	Daily; every 6 hours	5-10m	Multi-polarization; research with full polarimetry	10 – 50°	Year-round	VIS/IR
Landfast Sea Ice	C, L (Potential for interferometry)	Arctic and Antarctic coastal areas (Antarctic priority)	Daily; every 3 days acceptable	25-100m	Multi-polarization	20 – 50°	Year-round	VIS/IR, PMR, AMS

Table 8-2: Summary of Observation Requirements (cont.)

Variable	Frequency Band	Target Locations	Repeat	Resolution	Polarization	Incidence Angle	Seasonality	Complementary Sensors
Icebergs in Open Water	C or X ; investigate L	Arctic Ocean; Atlantic Ocean north of 50N; Antarctic south of 50S; specific glacier fronts	1-3 days	10-25m	HH+HV; research with full polarimetry	30 – 50°	Feb-Sep in North; year-round in South	Altimeter
Icebergs in Sea Ice	L, C, X (Potential for interferometry)	Arctic Ocean, Barents Sea, Baffin Bay, Fram Strait; target specific glaciers; Antarctic offshore waters	1-5 days	10-25m	HH+HV; research with full polarimetry	10 – 50°	Year-round	VIS/IR, Altimeter
Iceberg Characteristics	L, C, X (Potential for interferometry)	Individual icebergs in the vicinity of offshore operations or research field campaigns	Daily; weekly to monthly for grounded bergs	<5m	HH	10 – 60°	Year-round	Airborne stereophotography
Lake Freeze-up / Break-up	L, C, X; investigate C+L, X+L, Ku	Lake areas of North America and Eurasia north of 45N	Daily	<25m	HH, VV, HH+HV, VV+VH; research with full polarimetry	10 – 50°	Freeze-up to break-up	VIS/IR; PMR, AMS for large lakes
Lake Ice Concentration /Classification	C, X; investigate C+L, X+L, Ku	Large lakes of North America and Eurasia north of 45N; especially Great Lakes	Daily	<25m	HH, VV, HH+HV; research with full polarimetry	10 – 50°	Freeze-up to break-up	VIS/IR; PMR, AMS for large lakes
Lake Ice and Snow Thickness	C, X; investigate C+L, X+L, Ku (Potential for interferometry)	Lake areas of North America and Eurasia north of 45N	Daily	<10m	Research with multi-polarization and full polarimetry	10 – 50°	Freeze-up to break-up	VIS/IR; PMR, AMS for large lakes
River Freeze-up / Break-up	C, X; Investigate C+L, X+L, Ku (Potential for interferometry)	Rivers in North America and Eurasia north of 45N	Daily; hourly in break-up events	<10m	HH, VV, HH+HV; research with full polarimetry	10 – 50°	Freeze-up to break-up	VIS/IR; PMR
River Ice Classification	C, X; Investigate C+L, X+L, Ku (Potential for interferometry)	Rivers in North America and Eurasia north of 45N	Daily	<10m	HH+HV; research with full polarimetry	10 – 50°	Freeze-up to break-up	VIS/IR
River Ice Thickness	C, X; Investigate C+L, X+L, Ku (Potential for interferometry)	Rivers in North America and Eurasia north of 45N	Daily	<10m	Multi-polarization; research with full polarimetry	10 – 50°	Freeze-up to break-up	VIS/IR

8.1 Geographic Areas of Importance

The geographic areas of most interest to the scientific community are:

- The Arctic Ocean, from the Beaufort Sea to Fram Strait, to study the movement of sea ice in the Beaufort Gyre and its export from the Arctic through Fram Strait. This will aid in understanding the changes that have been observed in sea ice drift and deformation, concentration, volume, and thickness distribution. It is an area where considerable other activity, scientific and commercial, is on-going and offers opportunities for synergy.
- The Canadian Arctic Archipelago is an area that is greatly under-studied, especially where there are no operational needs, such as during freeze-up or in areas where there is no shipping. Because the channels are rather narrow, PMR and AMS data are not effective.
- The entire marine area around Antarctica and extending to the limit of iceberg drift is important to understand how the climate of the Antarctic differs from that of the Arctic. Of particular interest is West Antarctica in order to better understand the factors responsible for the rapid break-up of the ice sheet and sea ice transport in the Bellingshausen-Amundsen Seas.
- Comprehensive coverage of fast ice around the Antarctic ice sheet margins to understand the changes in ice sheet coastal dynamics.
- Marginal ice zones globally because of their importance for marine transportation, offshore resource development and biological activity.
- The Great Lakes–St Lawrence River system because of its large socio-economic impact.
- Lakes and large rivers of northern North America and Eurasia with particular emphasis on the Great Slave Lake/Great Bear Lake-Mackenzie River system; lakes in the Mackenzie Delta, Lena River Delta, Alaskan North Slope, Old Crow Flats, Hudson Bay Lowlands and the Canadian Arctic Archipelago; the Peace River and the Lena River system (especially if Russian collaborators can be found to undertake field studies).
- Barents Sea, Baffin Bay, Labrador Sea and around the Antarctic bases to observe icebergs in open water and in sea ice.

Although it is outside the scope of this study, it should be noted that there is a particular need for improved sea ice and iceberg information all around Antarctica during the shipping season (including real-/near real-time availability) to aid navigation and logistical resupply of the Antarctic bases.

8.2 Seasonality of Floating Ice Observations

The spring melt and autumn freeze-up periods are the most under-sampled times of the year but otherwise there is no seasonality to the requirement for sea ice and iceberg observations. There is a need for information to support scientific investigation in all seasons when ice is present or freeze-up is imminent.

9 A Satellite SAR Acquisition Strategy for Science Applications

This section outlines a broad strategy for SAR acquisitions to address the science requirements that have been outlined above. The general philosophy of this strategy is to:

- Aim for a complete coverage of the Northern and Southern Hemisphere ice regions on a daily basis, year-round, at C-band by integrating the baseline acquisition plans of the primary C-band satellites (RADARSAT-2, Sentinel-1, and RADARSAT Constellation Mission). C-band is important because it has the longest continuous time series of observations – a key requirement for climate research. The wide-area, consistent and frequent repeatability of both the Arctic and Antarctic is considered a basic essential by both the operational and scientific communities.
- Use additional acquisitions by the primaries (RADARSAT-2, Sentinel-1, RCM) to provide higher temporal resolution at C-band over particular target areas.
- Use acquisitions by other missions, especially X-band, to complement the primaries in order to increase spatial and temporal resolution.
- Overlap acquisitions by non-C-band missions with the primaries to provide multi-frequency observations.
- Take advantage of the high revisit time afforded by some satellite constellations (such as Cosmo-SkyMed and TerraSAR-X) to provide specific datasets for individual science projects requiring high temporal resolution.
- Acquire SAR data in several frequencies and polarizations for the purpose of comparing with PMR and AMS for cross-assessment and validation. The goal is to improve our understanding of PMR data not only to extend the area of coverage but also to provide complementary information, primarily for modeling applications.
- Undertake specific experiments to investigate the utility of SAR interferometry for measuring floating ice variables and to develop the necessary algorithms to exploit this capability in future.
- Design acquisition campaigns over targeted areas to investigate the potential of high-resolution quad-pol, compact polarimetry and fully polarimetric data.
- Coordinate acquisitions with known field campaigns - surface and/or aircraft - where possible.
- Target geographic areas that not only feature the ice characteristics of interest but are also synergistic with surface and airborne research campaigns and commercial activity (assuming that information-sharing agreements can be reached).

