# Preliminary Research Plan for Glacial Ice Hazards

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Environment Canada

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# EXECUTIVE SUMMARY

The Marine and Ice Services Division (MISD) of Environment Canada has agreed to take on a larger role in iceberg charting and forecasting in the context of its participation in the North American Ice Service (NAIS), and in light of the increased role for Canada in the new MET AREA definitions. This increased role will be felt first in Applied Science and is expected to trickle down to operations in later years.

Automated satellite detection of icebergs in ocean water is making strides forward due to availability of cross-pol SAR data with reasonably low noise floors, but discrimination between vessels/gear, and berg detection in sea ice remain challenging and operationally relevant. Smaller bergs can now be detected more reliably in a wider range of wind conditions. It may become possible in the next 5 years to track individual bergs in open water but some targeted research effort is needed in SAR detection/discrimination and drift modelling.

The drift model is in good shape and is well positioned to evolve, but the rest of the system supports only manual re-sighting of bergs on multiple observations, and the model does not adjust predictions to propagate observed drift velocity. In that sense the model is not fully able to use more frequent satellite detection to improve trajectory predictions. Furthermore the drift model does not support probabilistic modelling which would be helpful in estimating risks to navigation, and in allowing automated resighting of bergs over periods on the order of 24 hours (i.e. the time between expected satellite detections).

Statistical modelling of non-deterministic portions of the iceberg or ice island motion can be started on immediately using the methods of Garrett [Garrett, 1985ab] [deMargerie, 1985]. However improvements in modelling of iceberg deterioration and drift are hampered by a dearth of suitable *in-situ* observations. Basic physical processes need to be verified and then perhaps models can be simplified and better tuned. There is a need to support more and different observations in collaboration with partners. This is still applied science because it stands in the way of producing better charts. Elements will include advanced beacons reporting at fine time intervals, in-situ measurements of mass, Doppler current profiles and water temperature profiles under icebergs and ice islands, and met stations on large tabular ice islands to get actual surface barometric pressure, temperature and winds acting on the glacial ice mass.

Collaboration is important and MISD needs to foster more of it in a coordinated way. Ocean modellers, field people, academics, industry all have much to contribute and a series of biannual iceberg meetings should be sponsored by MISD Applied Science, but probably held in St John’s.

Transition to operations and operational participation in the planning of validation is important in order to get buy-in and up-take of improvements in iceberg detection, tracking and modelling.

## Acknowledgements

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# 1.0 INTRODUCTION

## *1.1 Context*

After a brief boom in iceberg research in the mid 1980's, two decades of comparatively little research activity followed. Operational needs for definition of the southern iceberg limit are being met by the International Ice Patrol, and industry is meeting iceberg management needs for offshore oil production which has concentrated on the Grand Banks. Climate change, renewed off-shore exploration further North, and political[1] and economic factors are creating the conditions for another surge in iceberg detection, trajectory prediction and deterioration modelling research. The challenge is significant because the areas of operational interest are huge, the risks are real, and there will have to be a shift from primarily airborne detection to satellite detection using synthetic aperture radar.

Environment Canada will assume a growing role in ice hazard charting and forecasting as part of Canada's commitment to provide marine meteorological services for additional MetNav Areas. This will be facilitated through collaborations with counterparts in the United States through in the context of its participation in the North American Ice Service (NAIS). This increased role will be supported by Marine and Ice Services Division's Applied Science Section in collaboration with EC Science and Technology Branch with R&D advances expected to transition to MISD Ice Operations on a regular basis. Through these collaborations, MISD Applied Science must address the current and future needs of MISD operations.

NAIS includes MISD (Environment Canada), the US National Ice Centre (US Navy), and the International Ice Patrol (IIP which is managed by the US Coast Guard and funded internationally). Since the Titanic disaster, the IIP has been in charge of defining the iceberg limit in the vicinity of the Grand Banks of Newfoundland for safe crossing of trans-Atlantic shipping. IIP has been asked to try to find ways of reducing their usage of Hercules HC-130J aircraft they currently used as their primary source of surveillance because this limited shared resource is in demand. At the same time, Canadian resource interests along the Labrador Coast and up into Davis Strait and Baffin Bay are mandating that the chart scope should at some point be expanded and the current crude iceberg density indications be improved. As the Northwest Passage opens up there will be a need to provide some kind of guidance to approaches as well as scientific support to help shape policy on how this route will be used by the international community.

[1] The Newfoundland government has imposed a research levy on the petroleum companies which has accumulated approximately $100m. This money is to be spent in Newfoundland on relevant R&D. A component of this is available for industry led initiatives.

Through participation in the World Meteorological Organization, Canada has agreed to take shared responsibility to provide forecasts for the entire north for domestic use and for the benefit of the international community. Currently, forecasts are rather poor because of a lack of observations and the need to apply resources in the south where Canadians demand high quality forecasts. Enhanced iceberg charts will be part of this expanded mandate and this is linked to sovereignty and Canadian's desire ensure safe and environmentally sound access to the Northern shipping routes.

Trends in satellite remote sensing show that Canada will soon have access to more frequent and capable synthetic aperture radar imagery that would better support iceberg detection. More frequent and reliable detection over large areas should improve the scope and accuracy of iceberg charts. It is important at this juncture to understand what can be done in terms of detection, and what changes will be needed in iceberg drift and deterioration models in order to exploit more frequent and abundant satellite detections with the aim of producing new and useful charts for icebergs.

## *1.2 Objectives and Scope*

The objectives were to survey literature and available experts and define some possible research directions for MISD Applied Science that would satisfy the research needs of Canada and NAIS in iceberg charting. The scope was to be 2 years.

This document attempts to define a range of required research that far exceeds the capacity of MISD Applied Science, with the idea that a subset of a coherent whole must be selected, and other partners be encouraged to tackle complementary components. As a consequence a wide review and engagement process will be needed to find some consensus on the overall research needs, and to foster collaboration.

Similarly the timeframe considered is larger, perhaps 6 years. The problems will take more than 2 years to resolve, however we define short term actions within the expertise of the Applied Science section that are consistent with the most pressing issues and with building collaborations that will be needed.

## *1.3 Methodology and Sources*

The primary methodology was through interviews with current and past experts in iceberg research but also related areas like satellite detection and oceanography. This was supported by a review of literature.

The consultation undertaken for this report is believed to be reasonably comprehensive since neither the number of experts nor the number of scientific papers were very large. The field of iceberg detection, drift modelling and deterioration modelling is very specialized and furthermore much remains to be done to observe the fundamental principles and to achieve operationally satisfactory models.

Icebergs affect a relatively small subset of cold oceans, and these places have tended to be remote, difficult to access and of limited economic interest until recently. For these reasons much progress could be made if some effort is made to push ahead with research into glacial ice hazards.

# 2.0 SURVEY OF CURRENT PRACTICE AND FUTURE DRIVERS

## *2.1 Current and future iceberg information products*

In the current CIS and IIP charts, the Limit of All Known Ice (LAKI) is well supported, but that includes only the southern limit and benefits from intensive airborne surveillance from HC-10J Hercules aircraft. The density counts are not believed to be reliable and could even be misleading. For economic, climatic and political reasons future charts must cover a much wider geographic area and be useful for operations and shipping within the iceberg zone. Since the new coverage will be an order of magnitude larger and more remote, it will not be practical to use airborne surveillance resources which are already dwindling.

> *"The meagre iceberg year in 2010 was due to strong persistent winds from the East which drove the icebergs onto the Labrador Coast where they died. Only one iceberg crossed the 48$^{th}$ parallel in 2010. The year before was a huge year with more than one thousand icebergs crossing 48N."*
> ***Luc Desjardins***

The iceberg chart products do an excellent job of defining the LAKI for trans-Atlantic shipping, but do so at very high cost using increasing scarce airborne assets. The charts do not provide useful guidance along the Labrador coast, in Davis Strait, in Baffin Bay, in Hudson Strait or the Strait of Belle Isle or, critically, in approaches to key infrastructure such as the oil refinery in Comebychance[2] or the nickel and iron concentrators at Edward's Cove near Voisey's Bay.

> *"Along the Labrador coast the berg trajectories can meander a lot, but 1 degree of latitude southward per week is a good rule of thumb."*
> ***Luc Desjardins***
> "*Along the Labrador Coast icebergs will drift south at a rate of about one third of a knot. This is a pretty good estimate most of the time."*
> ***Don Murphy***

The iceberg chart products from CIS and IIP are harmonized by using common models and by

[2] The North Atlantic Refinery has more tonnage of traffic coming through it than any port in Canada. The Petroleum tankers also pose a potential environmental threat in the event of an accident.

synchronizing the active iceberg database. However many of the airborne sightings are spaced widely in time (2-4 weeks) and the drift model which, according to drift model researchers, only has skill over about 5 days maximum is called upon to project drift trajectory for 10 to 30 days.

