Operational Sea Ice Monitoring by Satellites In Europe

FINAL REPORT

OSIMS REPORT No. 4

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by

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The cover photo: The vessel “Erika Dan” in polar ice near Qaqortoq on the south-west coast of Greenland.
Photograph taken by: Hans Valeur, DMI.

PROJECT SUMMARY

OBJECTIVES

The overall objective is to study the feasibility and cost benefits of using satellite data in operational ice monitoring and propose concepts for optimal use of satellite data in future sea ice monitoring and forecasting.

WHO WILL BENEFIT FROM THE WORK

Institutions with responsibilities and interests in operational sea ice monitoring, both in the public and private sector, will benefit from the study. These include national ice centres, weather services, sea transport authorities, shipping companies, oil companies, offshore industry and remote sensing value-added companies. Also space agencies such as ESA will benefit from the project in the planning of future missions for sea ice monitoring.

WORK TO BE PERFORMED

The study will start with a review of current ice monitoring activities in all countries where sea ice is a relevant problem. The organisation of sea ice monitoring and the users of sea ice information will also be described. User requirements and cost benefits of using satellite data in ice monitoring will be investigated. Changes in current ice monitoring services as a consequence of satellite data will be analysed. The technical feasibility of missions, instruments and ground structure for an operational ice monitoring system will be studied. Towards the end of the project concepts for optimal use of space data in ice monitoring and forecasting including EUROGOOS applications will be proposed. It is expected that there will be different concepts for the public and private sector, and that optimal solutions will vary from one region to another.

EXPECTED RESULTS

The study will identify problems related to operation use of satellite data in sea ice monitoring. The role of the different types of satellite data will be clarified, especially SAR data which are expected to be the most important source of information. The project will propose solutions for optimal use of satellite data in combination with other data, and describe requirements for future missions designed for sea ice monitoring.

PROJECT PARTICIPANTS

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PROJECT REPORTS

OSIMS report no.1: Description of ice monitoring systems and their users (WP1) and analysis of satellite data used in ice monitoring (WP2), June 1998.

OSIMS report no.2: Investigation of user requirements and cost benefits of using satellite data in ice monitoring (WP3), June 1998.

OSIMS report no.3: Technical feasibility of sensors, interments and ground structure and proposed concepts for optimal ice monitoring systems June 1998.

OSIMS report no.4: Final Report June 1998.

Contents

Executive Summary

The OSIMS project, performed in the period from November 1996 to May 1998, has investigated technical feasibility and benefits of using new satellite data in operational ice monitoring and forecasting. The project has studied the requirements for ice information from practical users such as ship traffic, icebreakers and offshore industry with focus on the Baltic Sea, the Greenland area and the Northern Sea Route. The implications of rapidly changing computer and communication technology on today's ice services, and the role of the private sector versus the public sector, have been discussed. The study has in its conclusion listed a number of requirements for future satellite systems to be used for cost-effective data acquisition in operational ice monitoring.

In the first part of the study sea ice monitoring activities in most countries where sea ice is a relevant problem have been reviewed and the role of satellite data discussed. The most important areas for ice monitoring in Europe are the Baltic Sea region, the Barents Sea and Svalbard area, the Russian Arctic, and the waters surrounding Greenland and Iceland. Outside of Europe there are extensive regional ice monitoring activities in Canada and USA. The National Ice Center in USA perform global ice monitoring, including the whole Arctic and Antarctic regions, based in satellites data. Ice monitoring is also important in north east Asia, in Russia, Japan and China.

Sea ice monitoring is a well-established and organised activity in countries where sea ice occur, because sea ice has important impact on sea transportation, climate, the biosphere and settlements. Data are obtained by several methods: aircraft/helicopter surveys, ship observations, reports from coastal and meteorological stations, data from drifting buoys and satellite data. The importance of satellite data have increased steadily over the last 10-20 years because better satellite data both in quantity and quality for sea ice monitoring have been available.

Global ice monitoring, which is one of the main elements in climate change detection, is only possible with use of satellite data. Starting with NASA's Nimbus-7 in 1978, passive microwave observations of the global ice areas have been regularly available for two decades, providing a unique data set to study seasonal, inter-annual and long-term variability of sea ice. On the other hand activities like the marine traffic and off-shore industry over the ice covered areas have increased and there is a growing needs for better ice monitoring data. Sea ice monitoring is therefore one of the most important applications of several types of satellite data (passive microwave, optical/infrared, active microwave systems), since satellites have clear advantages compared to other methods (aircraft, ships, etc.) which are expensive and not practical for observation of large areas. Use of satellite data have demonstrated promising capability to improve quality of the ice charts which are necessary for safe and cost-effective operations in ice areas. Systematic use of satellite data in operational ice monitoring, especially SAR data, will bring the quality of local and regional ice charts to a higher level than today and reduce the risks of damage and accidents caused by sea ice.

The background and justification for operational ice monitoring services, mainly financed by national governments, are the presence of important users who cannot work efficiently and carry out their duties without up-to-date and reliable ice information. The users represent both the public and private sector. The main public sector users include national maritime administrations, local administrations, navies and coast guards, weather services, icebreaker services and other governmental agencies responsible for marine, polar and environmental activities. The private sector users include first of all ship traffic in ice covered seas, shipping, offshore industry and other industries depending on sea transportation such as timber, paper, mining and many others.

The ice information needed by the different users include both real-time, daily monitoring and forecasting as well as statistical information based on historical data. In the study, a selection of users representing the public and private sector have been asked questions and participated in a workshop, in order to formulate specific requirements to ice information needed from satellite data.

Technical requirements are divided into the following categories:

- *Mission requirements.* Have satellite systems in continuous operation which can provide sea ice data.
- *Product requirements.* The data products from satellites must provide necessary ice information in sufficient resolution, in real or near real-time and available daily.
- *Infrastructure and communication requirements.* It is of primary importance that satellite data can be readily transferred from the receiving stations to the ice centres, and from the ice centres to the end users.
- *Information requirements.* With increasing amount of satellite data, many data and service providers, and a variety of different products and processing algorithms, there is a strong need to organise all relevant information and make it readily available to the users.

One of the topics investigated in OSIMS is to assess the role of the public versus the private sector in operational ice monitoring.

The user investigations suggest that the major component of the ice services will also be a public responsibility in the future, but it will be supplemented by the private financing. It is foreseen that the trend of decreasing public funding and increasing private funding will continue. The specialised needs from different customers, the availability of better space-borne data, the improvements in global communication, and last but not least the importance of computer technology to produce new ice products will stimulate a market where several companies and institutes will offer data and services related to ice monitoring.

The benefits of improved sea ice monitoring by satellite data are two-fold: First, there are economical benefits due to the fact that sea transportation, offshore oil/gas exploitation and other industries is possible and profitable in ice covered areas. Secondary, there are environmental and safety issues which require operators to use sea ice information to meet safety standards and regulations.

Future concepts for ice monitoring be optimised for regions where ice occur. Because the infra structures, especially data transmission and communication, are different from one region to another, it is foreseen that the Baltic region, the Greenland area and the Northern Sea Route will not follow the same concept in development of future operational ice monitoring. It is also expected that new concepts will allow several data and service providers to deliver ice information. The role of computer network will become more important serving as the information “highway” where all providers and users of ice information can deliver and retrieve data and data products as can be seen in the close co-operation between Finnish and Swedish icebreakers and ice services. Computer networks and fully digitised data will make exchange of sea ice data much easier. The private sector will play a more important role than before, but operational ice monitoring will still be funded mainly by governmental budgets.

An ideal ice monitoring system will use a combination of different satellite data, which are available in near real-time every day, and will be integrated with meteorological and oceanographic data and other ice data in a state-of-the-art GIS system. Access to data from different satellites and satellite receiving stations must be facilitated. Users should only need to contact one address/agency to get sea ice data and environmental data, e.g. weather and sea state, from a given area. On-line ordering and purchase of ice information products should be further developed.

The ice services should have access to all relevant satellite data in a streamlined manner which is not the case today. The products from the ice services should be improved to include forecast data and indicate drift of sea ice and icebergs. Products should include pictorial information (imagettes), optionally with drift vectors and/or weather information included. All data should in the widest possible extend be freely interchangeable between national ice services.

As a conclusion of the OSIMS study, the following recommendations are made concerning operational sea ice monitoring by satellites.

- Access to a combination of SAR, optical and passive microwave data from satellites is needed on daily basis because these instruments complement each other in a useful manner for ice monitoring.
- Long-term access to satellite data is necessary in order for ice centres to invest in infrastructure and human expertise necessary for exploitation of these data.
- The number of satellites in orbit must be sufficient to ensure coverage of the most important ice areas at least once per day.
- Receiving stations must exist to ensure real-time SAR data from all ice areas.
- High speed computer link from SAR receiving stations and ice centres and other main users is needed for transmission of the high data volumes of SAR data.
- Streamlining of SAR processing at receiving stations and image analysis at ice centres is necessary for rapid delivery of interpreted and classified SAR images.
- Communication to ships must be improved for transmission of SAR image products to users at sea
- The capability of onboard processing and direct downlink of SAR data from satellites to users should be developed to have a similar access system for SAR data as for AVHRR, Okean SLR and SSM/I data.
- The possibility to include ice information in ECDIS and/or other computer based systems on board ships should be further investigated. In near future it is envisaged that there will be integrated information systems on ships.
- Standardisation of digital ice products is necessary for efficient exchange and distribution of products. New and faster communication systems should be utilised for distribution of digital ice products.
- Increased co-operation between ice centres to ensure optimal data acquisition, processing and distribution should be encouraged. This is particular important as more satellite data will be used.
- Training and education in sea ice remote sensing is necessary for all users who are not familiar with satellite data.

1. Introduction

1.1 Background

The presence of sea ice has large practical and economical importance in several countries and regions in the world. Timely information on sea ice condition and its variability is essential for all operations in ice covered areas. The safety and efficiency of sea transportation, off-shore operations, and fisheries and other activities in polar regions have been the motivation to establish operational sea ice monitoring and forecasting services in many countries. Data from polar orbiting Earth Observation satellites are playing an increasingly important role in sea ice monitoring.

The two most heavily marine operated areas in the world, where the seasonal sea ice plays an important role in navigation, are the Gulf of St. Lawrence in Canada and the Baltic Sea in Europe. The Baltic Sea ice season last up to half a year, and approximately 40 % of the total amount of cargo turnover of 450 mill. tons (in 1995) occurs during winter months. But there are also many other sea ice areas with less ship traffic which are still very important for national and regional economics such as the Northern Sea Route, Greenland, Iceland, the Svalbard area and the Barents Sea.

Polar waters represents a significantly higher degree of risk to shipping than most other waters, by the presence of ice fields, wind driven ice forces, cold isolation and lack of full support-services. The Arctic navigator must also face lengthy voyages in ice, possible entrapment in pressure ridges in confined areas, and deceptively interlaced areas of multi-year ice. Human error is acknowledged to be a major factor in most of the marine accidents in Polar waters and the risk of errors is increased by the high demands placed on mariners. Another risk is the possibility of oil spill and other pollution which can cause severe damage to the environment. The presence of sea ice makes cleanup techniques normally employed in more temperate climates useless in ice covered areas.

It is unquestionable that improved and easily accessible ice information can improve safety and thereby reduce the risk for accidents, loss of life and equipment. Particularly, if oil, gas and mineral exploitation in polar regions increases, accurate and timely ice information is a prerequisite for safe and economic operations.

During the last two decades remote sensing techniques have attained an increasingly important role in operational ice monitoring, in particular satellite remote sensing. The World Meteorological Organisation (WMO) hosted the Second Operational Ice Remote Sensing Workshop at the Canadian Ice Centre in Ottawa, 10 - 13 September 1991 which gathered all important institutions in this field. The proceedings from the workshop (*AES report, 1991*) provided state-of-the-art in operational sea ice remote sensing before any satellite SAR systems became operational. Several satellite systems have been used in operational ice monitoring for several years, first of all the American systems NOAA AVHRR and DMSP SSM/I, and several Russian systems. The year 1991 represents the beginning of a new era in ice remote sensing with the launch of ERS-1, the first Earth Observation experimental satellite providing SAR coverage over large areas of sea ice. From 1995, ERS-2 continued SAR image acquisition over sea ice. With RADARSAT, which have provided wide swath SAR images since 1996, it is now possible to use SAR data in operational ice monitoring, covering all sea ice areas every 1 - 3 days, depending on latitude. The SAR gives more detailed and accurate ice information than any other satellite sensors.

1.2 Study objectives and tasks

The overall objective of the OSIMS project (Operational Sea Ice Monitoring by Satellites in Europe) has been to study the feasibility and cost benefit of using satellite data in operational ice monitoring and propose concepts for optimal use of satellite data in future sea ice monitoring and forecasting. The project has seven specific objectives which are the basis for the corresponding work packages:

- describe current ice monitoring systems and their users (WP 1);
- analyse the role of existing satellite data in ice monitoring (WP 2);
- investigate user requirements and cost benefits of using satellite data in ice monitoring (WP 3);
- analyse the technical feasibility of missions, instruments and ground structure (WP 4);
- propose concepts for optimal use of space data in ice monitoring and forecasting (WP 5);
- host a workshop with invited experts and users to review the concepts of using space data in operational sea ice monitoring (WP 6);
- synthesise project results with suggested solutions for future operational use of space data in sea ice monitoring (WP 7).

In WP1 the existing ice monitoring systems and their users have been reviewed. The most important areas for sea ice monitoring systems in Europe is the Baltic Sea, the areas around Greenland, Iceland, the Svalbard area, the Barents Sea, and the Kara Sea with adjacent rivers and water-ways. In severe winters sea ice also plays an important role for navigation on the coasts of Germany, the Netherlands and Denmark. The study also describes the ice monitoring efforts in Canada, USA, and the Far East for comparison with the European activities. The Russian ice monitoring system, which was built up to be the most extensive in the world in the 1980’s, is also included. The background and organisation of ice monitoring services and their main users are described. The characteristics of current ice monitoring systems are presented in chapter 2.

The role of existing satellite data in ice monitoring is reviewed in chapter 3. There are currently three important satellite remote sensing sensors: optical/infrared instruments, passive microwave radiometers and active microwave radars which have different roles in ice monitoring systems. They are operational on 5-10 satellites operated by space agencies in Europe, USA, Canada, Japan and Russia.

The ice parameters and ice features which need to be observed from satellites are discussed in chapter 4. The study of user requirements for operational ice monitoring is described in chapter 5. The study is based on interviews with representatives from key users representing both private and public sector and on the results of a workshop in Helsinki 5-6 February 1998, where approximately 15 experts discussed major topics in operational ice monitoring. The report of the workshop is given in the Appendix.

The technical feasibility of sensors, instruments and ground structure is discussed in chapter 6. Issues addressed includes review of limitations in current satellite systems, requirement for future systems, SAR receiving stations and their services, data handling capabilities at ice centres and distribution systems which can reach users at sea and in polar regions.

In chapter 7 concepts for optimal ice monitoring systems are proposed which takes into account new technologies in data processing and data distribution. The synthesis of project results with suggested solutions for future operational use of space data in sea ice monitoring are presented in Chapter 8 and 9. In addition to the final report there are three other technical reports which present more detailed results from the OSIMS project. These reports are available from the project leader on request.

2. Characteristics of ice monitoring systems

Sea ice monitoring is a well-established and organised activity in countries where sea ice occur, because sea ice has important impact on sea transportation, climate, the biosphere and settlements.

In Europe, sea ice monitoring is most important in the Baltic region during winter, in the Russian Arctic (Northern Sea Route), Barents Sea/Svalbard area, and in Greenland/Iceland waters all year around (Fig. 1). Outside Europe sea ice monitoring is done regionally in North America (Canada and USA), and in East Asia (Japan, China, Russia). Global ice monitoring, which includes the Arctic with surrounding seas and the Antarctic, is done for climate observations and to support transport and research expeditions in polar regions. The ice monitoring is organised nationally, some organisations are also making global ice monitoring. The operational ice services are collecting information from various sources: satellites, aircraft's, coastal and meteorological stations. In the ice services the data are collected, combined, analysed and transformed into information products like ice charts, ice reports, etc. The information products are sent daily to the users by telefax, data transfer or by other means.

