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132 Remote Sensing Ice Detection Capabilities - East Coast

Canadä

April 1995

The Environmental Studies Research Funds are financed from special levies on the oil and gas industry and administered by the National Energy Board for the Minister of Energy, Mines and Resources, and by the Northern Affairs Program for the Minister of Indian Affairs and Northern Development.

Environmental Studies Research Funds

Report No. 132

April 1995

REMOTE SENSING ICE DETECTION CAPABILITIES - EAST COAST

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Final Report

The correct citation for this report is:

Rossiter, J.R., J. Guigné, C. Hill, R. Pilkington, E. Reimer, J. Ryan, and B. Wright. 1995. Remote Sensing Ice Detection Capabilities - East Coast. Environmental Studies Research Funds Report No. 132, Calgary, 172 pp.

Published under the auspices of the Environmental Studies Research Funds
ISBN 0-921652-36-4

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ACKNOWLEDGEMENTS

The authors gratefully acknowledge the assistance provided by numerous organizations which provided information contained in this report, either through release of other reports, or through interviews, including:

Atlantic Airways
Canarctic Shipping Company Limited
C-Tech Ltd.
Canadian Centre for Marine Communications
Northern Radar Systems Limited
Petro-Canada
Sonetech Corporation

In addition, the review group, led by Dr. Bharat Dixit of the National Energy Board and composed of the following members, made numerous helpful suggestions which greatly improved the quality of the report:

Mr. David Burley, Canada-Newfoundland Offshore Petroleum Board
Mr. Phil Clarke, Petro-Canada Resources Ltd.
Mrs. Leslie Grattan, Hibernia Management and Development Company Ltd.
Mr. Andre Maillet, Canadian Coast Guard, Ice Operations
Dr. Mike Manore, Canada Centre for Remote Sensing, Ice Applications
Mr. Terry Mullane, Ice Centre, Environment Canada
Mr. Don Murphy, International Ice Patrol, U.S. Coast Guard
Dr. Venketa Neralla, Ice Centre, Environment Canada
Dr. Walt Spring, Mobil Research and Development Corporation
Mr. Robert Wolfe, Arctic Ship Safety, Coast Guard Northern

SUMMARY

This report summarizes the state-of-the-art in sensor technologies for the remote sensing of sea ice and icebergs off Canada's East Coast. It was prepared by a team of specialists who have experience in ice detection systems and operational requirements as a guide to what can be accomplished using current sensors in meeting operator needs. In addition, the report covers the team's best estimates of future improvements.

The study included four tasks:

1. Determination of operator needs
2. Comprehensive review of available sensors
3. Description of main technologies
4. Evaluation of sensors in relation to needs.

At the heart of the report are tables which provide:

- a summary of operator needs for four operating scenarios
- descriptions of individual sensors in a common format
- a matrix of sensors vs needs, for each scenario
- a summary of suggested systems for each scenario.

In addition, there are brief descriptions of all the main sensing technologies and a more quantitative discussion of radar, acoustic, and optical sensors. A section summarizing marine communications has also been included.

The report concludes that most of the operating requirements can be met with currently-available technology, with the exception of reliable detection of small ice masses in moderate and high sea states and in pack ice. Further implementation of advanced radar and sonar systems may overcome these limitations.

RÉSUMÉ

Le rapport résume l'état actuel des technologies des détecteurs pour la télédétection des champs de glace et des icebergs au large de la côte est du Canada. Une équipe de spécialistes, connaissant les systèmes et les besoins opérationnels en matière de détection des glaces, y signale comment les détecteurs actuels peuvent aider à répondre aux besoins des exploitants, et à quelles améliorations on peut s'attendre dans l'avenir.

L'étude comportait quatre volets :

1. la détermination des besoins des exploitants
2. un relevé détaillé des détecteurs disponibles
3. une description des principales technologies
4. une évaluation des détecteurs par rapport aux besoins.

Les tableaux qui figurent au rapport fournissent :

- un résumé des besoins des exploitants dans quatre scénarios d'exploitation
- une description, selon une présentation commune, des détecteurs
- une matrice détecteurs/besoins pour chaque scénario
- un résumé des systèmes suggérés pour chaque scénario.

En outre, une brève description de toutes les grandes technologies de détection et une discussion quantitative des détecteurs radar, acoustiques et optiques figurent au rapport. Une section résumant les systèmes de communications maritimes y est aussi comprise.

On conclut dans le rapport que la plupart des besoins opérationnels peuvent être satisfaits par les technologies disponibles, sauf la détection fiable des petites masses de glace dans des conditions de mer de force modérée et élevée, et de banquise. Ces contraintes pourraient disparaître lorsque des systèmes radar et sonar plus perfectionnés seront mis en oeuvre.

1.0 INTRODUCTION

Over the past two decades, the petroleum industry has carried out extensive exploration programs on the East Coast. To date, these efforts have resulted in a number of significant discoveries, including the Hibernia and Terra Nova oil fields. Recently, there has been a hiatus in East Coast exploration, which is consistent with the general decline in activity levels across the Canadian frontiers. However, development initiatives that began in the 1980s have continued, with most of industry's current efforts now focused on the Hibernia project, as well as the potential for oil development from Terra Nova. As these East Coast development projects proceed and become operational, it is likely that more exploration will be stimulated, and that smaller satellite fields such as the Ben Nevis and Hebron discoveries, will be tied into the available production infrastructure.

Because of these industry activities, a significant experience and expertise base has developed regarding environmental influences, offshore system design, and offshore operations on the East Coast. From an environmental perspective, the area is generally recognized as one of the most hostile operating environments in the world, since it is influenced by a range of adverse factors. The primary environmental constraints include high waves, icebergs and sea ice, all of which have constrained the exploration approaches used to date and have significantly influenced the design philosophies for the development systems that are being planned. Strong winds, structural icing, and poor visibility are also of concern, but are more important in terms of constraining operations than influencing design.

A critical element of effective East Coast ice management for Mobile Offshore Drilling Unit (MODU) drilling and production operations is ice detection; i.e., knowing the location and concentration of the sea ice edge; and location, sizes, and movements of icebergs and growlers. These aspects are also of importance to marine activities in support or related to the MODU operations such as movements of support vessels, and mooring or transit of crude carriers. Decisions, both strategic and tactical, related to Grand Banks drilling and production operations are significantly influenced by ice and iceberg detection capabilities. A variety of systems are available, or are under development, for both ice and iceberg detection (see Haykin et al., 1994). Various claims are made by proponents as to the effectiveness of each system or combination of systems.

This project has been initiated by the Environmental Studies Research Funds to conduct an independent review of actual and anticipated performance of ice detection systems. It encompassed the following tasks:

- Survey of User Needs
- Review of Available Instrumentation
- Evaluation of Technology Performance
- Assessment of Sensor Systems.

The results are presented in Chapters 3 to 6, respectively.

2.0 CONCLUSIONS AND RECOMMENDATIONS

2.1 CONCLUSIONS

The capabilities of remote sensing systems to detect and monitor sea ice and icebergs have improved markedly over the past twenty years. Not only has Canada taken a world lead in developing many of the appropriate sensor systems, but there exists the capability to utilize these sensors effectively under operational conditions.

In this study, four main operating scenarios were identified:

- field development - tactical
- field development - strategic
- ship transit - tactical
- ship transit - strategic.

For each of these scenarios, the most applicable sensors, for both sea ice and icebergs, have been suggested. Based on the known operating performance of available sensors, the major operating requirements can be met with current technology, with the exception of highly reliable detection of small ice pieces (growlers and bergy bits) under moderate and high sea state conditions, or within pack ice.

Sensors are continuing to develop, although the detection of ice is not the main technology driver that it was during the 1970s and 1980s. The main technology developments that are expected are the following:

a. Continued improvements in data processing and data fusion driven by significant improvements in low-cost computer performance, including user-friendly integrated display devices.
b. Availability of routinely available radar imagery from RADARSAT, starting in 1995.
c. Availability of data for much of the East Coast using over-the-horizon radar systems from the Newfoundland coast.
d. Ability to design and implement automated monitoring systems for ice detection.
e. Continued improvements to marine radar systems using both advanced processing, polarization diversity, and coherent sensors.
f. Improved access to advanced sonar systems that are emerging from military classification.

Underwater acoustic sensors, in particular, have received much less experimental testing for ice detection than radar sensors. As the costs of parametric sonars decrease, driven by general coastal surveillance markets, this technology has the potential to provide more reliable detection of small pieces of ice under higher sea state conditions. However, this possibility will have to be demonstrated in more extensive field trials than have been carried out to date.

2.2 RECOMMENDATIONS

2.2.1 Sensor Systems

Recommended suites of sensors, based on current capabilities, are presented in tabular form in Chapter 6. From these, it should be possible to determine an appropriate suite of sensors for most operating requirements.

Because of the complementary nature of several sensors, it is recommended that data from several sources be integrated at an ice information station appropriate to the operation. This approach could be as simple as combining visual and marine radar data, to a complex system that combines satellite, airborne, and surface information to meet ice detection requirements.

In particular, since detection of small ice pieces can be problematic, it is recommended that ice detection systems being assembled in a few years should specifically consider the state-of-the-art of sonar systems at that time.

2.2.2 Future Developments

As noted above, the major gap in the capabilities of current technology is in the detection of growlers and bergy bits under moderate to high sea states or in pack ice. It is expected that improvements to radar systems will make these sensors more effective. The Airborne Imaging Microwave Radiometer also has promise as an instrument capable of detecting bergy bits or growlers from the fresh water which surrounds them. It is also expected that appropriate underwater acoustic systems will become less costly, and could provide additional information. It is recommended that development work in these fields should be encouraged, especially in the area of experimental trials under quasi-operational conditions, similar to the studies undertaken for marine and airborne radars in the 1980s.

The ability to transmit, process, and display data will continue to advance rapidly over the next few years. Ice detection systems should take advantage of the rapid evolution of these technologies to improve the ability to quickly and inexpensively monitor ice conditions to the full capability of the sensors being used.

3.0 SURVEY OF USER NEEDS

3.1 OIL INDUSTRY ACTIVITIES

3.1.1 Exploration

More than 250 exploration and delineation wells have been completed on the East Coast over the past 25 years. These wells have been drilled with conventional floating drilling equipment, designed for open water use. Since these drilling systems are not ice-tolerant, most of the East Coast wells have been scheduled to avoid the seasonal periods with potential sea ice incursions and the highest iceberg encounter likelihood. Semisubmersibles have been the most common type of drilling system used to date. These vessels are preferred because of their superior performance characteristics in the area's relatively severe wave environment, although drillships have also been used.

Both types of drilling systems are quite capable of effective operations in the open water conditions experienced on the East Coast but, as noted above, are not ice-resistant, and have generally worked during seasonal operating windows to avoid sea ice intrusions and high iceberg occurrence frequencies. However, it is well known that the presence of some icebergs is unavoidable, even during these preferred exploratory drilling windows. As a result, the iceberg consideration has had a major influence on East Coast operations from the outset, and has required the development of specialized equipment and novel operating procedures designed to ensure safe and efficient drilling operations. In this regard, the Canadian oil industry has developed iceberg detection, management, alert and vessel move-off systems that are unique, and is in a well-demonstrated position to drill cost-effective exploration wells, with no major technical impediments.

From an exploration perspective, improvements in the efficiency and reliability of iceberg detection, forecasting and management systems would provide some benefit, but are by no means critical. Similarly, sea ice problems are simply avoided through appropriate scheduling. However, from a development perspective, the iceberg and sea ice constraints that are experienced on the East Coast are of more consequence, since they have a more significant influence on development system design and operations. Clearly, the development systems that are currently being pursued will be operated on a year-round basis, and as a result, will have to contend with all of the area's environmental influences, including icebergs and sea ice.

3.1.2 Development

To date, two fundamentally different approaches have been considered for the development of East Coast oil reserves, as illustrated by the Hibernia and Terra Nova production systems, proposed by Mobil Oil and Petro-Canada, respectively. Schematics of these generic development approaches are shown in Figures 3.1 and 3.2, where the key system components are indicated. These development approaches involve subsea wellheads, manifolds and flowlines, together with tanker loading systems and shuttle tankers that will periodically move produced oil to market.

The Hibernia scheme (Figure 3.1) is centered around a gravity based structure (GBS) which has internal oil storage and is designed to passively withstand all forces imposed by the environment, including those from extreme wave, sea-ice, and iceberg encounters. The benefit of this approach is that a fixed structure (with integral storage) will experience little, if any, production downtime due to adverse environmental conditions. However, the penalty is normally reflected by increased production facility costs, extended construction schedules, and longer time before the first oil is produced.

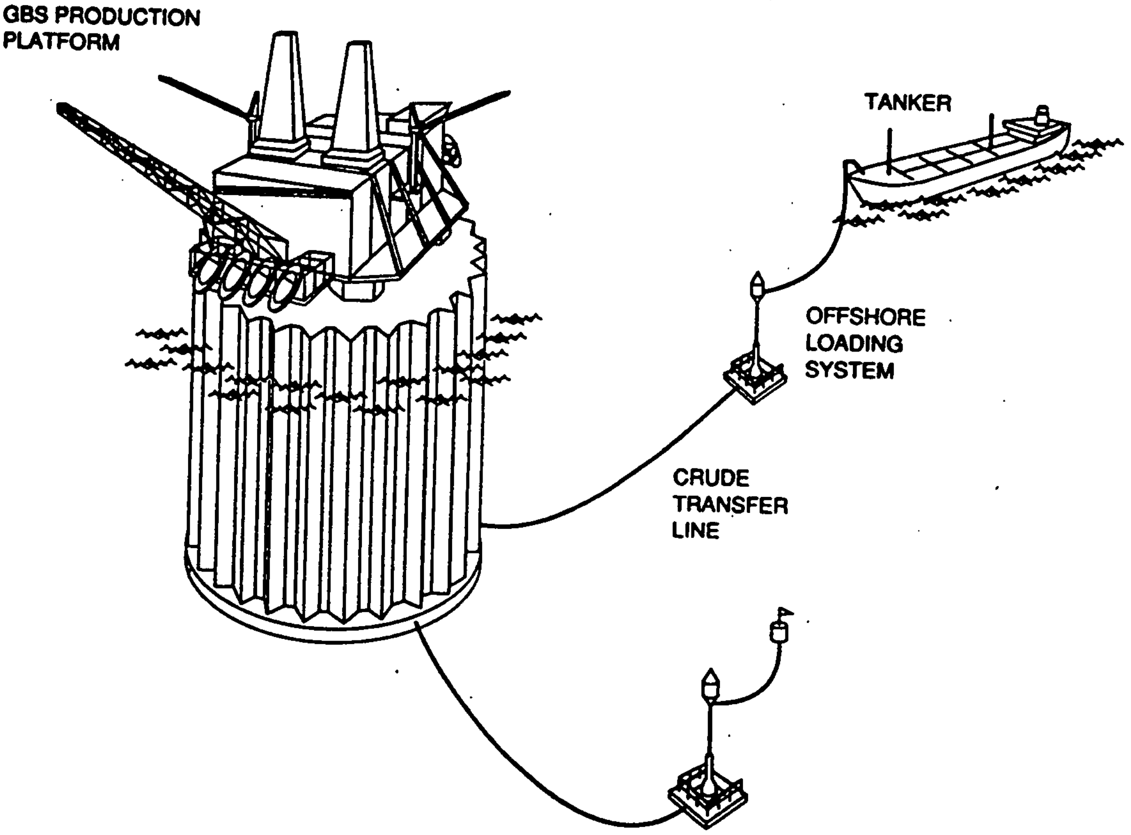

Figure 3.1 Sketch of Hibernia production system

A proposed Terra Nova development approach (Figure 3.2) involves a floating semi-submersible or ship-shape production vessel, that is designed to continue operations in normal to difficult environmental conditions, but will suspend production and move off location should extreme environmental events occur. If iceberg or sea ice avoidance is required, the vessel's mooring lines and the production riser are lowered to the seafloor and the vessel simply moves off under its own power. This approach is based upon an active design philosophy which reflects a high level of confidence in the experience base that has been developed with floating rigs during exploratory drilling activities. Generally, the advantage of a floating production vessel is lower capital cost, but the penalty is the potential for more environmental downtime due to ice and waves and the associated loss in production.

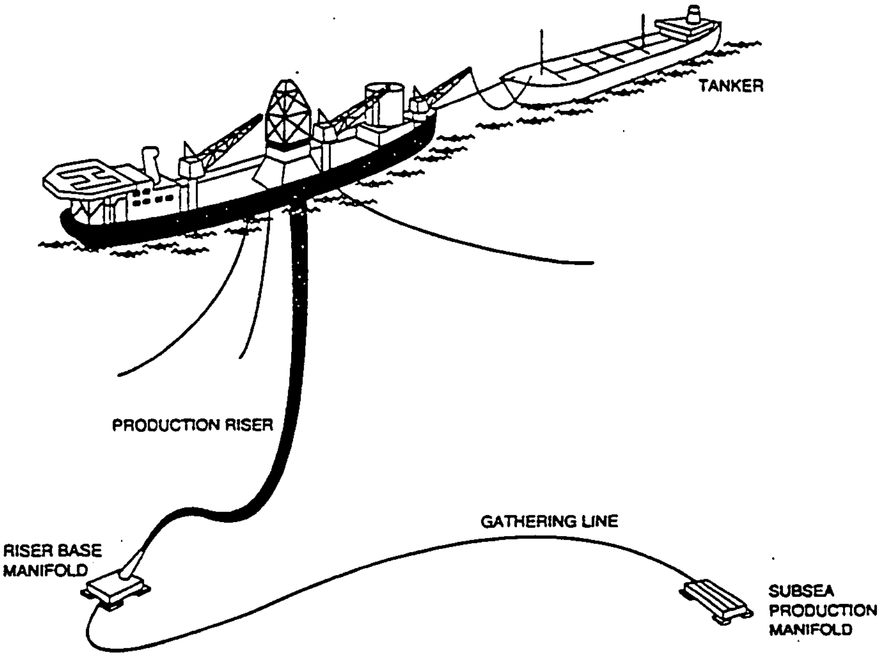

Figure 3.2 Sketch of proposed Terra Nova production system

Decisions regarding the best type of development system for a given field are normally based upon an assessment of comparative economics and relative risks, which balance downtime, lost production and increased operating costs for floaters against the increased capital cost and implementation schedules for fixed platforms.

Both the fixed and floating development approaches will involve oil transfer from the production facility to an offshore loading system (OLS), where ice-strengthened, double-hull shuttle tankers will load produced oil for subsequent transport to market. The oil transfer and loading arrangement is protected from most ice influences, being well below the waterline, but the actual tanker loading operation at the OLS will be susceptible to iceberg or sea ice incursions. Similarly, the shuttle tankers will be exposed to icebergs and sea ice during their transits to and from market. In terms of their powering and structural configurations, these tankers will be designed to contend with sea ice occurrences during transit, but will have to avoid icebergs and small glacial ice masses (with the possible exception of small features, several thousand tonnes or less). Supply vessels working in the area will be considerably more susceptible to the influences of sea ice and very small ice mass occurrences. Because the East Coast waters are relatively deep, the risk of seafloor scour is generally low. However, the subsea systems associated with developments will be protected from iceberg scour through placement within cased glory holes or trenches, that will be excavated to below the expected scour depth.

Clearly, the performance capabilities and limitations of the exploration and development systems intended for use on the East Coast are related to their ability to either withstand or avoid iceberg and sea ice effects. In this context, some of the systems are designed to avoid hazardous ice situations through integrated ice monitoring and alert procedures. For these systems, prudent operations are based upon a sound and spatially focused ice detection capability which is both timely and reliable.

3.2 ENVIRONMENTAL OVERVIEW

3.2.1 General

Exploration and development systems operating on Canada's East Coast will be exposed to a wide range of environmental conditions. Clearly, the presence of icebergs, small glacial ice masses and sea ice drives the need for an ice-detection capability while more specific characteristics of these ice features will govern the ice detection requirements and the most appropriate detection sensor configurations. Other environmental influences such as adverse weather and sea conditions, or mixed pack ice/iceberg occurrences, can also constrain sensor performance, and obviously must be addressed in terms of detection system functionality. Here, a brief description of the physical environmental conditions on the East Coast is given, as an overview. More thorough reviews of East Coast environmental conditions are available from a variety of sources (e.g., Canpolar Consultants Ltd., 1985). A summary is given in Appendix 1.

3.2.2 Waves and Weather

The East Coast wave climate is not unlike the North Sea, with extreme maximum wave heights in the order of 30 m. The area is often rough, and experiences frequent occurrences of moderate to high seas and longer period swell, particularly during the fall and winter periods, when storms move through the region. As an example, winter waves exceed 5 m significant wave height (Hs) about 15% of the time on the Grand Banks, with storm wave events typically lasting several days. The presence of rough seas can have a significant influence on the effectiveness of iceberg detection systems, since waves are located at the air/water interface (as are icebergs), and can have vertical dimensions comparable to some of the smaller ice masses of concern.

The weather on the East Coast is also recognized as quite inhospitable. Winds are relatively strong, with storm frequencies averaging about four per month in the summer and seven per month in the winter. For example, on the Grand Banks, mean summer winds are roughly 7 m/s (14 knots), whereas winter winds average 11 m/s (22 knots), and exceed 19 m/s (38 knots) about 10% of the time. Poor visibility caused by fog, low cloud cover, rain and blowing snow are also common occurrences in the general area.

Both fixed and floating systems have been used in this type of wave and weather environment. Monolithic gravity based structures and jack-ups are examples of existing bottom founded platforms, while semisubmersibles, shipshapes, and tension leg systems represent some of the floating systems now in use. Extreme waves and the associated wave forces govern the design of fixed structures intended solely for open water use, with load magnitudes depending upon the structural cross-section exposed to wave attack. Operations from floating platforms are limited by their wave induced motions and/or the associated tensions in their mooring lines. High seas, strong winds and poor visibility also influence the efficiency of marine operations such as tanker loading and resupply.

It should be noted that relatively low-cost fixed structures are now available that would be operationally effective in the East Coast's wave and weather climate. However, the presence of sea ice and icebergs, a range of possible ice loadings, and our inability to reliably eliminate a variety of ice threats limit the direct applicability of this conventional technology. In contrast, relatively conventional floating technology has and can be effectively used in this open water environment, given good ice detection and avoidance procedures.

3.2.3 Sea Ice

Sea ice is a design and operational concern for systems that will be working off Canada's East Coast for long time periods. For example, the development of Grand Banks oil reserves will involve production operations over project lifetimes of 15 to 20 years, so that some exposure to sea ice is inevitable. During exploration in the Grand Banks, much of the down time was due to the presence of sea ice. Sea ice can be advected into the area from the waters off northeast Newfoundland where pack ice both from the Labrador Sea and local formation occurs each winter. Typically, sea-ice intrusions are experienced every several years on the Grand Banks, lasting anywhere from a week to a month or more. In the Flemish Pass and Flemish Cap areas, and to the north of the Grand Banks, occurrences of sea ice can be more frequent.

The sea ice comprising this mobile East Coast pack is normally quite thin, in the order of 0.5 to 1.0 m, and is usually present in moderate concentrations, with floes that are tens of meters to hundreds of meters in extent. However, more extreme sea ice conditions can also occur which must be accommodated from a design and operational perspective. A representative extreme scenario would include high concentrations of first year sea ice comprised of some floes several kilometres in extent, with mean thicknesses approaching 2 m. Pressure ridges, rafted ice areas, small multiyear floe fragments, together with small glacial ice masses and icebergs can also be contained within the East Coast pack ice cover.

A fixed platform would have to be capable of sustaining the forces associated with these sea ice conditions, both globally and locally, while most conventional floaters would normally avoid sea ice incursions by moving off. In the case of purpose-built floating vessels, active ice management designed to reduce sea-ice forces would permit station-keeping, but would need a high level of reliability. Clearly, ice-strengthened floating systems would also require effective and reliable protection against glacial ice masses that were embedded in the pack ice cover in order to remain on location with confidence.

The occurrence of sea ice will also have a strong influence on various marine operations, including tanker loading from fixed and floating production platforms, regional ship transits and resupply. However, the significance and consequences of sea ice encounters will depend upon the design and performance characteristics of the vessels and loading systems employed. The unavoidable presence of icebergs and small ice masses within the sea ice is a further complication.

3.2.4 Icebergs

Icebergs pose a unique hazard to the design and operation of East Coast exploration and development systems because of their size, mass and energy. The waters off the Labrador coast are often referred to as Iceberg Alley since high numbers of icebergs move south in the Labrador Current towards the Grand Banks each year. Typically, more than 400 icebergs cross the 48th parallel annually, but there is considerable variability around this mean number from year to year. These icebergs are highly variable in size and shape, ranging in size from a few meters to hundreds of meters and in mass from hundreds to millions of tonnes (see Table 5.1).

Large icebergs are of most importance in terms of the global forces that they may exert on structures and the potential for deep iceberg keels to damage subsea facilities. Bottom-founded structures must be designed to withstand these force levels while floating structures must avoid them. Smaller glacial ice masses are also of concern to both types of systems due to the high local impact loads that they can impose. Similarly, the presence of icebergs and small ice masses are important for vessels navigating or station-keeping on the East Coast, since high speed interactions will likely result in structural damage.

Iceberg detection, monitoring, and management techniques will likely be used to reduce the risk of iceberg and small ice mass interactions through towing and water cannons. These techniques have often proven difficult to implement, particularly for smaller ice masses and unstable icebergs. Additionally, when icebergs and small ice masses have occurred during adverse weather conditions, ice detection and management have been difficult and unreliable.

3.3 ICE DETECTION REQUIREMENTS

3.3.1 Introduction

Clearly, a strong ice detection capability is of fundamental importance to any East Coast ice management system. Relevant ice information is required to support most aspects of exploration and development activities in the area, including related marine operations such as the mooring and transit of crude oil tankers and the movement of supply vessels. This section of the report focuses on ice detection requirements for industry's East Coast operations, and addresses both tactical and strategic ice information needs. These needs have been identified, in consultation with various East Coast operators, regulators and expertise groups, through a user survey process.

3.3.2 Preliminary Definition

By way of background, some of the East Coast ice detection requirements were assessed in the early 1990s, in conjunction with a Canadian Petroleum Association (CPA) review of Frontier Research and Development needs. This summary contained a consensus of views from the CPA's member companies, based upon operating scenarios that reflected industry's perception of projected activity levels in the Canadian frontiers. Generic technical issues considered important to these operating scenarios were first identified, and relative priorities for research were then defined for each scenario and issue area, as shown in Table 3.1. It may be seen that the ice detection topic was included in the "Ice detection, forecasting and management" issue area and, for most Grand Banks systems, was identified as a very important technical consideration. Industry participants also stated that they were much more likely to rely on real-time ice detection and ice management than on iceberg and sea ice forecasts, although forecasts can identify where and when to focus the use of tactical tools. As part of this CPA work, a commentary and brief overview of ice detection needs for the Grand Banks was also developed, as shown in Table 3.2.

The intent of the needs definition assessment in this current study was to build upon previous information and experience. Accordingly, the CPA summary information was used as a starting point and provided the basis for a more detailed and current definition of ice detection requirements for the East Coast.

Table 3.1 Canadian Petroleum Association technical priorities for operating scenarios

	GRAND BANKS					**NOVA SCOTIA**				
	Fixed Platform	Floating Platform	Pipelines/ Wellhead	Tankers	Exploration	Fixed Platform	Floating Platform	Pipelines/ Wellhead	Tankers	Exploration
Environmental Issues Chronic Impact	Medium/ high	Medium/ high	Low	Low	Low	Medium/ high	Low	Low	Low	Low
. Assessment	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low
. Environmental effects	Medium	Medium	Low	Low	Low	Medium	Low	Low	Low	Low
. Oil Spill	High	High	High	High	High	Medium	Medium	Medium	Medium	Medium
Safety and evacuation	High	High	NA[7]	Low	High	High	High	NA	Low	High
Sea Floor Issues	Medium[3]	Low	High	NA	Low	Low	Low	Low	NA	Low
Engineering and design	Medium[1]	Low/ Medium[6]	High	High[3]	Low	Low	Low	Low	Low	Low
Sea state and weather forecasting	Medium[3]	Medium	NA	Low	Meduim	Medium	Medium	NA	Low	Medium
Wave and current criteria	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low
Ice detection forecasting & mgmt	High	High	Medium	High[5]	Medium	NA[2]	NA[2]	NA	NA	NA
Ice/structure interaction	High	Medium/ High	High	Low	Low	NA[2]	NA[2]	NA	NA	NA

Notes:

1. CSA verification program, high priority.
2. For ice-free Nova Scotia waters.
3. Loading
4. Integrated detection and forecasting.
5. Detection.
6. "Low" for avoiding structures; "medium" for ice tolerant structures.
7. Not Applicable

Table 3.2 CPA Ice detection needs summary

GRAND BANKS OPERATING SCENARIOS

FIXED PLATFORMS - PRODUCTION (High)

Fixed platforms will be designed to resist forces from the most severe ice features on the Grand Banks. Therefore, the topic of ice detection, forecasting and management is less critical for fixed platforms than for floating systems. Nevertheless, the overall area is given a relatively high priority rating with the a view to the efficiency of marine supply, offloading and tanker loading operations in the vicinity of the platform.

FLOATING PLATFORMS - PRODUCTION (High)

Better ice detection, forecasting and management, especially of icebergs, will improve the operational efficiency, safety and economics of production using floating platforms. The detection of icebergs in darkness, fog and high seas (particularly small ice masses) is still not reliable. Clearly, the research needs in this area should be integrated with the ice tolerance capability of the platform.

PRODUCTION - WELLHEADS AND GATHERING LINES (Medium)

Improved ice detection and reliable forecasting of impending iceberg impacts with subsea facilities would enable timely shut down of production. However, this is a less preferable option or mode of operation than designing for iceberg impacts through burial or protection systems.

PRODUCTION TANKERS (High)

Tankers will need effective onboard ice detection and forecasting systems to avoid ice collisions and difficult ice. It is of high priority that evolving technology for detection systems be developed.

EXPLORATION (Medium)

Ice detection, forecasting and management as well as weather forecasting for Grand Banks exploration activities continue to receive medium priority for research. Onboard ice detection capability is of medium to high priority. Clearly, exploratory drilling can be conducted in a safe and effective manner with current technology as experienced by the offshore well drills over the last two decades.

TECHNICAL ISSUE:

Icebergs, small ice masses calved from these bergs and sea ice all have the potential to interfere with the safety and efficiency of production operations from or around platforms and, during vessel transits regionally.

TACTICALLY:

Detection:

It is important to have the ability to detect these glacial and sea ice features on demand from the platform and/or the marine vessels supporting production.

Space Scale:	5-10 km (9-19 nm)
Time Scale:	on demand (eg: continuous tracking)
Resolution:	features down to small ice masses (5 m x 5 m surface areas and 1-2 m freeboards)
Needs/Comments:	all weather detection in calm to rough sea conditions and in pack ice

STATEGICALLY:

Detection:

It is important to have the ability to detect icebergs and smaller ice masses along with sea ice of various types regionally for both platform operations planning and vessel routing.

Space Scale:	55-160 km (100-300 nm)
Time Scale:	1-2 days
Resolution:	features to scales of 10 - 20 m
Needs/Comments:	all weather detection in calm to rough seas technology such as over the horizon HF radar, SAR and search radars are currently applied/under development for this purpose data interpretation, display, dissemination and reliability (including resolution cut off) are important

LONG TERM:

Detection:

Regional detection capability suffices here.

3.3.3 Methodology

The ice detection requirements associated with future oil industry activities on the East Coast were identified, in consultation with various operators, regulators and expertise groups, through the user survey process, shown in Figure 3.3. The intent of this ice detection requirements definition study was to provide perspective for the ice detection capability assessment. The expertise base that has been established through prior East Coast design, operational and regulatory activities was recognized and several key individuals shown in Table 3.3 were identified for consultation. These individuals were then approached to provide their views on East Coast ice detection requirements, along with their rationale, observations, and associated priorities.

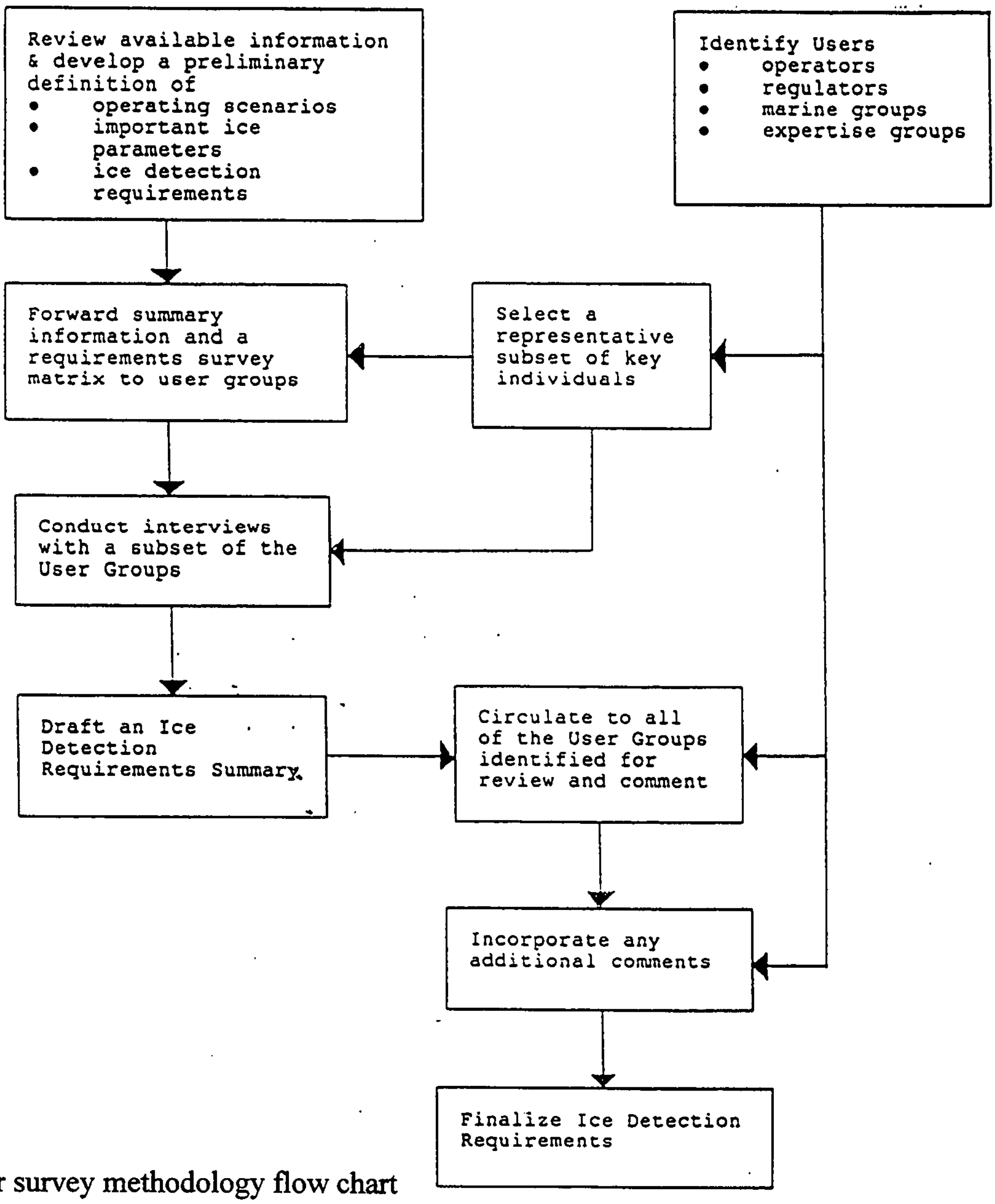

Figure 3.3 User survey methodology flow chart

Table 3.3 Organizations and individuals identified for survey

User Group	Organization	Individual
Industry	Amoco Canada	N. Vanderkooy[1]
	CAPP	D. Bruchet
	Chevron Canada	P. Rogers
	Gulf Canada	K. Gaida[1]
	Hibernia Holding	J. DeJong[1]
	Hibernia MDC	D. Goodridge[1]
	Husky Oil	T. Vonde
	Imperial Oil	J. Weaver
	Mobil Canada	W. Abel
	Mobil Oil	W. Spring[1]
	Petro-Canada	P. Clark[1]
	Petro-Canada	J. Miller
	Shell Canada	D. Mead
Former Industry	B. Wright	B. Wright[1]
	Consultant	G. Warbanski[1]
	ICL Isometrics Consulting	S. Hotzel
	K.R. Croasdale	K. Croasdale[1]
	TriWaste	J. Benoit
Regulator	CCG	M. VanRoosmalen
	CCG	B. Nash[1]
	CNOPB	D. Burley[1]
	NEB	B. Dixit[1]
	NEB	O. Mycyk
Marine	Canarctic Shipping	R. Gorman[1]
	Mobil Transportation	R. Bulow
	Fed Nav	T. Smith[1]
	Finnamore	T. Robinson
	Former BeauDril	P. Kimmerly[1]
Other	AES Ice Centre	T. Mullane[1]
	ABS	A. Tunik
	IIP/USCG	D. Murphy
	MacLaren Plansearch	S. Melrose
	SeaConsult	L. Davidson
	Noble Denton	M. Jacobs

Note:

1. Individuals interviewed as a representative subset of these user groups.

The survey work was carried out in two phases. The first involved one-on-one discussions with a subset of the individuals identified, followed by circulation of a draft summary to the total group for their review, comments and any further input. In most cases, the one-on-one discussions took the form of telephone interviews that followed a consistent interview format. Both written and verbal comments were received as part of the second review phase.

Through this extensive consultation process, ice detection requirements were defined on the basis of input from a broad spectrum of user groups. Within the scope of this work, the following technical considerations have been addressed:

- confirmation of the East Coast operating scenarios and system components of primary interest;
- identification of the types of ice of concern for given systems, including icebergs and sea ice;
- the size, scale and dynamics of these ice parameters of concern, along with their perceived hazard levels;
- discussion of tactical, strategic and any longer term ice information needs in this context;
- definition of specific ice detection requirements and priorities, including spatial and temporal detection coverage, target accuracies and resolutions, and information display preferences; and
- review of associated design and operational perspectives.

The results of this survey work have been synthesized and are summarized in the following sections. Although there were some differences in the opinions of the individual respondents, their overall message was reasonably consistent.

3.3.4 Operating Scenarios

In defining ice detection requirements for the East Coast, the three primary operating scenarios that were considered and agreed to included:

- oil production from a fixed structure, with a tanker export system
- oil production from a floating vessel, with a tanker export system
- further exploratory drilling, with conventional floating drilling vessels.

A variety of different operating scenarios are also conceivable, including fixed exploration structures, subsea production systems, and export pipelines to shore. However, these options were not considered in any detail, since the likelihood of their implementation is considered remote, at least in the foreseeable future.

The individual components of the systems that are associated with these three primary East Coast operating scenarios are identified in Table 3.4, together with a perspective on relative priorities for ice detection. Each system component has been categorized as either active or passive, to reflect the philosophy that is normally associated with its design and operation. The focus of this summary is directed towards ice detection and monitoring requirements during the course of sustained operations, with particular needs for the relatively short installation phase (e.g., tow and set down of a structure or a flowline installation) not explicitly considered. Clearly, good monitoring and forecasting systems will also be required to define acceptable windows for various installation operations.

Table 3.4 Ice detection requirements by system components

System Component	**Mode of Operation**	**Ice Detection Requirement**	**Comments**
Production Platform			
• Fixed	Passive	Low	
• Floating	Active	High	
Wellheads, Manifolds & Gathering Systems	Passive	Low/Medium	Possible use in preventative shut down, but is an unlikely approach
Export System			
•Tanker Loading Buoy	Passive	Medium	Won't be moved but some ice management is possible
• Tankers	Active	High	
• Pipeline	Passive	Low	
General Navigation			
• Tankers	Active	High	
• Supply Vessels	Active	High	
Exploration Platform			
• Floating	Active	Medium	Experience base in place

3.3.5 Ice Parameters

In order to begin focusing on a more specific definition of East Coast ice detection and monitoring requirements, various ice parameters were first identified as being of potential interest, since they can all influence the design and operation of the various system components identified in Table 3.4. These ice parameters are shown in Table 3.5, subdivided into iceberg and sea ice categories. Relative priorities that highlight the perceived importance of information about each of these ice parameters are also shown. It should be noted that icebergs and small glacial ice masses were generally considered as the primary area of concern for East Coast operations, while sea ice was generally seen as a secondary priority.

Table 3.5 Relative detection importance for various ice parameters

Icebergs		**Sea Ice**	
Parameter	Relative Importance	Parameter	Relative Importance
Presence/occurrence	High	Ice edge	High
Size/mass	High	Ice concentration	High
Length, width, height	Low	Ice type	Medium - High
Draft	Medium	Floe size	Low
Position/speed	High	Ice thickness	Low - Medium
Shape	Low	Ice roughness	Low - Medium
		Position/speed	High

Obviously, the underlying technical issue is that icebergs, small ice masses calved from these icebergs, and sea ice all have the potential to interfere with the safety and efficiency of operations on or around East Coast platforms, as well as during regional vessel transits. System components that are designed to withstand all of the area's environmental influences and operate passively (e.g. the Hibernia GBS or various subsea facilities) will have no functional requirement for ice information. However, system components designed to operate actively will have a high dependence on good ice detection and monitoring information, since the basis for their operation involves the avoidance of environmental situations and ice hazards that exceed their performance capabilities. Much of the equipment that will be used in future East Coast exploration and development activities falls into this active operations category.

3.3.6 Specific Requirements

As mentioned earlier, the main purpose of the user survey and review process was to specifically define ice detection requirements for the East Coast. The results of this work are given in Tables 3.6 to 3.9, where specific ice detection requirements and priorities are summarized. Clearly, the information that is provided here represents a synthesis of the individual views that were obtained. However, there were relatively few differences in the opinions of the individual respondents, and in this sense, these results reflect a reasonable consensus.