The sightings database relies a great deal on expensive airborne surveillance either through USCG Hercules flights or commercial surveillance flights by Provincial Aerospace Ltd of St John's. Many entries come from other sources such as ship reports and commercial airline reports but these are of variable quality. There are limitations on airborne resources for the Hercules (HC-130J) currently tasked by the IIP. Expense and logistics[3] dictate the 2-4 week intervals between airborne surveillance. Some satellite detections come into the database but these are currently sporadic[4] and do not benefit from advanced modes of RADARSAT-2 nor, of course, future satellite SAR sensors.

In future we must do a better job of showing where glacial ice hazards may exist beyond showing the southern LAKI. Industry is providing solutions for specific sites but hydrocarbon exploration around Greenland could benefit from larger scale efforts and potential user of the Northwest Passage will require some guidance on when they need to reduce speed and increase vigilance. Larger bergs can be seen on a ship's radar, but bergy bits and growlers may be difficult to see especially in bad weather. In such cases the captain can only reduce speed in anticipation of a risk of impact to improve safety.

*"Opening of the Northwest Passage will make iceberg charting more important in Davis Strait and Baffin Bay. It may be that charting can be done mainly for approaches to the Northwest Passage rather than for all of the North Atlantic"*
***Pablo Clemente-Colon***

## *2.2 A changing North and shifting responsibilities for Canada*

Climate drivers and economic factors have made detection of drifting glacial ice hazards more relevant and critical.

There has been several high profile calving events in recent years where large pieces of glacier tongues detach and form massive ice islands. These have waterline lengths of kilometres, and have very small draft to mass ratios which are not amenable to modelling using the current drift model. Their large size will make them easier to detect in open water, but they may be easily confused with much weaker sea ice floes. Current

[3] The USCG Hercules are stationed in Elizabeth City Air Station (ECAS), North Carolina and must mobilize to and from St. John's for a five day mission approximately every 2-3 weeks.
[4] Over the past few years C-CORE of St John's has provided iceberg sightings to the database using satellite detections derived from ENVISAT ASAR. This has been provided free of charge as a by-product of their research contracts with the European Space Agency.

operations on the Grand Banks are at risk because their shallow draft will allow ice islands to move over the shallows, whereas very large conventional bergs would be grounded before coming onto the Banks.

The opening of the Northwest Passage to navigation for a large fraction of the year means there is likely to be a greater need for Canada to exert its sovereignty over the new shipping routes in order to regulate, protect the environment, and respond to emergencies. A large part of this is awareness of the weather and other hazards such as glacial ice. The current charts only cover the Grand Banks and a small portion of the Labrador coast, and are far too small in scope and function to meet this challenge. More charts and more useful charts are needed to meet the needs of shipping and to support policy decisions.

According to the Arctic Marine Shipping Assessment, in the near term the traffic is likely to be destinational (cruise ships to Greenland, etc.). Eventually, there might be significant traffic in the Northwest Passage.

There has been a burst of offshore petroleum exploration around Greenland, driven by the rising cost of oil. The ice management community in St. John's has deployed to West Greenland in recent years to support exploratory drilling. Exploration is also active in Southern and Eastern Greenland. Canada would certainly be called upon to respond in the event of spills or rescue operations, and may suffer environmental damage in the event of an accident. While drill ships working in the remote North are supported by supply ships and surface radars, the big picture is lacking and no information is available in years between exploration cruises. Satellite imagery can contribute information here where airborne deployment is very costly and where there is little in the way of accumulated operational experience.

> *"The most damaging icebergs are the growlers or bergy bits about the size of a car or bus that are often difficult to see from a ship using radar or the naked eye. They are also generally too small to be seen with wide swath SAR."*
> ***Luc Desjardins***

The Meteorological Service of Canada (MSC) has been assigned expanded responsibilities for weather prediction by the WMO as part of the MET AREA changes. While MSC prepares forecasts for these areas, the quality is commensurate with the rather sparse population. The weather models are fed by relatively few observations, and for this reason the quality is hard to verify and anecdotally known to be rather poor. The resources available in terms of manpower are very limited, and under the current organisational structure the emphasis within the Prairie and Northern Region has to be the public broadcasts for the prairie population centres. Any expanded capability related to icebergs has to be as automated as possible.

There are two main technology areas in which the advancements are noteworthy and relevant: 1) improvements in satellite remote sensing technology using synthetic aperture radar (SAR); and 2) improvements in oceanographic models. These two areas are the subject of the next two subsections.

## *2.3 Satellite remote sensing technology improvements and developments*

At time of writing, Canada is implementing phase C of the RADARSAT Constellation Mission (RCM) – a system of three SAR satellites expected to launch in approximately 2015. RCM promises to offer more frequent (daily) coverage of Canadian waters. Furthermore the European Space Agency is launching the Sentinel-1 system of two SAR satellites beginning in 2013. RADARSAT-2 modes have also recently been developed which combine high resolution, dual polarization, and low noise floor with relatively wide swath. All of these suggest that sufficient high performance resources will be available in 5 years to allow systematic detection of medium and larger icebergs (60 m waterline or longer) on a daily basis in parallel with other marine applications.

The currently planned SAR systems will emphasize use of dual polarized SAR, typically HH/HV wide swath scanSAR modes. We can expect daily or better coverage of iceberg infested waters and detection of medium and larger bergs in typical wind conditions. The combination of the cross pol data and low noise floor of modern SAR systems reduces interference from wind-driven sea clutter and permits detection of returns from bergs within thermal noise of the sensor at a wide range of incidence angles. With like-polarized SAR data sea clutter will obscure icebergs at even moderate wind speeds, especially with smaller incidence angles. Also important is a larger pool of imaging resources so that the important sea ice and wind measurement applications can co-exist with the iceberg detection application.

> *"Honest oceanographers will admit they usually cannot make deterministic predictions. Therefore statistical methods are needed."*
> ***Chris Garrett***

## *2.4 Ocean modelling technology improvements and developments*

Legacy ocean models have been criticized because of their use of climate data rather than observations, and coarse resolution grids of 15 km or so. More recent models such as C-NOOFS, however, are expected to become pre-operational at CMC as early as late 2011. C-NOOFS will supersede CECOM and is expected to be much more useful for iceberg prediction than previous ocean models, although eddies and inertial oscillations will continue to be poorly modelled because of the lack of suitable observations at sufficiently[5] dense scale.

[5] While hurricanes have typical extent of 1000 km, eddies in water will have typical extent of 30 km due to the difference in density between ocean and atmosphere. For this reason the observations and grids needed for oceans are far denser than for the atmosphere. The improvements seen in atmospheric modeling in recent

C-NOOFS uses ocean surface height measurements from satellite radar altimetry and have grids of 1/12$^{th}$ of a degree (approximately 4 km or better at relevant latitudes). They are also able to assimilate other kinds of measurements. C-NOOFS is currently being upgraded and is expected to have very accurate tidal effects. It is hoped that this will allow modelling of some of the tidally induced loops in observed berg trajectories. It is expected that this will make a significant difference in the performance of iceberg drift models, although these improvements must also be supplemented by frequent iceberg detection to refine iceberg position and drift parameters.

While ocean models will improve over the next decade or two, it is unrealistic to expect them to resolve and accurately predict the small eddies which influence iceberg motion especially in areas like the Labrador coast where the eddy diameter can be as small as 10 km. The reasons are the required density of the model spatial grid as well as the required density of ocean observations are out of reach and will remain so for at least a decade.

For the foreseeable future, eddy-induced and inertial oscillation-induced motion of icebergs can only be predicted by the motion of icebergs themselves or possibly examination of the SAR imagery which may hint at the spatial patterns of the eddy surface. This is especially visible when sea ice is present.

## *2.5 The bi-directional linkage between detection and modeling*

The ability to reliably detect medium sized and larger icebergs in a wide variety of sea states on a daily basis means that different kinds of models will be needed. These models will have to have the following properties:

1. They will need to be able to automatically associate detections at different times with unique individual iceberg tracks when the density of bergs is sparse enough and/or the bergs are distinctive enough to be discriminated from each other. Currently re-sightings must be flagged manually by the operator, and this is difficult and fraught with error.
2. They will need to use the observed tracks of some bergs to infer the likely future trajectory for a short time into the future on the order of

> *"Tidally induced currents will probably be accurately modelled in C-NOOFS in 6 months to a year. Eddies and Inertial Oscillations due to sudden changes in wind will not be properly modelled for at least a decade and maybe much more because the weather people driving the development do not require that level of detail."*
> ***Charles Hannah***

decades are therefore not going to be repeated for ocean modeling unless huge investments in a global observation network are made.

24 hours. The deterministic portion of iceberg drift will still rely upon existing models, but the residual motion can best be handled statistically.

In addition

3. Where tracks can be automatically maintained and analysed, the trajectory response to wind and modelled currents might allow characteristics of the individual ice mass to be extracted (e.g. mass, wind drag, draft or some combination of these).
4. Models will need to model the likelihood of sub-detection smaller bergs (i.e. small bergs, bergy bits, and growlers) within a zone near the parent berg[6].
5. Models will need to estimate when and where the bergs will deteriorate entirely, thereby defining the limit of icebergs within a charted region. Currently, the operator must manually delete bergs from the sighting database based on percentage of melt.