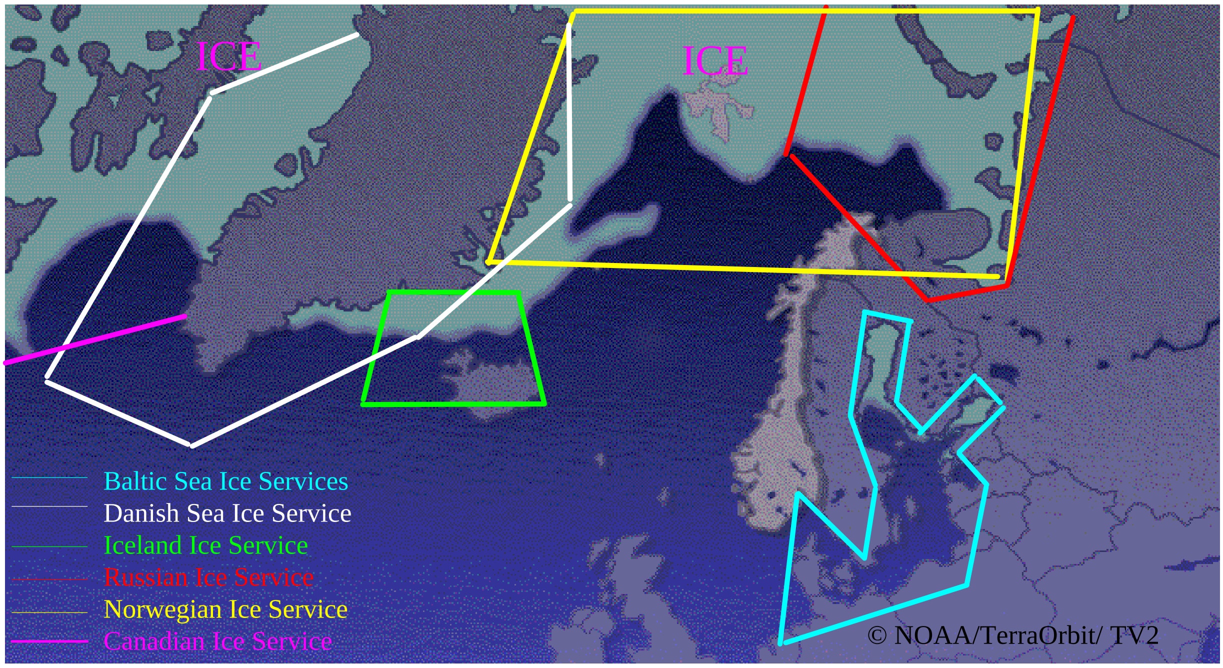

Figure 1. SSM/I image on 8 March 1998 showing the ice edge for early winter conditions. Coverage area for ice services are plotted.

Sea ice monitoring is one of the most important applications of satellite data, since satellites have clear advantages compared to other methods (aircraft, ships, etc.) which are expensive and not practical for observation of large areas. Visual and infrared satellite data have been used for more than two decades, while microwave data such as SAR have been introduced during the 1990s. Earth observation satellites have been carried out mostly various scientific objectives and are therefore not particularly designed for operational sea ice observations which requires data every day.

National ice services/centres play a key role as focal point between customers and suppliers. Most of the ice data collection except for the satellite data are organised by the ice services/centres. The ice services/centres analyse ice information and produce ice charts and other ice information products which are distributed to the customers, such as icebreakers, merchant ships, fishing vessels, coast guards, etc. (Fig. 2). From the customers point of view the ice services/centres are the providers of all data, services and information, which are relevant for ice monitoring. From the satellite data providers' point of view the ice centres are the major users of satellite sea ice data. Although most of the ice data and information are organised through the ice services/centres, or weather forecasting services/centres, there are many other institutions which provide specific ice information for dedicated users. These institutions can be research centres, companies, service and value-added industries.

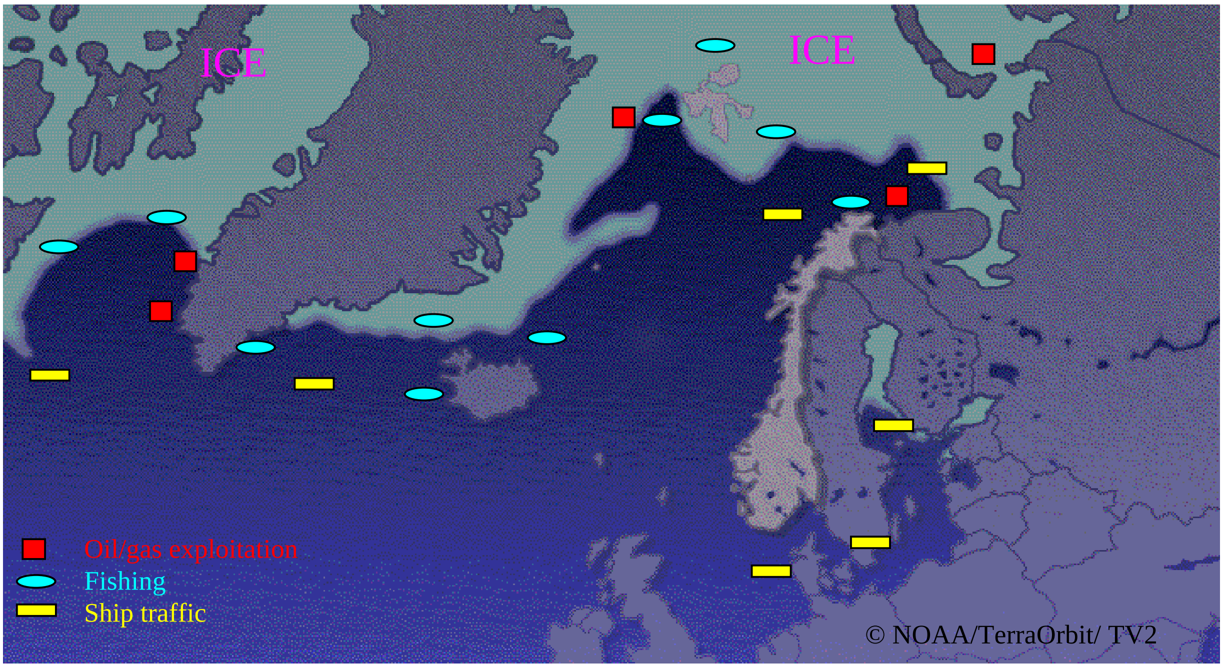

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Figure 2. Characteristic winter ice extent based on SSM/I image on 8 March 1998. Areas in or near the ice which are important for ship traffic, fishing, and oil platforms in ice covered areas or near the ice edge are marked qualitatively.

Sea ice monitoring involves significant economic investments from the governments in countries such as Finland, Canada, Russia, etc. In addition there is also some financial support from private industry to ice services, especially ship transportation paying a fee for icebreaker support, including ice mapping service.

Ice monitoring is an area where the public sector play a role. The public sector, especially national weather services and ice centres, has the most important role in ice services, being responsible for general ice information usually financed by the government. The private sector, become more and more important users of ice information, because of sea transport and oil industry, and thereby as financial contributors to the ice services.

The market for ice monitoring is growing due to increased ship traffic and more exploitation of oil, gas and other arctic resources. With new users there will be a demand for more ice services. It is foreseen that existing ice centres will expand their activities and that there will be opportunities for new companies to establish services.

As an example of an operational sea ice monitoring system, the Finnish Ice Service is shown in Figure 3, illustrating all sources of input data, data analysis and products provided by the ice centre, and distribution to users. Table 1 gives a summary of input data, products and distribution systems for several ice regions.

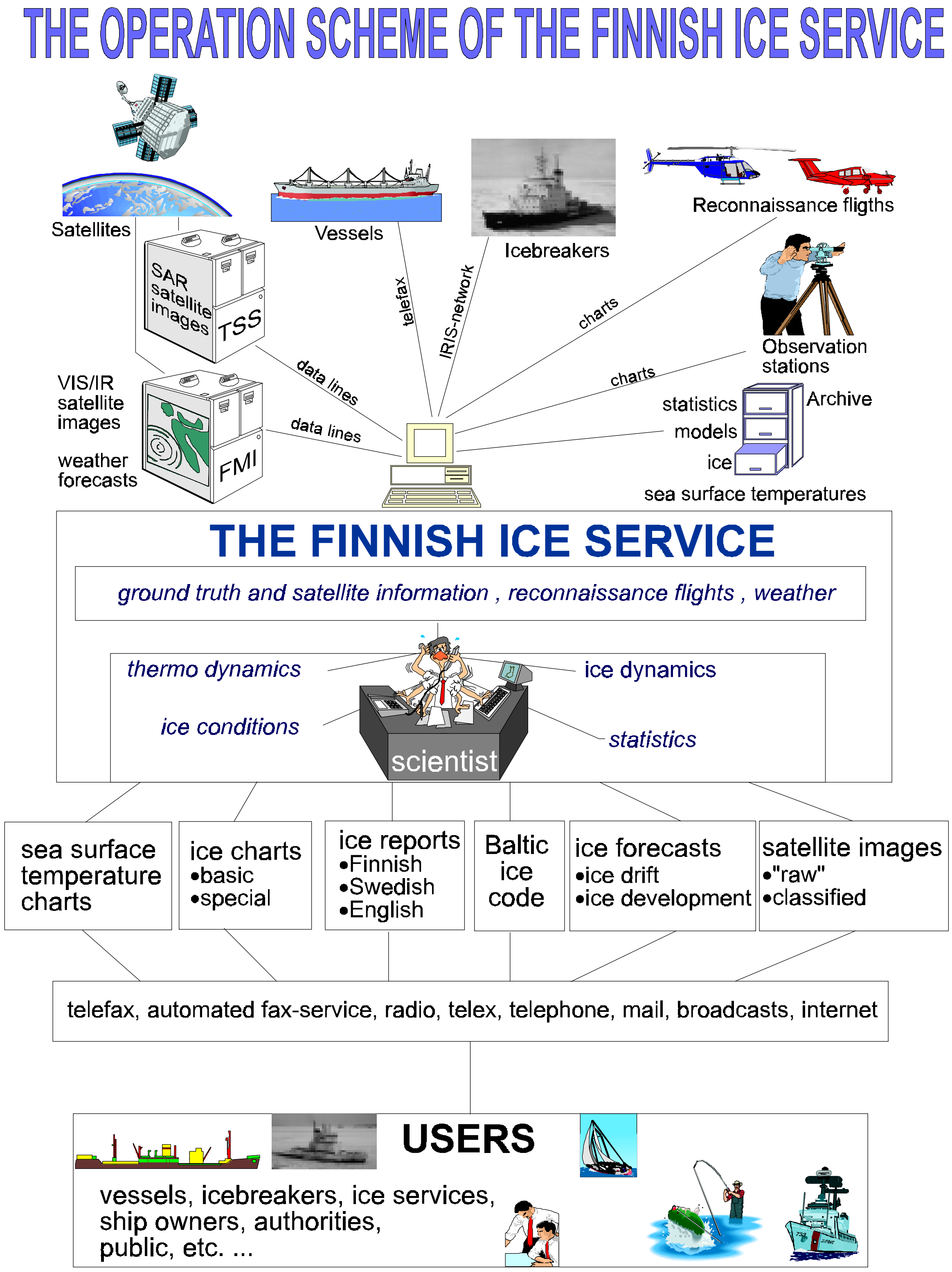

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Figure 3. The operational scheme of the Finnish ice service, showing all sources of input data (top), the data analysis and products issued by the centre (middle), and the distribution to users (bottom).

Table 1. Summary of data and products from ice services in four study areas.

Area	**Baltic Sea**	**Greenland Waters**	**Canadian Waters**	**Northern Sea Route**
Ice season	Seasonal	Year around	Year around	Year around
Ice type	First-year ice	First-year ice Multi-year ice Icebergs	First-year ice Multi-year ice Icebergs	First-year ice Multi-year ice Fresh water ice
Ice monitoring data sources				
Satellites	Yes	Yes	Yes	Yes
Aircraft's	Yes	Yes	Yes	Occasionally
In situ observations				
• Vessels	Yes	Occasionally	Yes	Yes
• Icebreakers	Yes	No	Yes	Yes
• Coastal stations	Yes	No	Yes	Yes
Space-borne data use				
AVHRR	Regular	Regular	Regular	Regular
ERS SAR	Occasionally	Occasionally	Regular	Occasionally
RADARSAT SAR	Regular	Occasionally	Regular	Occasionally
Product delivered:				
Basic ice charts	Yes	Yes	Yes	Yes
Special ice charts	Yes	Yes	Yes	
Ice reports	Yes	Yes	Yes	Yes
Digital ice charts	Yes	(Yes)	Yes	
Satellite images	Yes	(Yes)	Yes	Yes
Classified sat. images	Yes		Yes	Yes
Ice forecasts	Yes	No	Yes	Yes
Communication:				
Fax	Yes	Yes	Yes	Yes
Call-fax	Yes		Yes	
Mail	Yes		Yes	Yes
Network	Yes	Yes	Yes	
Digital sat. data transmitted to users at sea	Yes	Yes		
Users at sea	Many	Few	Many	Few
Users at land (national)	Many	Few	Many	Few
Users at land (international)	Many	Few	Many	Occasionally

3. The role of existing satellite data

Satellite data have been used as part of the data sources in ice monitoring for many years. The most commonly used data so far are NOAA AVHRR data (optical and infrared data) and DMSP SSM/I data (passive microwave data). But these data have limitations due to cloud cover and coarse resolution and are therefore not optimal for regional ice mapping which require detailed and regular data. Since 1991 the ERS-1 SAR data with 100 m resolution have been obtained in many sea ice research and demonstration projects (*Johannessen. et al., 1997, Gronvall et al., 1996, Håkansson et al., 1995*). The SAR has proven to be a very powerful instrument for sea ice observations due to high spatial resolution in combination with weather capability and it is planned to become the main instrument in operational sea ice monitoring, (Table 2 and 3).

Dedicated Earth Observation satellites, such as polar orbiting (NOAA) and geostationary (GOES) meteorological satellites used in operational weather forecast, are not yet made optimal for sea ice monitoring. The Canadian RADARSAT, operational from 1996, has ice monitoring as the prime objective and will provide SAR data of ice covered areas on operational basis. With RADARSAT data, a new era in operational ice monitoring by satellites has begun. Being a commercial satellite the data are rather expensive, so it is still uncertain how much these data will be used by ice centres outside Canada and USA.

Intensive use of SAR data has decreased the number of reconnaissance flights, at least in the Baltic Sea and in Greenland waters. The benefits of SAR images for mapping the ice conditions can potentially be large when SAR data become available on operational basis, but in general the financing of SAR data for use in ice monitoring is not yet resolved. In Canada, use of aircraft has been reduced as RADARSAT SAR data were introduced in the operational ice monitoring. In the winter of 1998 in the Baltic Sea RADARSAT data have been used operationally in Finland and Sweden.

Significant technical improvements for use of satellite data in ice monitoring are needed. The available EO SAR data are single frequency and polarisation which limits the possibility to classify ice types. Existing microwave radiometers (SSM/I) offer multi-frequency dual polarisation data which make ice classification possible. These data are important in global ice monitoring and in climate change studies, but they are of little use in regional basis such as the Baltic Sea because the resolution is too coarse for operational ice navigation. In the future it is envisaged that optional missions for operational ice monitoring should carry both active and passive microwave instruments, with resolution and coverage suitable for observing the key ice parameters.

The high resolution in SAR data demands interpretation methods, and the effects of different SAR parameters is not well investigated. Existing scattering models which relate physical ice parameters to SAR parameters are not good enough. Improved automatic ice classification algorithms for SAR images need to be developed further (*Gronvall et al., 1996, Sandven et al., 1998*).