In order to present a common definition of East Coast ice detection requirements, it was necessary to combine and simplify the range of responses received. During the interview process, specific needs discussions always tended to become focused around two primary operating scenarios:

- an all-inclusive field development system (either fixed or floating), including tanker loading in the vicinity of the platform and local marine operations; and

- regional vessel transit operations (primarily tanker transits).

Table 3.6: Field development system: iceberg information requirements

Need		Priority					
		Occurrence	Position	Mass	Draft	L/W/H[1]	Shape
Spatial Coverage							
• tactical	0 - 40 km	High	High	High	Medium	Low	Low
• strategic	40 - 200 km	High	High	Medium	Low	Low	Low
Temporal Coverage							
• tactical	on demand	High	High	High	Medium	Low	Low
• strategic	1 - 2 days	High	High	Medium	Low	Low	Low
Positional Accuracy							
• tactical[2]	100 - 500 m	High	High	High	Medium	Low	Low
• strategic[2]	1 - several km	High	Medium	Medium	Low	Low	Low
Resolution/Size							
• tactical	≈ 1,000 tonnes	High	High	High	Medium[3]	Low	Low
• strategic	≈ 10,000 tonnes	High	Medium	Medium	Low	Low	Low
Information Display	PPI or graphic equivalent in facility control room						

Notes:

1. Length/Width/Height
2. The accuracy requirement varies with the iceberg's range within the coverage area, and also relates to the need for sequential positioning to derive iceberg speeds and trajectories within the alert system.
3. Iceberg draft is of tactical interest for large, deep icebergs drifting in the vicinity of subsea facilities. Sonars deployed from workboats should provide an adequate level of information.

Table 3.7: Field development system: sea-ice information requirements

Need		Priority						
		Ice Edge	Ice Concentration	Position & Extent	Ice Type[1]	Ice Thickness	Ice Roughness	Floe Size
Spatial Coverage								
• tactical	0 - 40 km	High	High	High	Medium	Low	Low	Low
• strategic	40 - 200 km	High	High	Medium	Low	Low	Low	Low
Temporal Coverage								
• tactical	on demand	High	High	High	Medium	Low	Low	Low
• strategic	1 - 2 days	High	High	Medium	Low	Low	Low	Low
Positional Accuracy								
• tactical	500 m	High	High	High	Medium	Low	Low	Low
• strategic	2 - 4 km	High	Medium	Medium	Low	Low	Low	Low
Resolution								
• tactical	± 1/10th	-	High	High	Medium	Low	Low	Low
• strategic	± 1/10th	-	Medium	Medium	Low	Low	Low	Low
Information Display	map or graphic equivalent in facility control room							

Note:

1. The main interest in ice type is whether the pack is thin or thick first year ice, a general indication of roughness, and whether it contains any multi-year ice floes or glacial ice masses

Table 3.8: Vessel transits: iceberg information requirements

Need		Priority					
		Occurrence	Position	Mass	Draft	L/W/H[1]	Shape
Spatial Coverage							
• tactical	0 - 5 km	High	High	High	Low	Low	Low
• strategic	5 - 30 km	High	High	Medium	Low	Low	Low
Temporal Coverage							
• tactical	on demand	High	High	High	Low	Low	Low
• strategic	on demand	High	High	Medium	Low	Low	Low
Positional Accuracy							
• tactical	100 m	High	High	High	Low	Low	Low
• strategic	500 m	High	Medium	Medium	Low	Low	Low
Resolution/Size							
• tactical	≈ 1,000 tonnes	High	High	High	Low	Low	Low
• strategic	≈ 10,000 tonnes	High	Medium	Medium	Low	Low	Low
Information Display	PPI or graphic equivalent on vessel's bridge						

Note:
1. Length/Width/Height

Table 3.9 Vessel transits: sea-ice information requirements

Need		Priority						
		Ice Edge	Ice Concentration	Position & Extent	Ice Type[1]	Ice Thickness	Ice Roughness	Floe Size
Spatial Coverage								
• tactical	0 - 10 km	High	High	High	Medium	Low	Low	Low
• strategic[2]	10 - 50 km	High	High	Medium	Low	Low	Low	Low
Temporal Coverage								
• tactical	on demand	High	High	High	Medium	Low	Low	Low
• strategic	3 - 6 hours	High	High	Medium	Low	Low	Low	Low
Positional Accuracy								
• tactical	500 m	High	High	High	Medium	Low	Low	Low
• strategic	2 - 4 km	High	Medium	Medium	Low	Low	Low	Low
Resolution								
• tactical	± 1/10	-	High	High	Medium	Low	Low	Low
• strategic	± 1/10	-	Medium	Medium	Low	Low	Low	Low
Information Display	map or graphic equivalent on vessel's bridge							

Notes:

1. The main interest in ice type is whether the pack is thin or thick first-year ice, a general indication of roughness, and whether it contains any multiyear ice floes or glacial ice masses.

2. For regional space and time scales (200-300 km and 1-2 days), the level of information on the currently available AES ice charts was considered adequate.

Because of this, the ice detection requirements and priorities that are given here have been presented in relation to these two scenarios. Tables 3.6 and 3.8 summarize the key iceberg detection requirements for each scenario, whereas Tables 3.7 and 3.9 address the sea ice information needs for both cases. The requirements for a floating exploration system are similar to those for the general field development scenario.

The detection requirements summarized in Tables 3.6 to 3.9 have been specified in terms of tactical and strategic ice information needs, and highlight the requirements related to spatial and temporal coverage, positional accuracies, and resolutions. In each of these areas, relative priorities for information on different ice parameters have been assigned according to high, medium and low categories. Preferences regarding ice information displays are also given.

3.4 ADDITIONAL INFORMATION

During the survey process, there were a number of comments made that are not necessarily reflected by the ice detection requirements consensus information presented in Tables 3.6 to 3.9. Some of the key comments are presented here, in order to provide additional perspective to the information presented in Tables 3.6 to 3.9.

3.4.1 Iceberg Information Needs

a. The primary concern lies with the detectibility of small glacial ice masses (growlers and bergy bits) in various environmental conditions (waves and pack ice), as a function of distance, together with their probability of detection.

b. It is important that the application/development of systems to detect very small growlers is driven by need rather than technology, since a very high resolution capability is an expensive "nice to have", but in a practical, pragmatic sense, is not necessarily a strong requirement.

c. The risks associated with small ice mass interaction events are well recognized, together with limitations related to their detectibility, and are being accommodated by appropriate structural design for local ice loads, in combination with prudent operating procedures.

d. For a given ice situation (icebergs or sea ice), it is important to realistically identify the potential consequences of an ice interaction, assess design and operational solutions, and on this basis, establish thresholds where acceptable ice conditions become hazardous and then define ice detection requirements.

e. During exploration, the biggest problem was the lack of a continuous iceberg detection capability within the tactical zone, which if available, would have eliminated the need for ongoing iceberg re-identification and the problems associated with this activity.

f. Reliable and timely iceberg information is critical, otherwise it will lack credibility and will not be used.

g. Iceberg detection space and time scales are directly related to operational avoidance procedures (alert system zones) which are based on the location and speed of the ice hazard, and depend upon the response time of the particular system that is at risk.

h. A tanker or supply vessel's response to the occurrence of icebergs or small ice masses is avoidance over space scales of several kilometres and time scales of minutes, with the position and rough size of the hazard with respect to the vessel being the most important information.

i. Due to relative speeds, iceberg motions are not of interest to transitting vessels, with a number of respondents feeling that icebergs represent a tactical but not a strategic concern (whether there is 1 or 100 icebergs in an area, vessels would exercise the same level of caution and ongoing watch).

j. For field development systems, the precautionary alert response time frames are longer, since reactions involve ongoing monitoring, ice management where feasible, and ultimately, the suspension of operations if required.

k. For development systems, the speed of the ice feature (and sequential positioning) is much more important, as is information on iceberg size.

l. For tankers, growlers of ≤200 t are not considered to be a threat due to hull strengthening, whereas bergy bits of ≥ 10,000 t may result in some hull damage if impacted (outer skin puncture) but no catastrophic consequences in terms of oil loss or floating stability.

m. From a tanker perspective, this fixes the minimum detection size requirement in the 1000 t range, or an ice feature about 10 x 10 x 10 m.

n. Safe operating speeds are a standard marine practice that will also be used in bergy waters as a mitigative operational procedure, although the higher the vessel's service speed amongst small ice masses the better, from an efficiency standpoint.

o. Purpose-built supply vessels will have some ice strengthening and will be capable of sustaining some small ice mass impacts.

p. Standard marine radars will be used on these vessels (as they have been in the past), unless significant value added enhancements are available that are cost effective.

q. Operations on the development platform and at the adjacent tanker loading system will be more sensitive to the physical characteristics and speeds of icebergs, with identified concerns ranging from extreme iceberg impacts for GBS survivability, the depth of iceberg keels in relation to subsea facilities and the OLS system, to small growler and bergy bit impacts with floating production vessels and tankers being loaded at the OLS.

r. For a GBS development approach, the OLS located several kilometres from the platform is perceived as the weakest link in the system (or the passive component at greatest risk), with iceberg keels (for example, those ≥30 m in the Hibernia case) representing a potential hazard and therefore a prompt for as-required iceberg management actions.

s. For subsea facilities, large icebergs with deep keels are of interest, and will be investigated by supply boats (e.g. geometry, observations combined with rules of thumb for draft estimation, side-scan sonar profiles) to provide the Offshore Installation Manager with scour risk information in order to assess the need for a precautionary production shutdown.

t. Although floating production vessels will be ice strengthened to a certain level and/or will move off to avoid excessive ice loads, other design factors should be recognized, such as the requirement for semisubmersible legs to sustain accidental loads from supply vessel impacts (5000 t at 2.5 m/sec impact speed in the waterline area).

u. A variable accuracy in iceberg positional information is acceptable, with more accurate positions as an ice feature approaches a particular operation; i.e., a sliding scale that is a function of range, which provides a detection capability that parallels the alert and ice management systems being used.

v. For any particular operation, iceberg detection needs will also depend on the amount of conservatism that is built into the overall ice management plan.

w. The Atmospheric Environmental Services (AES) iceberg surveillance program is recognized as having the potential to provide low resolution regional iceberg information but discussions between operators and AES will be required to ensure that the regional information obtained by AES is properly meshed with the operator's strategic requirements in order to be useful.

3.4.2 Sea-ice Information Needs

a. Sea ice is generally considered to be a secondary concern because it is fairly infrequent and is typically present in the form of loose pack ice that is quite weak.

b. In areas off the Grand Banks and to the north, the relative priority associated with sea ice may be somewhat higher because of higher frequencies of occurrence.

c. Several respondents noted that sea ice incursions, rather than iceberg occurrences, have been the major cause of downtime during Grand Banks exploration, and felt that sea ice may be as influential on floating production and tanker offloading operations as icebergs.

d. The main interest is in the position of the ice edge, approximate ice concentrations within the pack, and the distribution of ice types in broad first-year and thin ice categories.

e. There is little interest in direct sea-ice thickness information but the presence of multiyear ice flow fragments, small ice masses, and icebergs within the pack is important, since they represent hazardous ice features.

f. From a tanker transit perspective, there will be no large course deviations due to sea ice because the tankers will be quite capable of good performance in the expected range of conditions, from both a structural and powering standpoint.

g. The regional distribution of sea ice all the way to the Newfoundland Coast is of interest, with the current level of AES ice chart detail seen as appropriate.

h. Direct sea ice observations obtained during routine transits to and from a development site (every several days) will be one of the best sources of strategic information during sea ice incursions.

i. GBS type structures are insensitive to sea-ice occurrences, although tanker loading at the OLS will be.

j. Floating production vessels (shipshapes or semisubmersibles) will also be sensitive to sea-ice intrusions, but the required level of information detail regarding local sea ice conditions will be determined by the operating philosophy (i.e., station-keeping in some sea ice versus moving off).

k. At times, sea-ice management will be very important to tanker offloading operations and to station-keeping for floating production vessels, but the attitude reflected is to learn by doing as these situations arise.

3.4.3 Ice Information Display Systems

a. In terms of the ice information that is required for tactical decisions it is very important to have on-demand ice detection and display systems that are located on the vessel's bridge or platform's control room, for direct and immediate use, as required.

b. Ice information that is downlinked or sent from afar is generally not considered to be acceptable for tactical support (since it must be available on demand at the decision-making location).

c. However, other respondents noted that satellite radar imagery downlinked to a production facility may have some tactical usefulness, especially when used to complement other systems.

d. For tanker-loading operations at an OLS, ice information passed from the production platform's control room will have to be integrated with ice information from detection systems available on the tanker itself.

e. Supply vessels operating in the field area will rely on their marine radars and radio communication for ice information, but certain data products may be sent to these vessels, if their cost is low.

f. In all likelihood, a shore-based ice office will manage the ice information requirements that are related to strategic and regional scales, and will provide routine products and services to field development and vessel locations.

4.0 AVAILABLE INSTRUMENTATION

4.1 INTRODUCTION

This chapter discusses the commercially available, state-of-the-art in remote sensing capabilities for detection of sea ice and icebergs off Canada's East Coast. It reviews the relevant sensor technologies available and documents their specifications, particularly as they relate to the high and medium priority concerns of sea ice and icebergs as defined in Chapter 3.

As discussed in Chapter 3, there are four broad areas of hydrocarbon related activity:

- Hydrocarbon exploration systems (floating or semi submersible).
- Field development systems consisting of production platforms (fixed, gravity-based or floating structures), wellheads, manifolds, and gathering systems.
- Export systems consisting of the tanker loading facilities and pipelines.
- Tankers and supply vessels moving in ice-infested waters.

Each ice occurrence scenario, or combination of scenarios, can be expected to affect various operational activities with varying degrees of severity. Consequently, dependable ice information will be required in varying degrees of detail, frequency, delivery time, etc.

In this chapter, various types of sensors that are currently available (or soon will be) are described. Physical models of the major sensor types are described in Chapter 5, together with more detailed performance estimates and experts' assessments of future developments.

This chapter is divided into the four principal sensor types:

- Radar (airborne, spaceborne, marine, and ground-based).
- Passive Microwave.
- Acoustic Systems.
- Optical Systems.

4.2 RADARS

Radars were invented prior to the Second World War, developed during the War, and have since been used extensively by the military, government, and industry. Radars rely on the reflection of microwave energy, generated by the radar transmitting antenna, from the surface onto which they are incident. The reflected signal, received by the radar antenna, is used to provide information about the reflecting surface, its location (range, distance, and bearing) relative to the radar system, and its radar reflectance signature, which can generally be used to provide more information about the object being illuminated. Marine radars have been used for the detection of ice since their first usage on arctic going vessels. Side looking airborne radars have been used since the early 1970s, and much more extensively from the mid 1970s onwards when industry commenced operations in the Arctic. However, the detection of ice by radar is not 100 % reliable, and relies on interpretation by an experienced person. There is a problem identifying ships from icebergs, as is discussed later.

Microwave energy is emitted at wavelengths of millimetres to centimetres, which is considerably longer than the wavelengths of visible light (400 to 700 nm wavelengths) and infra-red radiation (700 to 10,000 nm wavelengths). In the case of the aircraft and spacecraft borne side looking radars, the microwave energy is emitted in regular bursts downward and to the side of the craft such that the energy strikes the earth's surface obliquely. This oblique incidence results in a broad swath coverage of the surface during a single overflight of the surveillance aircraft or spacecraft.

The delay between microwave signal transmission and reception after its reflection, along with the intensity of the reflection can be digitized and used to present an image of the earth's surface, either through photographic or electronic display media, i.e., as a hard-copy picture, video picture, or computer screen picture.

The advantages of radar sensors are their ability to penetrate cloud cover and night-time darkness, plus their wide surface coverage. For comparison, a standard aerial photo flight at 3,000-m flying height would produce an image swath less than 6 km wide, provided there is good visibility. By contrast, the obliquely emitted radar beams of an airborne or spaceborne imaging radar will produce an image swath from many tens to hundreds of kilometres wide, in any weather condition.

Three attributes of imaging radar systems which significantly affect ice monitoring and detection are coherence, wavelength, and polarization.

All radar systems, be they airborne, spaceborne, surface-mounted, imaging or nonimaging, are either coherent or noncoherent. In a noncoherent system, wave phase is random from pulse to pulse. This is characteristic of most operational radar systems to date. In a coherent system, the phase of both transmitter and receiver is locked at a constant value. Thus, the phase of a received signal may be analyzed with reference to the phase of the transmitted signal (Haykin et al., 1994, Chapter 6). In a stationary surface-mounted radar system, the availability of phase data for processing can result in an instantaneous target velocity calculation derived from the apparent, or Doppler, phase shift between the received signal reflected by a moving target and the original transmitted signal, provided that transmission was from a fixed point (see subsection 4.2.4.2 on IPIX). In an imaging radar (e.g., synthetic aperture radar, see subsection 4.2.1.2), the phase shift data provides an additional piece of information by which the image resolution can be increased.

Radar systems generally make use of wavelengths ranging from 7.5 mm to 1 m, which correspond to frequencies descending from 40 GHz to 300 MHz. The most positive experience in ice interpretation from radar data has been gained from imagery collected at X band (3 cm). The adjacent band of longer wavelengths (lower frequencies) is designated as C band (5 cm) is an alternative for limited power ice surveillance systems which cannot generate the higher frequency X-band energy. Longer wave (15 - 30 cm), L band energy is used in systems focused on land surveillance. Marine radars are usually X band or S band (10 cm) for better rain penetration (see Chapter 5).

Polarization refers to a manner of filtering the microwave signals, both transmitted and received, such that electrical wave vibrations are restricted to a single plane perpendicular to the direction of microwave propagation (Lillesand and Kiefer, 1987). Unpolarized energy will vibrate in all directions perpendicular to propagation direction. In ice interpretation from radar imagery, energy polarized in the horizontal plane (transmitted and received) has permitted the most usable interpretations of ice surface characteristics.

Two versions of imaging radar are commonly in use: side-looking airborne radar (SLAR) and synthetic aperture radar (SAR). A good operational summary of these systems is given in Haykin et al., 1994, Chapter 10.

4.2.1 Airborne Systems

This section covers radar systems carried by aircraft.

4.2.1.1 SLAR systems

Technical description: The generic name, side looking airborne radar (SLAR), describes the sensor's basic operation, emitting energy outward and to the side, and the original survey platform, airplanes. SLAR has, however, also been installed in earth-orbiting satellites, specifically the *Cosmos 1500* spacecraft of the former Soviet Union.

Whether airborne or spaceborne, SLAR operates on the principle of "real aperture", that is the physical length of the radar antenna controls the beamwidth of the microwave energy pulse emitted. The longer the antenna used to generate the beam, the narrower will be the beamwidth and the greater the image resolution parallel to the flight path (the "azimuth" resolution). Because the beam of microwave energy becomes wider with distance from source, azimuth resolution will progressively degrade towards the far range of the swath. Resolution across the width of the radar swath (the "range") remains constant and is determined by the time, measured in microseconds (μs), in which an individual pulse of microwave energy is emitted. This time, is referred to as the pulse width. The rate of pulses transmitted per second is referred to as the pulse repetition frequency (PRF). A SLAR pixel size, then, will vary across the width of an image, becoming progressively elongated toward the outer edge of the image swath, although constant in size in the range direction (Figure 4.1).

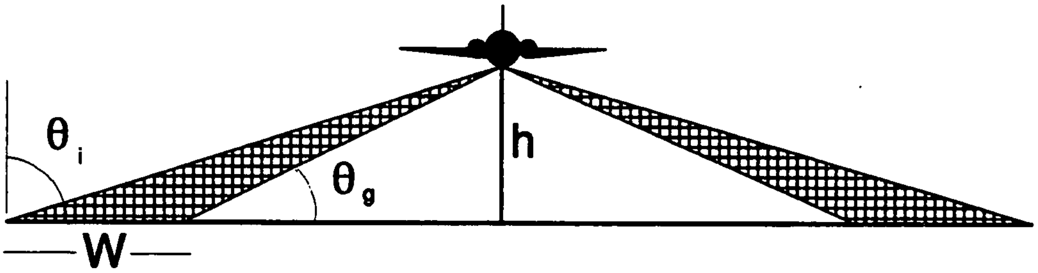

Figure 4.1 Region of cover of side-looking airborne radar. Airborne or space borne systems have similar coverage patterns (h is aircraft altitude, and W the swath width, θ_g is the depression angle and θ_i is the incident angle).

The capabilities of available SLAR packages with respect to ice detection are summarized in Tables 4.1 to 4.3. They are followed by key system specifications (Table 4.4) which will aid in estimating ice detection potentials which may not yet be satisfactorily quantified.

Experience base: SLAR has served as an operational ice monitoring tool for Canadian waters since early 1978, when Environment Canada's Ice Patrol initiated regular SLAR data collection flights in the Canadian Arctic with a Motorola APS 94/D mounted in an Electra aircraft (C-FNDZ); this continued into the 1980s. In 1979, The Bercha Group began commercial SLAR survey operations with its Motorola APS 94/D system mounted in a Gulfstream G159 aircraft (Bercha et al., 1991). During summer and fall of 1980, the original Ice Patrol SLAR also provided ice data acquisition services to Dome Petroleum's Beaufort Sea offshore operations. In 1985, the Canadian Atmosphere Environment Service (AES) brought into service its Canadian Astronautics Limited (CAL) SLAR for ice reconnaissance of the East Coast and Gulf of St. Lawrence. The International Ice Patrol (IIP) of the United States Coast Guard has also used SLAR as an operational ice monitoring tool since 1978 and has conducted or participated in specific SLAR ice detection trials in 1984 (Rossiter et al., 1985), 1985 (Robe et al., 1985), and 1991 (Ezman et al., 1993).

One of the problems was due to an operator flying over a large area expecting to identify all the icebergs and only the icebergs in the area, only to discover that many icebergs were missing and other targets, such as waves, fishing boats (often as many as 50 in the area), and oceanographic and navigation buoys were identified as icebergs. Icebergs which were weathered provided very poor radar reflectors and wave crests and ships provided good reflectors. Hence, the information would often result in a credibility gap between ice observers and rig managers. The International Ice Patrol, who operated a SLAR system, flew twice over the same area and looked for movements of the targets. Any targets which moved at more than about 1 m/s (2 kt) were boats, however, this still caused problems with stationary boats and buoys. SLAR was generally flown well above the clouds, which prevented visual verification of targets. SLAR found to be excellent for the detection of pack ice.

Experience with SLAR in the Beaufort Sea for the detection of sea ice indicated that in summer, the imagery provided by a well adjusted SLAR was comparable to that of SAR for the detection of ice floes in open water. However, in 10/10 ice cover, SLAR was definitely inferior to SAR, due to the latter's better spatial resolution, particularly in the far field. The Canadian government's AES SLAR on the DASH 7 was not as good as the commercially operated systems as it was optimized to detect the presence of ice and ice boundaries rather than ice type. However, the DASH 7 data were generally cheaper than the commercial data particularly if the area of interest was part of the regular overpass

Potential to satisfy user needs (icebergs): A major study of SLAR was conducted in 1984 (Rossiter et al., 1985). SLAR data apply to the high and medium priority items of occurrence and position of "large" and larger icebergs (see Table 5.1) for both field development systems and vessel transit. Spatial coverage addresses both tactical and strategic needs of field development systems but only strategic needs for vessel transit. Positional accuracy may restrict SLAR use to the strategic level for both field development and navigation, however, this has been improved considerably with the introduction of GPS. Assuming availability of a dedicated airborne SLAR, the "on demand" requirements of all operations can be met.

Potential to satisfy user needs (sea ice): SLAR image data is relevant to all concerns specified in Chapter 3, Tables 3.6 and 3.9 with the exception of ice thickness. The sensor appears to have the potential to address both tactical and strategic level needs in all areas with the exception of tactical positional accuracy for both field development systems and vessel transit. SLAR can also provide information on floe size and ice roughness, both of which are low priority concerns for both field development and navigation.

Operational application: Currently available SLAR sensors are airborne packages. The Canadian Ice Patrol's CAL SLAR flies on a DHC-7 (Dash 7) and the IIP SLAR is installed on board an HC-130 aircraft (Robe et al., 1985). The Bercha Group SLAR is presently configured for a Metro II aircraft (Bercha et al., 1991). It is currently not installed in an aircraft, but could be reinstalled if required.

Cost: With few systems available, the pricing policy for a given long-term project will always be negotiable. The one commercial SLAR operator does not offer a public pricing guideline due to the variety of client needs, survey locations, and length of any given project. A very approximate single flight cost of $5,000 may be calculated, based on such information as aircraft range, survey ground speed, swath width, and an estimated cost of $0.034 per km^2

(Bercha et al., 1991). One must also consider the extra cost of system mobilization, re-installation of the SLAR in the aircraft, and ferry cost to the site of operations.

Table 4.1: Side Looking Airborne Radar (APS 94/D) application to user-defined medium and high priority needs.

SENSOR:	**SLAR APS 94/D (Bercha Group)**	Field Development (icebergs)	Field Development (sea ice)	Vessel Transits (icebergs)	Vessel Transits (sea ice)
Sensor Relevance	Iceberg occurrence	Yes		Yes	
	Iceberg position	Yes		Yes	
	Iceberg draft	No		No	
	Sea-ice edge		Yes		Yes
	Sea-ice concentration		Yes		Yes
	Sea-ice position & extent		Yes		Yes
	Sea-ice type		Yes[1]		Yes[1]
Spatial Coverage	Tactical requirement:	0-40 km	0-40 km	0-5 km	0-10 km
	Strategic requirement:	40-200 km	40-200 km	5-30 km	10-50 km
	Offered:	25-200 km swath[2]	25-200 km swath[2]	25-200 km swath[2]	25-200 km swath[2]
Temporal Coverage	Tactical requirement:	on demand	on demand	on demand	on demand
	Strategic requirement:	1-2 days	1-2 days	on demand	3-6 hours
	Offered:	on demand	on demand	on demand	on demand
Positional Accuracy	Tactical requirement:	100-500 m	500 m	100 m	500 m
	Strategic requirement:	1-several km	2-4 km	500 m	2-4 km
	Offered:	[3]	[3]	[3]	[3]
Resolution or Size	Tactical requirement:	1,000 t	± 1-tenth	1,000 t	± 1-tenth
	Strategic requirement:	10,000 t	± 1-tenth	10,000 t	± 1-tenth
	Offered:	10,000 t[4]	± 1-tenth	10,000 t[4]	± 1-tenth

Notes:

1. Depends on interpretation of image.
2. Swath options are 25 km, 50 km, and 100 km on either or both sides of the reconnaissance aircraft.
3. Dependent on navigation system input. Current SLAR aircraft has the capability to use the high-accuracy Global Positioning System (GPS) input which would serve tactical and strategic requirements.
4. Estimate based on performance of three SLARs during Bergsearch '84 experiment (Rossiter et al., 1985), under conditions of low sea. Between 85% and 92% of bergy bits and less than 20% of growlers were detected.

Table 4.2: Side Looking Airborne Radar (CAL SLAR-200) application to user defined medium and high priority needs.

SENSOR	**CAL SLAR-200 (AES)**	Field Development (icebergs)	Field Development (sea ice)	Vessel Transits (icebergs)	Vessel Transits (sea ice)
Sensor Relevance	Iceberg occurrence	Yes		Yes	
	Iceberg position	Yes		Yes	
	Iceberg draft	No		No	
	Sea-ice edge		Yes		Yes
	Sea-ice concentration		Yes		Yes
	Sea-ice position & extent		Yes		Yes
	Sea-ice type		Yes[1]		Yes[1]
Spatial Coverage	Tactical requirement:	0-40 km	0-40 km	0-5 km	0-10 km
	Strategic requirement:	40-200 km	40-200 km	5-30 km	10-50 km
	Offered:	25-200 km swath[2]	25-200 km swath[2]	25-200 km swath[2]	25-200 km swath[2]
Temporal Coverage	Tactical requirement:	on demand	on demand	on demand	on demand
	Strategic requirement:	1-2 days	1-2 days	on demand	3-6 hours
	Offered:	on demand[3]	on demand[3]	on demand[3]	on demand[3]
Positional Accuracy	Tactical requirement:	100-500 m	500 m	100 m	500 m
	Strategic requirement:	1-several km	2-4 km	500 m	2-4 km
	Offered:	100 m[4]	100 m[4]	100 m[4]	100 m[4]
Resolution or Size	Tactical requirement:	1,000 t	± 1-tenth	1,000 t	± 1-tenth
	Strategic requirement:	10,000 t	± 1-tenth	10,000 t	± 1-tenth
	Offered:	>10,000 t (5)	± 1-tenth	10,000 t[5]	± 1-tenth

Notes:

1. Depends on interpretation of image.
2. Swath options are 25 km, 50 km, and 100 km on either or both sides of the reconnaissance aircraft.
3. Sensor is committed to government reconnaissance duties elsewhere during December-to-April period.
4. Dependent on navigation system input. Current SLAR aircraft has capability to use the high-accuracy GPS input which would serve tactical and strategic requirements.
5. Estimate based on performance of three other SLARs, as CAL SLAR was not part of Bergsearch '84 project (Rossiter et al., 1985).

Table 4.3: Side Looking Airborne Radar (AN/APS-135) application to user defined medium and high priority needs.

SENSOR:	**AN/APS-135 (IIP)**	Field Development (icebergs)	Field Development (sea-ice)	Vessel Transits (icebergs)	Vessel Transits (sea-ice)
Sensor Relevance	Iceberg occurrence	Yes		Yes	
	Iceberg position	Yes		Yes	
	Iceberg draft	No		No	
	Sea-ice edge		Yes		Yes
	Sea-ice concentration		Yes		Yes
	Sea-ice position & extent		Yes		Yes
	Sea-ice type		Yes[1]		Yes[1]
Spatial Coverage	Tactical requirement:	0-40 km	0-40 km	0-5 km	0-10 km
	Strategic requirement:	40-200 km	40-200 km	5-30 km	10-50 km
	Offered:	25-200 km swath[2]	25-200 km swath[2]	25-200 km swath[2]	25-200 km swath[2]
Temporal Coverage	Tactical requirement:	on demand	on demand	on demand	on demand
	Strategic requirement:	1-2 days	1-2 days	on demand	3-6 hours
	Offered:	if system available	if system available	if system available	if system available
Positional Accuracy	Tactical requirement:	100-500 m	500 m	100 m	500 m
	Strategic requirement:	1-several km	2-4 km	500 m	2-4 km
	Offered:	[3]	[3]	[3]	[3]
Resolution or Size	Tactical requirement:	1,000 t	± 1-tenth	1,000 t	± 1-tenth
	Strategic requirement:	10,000 t	± 1-tenth	10,000 t	± 1-tenth
	Offered:	>10,000 t [4]	± 1-tenth	>10,000 t [4]	± 1-tenth

Notes:

1. Depends on interpretation of image.
2. Swath options are 25 km and 50 km on either or both sides of the reconnaissance aircraft.
3. Dependent on navigation system input. Current SLAR aircraft has capability to use the high-accuracy GPS input which would serve tactical and strategic requirements.
4. Estimate based on performance of 3 other SLARs (Rossiter et al., 1983). AN/APS 135 was not part of Bergsearch '84 project.

Table 4.4 System parameters relevant to ice detection with Side Looking Airborne Radar

Parameter	**Motorola AN/APS 94-D Bercha Group**	**AN/APS-135 SLAR International Ice Patrol**	**CAL SLAR-200 AES**
Frequency (GHz)	9.25	9.25	9.25
Wavelength (cm)	3	3	3
Polarization (transmit & receive)	Horizontal	Vertical	Horizontal
Depression angle	45° to grazing	45° to grazing	45° to grazing
Pulse width (ns)	not available	200	200
PRF	not available	375 /sec or 750 /sec	not available
Beamwidth (degrees)	not available	0.47	0.45
Range resolution (m)	30	37	37
Swath options in km, on one or both sides.	25, 50, 100	25, 50	25, 50, 100
Data output	film, video, tape	film	film
Peak Transmitter Power (kW)	not available	200	not available
Data delivery	radio downlink	hard copy	radio downlink

4.2.1.2 SAR systems

Technical description: Finer and spatially consistent resolution is available from synthetic aperture radar (SAR) systems. This refinement of SLAR technology increases the effective length of the radar antenna by "synthesizing" a longer antenna by utilizing the motion of the sensor. SAR systems require a high speed data acquisition and analysis capability. See Haykin et al., 1994 , Chapter 11, for an in-depth technical description of SAR technology.

Experience base: The first non-military commercial SAR system was Intera Technology (Canada) Ltd's (Intera) STAR-1 (Table 4.5), which was designed specifically for ice reconnaissance and entered service in 1983 in support of offshore petroleum exploration operations in the Beaufort Sea. In 1990, Intera inaugurated the STAR-2 system (Table 4.6), which was contracted by the Canadian AES for regular monitoring of ice in the Canadian Arctic. The two systems are compared in Table 4.7. The Canada Centre for Remote Sensing (CCRS) has managed a research SAR package on board a Convair 580, referred to as the SAR-580, since 1977. Civilian development of airborne SAR over the past decade and a half has been based primarily on ice applications, hence there exists a strong body of research and operational data on its performance (e.g., Rossiter et al., 1985; Haykin et al., 1994). SAR data for icebergs suffers from a phenomenon called aszimuth smear which smears the position of iceberg targets on the imagery.

Experience with the Intera SAR in the Beaufort Sea operations are extremely positive for the identification and tracking of sea ice. Information was made available to the operation within about three hours of the overflight. The information was in the form of large format hard copy photos, with coast line and latitude and longitude clearly indicated. As such, the information was invaluable for strategic responses to ice movements and icebreaker transit, particularly when towing a barge or rig. The SAR imagery allowed identification of areas of rough and old ice. When a helicopter was not available to carry the imagery out to the rig, interpretation of the imagery was faxed. The Intera SAR was dedicated to the Beaufort Sea operations from 1983 to about 1985, this was expensive, but resulted in substantial savings to the drilling operation, due to increased drilling time and safety.

Potential to satisfy user needs (icebergs): SAR data can be expected to apply to the high and medium priority items of Occurrence and Position of icebergs for both Field Development Systems and Vessel Transit. Spatial coverage capability also addresses tactical and strategic needs of the two operations. Positional accuracy will be dependent, to a large degree, on the quality of aircraft navigation system input. Given the common SAR resolution cell (pixel) dimensions of 12 to 25 m, the needed tactical level positional accuracy for vessel transit of 100 m may be marginal. Assuming availability of a dedicated airborne SAR, the "on demand" requirements of all operations should be met. The STAR-2 imagery is of excellent quality and would be invaluable to any operations in ice infested waters. This system is currently operated by the government and so not available on demand to a particular operation. However, it is expected that this contract will terminate in the near future (when RADARSAT data are available) and the system will be more readily available.

Potential to satisfy user needs (sea ice): SAR image data is relevant to all concerns specified in Chapter 3, Tables 3.7 and 3.9 with the exception of Ice Thickness. The sensor appears to have the potential to address both tactical and strategic level needs in all areas. Again, positional accuracy will be dependent to a large degree on the quality of the aircraft navigation system in use; GPS should provide adequate accuracy for most purposes. SAR can also provide information on floe size and ice roughness, both of which are low priority concerns for both field development and navigation.

Operational application: The STAR-1 system is currently installed in a Cessna Conquest twin engine turbo-propeller aircraft. The STAR-2 system is installed in a Canadair Challenger 600 jet aircraft. Re-installation in other platforms would necessitate significant aircraft modifications subject to Transport Canada approval.

Cost: As with SLAR, the few available SAR system operators will negotiate the pricing policy for a major long-term project. Guideline figures provided by Intera are $500,000 per month standby charge for STAR-1 plus $750 per hour of use. STAR-2 is approaching the end of a long-term contract for the Canadian AES and has cost between $5 million and $8 million per 12-month period, depending on system utilization.

4.2.1.3 Recent developments to airborne SAR systems

Experimental programs are currently working to quantify the performance of hardware and software systems built on to existing airborne SARs. Airborne SAR interferometry work at the Canada Centre for Remote Sensing (CCRS) has added a second receiver antenna to the aircraft body above and to one side of CCRS's experimental C-band SAR antenna. Return radar signals are received at the main SAR receiver antenna and at the second receiver with different delay times. Corrected differential phases of the two receivers are indications of target elevation; hence interferometric SAR principles are applied to acquisition of terrain elevation data. The limited field experience with interferometric SAR indicates that terrain elevation data with a precision of 1.5 m to 5.0 m can be collected (Gray et al., 1992). Further refinements of the system are aimed at acquisition of data sufficient to measure radial displacements of SAR targets in a single SAR pass (Gray et al., 1994). Operationally-ready technology is not foreseen before 1998. To date, one short test run has been performed over first-year and multi-year sea-ice sites in the Canadian Arctic. No trials have been conducted over iceberg environments. The ice environment potential of the system lies in measurement of sea-ice ridges and ice floe and iceberg movements. Both concerns are of low priority for current offshore petroleum concerns.

The concept of a coherent polarimetric radar would permit synthesis of all polarimetric probabilities of a radar system. Consequently, a polarimetric signature could be established for targets within a radar scene. It has been suggested that a certain polarization combination might be selected which would minimize ocean surface reflectivity. Likewise, a second combination might be selected to maximize returns from growlers and other small ice masses (Haykin et al., 1994, Chapter 13). It is to be noted that radar polarimetry methods have not been widely applied to ice observation concerns and remain research activities beyond the time horizon of initiation of offshore production activities.

Table 4.5: Airborne Synthetic Airborne Radar application to user-defined medium and high priority needs.

SENSOR:	**STAR-1 SYSTEM (INTERA)**	Field Development (icebergs)	Field Development (sea ice)	Vessel Transits (icebergs)	Vessel Transits (sea ice)
Sensor Relevance	Iceberg occurrence	Yes		Yes	
	Iceberg position	Yes		Yes	
	Iceberg draft	No		No	
	Sea-ice edge		Yes		Yes
	Sea-ice concentration		Yes		Yes
	Sea-ice position & extent		Yes		Yes
	Sea-ice type		Yes[1]		Yes[1]
Spatial Coverage	Tactical requirement:	0-40 km	0-40 km	0-5 km	0-10 km
	Strategic requirement:	40-200 km	40-200 km	5-30 km	10-50 km
	Offered:	24-96 km swath[2]	24-96 km swath[2]	24-96 km swath[2]	24-96 km swath[2]
Temporal Coverage	Tactical requirement:	on demand	on demand	on demand	on demand
	Strategic requirement:	1-2 days	1-2 days	on demand	3-6 hours
	Offered:	on demand	on demand	on demand	on demand
Positional Accuracy	Tactical requirement:	100-500 m	500 m	100 m	500 m
	Strategic requirement:	1-several km	2-4 km	500 m	2-4 km
	Offered:	[3]	[3]	[3]	[3]
Resolution or Size	Tactical requirement:	1,000 t	± 1-tenth	1,000 t	± 1-tenth
	Strategic requirement:	10,000 t	± 1-tenth	10,000 t	± 1-tenth
	Offered:	10,000 t[4]	± 1-tenth	10,000 t[4]	± 1-tenth

Notes:

1. Ice type information must be interpreted by human agency.

2. Swath options are 24 km and 48 km on either or both sides of the reconnaissance aircraft.

3. Dependent on navigation system input. Current SAR aircraft has the capability to use the highly-accuracy GPS input which would serve tactical and strategic requirements.

4. Based on 81% detection rate of bergy bits at 6 m resolution during Bergsearch '84 experiment (Rossiter et al., 1985). Experiment was controlled and detection could be confirmed only by concurrent surface observation. Most of current operational SLAR and SAR systems have lower resolution and would be worst than indicated.

Table 4.6: Synthetic Airborne Radar (STAR-2) application to user-defined medium and high priority needs.

SENSOR:	**STAR-2 SYSTEM (INTERA)**	Field Development (icebergs)	Field Development (sea ice)	Vessel Transits (icebergs)	Vessel Transits (sea ice)
Sensor Relevance	Iceberg occurrence	Yes		Yes	
	Iceberg position	Yes		Yes	
	Iceberg draft	No		No	
	Sea-ice edge		Yes		Yes
	Sea-ice concentration		Yes		Yes
	Sea-ice position & extent		Yes		Yes
	Sea-ice type		Yes[1]		Yes[1]
Spatial Coverage	Tactical requirement:	0-40 km	0-40 km	0-5 km	0-10 km
	Strategic requirement:	40-200 km	40-200 km	5-30 km	10-50 km
	Offered:	65-208 km swath[2]	65-208 km swath[2]	65-208 km swath[2]	65-208 km swath[2]
Temporal Coverage	Tactical requirement:	on demand	on demand	on demand	on demand
	Strategic requirement:	1-2 days	1-2 days	on demand	3-6 hours
	Offered:	on demand	on demand	on demand	on demand
Positional Accuracy	Tactical requirement:	100-500 m	500 m	100 m	500 m
	Strategic requirement:	1-several km	2-4 km	500 m	2-4 km
	Offered:	[3]	[3]	[3]	[3]
Resolution or Size	Tactical requirement:	1,000 t	± 1-tenth	1,000 t	± 1-tenth
	Strategic requirement:	10,000 t	± 1-tenth	10,000 t	± 1-tenth
	Offered:	10,000 t[4]	± 1-tenth	10,000 t[4]	± 1-tenth

Notes:

1. Ice type information must be interpreted by human agency.
2. Swath options are 65 km and 104 km on either or both sides of the reconnaissance aircraft.
3. Dependent on navigation system input. Current SAR aircraft has the capability to use the high-accuracy GPS input which would serve tactical and strategic requirements.
4. Estimate only, assuming capabilities comparable to those of earlier STAR-1 technology; no iceberg detection test data available for the STAR-2 sensor.

Table 4.7: System parameters relevant to ice detection; Synthetic Airborne Radars.