# 3.0 SAR DETECTION OF ICEBERGS

In order for SAR detection of icebergs to be practical, we assume that it is fundamental that detection would be automated, using the K-CFAR technique described in [Power, 2001] and [Lane et al, 2004], and assuming open water. K-CFAR is well-established, published in detail, and performs well. More difficult is the discrimination of icebergs from other targets such as fishing gear, and this remains an unsolved problem.

## *3.1 Relevant modes of existing and coming SAR satellites*

Currently the best SAR satellite system for iceberg detection in orbit is RADARSAT-2. C-CORE has shown that the cross pol channel of dual polarization modes of RADARSAT-2 when used in a wide swath mode such as ScanSAR Narrow provides excellent performance for medium sized bergs (i.e. 60 -120 m) in a variety of wind speed conditions. [C-CORE, 2010] While icebergs could be seen in calm winds without dual pol, calm winds are very rare in the North Atlantic and it is difficult to justify expending imaging resources without having assurance that bergs will be visible. The primary difficulty in using RADARSAT-2 is that the sea ice application typically

> *"The combination of a cross polarized channel and low noise floor in modern SAR satellites like RADARSAT-2 and Sentinel-1 makes good iceberg detection possible if the resolution is similar to the waterline length of the iceberg."*
> ***Desmond Power***

[6] The work of [Crocker, 2004] is an initial attempt to gather relevant data.

uses the ScanSAR Wide mode, which has a much wider swath, but limited resolution. Detection of icebergs in clutter requires decent resolution to achieve good contrast. The operational imperative to provide sea ice charts makes it difficult to get time on the satellite to run dual pol ScanSAR Narrow beams.

The Sentinel-1 system is a two satellite SAR constellation [ESA, 2010] expected to be available within a few years. The Interferometric Wide Swath (IWS) mode of Sentinel-1 is expected to be able to reliably detect small icebergs (i.e. 15-60 m waterline length) over a 250 km swath, whereas the Extra Wide Swath (EWS) should be able to detect medium bergs (60-120m waterline length) over a 400 km swath. IWS has resolution of 20m, whereas EWS has a resolution of 50m (similar to RADARSAT-2 ScanSAR Narrow). Both of these are dual polarization modes, and the engineers expect to exceed the noise floor specification of -22dB NESZ by a wide margin. As explained elsewhere in this report, dual polarization and low noise floor are the characteristics which permit reliable detection of icebergs in a variety of realistic wind conditions. The resolution determines the size of the bergs that can be detected.

The RADARSAT Constellation Mission [MDA, 2009] is expected to be a three satellite constellation which could launch 3 years after Sentinel-1. The Medium Res mode should be good for detecting medium bergs over a 350 km swath width, but there is some concern that the noise floor may be just within the -22 dB NESZ spec which would lead to poorer performance than RADARSAT-2 ScanSAR Narrow. The higher resolution modes do not cover sufficient swath width to be very useful for berg detection. The Low Noise mode of RCM has quite poor resolution of 100m, but it is possible that other than large icebergs may be detectable if the background clutter is low. The dual polarization mode should be used to achieve good performance under typical wind conditions.

Other satellites such as COSMO SKYMED and TerraSAR-X have such narrow swaths that they are not expected to be of value for iceberg detection because they cannot cover the large areas of interest in reasonable timeframes.

## *3.2 Minimum detectable size and detection/false alarm performance*

The dual pol ScanSAR Narrow mode is the operationally relevant mode of RADARSAT-2, although it would be useful to extend the results to the soon-to-be-operational Ocean Surveillance Very-Wide Near (OSVN) mode of RADARSAT-2 which is expected to be available in June 2011. It is likely that OSVN will also have good performance similar to ScanSAR Narrow, but with a much wider swath width (530 km instead of 300 km). All statements below apply to ScanSAR Narrow mode.

New results show that HV polarization should be used for iceberg detection in open water over the majority of the swath, while HH polarization should be chosen for detection in sea ice. Medium and larger icebergs can be detected in realistic 5-10 m/s wind speeds in open water with probability of detection (PoD) well above 80% in typical conditions. In first year sea ice, medium and larger bergs can be detected in the HH channel with a PoD of about 5-10% lower than the open water case. In multi-year sea ice (and presumably mixed sea ice) the best PoD is in HH channel but that is rather poor at about 65% for large bergs only, with no significant capability for medium nor small bergs. The reader is referred to Appendix III, excerpts from the 2010 C-CORE report on iceberg detection using RADARSAT-2 for the full detail and influences with incidence angle, wind direction, and wind speed.

In open water for SCN mode with 5 to 10 m/s wind speed, the cross pol channel (HV) is best at detecting medium icebergs at all wind directions. The performance is in the range of 85% probability of detection. For large icebergs the probability of detection is on the order of 95%. For small bergs and the furthest incidence angles there is evidence of a small advantage in using HH for the far edge of the swath only. For small bergs the PoD is closer to 75-85%, which is reasonable.

In first year sea ice for SCN mode, the like polarization (specifically HH) is better than the cross pol channel. In first year ice, large icebergs have PoD on the order of 90%, and this drops to about 80% for medium bergs. For small bergs PoD in first year ice is on the order of 50% and this drops off with incidence angle. There is some evidence that at the near edge there may be a slight benefit to using the HV channel to get an extra 5% PoD. It is unclear that this result would hold in heavily rafted first year ice. If a dual pol product is ordered, both HH and HV can be available and used by an automation detection algorithm.

> *"In operations we sometimes see icebergs in sea ice because of linear tracks of disturbed ice or open water as the bergs move relative to the sea ice. This can happen if the bergs are grounded or if they are moving independently of the sea ice due to currents at greater depth."*
> ***Darlene Langlois***

In multi-year sea ice only large bergs can be seen in the HH channel only with marginal PoD of about 65%. Medium bergs are typically below 50% PoD in multi-year ice, and small bergs are at about 25% PoD which is unusable.

### *3.3 Effect of environmental conditions (wind, sea ice, other)*

Anything less than very low wind conditions in open water used to severely limit the open water iceberg performance for RADARSAT-1 which permitted only HH polarization. With use of the HV channel in the RADARSAT-2 dual pol modes, wind is much less of a problem.

Some decent detection capability on the order of 80% is reported by C-CORE for first year sea ice only for medium and large bergs. This is achieved using the HH channel rather than the HV channel favoured for open water. Multi-year sea ice remains a challenge for the iceberg detection problem. Only large and very large icebergs can be detected at marginally-useful PoD in multi-year ice.

In a nutshell, dual pol ScanSAR Narrow is useful for detection of medium and large icebergs over reasonably wide areas, offering reliable open water performance under typical wind conditions and decent performance for first year ice.

Detection of bergs in multi-year ice remains an unsolved problem through backscatter alone. It is possible that in certain conditions berg wakes through ice may be a proxy method of detection, but little is known about how commonly this occurs in the areas of interest and under what conditions this would be feasible.

It is to be hoped that OSVN mode can be evaluated by extension of C-CORE's work and that the performance would be similar to ScanSAR Narrow mode, but over a much larger swath width of 530 kilometres as opposed to 300 kilometres.

### 3.4 Discrimination between icebergs and other targets

As noted in Appendix I, fishing vessels appear on the Grand Banks in May and can result in many false contacts from the vessels themselves and their gear.

In [Howell, 2004] there is an approach described which uses ratio of cross and co-polarization backscatter which show some degree of correlation. Also cited is the more uniform brightness of ships compared to icebergs, and some approaches based on shape of the target.

None of these techniques seem to be entirely effective, and it is unclear whether there is an underlying physical difference that can be exploited to solve this problem finally.

### 3.5 Collaborations with DFO, industry, and academia

MISD has always been seen to be a leader in use of synthetic aperture radar data applied to cold oceans. This is where the organization has its strength and this is also where benefits are perceived, and this starts with access to data at relatively low cost.

MISD collaborates with DFO frequently in field work to surface truth satellite detections. Field work is a special expertise of the Oceans

> *"Imagery series of icebergs are useful so that we can validate and improve ocean models such as C-NOOF which in turn have potential to improve iceberg drift modelling. Collaboration with MISD would be useful for our efforts."*
> ***Fraser Davidson***

Science group which has also provided most of the original papers on icebergs.

Industry players such as C-CORE, Provincial Aerospace Ltd., and Oceans Ltd are active in the theory and practice of remote sensing, ice management, and in-situ instrumentation respectively. Collaboration with these players brings also links to the petroleum industry which provide the significant resources needed to field supply ships which are essential platforms for research and field observation.

*"A particularly severe iceberg year will occur when there is a characteristic tongue of sea ice that extends around the northern outer edge of the Grand Banks."* ***Carrie Young***

In satellite detection the University of Manitoba has been active in remote sensing of the cryosphere, particularly in electromagnetic modelling.