The main development trend is that microwave data, especially SAR, are expected to replace NOAA AVHRR data as the most important data source in ice monitoring. There will also be a development towards multi-channel and multi-polarisation SAR data which will enable better classification of ice types. The rapid development of computer and network technology, and the improvements in marine communication, will facilitate more use of satellite data in real-time onboard ships. It is also likely that the technological development will bring changes in data flows and organisation of the ice monitoring activities.

Table 2. The most common satellite data currently used in ice monitoring *.

	Satellite/Sensors	**Start**	**In operation**	**Comments**	**General comments**
Visual/ IR	NOAA AVHRR	1978	yes	most extensively used satellite data in ice monitoring	• useful during cloud-free conditions
	METEOR Resurs	1969 1988	yes yes	used by Russian ice service	
Active Microwave	ERS-2 SAR	1995-	yes	ERS-1 operated from 1991-1996 and ERS-2 operated in Tandem from August 1995 to June 1996. The first satellite to provide extensive SAR coverage in 100 km swath over ice.	• regional scale useful for mapping smaller areas due to the narrow swath of 100 km
	Okean SLR	1983-	yes	used for ice monitoring by Russian institutions combined with passive microwave and optical sensors.	• SAR is the most important space technique for ice observations because it provides more ice information than any other instrument
	RADARSAT	1996-	yes	first SAR satellite providing data for operational ice monitoring	
Passive Microwave	DMSP SSM/I Okean RMO8	1987 - 1983-	yes yes	climatology studies used by the Russian ice service	• low spatial resolution • global scale

* many other satellite data types for sea ice research are not listed

Table 3. Role of satellite data for different scales of monitoring.

Scale of ice monitoring	**Areas**	**Satellite versus aircraft**
1. Large scale global ice	Arctic, Antarctic	SSM/I and AVHRR are essential. SAR and SLR important supplement. Global mapping not possible without these.
2. Regional ice mapping	Baltic Sea Greenland Northern Sea Route Gulf of St. Lawrence/ St. Lawrence Seaway	SSM/I: too coarse resolution AVHRR: used whenever possible Okean/Meteor: used occasionally in the Northern Sea Route SAR: growing importance as a result of wide swath data from RADARSAT Aircraft surveys: more important before, is being replaced by more satellite data.
3. Local mapping	In straits and harbour, Near off-shore operations, For tactical ice navigation.	Aircraft and helicopters most important. SAR will play a growing role

4. Parameters needed for ice monitoring

The description of sea ice parameters has been standardised by the Sea Ice Working Group of WMO (*WMO, 1970, 1985*) which has defined a nomenclature used by all institutions producing ice maps today. Although the nomenclature is fairly well standardised, the symbols used in ice charting differ somewhat between the Russian, Canadian and Baltic Sea ice charts. The main ice parameters, which are descried in the WMO egg code are

- Ice concentration
- Ice types
- Age or stage of development
- Form (i.e. floe size)

In addition there are other ice characteristics which are described by specific symbols such as:

- Surface features (i.e. ridges), and
- Motion

The WMO egg code provides numerical values for ice concentration, stage of development (thickness) and form of the ice (floe size) for a more or less homogeneous areas of ice. In the national ice charts the WMO ice code and chart symbols are normally used. However, in some areas, like the Russian Arctic waters and in China the alternative set of symbols or the national codes and chart symbols are used.

The main problem of the WMO ice code is that it does not describe all the ice characteristics which are relevant for ice navigation. In countries where ice navigation is of major concern, the WMO code is supplemented by a number of other ice parameters. This is because it is difficult to define a few parameters which are sufficient to describe the navigability in sea ice.

4.1 Ice area and ice edge position

The most basic ice information needed by all users is identification of the ice edge and mapping of areas covered with ice. Several types of data are useful for this: AVHRR, SAR and SSM/I data are used more or less regularly, but other data such as scatterometer data and radar altimeter can provide information but are not used in operational monitoring.

4.2 Ice type development

The SAR microwaves are sensitive to surface roughness and dielectric constant of sea ice which depends on salinity contents in the surface layer of the ice. For multi-year ice most of the SAR's signature is caused by volume scattering because the surface layer has very low salinity, typically less than 1 ‰. Different ice types and ice conditions which need to be observed are illustrated in Figure 4.

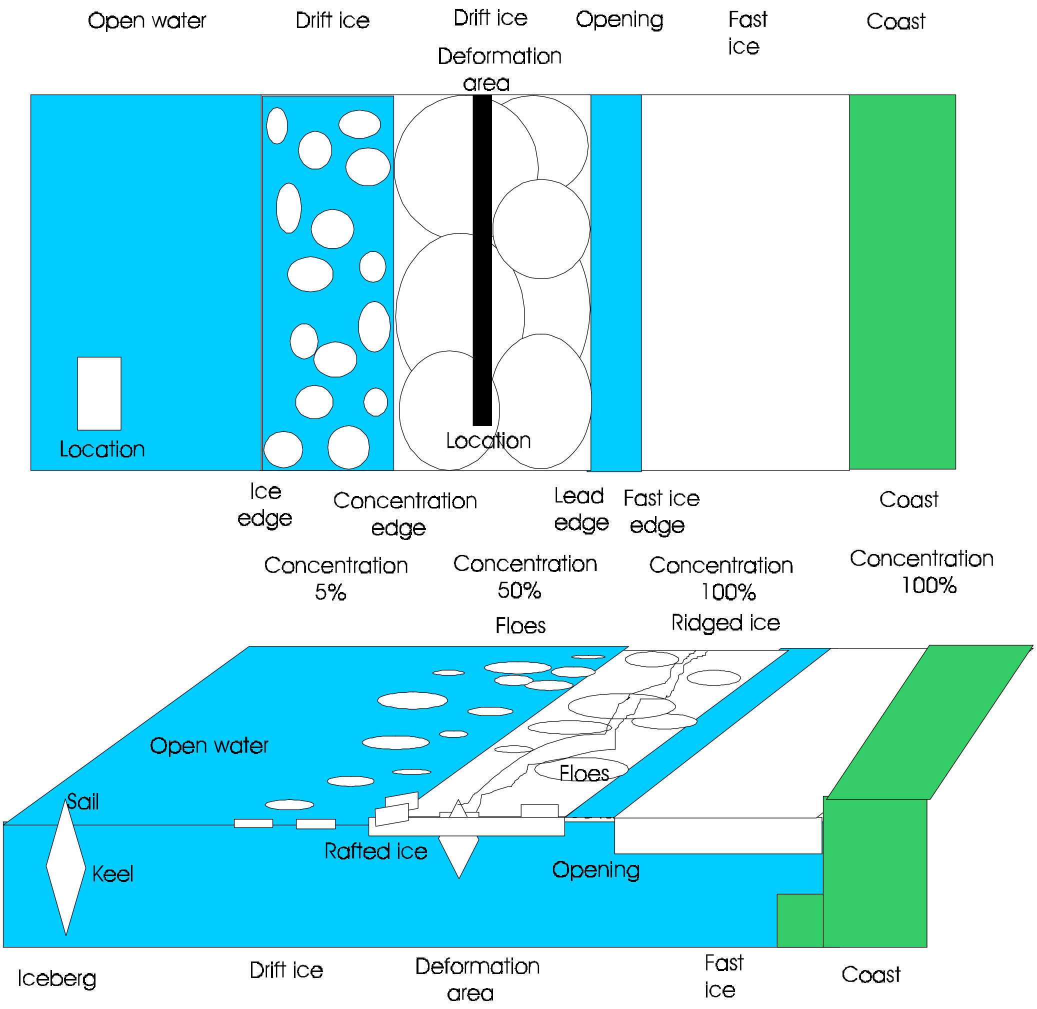


Figure 4. Simplified outline of ice conditions showing needed parameters for ice monitoring. A photograph of first-year ice floes is shown in Fig. 5.

The SAR parameters which have impact on ice classification are incidence angle, frequency, and polarisation. The same ice type can reflect backscatter intensities that are very different when the sensor parameters are altered. More research is needed to determine the dependence of sensor parameters to backscatter intensities related to different ice types. In spite of some ambiguities, SAR systems, with the high spatial resolution combined with cloud and light independence are the most important satellite observation methods for sea ice for operational ice monitoring.

Also passive microwave radiometers can distinguish between open water, first-year ice and multi-year ice, but the resolution is much poorer, which makes this instrument suitable only for large scale and regional observations.

Open water

If the resolution is not crucial, radiometers can be used quite reliably to distinguish between open water and different ice types because open water has lower emissivity than ice. Backscatter values of the SAR from open water is highly dependent on the current sea state. Rough sea state gives a higher backscatter than calm sea state. Discrimination between open water and ice in SAR can not be done only by backscatter differences, but must include texture information in the image.

New ice

New ice types such as frazil ice, grease ice, pancake ice and grey-white ice can easily be identified in SAR images (Fig. 6a). SAR backscatter from frazil and grease ice is very weak because of damping from surface waves. After a few days of freezing, grease ice is gradually transformed into pancake ice under influence of surface waves. Pancake ice is circular plates of ice of diameter from about 30 cm. The edges of the pancakes have high backscatter in SAR, which makes it possible to identify pancakes to a few meters.

Young ice

There are several stages in the further development of ice. All ice between 5 to 30 cm thick is called young ice, and the SAR image in Figure 6a shows examples of several types of young ice which can be identified by SAR.

First-year ice

First-year ice (Fig. 5) is defined as ice that grows into 1 - 2 m during one ice season. When it is more than 30 cm it is defined to be first-year ice if it has not survived a melt season. SAR backscatter intensity from first-year ice is dominated by surface scattering which reflects the roughness of the ice surface. Snow cover on top of the ice do not affect the SAR waves except when the snow is wet. The SAR is therefore useful to discriminate between level ice, medium deformed and heavily deformed first-year ice.

Multi-year ice

Multi-year ice is determined as ice that has survived over one melting season. It can be distinguished from first-year ice both by SAR (Fig. 6b) and by passive microwave data.

Figure 5. Photograph of first-year ice floes in the marginal ice zone of the Greenland Sea, typical floe size is 10-50 m.

Ice edge

Ice edge can be determined by all sensors, but the accuracy is very different among the sensors in use. SAR evidently gives the best results in terms of accuracy. The backscatter from open water using SAR instruments is depending greatly on the current sea state. With medium and rough sea state the ice edge can be distinguished quite reliably, in the case of calm sea state it is more difficult. When there is new ice that has grown in calm conditions, or in general ice that is smooth on the ice edge, interpretation of the boundary can be difficult.

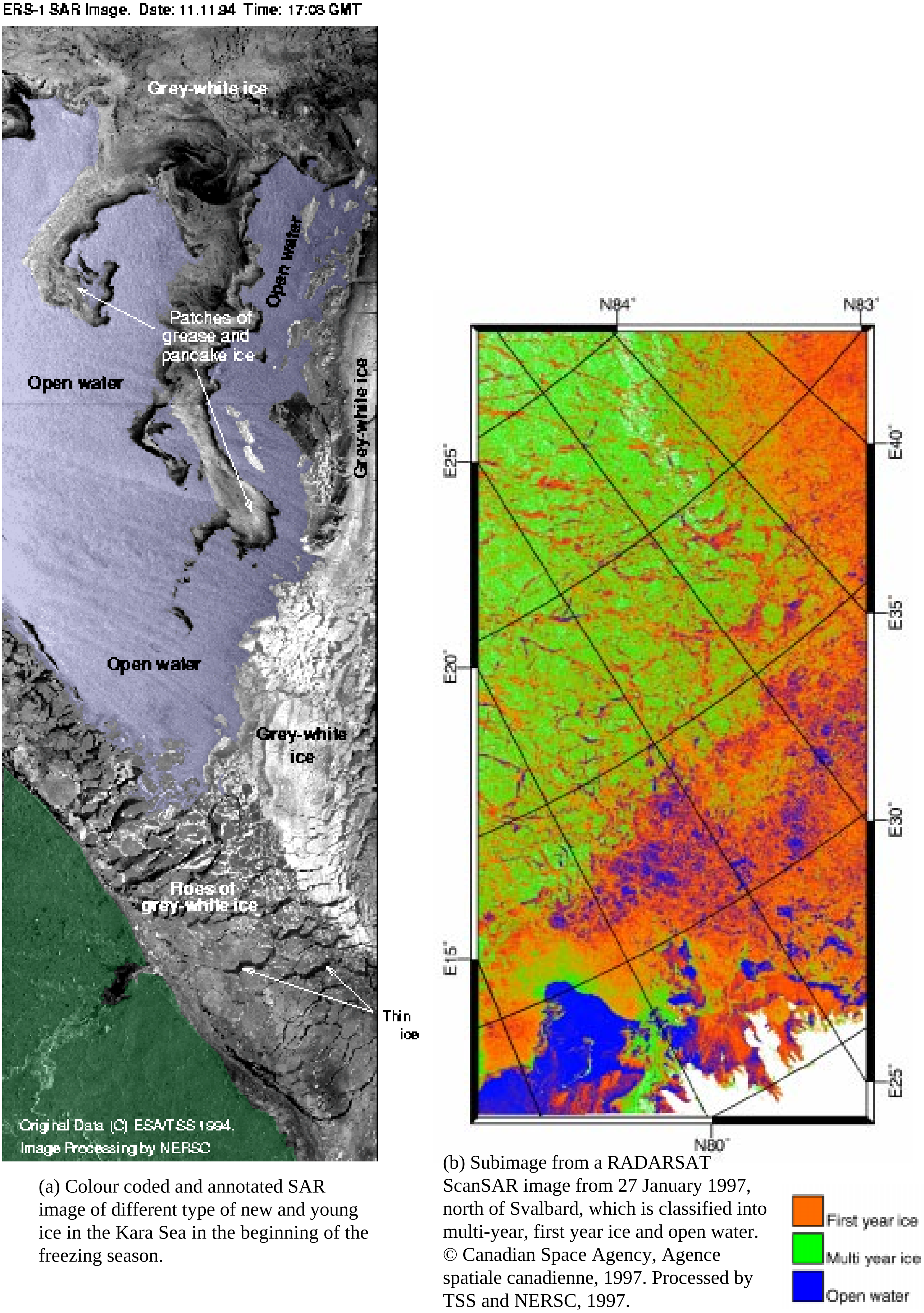
The use of radiometers have the advantage that surface emissivity is increasing from open water through new ice to young ice. Older and thicker ice types have also wider range of emissivities because of their snow cover and salinity fluctuations. Therefore identification of the ice edge can be done quite reliable. The problem is still the coarse resolution of present radiometers.

Ice thickness

Ice thickness can not be measured directly with any present satellite-based instrument, and this is a great disadvantage. Some information can be deduced from ice motion. Radiometers are also capable of separating new ice, young ice, first-year and multi-year ice from which conclusions can be made to asses ice thickness. However, the coarse resolution of present radiometers is a severe limitation.

The detection of different ice types with the SAR is possible. The strong dependence of backscatter due to surface roughness can lead to false interpretations when the sea state changes between calm and rough. There is still a lot of work to be done to understand how different frequencies, polarisations, and incidence angles effect the backscatter coefficient of different ice types. The technique of assessing ice thickness by identifying the ice type can therefore lead to false interpretations.

Indirect ways of estimating ice thickness, is for example by using combine measurements of surface temperatures of AVHRR with a thermodynamically ice growth model. The method has large uncertainties, up to 50% (*Yu, Y., and Rothrock, D. A., 1996*).



(a) Colour coded and annotated SAR image of different type of new and young ice in the Kara Sea in the beginning of the freezing season.

(b) Subimage from a RADARSAT ScanSAR image from 27 January 1997, north of Svalbard, which is classified into multi-year, first year ice and open water. © Canadian Space Agency, Agence spatiale canadienne, 1997. Processed by TSS and NERSC, 1997.

Figure 6. Example of ice type classification in ERS-1 SAR and RADARSAT ScanSAR images.