Parameter	**STAR-1 (Intera)**	**STAR-2 (Intera)**
Frequency	X-band	X-band
Wavelength (cm)	3	3
Polarization	horizontal (HH)	horizontal (HH)
Range resolution (m)	6 or 12	18 or 30
Ground range pixel size (m)	6 or 12	15 or 25
Azimuth resolution (m)	6	18 or 30
Azimuth pixel size (m)	4.2	15 or 25
Swath options	24 or 48 km on either side of aircraft	65 or 100 km on one or both sides of aircraft
Data output	dry silver paper, tape	hard disk
Data delivery	radio downlink	radio downlink

4.2.1.4 Search radars - APS 504 (V)5 Search Radar

Search radars, like imaging radars, emit microwave energy in wavelengths measured in millimetres and centimetres. The microwave energy is emitted in regularly pulsed bursts with the strength and return time of the energy reflections serving to locate the reflecting targets, be they ice or vessels.

Search radars are airborne with the transmit/receive antenna aimed at the earth's surface. Rather than remain at a fixed attitude with respect to the reconnaissance aircraft (as with imaging radars), the search radar antenna rotates, or sweeps, through an arc in the forward direction or may rotate through a full 360°. Because this type of radar sensor is sweeping back and forth over the search area, important ice targets can be captured on successive sweeps. This permits velocity calculations which aids in differentiating large ice masses from vessels. Multiple sweeps also provide the opportunity to locate smaller, but threatening, ice fragments which might otherwise not appear in imagery based on a single radar swath. To differentiate between icebergs and ships, the search radar is now often used with a forward looking infrared sensor, or the radar aircraft flies low over a target for visual identification. However, optical identification does not work in cloud, fog, or during precipitation.

Data acquired by airborne search radars are displayed on board the aircraft in real time via a plan position indicator (PPI), or a computer video monitor. Because microwave energy is used as the sensing signal, surface targets can be sensed through cloud cover and during nighttime darkness. Airplane flying conditions are the only weather-related limitation.

The Litton APS-504(V)3 Search Radar was designed for maritime surveillance and found to be quite good at detecting small and larger icebergs. However, this system has now been superseded by the APS-504(V)5 which was specially designed for the detection of small targets and this instrument is regularly used on the East Coast region for iceberg and sea-ice reconnaissance by Atlantic Airways. The International Ice Patrol (IIP) of the United States

Coast Guard (USCG) has recently inaugurated operations using an AN/APS 137 forward-looking airborne radar (FLAR).

Technical Description: The Litton Systems APS 504 (V)5 transmits microwaves at 16 operator-selectable frequencies ranging from 8.9 to 9.4 GHz, corresponding to a respective X-band wavelength range of 3.4 to 3.2 cm (Table 4.8). The antenna sweeps through a full 360°. Range resolution is 4.5 m, with seven range options available: i.e., 5.5, 11, 22, 46, 92.6, 185, 370 km (corresponding, respectively, to 3, 6, 12, 25, 50, 100, and 200 nautical miles). Data are displayed on board the reconnaissance aircraft in 16 grey levels on an 875-line video screen. An additional 1024 x 1024 line VGA computer screen serves to display the data with graphics overlay for analysis of the data and for transmission to surface vessels or ground-based operations facilities. The sensor can operate either in a search mode for small target detection (icebergs) or mapping mode (for ice).

Experience Base: The APS 504 (V)5 Search Radar has been used specifically for East Coast iceberg and sea-ice reconnaissance since 1983. Users include major offshore petroleum exploration concerns, Canadian government monitoring and regulating agencies, the IIP, and a fishing fleet manager. The 10 year experience with the sensor has resulted in refinements of the interpretation techniques and system optimization specific to ice reconnaissance. Detection rates have typically been good.

Potential to satisfy user needs: This sensor's potential lies in the provision of iceberg information, particularly on the medium- to high-priority concerns of iceberg occurrence, position, and mass. Both tactical and strategic level data, in terms of spatial coverage, temporal coverage, positional accuracy, and resolution/size can be realized. Tests have shown that the system is very good for the detection of small icebergs in Sea State 5 (3-m mean max wave height, 12.5 m/s (25 knot) winds). The report indicated that bergy bits could be detected with 50% reliability on average. The controlled tests did not deal with icebergs in pack ice, but this is clearly an area which requires considerable attention.

Operational application: The sensor system is configured as an airborne sensor with a real-time downlink to the user, either at sea or in a shore facility. Personnel trained in both technical operations and ice data analysis form part of the Atlantic Airways search radar system. The sensor cannot differentiate icebergs from other targets such as fishing boats. For distinguishing targets, visual confirmation and/or a forward looking infrared (FLIR) instrument is used.

Cost: Ice reconnaissance has a limited market of users, each with unique requirements and operational periods. Hence, system cost is negotiated on each contract. Total system cost estimates are not released by the contractor except in the context of contract negotiation. Costs will encompass recovery of investment on a $1.3 million sensor, installation of the sensor on the reconnaissance aircraft, computer analysis hardware and configuration, down linking, data storage, flight crew, sensor operations personnel, and flight time.

Table 4.8: Search Radar (APS 504(V)5) application to user-defined medium and high priority needs.

SENSOR:	APS 504 V5 SEARCH RADAR	Field Development (icebergs)	Field Development (sea-ice)	Vessel Transits (icebergs)	Vessel Transits (sea-ice)
Sensor Relevance	Iceberg occurrence	Yes		Yes	
	Iceberg position	Yes		Yes	
	Iceberg draft	No		No	
	Sea-ice edge		Yes		Yes
	Sea-ice concentration		No		No
	Sea-ice position & extent		No		No
	Sea-ice type		No		No
Spatial Coverage	Tactical requirement:	0-40 km	0-40 km	0-5 km	0-10 km
	Strategic requirement:	40-200 km	40-200 km	5-30 km	10-50 km
	Offered:	0-200 km[1]	0-200 km[1]	0-200 km[1]	0-200 km[1]
Temporal Coverage	Tactical requirement:	on demand	on demand	on demand	on demand
	Strategic requirement:	1-2 days	1-2 days	on demand	3-6 hours
	Offered:	on demand	on demand	on demand	on demand
Positional Accuracy	Tactical requirement:	100-500 m	500 m	100 m	500 m
	Strategic requirement:	1-several km	2-4 km	500 m	2-4 km
	Offered:	200 m[2]	200 m[2]	200 m[2]	200 m[2]
Resolution or Size	Tactical requirement:	1,000 t	± 1-tenth	1,000 t	± 1-tenth
	Strategic requirement:	10,000 t	± 1-tenth	10,000 t	± 1-tenth
	Offered:	1,000 t[3]	> 1-tenth	1,000 t[3]	> 1-tenth

Notes:

1. Sensor offers range displays from 5.5 to 370 km (3 to 200 nautical miles); sensor is also in a moving aircraft, with aircraft flying range effectively extending sensor range.

2. Figure represents normal radar ranging error of 2% of the 5.5 km (3 nautical mile) range display option plus the normal 100 m accuracy of aircraft GPS navigation data.

3. Figure represents claim to detect bergy bits in conditions up to Sea State 4 (Rossiter et al., 1985).

4.2.1.5 The AN/APS 137 forward-looking airborne radar (FLAR)

Technical description: The AN/APS 137 system (Tables 4.9 and 4.10) was developed to detect small targets in sea clutter. Of the three search modes built into the system (i.e., Periscope, Search, and Navigate), the Periscope mode maximizes the ice search capabilities. Periscope radar frequencies range from 9.05 to 10.55 GHz, corresponding to a respective X-band wavelength range of 3.31 to 2.84 cm. The antenna sweeps through 300° per second and emits a 0.5 μs width pulse 2000 times per second. Range resolution is 75 m, with seven range scale options of 15, 30, and 60 km (approximately 8, 16, and 32 nautical miles) available. Search mode offers additional range scale options to 370 km (200 nautical miles), a 60° per second sweep, reduced pulse repetition frequency (400 /s) and within a narrower radar frequency range of 9.6 to 9.7 GHz (wavelengths 3.12 to 3.09 cm). Data are displayed on board the reconnaissance aircraft via a 17-cm (7-inch) plan position indicator (PPI).

The AN/APS 137 also has an imaging mode, which is used to help distinguish between icebergs and vessels when there is no visibility. In this mode, the radar's antenna stops rotating and directs its radar beam at the target, taking advantage of the target's movement to generate a range versus Doppler display. The information is then converted into a video signal which shows the target outline and prominent features, such as king posts, exhaust stacks, etc. For a target to be imaged, it must first be detected in a surface search mode, as the imaging mode does not operate independently of the other modes (Trivers and Murphy, 1994).

The two systems reviewed are compared in Table 4.11.

Experience base: The AN/APS 137 search radar underwent field tests in the spring of 1991 (reported in 1993) over the Grand Banks region (Ezman et al., 1993). The system user, IIP, reports encouraging results but further refinement of operational techniques is required. The use of periscope mode can be limited by the low flying level required for optimal results. Flying heights above 1,680 m (about 5,500 ft) result in excessive sea clutter on the output display, even at the minimum antenna depression allowed by periscope mode. Reconnaissance flown below this level requires visual flight regulations (VFR) weather conditions, which occur infrequently in the Grand Banks region.

Potential to satisfy user needs: This sensor's potential lies in the provision of iceberg information, particularly on the medium- to high-priority concerns of iceberg occurrence, position, and mass. Both tactical and strategic level data, in terms of spatial coverage, temporal coverage, positional accuracy, and resolution/size can be realized (see Table 4.9).

Operational application: The sensor system is configured as an airborne sensor and is currently flown by IIP in an HC-130 aircraft. A real time downlink to the user, either at sea or in a shore facility would be required.

Cost: Costs to be incurred would include those associated with installation of an adequate downlink system to the operations area to take advantage of the regular IIP reconnaissance of the region. IIP priorities can be expected to dictate the availability of the existing operating sensor outside of regular IIP reconnaissance missions. Alternatively, a duplicate, dedicated system might be acquired for installation in a suitably modified airplane. As this system is not available for lease, IIP would not provide any cost figures.

Table 4.9: Search Radar (AN/APS 137) application to user-defined medium and high priority needs.

SENSOR:	**AN/APS 137 Forward-Looking Airborne Radar (FLAR)**	**Field Development (icebergs)**	**Field Development (sea ice)**	**Vessel Transits (icebergs)**	**Vessel Transits (sea ice)**
Sensor Relevance	Iceberg occurrence	Yes		Yes	
	Iceberg position	Yes		Yes	
	Iceberg draft	No		No	
	Sea-ice edge		Yes		Yes
	Sea-ice concentration		No		No
	Sea-ice position & extent		No		No
	Sea-ice type		No		No
Spatial Coverage	Tactical requirement:	0-40 km	0-40 km	0-5 km	0-10 km
	Strategic requirement:	40-200 km	40-200 km	5-30 km	10-50 km
	Offered:	0-200 km[1]	0-200 km[1]	0-200 km[1]	0-200 km[1]
Temporal Coverage	Tactical requirement:	on demand	on demand	on demand	on demand
	Strategic requirement:	1-2 days	1-2 days	on demand	3-6 hours
	Offered:	if available[2]	if available[2]	if available[2]	if available[2]
Positional Accuracy	Tactical requirement:	100-500 m	500 m	100 m	500 m
	Strategic requirement:	1-several km	2-4 km	500 m	2-4 km
	Offered:	>200 m[3]	>200 m[3]	>200 m[3]	>200 m[3]
Resolution or Size	Tactical requirement:	1,000 t	± 1-tenth	1,000 t	± 1-tenth
	Strategic requirement:	10,000 t	± 1-tenth	10,000 t	± 1-tenth
	Offered:	1,000 t[4]	> 1-tenth	1,000 t[4]	> 1-tenth

Notes:

1. Sensor offers range displays from 5.5 to 370 km (3 to 200 nautical miles); sensor is in a moving aircraft, with aircraft flying range effectively extending sensor range.

2. Operating sensor used by International Ice Patrol in regular IIP operations.

3. Figure represents normal radar ranging error of 2% of the 5.5 km (3 nautical mile) range display option plus the 100-m accuracy of aircraft GPS navigation data. Current International Ice Patrol aircraft not fitted with GPS.

4. Rossiter et al., (1985) claim to detect bergy bits in conditions up to Sea State 4 (mean maximum 2 m wave height)

Table 4.10: AN/APS 137 Radar System Parameters (after Perkins et al., 1994).

Parameter	**Value**
Radar Modes	
• Periscope	periscope and small target detection
- pulse repetition frequency (Hz)	2000
- antenna scan rate (rpm)	300
- compression pulse duration (ns)	2.5
• Navigate	navigation and weather avoidance
- pulse repetition frequency (Hz)	400
- antenna scan rate (rpm)	6
- compression pulse duration (ns)	500
• Search	long-range maritime surveillance
- Pulse repetition frequency (Hz)	400
- antenna scan rate (rpm)	60
- compression pulse duration (ns)	12
• Image	imaging
- pulse repetition frequency (Hz)	400 to 2000
- antenna scan rate (rpm)	searchlight
- compression pulse duration (ns)	12
Radar Outputs	
• transmitted power	500 W avg, 500 kW peak
• frequency (GHz)	9.45 to 10.05
• waveform	linear FM or pulse CW
• pulse width (μs)	0.5
• antenna gain (dB)	34
• azimuth beamwidth (degrees)	2.4
• elevation beamwidth (degrees)	4.0

Table 4.11: System parameters relevant to ice detection with airborne search radars.

Parameter	APS 504 (V)5	AN/APS 137 FLAR
Frequency	8.9 - 9.4 GHz, selectable	9.6 - 9.7 GHz, selectable
Wavelength	3.4 - 3.2 cm	3.12 - 3.09 cm
Pulse width		
• non-compressed	5, 30, 200 ns	500 ns
• compression modes	500:1, 210:1	2.5 - 12 ns
Pulse repetition frequency	300/s - 2300/s, selectable	400/2000 Hz, depending on mode
Beamwidth (degrees) (horizontal/vertical)	not available	2.4 / 4.0
Range resolution (m)	4.5	75
Range options (km)	5.5, 11, 22, 46, 93, 185, 370	(1)
Data output	video display, computer diskette	PPI.
Data delivery	radio downlink	real time on board aircraft

Note

1. Range options for FLAR:

Periscope mode	12.8, 25.6, 51.2 km
Search mode	12.8, 25.6, 51.2, 102.4, 205, 320 km
Navigate mode	1 to 320 km variable
Image mode	N/A

4.2.2 Spaceborne Systems

Currently, two orbiting spacecraft are equipped with SAR sensors, the European *ERS-1* and the Japanese *JERS-1*. A third SAR satellite, the Canadian RADARSAT, is scheduled for launch in late 1995. Tables 4.12 - 4.15 summarize key specifications of these three SAR sensors. A summary of all civilian SAR satellites is given in Haykin et al., 1994, Chapter 12.

The imaging principles for spaceborne SAR are the same as for airborne SAR. The *ERS-1* SAR operates and RADARSAT will operate, in the C-band of the electromagnetic spectrum (approximately 6 cm wavelength). Such wavelengths are longer than the X-band (3 cm wavelength) waves of airborne SARs and require less power. Night-time imaging and cloud penetration capabilities are preserved. The *JERS-1* SAR operates in the even longer wave L-band (24 cm wavelength) and is focused more on land operations (Shimada et al., 1993). All spaceborne SAR systems sense surface features at steeper radar beam incidence angles compared to airborne systems, resulting in less detailed data on ice surface relief features, e.g., ridges. In addition, current technology limits accessible spaceborne SAR technology to 25 m resolution, compared to 15-m (STAR-2) and 12-m (STAR-1) resolutions for current operational airborne SAR configurations.

4.2.2.1 RADARSAT

Technical description: The RADARSAT SAR (Table 4.12) design was strongly influenced by the need for regular all-weather data in support of ice monitoring operations (Haykin et al., 1994, Chapter 12). Relevant design aspects include horizontal polarization of the transmitted and received signals, frequent repeat coverage of high latitude regions, variable swath width options, and a SAR antenna which can be steered so as to view further off nadir in order to provide consecutive days coverage of areas of current interest. A target of three-hour maximum data turnaround has been established for RADARSAT's principal client, the Environment Canada Ice Centre (Denyer et al., 1993; St-Pierre, 1994). Figure 4.2 shows the different imaging modes of RADARSAT and Figure 4.3 shows the 1- and 3-day coverage for North America (Haykin et al., 1994, Chapter 12).

Experience base: Mosaics of 100-km swath SAR data from the *ERS-1* satellite have been processed in a simulation of wide-swath (500 km wide) SAR images to be expected of RADARSAT. These data sets have been processed so as to approximate, as closely as possible, RADARSAT output and to develop an experience base in advance of satellite launch. Narrower swath, higher resolution products are also promised from RADARSAT, which must be approximated from various airborne SAR samples (Haykin et al., 1994, Chapter 11).

Potential to satisfy user needs (icebergs): RADARSAT SAR data might apply to the high and medium priority concerns of occurrence and position of icebergs for field development systems, for large and very large icebergs. Identification of significant iceberg targets on RADARSAT SAR will be a function of sensor management and data interpretation procedures. Sensor management techniques will include, among other things, scheduling of SAR data acquisition at the user's preferred swath width and resolution options, programming of any antenna reorientation, and repeating an area coverage at different radar incidence angles. For very large icebergs, individual targets should be identifiable by a trained ice interpreter on a single image. Large icebergs (and possibly medium icebergs) may be identified based of converging evidence of the patterns observed in two or more images of the same area. Iceberg detection by RADARSAT should be reviewed when data are available. This review should cover not only the reliability of detecting icebergs which are there, but also the problem of counting too many icebergs (false positive identification), due to speckle on the image.

The sensor will not effectively address priority concerns for vessel transit, with respect to data availability. The regular and frequent area coverage afforded by the steerable SAR antenna and the three-day orbit revisit period will still fall short of a true "on demand" capability, needed for vessel transits. Data acquisition will still await positioning of the orbiting satellite at the appropriate latitude. Additional delay will be occasioned by the data processing and product delivery turnaround time.

Potential to satisfy user needs (sea ice): A true "on demand" response capability will not be available from RADARSAT to answer tactical level data requirements for either field development or navigation. RADARSAT SAR does offer capabilities which respond positively to strategic level needs for spatial coverage (10 to 200 km distant), temporal coverage (approximately every 3 days), positional accuracy (2 to 4 km) and resolution of ice concentrations (nearest one-tenth). SAR can also provide information on floe size and ice roughness, both of which are low priority concerns for both field development and navigation.

Operational Application: RADARSAT SAR data from 300 km and 500 km swaths, with respective resolutions of 50 and 100 m are expected to be available to the principal user, AES Ice Centre, within 3 hours (maximum) after data have been received at a ground station, through a bulletin board system. Users may expect to have access to geometrically corrected data from AES Ice Centre approximately 2 to 5 hours after a satellite overpass. Finer resolution (25 m) geocoded products, however, are expected to require a one week turnaround. The orbit pattern provides for a 24-day revisit cycle. Repeat coverage of a given point is possible every three or four days if the SAR antenna orientation is altered, or "steered" to cover the point of interest. Users may obtain data from RADARSAT International, a private sector company whose mandate includes the marketing of RADARSAT imagery. Coverage of particular areas can be obtained through prior arrangement.

Cost: Approximately $3,000.00 per scene (to be finalized).

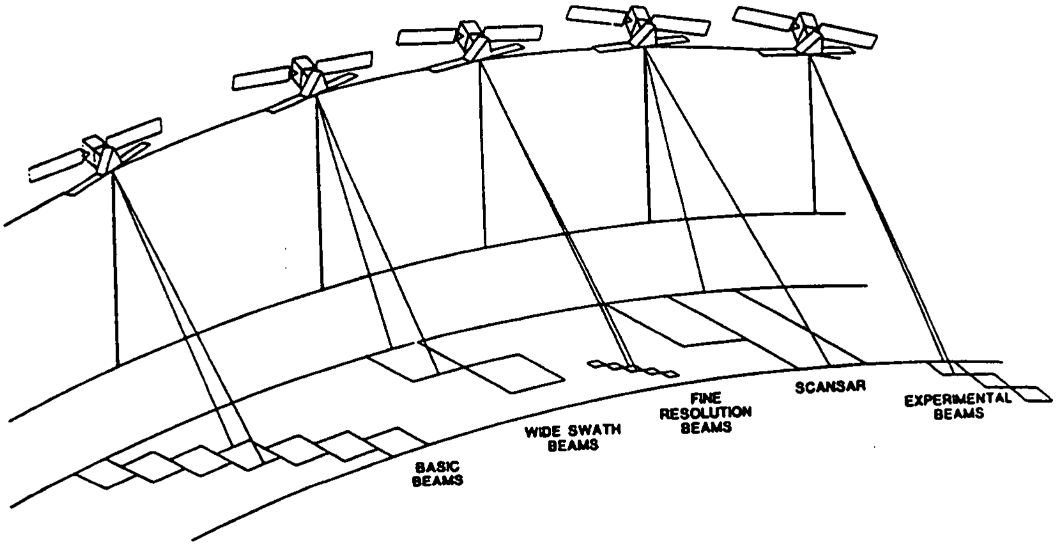

Figure 4.2 Illustration of RADARSAT imaging modes

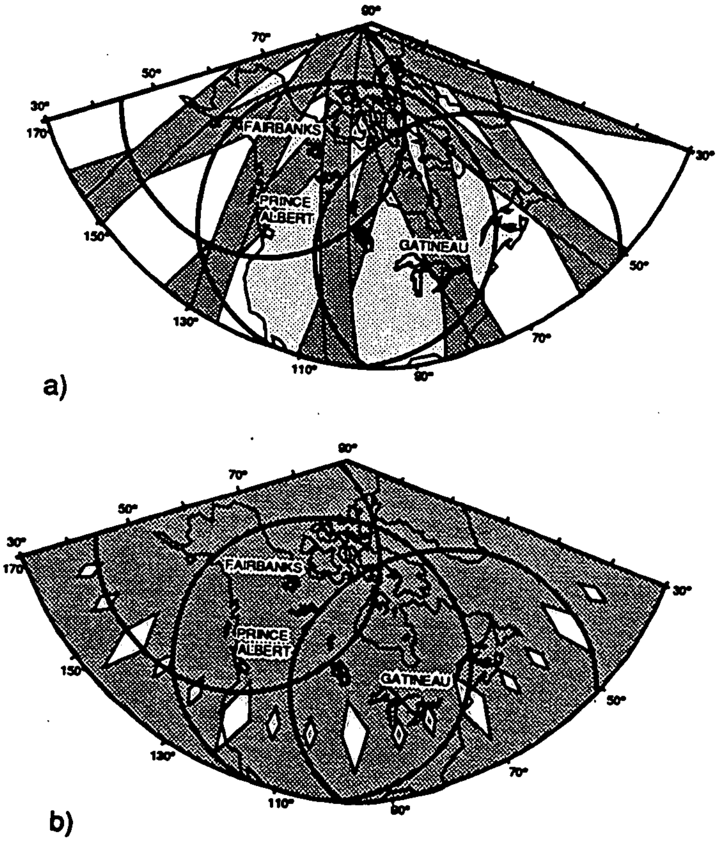

Figure 4.3 One-day (a) and 3-day (b) coverage for RADARSAT

Table 4.12: Spaceborne SAR (RADARSAT) application to user defined medium and high priority needs.

SENSOR:	**RADARSAT SAR**	**Field Development (icebergs)**	**Field Development (sea ice)**	**Vessel Transits (icebergs)**	**Vessel Transits (sea ice)**
Sensor Relevance	Iceberg occurrence	YES (1)		YES (1)	
	Iceberg position	YES (1)		YES (1)	
	Iceberg draft	NO		NO	
	Sea-ice edge		YES		YES
	Sea-ice concentration		YES		YES
	Sea-ice position & extent		YES		YES
	Sea-ice type		YES (2)		YES (2)
Spatial Coverage	Tactical requirement:	0-40 km	0-40 km	0-5 km	0-10 km
	Strategic requirement:	40-200 km	40-200 km	5-30 km	10-50 km
	Offered:	45-510 km swath (3)	45-510 km swath (3)	45-510 km swath (3)	45-510 km swath (3)
Temporal Coverage	Tactical requirement:	on demand	on demand	on demand	on demand
	Strategic requirement:	1-2 days	1-2 days	on demand	3-6 hours
	Offered:	3 days	3 days	3 days	3 days
Positional Accuracy	Tactical requirement:	100-500 m	500 m	100 m	500 m
	Strategic requirement:	1-several km	2-4 km	500 m	2-4 km
	Offered:	<1 km (4)	<1 km (4)	<1 km (4)	<1 km (4)
Resolution or Size	Tactical requirement:	1,000 t	± 1-tenth	1,000 t	± 1-tenth
	Strategic requirement:	10,000 t	± 1-tenth	10,000 t	± 1-tenth
	Offered:	>2 million t (5)	± 1-tenth	>2 million t (5)	± 1-tenth

Notes:

1. Definitive identification will require human interpretation supported by other data.

2. Depends on identification of ice type by trained observer.

3. Swath options are 45, 100, 150, 165, 305, and 510 km on one side only of the spacecraft; resolution varies according to swath option selected.

4. Estimate. Satellite orbit parameters will be known and imagery will be georeferenced to surveyed land positions. Distance of operations area from land control points contribute some positioning uncertainty.

5. Limited available iceberg detection test data indicate ability to detect only largest icebergs (in excess of 2 million t) for data suitable for strategic uses.

4.2.2.2 *ERS-1* Active Microwave Instrument (AMI)

Technical Description: The Active Microwave Instrument (AMI) SAR (Table 4.13), like that of RADARSAT, transmits microwaves at 5.3 GHz frequency/5.7 cm wavelength (C band). Image resolution is on the order of 30 m and data can be downlinked to the Gatineau satellite station near Ottawa. Swath options are limited to 80-100 km width, polarization is vertical (transmit and receive), and the antenna cannot be steered from its fixed 23° incidence angle for consecutive-day imaging. Further, the *ERS-1* mission is dedicated to research rather than operational support. Consequently, research phases which pre-empt use of the AMI imaging SAR, will occur during East Coast production operations.

At the time of writing, the *ERS-1* is approaching the end of its design life and awaiting replacement by the *ERS-2* satellite. *ERS-2* is currently slated for launch in 1995. It will carry an AMI SAR which is identical to that on *ERS-1*. Both satellites will operate together for 9 months, 1 day apart, to provide interferometric data.

Experience base: During its mission life, *ERS-1* operated in two so-called "ice phases", one in the northern winter (January to March) of 1992 and one in the winter of 1993-94. During these experimental data-gathering phases, the satellite orbit was modified to provide greater repeat coverage of high latitude areas (Proud and Battrick, 1992). Data sets of icebound and ice-infested areas of Canadian waters were obtained by CCRS for analysis and as the basis for image simulations of the planned RADARSAT SAR. AMI SAR images of various ice-covered seas have also been obtained by petroleum operators and their consultants for evaluating their applicability to potential hydrocarbon areas. In the latter cases, the vertically polarized data have produced images in which ice characteristics have proved more difficult to interpret by comparison with horizontally polarized X-band airborne SAR products. Whether this stated difficulty is due to polarization, wavelength, or differences in incidence angles is open to question given the limited operational use of the AMI SAR.

These data have not been used within an operational program, as far as we know, due to the delay in obtaining the data. Experience with SAR data interpretation indicates that floe sizes greater than about 250 m and rough ice could be identified but the differentiation between first year rubble or multi-year hummock fields was not possible in SAR imagery with pixel sizes greater than 15 m (CANATEC, 1992). As with RADARSAT, only the very large icebergs will be detectable by *ERS-1*.

Potential to satisfy user needs: The AMI SAR must be considered a data source of opportunity due to its commitment to a variety of research priorities outside of ice monitoring and the changes to orbit pattern throughout a satellite mission. SAR imagery of a given area of interest must be ordered well in advance of the actual satellite overpass. Currently, Ice Services Environment Canada is able to receive processed data from the Gatineau receiving station on the day of data reception. Significant East Coast operators can expect a similar turnaround (Nazarenko, 1994) from RADARSAT International, which is the designated distribution agent for *ERS-1* SAR in Canada.

Only under fast processing and delivery conditions would SAR from an opportune *ERS-1* orbit serve strategic level iceberg monitoring concerns of spatial coverage, temporal coverage and positional accuracy for field development. This also assumes the presence of previously acquired data sets for sequential tracking of targets. The sensor would not meet vessel transit concerns for reasons similar to those limiting the RADARSAT SAR, i.e., product delivery delay and lack of true "on demand" response.

Again, under conditions of fast data turnaround and opportune orbit, *ERS-1* SAR imagery should address strategic level needs at the production area and in transiting vessels for high priority sea-ice data, i.e., ice edge, concentration, position and extent.

Operational application: Other factors being equal, the AMI SAR and equivalent sensors on future *ERS-1* satellites will be available on an opportunity or "coincidence" basis. If the spacecraft is orbiting the operations area at a time of need and if the imaging SAR operation is not pre-empted by mission needs for other sensors, and if a Canadian ground station can process the data in a timely manner, *ERS-1* SAR imagery can be useful. *ERS-1* imagery has been used operationally for the past 2 years by AES Ice Centre. Data are received daily within 6 to 12 hours from the Gatineau Satellite Receiving Centre.

Cost: At the time of writing, each scene costs $1,375.00 (covering area of 100 x 100 km).

Table 4.13: Spaceborne SAR (*ERS-1* AMI) application to user-defined medium and high priority needs.

SENSOR:	***ERS-1* ACTIVE MICROWAVE INSTRUMENT (European Space Agency)**	**Field Development (icebergs)**	**Field Development (sea ice)**	**Vessel Transits (icebergs)**	**Vessel Transits (sea ice)**
Sensor Relevance	Iceberg occurrence	Yes[1]		Yes[1]	
	Iceberg position	Yes[1]		Yes[1]	
	Iceberg draft	No		No	
	Sea-ice edge		Yes		Yes
	Sea-ice concentration		Yes		Yes
	Sea-ice position & extent		Yes		Yes
	Sea-ice type		Yes[1]		Yes[1]
Spatial Coverage	Tactical requirement:	0-40 km	0-40 km	0-5 km	0-10 km
	Strategic requirement:	40-200 km	40-200 km	5-30 km	10-50 km
	Offered:	100 km swath	100 km swath	100 km swath	100 km swath
Temporal Coverage	Tactical requirement:	on demand	on demand	on demand	on demand
	Strategic requirement:	1-2 days	1-2 days	on demand	3-6 hours
	Offered:	35-day cycle[2]	35-day cycle[2]	35-day cycle[2]	35-day cycle[2]
Positional Accuracy	Tactical requirement:	100-500 m	500 m	100 m	500 m
	Strategic requirement:	1-several km	2-4 km	500 m	2-4 km
	Offered:	<1 km[3]	<1 km[3]	<1 km[3]	<1 km[3]
Resolution or Size	Tactical requirement:	1,000 t	± 1-tenth	1,000 t	± 1-tenth
	Strategic requirement:	10,000 t	± 1-tenth	10,000 t	± 1-tenth
	Offered:	[4]	± 1-tenth	[4]	± 1-tenth

Notes:

1. Definitive identification will require human interpretation supported by other data.

2. 3-day cycle was used January to March, 1994; same day data delivery.

3. Estimate. Satellite orbital parameters will be known and imagery georeferenced to surveyed land positions. Distance of operations area from land control points contribute some positioning uncertainty.

4. Limited available iceberg detection test data indicate ability to detect only largest icebergs (in excess of 2 million t).

4.2.2.3 *JERS-1* Synthetic Aperture Radar

Technical description: The *JERS-1* SAR uses a longer wavelength (23.5 cm in the L band) than do RADARSAT and *ERS-1* and employs horizontal polarization (Table 4.14). Resolution cell dimensions are 18 m by 18 m (Shimada et al., 1993). The three SAR systems reviewed are compared in Table 4.15.

Experience base: Like *ERS-1*, the *JERS-1* mission is committed to research rather than to operations support. The radar frequency of the SAR instrument is lower than that found to be optimal in sea-ice interpretation. The *JERS-1* spacecraft was launched in February 1992 and has not been as heavily drawn upon for ice data as has the *ERS-1* C-band sensor.

Potential to satisfy user needs: The *JERS-1* SAR must be considered, at best, a data source of opportunity due to its commitment to a variety of research priorities outside of ice monitoring. The qualifications mentioned for the *ERS-1* AMI as a coincidental sensor apply to the *JERS-1* SAR. Its greatest potential would be as a strategic level sensor for occurrence and location of icebergs, ice edge location, concentration, position, and extent of sea-ice.

Operational application: Other factors being equal, the *JERS-1* SAR and equivalent sensors on future *JERS-1* satellites will be available on an opportunity or "coincidence" basis. If the spacecraft is orbiting the operations area at a time of need and if the imaging SAR operation is not pre-empted by mission need for other sensors, and if the Canadian ground station, at Gatineau, Québec, can process the data in a timely manner, *JERS-1* SAR imagery would be of use.

Cost: Similar to *ERS-1*, approximately $1,375.00 per scene (60 km x 60 km area).

Table 4.14: Spaceborne SAR (*JERS-1*) application to user-defined medium and high priority needs.

SENSOR:	***JERS-1* SAR (JAPAN)**	**Field Development (icebergs)**	**Field Development (sea ice)**	**Vessel Transits (icebergs)**	**Vessel Transits (sea ice)**
Sensor Relevance	Iceberg occurrence	Yes[1]		Yes[1]	
	Iceberg position	Yes[1]		Yes[1]	
	Iceberg draft	No		No	
	Sea-ice edge		Yes		Yes
	Sea-ice concentration		Yes		Yes
	Sea-ice position & extent		Yes		Yes
	Sea-ice type		No		No
Spatial Coverage	Tactical requirement:	0-40 km	0-40 km	0-5 km	0-10 km
	Strategic requirement:	40-200 km	40-200 km	5-30 km	10-50 km
	Offered:	65 km swath	65 km swath	65 km swath	65 km swath
Temporal Coverage	Tactical requirement:	on demand	on demand	on demand	on demand
	Strategic requirement:	1-2 days	1-2 days	on demand	3-6 hours
	Offered:	41-day cycle	41-day cycle	41-day cycle	41-day cycle
Positional Accuracy	Tactical requirement:	100-500 m	500 m	100 m	500 m
	Strategic requirement:	1-several km	2-4 km	500 m	2-4 km
	Offered:	250 m[2]	250 m[2]	250 m[2]	250 m[2]
Resolution or Size	Tactical requirement:	1,000 t	± 1-tenth	1,000 t	± 1-tenth
	Strategic requirement:	10,000 t	± 1-tenth	10,000 t	± 1-tenth
	Offered:	[3]	± 1-tenth	[3]	± 1-tenth

Notes:

1. Definitive identification will require human interpretation supported by other data.
2. Estimate based on calculated *Seasat* L-band SAR positional accuracy over ocean area (Massom 1991).
3. Limited available iceberg detection test data. RADARSAT studies imply high orbit, steep angle SAR will detect only largest icebergs (Ramsay et al., 1993), probably in excess of 2 million t.

Table 4.15: System parameters relevant to ice detection for satellite-borne Synthetic Aperture Radar.

Parameter	**RADARSAT**	***ERS-1***	***JERS-1***
Frequency (GHz)	5.3	5.3	1.275
Wavelength (cm)	5.6	5.6	23.5
Polarization	horizontal (HH)[2]	vertical (VV)[2]	horizontal (HH)[2]
Depression angle (°)	20 to 49, steerable	23	35.2
Range resolution (m)	11, 25, 25, 25, 50, 100[1]	30	18
Ground range pixel size (m)	6.25, 12.5, 12.5, 12.5, 25, 50[1]		
Azimuth resolution (m)	9, 28, 28, 28, 50, 100[1]	30	18
Azimuth pixel size (m)	6.25, 12.5, 12.5, 12.5, 25, 50[1]		
Swath options (km)	45, 100, 150, 165, 305, 510[1]	100	65
Data output	Post-reception processed imagery	Post-reception processed imagery	Post-reception processed imagery
Data delivery	Downlink to line-of-sight earth station	Downlink to line-of-sight earth station	Downlink to line-of-sight earth station
Revisit	3 days	35 days	41 days

Note:

1. Pixel, resolution, and swath option figures listed in respective order.

2. HH indicates horizontally polarized beam transmitted and received; likewise for VV and a vertically polarized beam.

4.2.3 Marine Radars

Marine radars using rotating transmitter-receiver antennas and plan position indicator (PPI) displays have been used regularly by commercial mariners since 1945. The first systematic experiment aimed at quantifying the capability of marine radar to detect ice hazards to shipping was conducted in 1959 by the United States Coast Guard (Lewis et al., 1987). As with other active microwave systems, the intensities and return delays of transmitted radar energy serve to fix the presence and distance of targets of interest. Since radar pulses are emitted continuously during 360° sweeps of the antenna, target bearing is also determined. As the same region is covered by consecutive sweeps of the radar antenna, the target velocity can be estimated and data averaging can be used to enhance detection of smaller targets in sea surface clutter (see Chapter 5).

Of particular importance to ice and iceberg detection is the development of Automated Radar Plotting Aids (ARPA) and their integration into commercially available system packages. Initially conceived to keep constant track of radar detected marine traffic, ARPA are also used for monitoring of icebergs. Digital storage of ARPA maps is a regular feature in the higher level system packages.

Technical description: Standard marine radars operate either at X band (3-cm wavelength) or S band (10 cm wavelength). In general, the more powerful X-band wave will offer slightly greater range, while the longer wave S-band wave will offer better performance in sea clutter and adverse weather. The height of the scanner, sea clutter, etc., also affect the detection of ice hazards by marine radars (see section 5).

Experience Base: Marine radar has the longest practical history of remote ice sensors. An assessment of marine radar in the area of iceberg detection capability in the Grand Banks region was reported on in 1985 (Ryan et al., 1985). The average target size tends to increase with range.

Marine radars are a first line, local reconnaissance against any invading sea ice or icebergs. The systems are mechanically and electronically reliable and generally easy to operate, although operator training is recommended. For sea ice, the typical derrick top mounted radar will generally give bright spots on the PPI screen when rough ice is within about 10 km from the rig. However, this response is not 100% reliable due to the upper surface of the ice feature which may reflect the incident radar radiation away from the radar, rather than scattering it back. With large rubble fields, this does not tend to be a problem, as some radiation will always be reflected back. The reliability of iceberg detection by radar is discussed in Chapter 5; experience indicates that weathered iceberg targets can be missed. As indicated there, it depends on the size of iceberg, range, radar frequency, elevation of radar, sea state, and atmospheric conditions. Operator experience is also very important as is installation and maintenance of the radar. A trained operator dedicated to ice surveillance, greatly increases the reliability of ice and iceberg detection, as the operator can track potentially hazardous features and so interpolate periods when reflections are not received.

During vessel transits, marine radar imagery can be used to identify ice features evident in SAR or SLAR data. Thus the marine radar, despite its limited range, is useful for navigating a path though the thinner ice indicated on SAR or SLAR imagery.

Potential to satisfy user needs: Marine radar is a tactical level sensor (Table 4.16) in terms of spatial coverage (0.7 to 44 km / 0.4 to 24 nautical miles), temporal coverage (constant, real time with instantaneous read-out), and positional accuracy (range resolution at 1% of range limit used). Tactical discrimination of medium size icebergs (60 to 120 m length above waterline) proved to be reliable at ranges of 25 to 31 km (13.5 to 16.7 nautical miles) with a derrick-mounted, S-band system (Ryan et al., 1985). Conclusions could not be drawn on the reliability of detecting growlers and bergy bits (i.e., near the 1,000 t lower limit of concern) due to insufficient field data.

Operational application: Basic systems are commercially available for installation on offshore units and vessels. Configuration with ARPA would be part of a supplier's package (see Chapter 5).

Cost: Basic systems at the high end of product lines will cost on the order of $100,000. Additional costs would be incurred in making any necessary modifications to the sensor platform (vessel or rig) and in training of rig/vessel personnel in use of system to maximum potential.

Table 4.16: Marine radar application to user-defined medium and high priority needs.

SENSOR:	**Racal Decca BridgeMaster 340[1]**	**Field Development (icebergs)**	**Field Development (sea ice)**	**Vessel Transits (icebergs)**	**Vessel Transits (sea ice)**
Sensor Relevance	Iceberg occurrence	Yes		Yes	
	Iceberg position	Yes		Yes	
	Iceberg draft	No		No	
	Sea-ice edge		Yes		Yes
	Sea-ice concentration		No		No
	Sea-ice position & extent		No		No
	Sea-ice type		No		No
Spatial Coverage	Tactical requirement:	0-40 km	0-40 km	0-5 km	0-10 km
	Strategic requirement:	40-200 km	40-200 km	5-30 km	10-50 km
	Offered:	0-44 km[2]	0-10 km[2]	0- 44 km[2]	0 - 10 km[2]
Temporal Coverage	Tactical requirement:	on demand	on demand	on demand	on demand
	Strategic requirement:	1-2 days	1-2 days	on demand	3-6 hours
	Offered:	instantaneous	instantaneous	instantaneous	instantaneous
Positional Accuracy	Tactical requirement:	100-500 m	500 m	100 m	500 m
	Strategic requirement:	1-several km	2-4 km	500 m	2-4 km
	Offered:	50-1750 m[3]	50-1750 m[3]	50-1750 m[3]	50-1750 m[3]
Resolution or Size	Tactical requirement:	1,000 t	± 1-tenth	1,000 t	± 1-tenth
	Strategic requirement:	10,000 t	± 1-tenth	10,000 t	± 1-tenth
	Offered:	35,000 t[4]	> 1-tenth	35,000 t[4]	> 1-tenth

Notes:

1. Selected as representative of higher end of commercially available marine radars.

2. Sensor offers range displays from 5.5 to 180 km (3 to 96 nautical miles). A 44-km (24-nautical miles) range would be a practical maximum imposed by the radar horizon, however, from experience, sea ice can only be detected over a range of 5.5 to 11 km (3 to 6 nautical miles).