### *3.6 Two-year niche research plan alternatives for SAR detection of icebergs*

For iceberg detection using SAR, the way ahead is fairly clear.

1. Evaluate the OSVN (Ocean Surveillance Very-wide Near) beam (which is a subset of the Maritime Satellite Surveillance Radar mode) for detection of icebergs using extension of the theoretical work in the 2010 report [C-CORE, 2010].
2. Collect actual OSVN data during presence of icebergs simultaneous with surface truth surveys conducted by DFO, industry and academia. Confirm the feasibility of highly automated detection of floating glacial ice hazards.
3. Analyze existing datasets to verify and validate iceberg detection capability in sea ice. Data from 2009 and other data sets may be available through coordination with industry.
4. Develop a methodology to empirically estimate a relationship between iceberg waterline length and C-band microwave radar cross section and use available data to develop an initial formula. This will allow prediction of iceberg detection performance based upon the parameters of a SAR system using the methods pioneered by Dr Paris Vachon of Defence R&D Canada.

Uncertainties exist based upon available human and financial resources and, for item 2, whether there will be sufficient icebergs at easily accessible latitudes in spring of 2011[7].

[7] At time of writing, OSVN mode may be available just after the 2011 berg season ends. The 2011 season is expected to be meagre because sea ice extent in January is much below normal and this is likely to persist. As noted before, extensive sea ice at southern latitudes in the late winter is a reliable indicator of severity of the iceberg season.

# 4.0 DRIFT AND DETERIORATION MODELLING OF ICEBERGS

## *4.1 Strengths and limitations of the CIS drift and deterioration model*

The CIS iceberg model has been upgraded and has recently been approved for transition into operational use in CIS operations and also at the International Ice Patrol. The NAIS iceberg drift model includes models of berg calving and has been chosen for adoption as the NAIS standard primarily because it supports import of environmental data in popular formats such as GRIB and netCDF. Some experimental ensemble capability has been added which will be discussed later.

*"When there is a lot of ice along the Labrador Coast and it extends farther south than usual, it usually predicts a big year for icebergs. This is probably because this is an indication of colder water which slows the melt of the icebergs."*
***Ingrid Peterson***

The NAIS model (like the CIS model before it and the IIP's previous model) is a deterministic model that takes observations from a database and drifts and ablates the icebergs according to environmental inputs. The environmental inputs include modelled ocean current, observed and forecast ocean winds, significant wave height and direction, and sea surface temperature. The iceberg database provides a position and waterline length which is also an input to the model for each berg in question.

*"The most important factor affecting iceberg drift is ocean current. While the current models we use probably have the general trends correct, there are a lot of wiggles in the true current we don't capture. These wiggles have a big impact on individual iceberg trajectories."*
***Don Murphy***

The principle limitations of the NAIS drift and deterioration model are as follows:

- Lack of support for Ice Islands which are not properly characterized by waterline length alone.[8]
- Total deterministic reliance on environmental inputs such as the ocean current which do not provide the detail and accuracy required and will not do so for the foreseeable future.

[8] Ice islands are not properly supported because of their vastly different scale and the much high mass to draft ratio. It is likely that the waterline-length dependant assumed cross sectional profile used to estimate water and air drags will be inapplicable to ice islands. Ice islands have flat horizontal top and bottom surfaces and surface friction cannot be neglected.

- Reliance on observed waterline lengths which are notoriously difficult to make accurately.
- Inability to benefit from more frequent satellite detections other than to possibly reset position if re-sighting can be declared.

## *4.2 The need to incorporate more frequent and reliable satellite detection*

In the current iceberg forecasting process, aircraft-derived sightings of bergs at a particular instant are typically widely spaced at intervals of 10 days or more. As such, relatively precise positions in the iceberg database as used only to provide an initial position for the bergs, and re-sightings cannot normally be made unless they are made from other sources within a few days in a sparse berg environment.

> *"Why do icebergs typically spin slowly in a horizontal plane? If drag forces were the only forces at work, you would expect the iceberg to orient itself in some equilibrium orientation and stay there."*
> ***Greg Crocker***

Since we can look forward to approximately daily iceberg detection over a large area, in many cases re-sighting will become more common and could potentially be assisted by a drift model. When bergs are sparse and/or distinctive, and when observations are frequent, *tracking* of bergs will be possible. In tracking, an algorithm will predict the future position of a berg based upon past positions and environmental inputs, and detections *sufficiently close* to the predicted position will be deemed to be a re-sighting and will be associated with the existing iceberg track. This capability is not presently implemented.

The "sufficiently close" criterion is called a spatial gate in tracking terminology. It requires a statistical description (e.g. 97% likelihood of inclusion) that defines the contour of the Earth's surface within which the berg is likely to lie. Within the contour we have a resighting, outside of the contour it would be a new sighting. This contour could be provided using the methods of Garrett described in [Garrett, 1985a&b] and [deMargerie, 1985].

> *"I have observed a bergy bit which was expected to last a few days based on water temperature alone last about three times longer than predicted."*
> ***Pat Barron***

## *4.3 The need for more in-situ measurements to support modeling*

The NAIS model includes a large number of ablation effects including wave erosion, buoyant water convection, force water convection, sea surface temperature, and calving. There is very little data to validate any of the predictions of deterioration. In practice, forecasters use the deterioration model as a guideline, but rely upon human judgment on when to retire bergs from the database. To be conservative they may allow the bergs to melt to 150% or more. Part of this is that the iceberg sizes that accompany the sightings are not believed to be accurate. It is probably impossible to get a better handle on deterioration prediction without precise berg size measurements over time coincident with measurements of water temperature profile, wind, and current profile.

> *"It is a folk belief that icebergs tend to roll at dawn. There are no datasets available to verify if this is true or explain why this would be."*
> ***Tony King***

All the current deterministic modelling efforts are based upon the findings of Smith and Donaldson [Smith et al., 1987], which are in turn based upon the work of Banke and Donaldson [Banke et al, 1984]. While Smith and Donaldson used measurements within a few km of the bergs of current and wind, they found it necessary to vary the water and wind drag values to unrealistic values to get reasonable fit between observed and predicted tracks over several hours. Furthermore they found it necessary to alter the direction of both wind and towing force vectors to permit rough approximation of the observed tracks by the model. This was after discarding about 20% of the data which completely defied the assumption of motion primarily influenced by water and wind drags. They blamed the spatial variability of currents but also acknowledged that hydrodynamic and aerodynamic effects were likely at work.

It has been too convenient to blame differences between observed and predicted tracks solely on unknown currents. The best way to resolve the mystery is to measure directly the current profile under a tabular iceberg or ice island using an ADCP[9] attached to the glacial ice mass. This must be accompanied with very accurate and frequent positions measurements using GPS beacons which provide accurate and finely spaced position tracks which can be differentiated to get instantaneous velocities, and differentiated again to get instantaneous accelerations. The accelerations are related to net forces accelerating the berg.

Also it would be important to measure the wind speed and direction atop the same tabular berg using a portable met station. Then accelerations could be directly related to wind speed and direction changes and the direction of wind compared with the direction of acceleration. Water temperature profile, air temperature and barometric pressure would be useful as well. Some feel that thermistor chains into the berg would be helpful. All of this is costly and requires a great deal of planning to accomplish safely.

Most bergs are observed to spin in a horizontal plane. The effect of this spin, if any, on the iceberg drift is unknown because the spin has never been measured coincident with the

[9] Acoustic Doppler Current Profiler

iceberg track. A compass or some method using analysis of two GPS beacons would be needed (or some other method).

Table 1 below shows a listing of possible in-situ measurements that could be of interest:

| | | | |
|---|---|---|---|
| M-1 | Precision position/track over time | GPS or DGPS with Iridium | |
| M-2 | Current profile under the berg | Berg-Moored ADCP | |
| M-3 | Water temperature profile under the berg | Berg-moored thermistor chain with depth measurement | |
| M-4 | Wind speed and direction at the berg | Met station on a tabular berg or ice island | |
| M-5 | Berg spin rate and direction | Compass with telemetry on a tabular berg | |
| M-6 | Calving events | Accelerometer or acoustic sensors | |
| M-7 | Tow force | Load cell on tow rope along with angled measurement on rope | |
| M-8 | Berg mass | Unknown – possibly towing force step response | |
| M-9 | Glacial ice mass volume and shape | 3D sonar profiling below water, 3D laser profiling or stereo photogrammetry above water | |
| M-10 | Air temperature and pressure | Met station on a tabular berg | |
| M-11 | Glacial ice mass temperature | Thermistor chain | |
| M-12 | Airflow around the berg | Several hot wire anemometer sensors on the above-water surface of the berg or 3D profiles and simulation | |
| M-13 | Water flow around the berg | Several hot wire anemometer sensors on the underwater surface of the berg or 3D sonar profiles and simulation | |

## *4.4 The need to estimate risk of encounter*

The current integrated NAIS iceberg charts have three elements: the southern LAKI, the berg count density, and the sea ice edge. The charts cover only the grand banks and the Labrador Sea, not Davis Strait, Baffin Bay, Hudson Strait, or more approaches to the Northwest Passage.