4.3 Ice forms and features

Again SAR is the most useful instrument to identify ice forms and features. The most important parameters related to forms and features of sea ice are: floe size, deformation, leads and polynyas, icebergs/growlers and snow cover on ice.

Ice floes

The size of ice floes vary from a couple of meters up to more than 10 kilometres. SAR gives obviously best information, but larger floes can also be detected with infrared and microwave radiometers.

Deformed ice

Ridged and rafted ice are the main barriers for ships navigating in ice covered sea. SAR data are sensitive to surface roughness and are therefore a very useful tool for detection of deformed ice. The high spatial resolution is also an advantage which makes the instrument superior compared to infrared and microwave radiometers. Laser altimeters can provide more accurate data about ice deformations, because the surface topography can be obtained. Such data, however, are not yet available from satellites, and are sensitive to clouds and fog.

Leads and polynyas

Detection of leads and polynyas are of vital importance for navigation. SAR data have good capability to identify such features.

Icebergs and growlers

Icebergs (Fig. 7) and growlers can be very dangerous for ships and oil rigs in the Arctic waters, because they represent a small horizontal extent and large volumes of hard ice located below the surface and can therefore be difficult to detect. High resolution instruments are definitively needed. The SAR sensors have the problem due to the current sea state. Icebergs are more difficult to detect when the sea state is rough compared to calm conditions because surface roughness is one of the key factors that determine the backscatter intensity.

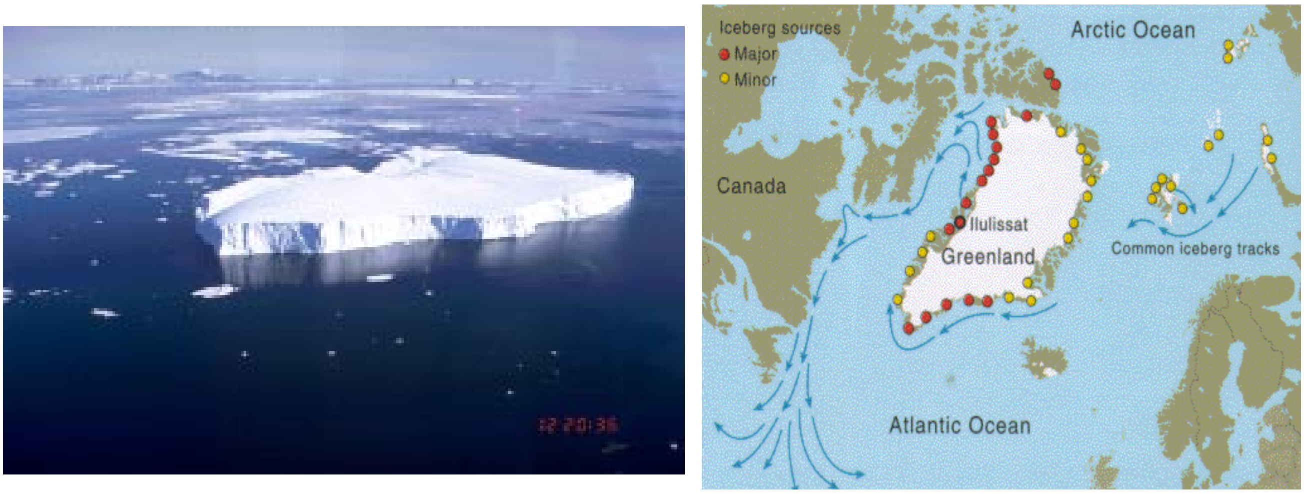


Figure 7. Icebergs are a spectacular feature of Arctic ice. They are pieces of glaciers that have broken off and floated away in the sea. Calving glaciers cover much of Greenland, Svalbard, Franz Joseph Land and the area of Severnaya Zemlya. Beneath the surface, icebergs can reach depths of more than 100 meters. The map shows the main drift paths for icebergs (*AMAP Report, 1997*).

Snow cover on ice

Snow on top of the ice is important in satellite observations because visual and infrared data basically see the snow and not the ice beneath the snow. Microwave systems (SAR and passive microwave radiometers) can see through the snow cover, except in the summer season when the snow is wet. Therefore microwave systems are more suitable for ice type class than visual and IR systems.

4.3 Ice dynamics

Sea ice is either stationary or drifting. Stationary ice, usually called fast ice, is typically found in coastal regions where it is attached throughout a winter season for first-year ice and for many years for multi year ice to the shorelines. Drifting ice is moving, as a result of winds and currents. To calculate the velocity and direction of motion for drift ice, the moving ice field must be localised in two different images in a reasonably short time interval. This means that the sensor must have a high resolution, and a frequent coverage over the area where the motion takes place. Most of the sea ice in deep waters and far away from coastlines is drifting ice.

Both AVHRR and SAR can be used to identify fast and drifting ice. SAR has the best capability to estimate ice velocities, because ice features can be recognised. The main problem with SAR is to get large enough coverage at regular time intervals to get representative data sets.

Table 4. Summary of the role of satellite data on ice parameters.

Main ice parameters	Role of satellite data
Ice area and ice edge position	AVHRR can provide good data during cloud-free conditions. SAR detects ice areas with high spatial resolution, independent cloud and light conditions. Ice edge is usually clearly defined by SAR except during specific wind conditions during the melt season Passive microwave data distinguish quite well between open water and ice.
Ice type development • New ice • Young ice • First-year ice • Multi-year ice	SAR parameters with impact on ice classification: incidence angle, frequency, and polarisation Backscatter values from open water is highly dependent on the current sea state. Rough sea state gives a higher backscatter than calm sea state. SAR backscatter from grease ice is very weak because of damping from surface waves. The edges of the pancakes has high backscatter. First-year and multi-year ice can also be distinguished, but not during the melt season.
Ice forms and features • Floe size • Deformation • Leads and polynyas • Icebergs/growlers • Snow cover on ice	SAR is the most useful instrument. It is sensitive to surface roughness. High spatial resolution. Sees through the snow cover, except in the summer season when the snow is wet.
Ice dynamics	AVHRR and SAR are used to identify fast and drifting ice. SAR has the best capability to estimate ice velocities, because ice features can be recognised. The main problem with SAR is to get large enough coverage at regular time intervals to get representative data sets.

5. User requirements for operational ice monitoring

In order to suggest concepts for optimal ice monitoring systems using satellite data, it is essential to know the requirements from the main users of ice information. A selection of representative users (Table 5) have been contacted to obtain specific information about their current/potential needs for ice data, which areas are relevant, demands for near real-time delivery, etc.

The user requirement study is based on:

- existing network of users and previous studies of requirements;
- the needs of the main users whose requirements define the ice services;
- division of requirements in categories: mission-, data/product-, communication-, beneficial, cost-effectiveness, etc.;
- requirements defined by the different ice conditions and ice problems in European ice regions;
- input from a user Workshop in Helsinki in February 1998.

The users of sea ice information can be divided into three main types according to their different roles, responsibilities and problems to be solved.

User type 1 are people in direct contact with ice in their daily work and need ice information to operate ships safely and cost effectively in ice covered seas. Typical users are icebreaker captains, cargo ships captains or skippers on fishing vessels or oil platform managers, managers of coast guard vessels.
User type 2 are people who are responsible for planning and implementation of sea transportation, icebreaker convoys, offshore operations and other marine operations in ice covered areas. These people often work at land, but have responsibilities and give directions to the people working at sea.
User type 3 are national institutions responsible for collection of ice data and production of ice chart, ice forecasts and other ice products to be delivered to user type 1 and 2. They are customers of satellite ice data, but they are providers of final ice products to user type 1 and 2.

Table 5. Users who have contributed to the requirement study.

Category	User organisation	Type
National Ice Service	FIMR, DMI, Ice central in Greenland, German Ice Service	Public
National Weather Services	DMI, FMI	Public
Shipping Companies	MSC (Russia), RAL (Greenland), TF (Finland),	Commercial
Oil Companies	Nunaoil (Greenland/Denmark), Statoil (Norway) Neste (Finland)	Commercial
Offshore Industries	Kvaerner Masa Yard	Commercial
Other National Institutes	FMA (Finland), Danish Coast Guard, Greenland US Coast Guard	Public
Other	Fishing vessel, (Russian) Oil Companies	Commercial

The OSIMS Workshop was hosted by FIMR in Helsinki onboard the icebreaker Urho 5-6 February 1998, with about 15 participants. A selection of users were invited to the workshop to discuss topics important for operational sea ice monitoring:

- Who are the main users: in each region
- Use of new satellite data: impact on European, regional and global scale
- Data collection: streamline access to
- Data integration and analysis: production of ice charts and other information products
- Distribution to users: the role of computer techniques, GIS and image processing

Is there a drive for better quality of the ice services which requires use of satellite data ?

- Yes, because the ice services themselves are actively seeking better quality of ice charts and ice forecast which requires more cost-effective access to information.
- Yes, because there are “heavy” customers who will demand better ice services, especially oil companies involved in oil and gas production in Arctic offshore areas. Also increased sea transportation in the Baltic Sea and the Northern Sea Route will be an important market for ice information.
- Yes, because increased interest in environmental questions related to sea ice (global warming, pollution transport) requires data which can only be obtained from satellite.

The workshop report is presented in Appendix A.

Since ice conditions, types of activities, infrastructure, communication and users are different from one region to another, the user requirements are analysed separately for the Baltic Sea, Greenland, the Northern Sea Route and Canada.

5.1 Baltic Sea

The Baltic Sea ice season can last from a few weeks to six months during the winter. During mild winters, the sea ice causes navigation difficulties in Finland, Sweden, Russian and Estonia. In average and severe winters, ice affects all the Baltic Sea countries. All the Baltic Sea countries have national ice services, which provide sea ice information emphasising their own territorial waters. Satellite data used at the ice services includes primary AVHRR and SAR data, (*Grönvall, 1996, Håkonsson, 1996, Stübing, 1997*). In 1998 ERS SAR is used primary in the German Ice Service, while RADARSAT SAR has been tested for the first time in Finland and Sweden (Fig. 8). RADARSAT SAR data are received in Tromsø, Norway, and has been sent to the ice services in 3.5 - 4 hours after the satellite overpass using Internet. The processing time is two hour at the TSS, and Internet transfer and reprocessing takes 1.5 - 2 hours.

Users of sea ice information in the Baltic region can be divided into the service providers and end-users. The service providers, like the Finnish Ice Service, collect information from various sources, integrate and analyse the data and prepare final products for the end-users. The main users are the merchant vessels and the icebreakers, other end-users are ship-brokers, export and import companies, off-shore industry responsible for sea transportation in winter, authorities, scientists, and the public.

Table 6. The requirements in the Baltic Sea.

Types of requirements	What is needed
Requirements to satellite data providers	Data coverage from satellites every day in the Baltic Sea ice area
Requirements for near real-time satellite data delivery	-Delivery within 2 hours to the ice services -Delivery within 6 hours onboard vessels
Requirements for the ice services	Ice monitoring and forecasting must be improved
Requirements for distribution and presentation at the end users’ site	Transmission of digital ice products to ships must be improved, and better presentation systems onboard ships must be developed.

The Baltic Sea has intensive ship traffic also during the winter season when sea ice is present. There are several cost factors which make winter navigation expensive: ice monitoring, operation of icebreakers, ice-strengthened merchant vessels and delays in transport schedules. If ice monitoring and icebreaker assistance could be made optimal for merchant vessels, considerable potential savings could be achieved, in Finland it is estimated that between 10 and 25 mill. ECU a year could be saved. This would demand satellite-based data, such as SAR, available in near real-time for the users at sea every day.

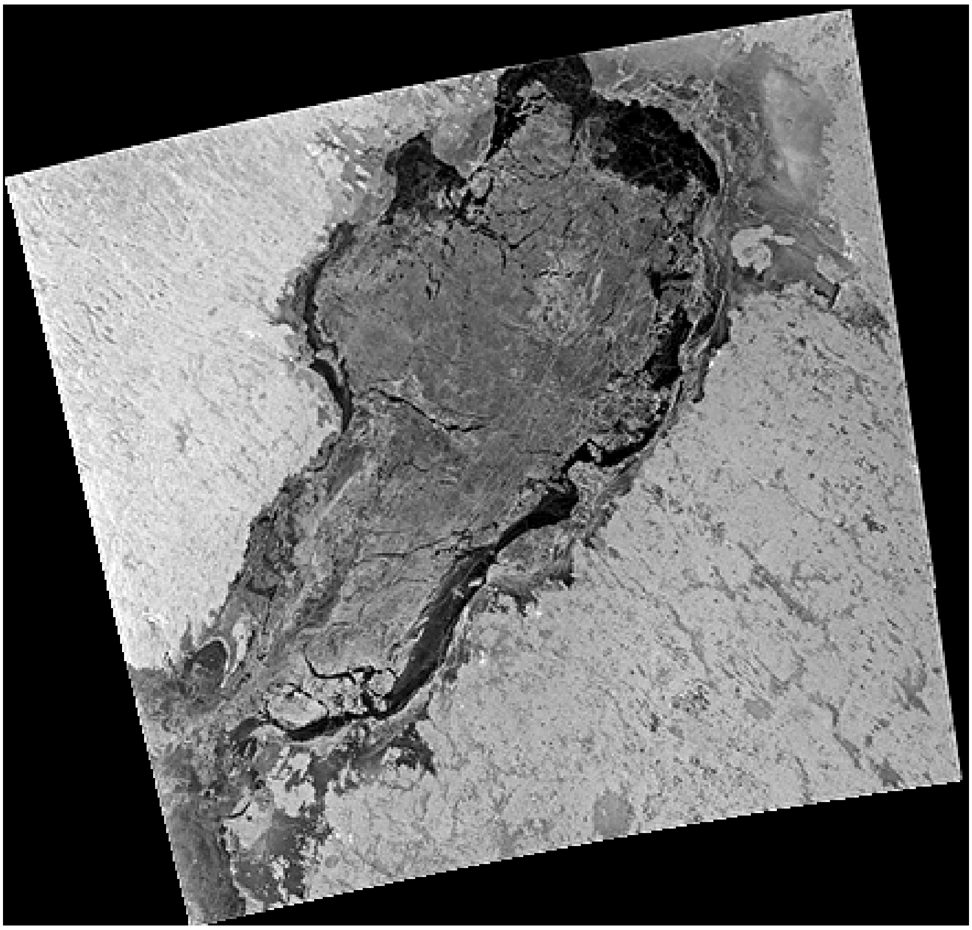


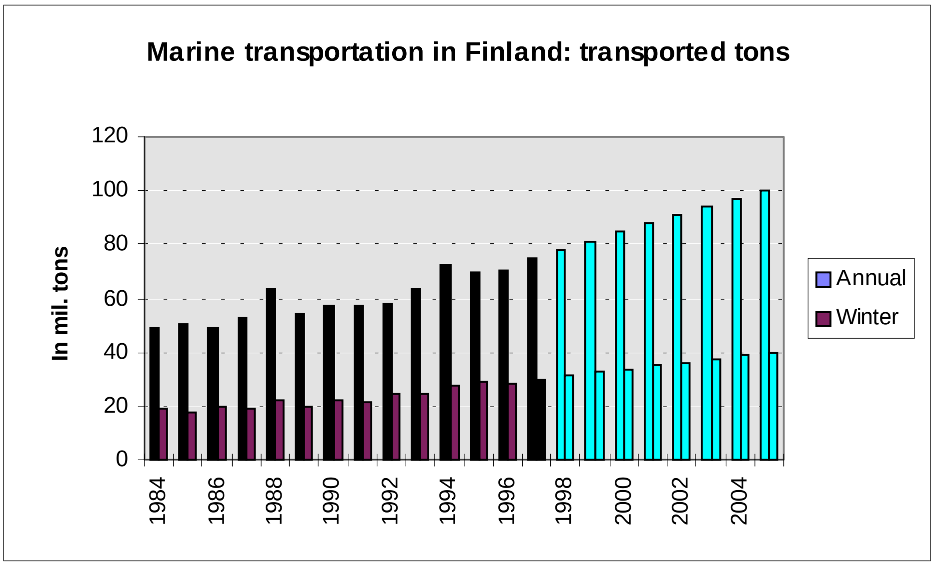
Figure 8. RADARSAT Scan SAR Narrow 300 by 300 km image from March 1998 with optimal coverage of the Bothnian Bay. © Canadian Space Agency, Agence spatiale canadienne, 1998. Processed by TSS and FIMR.