9.1 Multi-Resolution Nested Observations

Observing the same ice features at different resolutions can be valuable in understanding physical processes at various scales for model parameterization and to support development, refinement and validation of bulk flux models. Several campaigns should be designed around multi-sensor approaches where, for example, one or more sensors provide frequent, wide-area coverage at a coarser resolution while other sensors provide very high resolution with fully polarimetric, multi-frequency, multi-incidence angle capability, over more limited areas. The wide area sensor would provide the larger context for the fine resolution sensor. The Arctic Ocean and sea ice areas around Antarctica are the suggested geographic areas for these studies, with a priority to coverage of regions containing dedicated field operations and experiments.

9.2 Multi-Frequency Observations

9.2.1 C-band + L-band

Combining L-band with C-band has been identified as a priority for investigating many of the sea ice and lake/river ice variables, including the high priority sea ice thickness, snow cover and deformation variables. A valuable exercise would be to collect multi-polarization and/or full polarimetry C-band data (Sentinel-1, RADARSAT-2, RCM) as nearly coincident as possible with the ALOS-2 Polar Ice missions and potential SAOCOM missions. Coincident coverage should span the broadest areas of the Arctic and Antarctic offshore regions as possible at resolutions from 10-100 metres and with as frequent a repeat as possible. Three acquisition campaigns per year in autumn, winter and spring are necessary with a fourth in summer as a useful addition. To maximize data utility, the following geographic areas should be considered as part of the broader areal coverage:

- Acquisitions over Baffin Bay and the Barents Sea would have a high probability of imaging icebergs in both open water and sea ice to allow parallel investigation into iceberg detectability. There is potential synergy with the oil and gas industry in these areas as well.
- Acquisitions in Fram Strait during the melt season would support research into the applicability of L-band for sea ice motion with a wet surface as well as ice export from the Arctic Ocean.
- Acquisitions in the Beaufort Sea during the melt season would support research into the use of L-band for monitoring leads and polynyas under melt conditions.
- Acquisitions around the Antarctic coast would support research on landfast sea ice and polynyas.

In addition, more frequent coincident L- and C-band coverage of the Baltic Sea and Sea of Okhotsk during winter would be useful for investigating most sea ice variables including sea ice thickness, lead and floe size distribution.

Coincident C- and L-band has been identified for investigation of all of the lake and river ice variables. The ALOS-2 Basic Observation Scenario (Rosenqvist, et al., 2013) describes several acquisition plans primarily targeted at land but that could also be useful for observing northern lakes and rivers. While the SAOCOM mission plans are not available, there may be opportunity to include the SAOCOMs as well. It would be beneficial to coordinate C-band missions with ALOS-2 so as to acquire data as close in time and incidence angle as possible. C-band data should be collected with at least dual polarization and, preferably, full polarization. Daily acquisitions between ice-on and ice-off would be optimal but, given satellite constraints, daily acquisitions for several days at a time, repeated a few times during the ice season would be very useful. Target locations should be selected considering the availability of field campaigns. The Great Lakes is an obvious target location with high socio-economic value.

9.2.2 X-band + L-band

It is expected that the information content of X-band, for floating ice, will be quite similar to that of C-band. As such, there are no specific recommendations for unique X+L acquisitions. Rather, X+L missions could be used in place of C+L if they are more achievable.

9.2.3 *Multiple Frequencies*

There has been little success in observing the three high priority variables – sea ice thickness, snow cover and sea ice deformation – systematically with space-borne SAR so there is a dearth of knowledge to guide future acquisition plans. A majority of the community is expecting that some combination of frequency, polarization and incidence angles will yield breakthroughs. Various combinations of L-, S-, C-, X- and Ku-bands have been suggested as being a priority. Although it would be challenging to realize, a very worthwhile experiment would be to image a few target areas with as many of these frequencies as possible. The data would have to be acquired within a relatively short time span so as to minimize the environmental changes in the ice and snow. To maximize the data use, multi-polarization or full polarimetry should be acquired and at a high spatial resolution (<25m).

For investigations of sea ice thickness and snow cover, a high priority should be afforded to the Antarctic because so little is known about it. Besides that, areas with a relatively stable ice cover and atmosphere/ocean environment are suggested for multi-mission observations in order to relax the acquisition time window somewhat – perhaps to 1-2 weeks. Areas that could contain both landfast and pack ice in the same dataset are proposed, such as:

- Coastal Antarctica – e.g. Weddell Sea, Ross Sea, all of East Antarctica
- Coastal Arctic – e.g. Alaskan North Slope, Kara Sea
- Sea of Okhotsk

9.3 Increased Temporal Resolution

9.3.1 *C-band*

Obtaining a high temporal resolution of C-band data has been identified as a priority for observing many of the floating ice variables, including ice concentration; freeze-up and break-up (melt/freeze onset); melt ponds, leads and polynyas in sea ice; icebergs; sea ice motion; and, river ice thickness. This has also been noted as a requirement for better integration of SAR information with PMR and AMS data. It would be of great benefit to the scientific community to coordinate RADARSAT-2 and Sentinel-1 (especially after the second satellite is in operation), as well as RISAT-1 and -2, to increase the frequency of repeat observations over specific target areas. As a goal, several acquisitions per day with a spatial resolution of 10-25 metres should be acquired to resolve diurnal and tidal effects. At least dual polarization should be obtained, with multi-polarization and full polarimetry as available. Potentially valuable target areas are:

- Beaufort / Chukchi Seas
- Fram Strait
- Barents / Kara Seas
- Canadian Arctic Archipelago
- Weddell / Bellingshausen Seas
- East Antarctica
- Caspian Sea
- Sea of Okhotsk
- Targeted northern lakes and rivers

9.3.2 X-band

There is value in using the rapid re-visit capabilities of the TerraSAR-X and COSMO-Skymed constellations to obtain very frequent (i.e. multiple times per day) observations for a few days at a time of selected target areas. Observations would serve investigations of sea ice motion, deformation, polynya evolution and melt/freeze onset as well as studies of lake and river ice. At least dual polarization and preferably full polarimetry should be acquired with spatial resolutions from <10 to 25 metres. Potential target areas are:

- Beaufort / Chukchi Seas
- Fram Strait
- Barents / Kara Seas
- Canadian Arctic Archipelago
- Weddell / Bellingshausen Seas
- East Antarctica
- Caspian Sea
- Sea of Okhotsk
- Targeted northern lakes and rivers

9.3.3 L-Band

Frequent repeat of L-band acquisitions – as much as hourly – has been identified as a requirement for better understanding of ice deformation processes. Coordinated acquisitions of ALOS-2 and the SAOCOMs could perhaps come close to achieving this for a short period of time (few days) over a specific target area. Full polarimetry and fine spatial resolution (<10m) should be acquired if possible. The L-band SMAP radar (unfocused SAR) will have multiple polarizations including VV, HH, and HV and, with a resolution of 1-3 kilometres and very wide swath, will be useful for measuring a number of parameters characterizing floating ice (Entekhabi & Nghiem, 2011). Likely candidate target areas are:

- Beaufort / Chukchi Seas
- Hudson Strait
- Baltic Sea
- Parts of East Antarctica
- Sea of Okhotsk
- Caspian Sea

9.4 Multiple Polarizations

No additional specific recommendations for multi-polarization acquisitions are suggested. It is proposed that the suggestions above for multi-frequency and high temporal resolution will contain sufficient data at multiple polarizations to inform scientific investigations adequately.