3. Figures represent radar ranging error of 1% of the selected display range display option. At a 44 km (24 nautical miles) range, the resolution is 440 m.

4. Estimate based on trends in 1985 trials aboard MV Polar Circle; figure represents average size small iceberg, detected at a range of 9 - 13 km (5 to 7 nautical miles). Field data remain sparse and inconclusive (Ryan et al., 1985).

4.2.4 Shore-based Radars

Systems covered in this section are qualified as "over-the-horizon" (OTH) radars, due to their detection ranges on the order of tens to hundreds of kilometres. An OTH system could utilize ionospheric reflection to increase the maximum limit of delectability but at the cost of overlooking conditions in the near and mid ranges.

The OTH systems considered for operational iceberg and sea-ice detection are further qualified as "ground-wave radars" (GWR). These systems exploit the ground wave attenuation factor, by which a radiated energy wave follows the curvature of the earth by diffraction. This can result in a detection range in the order of hundreds of kilometres, depending, among other factors, on the wave frequency used and on the electrical conductivity of the earth's surface (Haykin et al., 1994, Chapter 7). The favoured wavelengths are in the lower part of the high frequency (HF) range (2 MHz to 30 MHz). The optimum conducting surface is sea water, as opposed to land or ice cover.

4.2.4.1 HF over-the-horizon radar

Technical Description: Northern Radar Systems Limited (NRSL) has built and operates a ground-wave radar (GWR) system which operates at Cape Race, Newfoundland (Table 4.17). Separate transmit and receive arrays consist of 40 elements and are approximately one kilometre in length. The frequency used in GWR is considerably lower than that used in other conventional radar remote sensors (i.e. airborne and satellite-borne imaging radars, marine radars). HF band waves (3 to 30 MHz) are generated from the transmit array and reflections received at the receiver array. Unlike the higher frequency marine radars, the GWR wave is conducted along the sea surface and so provides information on over-the-horizon targets up to 450 km distant. The 450-km figure is a maximum; results of NRSL trials are quoted with reference to 200 km range. The GWR is an all-weather, night-and-day system.

The existing system array is deployed at Cape Race, Newfoundland, and provides coverage of a 120° sector, covering the northwest area of the Grand Banks (Figure 4.4)

Experience Base: Results in detecting ice edge and medium to large icebergs is positive (Dawe, 1986; Haykin et al., 1994).

Potential to satisfy user needs: Current potential is in detecting the occurrence, position, and motion of icebergs. A working system may offer tactical and strategic support. The system is capable of detecting the position of the offshore sea-ice edge. It will not provide data on details of the sea-ice cover. The range of operation (over 200 km) is acceptable. On-demand data are available.

Operational application: As indicated in Figure 4.4, the OTH radar covers a range of approximately 200 km which extends from the shore to the northwest corner of the Grand Banks. The area of operation would have to be within this area.

Cost: The price of specialized long-term need of the system is to be negotiated. New installations require a 2 + km strip of land adjacent to the area of interest. The equipment costs several hundred thousand dollars.

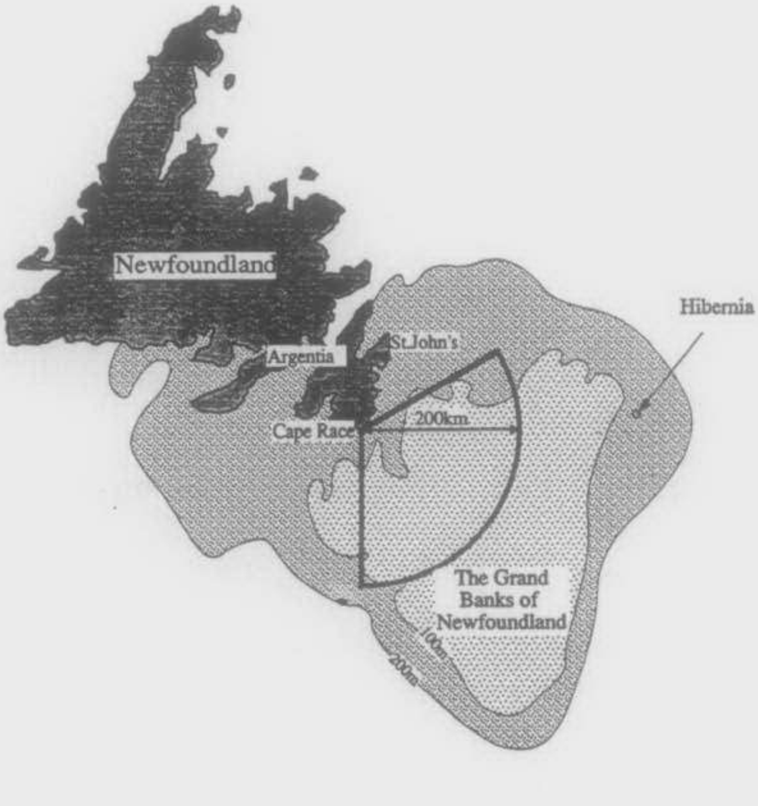

Figure 4.4 Area of coverage for the Over-the-horizon radar installation at Cape Race, Newfoundland

Table 4.17: Ground-wave radar application to user-defined medium and high priority needs.

SENSOR:	**CAPE RACE GWR (NSRL)[1]**	**Field Development (icebergs)**	**Field Development (sea ice)**	**Vessel Transits (icebergs)**	**Vessel Transits (sea ice)**
Sensor Relevance	Iceberg occurrence	Yes		Yes	
	Iceberg position	Yes		Yes	
	Iceberg draft	No		No	
	Sea-ice edge		Yes		Yes
	Sea-ice concentration		No		No
	Sea-ice position & extent		Yes		Yes
	Sea-ice type		No		No
Spatial Coverage	Tactical requirement:	0-40 km	0-40 km	0-5 km	0-10 km
	Strategic requirement:	40-200 km	40-200 km	5-30 km	10-50 km
	Offered:	0-400 km[2]	0-400 km[2]	0-400 km[2]	0-400 km[2]
Temporal Coverage	Tactical requirement:	on demand	on demand	on demand	on demand
	Strategic requirement:	1-2 days	1-2 days	on demand	3-6 hours
	Offered:	on demand	on demand	on demand	on demand
Positional Accuracy	Tactical requirement:	100-500 m	500 m	100 m	500 m
	Strategic requirement:	1-several km	2-4 km	500 m	2-4 km
	Offered:	600 m[3]	800 m[3]	600 m[3]	800 m[3]
Resolution or Size	Tactical requirement:	1,000 t	± 1-tenth	1,000 t	± 1-tenth
	Strategic requirement:	10,000 t	± 1-tenth	10,000 t	± 1-tenth
	Offered:	>10,000 t[4]	present or not	>10,000 t[4]	present or not

Notes:

1. Northern Radar Systems Ltd
2. From GWR site. Operations must be within this area to be covered by GWR.
3. Figure represents quoted range resolution. Azimuth resolution is 3.6°, which would be 25 km at far range of 400 km.
4. Small icebergs (15 - 60 m length) at 200-km range is smallest ice mass for which results are quoted by Northern Radar Systems Ltd.

4.2.4.2 Intelligent pixel-processing radar

Technical description: Intelligent Pixel-Processing Radar (IPIX) radar was conceived as a coherent, land-based radar with specific application to ice detection. As configured for 1989 trials at Cape Bonavista, Newfoundland, IPIX utilized a dual polarized (horizontal and vertical) dish antenna, capable of scanning a full 360° or through a sector of ocean out to about 10 km range. IPIX is not an imaging radar. Data from radar returns are interpreted from two dimensional plots of the reflected frequencies. Being a coherent radar, IPIX can process phase data so as to identify Doppler frequency shifts indicative of targets moving at different velocities. See Table 4.18 for system details.

Experience base: The IPIX concept is experimental. Trials were conducted over two weeks in 1989 at Cape Bonavista, Newfoundland, which demonstrated the detectability of growlers in sea clutter (Haykin et al., 1994, Chapter 9). The system is also capable of detecting the locations of sea-ice edges but cannot provide detailed data on the sea-ice cover.

Potential to satisfy user needs: The system's potential would appear to lie in tactical support of field development, assuming deployment of IPIX on an offshore platform. As a land-based system, range is currently inappropriate for any manner of East Coast support.

Operational application: Given the limited range of the experimental system during trials, the IPIX radar would need to be sited at the operations area to be of value. System changes of 1991-92 resulted in a trailer portable package. Deployment at the operations platform would then be feasible.

Cost: IPIX is not commercialized currently and continues to be developed.

Table 4.18: Intelligent Pixel-Processing Radar application to user-defined medium and high priority needs.

SENSOR:	**IPIX (CRL)[1]**	Field Development (icebergs)	Field Development (sea ice)	Vessel Transits (icebergs)	Vessel Transits (sea ice)
Sensor Relevance	Iceberg occurrence	Yes		Yes[2]	
	Iceberg position	Yes		Yes[2]	
	Iceberg draft	No		No	
	Sea-ice edge		Yes		Yes[2]
	Sea-ice concentration		No		No
	Sea-ice position & extent		Yes		Yes[2]
	Sea-ice type		No		No
Spatial Coverage	Tactical requirement:	0-40 km	0-40 km	0-5 km	0-10 km
	Strategic requirement:	40-200 km	40-200 km	5-30 km	10-50 km
	Offered:	10 km[3]	10 km[3]	10 km[3]	10 km[3]
Temporal Coverage	Tactical requirement:	on demand	on demand	on demand	on demand
	Strategic requirement:	1-2 days	1-2 days	on demand	3-6 hours
	Offered:	on demand	on demand	on demand	on demand
Positional Accuracy	Tactical requirement:	100-500 m	500 m	100 m	500 m
	Strategic requirement:	1-several km	2-4 km	500 m	2-4 km
	Offered:	156 m[4]	156 m[4]	156 m[4]	156 m[4]
Resolution or Size	Tactical requirement:	1,000 t	± 1-tenth	1,000 t	± 1-tenth
	Strategic requirement:	10,000 t	± 1-tenth	10,000 t	± 1-tenth
	Offered:	1,000 t[5]	none	1,000 t[5]	none

Notes:

1. Communications Research Laboratory, McMaster University
2. Useful only if route falls within limited range of sensor.
3. Range used in trials; antenna can also be rotated through 360°.
4. Based on azimuth resolution of 0.9 degree beamwidth at 10 km range.
5. Based on detection of growlers in sea clutter during trials.

4.2.5 Other Radar Development

4.2.5.1 Multistatic radar

The concept of interpreting data from a multi-static radar system (i.e., with more than one receiving element), was analyzed by Battelle Columbus Laboratories with emphasis on sea ice applications. The project report remains proprietary.

4.2.5.2 Millimetre wave radar

Marine radar systems operating on very short wave lengths, on the order of millimetres, are relatively common, particularly those operating in Q band (8 mm). Millimetre wave systems are suited to very close in tactical manoeuvres, as in harbour areas and in river navigation. Detection range beyond the vessel's immediate vicinity (1 - 2 km) is limited by wave absorption, or attenuation, atmospheric water vapour, and oxygen (Burger, 1978). The presence of rain, hail, or snow can produce radar echoes which may obscure returns from ice targets.

4.3 PASSIVE MICROWAVE SENSORS

Passive microwave sensors measure the radiation emitted by the target of interest, typically in the frequency range of 3 to 90 GHz. They are all-weather, day-night sensors, that provided the first synoptic overviews of the polar ice masses irrespective of weather, time of day and season (Carsey, 1992). The 3,000-km swath width at a typical resolution of 30 km by 30 km, allowed the creation of maps of the sea ice covers of both polar regions (poleward of 55° latitude) in their entirety once every 12 hours. As of 1991, 24 satelliteborne microwave sensors were in orbit about the Earth (Massom, 1991; Haykin et al., 1994, Chapter 5).

Radiometers measure the brightness temperature of the target, which is the product of the actual physical temperature and the emissivity of the surface. The value of microwave radiometry for ice detection depends primarily on the large contrast in microwave emissivity between ice and open water. Ice concentration is obtained from a linear interpolation between the brightness of open water and fully consolidated ice cover. The accuracy of this method is estimated to be about ±10%, depending on season. Multifrequency radiometers allow the determination of first-year and multiyear ice concentrations, and information on snow cover state (Haykin et al., 1994, Chapter 2).

4.3.1 Special Sensor Microwave/Imager

Technical description: The special sensor microwave imager (SSM/I) (Tables 4.19 to 4.21) was first lauched on June 18, 1987, and is carried on the U.S. Defense Meteorological Satellite Program (DMSP) series of satellites. It consists of a scanning microwave radiometer, with a swath width of 1,300 km and spatial resolution of 25 km after processing. It operates in the vertical and horizontal polarization modes at frequencies of 19.35, 37.0, and 85.5 GHz, and in the vertical polarization mode at a frequency of 22.24 GHz, which are optimized for the detection of sea ice and transmission through atmospheric water vapour, while lacking the capability of measuring the sea surface temperature (SST). The above frequencies allow the measurement of water vapour in the atmosphere and, hence, correction for their effects (Massom, 1991).

The SSM/I provides improved all-weather, all season, day and night routine mapping of the sea ice concentration and type at 25 km resolution (after processing), and ice edge delineation to 12.5 km on a daily basis. Future systems will provide slightly better spatial resolution (down to 15.0 km).

An airborne configuration of SSM/I has an angular resolution of 1° at 90 GHz, or about a 33-m instantaneous field of view (IFOV) for a typical flying altitude of 2,000 m (Paul et al., 1993).

Experience base: As indicated above, SSM/I data have been used to generate maps of the ice concentrations and types over the entire polar region each day. Very large icebergs (20 by 50 km) can be identified by these data from the fresh water runoff from the berg, which essentially increases its area of influence in the saline sea. However, without other corroborating information, it may not be possible to distinguish a large iceberg from an ice floe and smaller hazardous icebergs cannot be detected by current systems.

The information has been used for strategic planning of vessel transits to the Antarctic. Information collected by the satellite was processed in terms of ice concentration and type and was transmitted to the vessel in an easily understandable ice map, within six hours of the satellite obtaining the data. Reports from the vessel indicated that the data were quite accurate, and several vessels changed their routes to take advantage of the new information.

Potential to satisfy user needs: Passive microwave would be useful to identify the sea ice edge, concentration and average ice types, if at some distance from a rig or structure. A single DMSP platform is normally in operation and covers a given point on the earth's surface twice per day. The absence of "on demand" response and limited resolution render the sensor unsuitable for close-in tactical operations.

The wide resolution cell of 25 km makes the SSM/I impractical for detection of individual icebergs.

Operational applications: It is anticipated that passive microwave could service strategic requirements for sea ice edge and type, providing all weather ice information within six hours of a satellite overpass.

Cost: Typically $500 per processed image showing ice edge, concentration and type.

Table 4.19: Special Sensor Microwave Imager application to user-defined medium and high priority needs.

SENSOR:	**SSM/I Passive Microwave (U.S. Defense Dept.)**	Field Development (icebergs)	Field Development (sea ice)	Vessel Transits (icebergs)	Vessel Transits (sea ice)
Sensor Relevance	Iceberg occurrence	No		No	
	Iceberg position	No		No	
	Iceberg draft	No		No	
	Sea-ice edge		Yes		Yes
	Sea-ice concentration		Yes		Yes
	Sea-ice position & extent		Yes		Yes
	Sea-ice type		Yes[1]		Yes[1]
Spatial Coverage	Tactical requirement:	0-40 km	0-40 km	0-5 km	0-10 km
	Strategic requirement:	40-200 km	40-200 km	5-30 km	10-50 km
	Offered:	1300 km swath	1300 km swath	1300 km swath	1300 km swath
Temporal Coverage	Tactical requirement:	on demand	on demand	on demand	on demand
	Strategic requirement:	1-2 days	1-2 days	on demand	3-6 hours
	Offered:	2 passes per day[2]	2 passes per day[2]	2 passes per day[2]	2 passes per day[2]
Positional Accuracy	Tactical requirement:	100-500 m	500 m	100 m	500 m
	Strategic requirement:	1-several km	2-4 km	500 m	2-4 km
	Offered:	25 km[3]	25 km[4]	25 km[3]	25 km[4]
Resolution or Size	Tactical requirement:	1,000 t	± 1-tenth	1,000 t	± 1-tenth
	Strategic requirement:	10,000 t	± 1-tenth	10,000 t	± 1-tenth
	Offered:	[3]	± 1-tenth[5]	[3]	± 1-tenth[5]

Notes:

1. Can distinguish multi-year from other ice outside of melt season when surface water accumulation alters ice signatures.
2. A two-satellite system will double the number of daily data opportunities. Information can be provided within 6 hours of a satellite pass.
3. For very large icebergs only (see 1 above).
4. Pixel size = 25 km after processing of data. Ice edge can be provided with 12.5 km accuracy.
5. Accuracy of ice concentration is 10% in fall, less than 10% in winter, and 20% in spring and summer (Comiso, 1990).

4.3.2 Airborne Imaging Microwave Radiometer (AIMR)

Background: In order to overcome the large footprint of the satellite-borne microwave radiometers, the Atmospheric Environmental Service (AES) commissioned development of the airborne imaging microwave radiometer (AIMR), an airborne system (Tables 4.20 and 4.21). AIMR's principles of operation are similar to those of the SSM/I sensor, previously described. The AIMR system was developed by MPB Technologies Ltd. in 1989 and was mounted in the AES Lockheed Electra ice reconnaissance aircraft. When the aircraft was decommissioned a year later, AES did not have an aircraft large enough to carry the AIMR. It is currently on loan to the U.S. National Center for Atmospheric Research (NCAR), and is being used for ice detection research.

Technical description: AIMR is described by Paul et al. (1993) and Haykin et al. (1994). It operates at frequencies of 37 and 90 GHz, with beamwidths of 2.4° and 1°, respectively. It scans a line 60° to the left and right of the aircraft flight line by means of a rotating mirror. For a flying altitude of 2000 m, it has instantaneous fields of view (IFOV) of about 84 m (at 37 GHz) and 35 m (at 90 GHz), and a swath width of about 3.5 km on both sides of the aircraft flight line (7 km total swath width).

Experience base: As indicated above, AIMR was used for about one year by AES (600 hours of operations) and performed "very satisfactorily" (Paul et al., 1993; Ramseier, 1994, private communication), but no papers or reports on the capabilities of the instrument over sea-ice have been published to date, as far as we are aware. AIMR should be able to detect and differentiate between icebergs, first-year ice, multiyear ice, and open water. AIMR can detect ice floes, icebergs, or leads which are smaller than the IFOV due to the large difference in brightness temperature between ice and water. Warren (1994, private communication) indicated that it could probably detect a fresh water ice feature in saline water which has an area of about 1/10 the IFOV, i.e., about 8.4 m or 3.5 m, depending on the frequency selected, and assuming a flying height of 2000 m. AIMR also can detect the slush ice which generally surrounds icebergs, bergy bits, and growlers which results from the melting ice. Therefore, smaller pieces of ice can be detected indirectly.

This system has not been used in an offshore drilling or production setting, as far as we know. However, examples of data available to us (M. Collins, University of Calgary, 1994) clearly showed the ice type by colour coding, based on the ice surface temperature. This would be a great asset to an operation as it would provide more reliable ice interpretation and also provide a system which would be more-or-less stand alone without the need for an experienced ice interpreter.

Potential to satisfy user needs: AIMR could be used to identify the sea-ice edge, concentration, ice types, the presence of ridges, icebergs and bergy bits down to about 10 m dimension and possibly growlers. The AIMR could be flown on demand, weather permitting, and provide excellent coverage, with near real time data down-linked to the rig or vessel.

Operational applications: It is anticipated that AIMR could service both tactical and strategic requirements for all medium and high priority needs and provide all weather ice information in near real time with a down link to the rig or vessel. The system could be configured for operation by a person not experienced in ice interpretation who would provide near real time ice maps and reports on the basis of an on-board colour monitor display. There is currently no standard hard copy output.

Cost: The current AIMR system is quite large, requiring a platform on the dimensions of the Lockheed Electra. MPB have suggested a redesign of the AIMR for smaller aircraft at a cost of approximately $2.5 million. The current instrument is on loan to NCAR until 1997, but can be leased for research or operational trials for limited periods.

Table 4.20: Airborne imaging microwave radiometer application to user-defined medium and high priority needs

SENSOR:	**AIMR (AES)**	Field Development (icebergs)	Field Development (sea ice)	Vessel Transits (icebergs)	Vessel Transits (sea ice)
Sensor Relevance	Iceberg occurrence	Yes		Yes	
	Iceberg position	Yes		Yes	
	Iceberg draft	No		No	
	Sea-ice edge		Yes		Yes
	Sea-ice concentration		Yes		Yes
	Sea-ice position & extent		Yes		Yes
	Sea-ice type		Yes[1]		Yes[1]
Spatial Coverage	Tactical requirement:	0-40 km	0-40 km	0-5 km	0-10 km
	Strategic requirement:	40-200 km	40-200 km	5-30 km	10-50 km
	Offered:	7 km swath any distance[2]	7 km swath any distance[2]	7 km swath any distance[2]	7 km swath any distance[2]
Temporal Coverage	Tactical requirement:	on demand	on demand	on demand	on demand
	Strategic requirement:	1-2 days	1-2 days	on demand	3-6 hours
	Offered:	on demand[3]	on demand[3]	on demand[3]	on demand[3]
Positional Accuracy	Tactical requirement:	100-500 m	500 m	100 m	500 m
	Strategic requirement:	1-several km	2-4 km	500 m	2-4 km
	Offered:	100 m[4]	100 m[4]	100 m[4]	100 m[4]
Resolution or Size	Tactical requirement:	1,000 t	± 1-tenth	1,000 t	± 1-tenth
	Strategic requirement:	10,000 t	± 1-tenth	10,000 t	± 1-tenth
	Offered:	1,000 t[5]	± 1 tenth	1,000 t[5]	± 1-tenth

Notes:

1. Can distinguish multi-year from other ice outside of melt season when surface water accumulation alters ice signatures.

2. Based on the typical flying altitude of 2,000 m, swath is 7 km but aircraft could fly several passes and cover the tactical and strategic requirements.

3. Information could be downlinked directly to a rig or vessel.

4. Positional accuracy of aircraft.

5. Estimated iceberg size based on detection of fresh water feature in saline sea water which is 1/10th of the IFOV area. (Warren, 1994, private communication)

Table 4.21: Comparison of spaceborne and airborne passive microwave sensing systems

Parameter	SSM/I	AIMR
Platform	DMSP satellite	Airborne
Scan Mechanism	mechanical	mechanical
Resolution	25 km	about 33 m (depends on flying altitude)
Swath width	1300 km	7 km (depends on flying altitude)
Frequency	19.35, 22.235, 37.0, and 85.5 GHz	37 and 90 GHz
Sensors	SSM/I	AIMR
Data availability	two passes per day	On demand
Data delivery	order	down link to site
Data output	digital data for down load by user	colour monitor image and digital storage
On demand	no	could fly within a few hours of request
Daytime	yes	yes
Night time	yes	yes
Fog and cloud cover	yes	yes

4.4 ACOUSTIC SYSTEMS

There is a large class of target detection systems that are based on underwater acoustics or sonar (see Chapter 5). The delay in receiving the echo of an emitted sound wave is used to determine the distance between the sound source and a target. Although systems have been highly developed for military applications, little work has been done using them for iceberg (C-Tech, 1991) or sea ice (Haykin et al., 1994, Chapter 3) detection. The major use has been to estimate iceberg draft by lowering a horizontally-looking sonar transducer beside an iceberg (Rossiter and Gustajtis, 1978). Conceptual iceberg warning systems were described in Canpolar Consultants Ltd. (1985). The systems outlined below have very specialized applications applying to ice thickness and ice occurrence.

4.4.1 Ice Profiling System

Technical Description: The Ice Profiling System (IPS) (Table 4.22) consists of a sonar sensor which is aimed vertically upward at the underside of the ice cover (Hoare et al., 1980; Pilkington and Wright, 1991; Melling and Reidel, 1993; Wadhams, 1988) describes an IPS mounted on a submarine). The IPS sits on the sea floor or is tethered several metres below the water surface depending on water depth. The device determines the thickness of the ice every few seconds from the transmission time of a sonic pulse which is bounced off the underside of the ice. Information on the ice thickness is generally stored within the device for a year or more and thus would be available for analysis only upon physical retrieval of the IPS. A real time transmission capability can be added by either hard wired connection or sonic signal relay to a vessel or offshore structure. The IPS is generally deployed with an Acoustic Doppler Current Meter (commercially available from RD Instruments, San Diego), which indicates the velocity of the ice passing over the IPS.

Experience base: An IPS was first deployed by Dome Petroleum Limited in 1978 (results from Dome's deployments are described in Hoare et al., (1980), and Pilkington and Wright (1991). An improved IPS has been developed by the Institute of Ocean Sciences, Department of Fisheries and Oceans (DFO). IPS use to date has been restricted to collection of information on ice keels in various ice covered seas.

Attempts to use IPS's in a real-time ice monitoring system were made at Gulf Canada's Molikpaq structure in the Beaufort Sea. The results proved inconclusive. In the first year, the units were mounted in the toe of the Molikpaq and these appeared to be susceptible to reflections off the side of the structure, and to ice rubble developing around the structure. In the second year, IPS's mounted about 100 m off all four sides of the structure ceased to operate shortly after installation. Reasons advanced for this include equipment malfunction, ice scour, and the close presence of reflecting surfaces other than sea ice. IPS's installed well off-shore in various research programs have provided excellent ice thickness data (Hoare et al., 1980; Wadhams, 1988; Pilkington and Wright, 1991; Melling and Reidel, 1993).

Potential to Satisfy User Need: The principle of the IPS may be applied to detecting the approach of hazardous ice by deploying a sufficiently dense sensor network around an offshore structure or other point of importance. An IPS array is particularly suited to measurement of ice keels, be they of glacial ice or sea-ice. Information on ice keels carries medium to low priority (see Tables 3.6 to 3.9) but its measurement may aid in inferring ice mass, which carries a higher priority.

Operational Application: Given a 10,000 t ice fragment of 22-m diameter, a 20-m IPS footprint would necessitate maximum spacing of about 30 m and use of about 200 IPS units in a 1 km radius centred on the rig or structure. Smaller fragments of icebergs or sea-ice could conceivable pass undetected through such a configuration. The operator would need to increase the IPS footprint and/or adjust unit spacing appropriate to the minimum defined ice hazard size. A system requiring hundreds of units, however, would incur costs estimated in millions of dollars.

Cost: Basic equipment cost for components for a single sensor are in the order of $15,000. The several dozen sensors of a basic ice warning configuration would likely be cheaper per unit. Installation and maintenance would add to the costs.

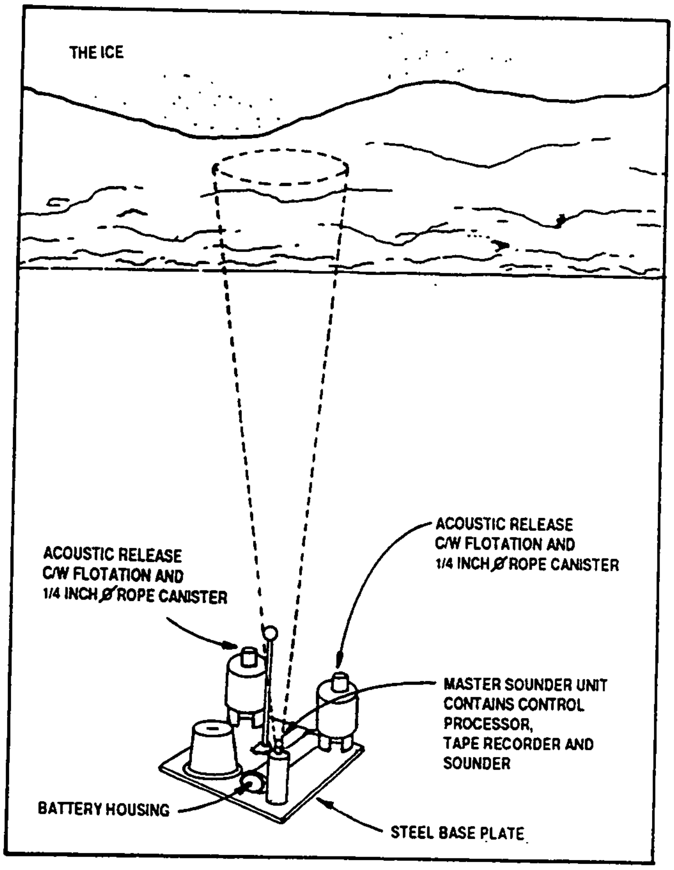

Figure 4.5 Ice Profiling Sonar as described by Hoare et al. (1980).

Table 4.22: Acoustic systems (IPS) application to user-defined medium and high priority needs

SENSOR:	**ICE PROFILING SYSTEM (IPS)**	Field Development (icebergs)	Field Development (sea ice)	Vessel Transits (icebergs)	Vessel Transits (sea ice)
Sensor Relevance	Iceberg occurrence	Yes		Yes	
	Iceberg position	Yes		Yes	
	Iceberg draft	Yes		Yes	
	Sea-ice edge		No		No
	Sea-ice concentration		No		No
	Sea-ice position & extent		No		No
	Sea-ice type		No		No
Spatial Coverage	Tactical requirement:	0-40 km	0-40 km	0-5 km	0-10 km
	Strategic requirement:	40-200 km	40-200 km	5-30 km	10-50 km
	Offered:	1 km	1 km	N/A	N/A
Temporal Coverage	Tactical requirement:	on demand	on demand	on demand	on demand
	Strategic requirement:	1-2 days	1-2 days	on demand	3-6 hours
	Offered:	on demand[1]	on demand[1]	on demand[1]	on demand[1]
Positional Accuracy	Tactical requirement:	100-500 m	500 m	100 m	500 m
	Strategic requirement:	1-several km	2-4 km	500 m	2-4 km
	Offered:	100 m[2]	100 m[2]	100 m[2]	100 m[2]
Resolution or Size	Tactical requirement:	1,000 t	± 1-tenth	1,000 t	± 1-tenth
	Strategic requirement:	10,000 t	± 1-tenth	10,000 t	± 1-tenth
	Offered:	1,000 t[3]	present or not	1,000 t[3]	present or not

Notes:

1. Assumes hardwire communications to rig data acquisition system.
2. GPS accuracy for deployment of units, but positional accuracy relative to host structure will be much better.
3. Will detect all passing ice masses, provided they cover reasonable amount of sensor footprint; confirmation dependent on interpretation techniques developed (Pilkington and Wright, 1991).

4.4.2 Ship-mounted Iceberg Avoidance Sonar

Technical Description: The ship-mounted iceberg avoidance sonar system is based on research carried out for the United States Navy, proposed by Martin Marietta Laboratories (Table 4.23). Operational systems are not yet available.

Martin Marietta proposes a system mounted in the bow of a vessel, consisting of a single sonic transmitter and a horizontal bank of receivers. The horizontally transmitted sonar pulse would bounce off any ice feature within the beam and would be received by the bank of receivers. The phase of the received pulses in the different receivers would indicate the bearing of the ice feature with respect to the system.

Experience Base: As indicated above, the system has never been used to detect ice as far as we know, although Martin Marietta provides estimates of detectable iceberg size versus range, which is believed to be based on their experience with propriety military systems.

Sonar systems have been used to profile ice feature keels at short range, in research programs and these work well, however, the application presented here is quite different. The manufacturer indicates that the device would only detect icebergs in ice-free water, and the system depends on the density profile of the water column.

Potential to Satisfy User Needs: The sensor system is conceived to provide tactical navigation support in ice-infested waters. Occurrence and position of ice features would be detectable.

Operational Application: The system requires a particular thermal gradient in the water column so that the sonic waves are refracted upwards. The manufacturer indicates that such a gradient occurs typically between March and June in the North Atlantic, which is the period of maximum iceberg densities. Water depth also appears to be an important parameter in the operation of the device.

Before this system could be used as a hazard detection system on an offshore rig, research would be required to determine whether it indeed detects ice and what the limitations are due to water depth, thermal profile, sea state, and nearness to an offshore structure. See Chapter 5 for a more complete discussion.

Cost: The manufacturer indicates that a test program could be organized in three months at an estimated cost of several hundred thousand dollars. Systems are expected to cost in the $1 million range but prices could drop significantly over the next decade.

Table 4.23: Acoustic Systems (ship-mounted iceberg avoidance sonar) application to user-defined medium and high priority needs

SENSOR:	**Ship Mounted Iceberg Avoidance Sonar**	Field Development (icebergs)	Field Development (sea ice)	Vessel Transits (icebergs)	Vessel Transits (sea ice)
Sensor Relevance	Iceberg occurrence Iceberg position Iceberg draft	Yes Yes Yes		Yes Yes Yes	
	Sea-ice edge Sea-ice concentration Sea-ice position & extent Sea-ice type		No No No No		No No No No
Spatial Coverage	Tactical requirement: Strategic requirement: Offered:	0-40 km 40-200 km 0-5 km	0-40 km 40-200 km N/A	0-5 km 5-30 km 0-5 km	0-10 km 10-50 km N/A
Temporal Coverage	Tactical requirement: Strategic requirement: Offered:	on demand 1-2 days on demand	on demand 1-2 days N/A	on demand on demand on demand	on demand 3-6 hours N/A
Positional Accuracy	Tactical requirement: Strategic requirement: Offered:	100-500 m 1-several km 100 m[1]	500 m 2-4 km N/A	100 m 500 m 100 m[1]	500 m 2-4 km N/A
Resolution or Size	Tactical requirement: Strategic requirement: Offered:	1,000 t 10,000 t 1,000 t	± 1-tenth ± 1-tenth N/A	1,000 t 10,000 t 1,000 t	± 1-tenth ± 1-tenth N/A

Note:
1. Figure refers to locational accuracy of target relative to vessel or rig.

4.4.3 Passive Acoustic Systems

Farmer and Xie (Haykin et al., 1994, Chapter 3) describe passive acoustics, i.e., the reception of sound radiated from a moving ice cover, as a result of sudden relief of stress, fracture, collapse, rubbing together of two ice pieces, wind, snow, and waves at exposed ice edges. Recent work indicates that each event type causes a unique dynamic character to the resulting acoustic signal. All the event descriptions in the literature refer to sheet ice. There is no reference to icebergs, except Farmer and Xie note that iceberg calving is an active acoustic source.

Passive acoustic noise appears to provide no indication of the type of ice, its thickness, or concentration, and it attenuates rapidly. Hence it is not considered to be relevant to the current study.

4.5 OPTICAL SYSTEMS

This section deals with systems which sense reflected visible light, infra-red (IR) and ultraviolet (UV) and which operate from either aircraft or satellite platforms.

The human eye is one of the most useful of all optical sensors, offering excellent spatial resolution, and coupled with the brain, provides information on ice type, surface features (thickness), and severity. However, it is limited to the range set by the optical horizon or the weather conditions and darkness (although the latter can be partly overcome by night viewing systems), and provides no recording media, except for hand written notes. Despite these limitations, the human eye will always be a primary system for ice and iceberg surveillance. Some theoretical aspects of the eye are provided in Chapter 5 for comparison with other sensors, and it is not considered further in this chapter.

Several optical sensors are available which have been applied to, or may be considered for, the detection of sea-ice and icebergs. A review and description of the general principles of such systems are provided by Lillesand and Kiefer (1987).

Optical systems generally offer extremely good spatial resolution, and the means to determine surface profiles from stereo imagery. Systems which employ electronic recording technology also offer capabilities of immediate data transmission and computer analysis. Disadvantages include the requirement of good visibility during daylight conditions, which is often a problem off the East coast. In addition, airborne optical systems provide images of a relatively small surface area although with greater mission planning flexibility. Satellite-borne systems offer greater spatial coverage but at the expense of a fixed revisit schedule and spatial resolution.

4.5.1 Photography

Aerial photography has been used for several decades and is well understood. This method involves the use of surveying cameras aimed vertically or obliquely at the earth's surface. The resulting exposed film must be chemically processed which results in a lengthy data turnaround time. This method offers very high spatial resolutions (the order of centimetres to tens of centimetres) but with limited spatial coverage (2 to 5 km) from conventional aircraft platforms. The method is not amenable to direct data transmission or immediate computer enhancement of the data. False colour imaging can be carried out with optical filters set in front of the camera system. For several colours, one must use several filters and cameras, or rotating filters so that sequential images taken by the camera are exposed to a different colour.

There are two modes of aerial photography. The film can be exposed to a two dimensional image of the ground with exposures made at regular time intervals (depending on the forward speed of the aircraft) to produce sequential images of the area of interest along the aircraft flight path. The images may be overlapping (for stereo analysis) of non-overlapping (for greater film economy and coverage). Alternatively, an image of a line on the ground is projected onto the film, and the film is moved past the line. This is known as "pushbroom" imaging. The photographic films available are sensitive to wavelengths in the ultra-violet to near infra-red spectral range.

Photographic images have been used extensively for the study of ice cover and ice surface features during research projects, and in particular, ridge height profiles using stereo photography. The process has proven to be extremely useful and a cost effective means of collecting information on ice cover.

4.5.2 Video Cameras

Video cameras can be used in the same way as film cameras. However, they offer lower spatial resolutions, degraded tone and texture qualities while offering comparable spatial coverage. Again, false colour images must be created by the use of several separate filters and cameras, or by rotating filters in front of one camera to provide sequential images of different colour. The advantage of using a video camera is that the data can be transmitted directly from the sensor platform to the user, and also the data can be more easily digitized and processed by computer. Video camera data cover a spectral range similar to that of aerial photographs.

Video cameras have been used to obtain a general view and documentation of the ice cover, mainly for presentations, as opposed to scientific or engineering studies.

4.5.3 Scanning Imagers

These systems utilize a rotating mirror and a single detector ("whiskbroom") or a line of detectors ("pushbroom") to scan a line perpendicular to the aircraft or spacecraft motion. The combination of the sensor platform's forward motion and the repeated across-track scan lines provides a two dimensional image of the earth's surface. Several whiskbroom and pushbroom systems have been developed to varying levels of operational readiness (Lillesand and Kiefer, 1987; Staenz, 1992).

These scanning imagers can be characterized by the Compact Airborne Spectrographic Imager (CASI), developed by Itres Research Ltd., Calgary. The CASI uses a two-dimensional optical sensor array to both scan the line perpendicular to aircraft motion and to measure the reflected light intensity at different specific wavelengths. This capability of sensing in a number of different wavelength segments makes CASI a "multispectral scanner". Satellite-borne sensors on the French *SPOT* and the U.S. *LANDSAT* series operate on similar principles, *SPOT* being a true pushbroom system and *LANDSAT* being a rotating mirror whiskbroom sensor. As alluded to above, the satellite sensors offer lower spatial resolution than do the airborne sensors while covering a significantly greater geographical area on a fixed orbit schedule. This precludes true "on demand" coverage but does provide wide area coverage of the earth's surface without the field logistics concern.

Another multispectral scanner, being developed by Daedalus (Staenz, 1992), is designed to operate at wavelengths between 440 nm (blue) and 820 nm (near IR), and 1160 to 1520 nm and

2000 to 2500 nm (short-wave infra-red, SWIR), and 8400 to 12,200 nm (thermal infra-red, TIR). Several instruments have been constructed using whiskbroom and pushbroom technology (Staenz, 1992), but their capabilities are similar to those of the CASI described above and so will not be covered separately.

4.5.3.1 Fluorescence line imager (FLI)

Technical Description: Developed by the Canadian Department of Fisheries and Oceans in 1981, the (FLI) is a high-sensitivity pushbroom imager sensitive to visible and near-infrared wavelengths (Table 4.24). The sensor was developed as an experimental package preparatory to development of a future satellite-borne sensor. The goal of the development project was to build a sensor capable of "mapping ocean and coastal phytoplankton concentrations by imaging the emissions from solar-stimulated fluorescence of chlorophyll a" (Gower et al., 1992). This original design application is reflected in the sensor name, however, the FLI does have more multidisciplinary potential.

The FLI images a ground swath approximately 1900 pixels wide, using an array of five charge coupled device (CCD) cameras. The field of view beneath the survey aircraft is 70°. Thus, a flying height of 305 m (1,000 feet) will yield an across-track spatial resolution of about 0.25 m and a swath of about 450 m.

In principle, the FLI can image 288 separate spectral intervals for each pixel. However, the volume of data produced is beyond the system's design capability to fully process or store. In the "spectral mode", data averaging processes preserve maximum spectral resolution at the cost of lower spatial resolution. In the "imaging mode", the full spatial resolution is preserved in up to eight spectral ranges. The FLI concept and principles have been refined and transferred to the CASI, considered in subsection 4.5.3.1.

Experience Base: The FLI has flown 100 missions in the period 1984 to 1990. These have dealt with phytoplankton mapping and depth measurements of shallow waters (Gower et al., 1992). No iceberg or sea-ice applications have been formally tested.

Potential to satisfy user needs: FLI's limited field of view renders the sensor unsuitable for strategic level reconnaissance, which requires a wide area view of overall ice conditions. Potential may lie in tactical support of field development.

Operational application: FLI is a daytime-only, clear weather sensor, requiring a twin engine fixed-wing aircraft platform.