The costs of operating icebreakers are significant but small compared to the total value of the merchant vessels and their cargo. The running cost of a good, large enough, ice-strengthened merchant vessel capable of navigating in the ice of the Bothnian Bay is about 10 kECU a day. During the ice season there are more than 20 000 port-calls and 30 mill. tons of transported cargo to Finland alone (Fig. 9). The schedules of the merchant vessels are very strict and the port-times are kept to a minimum. Any delay in schedule represent economical loss for the operators.

An attempt to quantify the savings, which a good ice service brings to the national economy, is to estimate time saving per vessel. If the time loss due to insufficient ice information is, say half a day for each 20 000 port-calls, the economical losses can be as high as 100 mill. ECU. If we take into account that 60% of the Finnish traffic is in the Gulf of Finland, the duration of ice season varies from harbour to another and the ice conditions are varying all the time, the losses will be lower. Not all vessels need icebreaker assistance and some need it only occasionally. Therefore we could estimate that the economical losses due the ice conditions could be between 10 and 25 mill. ECU in one ice season. In order to save this amount the ice information service must be perfect and captains of the vessels must be absolutely convinced that no unexpected obstructions will arise under any conditions.

Today ships are charged a certain fairway dues by the Finnish Marine Administration and Swedish Marine Administration which includes icebreaker assistance. All vessels must pay dues when they arrive to the harbours. The dues are paid according to the vessel's Finnish-Swedish ice class and its net tonnage.

If the winter navigation could be made more efficient, the shipping companies would achieve cost savings which could result in reduced price for transported goods. This would furthermore be beneficial for the national economy.



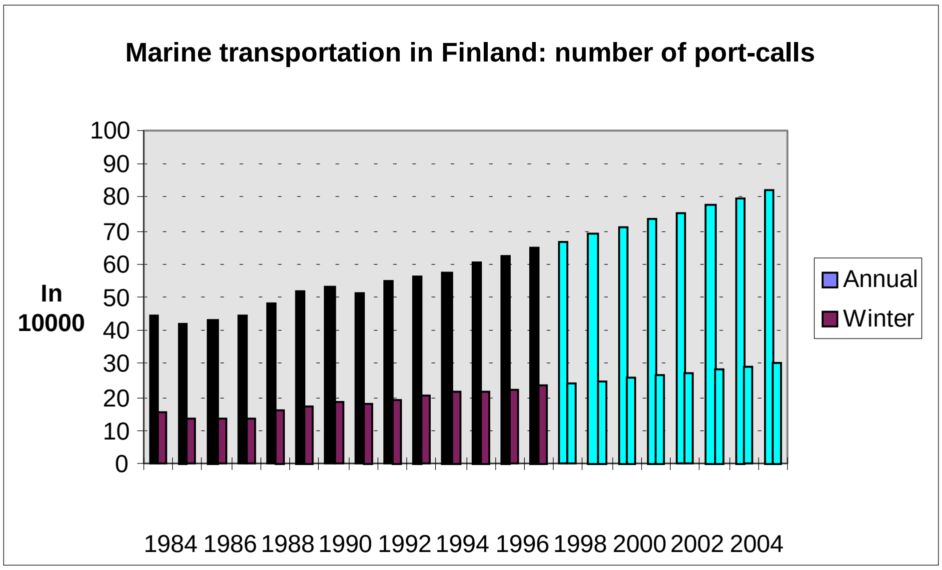
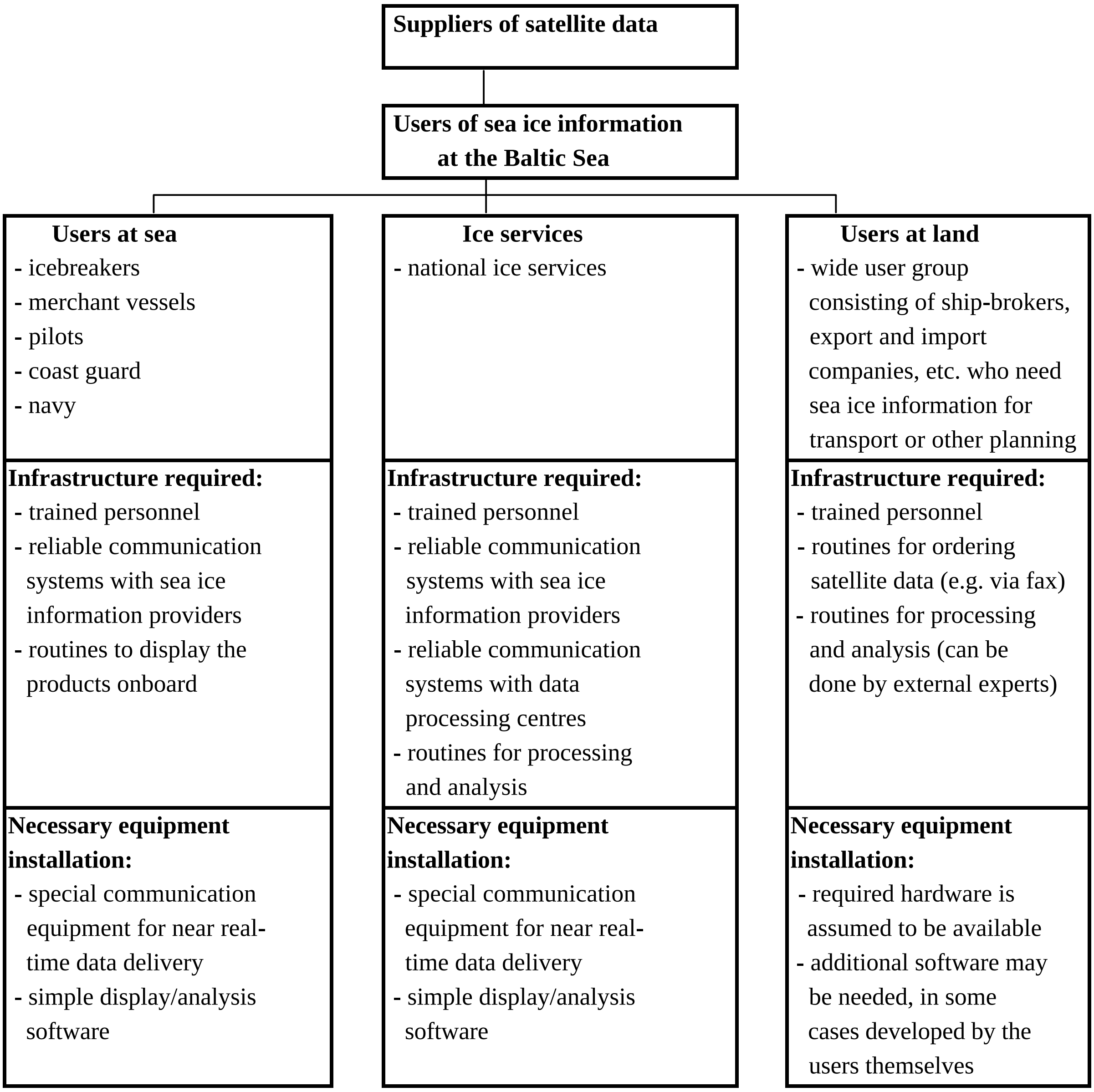


Figure 9. Marine transportation (annual and winter months) and number of port-calls in Finland 1984-1997 and estimates for 1998-2005. The traffic has gone up to about 30 during last 10 years and it is expected to go up another 30% in next 10 years. (Source: Finnish Marine Administration)

In the Baltic Sea the seasonal ice cover lasts up to half a year. This means that almost every winter sea ice makes navigation difficult in Finland, Sweden, Russia, and Estonia. During average and severe ice seasons traffic difficulties occur in all Baltic Sea countries and in Norway (Oslofjord) and the Netherlands. Considerable amount of goods are transported in the most difficult ice areas of the Baltic Sea. Therefore no significant reduction in ice service could be done in Finland, Sweden, Estonia and Russia without considerable economical losses.



Users at sea	**Ice services**	**Users at land**
- icebreakers - merchant vessels - pilots - coast guard - navy	- national ice services	- wide user group consisting of ship-brokers, export and import companies, etc. who need sea ice information for transport or other planning
Infrastructure required: - trained personnel - reliable communication systems with sea ice information providers - routines to display the products onboard	**Infrastructure required:** - trained personnel - reliable communication systems with sea ice information providers - reliable communication systems with data processing centres - routines for processing and analysis	**Infrastructure required:** - trained personnel - routines for ordering satellite data (e.g. via fax) - routines for processing and analysis (can be done by external experts)
Necessary equipment installation: - special communication equipment for near real-time data delivery - simple display/analysis software	**Necessary equipment installation:** - special communication equipment for near real-time data delivery - simple display/analysis software	**Necessary equipment installation:** - required hardware is assumed to be available - additional software may be needed, in some cases developed by the users themselves

Figure 10. Main user groups, required infrastructure and necessary equipment for the Baltic Sea ice radar monitoring.

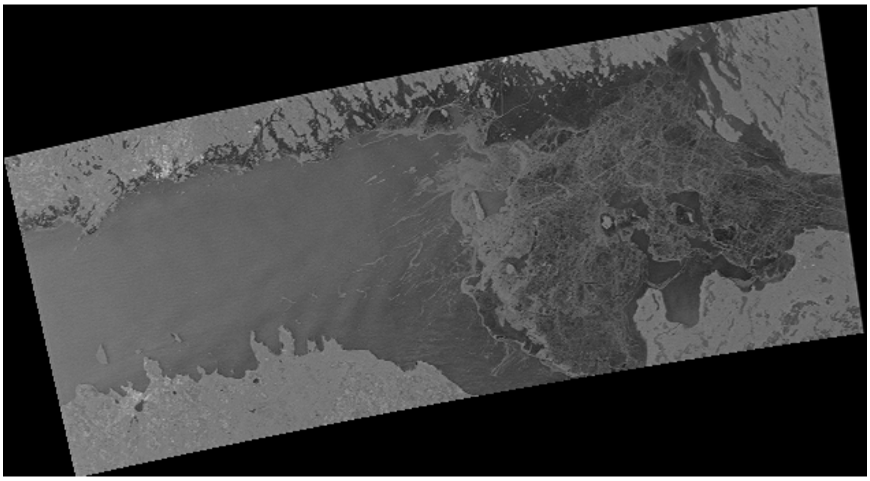


Figure 11 a. RADARSAT image from 26 February 1998 15:55 processed to 800 m resolution by FIMR. © Canadian Space Agency, Agence spatiale canadienne, 1998. The image is provided by TSS.

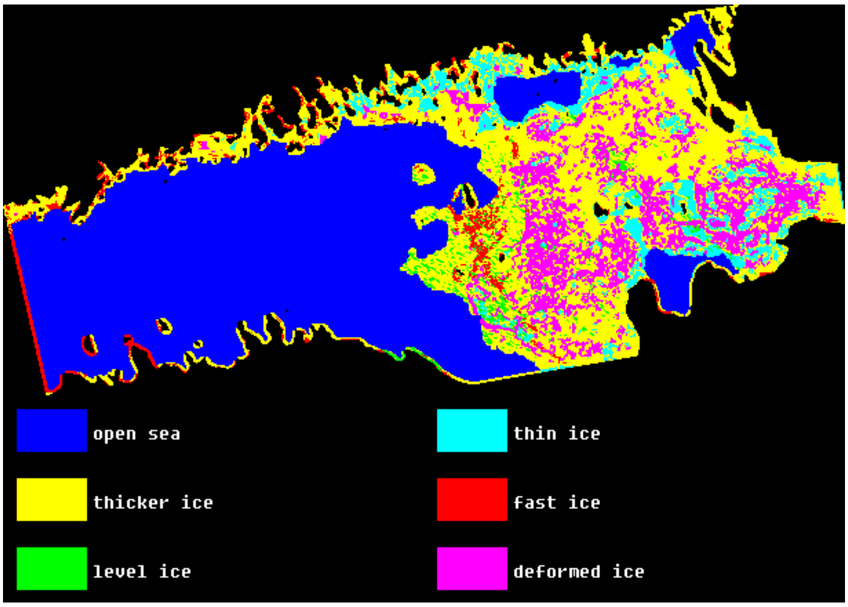


Figure 11 b. Classification of the image in Fig. 12a. © FIMR, 1998. The dark blue areas inside ice area are flooded ice.

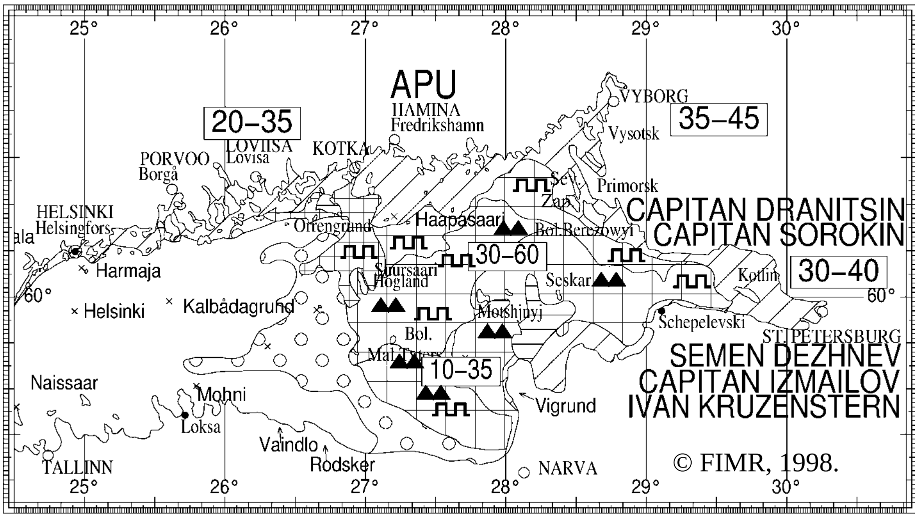


Figure 11 c. Ice chart produced from RADARSAT data for 26 February 1998.

5.2 Greenland Waters

In most Greenland waters surrounding sea ice is present all year round (Fig. 12). The ice regime is characterised by predominately old multi-year ice along the east coast and the southern part of the west coast, and by first-year ice which forms in the Baffin Bay, off the west coast of Greenland.