9.5 Interferometry

A number of floating ice variables including icebergs, ice deformation, landfast sea ice and sea ice floe size distribution, as well as lake and river ice break-up, thickness, concentration and classification, have potential to be effectively characterized with interferometric SAR. Repeat-pass interferometry with sufficient temporal resolution (typically no more than a few days) can be used to investigate relatively stable ice regimes. The single-pass interferometry capability of the TerraSAR-X/TanDEM-X mission should be exploited to investigate this capability for more dynamic floating ice situations. The purpose of these experiments would be to develop the necessary algorithms to further this capability in future. Specific campaigns, ideally coordinated with field observations, are suggested with each campaign acquiring a small number of images at appropriate times of the year. Possible study areas are:

- Coastal Greenland, Baffin Island – grounded icebergs
- Alaskan North Shore, Caspian Sea, Baltic Sea, Hudson Strait – ice ridges
- Coastal Antarctic - landfast ice
- Beaufort Sea, Kara Sea, Weddell Sea, Baltic Sea– sea ice floe size distribution
- Great Slave Lake, Great Bear Lake, Lake Baikal – lake ice thickness
- Mackenzie River, Peace River, Lena River – river ice variables

10 Conflict and Collaboration: Opportunities for Data Sharing

Satellite SAR missions are rapidly progressing from the purely scientific domain to the commercial realm. A significant concern of the scientific community is that the need to acquire data for commercial activities will reduce the quantity and variety of data available for research. The data providers have legitimate concerns that making commitments to supply data for science will hurt their business cases.

In general, commercial activities demand regular, on-time delivery of information for precise geographic locations, upon which business decisions can be made. Generating this information requires the use of data, processing and analysis techniques that are known and repeatable. There is little room for experimentation. On the other hand, scientific research needs new types of data that can be processed in different ways and for areas that are often far from commercial activity.

Despite these differences, there is considerable potential for the two communities to collaborate to the mutual benefit of both. Commercial interests acquire much larger volumes of SAR data than most research projects can afford and these data are usually accompanied by coincident environmental information valuable for research. The scientific community provides the continuing growth of knowledge that allows commercial entities to further exploit SAR data in future. Many research projects are not time-sensitive and can comfortably use data that are days and weeks old and typically don't release results for months or years –traits that could allow the communities to share the same data while protecting the commercial value of timely data.

It is a hope and a recommendation that the SAR data providers recognize the potential benefits of working together and seek ways to maximize the collaboration between the commercial and scientific communities. They can play a significant role in identifying opportunities, bringing parties together and facilitating agreements for data sharing and data release. The agreement among NOAA, Shell, Conoco-Phillips and Statoil (NOAA; Shell; Conoco-Phillips; Statoil, 2011), could perhaps serve as a model for collaboration with satellite SAR data.

11 Conclusion and General Recommendations

In the course of interacting with the scientific community during this study, several other recommendations were made with respect to satellite observations and SAR in particular:

- The near-simultaneous observation by different sensor types (passive and active, operating in the optical, thermal, and microwave parts of the electromagnetic spectrum) is necessary to characterize many important sea ice processes.
- It is at the regional modeling level with high spatial and temporal resolution that SAR products provide their greatest support to human infrastructure. Multiple satellites in tandem or constellation orbits can provide the greatest benefit in support of human polar activities, especially search-and-rescue, maritime security, and sustainability of coastal polar communities.
- Scientific advancement in the use of SAR data could benefit from closer collaboration between operational ice services and research institutes dealing with floating ice. The cost and availability of satellite SAR data remain major obstacles for some researchers while the operational centres have access to large quantities of data. Operational centres can also contribute ancillary information, such as buoy data, and analysis expertise to the research effort.
- A vast quantity of satellite SAR data has been collected and saved. However, much of this data remains inaccessible to the research community for a variety of reasons including copyright, lack of metadata and catalogue information, network bandwidth limitations and resource and policy constraints within operational centres. Government and private holders of SAR data should be encouraged to make their data accessible to the scientific community.
- Field data, while challenging to acquire, are an essential component of remote sensing research, not least in terms of calibration and validation of satellite data-derived products. International collaboration is of great benefit in these efforts but needs continuing attention and support.
- Closer coordination of data acquisition and distribution among satellite operators and data providers would be highly beneficial to the scientific community. Use of a central portal for access to data in common formats, such as NetCDF and HDF, should be encouraged.

Now, and over the next few years, we will see more satellites with a wider range of sensors for floating ice than ever before in history. The general expectation in the scientific community is that this will allow greater diversity in the way ice is observed. Together with a higher frequency of repeat observations, this will lead to greater understanding of the cryosphere allowing us to better monitor, predict and adapt to our changing environment.

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Appendix B – Previous Work

The table below contains a summary of floating ice observation requirements identified in previous studies. Where available, the accuracy, spatial resolution and temporal resolution requirements are given in that order. For brevity, where some studies identified current, threshold, or target capabilities, only the target values are shown. Units have been converted for comparison purposes.