Table 4.24: FLI application to user-defined medium and high priority needs

SENSOR:	**Fluorescence Line Imager (DFO)** [1]	Field Development (icebergs)	Field Development (sea ice)	Vessel Transits (icebergs)	Vessel Transits (sea ice)
Sensor Relevance	Iceberg occurrence Iceberg position Iceberg draft	Yes Yes No		Yes Yes No	
	Sea-ice edge Sea-ice concentration Sea-ice position & extent Sea-ice type		Yes[2] Yes[2] Yes[2] No		Yes[2] Yes[2] Yes[2] No
Spatial Coverage	Tactical requirement: Strategic requirement: Offered:	0-40 km 40-200 km 1,000 km[3]	0-40 km 40-200 km 1,000 km[3]	0-5 km 5-30 km 1,000 km[3]	0-10 km 10-50 km 1,000 km[3]
Temporal Coverage	Tactical requirement: Strategic requirement: Offered:	on demand 1-2 days on demand	on demand 1-2 days on demand	on demand on demand on demand	on demand 3-6 hours on demand
Positional Accuracy	Tactical requirement: Strategic requirement: Offered:	100-500 m 1-several km 100 m[4]	500 m 2-4 km 100 m[4]	100 m 500 m 100 m[4]	500 m 2-4 km 100 m[4]
Resolution or Size	Tactical requirement: Strategic requirement: Offered:	1,000 t 10,000 t 1,000 t[5]	± 1-tenth ± 1-tenth none	1,000 t 10,000 t 1,000 t[5]	± 1-tenth ± 1-tenth none

Notes:

1. Department of Fisheries and Oceans, Canada.
2. Information would be interpreted from imagery of very narrow field of view.
3. Representative figure for twin engine airplane.
4. Assumes aircraft use of GPS navigation.
5. Only available in clear day-time weather.

4.5.3.2 Compact airborne spectrographic imager (CASI)

Technical Description: The CASI system is an example of a pushbroom imager. A line on the ground is focused onto one axis of a two-dimensional Charge Coupled Device (CCD) sensor array and the forward motion of the aircraft moves this sensing line over the ground, thus causing the device to scan an area of width approximately equal to the aircraft's flying height. The sensed light passes through an interference filter which disperses the light into its spectral components over the second axis of the sensor array. Electronically scanning both dimensions of the array provides the light intensity along the sensing line on the ground at every 0.1° (1 to 2 m ground measurement depending on flying height) and at each 0.2 nm wavelength from 430 nm (blue) to 870 nm (near IR). See Table 4.25 for estimated capabilities in ice detection.

Two operational modes are possible, a spectral mode and a spatial mode. In the spectral mode the device is capable of full spectral resolution in over 40 different viewing directions within the field of view. In the spatial mode, the device is operated with full spatial resolution over a maximum of 15 different spectral bands.

Experience Base: The CASI has been used extensively for remote sensing of surface pollution, and crop and tree conditions. It has not been tested for the detection of icebergs and sea ice. It is possible that the spectral discrimination of first-year and multi-year ice and icebergs in the visible region will allow the differentiation of different ice types (first-year ice appears green to the eye, and multiyear ice appears blue), however, the effect of snow cover on the ice has not been evaluated. As this sensor operates in the visible range, it requires daylight and good visibility . It appears that no systematic analysis of the reflectance of sea-ice has been carried out for different ice types, sun angles, and sky conditions (Grenfell, 1979 and 1983; Grenfell and Maykut., 1977; Perovich and Grenfell, 1982; Massom, 1991). The information in the above-mentioned publications suggests that it should be possible to differentiate between ice types in certain conditions, but they do not allow one to determine whether ice type could be obtained unambiguously at all times; this would require a test program.

Potential to Satisfy User Needs: The CASI may be able to detect the presence of ice and also permit discrimination of first-year, old, and glacial ice, although this has not been demonstrated in the field. Disadvantages are CASI's requirement for daylight and good visibility and its limited spatial coverage.

Operational Application: The sensor package could be mounted on a helicopter used for ice reconnaissance in support of an offshore rig or icebreaker. If it performs as expected, it would provide maps of the ice conditions with areas of old and first-year ice delineated. Once set up, the device should operate unattended during the mission flight. Data would be computer processed to provide the specific information required by the user.

Cost: A basic unit sells for Can$400,000. The system can be leased.

Table 4.25: Optical Systems (CASI) application to user-defined medium and high priority needs

SENSOR:	**Compact Airborne Spectral Imager (CASI)**	Field Development (icebergs)	Field Development (sea ice)	Vessel Transits (icebergs)	Vessel Transits (sea ice)
Sensor Relevance	Iceberg occurrence Iceberg position Iceberg draft	Yes Yes No		Yes Yes No	
	Sea-ice edge Sea-ice concentration Sea-ice position & extent Sea-ice type		Yes Yes Yes ?[1]		Yes Yes Yes ?[1]
Spatial Coverage	Tactical requirement: Strategic requirement: Offered:	0-40 km 40-200 km 1.5 km swath[2]	0-40 km 40-200 km 1.5 km wath[2]	0-5 km 5-30 km 1.5 km swath [2]	0-10 km 10-50 km 1.5 km swath[2]
Temporal Coverage	Tactical requirement: Strategic requirement: Offered:	on demand 1-2 days on demand[3]	on demand 1-2 days on demand[3]	on demand on demand on demand[3]	on demand 3-6 hours on demand[3]
Positional Accuracy	Tactical requirement: Strategic requirement: Offered:	100-500 m 1-several km 100 m[4]	500 m 2-4 km 100 m[4]	100 m 500 m 100 m[4]	500 m 2-4 km 100 m[4]
Resolution or Size	Tactical requirement: Strategic requirement: Offered:	1,000 t 10,000 t 1,000 t[5]	± 1-tenth ± 1-tenth ± 1-tenth	1,000 t 10,000 t 1,000[5]	± 1-tenth ± 1-tenth ± 1-tenth

Notes

1. System expected to aid ice discrimination but this has still not been verified.
2. Area of coverage based on lens with 35.5° angle, providing 1.5 km swath for typical flying height of 1,500 m (4,920 feet).
3. On condition of good visibility.
4. Figure represents claimed GPS accuracy of aircraft.
5. Not tested and verified; based on 2-m spatial resolution, icebergs below 100 t could be identified.

4.5.3.3 Short wave infrared radiometer full spectrum imager

Technical Description: The SWIR full spectrum imager (SFSI) instrument is under development by the Canada Centre for Remote Sensing and National Research Council of Canada as an airborne research instrument. The instrument is a pushbroom imager which uses a two-dimensional sensor array to scan both spatially and spectrally (Neville and Powell, 1992). See Table 4.26.

The SFSI is designed to operate in the wavelength region of 1200 to 2400 nm. This region detects and enhances insect damage in trees, and soil, minerals, and rock type.

Experience base: There is no experience base for the use of SFSI over ice. However, if the ice is not covered with snow, the temperature of the surface depends on the ice thickness plus air temperature, wind speed, and solar radiation. Hence one might expect that the brightness of the ice surface in a particular region would be an indication of the ice thickness. However, this would not be the case if the ice was covered by snow, and so ice surface temperature alone would not be a completely reliable indicator of ice thickness.

Potential to Satisfy User Needs: Airborne SFSI offers resolution somewhat coarser than that of aerial photography. The pixel size is sufficiently fine to resolve targets of 4-m dimensions and less (Neville and Powell, 1992). The spectral flexibility would allow the operator to sense only the range of wavelengths required for confirmation of ice targets. The field of view (11.69°) will restrict the amount of area coverage in airborne mode.

Operational Applications: The experimental SFSI package is currently configured for airborne use. It is not currently in an operational configuration.

Cost: System is under development; sponsors currently unable to offer user cost estimate.

Table 4.26: SWIR Full Spectrum Imager application to user-defined medium and high priority needs

SENSOR:	**SWIR Full Spectrum Imager (SFSI); spaceborne**	Field Development (icebergs)	Field Development (sea ice)	Vessel Transits (icebergs)	Vessel Transits (sea ice)
Sensor Relevance	Iceberg occurrence	Yes		Yes	
	Iceberg position	Yes		Yes	
	Iceberg draft	No		No	
	Sea-ice edge		Yes		Yes
	Sea-ice concentration		Yes		Yes
	Sea-ice position & extent		Yes		Yes
	Sea-ice type		[1]		[1]
Spatial Coverage	Tactical requirement:	0-40 km	0-40 km	0-5 km	0-10 km
	Strategic requirement:	40-200 km	40-200 km	5-30 km	10-50 km
	Offered:	1 km swath[2]	1 km swath[2]	1 km swath[2]	1 km swath[2]
Temporal Coverage	Tactical requirement:	on demand	on demand	on demand	on demand
	Strategic requirement:	1-2 days	1-2 days	on demand	3-6 hours
	Offered:	note[3]	note[3]	note[3]	note[3]
Positional Accuracy	Tactical requirement:	100-500 m	500 m	100 m	500 m
	Strategic requirement:	1-several km	2-4 km	500 m	2-4 km
	Offered:	100 m[4]	100 m[4]	100 m[4]	100 m[4]
Resolution or Size	Tactical requirement:	1,000 t	± 1-tenth	1,000 t	± 1-tenth
	Strategic requirement:	10,000 t	± 1-tenth	10,000 t	± 1-tenth
	Offered:	>1,000 t[5]	± 1-tenth	>1,000 t[5]	± 1-tenth

Notes:

1. Sensor expected to aid discrimination of ice type but this has not been verified.
2. Area covered defined by 11.69° field of view, 0.4-km swath for flying height of 2,000 m (6,500 ft.); 0.8-km swath at 4,000 m (13,100 ft.).
3. Will depend on satellite orbit pattern and revisit schedule; currently airborne experimental package.
4. Satellite ephemeris and ground control points in image should provide positional accuracy finer than the tactical requirement.
5. Pixel size range 36.4 cm to 4.0 m, depending on flying height (Neville and Powell, 1992)

4.5.3.4 *LANDSAT* thematic mapper multispectral scanner

Technical Description: The optical sensor on board the *LANDSAT-5* spacecraft is the thematic mapper (TM), a multispectral whiskbroom sensor which provides imagery in six spectral intervals between the blue and near-IR regions, as well as a seventh interval in the thermal IR (TIR) region. Nominal ground resolution of the TM is 30 m in the six shorter wave length channels and 120 m in the TIR channel. See Table 4.27.

LANDSAT-7 (launch date to be announced, but not before 1996) will carry an Enhanced Thematic Mapper (ETM) which will sense in seven spectral channels, between 450 and 1250 nm, at 30-m resolution (120 m for the single TIR channel). The principal enhancement over the *LANDSAT-5* TM will be an eighth, panchromatic, band (500 to 860 nm range) offering 15- m resolution. The sensor swath width, as in previous *LANDSAT* missions, will measure 185 km, and will cover latitudes between 82°30' North and South. A second *LANDSAT-7* optical sensor will sense in 32 bands between 400 and 2500 nm at resolutions of 10 m (visible, near-IR) and 20 m (thermal IR). This new sensor will image a 41-km swath.

Experience Base: Multispectral data from *LANDSAT* have been used extensively to study ice cover. *LANDSAT* data can be used to detect linear or bright features which are smaller than the pixel size. In particular, icebergs and sea-ice floes, with their low surface temperature, contrast well against the water background in the near-IR spectral channel. The sensor data alone, however, are not sufficient to allow one to distinguish between icebergs and sea-ice floes. Previous operational use of *LANDSAT* data has been limited by the satellite's fixed revisit schedule, cloud interference, and relatively long data turnaround times. This latter concern has been partially addressed by recent advances in image file compression techniques for on-line data transfer. On the other hand, *LANDSAT* data have been useful in research studies providing good coverage of ice edge and concentration, but not ice type .

Potential to Satisfy User Needs: The *LANDSAT* data may be useful as a source of opportunity. Data are not available on demand. The satellites cover a given point once every 16 days at low and middle latitudes. There is a 34% overlap between adjacent image paths at 45° latitude; thus some points could be covered twice during the 16-day cycle.

Operational Application: Data covering pertinent areas off the East Coast are downlinked to the Gatineau satellite station, near Ottawa, upon acquisition by *LANDSAT*. Normal data turnaround ranges from 8 to 10 days due to the absence of a data link between the Gatineau receiving station and the processing facility in Vancouver, due to insufficient market. Given sufficient operational demand, the current delay could be reduce to three days (Nazarenko, 1994). Same-day delivery would require the direct ground station to processor link as well as an on-line product delivery system. Because of the temporal coverage of the satellite and the delay in obtaining data, this sensor is not considered useful for either tactical of strategic purposes.

Cost: $1,500 to $3,500 per scene, depending on options.

Table 4.27: *LANDSAT* Thematic Mapper application to user-defined medium and high priority needs

SENSOR:	***LANDSAT* Satellite series Thematic Mapper (TM)**	Field Development (icebergs)	Field Development (sea ice)	Vessel Transits (icebergs)	Vessel Transits (sea ice)
Sensor Relevance	Iceberg occurrence	Yes		Yes	
	Iceberg position	Yes[1]		Yes[1]	
	Iceberg draft	No		No	
	Sea-ice edge		Yes		Yes
	Sea-ice concentration		Yes		Yes
	Sea-ice position & extent		Yes		Yes
	Sea-ice type		Yes[2]		Yes[2]
Spatial Coverage	Tactical requirement:	0-40 km	0-40 km	0-5 km	0-10 km
	Strategic requirement:	40-200 km	40-200 km	5-30 km	10-50 km
	Offered:	185 km swath	185 km swath	185 km swath	185 km swath
Temporal Coverage	Tactical requirement:	on demand	on demand	on demand	on demand
	Strategic requirement:	1-2 days	1-2 days	on demand	3-6 hours
	Offered:	16 days[3]	16 days[3]	16 days[3]	16 days[3]
Positional Accuracy	Tactical requirement:	100-500 m	500 m	100 m	500 m
	Strategic requirement:	1-several km	2-4 km	500 m	2-4 km
	Offered:	100 m[4]	100 m[4]	100 m[4]	100 m[4]
Resolution or Size	Tactical requirement:	1,000 t	± 1-tenth	1,000 t	± 1-tenth
	Strategic requirement:	10,000 t	± 1-tenth	10,000 t	± 1-tenth
	Offered:	> 100,000 t[1]	± 1-tenth	> 100,000 t[1]	± 1-tenth

Notes:

1. Target position possible; sensor not capable of distinguishing icebergs from sea-ice floes.
2. Ice type can be interpreted from ice tone, texture, shape of floes, etc.
3. Satellite passes over given point once in 16 days with 34% overlap between adjacent paths at 45° latitude. Additional 8-10 days for data processing and delivery.
4. Satellite ephemeris and ground control points in image should provide positional accuracy finer than the tactical requirement.

4.5.3.5 Advanced very high resolution radiometer, satellite-borne

Technical Description: The currently operational *NOAA-9*, *-10*, and *-12* satellites carry a two-band advanced very high resolution radiometer (AVHRR) which measures in the visible band (daytime) and TIR (nighttime). The AVHRR is sensitive in the visible and near-IR bands with a spatial resolution of 1.1 km at the nadir degrading to 2.5 km at the edges of the sensor's 3,000-km swath width. Direct data reception by an inexpensive, omni-directional antenna is possible, with maximum resolution of 4 km at the nadir. The NOAA system offers good temporal coverage at high latitudes, and extensive archiving of the data. Although capable of day and nighttime use, it is still limited by cloud cover. Also, the distinction between clouds and ice may, at times, be unclear. The near-polar orbits of the NOAA satellites deliver several images a day, provides strategic coverage for most situations and allows an investigation of dynamic features. See Table 4.28.

Experience Base: *NOAA* AVHRR images have been used extensively for operational purposes in the Arctic because of their relatively low cost, the frequent revisit rate, and the fact that the data can be downlinked directly to a vessel or offshore platform. Such direct downlink data are most commonly (and economically) available at 4 km resolution, although some special purpose research vessels and the U.S. Coast Guard's Polar class icebreakers are now equipped with the costlier full resolution receiving facilities.

NOAA data have been used extensively in operations due to their coverage, temporal frequency, and low cost. It is useful for the identification of ice edge, and large old floes can generally be identified based on their tone and location, and the general knowledge of regional ice characteristics.

Potential to satisfy User Need: The data would not apply directly to the defined high and medium priority needs due to coarse resolution and the uncertainty of obtaining cloud-free images on demand. The frequency of coverage and speed of data delivery, however, suggest that *NOAA* imagery may serve as useful information in support of ice and iceberg interpretations taken from data provided by other, higher resolution, remote sensors.

Operational Application: AVHRR data at 4-km maximum resolution can be transmitted directly to an offshore rig or vessel whenever there is a satellite pass. The optimum resolution (1.1 km) image product can be transmitted, as a digital file, from the ground processing station to an offshore user via regular data communication links. In this way, an image is made available within a few hours of data acquisition. Alternatively, a full resolution AVHRR receiving and processing facility could be established on the offshore structure.

Cost: Via modem, $20 per scene.

Table 4.28: *NOAA* Advanced Very High Resolution Radiometer application to user-defined medium and high priority needs

SENSOR:	***NOAA* Satellite series AVHRR**	Field Development (icebergs)	Field Development (sea ice)	Vessel Transits (icebergs)	Vessel Transits (sea ice)
Sensor Relevance	Iceberg occurrence Iceberg position Iceberg draft	No[1] No No		No[1] No No	
	Sea-ice edge Sea-ice concentration Sea-ice position & extent Sea-ice type		Yes No Yes Yes[2]		Yes No Yes Yes[2]
Spatial Coverage	Tactical requirement: Strategic requirement:	0-40 km 40-200 km	0-40 km 40-200 km	0-5 km 5-30 km	0-10 km 10-50 km
	Offered:	3000 km swath	3000 km swath	3000 km swath	3000 km swath
Temporal Coverage	Tactical requirement: Strategic requirement:	on demand 1-2 days	on demand 1-2 days	on demand on demand	on demand 3-6 hours
	Offered:	4 times per day[3]	4 times per day[3]	4 times per day[3]	4 times per day[3]
Positional Accuracy	Tactical requirement: Strategic requirement:	100-500 m 1-several km	500 m 2-4 km	100 m 500 m	500 m 2-4 km
	Offered:	1.1 to 2.5 km[4]	1.1 to 2.5 km[4]	1.1 to 2.5 km[4]	1.1 to 2.5 km[4]
Resolution or Size	Tactical requirement: Strategic requirement:	1,000 t 10,000 t	± 1-tenth ± 1-tenth	1,000 t 10,000 t	± 1-tenth ± 1-tenth
	Offered:	N/A[1]	± 1-tenth	N/A[1]	± 1-tenth

Notes:

1) AVHRR resolution of 1.1 km at nadir, 2.5 km at swath edge, would detect only the very largest icebergs (>10,000,000 t).

2) Areas of old, young, and new ice can be identified from system grey scale by an experienced interpreter

3) Normal two satellite system with each spacecraft imaging on at least two relevant orbits per day. Wide swath and high latitude convergence of orbits will put a location of interest in more than 4 images per day; however, imager quality can be affected by cloud and fog.

4) Resolution of system. Wide image swath will include land control points.

4.5.3.6 Satellite Pour l'Observation de la Terre *(SPOT)*

Technical Description: Launched by the French into polar orbit on 26 February 1986, the Système Probatoire Pour l'Observation de la Terre *(SPOT)* satellite carries two identical high resolution visual (HRV) scanners with resolutions of 10 m and 20 m, for panchromatic and multispectral modes, respectively. The sensors require clear weather and daylight, have a 60-km swath width, and collect data between 84° latitude, north and south. Repeat coverage of a point on the earth is 26 days, however, the sensors can be adjusted up to 27° inclination from nadir, to permit coverage of a point on adjacent orbits. The sensor uses charge coupled diode (CCD) pushbroom technology. The satellite's forward motion builds up a sequence of image scan lines sensed by a CCD across-track, pushbroom array. The satellite can store 23 minutes of data for each HRV scanner, the data being transmitted to earth when the satellite is in line-of-sight of a ground receiving station. See Table 4.29 for relevant ice detection capabilities of the *SPOT*. Table 4.30 summarizes the relevant technical aspects of the three satellite optical sensing systems considered.

Experience Base: The *SPOT* data have not been used for operational purposes for reasons similar to those limiting such use of LANDSAT data. The satellite's orbit schedule, requirement for cloud-free conditions, slow product turnaround due to data processing time and logistics, and cost render it unsuitable for "on demand" operational priorities.

The use of *SPOT* data in a recent research project (Canatec, 1992) proved the data to be very useful for the interpretation of extreme ice features, which required analysis of ice surface features. Ice type could be identified in floes greater than about 200 to 300 m across, although smaller floes or features could be identified.

Potential to Satisfy User Needs: The *SPOT* sensors are unlikely to serve as first-level, regular ice data providers due to the limitations stated above. The excellent resolution of the images and the predictability of satellite overpass, however, give the HRV scanners potential as data sources of opportunity. If made available to offshore users in a timely fashion, HRV imagery could respond to strategic level needs for data on sea-ice concentration and presence of small (and larger) icebergs. The images would require interpretation and reference to other data sources in order to definitively distinguish sea-ice floes from icebergs.

Operational Application: The regular orbit pattern of the *SPOT* satellite permits advance planning and ordering of images, on the likelihood that reasonably cloud-free conditions will prevail. The image purchase policy does not oblige the user to purchase pre-ordered imagery which contains excessive cloud. Normal data delivery delay is on the order of 8 to 10 days. Development of a significant operational market on the East Coast could modify the data distributor's priorities so as to provide a 72-hour turnaround (Nazarenko, 1994). Same-day delivery capability will require establishment of a direct data link between ground receiving station and processing facility as well as the establishment of an on-line product delivery service.

Cost: Estimate $1,500 to $3,500 per scene.

Table 4.29: *SPOT* high resolution visual application to user-defined medium and high priority needs

SENSOR:	***SPOT*: HRV scanners**	Field Development (icebergs)	Field Development (sea ice)	Vessel Transits (icebergs)	Vessel Transits (sea ice)
Sensor Relevance	Iceberg occurrence	Yes[1]		Yes[1]	
	Iceberg position	Yes[1]		Yes[1]	
	Iceberg draft	No		No	
	Sea-ice edge		Yes		Yes
	Sea-ice concentration		Yes		Yes
	Sea-ice position & extent		Yes		Yes
	Sea-ice type		Yes[2]		Yes[2]
Spatial Coverage	Tactical requirement:	0-40 km	0-40 km	0-5 km	0-10 km
	Strategic requirement:	40-200 km	40-200 km	5-30 km	10-50 km
	Offered:	60 km swath	60 km swath	60 km swath	60 km swath
Temporal Coverage	Tactical requirement:	on demand	on demand	on demand	on demand
	Strategic requirement:	1-2 days	1-2 days	on demand	3-6 hours
	Offered:	Every 26 days[3]	Every 26 days[3]	Every 26 days[3]	Every 26 days[3]
Positional Accuracy	Tactical requirement:	100-500 m	500 m	100 m	500 m
	Strategic requirement:	1-several km	2-4 km	500 m	2-4 km
	Offered:	100 m[4]	100 m[4]	100 m[4]	100 m[4]
Resolution or Size	Tactical requirement:	1,000 t	± 1-tenth	1,000 t	± 1-tenth
	Strategic requirement:	10,000 t	± 1-tenth	10,000 t	± 1-tenth
	Offered:	>10,000 t[1]	± 1-tenth	> 10,000 t[1]	± 1-tenth

Notes:

1. Resolution of sensors is 10 m. Small icebergs should be identifiable although not necessarily distinguishable from small ice floes.
2. Ice type can be inferred from ice tone and texture and shape of floes.
3. The sensors can be inclined to allow them to capture the same location on consecutive passes.
4. Positional accuracy depends on positional accuracy of satellite which is about 100 m if a land reference is available; otherwise 250 m for the far offshore (Massom, 1991).

Table 4.30: Comparison of current spaceborne optical scanning systems

Parameter	***LANDSAT*TM**	***NOAA* AVHRR**	***SPOT* HRV**
Satellites	*LANDSAT-5*	*NOAA -9, -10, -12*	*SPOT -1* and *-2*
Scan mechanism	mechanical	mechanical	electronic
Resolution	30 m visible 120 m TIR	1.1 to 2.5 km	10 and 20 m
Swath width	185 km	2,580 km	60 km
Sensitivity	VIS & near-IR	VIS/near-IR/IR/ TIR	VIS/near-IR
Data availability	3 passes then 13 day gap	4 passes per day on 2-satellite system	26-day revisit schedule; steerable sensor can produce 2 images in 26 days
Data delivery	pre-order; delivery if cloud-free; long turnaround	offshore file download from ground station	pre-order; delivery if cloud-free; long turnaround
Data output	hard & soft copy	hard & soft copy	hard & soft copy
On demand	no	no, but frequent imagery	no
Daytime	yes	yes	yes
Night time	yes	yes	no
Fog and cloud cover	no	no	no

4.6 OTHER SENSORS

4.6.1 Ice Probe

Technical Description: A multisensor ice thickness measurement system, Ice Probe, is offered by Aerodat Limited and Canpolar Inc. (Haykin et al., 1994, Chapter 4). Its unique ability lies in the remote measurement of the thickness of relatively level sea ice. A sensor pod, or bird, is slung from a helicopter and flown 25 to 30 m above the ice/snow surface (Figure 4.6). The system comprises of three elements: a multifrequency electromagnetic (EM) sounding system and a laser profilometer mounted in the towed bird, and a downlooking video camera in the helicopter. The laser profilometer measures sensor height above the snow/ice surface and the EM sensor measures the sensor height above the water surface from the induced EM field. The difference between the two measurements represents the combined ice plus snow thickness. The system also gives an approximate estimate of ice strength, based on the conductivity (and hence salinity) of the ice.

Experience Base: The system has undergone successful field testing in the Arctic, Gulf of St. Lawrence, and off Newfoundland. Table 4.31 was compiled on the basis of these field test results.

Potential to Satisfy User Need: Although ice thickness is low-medium priority in the region, this sensor appears able to meet the needs for transit support. The system provides ice thickness directly below the helicopter only, but can be used to calibrate SAR, SLAR, or other imagery. Results are available in quick-look form in real-time.

Operational Application: Needs a helicopter.

Cost: System price is approximately $250,000. Operations can be performed for approximately to $2,000 per day, plus helicopter costs.

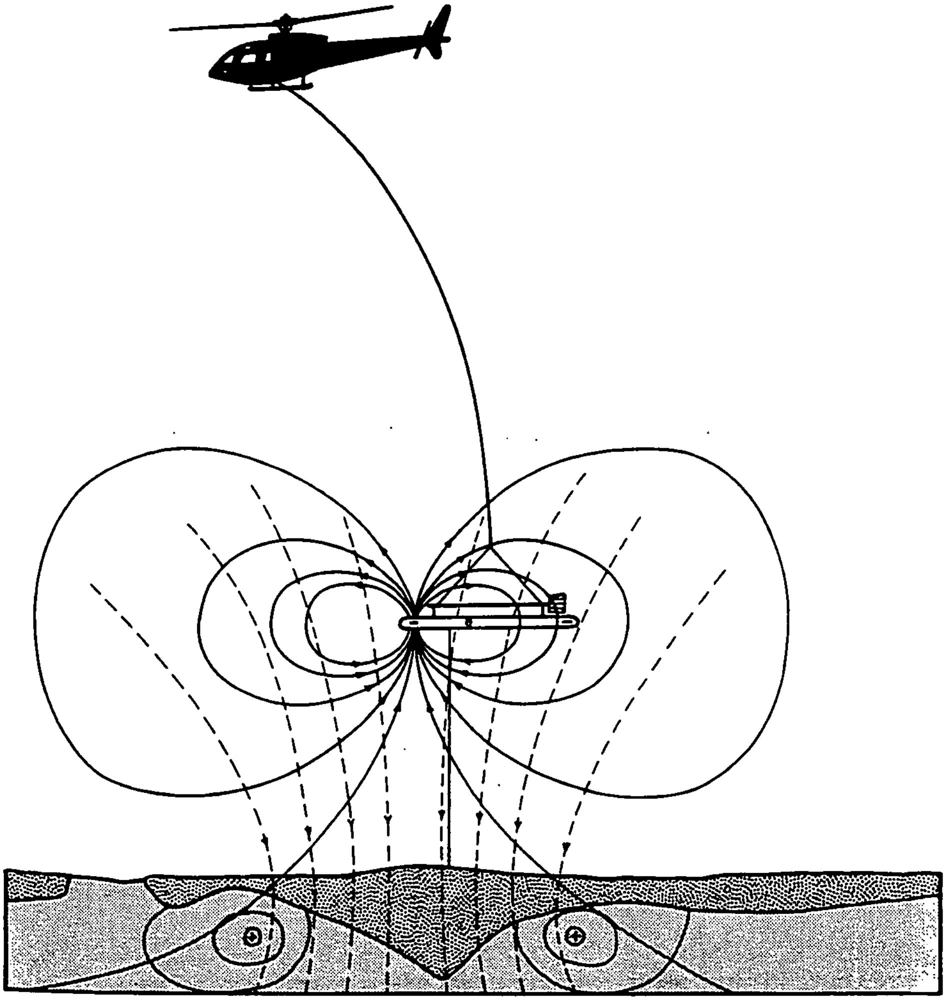

Figure 4.6 Ice probe mode of operation

Table 4.31: Ice probe application to user-defined medium and high priority needs

SENSOR:	**Ice Probe**	Field Development (icebergs)	Field Development (sea ice)	Vessel Transits (icebergs)	Vessel Transits (sea ice)
Sensor Relevance	Iceberg occurrence	NO		NO	
	Iceberg position	NO		NO	
	Iceberg draft	NO[1]		NO[1]	
	Sea-ice edge		NO		NO
	Sea-ice concentration		NO		NO
	Sea-ice position & extent		NO		NO
	Sea-ice type		YES[1]		YES[1]
Spatial Coverage	Tactical requirement:	0-40 km	0-40 km	0-5 km	0-10 km
	Strategic requirement:	40-200 km	40-200 km	5-30 km	10-50 km
	Offered:	N/A	helicopter range	N/A	helicopter range
Temporal Coverage	Tactical requirement:	on demand	on demand	on demand	on demand
	Strategic requirement:	1-2 days	1-2 days	on demand	3-6 hours
	Offered:	N/A	on demand	N/A	on demand
Positional Accuracy	Tactical requirement:	100-500 m	500 m	100 m	500 m
	Strategic requirement:	1-several km	2-4 km	500 m	2-4 km
	Offered:	N/A	100 m[2]	N/A	100 m[2]
Resolution or Size	Tactical requirement:	1,000 t	± 1-tenth	1,000 t	± 1-tenth
	Strategic requirement:	10,000 t	± 1-tenth	10,000 t	± 1-tenth
	Offered:	N/A[3]	N/A[3]	N/A[3]	N/A[3]

Notes:

1. Sensor is specialized for measurement of sea-ice thickness, which is a low-medium priority concern (see Chapter 3). Might be able to measure thickness of tabular icebergs. Can estimate ice strength.

2. Figure represents GPS accuracy of sensor helicopter.

3. Offers 0.1 m thickness measurement accuracy over relatively level ice.

4.6.2 Underwater Electromagnetic Sensors

Relatively low frequency EM waves (less than a few hundred Hz) can propagate several hundred meters in sea water. An EM system was built in the late 1980s and based on its performance, its ability to detect icebergs was evaluated (Canpolar Consultants Ltd., 1985). Although EM systems appear feasible, they do not appear to offer significant price or performance advantages over existing technologies. Also, EM systems to not appear to be able to provide any of the user required information, except possibly for indicating the presence of ice.

4.6.3 Laser Profilometer

A laser profilometer is part of the Ice Probe package to indicate the height of the helicopter and the ice surface profile. However, a laser can be operated alone to indicate the surface profile of the ice which can be used to measure ice surface topography. This device indicates only the ice surface profile along the line directly below the helicopter. The sensor has been used extensively in the Arctic to estimate ridge statistics, but has limited application to the East Coast.

5.0 EVALUATION OF TECHNOLOGY PERFORMANCE

This chapter examines the major sensing technologies in more detail: radar, acoustic and optical/visible. The current state-of-the-art of each technology is reviewed by a specialist in the field and an outlook for the future is described. The goal is to give the reader a sense of how each of these generic sensor types could contribute to an ice detection system which might combine several sensors. A summary of current marine two-way communications networks and planned networks is also provided.

5.1 RADAR SENSORS

Radar will be used as a primary surveillance tool in support of iceberg management operations for oil production off Canada's East Coast. Radar performance is influenced by a variety of factors that include iceberg size, ocean wave height, wind speed, and meteorological conditions. In general, it has been found that X-band (10 GHz) and S-band (3 GHz) radars are complementary in their ability to detect icebergs with X band normally providing longer detection ranges and S band providing better performance in sea clutter and adverse weather conditions. The radar return from the ocean, sea clutter, is one of the major limitations on the ability of radar to detect icebergs. Under calm sea conditions standard marine radars can detect icebergs as small as growler size. In normal vessel and platform mounted configurations fog does not pose a problem for detection at S band, however, X band will be adversely affected by rain and heavy fog. S band provides good penetration through moderate rain (4 mm/h), however, its performance will affected by heavy rain (16 mm/h).

5.1.1 Background

A number of factors combine to make iceberg detection using radar one of the more challenging problems in the field of radar. Objects having high conductivity such as metal ships are very good reflectors of radio waves and therefore make good radar targets. On the other hand, objects with low conductivity such as wooden boats, rubber life rafts, and icebergs are all very poor reflectors of radar signals. Shape and surface conditions are also important in determining the strength of signal reflected from a target. The unique nature of icebergs results in a wide range of detection performance, even among icebergs with similar above-water physical dimensions. Steep-faced blocky icebergs tend to give stronger reflections than smoother dome- shaped icebergs. Table 5.1 provides the standard iceberg classifications and their size ranges.

Table 5.1 Iceberg size classification (WMO standard)

Size	Height (m)		Length (m)	
	Tabular	Other shapes	Tabular	Other shapes
Growler		<1		<6
Bergy bit		1-5		6-20
Small	<6	5-15	<90	20-60
Medium	6-15	15-45	90-120	60-120
Large	>15	45-75	>120	120-210
Very large		>75		>210

The size of a target as seen by a radar is referred to as the target radar cross-section, σ (sigma), which has units of area. The radar cross-section is useful for comparing different types of targets. Table 5.2 provides a comparison of radar cross-sections of several ice, ship and search and rescue targets. It may be seen from this table that iceberg targets have quite small radar cross-sections compared to a supply boat. A manned rubber life raft will have a radar cross-section comparable to a growler/bergy bit sized iceberg. The radar cross-section of an iceberg is proportional to its exposed area (above the water line). Research has indicated that the ratio of radar cross-section to iceberg area can vary from 0.10 to 0.01, depending on the iceberg shape and condition.

Table 5.2 Typical radar cross-sections for various targets

Target	Radar Cross-section (m^2)	Projected Area (m^2)
Growler	0.01 - 0.10	2
Bergy bit	0.5 - 1.0	60
Small iceberg	5 - 10	400
Supply vessel	150	400
Liferaft (4 person)	0.25 - 0.50	3
Steel sphere (1.13 m diameter)	1	1

The detection problem is compounded by the necessity of detecting these weak radar targets in a background signal from the ocean itself, sea clutter. The ocean, composed of electrically conductive brine, may provide stronger radar reflections than an iceberg which is composed of salt-free glacial ice. Reflections from the ocean increase with increasing wind speed and wave height making detection more difficult.

Research on icebergs has been ongoing for the past 70 to 80 years, having been instigated after the sinking of the Titanic in 1912, predating the development of radar. Subsequent to the loss of the Titanic, the IIP was established to monitor iceberg movement in the North Atlantic in efforts to avoid future accidents. After the Second World War, research turned to investigations concerning the use of radar for iceberg detection, and the United States Coast Guard and others undertook a number of studies dating from 1945. In the 1970s concern for the safety of oil exploration platforms spurred new interest in the use of radar for ice detection. Microwave radar became a valuable tool for iceberg management. Unfortunately, operational experience indicated that radars did not always perform up to expectation and under certain environmental conditions could not reliably detect the smaller icebergs.

With the discovery of Hibernia and other significant oil reserves, the shift towards production systems became of concern and the quest for definitive answers concerning the iceberg detection capability of radar was undertaken. Several were undertaken from 1984 to 1987 to investigate the performance capabilities of marine and airborne radar. These studies had two main objectives. The first was to establish the operational capabilities of specific radars under the available test conditions and the second was to acquire radar data on icebergs and ocean to aid radar model development. A modeling capability would permit the prediction of radar performance for situations that were not encountered during the field experiments. Research has been undertaken by other groups, such as McMaster University and Swedish National Defense Research Institute, on the use of radar for ice type discrimination and iceberg detection. The following sections summarize pertinent aspects of this research.

5.1.1.1 Marine radar studies

In the winter of 1984, a field program was undertaken on board the *SEDCO 706* semi-submersible drilling platform (Ryan et al., 1985). During this program, digital radar data was collected on icebergs and sea clutter using X- and S-band marine radars. This program was extended into 1985 with a ship mounted radar experiment using the MV *Polar Circle*. These two programs saw the collection of data on about 50 icebergs ranging in size from growler to large.

The marine radar trials used probably one of the more advanced marine radars available at the time. The unit consisted of a dual X-/S-band system in which the X-band antenna is mounted directly on top of the S-band antenna. This mounting configuration permitted the synchronization of data from both radars and subsequent combining of their signals at the display. In 1984 this radar system (Racal-Decca 2459 F/I) was in operational use on the *SEDCO 706*. The antenna and X- and S-band transceiver units were mounted on the derrick top at a height of 75 m. This height gives a radar horizon of about 36 km (19 nautical miles). These two radars were instrumented with separate X- and S-band units mounted close to deck level. Data were collected on 12 icebergs during April and May. The major findings in this study were:

a. The derrick-mounted S-band radar outperformed all other radars. The poor performance of the deck units was attributed to the lack of recent maintenance and excessively long waveguide runs. The X-band, derrick-mounted radar did not perform as well as expected and its low noise front end was suspected as cause. This defect was confirmed in tests after the field trials.

b. Propagation conditions were identified as having an influence on detection ranges of the larger icebergs. Most of the data obtained during this experiment were from medium icebergs. During enhanced propagation conditions (ducting) medium icebergs were detected in the 31 - 37 km (17 - 20 nautical miles) range. During normal and foggy conditions detection ranges for medium icebergs were in the range of 26 - 31 km (14 - 17 nautical miles).

c. Automatic Radar Plotting Aid (ARPA) units do not provide very good performance in clutter-limited detection and tracking.

d. Ongoing maintenance and performance monitoring should be an integral component of radar operations.

In 1985 another field program was undertaken with the intention of collecting data on smaller icebergs in high sea conditions (Ryan, 1991). The Racal-Decca radar used in the rig-based experiment was installed on the MV *Polar Circle* at a height of 15 m, giving a radar horizon of 16 km (8.6 nautical miles). A lower power, X-band marine radar was situated about 5 m above the installed radar. Data were collected over a one month-period on 38 icebergs and numerous other sea-ice targets. The major conclusions of this study were:

a. S-band radar was preferred for operational detection of icebergs in sea clutter although quantitatively there was not a significant difference in measured signal-to-clutter ratio between X and S bands.

b. Very little difference between X and S band for maximum detection range was observed, however, the X-band ranges tended to be slightly greater. The X-band radar mounted at 20-m height normally had the maximum detection range.

c. Detection ranges for small icebergs varied from 9 - 13 km (5 to 7 nautical miles) with the average detection range of 11 km (6 nautical miles) and average size 9 m high by 40 m across.

d. Detection ranges for medium icebergs varied from 12 - 25 km (6.4 to 13.3 nautical miles) with an average of 16 km (10 nautical miles). Average iceberg size was 26 m high and 100 m across. Detection is, usually, horizon-limited.

e. Signal processing can improve detectability of smaller iceberg targets significantly in sea clutter.

Analysis of data from these experiments clearly identified uniform weight scan-to-scan averaging as a powerful signal processing technique for improving iceberg detection in sea clutter.

5.1.1.2 Search radar studies

In 1985, Mobil Oil sponsored a one-week experimental study to investigate the suitability of airborne search radar to detect icebergs (Currie & Haykin, 1985). The study was qualitative in nature; however, it did demonstrate the potential of search radar to detect icebergs and concluded that search radar would make a useful addition to an iceberg detection and management system.

In 1986, the first operational use of airborne search radar for iceberg surveillance began, using a low-resolution maritime surveillance radar, Litton Systems Ltd. APS-504(V)3 (Klein et al., 1987; Ryan, 1989). At that time the ESRF funded an evaluation program similar to marine radar studies conducted in 1984 and 1985. The second phase of this program was conducted in 1987, using a more advanced version of the search radar, the APS-504(V)5. During the search radar programs of 1986 and 1987 radar signal data was collected on 27 icebergs, ranging in size from growler to large.

The Litton APS-504(V)3 was designed for maritime surveillance with intended applications in ship detection and tracking. It is a conventional noncoherent pulsed radar having a short pulse of 0.5 μs and a transmitter peak power of 100 kW. In general, it was found that the (V)3 radar provided very good detection of medium icebergs and good detection of small icebergs in lower sea states. Detections of bergy bits and growlers were observed, however, this was during very calm conditions. Overall, the radar was found to be reliable; although, its poor performance in detecting smaller icebergs in sea clutter limits its usefulness for iceberg surveillance.

The Litton APS-504(V)5 is a more advanced version of the (V)3 and was designed for the detection of much smaller targets, such as submarine periscopes. Specifically, it was the objective of the (V)5 design to detect a 1-m^2 radar cross-section in a Sea State 3 (1.3-m significant wave height and 7.5 m/s or 15-knot wind). The radar uses pulse compression to achieve an effective pulse length of 0.03 μs and an effective peak transmitter power of 4000 kW. The (V)5 also has a longer pulse (0.2 μs) for use in maritime surveillance. The radar uses pulse-to-pulse frequency agility to help in the suppression of sea clutter returns. Some of the significant findings of the study were:

a. The (V)5 provided significantly better performance than the (V)3 with useful levels of detection of bergy bits and small icebergs, in the conditions encountered.

b. Best overall performance was achieved using the shortest pulse.

c. Detection of small icebergs reached 80% over the range of sea states encountered (up to about Sea State 5; 3-m wave height and 12 m/s (23 knot) wind for a line spacing of 37 km (20 nmi) using the short pulse and looking downwind. Performance was typically better for small icebergs using the longer pulse indicating that if small icebergs are of primary concern the longer pulse may be more appropriate.