The southern LAKI is felt to be reliable and useful, and single hulled trans-Atlantic shipping respects this and detours south if required unless they carry collision insurance.

The berg counts are not reliable enough to be used in navigation. They show an estimate of the number of icebergs within a 1 degree by 1 degree cell. Many cells are empty which indicate that no bergs are modelled as present, but the intent is that anywhere north of the LAKI could carry significant risk of iceberg encounter.

Not enough is known about what future products could show. It is possible that a more fully formed LAKI could be generated which shows the contour outside of which there is negligible risk of encountering a berg. It is unlikely that this could be done for the entire North Atlantic because when the water is very cold, bergy bits and growlers could persist for long periods and drift far.

> *"Oceans Ltd provides 3D underwater profiling services that are used on the ice management supply ships. It would not cost a penny more to take more frequent measurements that could be used for ablation measurements. Someone just has to request it."*
> ***Judith Bobbitt***

It is likely that where there is no LAKI, or interior to a LAKI contour, future products could show zones where there is elevated risk of encountering a glacial ice hazard. These zones would show the zone of possible positions for a previously observed berg or child bergs thereof. It is expected that captains would slow down or avoid these zones, and perhaps double the watch.

## *4.5 Collaborations with DFO, industry, and academia*

As noted earlier, MISD collaborates with DFO frequently in field work, and this has been applied to the validation of drift models. This valued cooperation will continue and become more relevant.

DFO also has great strength in ocean modelling. The ocean modellers are able to improve the input to the drift and deterioration model and provide guidance on what can be expected from the ocean models in terms of skill.

Academia also has a role to play in making in-situ measurements and doing basic research such as those question listed in Appendix IV. Memorial University of Newfoundland is active in iceberg research and AUVs, and in the past Dalhousie University has been active. University networks such as Arcticnet or the propose ICEBERGS network have access to field resources such as the Amundsen and student labour. Both theoretical and field observation has been a strength in academia

Industry players such as C-CORE, Provincial Aerospace Ltd., and Oceans Ltd are active in the theory and practice of remote sensing, ice management, and instrument design. Collaboration with these players brings also links to the petroleum industry which provides the significant resources needed to field supply ships which are essential platforms for research, validation of drift and deterioration models, and varied field observation.

> *"The causes of periodic motions of icebergs can be analysed by timescale. Diurnal or semi-diurnal periods are tidal. Inertial oscillations are at a different period that is latitude dependant. These two phenomena can cause looping in iceberg trajectories. Motions at longer periods are due to synoptic weather events. Periodic motions with periods on the order of minutes are due to internal waves."*
> ***Dave Fissel***

### *4.6 Two-year niche research plan alternatives for iceberg/island modelling*

The ice island issue is of pressing concern and great general interest. Some work must be done to examine the NAIS model to identify what must be done to update the draft, water drag and wind drag calculations. Currently waterline length is used to derive typical values which are not typical of ice islands. Other aspects could be affected and a systematic review should be done based on good knowledge of the underlying models.

Some work should be done to provide difference trajectories based on the subtraction of real and modelled trajectories. These residual motions may be amenable to statistic modelling using a "dead reckoning" approach based on persistence of motion once wind and tidal effects are accurately represented in the NAIS model. If this bears out, the simple statistical approach of Garret can be implemented on a preliminary basis over perhaps a period of a few months.

> *"When a bergy bit is towed by an ice management vessel on the Grand Banks, it is seen to fall apart rapidly because of the flow of warm water around it."*
> ***Carl Howell***

Some opportunistic support of other partners should be undertaken to allow collection of data sets such as precision position, environmental variables directly over and under bergs, and berg characteristics. A sample of the wide variety of data of interest is described in Table 1 of this report.

# 5.0 TABULAR SUMMARY OF RECOMMENDATIONS

## *5.1 General recommendations*

| ID | Description | Status |
|---|---|---|
| G-1 | A bi-annual meeting series on glacial ice hazards should be initiated by the Applied Science Group of the Marine and Ice Services Division starting in spring 2011. Suggested venue: St. John's Newfoundland. A budget should be set aside to bring experts from Victoria, Halifax, Calgary and Kingston to the meeting by invitation. | |
| G-2 | MISD AWIS should sponsor a study to mock up different future glacial ice hazard information products and gather user input from the marine community to help refine these mock-ups | |
| G-3 | MISD should explore the possibility of taking the lead in developing a large collaborative research program that could be funded by multiple sources for multiple years. This would require significant effort but could provide the foundation for meaningful advancements. | |

## *5.2 Recommendations related to SAR detection of icebergs and ice islands*

| ID | Description | Status |
|---|---|---|
| D-1 | The new OSVN mode for RADARSAT-2 should be validated for iceberg detection in open water including cross validation against airborne surveillance, marine radar, and other sightings including surface measurements for selected targets. | |
| D-2 | Data sets from 2009 of R2 data of icebergs within sea ice along the Labrador coast should be analyzed to confirm and quantify capability to detect bergs in sea ice using wide swath data. | |
| D-3 | A relationship should be made between iceberg waterline length and radar cross section. This could be done with the same methodology used by Dr Vachon of DRDC for ships, and would allow estimation of performance with some precision based on radar parameters. | |
| D-4 | External or internal capability to automatically detect icebergs in SAR data should be maintained or developed. Techniques to discriminate between icebergs and other targets should be monitored and applied with caution. | |

## *5.3 Recommendations related to modeling of icebergs/ice islands*

| ID | Description | Status |
|---|---|---|
| M-1 | The drift and deterioration model should be evaluated to determine how the air and water drag parameterization should change to accommodate ice islands. Current linkage of these drags to waterline length will not be appropriate because the horizontal surface drag will be significant rather than just the lateral cross sectional profile. | |
| M-2 | Some applied research should be done to use the approach of Garret [Garret 1985] to model the position error residuals between predicted and observed trajectories. This may allow more accurate trajectory prediction and provides a theoretically sound basis for calculating error circles based on the residuals. The existing drift model can be used for prediction and the statistical model will estimate the deltas. | |
| M-3 | A tracking theory framework should be developed whereby the combination of automatic satellite detection, statistically drift modelling, and automating re-sighting (i.e. track maintenance) can be exploited to associated individual detections over time into coherent individual iceberg tracks wherever possible. | |
| M-4 | Partners should be encouraged and supported in the collection of valuable *in-situ* data on ice mass deterioration and drift. This may include many of the variables listed in Table 1. Data collection and observations may be carried out by Industry and Academia who have access to icebergs and supply or research vessels. AUVs may be a good source of data as well. | |

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# APPENDIX I: Four Phases of the Iceberg Season Off Newfoundland

** This description is based on discussions with Don Murphy of the International Ice Patrol**

The iceberg season exists because seasonal cold water along the Labrador coast from late winter to late summer normally allows a portion of the icebergs from further north to survive long enough to appear as ice masses as they drift southward along under the influence of ocean currents. At other times of year, the water mass from completely melted bergs is mixed with the ocean currents and of course poses no threat to navigation.

The average time a sighted Newfoundland iceberg takes to travel from its glacial point of origin is believed to be 1 to 3 years, with wide variation depending on the specific meandering route and the length of periods of grounding or capture within sea ice packs or fiords. Bergs are plentiful in Baffin Bay and northern Davis Strait year round. The paths taken by bergs are famously unpredictable so little forecasting benefit can be gained from tracking their movements until they drift south of Cape Chidley and are in the waters east of the Labrador coast itself.

PHASE I GROWTH OF LOCAL SEA ICE AND GROWING BERG THREAT
Start: By late Jan/Early February the sea ice has reached the Strait of Belle Isle

This is a challenging time for reconnaissance. We don't know if there are icebergs in the sea ice or how many. The mixed and rafted sea ice confounds efforts to find the bergs by radar or visual means alike.

PHASE II START OF LOCAL SEA ICE RETREAT
Start: Around mid-March, the sea ice extent starts to shrink

This is the most dangerous season. A lot of sea ice extends south, possibly as far as 45 degrees North latitude in severe years. When the pace of sea ice retreat quickens, some bergs previously unsighted are revealed. Sea ice continues to be a problem for berg detection.

PHASE III BERGS MOBILE
Start: Around May the bergs are widely scattered and extend east to the Flemish Cap.

The bergs are easier to see because of the lack of sea ice, but the fishing vessels come in. Crabbers and long liners, plus fishing markers with radar reflectors make for lots of radar contacts which need to be discriminated from bergs.

PHASE IV BERGS RETREAT
Start: Around June the number of bergs is dropping rapidly and the ocean warms to about 5 degrees Celsius

Sea ice is no longer a factor. Iceberg destruction is accelerated in the warm water and there are few targets, widely scattered and smaller than at other phases.