PARAMETER	**SEN4SCI 2012 - Goals**	**ESA Sea Ice CCI URD 2012 - Objective**				**GCOS 2011**	**IGOS 2007**		**IICWG 2007**		
SEA ICE		*NWP Regional*	*NWP Global*	*Ocean coastal*	*Climate*	*Climate*	*Operations*	*Climate*	*Operations*	*NWP*	*Climate*
Ice Extent / Ice Edge Location	0.5km; 1km; 24hr					5km; 1-5km; 7day	0.1km	1-5km	0.05-0.1km	5km	15km
Ice Concentration	5%; 5km; 24hr	5%; 1km; 3hr	5%; 5km; 24hr	2%; 1km; 6hr	2%; 15km; 24hr	5%; 10-15km; 7day	<5%, 10km; 24hr	<5%; 10km; 24hr	10%	5%	5%
Ice Classification	5%; 5km; 24hr	2%; 5 km; 24hr	10%; 10km; 24hr	5%; 2km; 6hrs			<5%, 10km; 24hr	<5%, 10km; 24hr	90%		
Ice Thickness	10cm; 0.5km; 24hr	10cm; 10km; 48hr	10cm; 20km; 48hr	5cm; 1km; 12hr	20cm; 5km; 24hr	10cm; 25km; 30day	10%; 0.5km;24hr	10cm; 25km; 30day	10cm	50cm	50cm
Leads / Polynyas	5%; 0.1km^2; 24hr						0.1km^2; 0.1m; 24hr	5%; 10km; 24hr	25m		1% of ice area
Meltponds (% area)								1-5%; 0.5km; 24hr	10%	10%	
Ridge Height								1m	1m	2m	
Ice Motion	1km/day; 1km; 24hr	2km/day; 1km; 6hr		2km/day; 1km; 6hr	4km/day; 5km; 24hr	1km/day; 5km; 7day	0.5km/day	1km/day	1km/day		1km/day
Snow Depth on Ice	0.5km; 5km; 24hr			5cm; 10km; 48hr				2cm; 5km; 24hr			
Melt Onset								24hr; 10km; 24hr			
ICEBERGS											
Size	30%; 10m; 24hr								25m		
Position	1km; 1km; 2hr										
Draft	1m; 1m; 24hr										
Drift Velocity	10%; 0.5km/day; 2hr										
FRESHWATER ICE											
River Ice Edge Location									3-10m		
River Ice Concentration							5%; 30m; 24hr	5%; 30m; 24hr	5%		
River/Lake Ice Concentration	5%; 30m; 24hr										
River/Lake Ice Thickness	2cm; 30m; 24hr										

Appendix C - Satellite SAR Systems

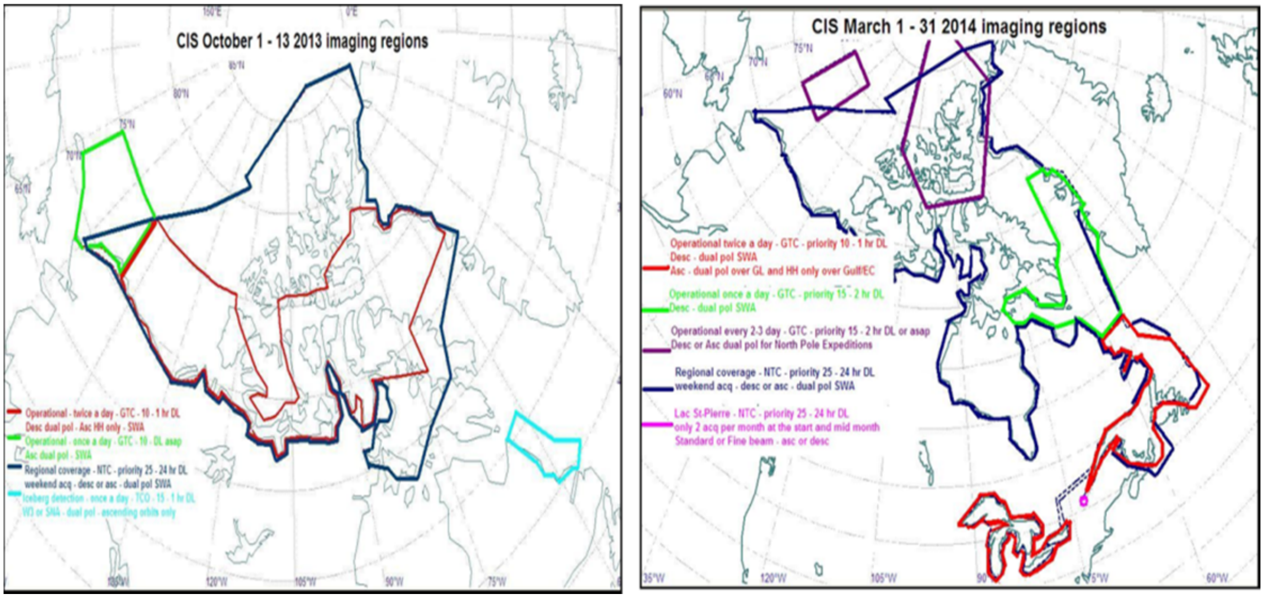
RADARSAT-2 (Canada)

Single Satellite
Operational
Frequency: C-band

Imaging Mode	Resolution (m)	Swath Width (km)	Incidence Angle Range	Polarization Options
Spotlight	2-5 x 1	18	20-49°	HH, VV, HV, VH
Ultra-Fine	2-5 x 3	20	20-49°	HH, VV, HV, VH
Fine	7-10 x 8	50	30-50°	HH, VV, HV, VH, HH+HV, VV+VH
Standard	18-27 x 25	100	20-49°	HH, VV, HV, VH, HH+HV, VV+VH
Wide	19-40 x 25	150	20-45°	HH, VV, HV, VH, HH+HV, VV+VH
ScanSAR Narrow	38-80 x 60	300	20-46°	HH, VV, HV, VH, HH+HV, VV+VH
ScanSAR Wide	72-160 x 100	500	20-49°	HH, VV, HV, VH, HH+HV, VV+VH
Extended High	16-18 x 25	75	49-60°	HH
Extended Low	23-53 x 25	170	10-23°	HH
Fine Quad-Pol	7-17 x 8	25	18-49°	HH+VV+HV+VH
Standard Quad-Pol	18-29 x 8	25	18-49°	HH+VV+HV+VH

(MDA, 2009)

RADARSAT-2 is owned and operated by MDA Corporation. MDA provides SAR data on a commercial basis to broad range of clientele, including the Canadian government which purchases large quantities of data for ice monitoring, marine winds, marine oil spill detection and vessel surveillance, among other applications.



Examples of Canadian Ice Service RADARSAT-2 acquisition plan (for illustration only)
Courtesy Canadian Ice Service

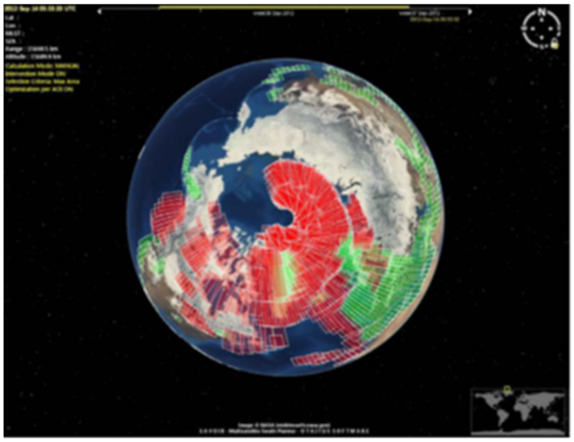
Sentinel-1 (European Space Agency)

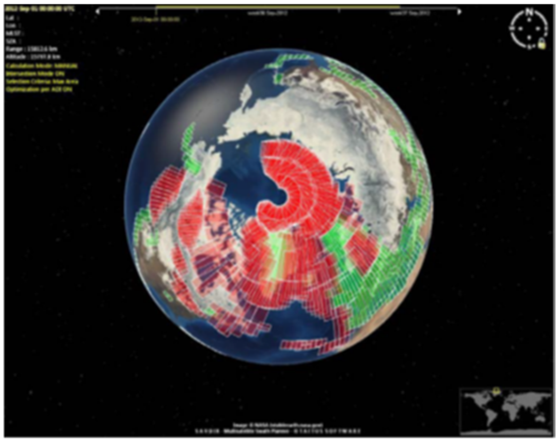
Two satellite constellation
Launches: Spring 2014 and late 2015
Frequency: C-band