Overall, the search radar was found to provide significant benefits in iceberg detection in an operational context. The low-altitude searching mode typical of small aircraft surveillance facilitates target verification and identification.

5.1.2 Radar Performance

A number of radar systems will be available for use in support of iceberg management. These systems include microwave marine radar, airborne search radar and potentially airborne imaging radar such as SAR (synthetic aperture radar). Standard marine radars available today do not provide adequate signal processing in the small target detection role and are therefore not optimized for the iceberg detection task (Ryan, 1985). However, recent advances in radar signal processing hardware have addressed this issue and add-on systems are now available that will enhance the capability of marine radar in the iceberg detection role. In the following review standard radars have been assumed for vessel and platform installations. This approach will provide baseline performance for these systems and makes extensive use of modelling work carried out for Petro-Canada (C-CORE, 1992). A discussion is provided on the capabilities of advanced signal processing hardware and expected performance improvements. The APS-504(V)5 has been used for offshore iceberg surveillance since 1987 and its performance was evaluated during 1987 in this role. Predicted performance on the APS-504(V)5 is provided against various icebergs.

5.1.2.1 Radar horizon

Microwave radar has a limited maximum detection range due to the earth's horizon. This horizon will limit detection of the larger icebergs in most cases. The radar capabilities will normally limit the detection of the smaller targets to ranges less than the radar horizon. Figure 5.1 depicts the radar horizon as a function of antenna height. The radar horizon for various platform heights are given on the figure. For example, a derrick mounted antenna atop the Hibernia GBS will have a 48 km (26 nmi) radar horizon as compared to a radar horizon of 17 km (9 nmi) for a support vessel. The radar horizon in nautical miles is the square root of five times the antenna height in meters. Aircraft mounted radar can have greater radar horizon depending on the flying altitude. The APS-504(V)5 has been found effective at altitudes of 150 to 450 meters depending on the iceberg targets of interest giving radar horizons in the 50-87 km (27 to 47 nmi) range (Klein et al., 1987).

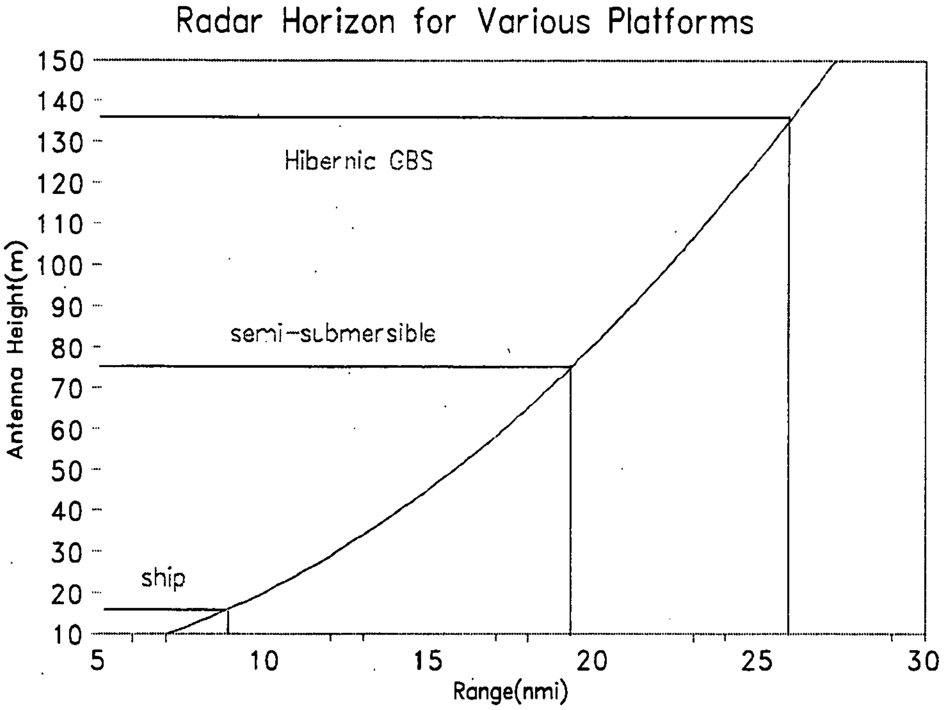

Figure 5.1 Radar horizon versus antenna height for various platforms

5.1.2.2 Radar parameters

The radar parameters have a significant effect on radar performance. The importance of these parameters may be considered in terms of the operational situation. If the sea is calm and air is clear target detection will be limited by system noise and the important radar parameters are summarized below with typical values:

Transmitter Power:	25 to 60 kW
Antenna Gain:	28 to 33 dB
Receiver Noise Figure:	5 to 10 dB
Receiver Bandwidth	2.5 to 20 MHz
System Losses:	2 to 4 dB

For a given radar frequency, increasing detection range for a given target may be accomplished by increasing the transmitter peak power and/or antenna gain. Increasing antenna gain normally requires increasing the antenna physical size. The maximum detection range may also be increased by improving the sensitivity of the radar. This may be accomplished by reducing the receiver noise figure and receiver bandwidth. Most advanced radars closely match the receiver bandwidth with the radar pulse length in a reciprocal relationship. That is, longer pulse lengths use smaller receiver bandwidths. This is why all radars use their longest pulse lengths on their greater range scales.

The other situation of interest occurs when the detection is limited by clutter from rain or sea reflections. In this case the echo from the target must compete against echoes from surrounding sea or rain. In this case the important radar parameters are:

Radar Frequency:	X (9.5 GHz) and S (3 GHz) bands
Antenna Horizontal Beamwidth	0.5° to 2.5°
Antenna Vertical Beamwidth	10° to 25°
Radar Pulse Length	0.03 to 1.2 microseconds

The antenna horizontal beamwidth and the radar pulse length govern the area of sea illuminated by the radar pulse. By reducing these parameters it is possible to reduce sea clutter. Similarly, the vertical and horizontal beamwidths and pulse length control the volume of rain illuminated by the radar.

In these two situations there is one important compromise that must be recognized: it is not possible to choose a single set of values that maximizes both detection range and performance in clutter-limited detection. Radar manufacturers address this problem by offering various pulse lengths on a particular radar and assigning pulse lengths to appropriate sets of range scales. For example, the shortest pulse, which is best for detection of targets in sea clutter, is normally only available on ranges of 2.8 km (1.5 nmi) and less. Normal radar operations would require that the radar operator choose the appropriate range scale to ensure that optimum radar performance is achieved. Some recent radars offer the ability to alternate pulse lengths on a pulse-to-pulse basis permitting essentially optimum performance at all times. The Canadian Marconi CMR-91 is an example of this type of radar.

5.1.2.3 Radar performance

In the following a section review of basic radar system performance is provided for the cases of derrick mounted X- and S-band radars at a height of 75 m on a semisubmersible and a vessel mounted S-band radar. Examples of the effect of sea state, fog, rain, and wind direction on detection are provided. Appendix 2 provides a more comprehensive series of tables of detection range for various radar configurations.

Tables 5.3 and 5.4 provide a list of radar specifications and parameters that have been used for the analysis. Radar parameters such as pulse length have been selected as a compromise for vessel and platform radars as this pulse is normally used for medium range (22 km or 12 nmi) detection when sea clutter is present. Longer pulse lengths will tend to give greater detection ranges when detection is not horizon-limited. Similarly, shorter pulse lengths will provide better near range performance. Aircraft altitude has been set at 150 m (500 feet) as this altitude has been found to be most effective when searching for bergy bit size icebergs. If larger icebergs are of interest then higher altitudes, such as 450 m (1,500 feet), may be more appropriate.

Radar performance is normally given in terms of probability of detection versus range (for average sea state values). Figure 5.2 presents the modelling results for the platform mounted S-band radar and detection of three icebergs in 5-m seas. The icebergs are given in terms of their water line length. Table A 2.1 in Appendix 2 lists cases of radar performance provided in the Petro-Canada study (C-CORE, 1992) and the relationship between iceberg length and projected area. In interpreting these plots we use a detection criteria that is less than 100%. At 50% probability of detection the radar echo will be displayed on average half of the time, so that over 10 radar scans the target will appear in five scans. This criterion is normally taken as the absolute limit of detectability. In the iceberg detection analysis conducted for Petro-Canada a criteria of 67% was used. The target would show up on the radar screen on an average two out of three scans.

It should be noted that performance varies with range. Near-range detection is limited by sea clutter resulting, in this case, in a region from about 5 to 20 km where detection performance is degraded. Outside the clutter the larger target is detectable out to 28 km. In the case of the 40-m iceberg and a 67% detection criteria the target would not be detectable except for at very close range (less than 2 km). In the case of the 50-m iceberg the target would be detectable in the range interval from 0 to 8 km and from 17 to 28 km. If this target is to be detected, it is assumed that an appropriate radar watch schedule is implemented such that the target would be detected when it exceeds the threshold. For example, a target moving at 1 m/s (2 knots) would take about 50 minutes to travel from 28 to 25 km if the radar is stationary. Associated with these plots is a false alarm time. This is the average time between false alarms caused by either noise or sea clutter and in this case has been chosen to be 6 hours.

Table 5.3 Marine radar specifications

	X band	**S band**
Frequency (GHz)	9.5	3.0
Transmitter power (kW)	50	30
Receiver noise figure (dB)	5	5
Receiver bandwidth (MHz)	4	4
Pulse length (ns)	250	250
Range resolution (m)	37.5	37.5
Pulse repetition frequency (Hz)	1600	1600
Antenna gain (dB)	32	27
Horizontal beamwidth (degrees)	0.8	2.0
Antenna speed (rpm)	30	30
Antenna height (m)	75	75 and 15[1]
Signal processing :		
Pulse-to-pulse integration	Yes	Yes
Scan-to-scan integration	No	No
Typical clutter controls such as Sensitivity Time Control (STC)[2]	Yes	Yes

Notes:

1. Antenna height is 75 m for platform mounted radar and 15 m for support vessel radar.
2. Sensitivity Time Control (STC) is used by the operator to remove background clutter that is range dependent.

Table 5.4 Litton APS-504 (V)5 search radar specifications

	X band
Frequency (GHz)	8.9 - 9.4
Transmitter peak power (kW)	8
Receiver noise Figure (dB)	5
Receiver Bandwidth (MHz)	50
Pulse length (ns):	
Uncompressed	10,000
Compressed	30
Range Resolution (m)	4.5
Pulse repetition frequency (Hz)	1,350
Antenna gain (dB)	32
Horizontal beamwidth (degrees)	2.3
Antenna Speed (rpm)	30
Antenna height (m)	152
Signal Processing:	
Pulse-to-pulse integration	Yes
Scan-to-scan integration	Yes
Clutter controls	Cell averaging CFAR[1] STC[2]

Notes:

1. Constant false alarm rate.
2. Sensitivity Time Control is used by the operator to remove background clutter that is range dependent.

Probability of detection, such as that in Figure 5.2, might also be used to compute a cumulative probability that an iceberg would be detected by the time it reaches a specific range.

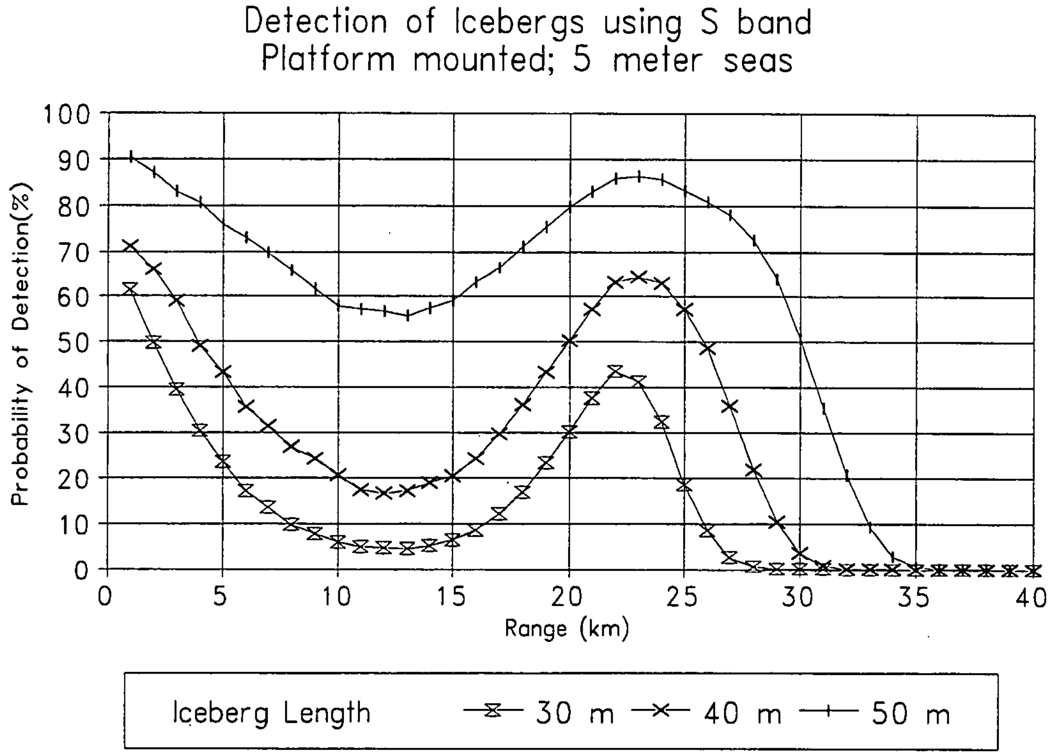

Figure 5.2 Probability of detection for three icebergs in 5-m seas, using platform-mounted, S-band radar

Figure 5.3 provides an example on the effect of rain on S-band radar performance. It may be seen from the figure that moderate rain (4 mm/h) has little effect on performance, whereas heavy rain (16 mm/h) will cause loss of performance at longer ranges. Note that even during heavy rain, performance is not severely degraded at near range and this iceberg would be detectable at 6 km.

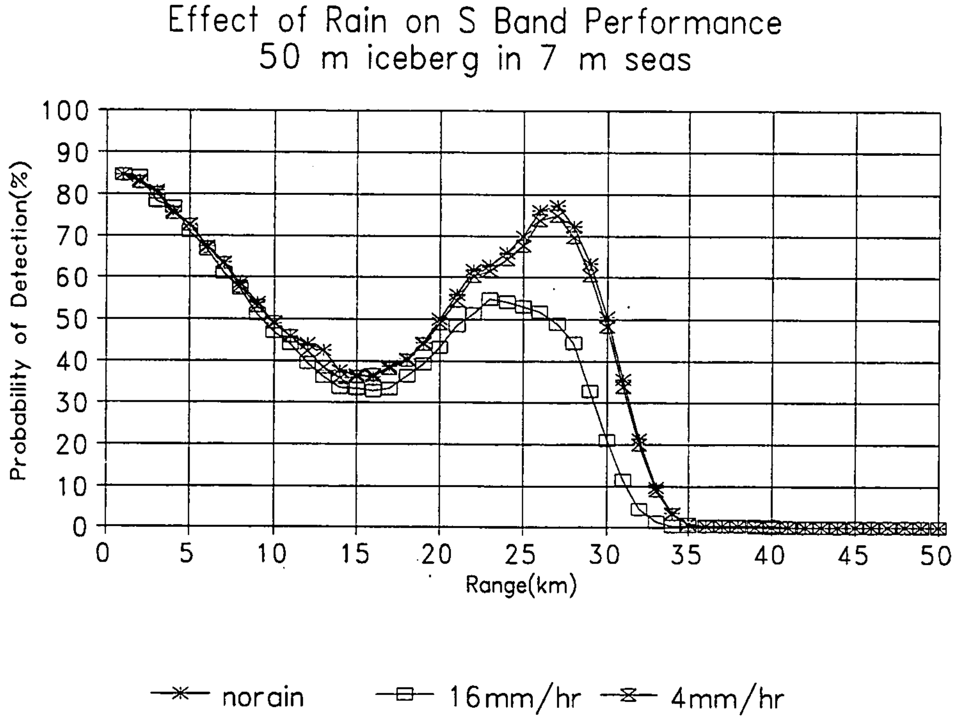

Figure 5.3 Effect of rain on platform-mounted, S-band radar performance, for a 50-m iceberg in 7-m seas.

Figure 5.4 provides an example of how fog may affect the performance of a platform mounted X-band radar. In fog, with 100-m visibility, the maximum detection range will be reduced. This may cause a problem for detection in heavy seas when near range detection is limited by sea clutter.

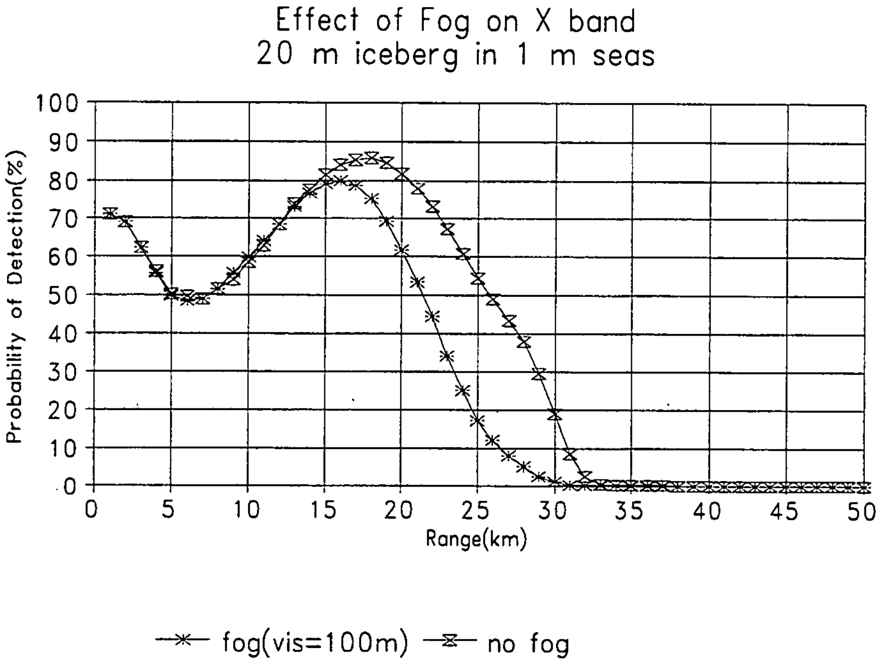

Figure 5.4 Effect of fog on platform-mounted, X-band radar performance, for a 20-m iceberg in 1-m seas.

Figure 5.5 provides an illustration of the effect of wind direction on detection. If the iceberg is approaching the radar from the downwind direction it will be detectable at all ranges out to 29 km, however, performance for the upwind case is not nearly as good with worst detection at around 15 km.

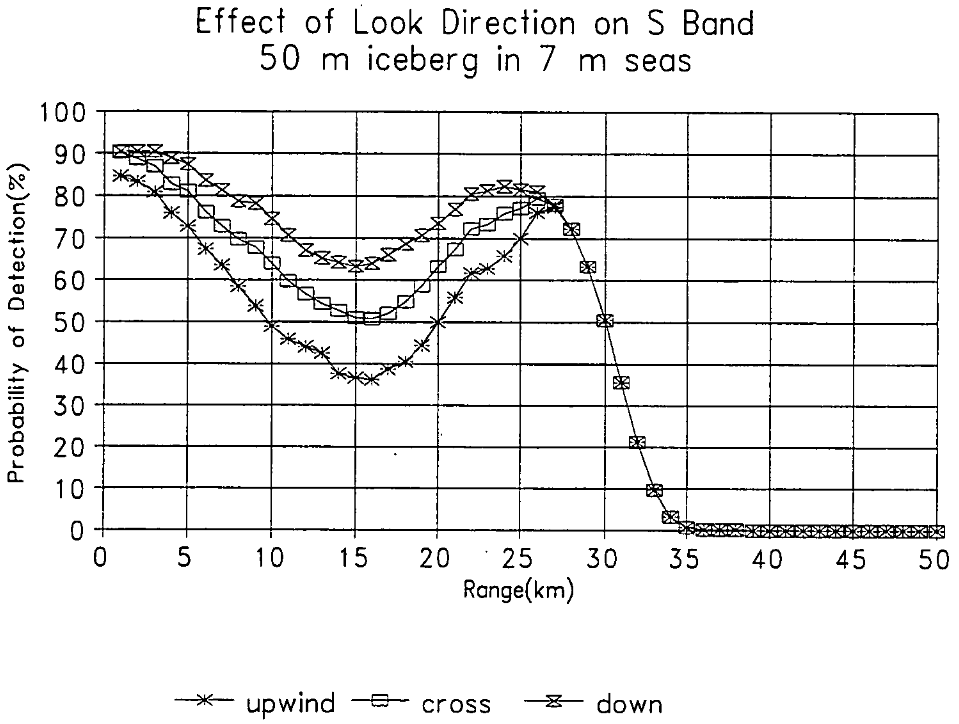

Figure 5.5 Effect of look direction with respect to wind on S-band radar performance, for a 50-m iceberg in 7-m seas.

5.1.3 Enhanced Marine Radar

It has long been recognized that radar signal processing can significantly improve the detection of targets in clutter and much research has been conducted on various algorithms for this purpose; however, the processing power required to implement these algorithms in a real-time environment was considered too expensive for marine radar implementation. Recent and continuing advances in processor technology has now made it possible to implement proven radar signal processing algorithms cost effectively.

Over the years, it has been identified that there are three main areas where radar signal processing can be beneficial. These include pulse-to-pulse processing to improve target detection in noise, scan-to-scan processing to improve target detection in sea clutter, and constant false alarm rate (CFAR) processing to present the operator with a radar display that has the same characteristics at all ranges.

5.1.3.1 Pulse-to-pulse processing

Marcum (1963) and Swerling (1960) discussed the uniform weight integrator to improve the detectability of signals in noise. This work has been the basis of much radar analysis and is still used for the assessment of radar performance when pulse-to-pulse integration is used. The earliest form of pulse-to-pulse processing occurred in the phosphor of the analogue radar display (PPI). As successive pulses of data were written to the display, the overlap caused an integration in the phosphor. Various versions of pulse-to-pulse integrators have been implemented in recent years. With the use of digital technology it became possible to store successive radar pulses and use digital filtering techniques to achieve the desired result. The optimum pulse-to-pulse integrator would multiply each incoming pulse with a weight based on the antenna horizontal beam pattern. It has been shown that the two-pole digital filter achieves near optimum performance with reduced complexity in implementation.

5.1.3.2 Scan-to-scan processing

Croney (1966) demonstrated one of the most powerful techniques for improving target detection in sea clutter to be scan-to-scan processing. In experiments using photographic techniques, Croney showed that when radar sea clutter is integrated or averaged over successive radar scans the sea clutter becomes very smooth making it much easier to identify targets. This occurs because the sea clutter changes considerably from scan to scan, so that when the sea clutter is averaged much of its spikiness or fluctuation is removed. The target's fluctuations are also smoothed. In recent implementations of digital scan-to-scan processors most use the exponential weight integrator, scan-to-scan correlation techniques (or "M of N detection") processing. Radar sea clutter is often very spiky in nature, especially for short-pulse radar operation and high-resolution radars. The uniform weight integrator is less susceptible to spiky clutter than other scan-to-scan processing techniques, especially the exponential weight integrator. The exponential weight integrator is often used as it requires only storage of one scan radar data. The uniform weight integrator, on the other hand, requires the storage of all the scans to be integrated.

5.1.3.3 CFAR and display

When target detection is of primary concern, a CFAR processor may be used to remove the clutter background level from the data prior to display. This mode is ideally suited to the small target detection scenario. CFAR techniques have been proposed as early as 1956 (Croney) using analogue filtering techniques to remove the clutter. These early techniques were effective under certain circumstances for low resolution radars, however, for small targets in spiky sea clutter these techniques do not work very well. The most common approach to CFAR used today in advanced radar signal processors is to compute an estimate of the clutter background using a moving window passing over the radar signal in range. Many techniques for computing the estimate have been proposed including the average of the data contained in the window.

In recent years a lot of attention has been paid to the ordered statistic (OS) CFAR (Rholing, 1983). The OS CFAR estimates the clutter level by sorting all the samples in the range window and choosing a particular rank as the estimate. If, for example, there are 31 samples in the range window and we use the 16th entry after sorting, them the estimate will be the median of the data in the window. This technique is very powerful as the estimate will not be biased high by clutter spike or multiple targets. The problem with OS CFAR is that the processing requirements are very high, however, recent advances in signal processors have made it possible to implement OS CFAR in software.

5.1.3.4 TITAN processor

TITAN Radar International Inc., of Dartmouth, Nova Scotia, has developed a radar signal processor that is capable of improving standard marine radar performance (Ryan et al., 1994). The TITAN processor is comprised of a two card set built to the form factor of the IBM PC AT. All radar signal processing and radar interfacing circuitry are located on these cards. The host processor is a 80486 DX2 66 or higher and is used for processor and display control. The graphics display subsystem is based on the Ultra VGA resolution of 1280 x 1024 and a VESA or PCI local bus graphics card for high speed display updates. The host processor also provides the user interface control and auxiliary data input. Typical radar display functionality is provided. The unit may be configured to control the radar system via a serial port if this option is available on the radar. The TITAN processor allows pulse-to-pulse and/or standardized scan-to-scan processing.

The emphasis in the design of the TITAN processor is to enhance target signal-to-clutter ration prior to detection. This approach leaves any thresholding to the very last step prior to display. The processor is designed to maintain 8 bits of radar signal resolution throughout the signal processing chain, even to the point of display, if desired. In some applications it is advantageous to maintain full signal dynamic range to the display. In this mode the TITAN processor provides processed data with 8-bit amplitude resolution to the host processor and the data is displayed in grey scale on the system display. This mode is very useful for ice navigation and navigation in coastal waters. When navigation is in ice, the grey scale information enhances the operator's ability to discern open leads, icebergs and ridges.

The benefit of the TITAN processor may be illustrated by example. Figure 5.6 presents the predicted performance of an S-band, platform-mounted radar for a 30-m iceberg in a 5 m sea. The detection performance of the standard radar without processing is quite poor. Using the TITAN processing with 16 scans averaged dramatically improves the situation with detection rising to 100% out to a range of 26 km.

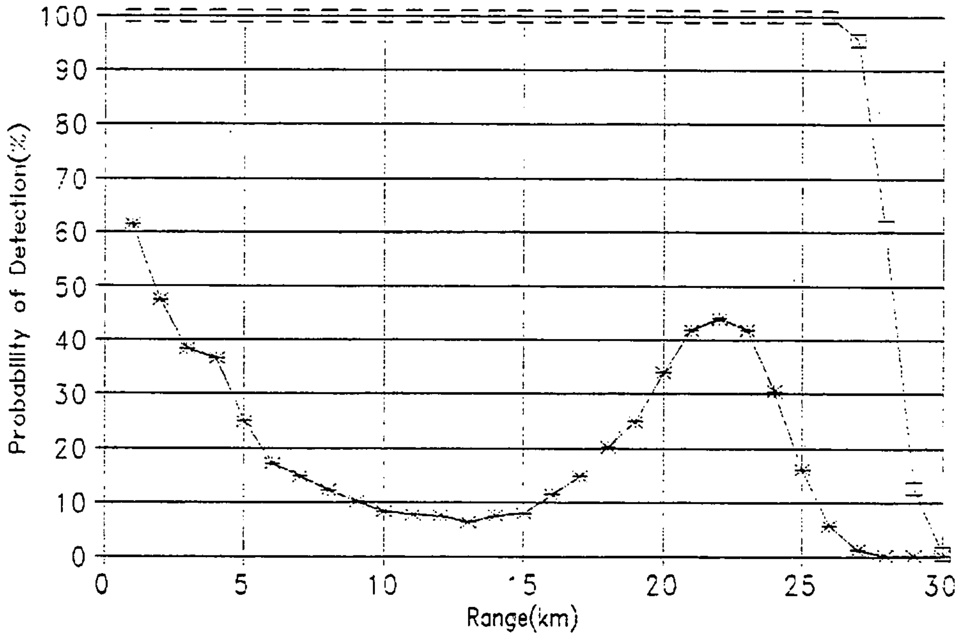

Figure 5.6 Effect of radar signal processing on iceberg detection. Standard radar versus TITAN processor with 16 scans averaged. Radar as given in Table 5.3

In this case, the TITAN processor processes the radar signal over 16 radar scans or about 32 s. An iceberg moving at 0.5 m/s (1 knot) will travel 16 m in this period. The radar range resolution in this case is 37.5 meters so that the target remains well within the range resolution cell of the radar during the processing.

5.1.4 New Radar Technologies

5.1.4.1 Coherent radar

Since the early 1980s the Communications Research Laboratory (CRL) of McMaster University has been involved in experimental work investigating the ability of radar to discriminate ice types (Haykin et al., 1994, Chapter 9). A significant amount of their research was conducted in the Arctic where it is desirable, for navigation purposes, to discern the difference between older, harder multiyear ice, icebergs, and softer first-year ice. Through a series of experiments CRL selected a set of desirable parameters for an instrumentation-quality research radar. This radar, named IPIX, was first used for experimental data collection in 1988 at Cape Bonavista, Newfoundland. The IPIX radar had a number of features presently not available in standard marine radar. The two significant features are:

a. Dual polarization benefits ice discrimination.

b. Coherence permits analysis or processing of data from a Doppler spectrum point of view. This feature shows the most promise in the application of iceberg detection.

The coherent Doppler processing capability of the IPIX radar is very similar to the prototype, operational radar developed by the Swedish National Defense Research Institute, ICERAD, and reported by Larsson et al. (1987). ICERAD was abandoned due to a lack of civilian funding and a shift of emphasis to other targets of military interest. Very little quantitative data is available on the performance of ICERAD in the detection of icebergs, or on development plans.

CRL has conducted shore-based tests of the IPIX radar at Cape Bonavista, Newfoundland and has demonstrated successful detection of iceberg targets in moderate sea conditions.

5.1.4.2 Neural networks

At present there are two development projects being carried out with respect to the use of neural networks for target detection and tracking. McMaster University is presently investigation the use of the neural network as a better predictive filter for sea clutter making use of the chaotic behaviour of the sea clutter signal (Haykin et al., 1994, Chapter 9). The initial objective of this work is to provide better detection and tracking for vessel traffic radar systems.

Sigma Engineering Limited and the Canadian Centre for Marine Communications have completed a "proof of concept" phase for a neural network-based target detection system. The objective of this work is to provide improved detection performance over that available from conventional non-coherent signal processing techniques. The results of the first phase were favourable and a second phase has commenced that will see the development of a prototype unit for field testing. It is expected that the neural network processor would be complementary to a TITAN type radar signal processor.

5.1.5 Conclusion

A significant amount of research has been undertaken on the use of radar for iceberg detection. This research has identified the fundamental capabilities of existing radar and provided important measurements on the radar characteristics of icebergs and ocean. This knowledge has been used to develop a comprehensive radar performance prediction model that may be used to evaluate candidate radars and signal processing hardware for offshore platform and tanker applications.

The research also indicated that there are substantial improvements in performance that can be achieved using standard marine radar technology supplemented with non-coherent processing techniques. These processing schemes have been proven to work on iceberg signals. Real-time versions of this technology are just coming on the market now. New radar technology such as the IPIX radar show promise for use in iceberg detection; however, it is expected that these systems will be substantially more expensive than an enhanced standard marine radar.

5.2 ACOUSTIC SYSTEMS

Existing acoustic sensor technologies can provide adequate information on icebergs in open and ice-covered waters, to allow optimum course selection and/or collision avoidance maneuvers. This section presents system performance evaluations of five acoustic systems, four of which were designed specifically for iceberg detection and ranging. Only two of these systems discussed below are fully operational. However, for the other systems (either experimental or conceptual), detection ranges and environmental factors effecting these range detections can be stated, based on theoretical modeling and/or experimentation (depending on how far along the design stage each system has reached).

Sonar design for small object detection at distance has traditionally been restricted to defense applications. With the relaxing of relations between Russian and NATO countries, these systems have become declassified. Military-directed firms that designed these systems are now searching aggressively for new markets and are attempting to find commercial niches for their hardware. The cost of these systems has not come down to market level, as the developments were undertaken under large military budgets. In the next 5 to 10 years, it is expected that they will be available to industry at an approximate cost of US$200,000 for purchase and US$3,000/day for rental. At present, these sonar developers are looking for immediate users who have large budgets. This is why the promotional interest to the oil and gas sector (such as for the Hibernia project) is so high, and why iceberg detection is now a priority and is attainable.

5.2.1 Background

Acoustics pertains to the physical properties of sound wave propagation. Acoustic sensing devices use sound waves to process information on the spatial distribution of objects in a given environment. Sonar (sound navigation and ranging) is an underwater acoustic system that is used to find and determine the location of underwater objects. Most sonar systems are active, that is, they transmit sound waves via electro-acoustic transducers over the profiling area, and they receive the reflected waves from the target(s) that lie within the area to which the sonar is transmitting the waves. The returned sound waves from the target(s) are captured via a receiving transducer that converts the acoustic wave energy into an electrical signal. Advanced signal processing is then used to determine the signature of the target signals contained in this electric signal and the location of the target(s) with respect to the sonar.

Sonar was developed in the Second World War for detection of submarines. Much of the underwater acoustic research and developed technology was slow to come into the commercial world, as it was classified and not made available to the public until many years later. In peacetime, it has been used mostly to navigate ships through shallow and hazardous waters, but also to profile the seabed and to find schools of fish. In recent years, research has been undertaken to investigate the feasibility of sonar-aided navigation in the Arctic environment. In addition to sonar, atmospheric acoustic echo sounders, or SODARs (sound detection and ranging), have been used in experiments to determine their usefulness in iceberg detection. The major consideration in the use of acoustic sensors is the range of iceberg detection and the size of the icebergs that can be detected at a specified range.

5.2.2 Parametric Sonar

Parametric array sources are sonar devices that exploit the nonlinear acoustic properties of sea water, to generate a narrow beam of sound without a large physical aperture. In a conventional acoustic projector, an array of electro-acoustic transducer elements is driven with the desired transmit signal at frequency ω_d to produce a beam. The angular beam width is approximately λ/D (radians), where D is the linear dimension of the array and λ is the wavelength of the transmitted pulse.

The parametric array operates by producing a large amplitude, high frequency "primary acoustic wave" (at frequency ω_p) with an acoustic projector which is large in comparison to the primary wavelength (λ_p), to produce a collimated beam with a long nearfield and farfield angular spreading on the order of λ_p/D. The nearfield collimated region is on the order of A/λ_p where A is the projector area. The primary wave signal is amplitude modulated at a frequency $\omega_d/2$ to produce an endfire "virtual array " from the nonlinear acoustic interaction of different frequency components of the signal in the medium. In the original calculations (Westervelt, 1963), the length of the virtual array was assumed to be limited by medium attenuation at the primary wave frequency (the so-called "absorption limited regime"). The term "regime" here refers to how the acoustic propagation is modeled. The absorption limited regime assumption is valid when the nearfield of the primary wave is as long or longer than the attenuation length at the primary wave frequency. The virtual array "launches" a secondary wave (frequency is ω_d) which is highly directive in nature. This is due to the substantial length of the virtual array. In this regime, the beam pattern and secondary source level is solvable analytically. The analytical result is known as the Westervelt endfire directivity pattern.

In short, a parametric array can produce a narrow beam with low frequency wave components with a much smaller-sized transducer. Due to the physics of linear acoustics, a conventional transducer would have to be larger than that of a parametric array to transmit the same low frequency components. Also, with the conventional transducer, the lower the frequency of the transmitted wave, the wider the beam width. With a parametric array, the secondary lower frequency wave generated by the nonlinear interaction of the medium is as narrow as the primary wave. More information on the theory of parametric arrays is available (Novikov *et al.*, 1987; Clay and Medwin, 1977; and NUSC, 1985).

The benefits from using parametric array sonar over conventional sonar are:

a. A reduced overall reverberation level, due to the reduced beamwidth and large bandwidth of the parametric array.

b. An increase in signal time-bandwidth product, resulting in increased processing gain. This is due to the creation of the secondary lower frequency wave.

c. An additional reduction in propagation loss and reverberation when used in bistatic operation mode.

An additional benefit from parametric systems is the ability to select particular propagation paths, to improve either propagation or to reduce "clutter." For example, in downward refracting sound-speed profile environments, a bottom-mounted parametric system can be beam-steered electronically such that its ray paths never reach the surface. Therefore, only subsurface targets are detected. This could be important in discriminating icebergs from surface vessels. By vertical beam steering, the iceberg can be imaged using algorithms to assess the depth to which the iceberg penetrates below the ocean surface. Imaging of an iceberg could be a significant factor in producing an estimate of the threat of the iceberg to offshore rigs, pipelines, or ship traffic. Also, since the sound speed profile results in a downward refraction and the beam is electrically steered to avoid the surface, the effects of high sea states can be greatly reduced.

Sonetech Corporation, located in Bedford, New Hampshire, is developing a parametric sonar system for iceberg detection. The company has been granted two patents in the area of fixed bistatic parametric sonar (one for choke point and one for fencepost configurations). It also possesses a patent for platform-carried bistatic sonar. The sonar can be deployed in the seabed and on a ship platform. Theoretical modeling results with this sonar system have shown range detection of up to 50 km for icebergs, and about 3- to 5-km range detection for bergy bits and smaller. The source beam can be directed across the surface of the ocean (just under the surface) to detect ice floes and ice edges; however, this path is effected by sea state. Thus, the effects of sea state depend on the direction of the source beam. The system that Sonetech is designing is seabed-deployed, and to launch an installation program for the Hibernia site is estimated (by Sonetech) at several million dollars. While it is still in the process of design refinements, it can (according to Sonetech), be fully operational by the late 1990s.

5.2.3 Ship Mounted Iceberg Avoidance Sonar

This sonar system is currently being designed by Martin Marietta Laboratories of Baltimore, Maryland. As its name implies, it is ship-mounted and its features lie within its signal processing procedures. The system uses a beam-forming approach with its transducer array to enhance its directivity. The sonar is designed to generate a frequency-modulated pulse that has an operating frequency of 20 kHz and 1 kHz bandwidth. The pulse length is 200 ms. The array depth is 10 m.

The sonar is designed to predict sound propagation paths using sound speed profiles. It is expected to compute the transmission loss of the generated source pulse. It relies on its transmit signal's bandwidth to discriminate against reverberation, and thus enhance the target signal. Its processing range resolution cell size is approximately $C/2B$ for any waveform where C is the speed of sound at the given time of operation and B is the bandwidth of the transmitted pulse. Reduction of target cell size increases signal-to-reverberation ratio by including fewer scatterers in the target cell.

According to an informal report (Martin Marietta Laboratories, 1994) from which this information was taken, the sonar is expected to detect the presence and location of icebergs ahead of ship for up to a minimum range of about 3.6 km for 100- to 500-t bergy bits, and to a minimum of 5.5 km for icebergs greater than 1,000 t. The range and angular accuracy for icebergs is ±90 m and ±1 degree, respectively. The 'display iceberg location' for bridge personnel updates the area scan information every 12 s (90 m at 7.5 m/s or 15 knots). Individual locations of multiple icebergs could be shown simultaneously. The display system provides auto-alert of iceberg detection. It provides sufficient angular coverage to indicate possible avoidance maneuvers. The above detection ranges are also valid for up to, and including, sea state 6 (maximum wave height 6 m or 20 feet).

This system is still in the developmental stages and the above is a performance design specification. This specification is not complete, and Martin Marietta is still holding most of its information on its sonar system as proprietary and competition sensitive. Therefore, there is no information as to the cost of this system, or where its development is heading.

5.2.4 Automated Vessel Alert System (AVERT)

This system was developed by Raytheon. It is not specifically designed for iceberg detection; however, it may be used for such a purpose. The AVERT system is intended for use on vessels as an aid in detecting and avoiding underwater obstructions, (charted or otherwise) which, if struck, could endanger crew and passenger safety, cause damage to the vessel's hull, or result in a spill of pollutants. It can also detect and locate stationary or slow-moving objects on or near the surface of the water. The system consists of a forward-looking transducer array, a transmitter and preamplifiers which can be installed in an environmentally-controlled enclosure, a control and display console, and a remote monitor. It is an active system that uses a step-FM pulse for its transmit signal. The system can be easily installed on a ship and is operational on a commercial basis. Raytheon has the system patented in the U.S. It sells on the market in two versions: U.S.$400,00 for the 12-kHz operating frequency model; U.S.$800,000 for the 7.5-kHz operating frequency model. The 7.5-kHz model is more expensive as it requires a larger array and operates with a higher power output.

The forward-looking sonar continuously compares consistent sonar echoes with charted depth profiles in its electronic chart data base. Sonar returns which do not correlate with the chart result in an alert to the bridge personnel. The ship's position, as determined by the Global Positioning System, is continuously displayed and monitored relative to the charted navigational data base. A safe path ahead is provided which shows at a glance, a 20-minute envelope through which the ship will pass. Should an evasive maneuver be required, the safe path shows the degree of turn needed to avoid the object.

As mentioned above, the AVERT system is not specifically designed for iceberg detection. However, it is expected to be capable of detecting objects including icebergs, ice edges, and small floes within 8 km (about 5 nautical miles). This is the detection range that Raytheon claims its system is capable of, as mentioned in its system description brochure (Raytheon Equipment Division). Due to the sonar's beam being forward-looking, sea state will affect object detection range. This is because increased sea state increases surface reverberation which, in turn, restricts the range determination of the system. Operating this sonar in very high sea state would likely reduce the detection range significantly.

5.2.5 Air Acoustic Detector (SODAR)

SODAR is totally different from the above-mentioned devices in that it operates in air, not water. It is the acoustic equivalent of radar. Arctic Sciences Ltd. (Sidney, B.C.) have experimented with a SODAR (Marko, 1987). The SODAR was constructed by Xontech of Van Nuys, CA, for conventional use as a detector of turbulence and wind velocity profiles in the atmospheric boundary layer. The use of this system for ice detection is purely experimental. Instead of using a transducer for source transmission, it uses an atmospheric acoustic antenna to transmit the source wave through the air. It captures return signals via an acoustic receive antenna. The SODAR transmits its acoustic beam over the surface of the ocean with a given angle of elevation and operating frequency.