# APPENDIX II: Experts Consulted for this Study

The following tabular pages contain the names, affiliations, and relevant expertise of the individual, and whether or not they have provided review. The author expresses gratitude for the time and effort spent by these experts, which varied from a short conversation or email to a series of detailed consultations covering many hours. I have sorted these approximately in order of the influence on this report. Any errors are the responsibility of the author and, while an attempt was made to capture the advice accurately, it is likely some interpretations were made that would differ from those of the expert. For this reason I have added a column to indicate whether review has been obtained from the expert and this should be updated periodically.

| NAME | AFFILIATION | CONTACT INFO | APPLICABLE EXPERTISE |
|---|---|---|---|
| Don Murphy – Chief Scientist | International Ice Patrol New London, CT, USA | donald.l.murphy@uscg.mil 860-271-2635 | Iceberg surveillance and modelling |
| Roger deAbreu – Scientist | Marine and Ice Services Division, Environment Canada, Ottawa | roger.deabreu@ec.gc.ca 613-995-5125 | Marine remote sensing of the cryosphere |
| Tom Carrieres-Scientist | Marine and Ice Services Division, Environment Canada, Ottawa | Tom.Carrieres@ec.gc.ca 613-996-4674 | Modelling of sea ice and icebergs |
| Luc Desjardins – Forecaster | Marine and Ice Services Division, Environment Canada, Ottawa | luc.desjardins@ec.gc.ca 613-996-1617 | Iceberg and sea ice forecasting |
| Pablo Clemente-Colon – Chief Scientist | National/Naval Ice Center, Washington, D.C. | Pablo.Clemente-Colon@noaa.gov 301-817-3944 | Remote sensing and ocean science |
| Paris Vachon – Scientist | Defence R&D Canada, Ottawa | Paris.Vachon@drdc-rddc.gc.ca 613-991-2584 | Microwave remote sensing of the marine environment |
| Simon Prinsenberg – Scientist | | Simon.Prinsenberg@@dfo-mpo.gc.ca 902-426-5928 | Ocean science, sea ice and icebergs |
| Ingrid Petersen | | Ingrid.peterson@dfo-mpo.gc.ca 902-426-6929 | Ice and iceberg science |
| Desmond Power – Manager Vision and Remote Sensing | C-CORE, St.John's | Des.Power@c-core.ca 709-864-8353 | Microwave remote sensing of icebergs |
| Greg Crocker – Engineer | Ballicater Consulting, Kingston | ballicater@sympatico.ca 613-531-3672 | Ice and iceberg science |

| | | | |
|---|---|---|---|
| Steve Bruneau – Professor | Memorial University, St, John's | sbruneau@mun.ca<br>709-737-8812 | Iceberg science and ice engineering |
| Carrie Young - | Provincial Aerospace Limited, St. John's | cyoung@provair.com<br>709-576-1226 | Ice management |
| Pat Barron - Manager | Provincial Aerospace Limited, St. John's | pbarron@provair.com<br>709-576-1939 | Ice management |
| Carl Howell – Ice Engineer | C-CORE, St.John's | carl.howell@c-core.ca<br>709- | Remote sensing and ice engineering |
| Chris Garrett – Oceanographer | | cgarrett@uvic.ca<br>250-598-1345 | Statistical iceberg drift modelling, oceanography |
| Charles Hannah - Scientist | DFO, Oceans Sciences, Dartmouth | Charles.Hannah@dfo-mpo.gc.ca<br>902-426-5961 | Ocean modelling |
| Judith Bobbitt | Oceans Ltd, St. John's | jbobbitt@oceans.nf.net<br>709-753-5788 | Ocean current forecasting and iceberg science |
| Dave Fissell | ASL, Victoria | dfissel@aslenv.com<br>1-877-656-0177 | Iceberg science and oceanography |
| Norbert Yankielun - Engineer | SAIC, Maine | Norbert.E.Yankielun@SAIC.COM<br>207 - 348-2391 | Radar sensing of ice |
| Fraser Davidson – Oceanographer | Department of Fisheries and Oceans, St. John's | Fraser.Davidson@dfo-mpo.gc.ca<br>709-772-8963 | Ocean modelling |
| Tony King – Ice Engineer | C-CORE, St. John's | Tony.King@c-core.ca<br>709-737-2655 | Ice Engineering |
| Freeman Ralph – Director, Ice Engineer | C-CORE, St. John's | Freeman.Ralph@c-core.ca<br>709- 737-8354 | Ice Engineering |
| Ivana Kubat – Project Engineer | Canadian Hydraulics Centre (NRC), Ottawa | Ivana.Kubat@nrc-cnrc.gc.ca<br>613-993-7695 | Iceberg modelling, ice engineering |
| Mohamed Sayed – Project Engineer | Canadian Hydraulics Centre (NRC), Ottawa | Mohammed.Sayed@nrc-cnrc.gc.ca<br>613-990-6958 | Iceberg modelling, ice engineering |
| Jean-Éric Tremblay | Laval University | Jean-Eric.Tremblay@bio.ulaval.ca | Iceberg science and cryosphere |

| | | | |
|---|---|---|---|
| – Professor | | 418-656-2131 ext. 6140 | biology |
| Ralph Bachmayer – Professor | Memorial University, St, John's | bachmayer@mun.ca<br>709-864-6793 | Autonomous Underwater Vehicles, cold ocean research |
| Derek Mueller - Professor | Carleton University, Geography Department, Ottawa | dmueller@connect.carleton.ca<br>613-520-2600, ext. 1984 | Ice islands, computer methods |
| Scott Tiffin President | Canatec Associates International Ltd, Calgary | Scott_Tiffin@canatec.ca<br>403-228-0962 | Ice beacons, field logistics |
| Sylvain deMargerie, Manager | DFO, Direct ISDM, Ottawa | Sylvain.demargerie@dfo-mpo.gc.ca<br>613- 990-0265 | Statistical iceberg drift modelling |
| Robert Gagnon – Engineer | IOT, St John's | Robert.Gagnon@nrc-cnrc.gc.ca<br>709-772-2475 | Ice Engineering |
| Keith Thompson | Dalhousie University, Oceanography Department | | Oceanography and mathematics |
| Humfrey Melling | IOS, DFO, Victoria | | Oceanography |
| Brian Petrie | BIO, Dartmouth | | Oceanography |

# APPENDIX III: Excerpts from C-CORE Report on Iceberg Detection Using RADARSAT-2

# 3 ICEBERG DETECTION RESULTS

The goal of this work was to evaluate iceberg POD for RADARSAT-2 SCN mode. Since this was accomplished using RADARSAT-2 Fine Mode imagery, tables of POD were generated for both Fine and SCN modes to facilitate a tradeoff analysis of the two different modes. This provides a good benchmark for two extremes of SAR imagery – high resolution (Fine) and low resolution (SCN). POD tables were generated as a function of wind direction, wind speed, iceberg size, polarization and incidence angle. While some Quad polarization data were collected for this study, the majority of data were collected with dual polarization HH and HV. Thus, POD is only reported for HH and HV and not for VV.

## 3.1 Fine Mode Iceberg detection

Fine mode iceberg POD analyses for both ocean and sea ice backgrounds were evaluated. For the ocean backscatter, this was accomplished by binning the available ocean background data based on wind speed at 5 m/s increments, wind direction at 30 degree increments, and incidence angle at 5 degree increments. For sea ice backscatter, the data were binned based on incidence angle at 5 degree increments. The three types of sea ice evaluated were New Ice, First-Year Sea Ice and Multi-Year Sea Ice, all in the winter ablation state.

From Section 2.1.1, there was no significant trend in this data set with respect to iceberg signature and incidence angle. Thus, all iceberg targets were used in evaluating the variable ocean and sea ice backscatter in each of the binned data samples. The results in each bin are presented for icebergs of size Small (15–60 m waterline length – red), Medium (61–120 m waterline length – blue), and Large (121–200 m waterline length – green), as shown in Table 3.1 though Table 3.4. All of the results were generated using a CFAR of $1\times10^{-7}$.