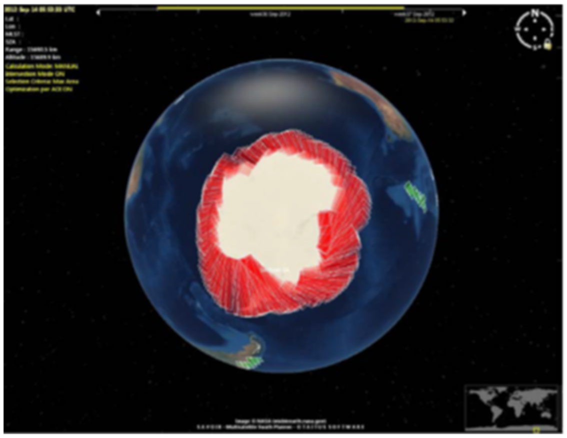
Imaging Mode	**Resolution** (m)	**Swath Width** (km)	**Incidence Angle Range**	**Polarization Options**
Stripmap Mode	5 x 5	80	18-47°	HH, VV, HH+HV, VV+VH
Interferometric Wide Swath Mode	20 x 5	250	29-46°	HH, VV, HH+HV, VV+VH
Extra-Wide Swath Mode	40 x 20	400	19-47°	HH, VV, HH+HV, VV+VH

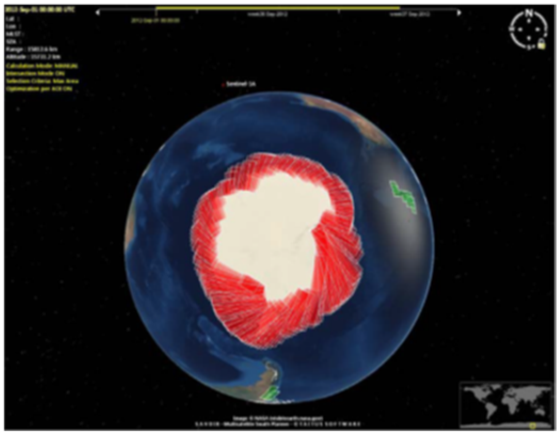
The European Space Agency (ESA) intends to operate Sentinel-1 in a stable imaging configuration to ensure systematic and routine provision of data allowing operational services to run on a routine basis. Once Sentinel-1 reaches its full operations capacity with two satellites, the predominant mode for sea ice areas will be Extra-Wide Swath with HH+HV polarization. Other modes will be used for specific operational situations or research projects. In the Arctic sea ice areas, daily repeat will be available for most areas. In the Antarctic, a repeat every 3 days is planned.

Prior to full operations capacity, there will be reduced repeat coverage available outside of European waters and the Antarctic coverage will be predominantly single polarization HH. (ESA Earth Observations Programme Board, 2013)









RADARSAT Constellation Mission (Canada)

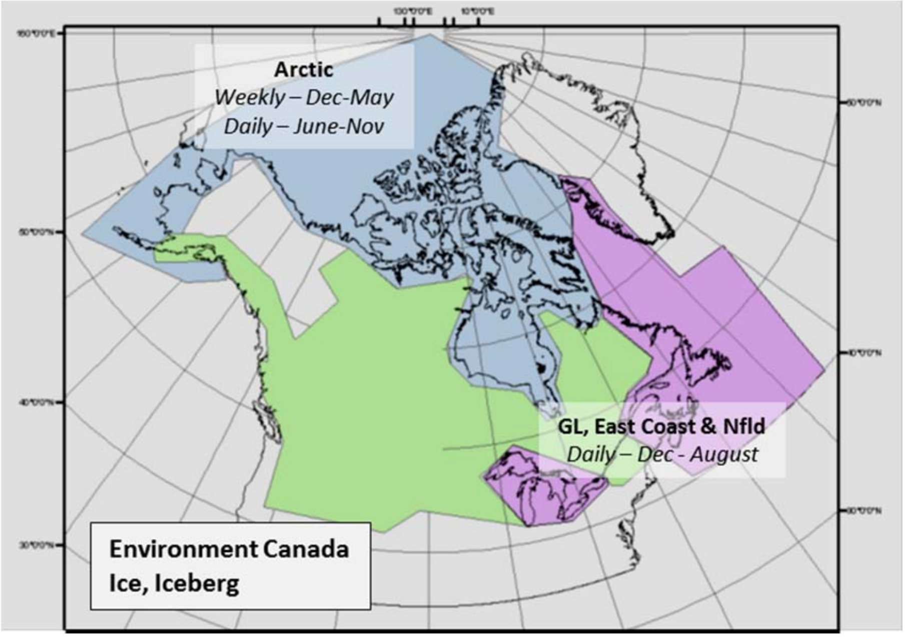
Three satellite constellation
Launch date: 2018
Frequency: C-band

Imaging Mode	**Resolution** (m)	**Swath Width** (km)	**Incidence Angle Range**	**Polarization Options**
Spotlight	3 x 1	5	19-47°	HH, VV, HV, VH, HH+HV, VV+VH, Compact
Low Resolution	100	500	19-55°	HH, VV, HV, VH, HH+HV, VV+VH, HH+VV, Compact
Medium Resolution 50	50	350	19-58°	HH, VV, HV, VH, HH+HV, VV+VH, HH+VV, Compact
Medium Resolution 16	16	30	20-47°	HH, VV, HV, VH, HH+HV, VV+VH, HH+VV, Compact
Medium Resolution 30	30	125	17-48°	HH, VV, HV, VH, HH+HV, VV+VH, HH+VV, Compact
High Resolution	5	30	19-54°	HH, VV, HV, VH, HH+HV, VV+VH, HH+VV, Compact
Very High Resolution	3	20	18-54°	HH, VV, HV, VH, HH+HV, VV+VH, HH+VV, Compact
Low Noise	100	350	19-58°	HH, VV, HV, VH, HH+HV, VV+VH, Compact
Ship Detection	Variable	350	19-58°	HH, VV, HV, VH, HH+HV, VV+VH, Compact
Quad-Polarization	?	>20	24-44°	HH+VV+HV+VH

(Canadian Space Agency, 2011)

Data Request:

- Medium Res Dual co- and cross-pol
- Availability of a Low-Noise Medium-Res mode for discrimination of low return features.
- Availability of higher res modes for Tactical Ship Routing and/or targeted Iceberg Detection.
- Compact Polarimetry on Medium Res (50m), High (5m), and Very High (3m) modes