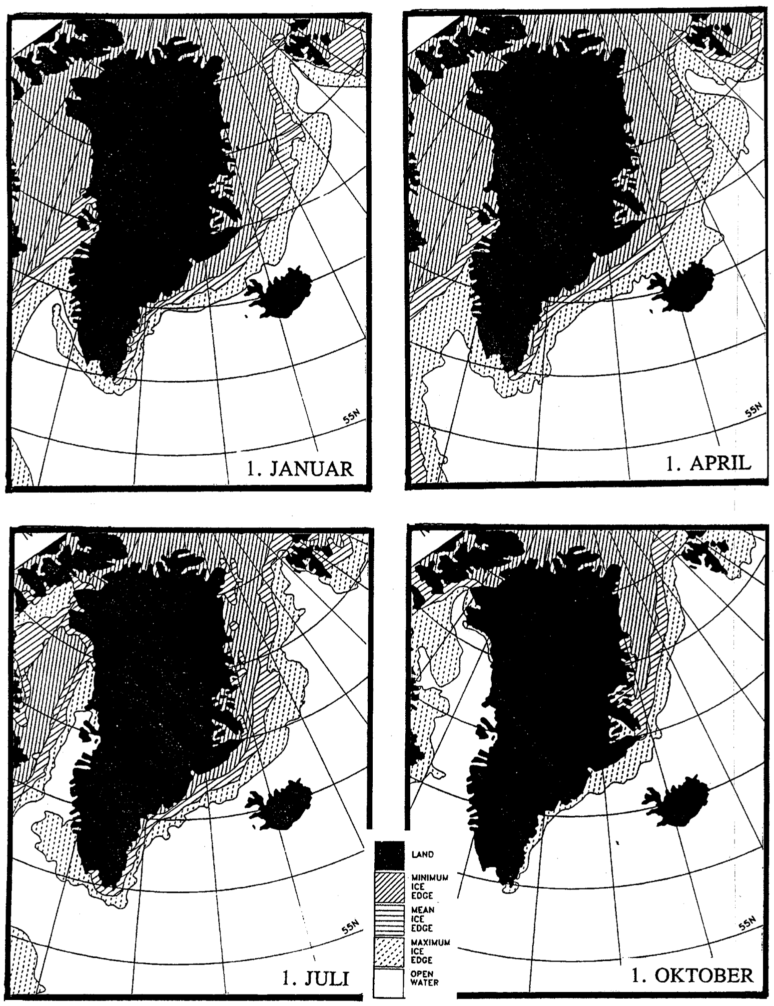


Figure 12. Ice coverage around Greenland at the beginning of January, April, July and October. Ice distribution with a concentration of 4/10 or more (*Naturens Verden 1993*).

Most of the ice in the Arctic Sea is several years old with an average thickness of 3.5 - 5 m. This ice flows through the Fram Strait and covers the entire east coast of Greenland most of the year. As the multi-year ice drifts southwards, the floes break into smaller pieces and are mixed with ice which is formed locally. During the melting season the thickness of the multi-year ice decreases from about 4-5 m in the Fram Strait to about 2 m in the Cape Farewell area. In most years, small floes of old ice is present in the Cape Farewell area for several months. At the seasonal maximum in March-June, the ice may reach 700 km up along the west coast. While most of the ice along the east coast originates from the Arctic basin, nearly all ice present in the Baffin Bay has been formed locally during the winter and is a considerably less threat to navigation. The thickness of this winter ice usually increases to a maximum of about 70 - 100 cm in April, when the ice covers the entire Baffin Bay leaving only the south-west coast of Greenland, ice free in most years. Even more dangerous to navigation than the sea ice is the occurrence of icebergs and calved ice from the inland ice. This ice may be found in most Greenland waters as shown in Figure 7.

The users of ice information are primarily merchant vessels passing Cape Farewell and local traffic, especially in West Greenland south of 69°N. Since no inter urban roads exist in Greenland, all traffic has to go by air or sea. Consequently, the local freight traffic carried out by ships is large compared to the relatively low number of inhabitants. (The ship traffic has been reduced from 500 to 300 port calls per year due to use of larger vessels.) In addition, fishing vessels are also using the ice information, particular information about the ice edge position. In recent years information from the Ice Service in Greenland is requested by a wide range of new users such as the increasing number of cruise ships (with up to 1200 passengers each) and companies working with exploration of oil, gas and mineral resources. Ships navigating the Greenland waters may be divided into two groups with respect to ice information requirements, i.e. ships that need to go through the ice and ships which only need to circumnavigate the ice. It is also important to stress that icebreaker assistance is not available anywhere in the Greenland waters.

The Cape Farewell area is the most important sea ice area since all ships to the major cities on the west coast need to pass this area. Users therefore require ice charts of this area and the ice charts must in particular contain timely information about the position of the ice edge. This means that in most cases the information should not be older than 6 to 8 hours. Information about the ice edge is often sufficient because most ships will circumnavigate the ice. To meet this requirement 3-5 ice charts of the Cape Farewell area must be issued every week throughout the year, because the ice analyst needs to know the history of the development and movement of the ice to interpret a given ice situation correctly. This information is especially acquired by RAL cargo ships, but also fishing vessels and tourist ships use this information regularly. Daily ice information is needed from satellites and/or aircrafts.

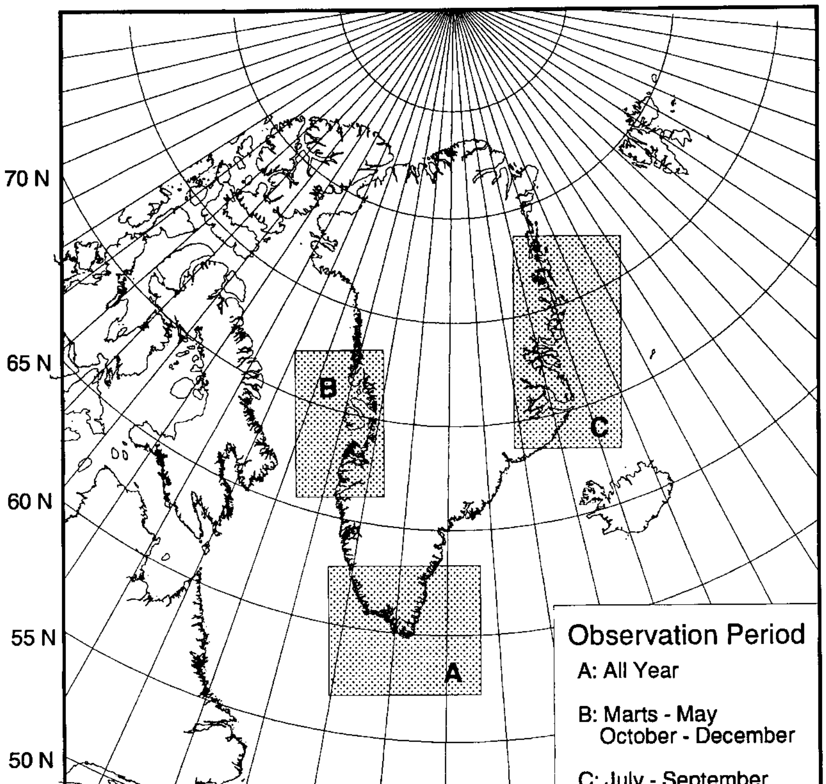


Figure 13. Map of Greenland showing three of the areas where ice maps are produced by DMI. Area A (Cape Farewell) is the most important area because of year round ship traffic.

During the summer information about the ice type and concentration is also needed to approach harbours on the Eastern part of the Greenland coast. Since there is a limited number of port calls within a narrow time frame, the ice monitoring of especially these areas must be co-ordinated with the ships sailing plans. In these areas a ship will navigate using a combination of ice chart information and helicopter reconnaissance. The ice charts should therefore be as timely as possible to assist in navigation and for planning of helicopter reconnaissance. In comparison to the Cape Farewell area the ice information must indicate more than only ice edge position, since the ship have pass through the ice and detailed information about ice concentration and leads can be important. The information should be updated regularly while the ship is sailing within the ice edge. The calling of harbours in the North Western part of the coast is limited to the ice free period. Identification of the time of sea ice break up and closing is therefore important.

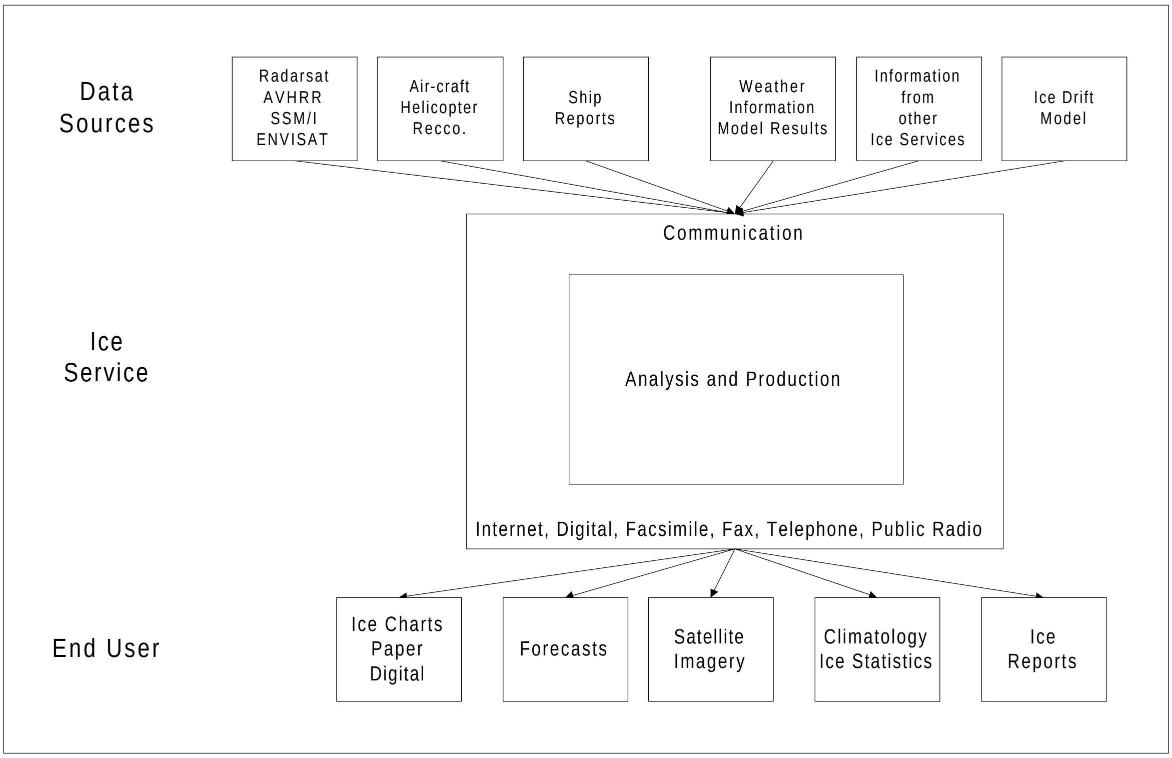


Figure 14. The ice monitoring system in Greenland.

Navigating the Greenland waters without any ice information is dangerous and can cause much larger sailing times. If the ships are caught within the ice for days or weeks, severe time loss, damage to the ship and in the worst case loss of ship can occur. RAL indicate, that without any information about the ice conditions the travel time may increase up to 24 hours which is equivalent to approximately 15.000 ECU of extra costs. Furthermore, it can be anticipated that cost of repair of damages to the ship, will add to this figure. For passenger, ship cancellations due to lack of ice information may lead to additional costs because passengers are entitled to alternative transportation, i.e. by air. Furthermore, lack of inshore ice information could easily mean that a passenger ship could be locked in the ice for a period of days to weeks leading to severe economical losses and potential damage of the ship. Offshore operations, such as seismic measurements are carried out by specially equipped vessels. They may work within or near the ice edge. During seismic surveys it is very important to have access to actual and accurate ice information for selection of potential areas of operation. Accurate ice information may therefore lead to significant cost reductions.

The main cost factors for the ice monitoring service are data collection from aircraft and satellites. DMI plans to use more satellite data, especially RADARSAT data, and reduce the use of aircraft surveys. The cost-benefit of using more SAR data instead of aircraft data, depends on the cost of the SAR data, which is annually negotiated with the data provider.

Figure 15. Fast ice in Greenland can also be beneficial for transportation. (*Naturens Verden, 1993*)

Figure 16. The Greenland Ice Service uses ships, aircraft and helicopters for ice reconnaissance. (*Naturens Verden, 1993*)

It is unquestionable that improved ice information accessible for the users will reduce the risk of accidents and economic losses. Particularly, the accurate and timely ice information is a prerequisite for safe operations of oil platforms, tankers and other vessels. At the moment there is no market for oil and mining industry to become important in Greenland. However, this may change when oil exploration and mining start to develop in Greenland because these industries need more specific and intensive ice service than what is offered today.

The main issue for the ice service is whether satellite data such as RADARSAT can replace use of aircraft surveillance. Currently there is evidence that in summer the RADARSAT data are not reliable, so aircraft will definitely be necessary in this period. The annual cost of 1.7 MECU per year for aircraft surveillance cannot be reduced sufficiently to allow purchase of SAR data at the official price.

During seismic investigations in the last 4 - 5 years, it has been very important to have near real-time and accurate ice information for planning the location of the seismic profiles. Especially off the north-east coast of Greenland, ice charts from DMI have been used successfully. Without this information it would be impossible to operate effectively in these waters, where considerable amount of sea ice is present also in summer. The accurate ice information has been essential for optimal ship operations. Other users of ice information are insurance companies which need to estimate if ship and its cargo is able to reach a given destination without having problems with sea ice.

Table 7. Summary of users in Greenland and their requirements for ice information.

Ice information	User	Requirement for information
Ice edge position	RAL* and other ships (e.g. tourist vessels) passing Cape Farewell while circumnavigating the ice Fishing boats working outside the ice.	Ice charts (1:1.000.000) with the ice edge position indicated. The chart should not be older than 6-8 hours.
Ice type and concentration	RAL* and passenger ships which need to pass through the ice Offshore operations performed near or within the sea ice	Ice charts (1:1.000.000) where the ice type and concentration is estimated.
Free passage	Inshore route passenger ships	A ship will need to contact the ice service (e.g. by telephone) to update information about present route conditions
Ice extent	National weather service	A daily map covering Greenland waters (1:10.000.000) showing where sea ice is present.
Ice concentration	Shipping companies and other users who want a general picture of the ice conditions around Greenland, e.g. for planning purposes.	A weekly updated overview map (1:10.000.000) covering Greenland waters

* RAL: Royal Arctic Line; the main shipping company operating in Greenland

5.3 Northern Sea Route

The Northern Sea Route (NSR) is the world's longest sailing route in ice-covered waters (Fig. 17), extending from the Barents Sea in west to the Bering Strait in the east. The sailing route is of vital importance for the national Russian transport system, because it includes many rivers and inland waterways connected to the Arctic Ocean. The ice conditions restrict sea transportation which requires ice class vessels as well as icebreaker assistance throughout the year. In summer there is traffic in the whole Northern Sea Route, whereas in winter it is limited to the western part between Murmansk and the Yenisey River.

An extensive ice monitoring and forecasting service has been built up in Russia over the last 50 years with a main objective to serve the icebreaker fleet and the cargo transport in the Northern Sea Route (*Smirnov et al., 1998*). Use of space-borne SAR has not yet been part of this service until the start of the ICEWATCH programme (*Johannessen et al., 1996, 1997a, b*). The users of ice information are primarily the shipping companies responsible for the cargo transport as well as the supporting icebreakers. In addition, oil companies, and their supporting consulting companies need ice information to plan offshore operations. Research expeditions have temporary needs for near real-time sea ice information in order to facilitate and optimise their research field programs.

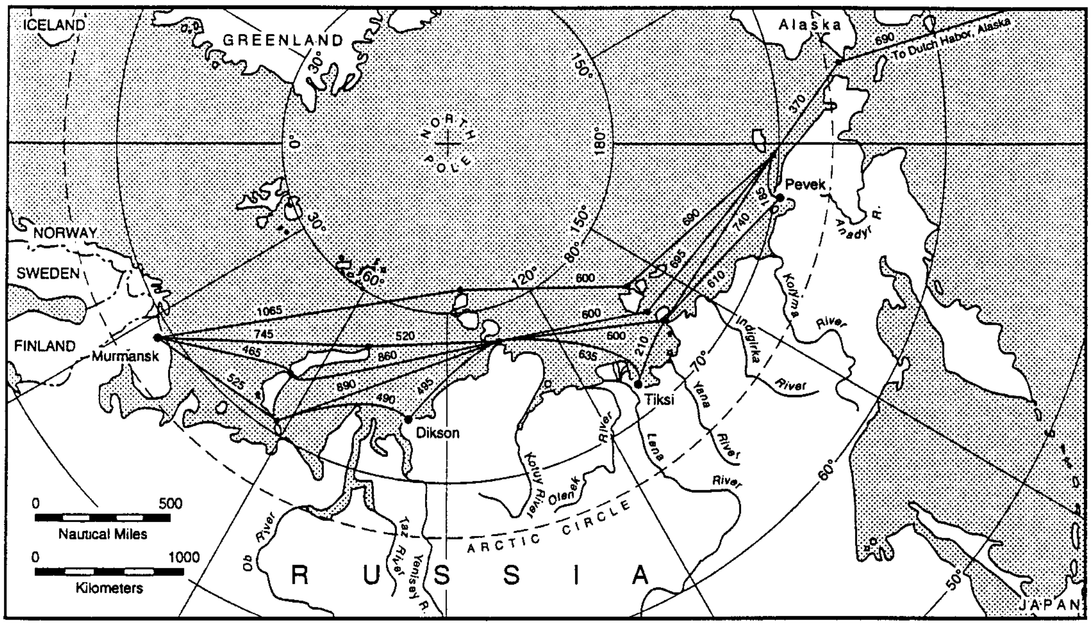


Figure 17. Approximate distances, in nautical miles, of the various route segments between Murmansk and the Bering Strait. The sailing distance along the coastal route is about 3300 nautical miles. (*Mulherin et al. 1996*)

Three Russian shipping companies are responsible for most of the transportation in various parts of the Russian Arctic. The largest is Murmansk Shipping Company which is responsible for the governmental icebreaker fleet (Fig. 18), operating mainly along the western parts of the Siberian coast and in its rivers. The fleet consists of about 10 icebreakers and several ice strengthened cargo vessels. The Northern Shipping Company and the White Sea - Onega Shipping Company are operating in the White Sea and on the lakes and rivers between the White Sea and the Baltic Sea.