The main advantage to the SODAR, compared to marine radar, is that target detection is not hindered by sea clutter. Therefore, no signal processing is required to extract sea clutter turns in the echo signal. However, since this SODAR system is operating in air, it is very sensitive to wind; thus, high winds will reduce range detection.

Table 5.6 Acoustic device detection performance

Sensor Type	Iceberg Type	Detection Range	Weather effects
Parametric Sonar	Bergy bits to large icebergs	50 km (large iceberg) (theoretical)	Sea-state sensitive for horizontal beam
Ship-mounted Iceberg Avoidance Sonar	Bergy bits to large icebergs	5.5 km (large iceberg)	Sea-state sensitive for horizontal beam
AVERT System	All types	8 km (large iceberg)	Sea-state sensitive
SODAR	All types	1-1.5 km (large iceberg to bergy bit)	Sea-state sensitive

These results give only a rough estimate of the practical feasibility of acoustic systems operationally. More research is required to determine which system will be most successful for efficient iceberg and pack ice detection. The following comments apply:

a. Parametric sonar has the most potential for long range detection. It is not yet operational for ice detection applications.

b. The AVERT system is on the market, and in current use in the U.S. today. It has reasonable range detection; however, it can still be hampered by very high wind speeds.

c. The SODAR system is very range-limited and this range detection can be significantly reduced in the event of very high wind speeds. The feasibility of this system for iceberg detection is speculative.

d. The other systems are still in developmental stages. Experimentation with the prototypes of these new systems still has to be undertaken before they can be labeled suitable for commercial use. The prototypes for these experimental systems must have hardware to withstand operational environments - an example of such hardware is the ruggedized transducer subsystem which is used to transmit the given sonar system's beam source.

5.3 OPTICAL AND VISIBLE SYSTEMS

Until mid-twentieth century, optical sensors were the only commonly used ice and iceberg detection technology. Optical band (0.3 - 15.0 μm) sensors applicable to ice detection include visible and infrared cameras, active and passive scanners, and a variety of nonimaging detectors. The human eye is perhaps the most sophisticated and certainly ubiquitous of these sensors.

All optical band sensors are range-limited by fog, rain, snow, and atmospheric absorption. Radar technologies have supplemented optics for sensing through clouds and fog. Nevertheless, human vision is the (often unacknowledged) sensor of choice for long- and short-range sensing.

Visible light and IR technologies applicable to ice and iceberg detection were reviewed by Canpolar Consultants (1985). The report provided a comprehensive summary of technical factors pertinent to visible and IR detection of icebergs. The report also provided some computational models for calculating range detection limits. A significant observation from the 1985 review was that, with the exception of two reports from 1981 and 1982, there had been no systematic investigation of iceberg detection with optical sensors. The investigative anomaly extends to the present day.

This section fills in part of the gap, providing a technical description and quantitative detection range factors for the primary visible light sensor, the human eye. Adjunct technologies are presented in terms of their capacity to extend the range and sensitivity of visual detection. The chapter also presents a technology update and a forecast for future developments.

5.3.1 Technical Description

The human eye is a wide field of view camera with a 17-mm lens. The central 0.7° portion of the field of view, the forea, provides high acuity colour vision. The remainder of the eye provides low acuity, high sensitivity monochrome vision. Average functional characteristics of the eye are listed below (after Canpolar East Inc., 1994):

Field of view:	2.6 x 3.6 rad
Spatial resolution (minimum separation), fovea:	0.12 mrad
Modulation transfer function, fovea:	0.5 cycles/mrad
Acuity (Snellen Letter Test):	0.3 mrad
Intensity discrimination, C_L:	0.003
Colour discrimination C_C:	0.002 - 0.01
Dynamic range:	10^{-6} - 10^{3} cd/m^{2} (10^{9}:1)
"Frame rate":	25 Hz max.
Spectral range:	400 -700 nm
Sensor array:	120 x 10^{6} detectors
Experience base:	ubiquitous
Potential to satisfy user need:	limited by atmospheric interference and by human fatigue
Cost:	Typically \$25 - \$100/hour.

Maximum visual range in clear air is limited to 100 - 300 km by molecular scattering and absorption. Atmospheric aerosols (fog) further reduce visibility. Visual range is determined by visual acuity and by contrast sensitivity. The same considerations apply to all optical sensors. For a given atmospheric condition the relative performance of different types of sensors can be calculated.

For an isolated object surrounded by a uniform background the inherent contrast, C_O, is defined by:

$$C_0 = \frac{B_o - B^1}{B^1}$$

Where B_O is the luminance of the object and B^1 is the luminance of the background. Atmospheric scattering reduces apparent contrast C_R according to:

$$C_R = C_o e^{-\sigma_L}$$

Where σ is the extinction coefficient of the atmosphere and L is range. The minimum contrast required to just distinguish an object is the *threshold of brightness contrast* ε.
For a given value of ε the detection range, L_V, can be calculated as:

$$L_V = \frac{-\ln(\varepsilon)}{\sigma}$$

Meteorological range is defined as the distance which yields a visual contrast of 0.02 regardless of uniformity of σ. The extinction coefficient σ includes both absorption and scattering effects. The value of σ is a function of scattering particle size, wavelength of light, particle geometry and absorption bands in the aerosol and the atmosphere. Atmospheric aerosols (e.g., fog) have typical dimensions of 0.01 - 10 μm, similar to the optical band wavelengths. Mie scattering effects dominate (Schanda, 1986). It is, therefore, not possible to provide *a priori* rules as to whether some optical bands will provide superior detection range in fog. For rain and snow, particles sizes are much larger than the optical wavelengths and no wavelength-dependent range effects should be anticipated. In the absence of aerosols or particulates, the visible detection range is limited only by atmospheric absorption and by molecular scattering. Optimum range occurs in the atmospheric passband which (not surprisingly) corresponds to the visible wavelengths. Other less advantageous passbands exist in the IR (Reeves et al., 1975).

Detection range is also affected by apparent target object size. For the human eye and for most other sensors the smallest detectable non-luminous target must subtend the area of at least one photodetector element in the sensor array. Luminous targets can have a contrast $C_O > 1$ and therefore can be detected at arbitrarily small sizes if the energy falling on the photodetector exceeds the average background signal by the threshold value, ε.

The functional performance of the human eye as a sea-ice and iceberg detection system is documented in Table 5.7.

Table 5.7 Human eye search applications

Parameter	**Performance**
Relevance	Iceberg occurrence and position sea-ice edge, concentration. location, type
Spatial Coverage	0 - 200 km
Temporal	on demand
Positional Accuracy	< 1 mrad
Resolution	0.1 mrad

Optical band detection and imaging technologies offer a means of extending or enhancing visual detection. Most optical enhancement or imaging technologies are used as adjuncts to the human eye. The primary enhancements are set out in Table 5.8. Almost all techniques for extending visual sensitivity carry inherent limitations which restrict their usefulness in target detection applications.

Table 5.8 Technology enchancements to visual detection

Factor	**Technology**	**Enhancement**	**Relevance to Iceberg Detection**
Light Level	Night vision scope Low -light television	Functional imaging at 10^{-8} Lux	Night detection
Bandwidth	Infrared scanners Focal plane arrays	Imaging in infrared including thermal difference imaging	Thermal imaging .02°C contrast discrimination
Spatial Resolution	Telescope (with eye or camera)	Unlimited enhancement in spatial resolution	Long range detection or measurement
Spectral Resolution	Bandpass filters Diffraction grating	Enhanced spectral discrimination	Spectral signature identification of targets
Contrast	Detector dynamic range	12 Bit $\varepsilon=0.0002$ 16 Bit $\varepsilon=0.00002$	Extended detection range
Fatigue	Electronics	Time invariant performance	Sensor reliability

Because of its very high effective data rate (Table 5.9) the human eye is difficult to match as a target search tool. Adjunct technologies which may extend some aspects of vision performance often result in an effective reduction in data rates and may not result in improved detection performance.

Table 5.9 Comparison of human eye to optical sensors

	Detectors	**Intensity Resolution (bits)**	**Frequency (Hz)**	**Effective Data Rate (Gbit/s)**
Human Eye[1]	126×10^6	8	10	10
Advanced CCD	25×10^6	16	2	0.8
Standard Video	0.25×10^6	24	30	0.2

Note: 1. Preprocessing in the retina reduces optic nerve data rates to about 0.1 Gbit/s.

Of the various enhancement factors listed in Table 5.8 only fatigue stands out as an area in which contemporary technology can provide significant improvement in detection. Optical imaging or scanning devices equipped with automated target recognition technologies are now in limited use in security surveillance and in process inspection applications. In principle, it is possible to apply these same technologies to iceberg detection. To the best of our knowledge such applications have not been investigated.

5.3.2 Technology Update

The availability, performance and physics of visible and infrared sensors for iceberg detection has been extensively reviewed and reported (Canpolar Consultants, 1985). In the intervening decade there have been some changes in technology and in performance, which are summarized in Table 5.10.

Table 5.10 Recent changes in optical sensor technology applicable to iceberg detection since 1985

Sensor Technology	**Significant Performance Advances**	**Significant Technology Advances**
Photographic Cameras	No	No
Films	No	No
Filters	No	No
Video Cameras (Visible)	No	Yes
Video Cameras (IR)	Yes	-
Scanners	No	No
Illuminators	No	Yes
Illuminator / Detector Systems	Yes	-
Detector / Analyzer Systems	Yes	Yes

5.3.2.1 Video cameras (visible)

Vidicon tubes have been replaced by CCD (charge coupled device) arrays in almost all consumer and industrial cameras. CCDs are solid state sensors with significant advantages over vidicons in respect to size, power consumption, robustness and anti-blooming. Single chip cameras are available. Standard two-dimensional CCD arrays are typically 500 x 500 or 750 elements. Arrays as large as 5000 x 5000 can be obtained for very high resolution imaging. Single line arrays up to 6000 elements are commonly used in line scan cameras for industrial application. Off-the-shelf, line-scan cameras include colour sensing and time domain integration (TDI) capabilities. All of these technologies are more sophisticated and less expensive than the line scanners and cameras in use a decade ago.

The most significant changes in remote imaging have been in the development of hyperspectral imaging based on the use of two-dimensional detector arrays for multiband line scanning (Lewotsky, 1994). The current generation of hyperspectral imaging systems can synthesize images over a band from 0.4 to 2.5 μm with 3 to 10 nm spectral resolution. The data density in these images provides unprecedented options for the recognition of target objects on the basis of unique spectral signatures.

IR cameras have improved over the decade with the introduction of focal plane detector arrays. It is now possible to purchase infrared video cameras with 256 x 256 resolution, 1000-Hz frame rates and thermal resolution of better than 0.02°C. IR video has the potential to enhance iceberg detection on the basis of thermal signature.

5.3.2.2. Illuminators

The decade has seen significant advances in solid state illumination techniques. Solid state diode pumped visible and IR lasers in the milliwatt to kilowatt class are readily available. These units occupy about 1/100 the volume of the gas laser technologies which were state-of-the-art in the 1980s. The power conversion efficiency of the current generation of solid state lasers can be as high as 40%, compared with 0.01% typical of gas lasers or 1% - 5% typical of incandescent and arc lamps. This efficiency provides a significant engineering advantage for active sensing devices. Blue-green solid-state diode-pumped lasers are in use for aircraft/submarine communications and for laser bathymetry. Light emitting diodes have steadily improved in brightness and output power to the point of practical application as illuminators for imaging systems.

5.3.2.3 Illuminator/detector systems

The effects of atmospheric scattering can be significantly reduced through the use of pulsed illuminators and time-gated detectors which discriminate between scattered and unscattered radiation on the basis of time of flight. A family of trans-illumination imaging techniques have been under development since about 1989 under a variety of descriptive names, including chromo-coherent imaging, time resolved imaging, ballistic imaging, snake light. All of these techniques resolve scattered photons from unscattered photons from time-of-flight differences.

Front lighting is the most common active illumination geometry. In the presence of fog, rain or snow, backscatter from particles between the illuminator and the target diminishes image contrast. One technique for eliminating the backscattering component is to use a pulsed light source and a time-gated imaging device which detects only the segment of the pulse backscattered from a selected range (identical to radar operation). This technique has been applied in underwater imaging.

5.3.2.4 Detectors/analyzers

The most significant fundamental change in optical imaging sensors has been in the development of computers and image analysis techniques. It is now possible to construct target specific image sensors.

Real time automated video image analysis for target detection has become economically and technically feasible in the 1990s. The availability of microprocessors and digital signal processors has enabled the development of integrated sensor packages capable of real-time target identification and tracking. These systems are not capable of sensitive visual discrimination comparable with human vision. However, they are excellent as inexpensive back-up surveillance or remote monitoring systems in which continuous human observation is impractical or uneconomical. Automated systems can be superior to human vision in cases where speed (e.g., counting) and dimensional accuracy (measurement or location) are required.

Target-specific sensors offer new strategic options for iceberg detection. The options include remote (fixed) installations capable of unattended operation and reporting.

5.3.3 Future Development

Technology evolution in visible light imaging sensors is rapid compared to most other sensor groups. The primary driving forces are the visual entertainment and communications industries. Technology development budgets are billions of dollars per annum. Sensors operating in the near IR benefit from spill-over. Sensors in the far IR do not receive much attention or spill-over. Visible light imaging sensors (e.g., television) with enhanced resolution and data bandwidth will become available within the decade.

Most visible light and many infrared detector technologies operate with quantum efficiencies in the 10% to 50% range. These near-ideal detector technologies will not see significant improvement over the coming decades. Photo conductors, photo emissive devices and other techniques for converting light to an electronic signal function much more effectively in the visible band than in the IR band. Fundamental detector technology has not changed significantly since mid-century and is unlikely to change in the next few decades. The sophistication of multidetector arrays has improved dramatically and will continue to change rapidly over the next decade.

Scattering from water condensate in the form of fog, cloud (aerosols) and precipitation is a predominant factor limiting the range and effectiveness of visible light sensors. Optical techniques for imaging through dense scattering media are currently being developed for biomedical imaging applications. While these techniques are not directly relevant to iceberg detection there will be some spill-over into imaging and detection in fog, rain and snow. Improvements should be anticipated.

Rapid changes can be anticipated in image analysis technologies for automated target detection. Limitations will relate primarily to the available computer processing power; however, as a rule of thumb, available power for a given cost/size package doubles every 18 months. By the end of the decade automated iceberg detection via optical imaging sensors could be quite reliable.

5.3.4 Conclusion

The human eye is the most commonly applied sensor for iceberg detection in the visible band. In spite of its long history of use and its universal application as the backup and confirmation device for all other sensors, there has been little systematic study of its functional capacity in iceberg detection. In addition, experience in search and rescue efforts to detect small targets (such as life rafts) has shown that targets that are within visual range are often missed. It is likely that detection of ice and icebergs, particularly growlers or bergy bits in high seas states, will suffer the same limitation.

All optical-band electromagnetic sensors are range limited by fog, rain, and snow and by atmospheric absorption. Combinations of sensor and illumination technologies can improve range detection limits. Regardless of the enhancement, the best of these optical technologies are non-functional under a significant range of normal environmental conditions. Over the next decade there may be some modest range improvements resulting from new detection and illumination techniques.

There have been significant recent advances in the development and availability of smart imaging sensors capable of recognizing specified targets. These technologies offer new strategic possibilities for iceberg detection and surveillance. Prospects include geographically distributed sensing stations capable of autonomous surveillance and reporting. Smart sensor capabilities will advance rapidly during this decade.

5.4 COMMUNICATIONS NETWORKS

One of the key aspects of effective offshore operations is communications capabilities, particularly for the kinds of high data volumes that some ice detection sensors can provide. As sensor technologies are advancing, so too are the communications networks that will enable a wide range of services, including analog and digital voice, data, fax, e-mail, and distress alerting. Although communications technology is a field in its own right and beyond the scope of this report, this section has been provided to give a sense of the range of options available.

Table 5.11 presents a summary of marine mobile two-way communications networks serving Canada, as of February 1995 (prepared by the Canadian Centre for Marine Communications, St. John's, Newfoundland). Although Inmarsat is presently the only global maritime data communications provider of a complete range of services, other options are emerging. For example, digital cellular is becoming commonly used for data in the Gulf of St. Lawrence.

A wide variety of new satellite-based communications systems are expected to become available over the next few years, as shown in Table 5.12 (also courtesy of CCMC).. For example, MSAT is expected to be available by fall 1995, and a number of other systems are being planned using medium-Earth orbit (MEO) and low-Earth orbit (LEO) satellites. Although costs can be fairly high, as indicated in the tables, VHF digital radio is being developed, especially for digital selective calling (DSC). DSC sill be mandatory for GMDSS (distress alerting) compliance of SOLAS vessels by 1999. The Canadian Coast Guard is also encouraging use of automated dependent surveillance (ADS) systems. Some of the systems being explored will also, in all likelihood, be equipped to handle three-dimensional electronic chart updates and other forms of electronic data interchange (EDI).

It is clear that the communications field is moving very rapidly, and that communications options need to be examined thoroughly in the context of which systems of sensors are deployed, where data are collected (e.g. satellite, aircraft, ship, land, seabed, etc.) and in what form (e.g. raw imagery or processed results) they are needed for operational decision-making.

Table 5.11 Marine mobile two-way communications networks serving Canada, as of February, 1995

Network Developers/Providers	System	Technology (no of satellites)	Frequency (Mobile)	Coverage	Function		Data Rate (KBPS)	Subscriber Fee	Usage Cost (appr. $US)[4]	Ship Equipment Physical Description	Ship. Equip. Cost (appr. $US)[4]	Contact
Comsat, IDB Mobile, Teleglobe Canada[3], NewEast Wireless Telecom[3]	Inmarsat A, B, C, & M	GEO Satellite (4)	L Band	Global up to 80° lat.	A	Analog Voice, high speed data, fax & position, distress alerting (GMDSS)	up to 9.6 plus 56/64	Yes	$9 (peak)/min	>50 kg fixed installation	$35-40K	Teleglobe Canada (514) 868-7272 NewEast Wireless Telecom (709) 576-0225
					B	Digital voice, high speed data, fax & position, distress alerting (GMDSS)	up to 16	Yes	$6 (peak)/min	>50 kg fixed installation	$35-35K	(same as above)
					C	Data, fax. telex, e-mail, position and fleet management, distress alerting (GMDSS)	0.6	Yes	$10-20 /kchar[2]	<10 kg, very small aperture, fixed and briefcase transportable	$7-12K	(same as above)
					M	Digital voice, data, fax & position	up to 2.4	Yes	$5 (peak)/min	<25kg fixed and <10kg briefcas transportable	$13-22K	(same as above)
QUALCOMM Inc., Canadian Satellite Communications Inc. (CANCOM)[3], BOATRACS/OceanTrak Systems Limited[3]	OmniTRACS/ QTRACS and Cancom Mobile	GEO Satellite (2)	Ku #Band	Continental USA and Canada coastal waters	Mail box messaging, fax, e-mail, position and fleet management		[2]	Yes	$5-10 /kiloChar	<15 kg, very small aperture, fixed installation	<$8K	OceanTrak Systems Limited (902) 749-1955
New East Wireless Telcom[1]	Tors Cove Radio	SSB Radio	MF/HF	East coast of North America and North Atlantic Ocean	Radio telephone, e-mail, facsimile, telex, and telegrams		<150	No	<$3.5 (1st minute) + <$2 ea. add. min.	Long vertical or horizontal wire antenna, fixed installation	$6-9K for SSB	NewEast Wireless Telecom (709) 576-0225
Globe Wireless (KFS)[3]	Super-Station ™ (includes Tors Cove Radio)			East and west coast of North America, North Atlantic and Pacific Oceans, Caribbean Sea, Gulf of Mexico and Panama Canal	International telex - SITOR				[1]			Globe Wireless (KFS) (415) 726-6588 (709) 576-0225
Canada Coast Guard Radio, U.S. coast stations	[2]		MF/HF	All coasts of North America and Great Lakes	Radio telephone, E-mail, facsimile, telex, and telegrams, distress monitoring				<$6 (3 minute min.) + <$2 ea add. min.). also per word rates on telegrams			Canada Coast Guard (613) 998-1504
			VHF	Coastal North America out of 60km Broken Labrador, no Artic	Voice, distress monitoring		[2]		[1]	Vertical antenna, <10 kg fixed installation		U.S. Coast Guard (202) 267-2680
U.S. Coast Guard	Comm. Stn. Boston	DSC Radio	HF	East coast of North America and North Atlantic Ocean	DSC compatible services including distress		[2]	No	[2]	Long vertical or horizontal wire antenna, fixed installation	[1]	U.S. Coast Guard (202) 267-2680
Bell Mobility[3], Cantel[3], and others	[1]	Cellular Radio	UFH	Broken coverage of east and west coasts of North American and Great Lakes out to 60 km	Voice, facsimile and data		14.4(v.42)	Yes	$0.3-0.9/ min	Portable hand held, fixed and transportable	$200-1000	Bell Mobility (800) 387-4869 CANTEL (800) 265-6565

Notes:

[1] denotes Not Available; [2] denotes Not Applicable

[3] Denotes significant Canadian ownership or involvement either established or in process of negotiation.

[4] Prices are based on a range of commercial equipment and include all required components, installation extra. The numbers are supplied for comparison purposed only and are subject to change without notice.

Table 5.12 Marine mobile two-way communications networks planned as of January, 1995

Network Developers	System (expected date)	Technology (no. of satellites)	Frequency (Mobile)	Coverage	Function	Data Rate (KBPS)	Subscriber Fee	Usage Cost (appr. $US)[4]	Ship Equipment Physical Description	Ship. Equip. Cost (appr. $US)[4]	Contact
Amer. Mobile Satellite Corp., TMI Comm. Inc.[3]	MSAT (1995)	Spot Beam GEO Satellite (2)	L Band	North America, Hawaii, Caribbean and Coastal Waters out 300Km (limited Arctic to 80°N)	Digital voice, data, fax, messaging & position + cellular mode option	up to 4.8	Yes	<$2/min	5-10 kg, small aperture, fixed, transportable and remote handheld	$3-5K	TMI Communications (613) 742-0000 GLENTEL Inc. (604) 431-2345
Comsat, IDB Mobile, Teleglobe Canada[3], NewEast Wireless Telcom [3]	Immarsat Mini M (1996)	Spot Beam GEO Satellite (4)	L Band	Global up to 80° latitude	Digital voice, data, fax & position	up to 2.4	Yes	[1]	<15 kg, small aperture, fixed, transportable and remote handheld	[1]	Teleglobe Canada (514) 868-7272 NewEast Wireless Telecom (709) 576-0225
Amer. Mobile Satellitte Corp.	[1]	MEO Satellite (12)	L Band	Global	Digital voice, data, fax messaging & position (cell option)	[1]	Yes	[1]	Portable hand-held, fixed and transportable	[1]	AMSC (703) 758-6000
Mobile Communications Holdings Inc.	Ellipse™-[1] (1997)	HEO Satellite (24)	L Band	Optimized for populated areas	Digital voice, data, fax messaging & position (cell option)	[1]	Yes	<$1/min	Portable hand-held, fixed and transportable	<$500 as add-on to cell	Mobile Communications Holdings Inc. (202) 466-4488
Inmarsat (Project 21) Comsat Corp. and Others	Inmarsat P. (1999)	MEO Satellite (12)	L/S Bands	Limited Global	Digital voice, data, fax messaging & position (cell option)	[1]	Yes	1	Portable hand-held, fixed and transportable	<$1,000	Inmarsata (Project 211) (44) 628-73331
Loral/Qualcomm Limited Partnership	Globalstar (1998)	LEO Satellite (8x6=48)	L Band	Limited Global	Digital voice, data, fax, messaging & position + cellular mode option	>9600	Yes	[1]	Portable hand-held, fixed and transportable	<$1,000	Globalstar (703) 416-5524
Iridium, Inc.[3] (Motorola et al.)	Iridium (1998)	LEO Satellite/ (6 x 11 = 66)	L Band (K Band x-links)	Global including poles	Digital voice, data, fax messaging & position (cell option)	[1]	Yes	[1]	Portable hand-held, fixed and transportable	<$1,000	Iridium Inc. (202) 326-5600
TRW[3]	Odyssey (1998)	MEO Satellite/ (4 x 3 =12)	L Band	Limited global	Digital voice, data, fax messaging & position (cell option)	[1]	Yes	$0.65/min	Portable hand-held, fixed and transportable	<$500	Teleglobe World Mobility (514) 868-8082
Teledesic Corp.	Telemedic (TBD)	LEO Satellite (850+)	Ka Band	Global	Global Internet	[1]	Yes	[1]	Portable hand-held, fixed and transportable	[1]	[1]
Orbital Communications	Orbcomm (1996)	LEO Satellite (8x3) + (2 x 1)=26	VHF	Limited global	Data and short message, fax, e-mail & position, limited store and forward	2.4-4.8	Yes	[1]	Pocket transceiver with attached antenna and OEM data terminals	$100-400	Teleglobe World Mobility (514) 868-8082
Starsys Inc.	Starnet (early Entry Program, present - 1997)	LEO Satellite (24)	VHF	Limited global	Data and short message, e-mail, position	2.4-4.8	Yes	[1]	Pocket transceiver with attached antenna and OEM data terminals	<$500	Starsys Global Positioning Inc. (301) 341-0622
US Coast Guard	Coastal Comm. Stations (1999)	DSC Radio	MF/HF/VHF	All marine areas of USA	Digital Selective Calling SSB voice and distress alerting (GMDSS)	[2]	No	[1]	Vertical antenna, <10kg fixed installation	$5-26K for MF/HF	Commandant (G-TTM) U.S. Coast Guard (202) 267-2680

Notes:

[1] denotes Not available; [2] denotes Not Applicable

[3] Denotes significant Canadian ownership or involvement either established or in process of negotiation

[4] Prices are based on a range of commercial equipment and include all required components, installation extra. The numbers are supplied for comparison purposes only and are subject to change without notice.

6.0 ASSESSMENT OF SENSOR SYSTEMS

This chapter presents comparative evaluations of the key sensors that have been described in earlier chapters, particularly in terms of the needs described in Chapter 3. Since data from various sensors are often complementary, practical suites of sensors are also discussed. These qualitative results can be used to update more quantitative model results given by Canpolar Consultants (1985;1986a).

6.1 COMMERCIALLY-AVAILABLE SENSORS

In order to evaluate the effectiveness of each of the key sensors, the four main operating scenarios, described in Chapter 3 (Tables 3.6 to 3.9) were taken as a starting point; i.e.:

- Field development - icebergs
- Field development - sea ice
- Vessel transits - icebergs
- Vessel transits - sea ice.

Both tactical and strategic requirements were considered. Against this framework, each of the important sensor types was considered in terms of its ability to meet the determined needs.

In order to keep the analysis tractable, only sensors commercially available in 1994 were included. The definition of "commercially available" was taken to mean that an operational service could be obtained from proven operators on a commercial basis. Excluded were systems that have been demonstrated but are still in prototype form (such as the airborne imaging microwave radiometer or the McMaster University IPIX radar). Included were satellite SAR, although RADARSAT has not yet been launched (*ERS-1* is operating), and over-the-horizon radar.

The results are presented in Tables 6.1 through 6.4, corresponding to Tables 3.6 through 3.9, respectively. Capsule comments on how well each of the sensors meets the stated needs are given. In order to provide the information in a concise format, the comments are necessarily brief, but can serve as a guide to the greater detail found in Chapters 4 and 5. The sensors are grouped by deployment; i.e., ship-or rig-based, airborne, satellite, and shore-based.

Table 6.1 Operating Scenario: Iceberg Detection Sensors for Field Development System (commercial 1994)

		Surface (sea):		*Airborne*				*Spaceborne:*				*Surface/Shore:*
Attribute:	**Need:**	**Marine radar**	**Visual & Optical**	**SLAR**	**SAR**	**Search radar**	**Visual & Optical**	**SAR**	**SPOT**	**NOAA**	**Passive microwave**	**Over horizon radar**
TACTICAL: Spatial	0 to 40 km	<40 km	Limited by fog & darkness <10 km	All weather day/night Yes	All weather day/night Yes	All weather day/night (except visual confirm)	Good visibility beneath clouds	All weather day/night Yes	Clear weather only Yes	Clear weather only Yes	All weather day/night Yes	All weather Day/night < 200 km
Temporal	On demand	On demand	On demand	Overflights as required, if airport open	Overflights as required, if airport open	Overflights as required, if airport open	Overflights as required, if airport open	No	No	No	No	On demand
Positional	100 to 500 m	Yes	Varies w/ range, visibility, sea-state; 500 m	Yes	Yes	Yes	Yes	1 km	1 km	No	No	400 m x 10 km @ 200 km range No
Resolution	1000 t	Limited range; sea state<1	< 1 km	Some sea-state < 1	Some sea-state < 1	Yes Sea state <3	Yes	No	No	No	No	No
STRATEGIC: Spatial	40 to 200 km	<40 km	Limited by fog & darkness < 10 km	All weather day/night yes	All weather day/night Yes	All weather day/night Yes	Good visibility beneath clouds	All weather day/night Yes	Clear weather only Yes	Clear weather only Yes	All weather day/night	All weather < 200 km from shore
Temporal	1 to 2 days	Yes	Yes	Overflights as required, if airport open	Overflights as required, if airport open	Overflights as required, if airport open	Overflights as required, if airport open	3 to 4 days	26 days (13 if antenna steered)	4 times per day	2 passes per day	Yes
Positional	1 to several km	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	1.1 to 2.5 km	25 km	400 m x 10 km @ 200 km range Yes
Resolution	10,000 t	Limited range; sea state<3	Yes	Yes Sea state < 3 *(Cannot distinguish ships from icebergs)*	Yes Sea state < 3	Yes Sea state <3	Yes	No	No	No	No	Sea state < 3 No ionospheric interference
Display		PPI on bridge or CRT digital	Visual only or CRT	Downlink to structure	Downlink to structure	Downlink to structure	Downlink map; optical; CRT	Hard copy or downlink from shore	Hard copy or downlink from shore	Downlink to structure	From shore	Map from shore
Iceberg Size		Possible	Yes shape info	Very large bergs only	Very large bergs only	No	Yes	No	No	No	No	No
Iceberg draft		No	No		No	No	No	No	No	No	No	No

Table 6.2 Operating Scenario: Sea-Ice Detection Sensors for Field Development System (commercial 1994)

		Surface (sea):		*Airborne*				*Spaceborne:*				*Surface/Shore:*
Attribute:	**Need:**	**Marine radar**	**Visual & Optical**	**SLAR**	**SAR**	**Search radar**	**Visual & Optical**	**SAR**	**SPOT**	**NOAA**	**Passive microwave**	**Over horizon radar**
TACTICAL: Spatial	0-40km	<40 km All weather day/night	limited by fog and darkness < 10 km	All weather day/night Yes	All weather day/night Yes	All weather day/night Yes	Good visibility beneath clouds	All weather day/night Yes	Clear weather only Yes	Clear weather only Yes	All weather day/night Yes	All weather day/night < 200 km
Temporal	On demand	On demand	On demand	Overflights as required, if air-port open	Overflights as required, if air-port open	Overflights as required, if air-port open	Overflights as required, if air-port open	No	No	No	No	On demand
Positional	500 m	Yes	Varies w/ rge, visibility, sea state; 500 m	Yes	Yes	Yes	Yes	1 km positional accuracy	1 km	No	No	400 m x 10 km @ 200 km rge No
Resolution	+/- 1/10	limited range	< 1 km	Yes	Yes	Yes	Yes	No	No	No	No	No
STRATEGIC: Spatial	40 to 200 km	<40 km All weather Day/Night	Limited by fog and darkness < 10 km	All weather day/night Yes	All weather day/night Yes	All weather day/night Yes	Good visibility beneath clouds	All weather day/night Yes	Clear weather only Yes	Clear weather only Yes	All weather day/night	All weather < 200 km from shore
Temporal	1 to 2 days	Yes	Yes	Overflights as required, if air-port open	Overflights as required, if air-port open	Overflights as required, if air-port open	Overflights as required, if air-port open	3 to 4 days	26 days (13 if anten-na steered)	4 times per day	2 passes per day	Yes
Positional	2 to 4 km	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	1.1 to 2.5 km	25 km	400 m x 10 km @ 200 km rge Yes
Resolution	plus/minus 1/10	limited range	< 1 km	Yes	Yes	Yes	Yes	Yes	Yes	No	No	Sea state < 5 No ionospheric interference
Display	Available in control room. User friendly	ppi on bridge or CRT digital	Visual only or CRT	Downlink to facility	Downlink to facility	Downlink to facility	Downlink map Optical - CRT	Hard copy or downlink from shore	Hard copy or downlink from shore	Downlink facility	From shore	Map from shore
Ice characteristics	Concentration	Yes	Yes < 1-5 km	Yes	Yes	No	Yes	Yes	Yes	Yes (limited)	No	No
	Roughness	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No
	Thickness	No	No	No	No	No	No	No	No	No		
	Floe size	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes (large)		
Ice Type		No	Yes, at < 1 km	Yes, inter-pret from imagery	Yes, inter-pret from imagery	Yes, inter-pret from imagery	Yes general char-acteristics	Yes, inter-pret from imagery	No, inter-pret from imagery	No	Discriminate MY/FY using algorithm	No

Table 6.3 Operating Scenario: Iceberg Detection Sensors for Vessel Transits (commercial 1994)

		Surface (sea):		*Airborne*				*Spaceborne:*			
Attribute:	**Need:**	**Marine radar**	**Visual & Optical**	**SLAR** (e.g., CAL 200)	**SAR**	**Search radar**	**Visual & Optical**	**SAR** (RADARSAT)	**SPOT**	**NoAA**	**Passive microwave**
TACTICAL Spatial	0 to 5 km	0 - 40 km All weather day/night	Limited by fog & darkness 0 - 10 km	All weather day/night 25 - 200 km	All weather day/night 24 - 96 km	All weather day/night 0 - 200 km	Requires good visibility beneath clouds	All weather day/night 45 - 510 km	Clear weather only 60 km swath	Clear weather only 3000 km swath	All weather day/night 1300 km
Temporal	On demand	On demand	On demand	Flights within 2 -4 hrs, if airport open	Flights within 2-4 hrs if airport open	Flights within 2-4 hrs if airport open	Overflights as required, if airport open	3 days	No every 26 days	No 4 times per day	No 2 passes per day
Positional	100 m	Yes 50 to 1,750 m	Varies w/ range, visibility, sea state, 500 m	Yes 100 m GPS accuracy	100 m GPS accuracy	200 m GPS acuracy	200 m GPS accuracy	< 1 km	Yes 100 m	No 1.1 to 2.5 km	No 25 km
Resolution	1,000 t	sea state <1	Possible within about 1 km	> 10,000 t	10,000 t	1,000 t	> 1,000 t	No: limited data indicate >2 million t	plus/minus 1/10	plus/minus 1/10	plus/minus 1/10
STRATEGIC Spatial	5 to 30 km	0 - 40 km All weather day/night	Limited by fog & darkness 0 - 10 km	All weather day/night 25 - 200 km	All weather day/night 24-96 km	All weather day/night 0 - 200 km	Requires good visibility beneath clouds	All weather day/night 45 - 510 km	Clear weather only 60 km swath	Clear weather only 3000 km swath	All weather day/night 1300 km swath
Temporal	On demand	Yes	Yes	Flights with in 2 - 4 hrs, if airport open	Flights within 2 - 4 hrs if airport open	Flights within 2 to 4 hrs, if airport open	Overflights as required, if airport open	3 days typical	Every 26 days (13 if antenna steered)	4 times per day	2 passes per day
Positional	500 m	Yes 50 to 1,750 m	Yes	100 m GPS accuracy	100 m GPS accuracy	200 m GPS accuracy	200 m GPS accuracy	< 1 km	Yes; 100 m	1.1 to 2.5 km	25 km
Resolution	10,000 t	sea state <3	Possible within within ~1 km of vessel	> 10,000 t	>10,000 t	1,000 t	> 1,000 t	No: limited data indicate >2 million t	Yes plus/minus 1/10	plus/minus 1/10	No plus/minus 1/10
Display	PPI or graphic equivalent on vessel bridge	PPI on bridge or CRT digital	Visual only, or CRT	Downlink image to vessel	Downlink image to vessel	Downlink image to vessel	Downlink map; optical-CRT	Hard copy or downlink from shore	Hard copy or downlink from shore	Downlink to ship	From shore
Iceberg characteristics	Occurrence	Yes	Yes < 1-5 km	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes
	Position	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Draft	No	No	No	No	No	No	No	No	No	No
	Mass	No	No	No	No	No	No	No	No	No	No
	L/W/H	No	Yes	No	No	No	Yes	No	Yes	Yes (large)	Yes

Table 6.4 Operating Scenario: Sea-ice Detection Sensors for Vessel Transits (commercial 1994)

		Surface (sea):		*Airborne*						*Spaceborne*			
Attribute:	**Need:**	**Marine radar**	**Visual & Optical**	**SLAR** (e.g., CAL 200)	**SAR**	**Search radar**	**Laser Profilometer**	**Ice Probe**	**Visual & Optical**	**SAR**	**SPOT**	**NoAA**	**Passive microwave**
TACTICAL Spatial	0 to 10 km	<40 km All weather day/night	Limited by fog & darkness <10 km	All weather day/night Yes	All weather day/night Yes	All weather day/night Yes	Clear weather	Helicopter range	Good beneath clouds	All day/night 45 - 510	Clear weather only 60 km swath	Clear weather only 3000 km swath	All weather day/night 1300 km
Temporal	On demand	On demand	On demand	Overflights as required, if airport open	Overflights as required, if airport open	Overflights as required, if airport open	Helicopter flying weather required	Helicopter flying weather required	Overflights as required, if airport open	3 days	No every 26 days	No; 4 times per day	No 2 passes per day
Positional	500 m	Yes	Varies w/ range, visibility, sea state, 500 m	Yes	Yes	Yes	100 m (GPS accuracy)	100 m (GPS accuracy)	Yes	<1 km	Yes; 100 m	No; 1.1 to 2.5 km	No 25 km
Resolution	plus/minus 1/10	over limited range	possible within about 1 km	Yes	Yes	Yes	Not indicated	Not indicated	Yes	Yes	plus/minus 1/10	plus/minus 1/10	plus/minus 1/10
STRATEGIC Spatial	10 to 50 km	<40 km All weather day/night	Limited by fog & darkness <10 km	All weather day/night Yes	All weather day/night Yes	All weather day/night Yes	Helicopter range	helicopter range	Good beneath clouds	All day/night 45 - 510	Clear weather only 60 km swath	Clear weather only 3000 km swath	All weather day/night 1300 km swath
Temporal	3 to 6 hours	Yes	Yes	Overflights as required, if airport open	Overflights as required, if airport open	Overflights as required, if airport open	Helicopter on demand (flying restrictions)	Helicopter on demand (flying restrictions)	Overflights as required, if airport open	3 days typical	Every 26 days (13 if antenna steered)	4 times per day	2 passes per day
Positional	2 to 4 km	Yes	Yes	Yes	Yes	Yes	100 m	100 m	Yes	Yes <1 km	Yes; 100 m	1.1 to 2.5 km	25 km
Resolution	plus/minus 1/10	over limited range	within about 1 km of vessel	Yes	Yes	Yes	Not indicated	Not indicated	Yes	Yes plus/minus 1/10	Yes plus/minus 1/10	plus/minus 1/10	No plus/minus 1/10
Display	Map or graphic equivalent on vessel bridge	PPI on bridge or CRT digital	Visual only, or CRT	Downlink image to vessel	Downlink image to vessel	Downlink image to vessel	line record	None	Downlink map; optical - CRT	Hard copy or downlink from shore	Hard copy or downlink from shore	Downlink to ship	From shore
Ice characteristics	Concentration Ice edge Thickness Position/extent	Yes Yes No Yes	Yes < 1-5 km Yes No Yes	Yes Yes No Yes	Yes Yes No Yes	No Yes No Yes	No Yes No (implied) No	No Yes Yes No	Yes Yes No Yes	Yes Yes No Yes	Yes Yes No Yes	No Yes No Yes (large)	Yes Yes No Yes
Ice Type		No	Yes, up to about 1 km	Yes, interpret from imagery	Yes, interpret from imagery	Yes interpret from imagery	No	No; can be implied	Yes; general characteristics	Yes; can be inferred from imagery	Yes; can be inferred from imagery	No; can be inferred from imagery	Discriminate MY/FY using algorithm

6.2 ICE DETECTION SYSTEM SUMMARY

In order to synthesize the results of the study, each of the four operating scenarios, broken down by tactical and strategic requirements, were again taken as the starting point. For each of these, primary, secondary, and inappropriate sensor types are presented. Comments on the strengths and weaknesses of each sensor are included. This information is given in Tables 6.5 through 6.12.

From these tables, it can be seen that available technology is able to meet the majority of the operating requirements. In particular, it was felt that current technology meets the field development requirements for strategic iceberg detection, and for both strategic and tactical sea ice detection. For tactical iceberg detection, current technology is limited to low to moderate sea states in order to reliably detect smaller ice pieces. There can also be problems in detecting small glacial ice pieces in pack ice. For vessel transit requirements, the strategic iceberg detection requirement can be met. The tactical requirement is limited to low to moderate sea states. For sea ice detection, current technology can meet the main requirements, but identification of ice type and thickness cannot be performed under all conditions.

Although the requirements may be met with existing technology, very little has been said concerning costs of implementation, although qualitative costs are presented in Chapters 4 and 5. Clearly costs are always an operational consideration, and these may change substantially over the next decade as certain technologies become more widely available.