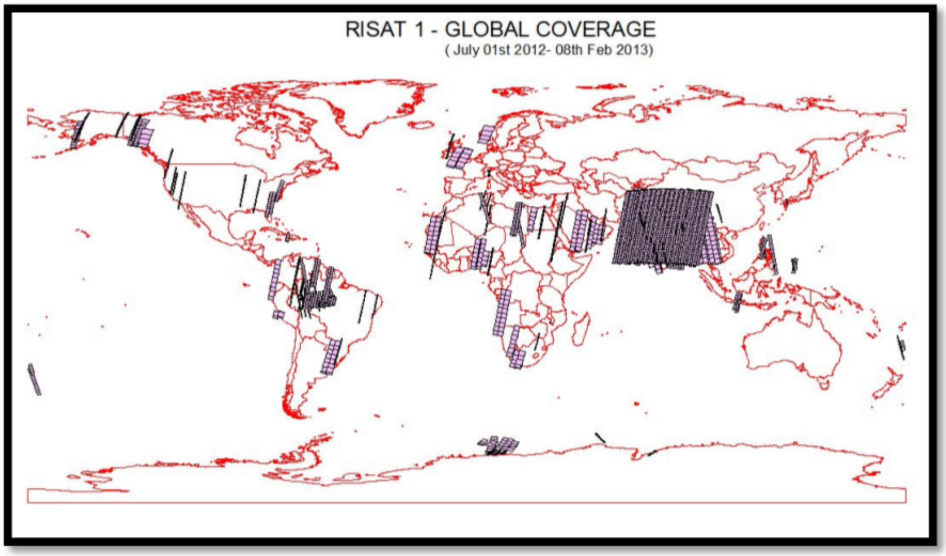
(Crevier & Flett, 2010)

RISAT-1 (India)

Two satellites
One operational; other on orbit
Frequency: C-band

Imaging Mode	Resolution (m)	Swath Width (km)	Incidence Angle Range	Polarization Options
FRS-1	2-13	25	11-49°	HH, VV, HV or VH (single) HH+HV, VV+VH (dual) RV, RH, Polarimetry
FRS-2	3-13 x 2-10	25	11-49°	HH, VV, HV or VH (single) HH+HV, VV+VH (dual) RV, RH, Polarimetry
FRS-2	10 x 5	25	11-49°	HH+HV+VV+VH (quad)
MRS	23 x 8-43	115	11-49°	HH, VV, HV or VH (single) HH+HV, VV+VH (dual) RV, RH, Polarimetry
CRS	48 x 45-135	223	11-49°	HH, VV, HV or VH (single) HH+HV, VV+VH (dual) RV, RH, Polarimetry
HRS (Spotlight)	1	10	11-49°	HH, VV, HV or VH (single) HH+HV, VV+VH (dual) RV, RH, Polarimetry

This information is taken from a presentation by Vinay K. Dadhwal, Director of the National Remote Sensing Centre of India in February 2013.



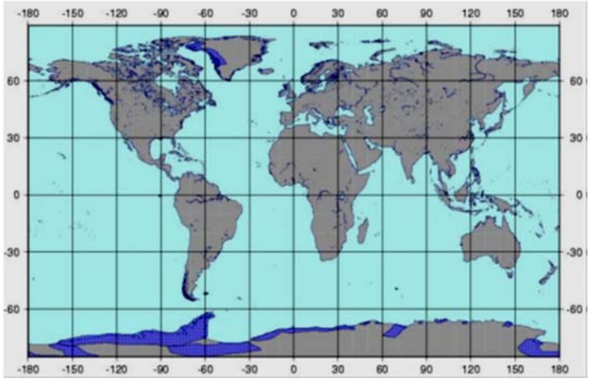
(Dadhwal, 2013)

ALOS-2 (Japan)

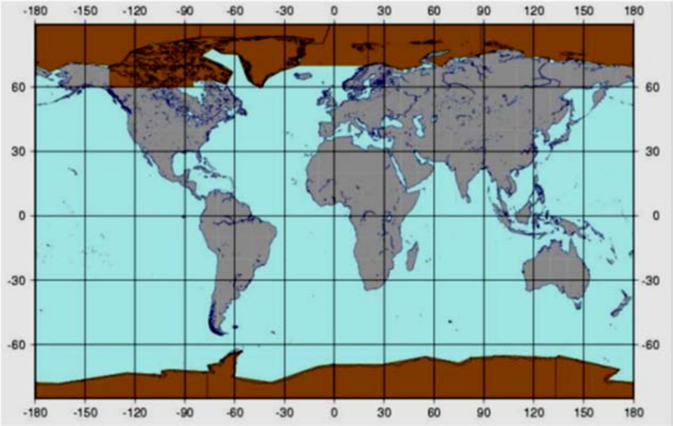
Single satellite
Planned launch in 2014
Frequency: L-band

Imaging Mode	**Resolution** (m)	**Swath Width** (km)	**Incidence Angle Range**	**Polarization Options**
Stripmap UltraFine	3	50	8-70°	HH, VV or HV (single) HH+HV or VV+VH (dual)
Stripmap High sensitive	6	50	8-70°	HH, VV or HV (single) HH+HV or VV+VH (dual) HH+HV+VH+VV (full) Compact pol
Stripmap Fine	10	70	8-70°	HH, VV or HV (single) HH+HV or VV+VH (dual) HH+HV+VH+VV (full) Compact pol
ScanSAR Wide	60	490	8-70°	HH, VV or HV (single) HH+HV or VV+VH (dual)
ScanSAR Nominal	100	350	8-70°	HH, VV or HV (single) HH+HV or VV+VH (dual)
Spotlight	3 x 1	25	8-70°	HH, VV or HV (single)

While primarily aimed at land applications, there is opportunity for ALOS-2 to image ice areas. A global systematic acquisition strategy has been developed that contains the following relevant information (Rosenqvist, et al., 2013).



Polar Ice
Temporal repeat: 3 cov/year
GSD: 10 m (off-nadir 32.5°)
Mode: Stripmap Dual-pol (HH+HV/28MHz)



Polar Ice
Temporal repeat: 3 cov/year
GSD: 100 m (off-nadir 26.2°– 41.8°)
Mode: ScanSAR 350km (HH+HV/14MHz)

SAOCOM (Argentina)

Four satellite constellation
Launch dates: December 2014, December 2015, 2019, 2020
Frequency: L-band

Imaging Mode	Resolution (m)	Swath Width (km)	Incidence Angle Range	Polarization Options
Stripmap	<10	>40	21-50°	HH, VV, HV, VH (single) HH+HV, VV+VH (dual)
Stripmap (Quad-pol)	<10	>20	18-36°	HH+HV+VV+VH (quad)
TOPSAR Narrow	<30	>150	25-47°	HH, VV, HV, VH (single) HH+HV, VV+VH (dual)
TOPSAR Narrow Quad-pol)	<50	>100	18-36°	HH+HV+VV+VH (quad)
TOPSAR Wide	<50	>350	25-49°	HH, VV, HV, VH (single) HH+HV, VV+VH (dual)
TOPSAR Wide (Quad-pol)	<100	>220	18-36°	HH+HV+VV+VH (quad)
TOPSAR Wide CL-POL	<50	>350	25-49°	RH+RV or LH+LV (circular)

(Frulla, Medina, Milovich, Ortega, & Thibeault, 2011)

The SAOCOM constellation is being developed by the Argentine national space agency (CONAE) in two phases. SAOCOM-1a and -1b will be launched first followed by the second two in later years. Although primarily aimed at agriculture, hydrology and health, there is likely some capacity to address floating ice science.