Figure 18. The Russian icebreaker ‘Sibiria’. Image courtesy: Murmansk Shipping Company.

Sea ice information is required in all seasons, because of the raise in transport operation in parts of the Northern Sea Route throughout the year. The purpose of ice monitoring and forecasting is to optimise the ship operations, as well as to obtain the best sailing routes and minimise the risk of damage on icebreakers and escorted vessels. This requires detailed information on many sea ice parameters; ice edge location, ice type (or it's age) classification, ice movement, coastal polynyas, fast ice, shear zones, leads, and ice roughness.

The most important ice information produced are the comprehensive ice maps (CIM) generated by the Russian ice service (*Smirnov et al., 1998*). These maps are based on several types of satellite data (NOAA AVHRR, Okean SLR, Meteor, etc.), ship observations, meteorological and oceanographical data. Use of aircraft surveillance with SLAR and SAR was the most important source of data for many years, but now this monitoring has been cancelled due to the difficult financial situation. Use of satellite SAR (ERS-1 and ERS-2) in ice monitoring of the Northern Sea Route has been tested in several demonstration projects since 1991 (*Johannessen et al., 1997*). The use of SAR data will clearly be beneficial to improve these maps and provide more details about the ice cover. The most promising technique is direct use of SAR data onboard icebreakers in tactical ice navigation where images are transmitted to the icebreakers in near real-time.

Low Resolution Images (LRI) contains information, not included in ordinary ice maps, needed by the ice pilots onboard the ships. In this respect there is a need for education and training of the ice pilots in order to perform the correct onboard interpretation of the ice information in SAR images. For practical use the ERS SAR coverage is very limited with respect to the ice monitoring, although when available the data are efficient and optimal for planning of the tactical navigation.

Ice data for support of navigation in the Northern Sea Route must be obtained at strategic, operative and tactical levels, defined by different spatial and temporal scales as shown in Table 8.

Table 8. Summary of requirements to sea ice information for ice navigation in the Northern Sea Route.

	Strategic	**Operative**	**Tactical**
Users	User category 1: NSRA, User category 2: MOH	User category 2: MOH, icebreaker captains	User category 2: icebreaker captains
Coverage	Global (the whole NSR including the Eurasian sector of the Arctic Ocean	Regional (Murmansk - Dikson)	Local
Spatial resolution	~ 10 km	< 1 - 2 km	< 100 m
Required repeat period	10 days	2 - 3 days	< 100 m
Products	ice charts with scales 1 : 7 000 000 1 : 5 000 000 1 : 2 000 000	ice charts with scales 1 : 7 000 000 1 : 5 000 000 1 : 2 000 000	ice charts with scales 1 : 500 000 1 : 200 000
Requirement for archived data	very important for statistics	important for interpretation of satellite images	not required
Requirement for real-time data	not required	important within one day	important within 2 - 3 hours
Requirement for ice forecast	long term forecast: monthly and seasonal forecast	forecasts up to 7 days	short term forecast

Strategic sea ice information

Strategic (survey) ice information is used by the Northern Sea Route Administration and Marine Operations Headquarters to plan the icebreaker fleet operation for the whole Northern Sea Route.

The main tasks are:

- to select ports where cargo traffic will be concentrated and points of cargo delivery in the Arctic;
- to determine the conditions and duration of the navigation period;
- to select and distribute the transport ships and icebreakers according to the type of transport;
- to calculate the operative-economic indices of the planned sea operations.

The main method to obtain strategic ice reconnaissance is to use satellite data with a low resolution (approximately 5 - 10 km local) and large area coverage. Satellite data of higher resolution as well as data from aircraft and from other sources can be used as additional information to obtain more detailed estimates of sea ice parameters.

Operative sea ice information

Operative ice maps are used by the MOH and icebreaker captains to solve ice related problems during icebreaker operations: choice of routes, convoy formation and administration of icebreaker fleet.

The operative ice maps and ice forecasts are transmitted to all the icebreakers and ships working in a specific region such as the Kara Sea. This information is used to select routes and plan measures to ensure the safety of ice navigation.

Data for operative ice charts are obtained from satellites with medium to high resolution, aircraft surveys, observations from polar stations, ships, and data from expeditions. In recent years satellite data has become the main source of information for operative ice charts, while aircraft surveys have been drastically reduced. In addition to ice charts, weather forecasts and ice forecasts are prepared up to 7 days in advance.

Tactical sea ice information

The main users of tactical ice information are the navigators onboard the icebreakers and vessels. Tactical ice reconnaissance is carried out episodically during specific sea operation such as ship or convoy steering, autonomous icebreaker voyage, cargo operations away from the ports (ship to shore or ship to ship). The main goal of the tactical ice reconnaissance is to choose an optimal route for ice navigation, on local scale by using leads, polynyas and thin ice areas and avoid thick ice, large floes and areas of heavy compression.

The major sources of the data of the tactical ice reconnaissance are:

- airborne visual ice survey flight from helicopters carried by icebreakers;
- instrumental survey from aircraft equipped with side-looking radar;
- space-derived high-resolution imagery such as SAR.

Since the Northern Sea Route is the longest and most difficult ice navigation route, ice information has severe economic impact on transportation. The most important cost factors are damage to ships and time loss due to difficult ice navigation.

The most frequently used satellite data are NOAA AVHRR data because it is free-of-charge and can be obtained by simple receiving equipment. SAR data have proven to be the most powerful tool for ice monitoring, but operational use has not been possible due to high cost of data and insufficient coverage. With RADARSAT and ENVISAT the coverage has been and will be significantly improved, but the data cost will still be a problem.

Availability of SAR images and derived sea ice information may replace parts of the expensive and in periods extensive need for use of helicopters for local reconnaissance of the sea ice conditions. Use of

SAR images in near real-time can help ships avoid heavy ice and save sailing time by following the optimal route. With a daily operation cost of order $ 50 000 or more for the larger icebreakers, it is clear that significant savings can be made if their operations can be made more efficient by using real-time satellite images to select optimal sailing routes (*Wergeland, 1991*).

It has been estimated by N. Babich at MSC icebreaker fleet that with SAR coverage from RADARSATs ScanSAR it will in theory be possible to double the productivity of the icebreaker fleet of Murmansk Shipping Company. This is illustrated in Figure 20, that the mean icebreaker speed will increase from the present situation with no use of SAR (bold line) to the dotted line representing a situation with use of RADARSAT images. The hatched area represents the improvement in productivity as a function of season.

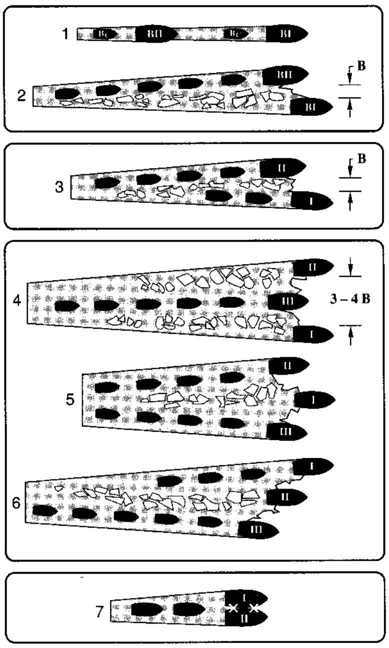


Figure 19. Seven examples of icebreaker convoy formation which need tactical ice information (*Brigham, 1991*).

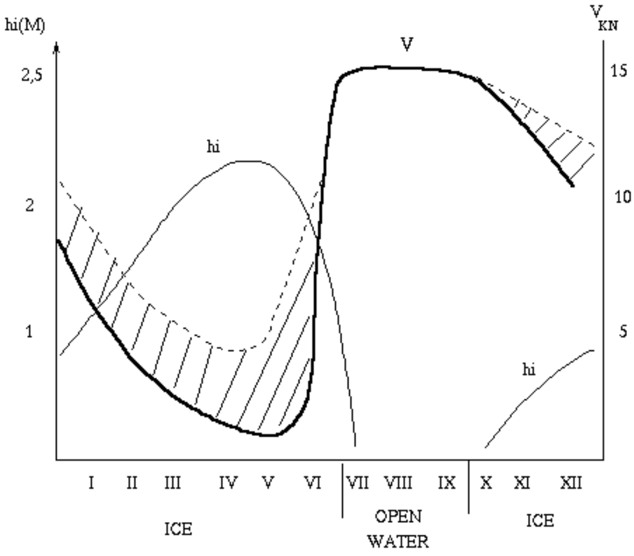


Figure 20. Mean icebreaker convoy speed (V) and mean ice thickness (hi) as function of month in the Northern Sea Route. (*N. Babich, personal communications*). The bold line shows average convoy speed without any SAR information and the dashed line shows improvement of the average convoy speed with use of SAR coverage from satellites such as RADARSAT.

5.4 Canada

Canada, together with Russia, has the largest ice areas in the world within its national territory, which requires an extensive national ice service. Operational ice monitoring is performed in ten regions by the Canadian Ice Service (CIS), as shown in Figure 22. The purpose of the service is to ensure safe and efficient maritime operations and to protect Canada's environment by providing reliable and timely information about ice conditions including icebergs. CIS is responsible for collecting and analysing data of ice conditions in all regions of the country where sea ice is present. In summer CIS focuses on conditions in the Arctic and the Hudson Bay region. In winter and spring attention shifts to the Labrador coast and East Newfoundland waters, the Gulf of St. Lawrence, the St. Lawrence Sea Way and the Great Lakes (Fig. 21).

Canada has also launched its own SAR satellite, RADARSAT (Fig. 22), which has operational sea ice monitoring as one of the prime objectives. For Europe it is therefore interesting to study how the Canadian Ice Service changes its ice monitoring methods to more use of satellite SAR data and less use of aircraft surveillance.

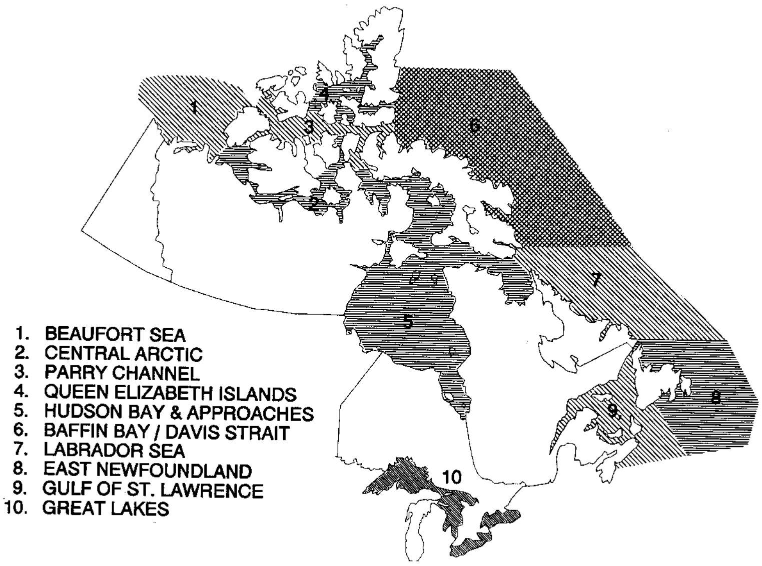


Figure 21. Primary Canadian ice areas regularly observed by he Ice Centre (*Haykin, 1994*).

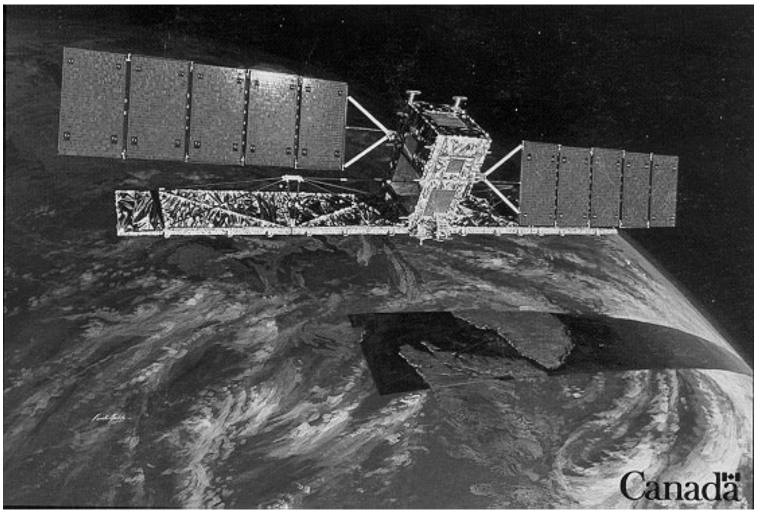


Figure 22. RADARSAT satellite, (*Canadian Journal of Remote Sensing, 1993*).

The major user of ice information issued by CIS is the Canadian Coast Guard (CCG). All major CCG icebreakers and the Ice Operation Offices are equipped with a communication and display system application (IceVu) developed by CIS designed to capture and display RADARSAT, airborne SLAR and ancillary data. The regional coverage of RADARSAT ScanSAR data provides CCG with the ice information they require to plan sailing routes and to organise deployment of icebreakers between operations in the Gulf of St. Lawrence and the St. Lawrence River. The data are received within hours of capture allowing Ice Operations Officers to more effectively deploy their ships to areas where ice poses a hazard. The Clients Services division of the CIS will acquire higher resolution imagery from other RADARSAT modes for clients requiring more detailed surveillance over smaller areas.

Ice charts and a variety of image and other map products are generated from RADARSAT images as well as many other data sources listed in Table 9. These products are then relayed to marine customers by means of satellite, cellular phone and land line links. The RADARSAT image analysis charts and RADARSAT sub images have become standard products available through a dial-up bulletin board system. Imagery products in ERDAS Imagine or JPEG format are normally available within 3 hours after capture and the analysis are normally available within 6 hours.

Feedback from Canadian Coast Guard indicates that there is an improvement in the accuracy of the daily chart which is directly attributable to the greater availability of near real-time data from RADARSAT. This has lead to improved accuracy in the provision of warnings of hazardous ice conditions. For the CCG the operational value of the RADARSAT data increases directly with the rate it is processed and products are disseminated to the icebreakers (*Weir*, *1996*). Experienced/frequent users like the CCG, demand a broader range and more detailed and accurate products. Other users have almost no requirements as they simply follow ice routing guidance with icebreaker support. Generally, the users of ice products from the CIS are satisfied with the products.

Table 9. Remote sensing data sets used by the Canadian Ice Service.