Table 3.1. RADARSAT-2 Fine mode iceberg POD for wind directions 0–30º from the SAR look direction

| Polarization | HH | | | | HV | | | |
|---|---|---|---|---|---|---|---|---|
| Wind Speed m/s / Incidence Angle | 0-5 | 5-10 | 10-15 | 15-20 | 0-5 | 5-10 | 10-15 | 15-20 |
| 40-45 | | | | | | | 0.77 | |
| | | | | | | | 0.92 | |
| | | | | | | | 1.00 | |
| 35-40 | 0.94 | 0.88 | 0.82 | | 0.85 | 0.92 | 0.85 | 0.70 |
| | 0.96 | 0.95 | 0.95 | | 0.93 | 0.97 | 0.95 | 0.91 |
| | 1.00 | 0.99 | 0.98 | | 0.99 | 1.00 | 1.00 | 1.00 |
| 30-35 | 0.76 | 0.74 | 0.64 | | 0.85 | 0.89 | 0.77 | 0.53 |
| | 0.90 | 0.92 | 0.86 | | 0.95 | 0.96 | 0.92 | 0.78 |
| | 0.96 | 0.96 | 0.95 | | 1.00 | 0.99 | 1.00 | 0.98 |
| 25-30 | 0.51 | 0.43 | 0.29 | | 0.92 | 0.93 | 0.79 | 0.53 |
| | 0.77 | 0.74 | 0.62 | | 0.98 | 0.98 | 0.93 | 0.77 |
| | 0.87 | 0.87 | 0.76 | | 1.00 | 1.00 | 1.00 | 0.98 |
| 20-25 | 0.28 | 0.15 | 0.13 | 0.13 | 0.87 | 0.90 | 0.72 | 0.65 |
| | 0.47 | 0.36 | 0.31 | 0.28 | 0.95 | 0.97 | 0.90 | 0.85 |
| | 0.63 | 0.60 | 0.52 | 0.52 | 1.00 | 1.00 | 0.99 | 0.98 |

* Legend: red small, blue medium, green large iceberg POD

Table 3.2. RADARSAT-2 Fine mode iceberg POD for wind directions 30–60º from the SAR look direction

| Polarization | HH | | | | HV | | | |
|---|---|---|---|---|---|---|---|---|
| Wind Speed m/s / Incidence Angle | 0-5 | 5-10 | 10-15 | 15-20 | 0-5 | 5-10 | 10-15 | 15-20 |
| 40-45 | 0.97 | | 0.97 | | | | 0.87 | |
| | 0.98 | | 0.95 | | | | 0.95 | |
| | 1.00 | | 1.00 | | | | 1.00 | |
| 35-40 | 0.91 | 0.91 | 0.79 | | 0.83 | 0.94 | 0.80 | 0.70 |
| | 0.96 | 0.96 | 0.92 | | 0.95 | 0.99 | 0.93 | 0.89 |
| | 0.99 | 0.99 | 0.96 | | 0.99 | 1.00 | 1.00 | 1.00 |
| 30-35 | 0.81 | 0.75 | 0.55 | 0.67 | 0.80 | 0.95 | 0.77 | 0.80 |
| | 0.93 | 0.93 | 0.81 | 0.88 | 0.94 | 0.99 | 0.92 | 0.92 |
| | 0.97 | 0.97 | 0.91 | 0.96 | 1.00 | 1.00 | 1.00 | 1.00 |
| 25-30 | 0.64 | 0.48 | 0.32 | | 0.90 | 0.94 | 0.88 | |
| | 0.87 | 0.76 | 0.60 | | 0.97 | 0.99 | 0.95 | |
| | 0.94 | 0.88 | 0.78 | | 1.00 | 1.00 | 1.00 | |
| 20-25 | 0.39 | 0.23 | 0.13 | 0.13 | 0.97 | 0.97 | 0.72 | 0.50 |
| | 0.63 | 0.52 | 0.24 | 0.32 | 1.00 | 1.00 | 0.88 | 0.74 |
| | 0.75 | 0.73 | 0.43 | 0.54 | 1.00 | 1.00 | 0.99 | 0.96 |

* Legend: red small, blue medium, green large iceberg POD

Table 3.3. RADARSAT-2 Fine Mode iceberg POD for wind directions 60–90° from the SAR look direction

| | HH | | | | HV | | | |
|---|---|---|---|---|---|---|---|---|
| Wind Speed m/s / Incidence Angle | 0-5 | 5-10 | 10-15 | 15-20 | 0-5 | 5-10 | 10-15 | 15-20 |
| 40-45 | | 0.96 | | | | 0.87 | 0.60 | |
| | | 0.97 | | | | 0.95 | 0.86 | |
| | | 1.00 | | | | 0.99 | 1.00 | |
| 35-40 | 0.90 | 0.94 | 0.90 | | 0.90 | 0.92 | 0.83 | |
| | 0.96 | 0.96 | 0.94 | | 0.97 | 0.98 | 0.95 | |
| | 0.99 | 1.00 | 0.99 | | 1.00 | 1.00 | 1.00 | |
| 30-35 | 0.84 | 0.75 | 0.72 | 0.70 | 0.96 | 0.87 | 0.89 | 0.70 |
| | 0.94 | 0.91 | 0.92 | 0.91 | 0.99 | 0.96 | 0.97 | 0.91 |
| | 0.98 | 0.97 | 0.96 | 0.96 | 1.00 | 1.00 | 1.00 | 1.00 |
| 25-30 | 0.80 | 0.53 | 0.40 | 0.33 | 0.87 | 0.96 | 0.86 | 0.67 |
| | 0.91 | 0.79 | 0.70 | 0.69 | 0.94 | 0.99 | 0.95 | 0.89 |
| | 0.96 | 0.90 | 0.81 | 0.77 | 0.99 | 1.00 | 1.00 | 1.00 |
| 20-25 | 0.19 | 0.18 | 0.14 | | 0.97 | 0.96 | 0.79 | |
| | 0.45 | 0.46 | 0.35 | | 1.00 | 1.00 | 0.92 | |
| | 0.66 | 0.69 | 0.58 | | 1.00 | 1.00 | 0.99 | |

* Legend: red small, blue medium, green large iceberg POD

Table 3.4. RADARSAT-2 Fine mode iceberg POD in sea ice

| Polarization | HH | | | HV | | |
|---|---|---|---|---|---|---|
| Incidence Angle / Ice Type | New Ice | First-Year Sea Ice | Multi-Year Sea Ice | New Ice | First-Year Sea Ice | Multi-Year Sea Ice |
| 40-45 | | 0.80 | 0.45 | | 0.17 | 0.11 |
| | | 0.91 | 0.73 | | 0.35 | 0.21 |
| | | 0.96 | 0.85 | | 0.56 | 0.38 |
| 35-40 | 0.88 | 0.72 | 0.43 | 0.76 | 0.44 | 0.11 |
| | 0.95 | 0.90 | 0.71 | 0.90 | 0.67 | 0.24 |
| | 0.99 | 0.95 | 0.84 | 0.99 | 0.86 | 0.44 |
| 30-35 | 0.81 | 0.70 | 0.20 | 0.60 | 0.45 | 0.08 |
| | 0.91 | 0.91 | 0.50 | 0.86 | 0.70 | 0.15 |
| | 0.96 | 0.96 | 0.73 | 1.00 | 0.92 | 0.38 |
| 25-30 | | 0.69 | 0.20 | 0.20 | 0.62 | 0.00 |
| | | 0.88 | 0.49 | 0.58 | 0.83 | 0.02 |
| | | 0.96 | 0.73 | 0.88 | 0.99 | 0.08 |
| 20-25 | | 0.50 | 0.13 | | 0.51 | 0.00 |
| | | 0.70 | 0.37 | | 0.72 | 0.02 |
| | | 0.84 | 0.60 | | 0.91 | 0.04 |

* Legend: red small, blue medium, green large iceberg POD

## 3.2 SCN Mode Iceberg detection

SCN mode iceberg POD analyses for both ocean and sea ice backgrounds were evaluated. For the ocean backscatter this was accomplished by binning the data based on wind speed at 5 m/s increments, wind direction at 30 degree increments, and incidence angle at 5 degree increments. For sea ice backscatter the data were binned based on incidence angle at 5 degree increments. The three types of sea ice evaluated were the winter ablation states of New Ice, First-Year Sea Ice and Multi-Year Sea Ice.

From Section 2.1.1, there was no significant trend in this data set with respect to iceberg signature and incidence angle. From this, all iceberg targets were used in evaluating the variable ocean and sea ice backscatter in each of the binned data samples. The results in each bin are presented for icebergs of size Small (15-60 m waterline length – red), Medium (61-120 m waterline length – blue), and Large (121-200 m waterline length – green), ad shown in Table 3.5 though Table 3.8. All of the results were generated using a CFAR of $1\times10^{-7}$.