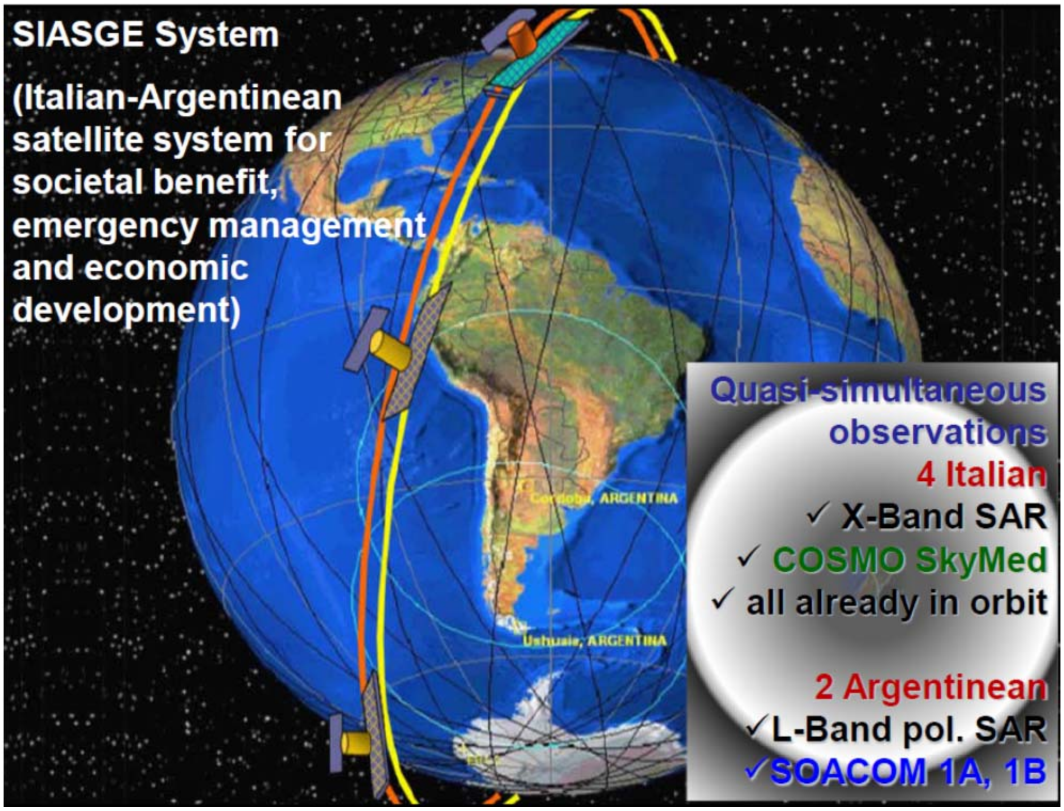


Image from (Frulla, Medina, Milovich, Ortega, & Thibeault, 2011)

TerraSAR-X / TanDEM-X / PAZ (Germany-Spain)

Three-satellite constellation
Currently TerraSAR-X and TanDEM-X are operational; PAZ launch in late 2014
Frequency: X-band

Imaging Mode	**Resolution** (m)	**Swath Width** (km)	**Incidence Angle Range**	**Polarization Options**
Stripmap	3	30	15-60°	HH, VV, HH+HV, VV+VH, HH+VV (single+dual)
ScanSAR	18.5	100	15-60°	HH, VV, HV, VH (single)
WideScan-SAR	40	up to 270	16-49°	HH, VV,HV, VH (single)
SpotLight	2	10	15-60°	HH, VV, HH+VV (single+dual)
High Resolution SpotLight	1	10	15-60°	HH, VV, HH+VV (single+dual)
Staring SpotLight	Down to 0.25	Depends on Incidence angle (e.g. ~8km at 20°)	15-60°	HH, VV (single)

TerraSAR-X and TanDEM-X are operated as a Public-Private Partnership between the German Aerospace Centre (DLR) and Airbus Defence and Space (formerly Astrium GmbH). PAZ (owner and operator: Hisdesat) is part of the Spanish National Earth Observation Programme and will be operated in the same orbit as TerraSAR-X and TanDEM-X. The three nearly identical satellites offer identical imaging modes (including Staring SpotLight and Wide ScanSAR) and can be operated independently or together for interferometry. The constellation offers up to 28 hour revisit time for monitoring and a 4/7 days revisit time for interferometric applications.

COSMO-SkyMed (Italy)

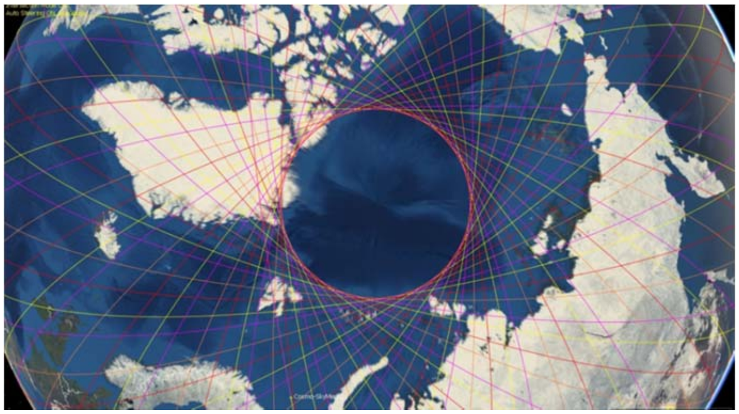
Four satellite constellation
Operational
Frequency: X-band

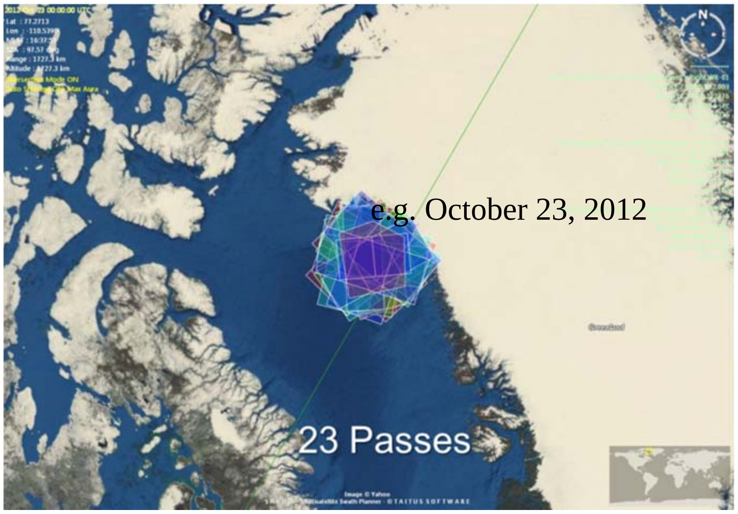
Imaging Mode	**Resolution** (m)	**Swath Width** (km)	**Incidence Angle Range**	**Polarization Options**
Stripmap HIMAGE Mode	3	40	20-60°	HH, VV, HV or VH (single)
Stripmap Ping Pong Mode	20 (multi-look)	30	20-60°	HH+VV, HH+HV, VV+VH (dual)
ScanSAR Wide Region	30 (multi-look)	100-160	20-60°	HH, VV, HV or VH (single)
ScanSAR Huge Region	100 (multi-look)	170-240	20-60°	HH, VV, HV or VH (single)
Spotlight-2	1	10	20-60°	HH, VV (single)