It is clear that the largest gap in existing capability lies in the reliable detection of small pieces of ice under high sea state, poor visibility conditions, and in pack ice. Therefore, these issues are appropriate for continued development work, both in terms of improving the sensors and in encouraging their field testing under realistic conditions. Both enhanced marine radar systems and new sonar systems have the potential to provide improved capability to overcome some of these limitations, especially as their performance is improved through improved computer processing in real-time. It appears that the basic sensor technology exists (for both sensor types), but that further field demonstration is required. As is typical, costs for newer sensors are still relatively high, but would be expected to decrease with wider commercial use.

Table 6.5: Summary of iceberg detection systems: tactical requirements for field development

PRIMARY SYSTEMS		SECONDARY SYSTEMS		NOT USEFUL SYSTEMS	
SENSORS	REASONS	SENSORS	REASONS	SENSORS	REASONS
marine radar on structure and support vessels	- moderate-cost, standard sensor capable of providing local iceberg detection on demand - good detection of small ice masses in low to moderate sea states - all-weather, day/night	airborne and satellite SAR/SLAR	- iceberg detection not 100% reliable - sensors operate over large area with reasonable to limited resolution - airborne sensor is not a true on-demand sensor, however, airborne SAR could be flown within few hours if dedicated to operation	SPOT, HRV NOAA AVHRR passive micro-wave	- not on demand (although NOAA has high frequency of coverage - NOAA and passive micro-wave cannot resolve icebergs - SPOT and NOAA are not all-weather, day/night
visual from structure and support vessels	- obviously part of operation, although limited by poor weather conditions	surface HF radar	- on demand - fixed, limited area of coverage (acceptable for most of Grand Banks) - only medium to large icebergs		
search radar	- sensor with best possibility of detecting icebergs down to 1,000 t in low sea states and 10,000 t in moderate sea states - not a true on-demand sensor (generally flights are scheduled, but on 2-to 4-hour notice) - must be part of greater over-all system - discriminating targets needs visual or FLIR confirmation				
CONCLUSIONS: Available sensors will satisfy user requirements in low sea states; limited in moderate to high sea states.					

Notes:

Tactical requirements are for:

- large icebergs to growlers within 40 km of the site.
- information on demand for icebergs of 1,000 t and greater, with positional accuracy of 100 to 500 m.

Table 6.6: Summary of iceberg detection systems: strategic requirements for field development

PRIMARY SYSTEMS		SECONDARY SYSTEMS		NOT USEFUL SYSTEMS	
SENSORS	REASONS	SENSORS	REASONS	SENSORS	REASONS
search radar	- not true on-demand sensor, but can be used within context of monitoring system - high resolution over all iceberg sizes	airborne visual and optical sensors	- clear weather only - good for distinguishing icebergs from ships, etc. - limited coverage with respect to aircraft flight path - spatial resolution of optical sensors degrades with increased flying height - photography has good resolution but requires development time	NOAA, SPOT, passive microwave	- not on demand (although NOAA provides frequent coverage - cannot resolve icebergs - NOAA and SPOT are not all-weather or day/night sensors
airborne SAR/SLAR	- broad coverage - good detectability under moderate sea conditions for large to small icebergs	marine radar on support vessel	- vessel could be sent out any distance to investigate - marine radar aspects described in previous table	marine radar	- limited range
satellite SAR	- as above, with limited coverage frequency	surface HF radar	- on demand, but only capable of detecting medium to large icebergs - good for sequential tracking, eliminating need for re-identification and providing motion information - limited, fixed area of coverage		
CONCLUSIONS: Available sensors satisfy user needs in any conditions					

Notes:

Strategic requirements are for:

- large to small icebergs and groups of bergy bits and growlers 40 to 200 km from site.
- preferably on demand, but sequential coverage on time scales of 1 to 2 days is adequate with positional accuracies of 1 to several km.

Table 6.7 Summary of sea-ice detection systems: tactical requirements for field development

PRIMARY SYSTEMS		SECONDARY SYSTEMS		NOT USEFUL SYSTEMS	
SENSORS	REASONS	SENSORS	REASONS	SENSORS	REASONS
marine radar on structure and support vessels	- moderate-cost, standard sensor capable of providing local iceberg detection on demand - good detection of ice edge in low to moderate sea states to range of several km. - all-weather, day/night	airborne and satellite SAR, airborne SLAR	- not true on-demand sensors - sensors operate over large area with high resolution (SAR), moderate resolution (SLAR) - airborne sensors can be flown within few hours if dedicated to operation	SPOT, NOAA, passive microwave	- not on-demand (although NOAA has high frequency of coverage) - NOAA and passive microwave have low resolution - SPOT and NOAA are not all-weather
visual on structure and support vessels	- obviously part of operation, although limited by poor weather conditions	search radar	- not true on-demand sensor (generally flights are scheduled, but on 2 to 4 hour notice - acceptable for determining ice edge, but not for discriminating ice features within pack ice		
		surface HF radar	- on deamand - fixed, limited area of coverage (acceptable for most of Grand Banks) - gives ice edge only, not features		

CONCLUSIONS:

Available sensors will satisfy user requirements.

Notes:

Tactical requirements are for:

- ice edge, concentration, position, and extent within 40 km of the site.
- information on demand.
- concentration resolution of +/- 1-tenth, with accuracy of 100 to 500 m.

Table 6.8: Summary of sea-ice detection systems: strategic requirements for field development

PRIMARY SYSTEMS		SECONDARY SYSTEMS		NOT USEFUL SYSTEMS	
SENSORS	REASONS	SENSORS	REASONS	SENSORS	REASONS
airborne SAR/SLAR	- broad coverage - good detectability under moderate sea conditions for all sea ice - ice type can be inferred from imagery	airborne visual and optical sensors	- clear weather only - limited coverage with respect to aircraft flight path - photography has good resolution but requires development time	SPOT	- not on demand - requires clear weather and daylight
satellite SAR	- as above, but limited coverage frequency	search radar	- not truly on demand, but can be used within the context of an monitoring system - providesonly ice edge, not ice surface features	marine radar on structure	- provides on-demand information on ice local to site but not at distance
NOAA	- inexpensive and can be downlinked directly to shore based office or rig - frequent daily coverage - large aerial coverage - provides very useful definition of ice cover - not all weather	surface HF radar	- on demand but only capable of detecting ice edge, not surface features - good for sequential tracking - can provide information on changes		
passive microwave	- all weather, day/night - very coarse spatial resolution - provides ice type - data can be provided within few hours of satellite overpass	marine radar and visible on support vessels	- sensors available - vessel can be sent out to any distance from structure		
CONCLUSIONS: Available sensors satisfy user needs in any conditions.					

Notes:

Strategic requirements are for:

- ice edge, concentration, position, extent and ice type within 40 to 200 km from site.
- information should be available in 1 - 2 days, with positional accuracy of 2 to 4 km.
- concentration resolution of +/- 1/10.

Table 6.9 Summary of iceberg detection systems: tactical requirements for vessel transits

PRIMARY SYSTEMS		SECONDARY SYSTEMS		NOT USEFUL SYSTEMS	
SENSORS	REASONS	SENSORS	REASONS	SENSORS	REASONS
marine radar	- moderate-cost, standard sensor capable of providing local iceberg detection on demand - good detection of small ice masses in low to moderate sea states. - all-weather, day/night	airborne SAR/SLAR	- not true on demand sensors - iceberg detection not 100% reliable - sensor operates over large area with good resolution - could be flown within a few hours if dedicated to operation	SPOT, NOAA, satellite SAR, passive microwave	- not on demand (although NOAA has high frequency of coverage) - NOAA and passive microwave cannot resolve icebergs - SPOT and NOAA are not all-weather, day/night
visual reconnaissance	- obviously part of operation, although limited by poor weather conditions	surface HF radar	- on demand - fixed, limited area of coverage (current system covers NW Grand Banks to Newfoundland shore)		
		search radar	- sensor with best possibility of detecting icebergs down to 1,000 t in low sea states and 10,000 t in moderate sea states - not true on demand sensor - must be part of greater over-all system - discriminating targets needs visual or FLIR confirmation		
CONCLUSIONS: Available sensors will satisfy user requirements in low sea states; limited in moderate to high sea states					

Notes:

Tactical requirements are for:

- presence of growlers, bergy bits, and larger within 5 km of vessel.
- information on demand for icebergs of 1,000 t and greater, with positional accuracy of 100 m.

Table 6.10 Summary of iceberg detection systems: strategic requirements for vessel transits

PRIMARY SYSTEMS		SECONDARY SYSTEMS		NOT USEFUL SYSTEMS	
SENSORS	REASONS	SENSORS	REASONS	SENSORS	REASONS
search radar	- not true on-demand sensor but can be used within context of a monitoring system - high resolution over all iceberg sizes	airborne visual and optical sensors	- clear weather only - good for distinguishing icebergs from ships etc. - limited coverage with respect to aircraft flight path - photography has good resolution but requires development time - spatial resolution of optical sensors degrades with increased flying height	NOAA, SPOT, passive microwave	- not on demand (although NOAA has high frequency of coverage) - NOAA and passive microwave cannot resolve icebergs - SPOT and NOAA are not all-weather
airborne SAR, SLAR	- broad coverage - good detectability under moderate sea conditions for large to small icebergs	satellite SAR	- limited coverage frequency - good detectability under moderate condtions for large and small icebergs - sensor of opportunity	visual on vessel	- useful range limited
marine radar on vessel	- moderate-cost standard system capable of providing local iceberg detection on demand - good detection of small ice masses in low to moderate sea states - all-weather, day/night - advanced systems can provide discrimination of icebergs in pack ice	surface HF radar	- on demand, but only capable of detecting medium to large icebergs - good for sequential tracking, of icebergs - current system useful only in area of NW Grand Banks to Newfoundland shore		

CONCLUSIONS:

Available sensors will satisfy user requirements in low sea states; limited in moderate to high sea states..

Notes:

Strategic requirements are for:

- presence of bergy bits, growlers, and larger from 5 to 30 km from vessel.
- information on-demand of icebergs of 10,000 t and greater, with positional accuracy of 500 m.

Table 6.11 Summary of sea-ice detection systems: tactical requirements for vessel transits

PRIMARY SYSTEMS		**SECONDARY SYSTEMS**		**NOT USEFUL SYSTEMS**	
SENSORS	REASONS	SENSORS	REASONS	SENSORS	REASONS
marine radar	- moderate-cost standard system capable of providing local sea ice detection on demand - all-weather, day/night	airborne SAR, SLAR	- not true on-demand sensor - sensor operates over large area with good resolution - could be flown within a few hours if dedicated to operation	SPOT, NOAA, satellite SAR, passive micro-wave	- not on demand (although NOAA has high frequency of coverage) - SPOT and NOAA are not all-weather
visual	- obviously part of operation, although limited by poor weather conditions	search radar	- not true on-demand sensor (generally flights are scheduled, but on 2 to 4 hour notice) - acceptable for determining ice edge, but not for discriminating ice features within cover	surface HF radar	- on demand - fixed, limited area of coverage (current system covers NW Grand Banks to Newfoundland shore) - gives ice edge only, not ice features
		Ice Probe	- requires helicopter - gives approximate ice strength		
CONCLUSIONS: Available sensors will satisfy much of the user's requirement, but will not guarantee identification of ice types and thickness under all environmental conditions.					

Notes:

Tactical requirements are for:

- ice edge, concentration, position, extent, ice type, and thickness within 10 km of vessel.
- information on-demand.
- concentration resolution of +/- 1/10, with accuracy of 500 m.

Table 6.12 Summary of sea-ice detection systems: strategic requirements for vessel transit

PRIMARY SYSTEMS		SECONDARY SYSTEMS		NOT USEFUL SYSTEMS	
SENSORS	REASONS	SENSORS	REASONS	SENSORS	REASONS
marine radar	- provides on-demand information on ice within near regions of critical range - all weather, day/night	search radar	- not truly on demand, but can be used within the context of a monitoring system - provides only ice edge, not ice surface features	SPOT	- not on-demand - requires clear weather and daylight
airborne SAR/SLAR	- broad coverage - good detectability under moderate conditions for all sea ice - ice type can be inferred from imagery - not truly on demand	surface HF radar	- on demand but only capable of detecting ice edge, not surface features - good for sequential tracking, - can provide motion information	visual on vessel	- limited by range
satellite SAR	- good detectability under moderate conditions for all sea ice - orbit must coincide with period of need	visual reconnaissance on aircraft	- limited by weather conditions		
		NOAA, passive microwave	- NOAA limited by cloud cover - passive microwave can give ice type		
CONCLUSIONS: Available sensors will satisfy much of the user's requirement, but will not guarantee identification of ice types and thickness under all environmental conditions.					

Notes:

Strategic requirements are for:
- ice edge, concentration, position, extent, ice type, and thickness from 10 to 50 km from vessel.
- information should be available in 3 - 6 hours, with positional accuracy of 2 to 4 km.
- concentration resolution of +/- 1/10.

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ABBREVIATIONS

ADS	automated dependent surveillance
AES	Atmospheric Environment Service (Environment Canada)
AIMR	airborne imaging microwave radiometer
AMI	active microwave instrument, on *ERS-1*
ARPA	Automated Radar Plotting Aids
AVERT	automated vessel alert
AVHRR	advanced very high resolution radiometer
CAL	Canadian Astronautics Ltd.
CASI	compact airborne spectrographic imager
CCD	charge coupled device
CCMC	Canadian Centre for Marine Communications
CCRS	Canada Centre for Remote Sensing (Natural Resources Canada)
CFAR	constant false alarm rate
CPA	Canadian Petroleum Association
CRL	Communications Research Laboratory (McMaster University)
DFO	Department of Fisheries and Oceans
DMA	direct memory access
DMSP	Defense Meteorological Satellite Program (U.S. Department of Defense)
DSC	digital selective calling
DSP	digital signal processor
EDI	electronic data interchange
EM	electromagnetic
ERS-1	Earth Resources Satellite (European Commission)
ESP	environmental signal processor
ETM	enhanced thematic mapper
FLAR	forward-looking airborne radar
FLI	fluorescence line imager
FLIR	forward-looking infra-red
GBS	gravity based structure
GEO	geosynchronous earth orbit
GMDSS	Global Maritime Distress Safety System
GPS	Global Positioning System
GWR	ground-wave radar
HEO	highly elliptical orbit
HF	high frequency (3 - 30 MHz)
HRV	high return vidicom
IFOV	instantaneous field of view
IIP	International Ice Patrol (United States Coast Guard)
IPIX	intelligent pixel-processing radar (McMaster University)
IPS	ice profiling system
IR	infra-red

JERS-1	Japanese Earth Resources Satellite
kts	knots
LEO	low earth orbit (less than 1,000 miles altitude)
MEO	medium earth orbit (1,000 - 10,000 miles altitude)
MF	medium frequency (0.3 - 3 MHz)
MODU	mobile offshore drilling unit
MSAT	mobile satellite
NCAR	National Center for Atmospheric Research (U.S.)
nmi	nautical miles
NOAA	National Oceanic and Atmospheric Administration (U.S.)
NRSL	Northern Radar Systems Ltd.
NUSC	Naval Underwater Systems Center (U.S.)
OLS	offshore loading system
OS	ordered statistic
OTH	over-the-horizon radar
PPI	plan position indicator
RF	radio frequency
SAR	synthetic aperture radar
SFSI	SWIR full spectrum imager
SITOR	simplex teleprinting over radio
SLAR	side-looking airborne radar
SODAR	sound detection and ranging
SOLAR	safety of life at sea
SPOT	Système Probatoire Pour l'Obervation de la Terre (France)
SSB	single side-band
SSM/I	special sensor microwave/imager, on DMSP satellites
STAR-1, -2	synthetic aperture radar systems of Intera Technologies (Canada) Ltd.
STC	sensitivity time control
SWIR	short-wave infra-red
TDI	time domain integration
TIR	thermal infra-red
TM	thematic mapper
UHF	ultra high frequency (300 - 3,000 MHz)
UV	ultraviolet
VHF	very high frequency (30 - 300 MHz)

APPENDIX 1 - SUMMARY OF ENVIRONMENTAL CONDITIONS

This appendix provides a summary of the key environmental conditions that affect ice detection off the East Coast. Data for the Scotia Shelf and Grand Banks areas are presented.

A1.1 SCOTIA SHELF

Information for this section comes from the Cohasset/Panuke Development Project. Preliminary Development Plan, Part 1, June 1989, Chapter 6, Meteorology and Oceanography and references quoted therein. The Marine Climatological Database is from the Mobil Oil Venture Project Environmental Impact Statement, 1983-84.

A1.1.1 Temperature

Figure A1.1 shows the air temperature variation for the Scotia Shelf. The maximum temperature which has been recorded in summer is 31.3°, and minimum temperature in the winter, -20.2°C. Even during the coldest month (February), the temperature is below 0° C for only about 4% of the time.

A1.1.2 Wind

The Marine Climatological Database was accessed to develop the wind statistics. The data are essentially for the area 42°45'-45°00'N and 59°00'-63°00'W. The annual mean wind is 9.6 m/s (18.9 kts) from 258°T, ranging from a high of 11.9 m/s (23.3 kts) at 279°T in January, to a low of 6.8 m/s (13.3 kts) 230°T in August. The maximum measured wind speed is 48 m/s (94 kts), which was measured in June. The 100-year extreme wind speed is calculated to be 52 m/s (101 kts) (1-hour) and 70 m/s (138 kts) (3-s gust). These extreme winds were determined from an analysis of 300 wind storms compiled for the general area. Values obtained by other means vary significantly from these values.

A1.1.3 Precipitation

These data are from the Marine Climatological Database. Precipitation varies between rain in summer and snow in winter. Precipitation is most frequent during the winter months (December to March), and varies between 41% (12.7% rain and 28.4% snow) in January and 9% (all rain) in July.

A1.1.4 Atmospheric Icing

Icing from sea spray, freezing rain, drizzle, fog or cloud droplets is essentially restricted to the months December through March. The greatest potential for icing (25.3%) occurs in February.

A1.1.5 Sea Ice

Sea ice rarely extends into this area.

A1.1.6 Waves

Knowledge of the wave climate is required for the design of offshore structures and for selecting equipment that will be able to operate in the wave conditions which are generally present.

The most appropriate data set available for establishing the wave climate in the area is the ODGP (Ocean Data Gathering Program) which consists of a 3-year time series of directional wave information calculated for selected grid point locations. Wave height, period, and spectral wave energies are available for each gird point every 6 hours. Wave heights calculated from these data have been verified against wave rider buoy data from MEDS (Marine Environmental Data Service).

Figure A1.2 shows the percent exceedance wave heights based on the above data set for significant and maximum wave heights. This indicates that 10% of waves are above 4 m significant height and 8 m maximum. Peak periods range from 5 to 10 seconds. The maximum monthly wave varies from 9.9 m (14.5 s maximum period) in October to about 4.4 m (10.6 s maximum period) in June. The percentage exceedance wave height distribution indicates the percent of downtime which might be expected by offshore structures and vessels. Floating systems are generally affected by waves over several meters significant wave height, although the wave climate in this area is relatively mild compared to that in other areas.

Extreme wave amplitudes and return periods are required for structural design. The extreme waves are based on a study of 50 storms over 30 years in the Scotia Shelf and Grand Banks region. The 100 year return period significant wave height is 11.75 m with a peak period of 17.23 s.

A1.1.7 Tides

Tides in this area have been obtained by means of models. The most dominant component is the lunar semidiurnal component. The maximum tidal height is typically 0.9 m. The height occurs at the peak of the tidal cycle, 2 cycles each day, during the spring tides (twice a month). The maximum tidal elevation on Sable Island bank is 1.6 m.

A1.1.8 Storm Surges and Tsunamis

The maximum water level changes caused by the passage of severe storms through the area have been estimated from the Sable Island area. The 50 and 100 year return period values for a site located west of Sable Island were 0.55 and 0.62 m, respectively. These are considered representative of sites offshore.

Tsunamis are rare in this area. A Grand Banks earthquake caused a maximum wave amplitude of 0.5 m..

A1.1.9 Currents

All historical current meter data have been collected from the Scotia Shelf. The maximum near surface current is 111.7 cm/s, measured in July. Mean monthly currents are typically 20±10 cm/s at both the surface and near-bottom.

Tidal currents vary from 68.7 cm/s at 10 m, 48.72 cm/s at 24.6 m and 37.46 cm/s at 43.6 m.

A1.2 GRAND BANKS

Information for this sector comes from the Hibernia Development Project, Environmental Impact Statement, Volume II, Project Description and Volume IIIa, Biophysical Assessment, written by Mobil Oil Canada Ltd., 1985. Except as noted, most results were taken at the Hibernia site.

The climate of the Grand Banks is determined principally by general atmospheric circulation and by its location near the boundary between a large continent and a large ocean. During winter, continental arctic air moving offshore is rapidly warmed by the underlying ocean waters, becomes unstable and may present snow squalls. During summer, warm humid air from the south reaches the cold waters of the Grand Banks causing low cloud, fog, drizzle and consequently, low visibility.

The most intense storms which reach the Grand Banks, generally from the south, develop rapidly over the ocean to the south of Nova Scotia, and move northward quickly. Storms are more frequent and intense in winter than in summer. The Grand Banks, because of its location, is prone to storms in all seasons and at no time can be expected to be free of storms for any prolonged period. Tropical weather systems form in the trade wind belt of the North Atlantic. Once formed, a hurricane will continue as long as a sufficient supply of warm humid air is available.

A1.2.1 Temperature

Figure A1.3 shows the air temperature variation for the Hibernia area. During the summer, the mean daily temperature is 12°C and in winter 0°C at Hibernia (compared to 15°C in summer and -5°C in winter, respectively, in St. John's). The maximum temperatures recorded are 26.8°C in summer and -13.7°C in winter.

A1.2.2 Wind

On a seasonal basis, there are significant changes in both the direction and the speed of winds at the Grand Banks. In winter, westerly winds dominate, while in summer southwesterly winds are most common. Wind speeds are greater in winter than in summer. In winter, 50% of winds are approximately 10 m/s (20 kts) or greater, while in summer, 50% of winds are 6 m/s (12 kts) or greater. The maximum hourly wind actually observed at Hibernia is 40 m/s (80 kts), from the south, in February, and the strongest gust is 47 m/s (92 kts) again from the south in February. The calculated 100 year wind, 1 minute duration, is 40 m/s (80 kts). A study of wind persistence indicates that winds can exceed 13 m/s (25 kts) for about 6 hours from any direction.

A1.2.3 Visibility

Restricted visibility due to fog affects aircraft and marine operations. Advection fog, which occurs in summer when warm air moves across the cold waters of the Grand Banks, is the most common type of fog. Frontal fog, caused by precipitation from warm air aloft falling into colder air near the earth's surface also occurs, particularly in winter. An analysis of well site data indicates that the occurrence of fog resulting in visibility less than 1 km, varies from 40% in winter to over 80% in June and July. Fog forms when winds are from the southwest or south and visibility is at its best when winds are from the west through north.

A1.2.4 Precipitation

The data described here are for St. John's as no long term records are available for precipitation offshore. Mean annual rainfall is 1514 mm accumulating over a period of 217 days. The mean annual snowfall is 359 cm falling on an average of 88 days. About twice as much precipitation occurs in winter (167 mm in December over about 22 days) compared to summer (83 mm in July over 13 days). The monthly extremes are uniformly high with approximately 200 mm or more having been recorded in all months.

On the Grand Banks, rain has been observed in all months and snow in all months except July and August. Heavy rains generally occur most frequently between June and November and heavy snow most commonly in February.

Freezing precipitation, when the rain or drizzle freezes on impact with a surface, is not uncommon in the Newfoundland area. Such precipitation, which can produce intense glaze or ice storms, is generally short lived, although it once occurred continuously for 48 hours in St. John's. On the Grand Banks, freezing precipitation can occur in up to .4% of hourly observations in January and February and at St. John's, up to 5% of observations.

A1.2.5 Atmospheric Icing

Heavy superstructure icing occurs most often along the eastern edge of land masses which are very cold in winter. Based on wind and temperature observations, the potential for freezing spray on the Grand Banks has been estimated to vary from 15% for light to 2% for heavy spray ice potential in February, the worst month.

A1.2.6 Ice

Both sea ice and icebergs affect the study area. The data presented here originate from about 70 years of observations by the International Ice Patrol, 30 years of ice reconnaissance flights, 15 years of satellite data, 5 years of rig data, and historical records from coastal stations and ships at sea.

A1.2.6.1 Sea ice

Sea ice is an operational consideration for systems that will be working off Newfoundland's southeast coast for long periods of time. Most of the ice encountered is carried down from the north by the Labrador current but strong ocean currents and frequent westerly winds tend to keep a large portion of the ice off the Grand Banks. Ice forms off the Labrador coast in early December and moves southward, meeting the warmer water and air temperatures on the Grand Banks. Northwesterly winds keep the ice offshore. Easterly or northeasterly winds from cyclones often interrupt the prevailing westerlies and cause dramatic influxes of ice on the Grand Banks.

Over the period 1960 to 1984, ice came within 46 km of the Hibernia site in 12 of the 25 years. In 2 years the extreme edge of the ice reached the site in late March and persisted for less than 6 weeks. The most severe period was between 1972 to 1977 when ice reached the site every year. Ice concentration at the site was generally less than 6/10 of young and first-year ice; the maximum concentration reported during the 25 years was over 9/10 of young and first year ice. Figure A1.4 shows the median historical southern extent of the ice on April 2, the maximum historical extent, and the 1983 limit; 1983 being a bad year.

Ice in the area is in the form of small floes, typically 30 m in diameter. Big floes over 500 m diameter are rare south of 50°N. Ice thickness is determined by the characteristics of the ice carried into the region by the Labrador current, as minimal local ice growth occurs. Ice thicknesses of 2 m maximum are common.

The ice in the area consists of highly deformed but largely unconsolidated floes. Compared to the Arctic, ridges are small, with heights of typically 1 to 2 m sail height, 4 to 10 m keel depth. Due to the warm water on the Grand Banks, the keels are expected to be unconsolidated and eroded.

A1.2.6.2 Icebergs

Icebergs are the most formidable environmental consideration for the design and operation of Grand Banks production because of their size, mass and energy. The waters off the Labrador coast are often referred to as "Iceberg Alley" since high numbers of icebergs move through them each year. Icebergs encountered along the east coast of Canada originate mainly from glaciers in western Greenland, but also from eastern Greenland and Ellesmere Island. The icebergs travel southward along the coasts of Baffin Island and Labrador. About 40,000 medium sized icebergs calve each year. Typically, more than 400 icebergs cross the 48th parallel annually but this can vary from zero to over 2,000 in any year, see Figure A1.5. These bergs are highly variable in size, mass and shape and, recognizing processes such as deterioration and calving, can be present in sizes ranging from a few meters to hundreds of meters and masses from hundreds to millions of tonnes. Large icebergs are of most importance in terms of the global loads that they may impose on structures but can also develop high local loads during their failure process. Bottom founded structures may be designed to withstand these loads while floating structures must avoid them. Smaller ice masses moving at high speed are also of concern to both types of systems due to the high local impact loads they can exert.

The mean and maximum iceberg sizes are indicated in Table A1.1. The relatively shallow water depths of the Grand Banks tend to act as a filter, eliminating the occurrence of extremely large icebergs which normally have very deep keels. Many of the icebergs drifting in this area are inherently unstable while reasonably high frequency of smaller ice masses are also expected.

When deep icebergs move into shallow water, their keels may contact the seabed and the iceberg may either rotate, if unstable, or scour the seabed, possibly damaging well head devices and pipelines. The length, depth, and width of a scour depends on the shape of the keel of the scouring iceberg. Figure A1.6 shows the depth, width and number of scours in the vicinity of Hibernia. Scours are typically dish shaped in cross section and oriented north-northeast to south southwest, aligned with the prevailing current. Most scours on the Grand Banks are in water depths of 110 to 170 m and 250 to 260 m, the number decreasing dramatically in water depths of 70 to 100 m. A typical scouring frequency of $0.074/\text{km}^2$ has been measured on the Grand Banks. The greatest scour depth measured is 7 m in 160 m of water approximately 90 km from the Hibernia site.

A1.2.7 Waves

The wave climate is not unlike the North Sea with 100 year significant wave heights of 15 m, maximum wave heights in the order of 30 m, and a peak period of 16 s. The area is typically rough with frequent occurrences of moderate to high seas and longer period swell, particularly during the fall and winter periods when storms move through the region. Extreme waves and the associated loadings govern the design of fixed production structures with load magnitudes depending upon the structural cross section exposed to wave attack.

A1.2.8 Tides

Tides at the Grand Banks are semi-diurnal. The maximum astronomical and storm tide is 1.7 m.

A1.2.9 Currents

Currents in the Grand Banks area are dominated by the Labrador Current which comes down from the north and its many branches, the Slope Water Current which comes from the west and is a mixture of North Atlantic water from the Gulf Stream, freshwater runoff from the St. Lawrence

River, and cold fresh water from the Labrador Current. The Gulf Stream brings warm saline water in from the south. Typical current speeds over the Grand Banks are 2 - 15 cm/s for the Labrador Current, 25 cm/s for the Slope Water Current, and 50 - 100 cm/s for the Gulf Stream.

Surface circulation over the Grand Banks is caused by the above currents and the winds, waves, tides and water density gradients. Maximum near-surface currents at the Grand Banks range from 60-80 cm/s during the late summer and early autumn and from 45-60 cm/s in winter. Tidal currents have maximum speeds of 28 cm/s at 25 m, 18 cm/s at 50 m, and 15 cm/s at 80 m depth.

The 100 year extreme currents, as a result of summing the above, are 125 cm/s at the surface, 89 cm/s at 50 m, and 45 cm/s at 90 m depth.

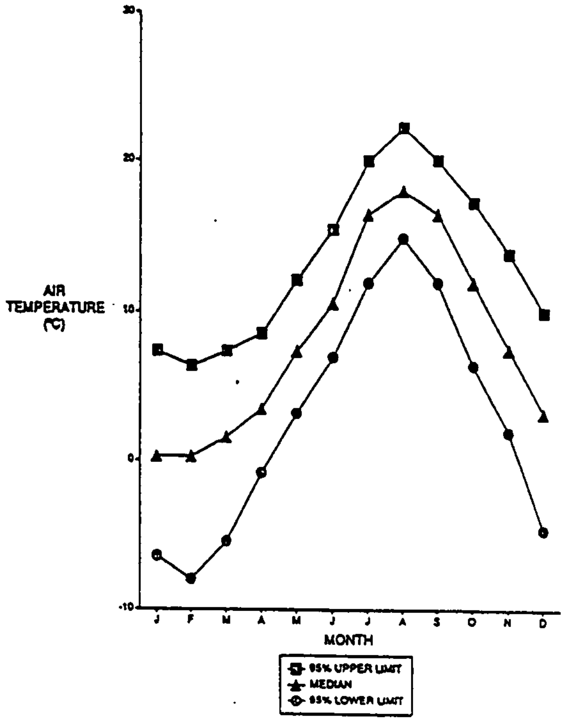

Figure A1.1: Temperature - Scotia Shelf

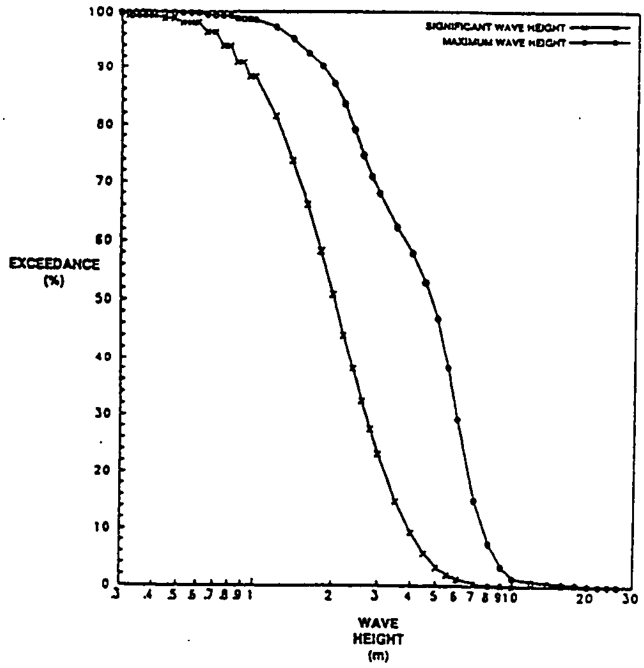

Figure A1.2: Percentage Exceedence, Wave Heights - Scotia Shelf

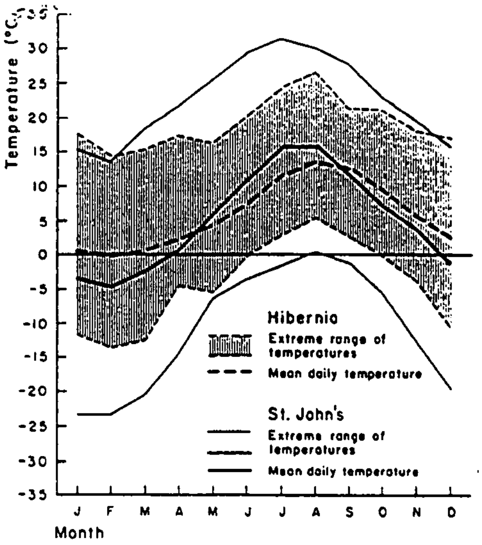

Figure A1.3: Temperature - Hibernia

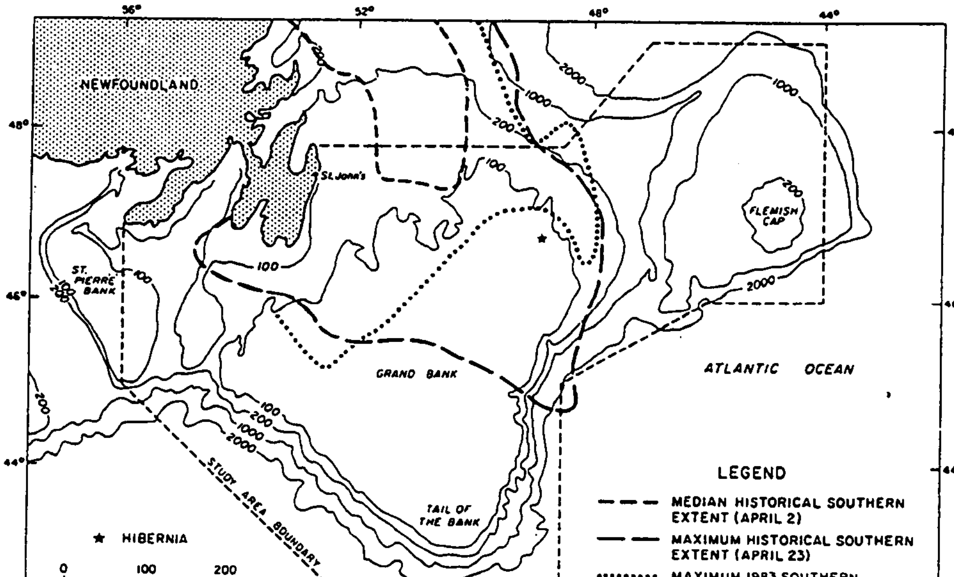

Figure A1.4: Sea Ice Extent - Grand Banks

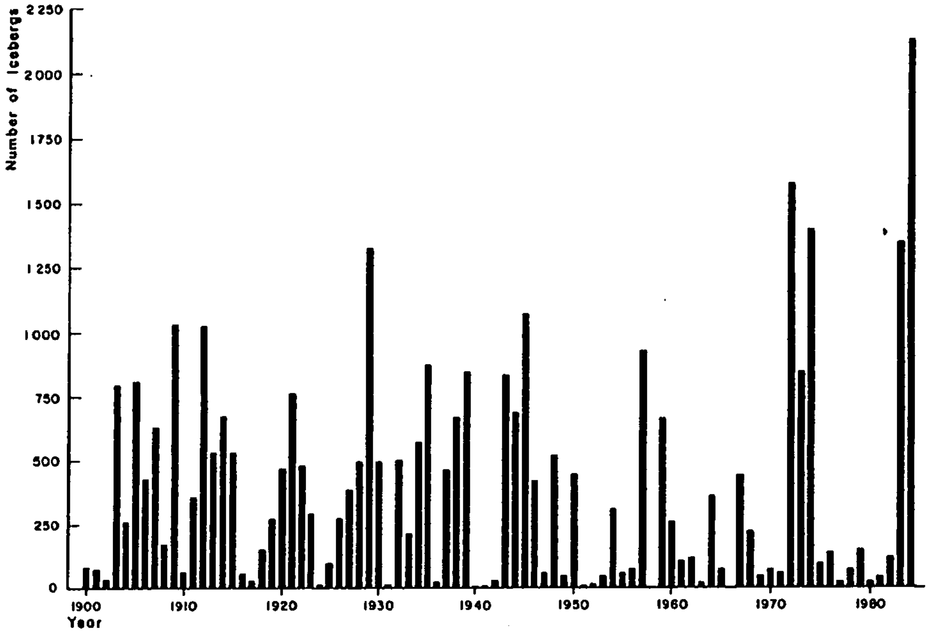

Figure A1.5: Numbers of Icebergs Drifting South of 48°N.

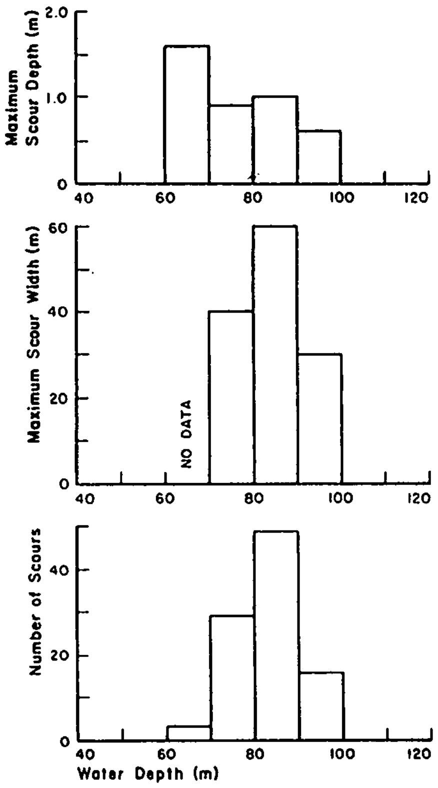

Figure A1.6: Size of Iceberg Scours - Hibernia

Table A1.1: Mean and Maximum Iceberg Dimensions.

	Mean	Maximum
Draft	95 m	200 m
Mass (t x 10^6)	0.6	10
Sail Height	20 m	70 m
Longest Waterline Length	110 m	320 m

APPENDIX 2 - RADAR PERFORMANCE CALCULATIONS

Model runs have been made from a predetermined matrix of iceberg length and wave height (C-CORE, 1992). Table A2.1 provides this matrix and indicates with an 'X' the combinations that have been run. Cases were selected such that transitions between detectable and not detectable could be ascertained without running all the cases in the matrix. This was accomplished by performing preliminary runs to bracket the cases of interest and then filling in the matrix where required. It has been assumed that the iceberg height is one third of its length and that wind speed will be taken as that corresponding to a fully developed sea for the selected significant wave height.

Table A2.1 Summary of radar performance model runs

Iceberg		**Significant Wave Height (m)/Windspeed (m/s)**							
Length (m)	Area (m^2)	1/6	3/11	5/14	7/17	9/20	11/22	13/25	15 /26
5	8	X							
10	33	X	X						
20	133	X	X	X		X			
30	300		X	X	X	X			
40	533			X	X	X			
50	833			X	X	X			X
60	1200								X
70	1633								X
80	2133								X
90	2700								
100	3333			X		X			X

All the cases of Table A2.1 were run assuming no rain or fog present and the radar is looking into the wind. A number of additional runs (not shown) were made to illustrate the effect of rain, fog and look direction on performance.

Tables A2.2 to A2.5 present the detection results obtained. The ranges are given in kilometers and represent the maximum range for each combination of parameters. Detection often occurs in range intervals; however, for these tables the maximum detection range has been taken.

Table A2.2 Maximum iceberg detection range using platform-mounted X-band radar

	Significant Wave Height (m)					
Iceberg Length (m)	1	3	5	7	9	15
5	0	0	0	0	0	0
10	0	0	0	0	0	0
20	23	0	0	0	0	0
30	30	0	0	0	0	0
40	32	32	0	0	0	0
50	36	36	36	36	35	0
60	36	36	36	36	36	0
70	36.5	36.5	36.5	36.5	36.5	0
80	37	37	37	37	37	37

Table A2.3 Maximum iceberg detection range using platform-mounted S-band radar

	Significant Wave Height (m)					
Iceberg Length (m)	1	3	5	7	9	15
5	0	0	0	0	0	0
10	13	0	0	0	0	0
20	19	0	0	0	0	0
30	22	22	0	0	0	0
40	24	24	2	0	0	0
50	28	28	28	28	4	0
60	31	31	31	31	31	7
70	33	33	33	33	33	33
80	35	35	35	35	35	35

Table A2.4 Maximum detection range using vessel-mounted S-band radar

	Significant Wave Height (m)					
Iceberg Length (m)	1	3	5	7	9	15
5	0	0	0	0	0	0
10	6.5	0	0	0	0	0
20	9.5	9.5	0	0	0	0
30	12	12	12	0	0	0
40	14.5	14.5	14.5	14.5	0	0
50	17	17	17	17	17	17
60	19	19	19	19	19	19
70	21	21	21	21	21	21
80	22	22	22	22	22	22

Table A2.5 Maximum iceberg detection range using APS-504(V)5 airborne search radar

	Significant Wave Height(m)					
Iceberg Length (m)	1	3	5	7	9	15
5	29	0	0	0	0	0
10	39	0	0	0	0	0
20	46	46	46	0	0	0
30	51	51	51	51	50	0
40	54	54	54	54	54	0
50	56	56	56	56	56	56
60	58	58	58	58	58	58
70	60	60	60	60	60	60
80	63	63	63	63	63	63