Table 3.5. RADARSAT-2 simulated SCN mode iceberg POD for wind directions 0–30º from the SAR look direction

| | HH | | | | HV | | | |
|---|---|---|---|---|---|---|---|---|
| Incidence Angle \ Wind Speed m/s | 0-5 | 5-10 | 10-15 | 15-20 | 0-5 | 5-10 | 10-15 | 15-20 |
| 40-45 | | | | | | | 0.70 | |
| | | | | | | | 0.88 | |
| | | | | | | | 0.98 | |
| 35-40 | 0.86 | 0.74 | 0.67 | | 0.56 | 0.67 | 0.76 | 0.60 |
| | 0.95 | 0.91 | 0.88 | | 0.77 | 0.80 | 0.93 | 0.82 |
| | 0.99 | 0.97 | 0.96 | | 0.96 | 0.93 | 1.00 | 1.00 |
| 30-35 | 0.60 | 0.56 | 0.36 | | 0.54 | 0.78 | 0.67 | 0.33 |
| | 0.80 | 0.82 | 0.68 | | 0.76 | 0.89 | 0.87 | 0.65 |
| | 0.91 | 0.93 | 0.88 | | 0.97 | 0.98 | 0.99 | 0.94 |
| 25-30 | 0.33 | 0.29 | 0.15 | | 0.70 | 0.83 | 0.67 | 0.28 |
| | 0.57 | 0.52 | 0.40 | | 0.84 | 0.93 | 0.89 | 0.59 |
| | 0.80 | 0.78 | 0.68 | | 0.98 | 0.99 | 0.99 | 0.94 |
| 20-25 | 0.12 | 0.04 | 0.02 | 0.02 | 0.67 | 0.84 | 0.57 | 0.48 |
| | 0.26 | 0.15 | 0.09 | 0.08 | 0.85 | 0.94 | 0.81 | 0.75 |
| | 0.47 | 0.37 | 0.29 | 0.25 | 0.97 | 0.98 | 0.98 | 0.98 |

* Legend: red small, blue medium, green large iceberg POD

Table 3.6. RADARSAT-2 simulated SCN mode iceberg POD for wind directions 30–60º from the SAR look direction

| Incidence Angle \ Wind Speed m/s | HH 0-5 | HH 5-10 | HH 10-15 | HH 15-20 | HV 0-5 | HV 5-10 | HV 10-15 | HV 15-20 |
|---|---|---|---|---|---|---|---|---|
| 40-45 | 1.00 | | 0.77 | | | | 0.87 | |
| | 0.97 | | 0.95 | | | | 0.97 | |
| | 1.00 | | 0.96 | | | | 1.00 | |
| 35-40 | 0.84 | 0.81 | 0.56 | | 0.59 | 0.69 | 0.73 | 0.54 |
| | 0.94 | 0.93 | 0.76 | | 0.78 | 0.82 | 0.90 | 0.79 |
| | 0.98 | 0.98 | 0.85 | | 0.98 | 0.96 | 0.99 | 0.99 |
| 30-35 | 0.72 | 0.60 | 0.34 | 0.37 | 0.66 | 0.97 | 0.70 | 0.67 |
| | 0.87 | 0.84 | 0.61 | 0.68 | 0.84 | 1.00 | 0.88 | 0.91 |
| | 0.96 | 0.94 | 0.85 | 0.88 | 0.98 | 1.00 | 0.99 | 1.00 |
| 25-30 | 0.46 | 0.30 | 0.18 | | 0.81 | 0.95 | 0.79 | |
| | 0.74 | 0.53 | 0.38 | | 0.90 | 0.99 | 0.95 | |
| | 0.88 | 0.79 | 0.65 | | 0.99 | 1.00 | 1.00 | |
| 20-25 | 0.22 | 0.11 | 0.01 | 0.02 | 0.95 | 0.85 | 0.59 | 0.27 |
| | 0.43 | 0.32 | 0.06 | 0.12 | 0.97 | 0.91 | 0.83 | 0.57 |
| | 0.64 | 0.60 | 0.21 | 0.31 | 1.00 | 0.98 | 0.99 | 0.90 |

* Legend: red small, blue medium, green large iceberg POD

Table 3.7. RADARSAT-2 simulated SCN mode iceberg POD for wind directions 60–-90º from the SAR look direction

| Incidence Angle \ Wind Speed m/s | HH 0-5 | HH 5-10 | HH 10-15 | HH 15-20 | HV 0-5 | HV 5-10 | HV 10-15 | HV 15-20 |
|---|---|---|---|---|---|---|---|---|
| 40-45 | | 0.89 | | | | 0.80 | 0.43 | |
| | | 0.95 | | | | 0.89 | 0.72 | |
| | | 0.99 | | | | 0.98 | 0.96 | |
| 35-40 | 0.85 | 0.83 | 0.74 | | 0.74 | 0.80 | 0.61 | |
| | 0.94 | 0.94 | 0.92 | | 0.86 | 0.89 | 0.79 | |
| | 0.98 | 0.98 | 0.96 | | 0.95 | 0.98 | 0.93 | |
| 30-35 | 0.71 | 0.59 | 0.52 | 0.53 | 0.68 | 0.65 | 0.89 | 0.60 |
| | 0.88 | 0.82 | 0.82 | 0.82 | 0.83 | 0.81 | 0.97 | 0.82 |
| | 0.95 | 0.94 | 0.94 | 0.92 | 0.98 | 0.97 | 1.00 | 1.00 |
| 25-30 | 0.67 | 0.33 | 0.23 | 0.20 | 0.61 | 0.76 | 0.83 | 0.53 |
| | 0.83 | 0.59 | 0.47 | 0.45 | 0.80 | 0.87 | 0.95 | 0.77 |
| | 0.92 | 0.83 | 0.76 | 0.73 | 0.97 | 0.97 | 1.00 | 0.96 |
| 20-25 | 0.10 | 0.08 | 0.04 | | | 0.77 | 0.69 | |
| | 0.24 | 0.25 | 0.15 | | | 0.87 | 0.87 | |
| | 0.47 | 0.52 | 0.35 | | | 0.98 | 0.99 | |

Table 3.8. RADARSAT-2 simulated SCN iceberg POD in sea ice

| | HH | | | HV | | |
|---|---|---|---|---|---|---|
| Incidence Angle / Ice Type | New Ice | First-Year Sea Ice | Multi-Year Sea Ice | New Ice | First-Year Sea Ice | Multi-Year Sea Ice |
| 40-45 | | 0.71 | 0.30 | | 0.08 | 0.05 |
| | | 0.85 | 0.55 | | 0.19 | 0.12 |
| | | 0.95 | 0.78 | | 0.35 | 0.24 |
| 35-40 | 0.79 | 0.57 | 0.28 | 0.39 | 0.30 | 0.05 |
| | 0.92 | 0.82 | 0.50 | 0.58 | 0.53 | 0.10 |
| | 0.97 | 0.92 | 0.75 | 0.78 | 0.75 | 0.22 |
| 30-35 | 0.59 | 0.55 | 0.17 | 0.43 | 0.28 | 0.05 |
| | 0.84 | 0.80 | 0.37 | 0.69 | 0.52 | 0.07 |
| | 0.94 | 0.91 | 0.65 | 0.96 | 0.79 | 0.21 |
| 25-30 | | 0.50 | 0.13 | 0.10 | 0.43 | 0.00 |
| | | 0.78 | 0.32 | 0.17 | 0.71 | 0.00 |
| | | 0.92 | 0.62 | 0.42 | 0.96 | 0.04 |
| 20-25 | | 0.31 | 0.05 | | 0.32 | 0.00 |
| | | 0.55 | 0.17 | | 0.57 | 0.00 |
| | | 0.75 | 0.42 | | 0.84 | 0.04 |

* Legend: red small, blue medium, green large iceberg POD

# APPENDIX IV: List of Basic Research Questions

| | | |
|---|---|---|
| R-1 | If winds above bergs and current profiles directly under an iceberg are measured, will wind and water drag completely explain berg drift? | Even the earliest references hypothesize that the wind force may be different from the wind direction. Underwater shape may influence hydrodynamic effects while the berg moves relative to currents. Spin (see R-6) may also have an effect. |
| R-2 | Does hydrodynamic lift change the potential forces that could affect speed and direction of berg motion? | The irregular shapes of bergs are likely to drastically influence the forces acting on the berg. It is likely that bergs which drift south have already been selected by characteristics which allow them to travel into warmer waters before they deteriorate. |
| R-3 | Can we measure water temperature profiles and use this information to refine deterioration models? | [Bruneau, 2011] has shown that the depth of warm water changes drastically with season. Generalization of this finding to other study locations would be valuable and could lead to better modelling of water temperature or validation of ocean models which include temperature profiles. |
| R-4 | If a medium or large berg is detected from satellite imagery, what can be said about small bergs, bergy bits and growlers in terms of the danger zone around the parent berg? | [Crocker, 2004] made some estimates of the ratio of the number of small ice masses to parent bergs on the Grand Banks, but the results do not relate the distance and direction from the parent berg. It was found the ratio varies in different parts of the Grand Banks, and the number and distribution of small glacial ice masses is likely to depend on water temperature and other variables affecting deterioration, calving and drift. |
| R-5 | Why do bergs spin? | Greg Crocker asked this question in a personal communication and felt that drag forces cannot explain the spin which is typical of bergs. |
| R-6 | Does the berg spin affect the speed or direction of drift? | It seems likely that spin would affect drift in a way similar to the way a curling rock is deflected by spin. |
| R-7 | Does a rapidly melting berg in warm water have the same water drag as it would if it were in very cold water and not melting? | Some towing experiments including detailed underwater profiling done at the Grand Banks and much further north could be done with carefully measured tow force and simultaneous iceberg position/velocity/acceleration. Tow force can be measured using a load cell and angle measurement on the rope to get towing vector. Iceberg response could be achieved using GPS or differential GPS over time. Current profile may be needed as well and winds likely should be near zero. Such experiments may also be able to measure mass indirectly. |