COSMO-Skymed is owned by the Italian Space Agency and the Italian Ministry of Defence and is operated by Telespazio and e-GEOS, with exclusive commercial data distribution through e-GEOS. The 4-satellite constellation affords acquisitions that can be very close in time or cover a larger area at fine resolution. The constellation can provide a minimum revisit of 18 minutes (same pass, different satellites) with several available intervals up to three hours. Interferometric revisit can be from 1 day to 16 days.

At 70° latitude:

- Can maximize revisit by acquiring up to 8 Right-looking + 8 Left-looking acquisitions
- Or maximize coverage, by using the right and left looking modes for each of the 4 satellites





Courtesy D. Giampaolo (e-GEOS)

METEOR-M (Russia)

Satellite series
Launch dates: N1(2009-2014), N2(2014-2018), N2-1(2014-2019), N2-2(2015-2020)
Frequency: X-band

Imaging Mode	**Resolution** (m)	**Swath Width** (km)	**Incidence Angle Range**	**Polarization Options**
Medium Resolution	400-500	450-600	25-48°	VV
Low Resolution	700-1000	450-600	25-48°	VV

Beginning with Meteor-M-N3, it is planned to upgrade the SAR as follows:
Launch dates: N3(2017-2022), MP-N3(2019-2024)
Frequency: X-band

Imaging Mode	**Resolution** (m)	**Swath Width** (km)	**Incidence Angle Range**	**Polarization Options**
Stripmap	5	30		HH or VV or HV or VH
ScanSAR Narrow	50	130		HH or VV or HV or VH
ScanSAR Medium	200	600		HH or VV or HV or VH
ScanSAR Wide	500	750		HH or VV or HV or VH
Spotlight	1	10		HH or VV or HV or VH

(WMO-OSCAR)

KOMPSAT-5 (Korea)

One SAR satellite in the KOMPSAT series
Launch date: 2013
Frequency: X-band

Imaging Mode	**Resolution** (m)	**Swath Width** (km)	**Incidence Angle Range**	**Polarization Options**
Standard mode (stripmap)	3	30	20°-55°	HH, VV, HV, VH (single polarization)
High resolution (spotlight)	1	5	20°-55°	HH, VV, HV, VH (single polarization)
Wide swath mode (ScanSAR)	20	100	20°-55°	HH, VV, HV, VH (single polarization)

Operated by the Korea Aerospace Research Institute (KARI), KOMPSAT-5 is the 5th satellite in the series but the only one that carries a SAR instrument (COSI – Corea SAR Instrument). The primary mission of KOMPSAT-5 is mapping and resource management over the Korean peninsula.

HJ-1C (China)

Single satellite
Operational
Frequency: S-band

Imaging Mode	Resolution (m)	Swath Width (km)	Incidence Angle Range	Polarization Options
Stripmap	5	40	31-45°	VV
Scan	20	100	31-45°	VV

(CRESDA)

NovaSAR-S (U.K. Commercial)

Single satellite
Launch date: earliest is latter part of 2015
Frequency: S-band

Imaging Mode	Resolution (m)	Swath Width (km)	Incidence Angle Range	Polarization Options
Stripmap	6	25-20	16-31°	HH+VV+HV+VH
ScanSAR	20	100	16-30°	HH+VV+HV+VH
ScanSAR Wide	30	140	14-32°	HH+VV+HV+VH
Maritime Surveillance	30	750	48-73°	HH+VV+HV+VH

(Surrey Satellite Technology Ltd.)

Appendix D – Acronyms

ALOS	……	Advanced Land Observing Satellite
AMS	……	Active Microwave Scatterometer
AMSR	……	Advanced Microwave Scanning Radiometer
ASAR	……	Advanced Synthetic Aperture Radar
ASCAT	……	Advanced Scatterometer
AVHRR	……	Advanced Very High Resolution Radiometer
CliC	……	Climate and Cryosphere Project
CONAE	……	Comisión Nacional de Actividades Espaciales (Brazil)
COSI	……	Corea SAR Instrument
DEM	……	Digital Elevation Model
DLR	……	Deutsches Zentrum für Luft- und Raumfahrt (Germany)
ESA	……	European Space Agency
FYI	……	First Year (sea) Ice
GCOS	……	Global Climate Observing System
GPM	……	Global Precipitation Measurement
HDF	……	A set of file formats and libraries designed to store and organize large amounts of numerical data
HH	……	Horizontal Transmit - Horizontal Receive (SAR polarization)
HV	……	Horizontal Transmit - Vertical Receive (SAR polarization)
IGOS	……	Integrated Global Observing Strategy
IICWG	……	International Ice Charting Working Group
KARI	……	Korea Aerospace Research Institute
MYI	……	Multi-Year (sea) Ice
NASA	……	National Aeronautics and Space Administration
NESDIS	……	National Environmental Satellite, Data and Information Service
NetCDF	……	A set of software libraries and self-describing, machine-independent data formats that support the creation, access and sharing of array-oriented scientific data
NOAA	……	National Oceanic and Atmospheric Administration
NSIDC	……	National Snow and Ice Data Center
NWP	……	Numerical Weather Prediction

OSCAR	……	Observing Systems Capability Analysis and Review Tool
PMR	……	Passive Microwave Radiometer
RCM	……	RADARSAT Constellation Mission
RISAT	……	Radar Imaging Satellite
SAOCOM	……	Satélite Argentino de Observación Con Microondas
SAR	……	Synthetic Aperture Radar
SEN4SCI	……	Sentinels for Science
SMAP	……	Soil Moisture Active-Passive (satellite)
SMMR	……	Scanning Multichannel Microwave Radiometer
SMOS	……	Soil Moisture and Ocean Salinity (satellite)
SSM/I	……	Special Sensor Microwave Imager
SSMIS	……	Special Sensor Microwave Imager Sounder
UNFCCC	……	United Nations Framework Convention on Climate Change
VH	……	Vertical Transmit - Horizontal Receive (SAR polarization)
VIS/IR	……	Visible / InfraRed (includes near- and thermal infrared)
VV	……	Vertical Transmit - Vertical Receive (SAR polarization)
WCRP	……	World Climate Research Program
WMO	……	World Meteorological Organization
WWRP	……	World Weather Research Programme