Source/sensor	**Typical pixel (m)**	**Swath (km)**	**Sensor characteristics**
NOAA/AVHRR	1000	2000	Passive optical sensor using 5 channels from visible to thermal infrared
DMSP SSM/I	25 000	1400	Passive microwave sensor using 5 channels from 19 to 85 GHz
Aircraft SAR	25	200	Active microwave sensor using X band, HH polarised
Aircraft SLAR	25-400	200	Active microwave sensor using X band, HH polarised
ERS-1 SAR	50	100	Active microwave sensor using C band, VV polarised (pixel size degraded from original image product)
RADARSAT SAR	100	500	Active microwave sensor using C band, HH polarised (pixel size corresponds to the ScanSAR mode data product)

For the CIS the main cost factors are primarily data acquisition, secondly computer and communication and thirdly salaries to personnel, RADARSAT data are obtained at reduced prices and ERS data have been obtained free of charge. Increased use of RADARSAT data has lead to a reduction of airborne surveillance. Now, aircraft are used more directly in tactical support to the icebreakers. It may be anticipated that ice information can become cheaper and more accurate using satellite data. The price level of SAR data is a crucial factor which determines the cost-benefit of using SAR data in ice monitoring.

CIS operates on public funding providing ice information of public interest. For example, public safety, pollution prevention and detection, and emergency response are all of public interest. The infrastructure necessary to provide this service should also be a public responsibility. If governmental funding should decrease significantly the quality and quantity of public services would deteriorate. This could stimulate more private funding, but it could also imply that some private operations, such as commercial cargo freights, become too expensive to carry out in ice-covered waters. On the other hand private funding should finance any special customer-requested service which go beyond the public ice service. At the moment there is little commercial competition for the national ice service. Some private companies, primarily engineering and environmental firms, provide site specific or customer specific services.

5.5 Summary of data and product requirements

Baltic Sea

What can EO data offer ?

- SAR from RADARSAT with 100 m resolution and coverage of most of the region every 2-3 days.
- AVHRR data from NOAA with 1 km resolution, coverage of cloud free areas, several passes a day.
- SSM/I has too coarse resolution for the region.

What the users need:

- Ice charts with resolution down to 100 m.
- Ice forecasts up to 5 days or more.
- Classified SAR images with resolution down to 100 m in specific areas: off ports, along sailing routes.

Greenland Waters.

What can EO data offer ?

- SAR from RADARSAT with 100 m resolution and coverage of most of the region every 2-3 days. Some limitation in use during the summer.
- AVHRR data from NOAA are used routinely but frequent cloud cover, especially in Cape-Farewell area make the data unreliable.

What the users need:

- Daily regional ice charts in the regions with most traffic and less frequent ice charts in other areas.
- Iceberg maps showing the extent and distribution of icebergs and growlers.
- More detail ice charts in sailing routes near the coast.

Northern Sea Route

What EO data offer?

- SSM/I offers large-scale, coarse resolution ice charts for strategic planning of sea operation.
- AVHRR data offers regional ice extent data and ice concentration in cloud free situations.
- SAR data from RADARSAT and ERS offers unique ice information (ice types, leads, polynyas) in parts of the Northern Sea Route which are very useful for strategic operative and tactical navigation.

- Russian satellites (Okean, Meteor) can provide data similar to AVHRR and coarse resolution SAR.

What the users need:

- Strategic ice information for the whole NSR every 10 days, with spatial resolution of order 10 km.
- Operative ice information with 1-2 km resolution every 2-3 days.
- Tactical ice information with resolution 100 m and time interval of 2-3 hours.

5.6 Other factors influencing user requirements

In addition to the specific requirements discussed for the four regions, there are new developments which will have impact on user requirements for sea ice information in the future. Four issues will be addressed which we believe will be of importance: 1) New international rules for ship operation in Polar waters; 2) increased use of electronic sea charts; 3) introduction of ice routing simulation models; and 4) the Ocean and Sea ice Satellite Application Facility by EUMETSAT.

5.6.1 Polar Code

A new International Code of Safety for ships in polar waters (the Polar Code) is developed under the auspices of the International Maritime Organisation (IMO). The Polar Code (*Polar Code, 1997*) recognises that safe operation requires an integrated approach, involving design and outfitting of ships to meet the challenges of the operating conditions, the crewing by sufficient number of suitable qualified personnel, and their operation in a planned and prudent manner. The safety of life and the prevention of pollution have been given equal importance in the development of the code. The Code is intended to promote responsible polar operations, therefore its provisions should demonstrate a positive cost/benefit balance. Access to reliable sea ice information from satellite data can therefore become a consequence of the Polar Code.

5.6.2 Electronic Sea charts

The development of electronic sea charts ECDIS (Electronic Chart Display and Information System) and other digital information systems on ship raise the question how to integrate sea ice data into such systems. It is a requirement from several captains that future ice information should be included into electronic charts and be displayed together with bathymetric data and other relevant information on one terminal on the bridge. The situation today with more and more PCs on the bridge, serving different purposes, is not optimal for the captain. The standards for electronic charts are very strict because of legal requirement. It is therefore not yet clear if and how sea ice data can become part of an integrated digital information system onboard ships. The question is under discussion and it is believed that some integration of ice data with sea charts will sooner or later become a reality.

5.6.3 Ice Routing Simulation models

Increased use of digital data in marine operations has encouraged development of ice routing simulation models. Such models use ship parameters, environmental parameter, geographical and infrastructure data as input and calculate optimal sailing routes which are used by ship owners and captains of different routes. Sea ice information is an essential part of the input data in such models. The data, together with meteorological and oceanographic data, can either be of statistical type where averages are used, or real-time data including forecast for use in planning of actual voyages. One such model, using monthly sea ice statistics is constructed for the Northern Sea Route to estimate transit time between Murmansk and the Bering Strait and cost of potential marine shipments via the Russian Northern Sea Route (*Mulherin et al., 1996*). At each route, the probability distribution for ice thickness, concentration, and pressure, wind speed and direction, wave heights, probability of fog, snowstorms and icing are used to calculate the estimated travel-time and it's costs. Other routing models attempt to find the optimum sailing routes from SAR images, such as shown in the ICE ROUTES project (*ICE ROUTES, Final Report, 1998*).

5.6.4 EUMETSAT's Ocean and Sea Ice SAF

EUMETSAT is building up Satellite Application Facilities which will process satellite data and provide data products for the weather services. One of these facilities works with ocean and sea ice, and will provide sea ice parameters primarily from AVHRR and scatterometer, but also from SAR and other new instruments. The sea ice parameters (ice edge, ice cove, ice type) will be provided in 10 km resolution with global coverage. The requirements from the weather services will determine types of satellite data, temporal and spatial resolution, and derived products from the ocean and ice SAF in the future (*Breivik et al., 1998*).

6. Satellite systems and ground structure

This chapter describes the technical feasibility of sensors, instruments, ground structure and data transmission to the users. There are two central themes which determine to what extent operational ice monitoring can be based on satellite data. The first is the existence of satellite systems which can supply data from relevant instruments now and in future. The second is the ground infrastructure which includes receiving stations, data processing capabilities and distribution systems which can reach the users.

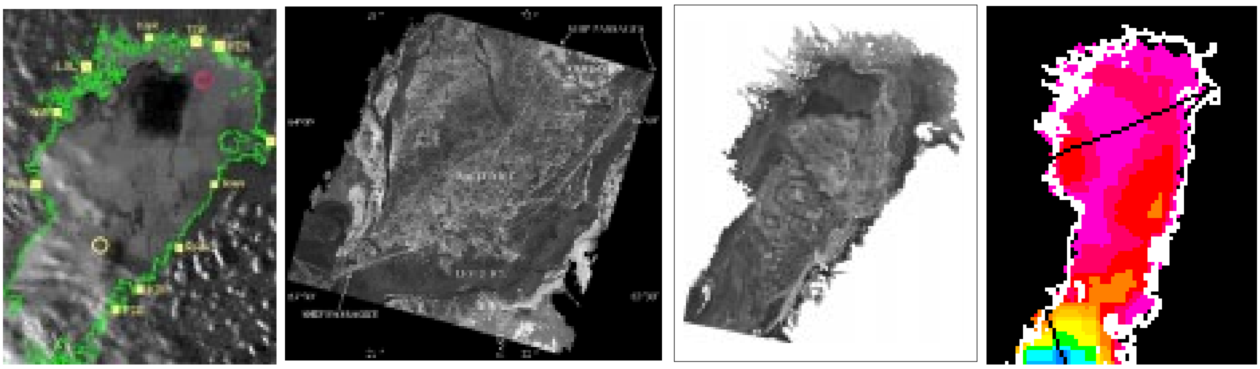
6.1 Capabilities and limitations of current satellite systems

Polar orbiting satellites give frequent coverage at high latitudes and are preferred in sea ice monitoring since geostationary satellites give poor coverage of the high latitudes. A summary of the main technical parameters for the polar orbiting satellite systems used in ice monitoring is given in Table 10. The two most frequently used satellite data in ice monitoring are the American SSM/I and AVHRR data which are available free-of-charge and can be obtained with fairly simple equipment. The Russian satellite data are almost exclusively used by Russian institutions. European and Canadian SAR data are used more and more in ice monitoring, but high data costs and cumbersome ordering procedures are limiting factors. The different systems have advantages and disadvantages in observation of the ice parameters, which have been discussed in Chapter 3 and 4. The capabilities and limitations of four different systems are illustrated in Fig. 23. The AVHHR (a) image has good spatial coverage, but is limited by clouds. ERS SAR (b) gives very good and detailed information, but has limited coverage. RADARSAT SAR (c) combines good coverage with rich information, but the data cost is high. SSM/I data (d) has too coarse resolution to be really useful in the Baltic Sea.

Table 10. Some technical data on the main ice monitoring satellites.

Countries/ Agency	Satellite programme	No of satellites **	Instrument	Channels	Resolution (m)*	Swath (km)*
USA	DMSP	2	SSM/I Passive microwave	19, 22, 37 and 85 GHz	30000	1400
USA	NOAA	2	AVHRR Visual / IR	5 (0.58-12.4 microns)	1000	2600
Russia	Okean		SLR	1 (3.0 cm)	1300 by 2500	450 km
Russia	Resurs		MSU-SK Visual / IR	5 (0.5-12.6 microns)	170 (vis./NIR) 600 (TIR)	600
Russia	Meteor	2	Scanning TV Visual	1 (0.5-0.7 microns)	1500	2100-2600
European Space Agency	ERS	1	SAR	single 5.3 GHz, VV pol.	100	100
Canadian Space Agency	RADARSAT	1	SAR	5.3 GHz, HH pol.	50-100	45-500

* Commonly used resolution and swath in ice monitoring
** Currently in operation



a) b) c) d)

Figure 23. Ice mapping in the Bothnian Bay from a) NOAA AVHRR, b) ERS SAR, c) RADARSAT SAR and d) DMSP SSM/I.

6.1.1 Imaging multispectral radiometers in IR and visual band

NOAA polar orbiting satellites with AVHRR provide a wide range of data of interest, including sea surface temperature, sea ice data, cloud cover, data for land studies and temperature and humidity profiles. Two satellites are maintained in orbit an any one time, one in a ‘morning’ orbit and one in an ‘afternoon’ orbit. At high latitudes 6-8 orbits are available daily. The series of NOAA satellites have been in operation for many years. Now AVHRR/3 is used on the NOAA K-N’ missions.

AVHRR data is the basic EO data in ice monitoring, because the data are free of charge, they are easy to receive by fairly simple equipment. The resolution of 1 km and swath width of 2600 km is good enough for general ice mapping. The Arctic area including Greenland and the Baltic Sea are frequently covered by clouds especially connected to low pressure activities, and as major changes occur during low pressure activities, visible/infrared data cannot observe the ocean surface. It has been estimated, that in the Baltic Sea area some 60% of images are useless because of cloud cover, in the Arctic waters the figure is larger.

There are several satellite programmes which operates this type of instrument; in Russia Meteor and Resurs MSU data are used in ice monitoring. Russia maintains a series of Resurs satellites such as the recently launched Resurs-01 N3. ESA’s ATSR is used for SST and can complement AVHRR in ice observation. NOAA will continue the AVHRR programme, ESA will have AATSR on ENVISAT and EUMETSAT will operate AVHRR on METOP from 2003. Several other satellite programmes will ensure that medium resolution IR/visual data will be available in the future. Meteor 3 visible image is shown in Figure 24 (*Smirnov et al., 1998*).

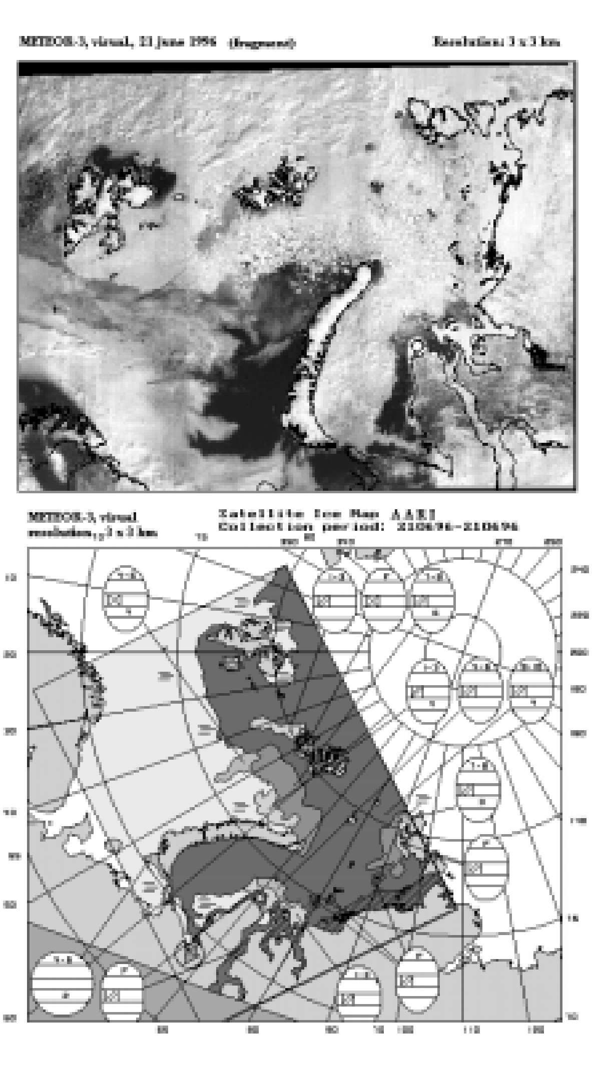


Figure 24. The lower figure displays an ice chart derived from the visible "Meteor-3" image shown in the upper figure. (*Smirnov et al., 1998*).

6.1.2 Passive microwave radiometer data

Passive microwave data has been obtained over sea ice areas for two decades, from NIMBUS 7 SMMR (1978-1987) and DMSP SSM/I (1987-1998). Because these data are obtained independent of cloud and light conditions, there is now a time series of regular data which shows global and regional variability and trends in sea ice extent and concentration. Concentration of first-year, multi-year and total ice can be estimated using algorithms which combines data from several channels (99 and 37 GHz).These time series are very valuable for climate research (*Bjørgo et al., 1997*) as well as for near real-time monitoring. With use of several channels, including the 85 GHz, it is possible to obtain a resolution of about 10 km. Also large scale ice motion can be derived from time series of SSM/I data (*Kwok et al., 1998*). The SSM/I is the only satellite system which provides regular, gridded data sets which are useful in sea ice forecasting models.

6.1.3 Active microwave systems

SAR data are ideal for regional and local ice monitoring, because of the high resolution (~100 m) which gives detailed images of the ice cover. There are several instruments which can observe sea ice:

Side-Looking-Radar (SLR), Synthetic Aperture Radar (SAR), scatterometer and altimeter. All microwave instruments obtain data from the ice surface independent of clouds and light. The latter is not used in ice monitoring because it gives only profiles along the satellite orbit.

SAR data are much more challenging to use in operational ice monitoring because:

- Raw SAR data from the satellite needs to be transformed to SAR images, which is a computer-demanding process.
- Delivery of SAR data in near real-time is only provided by a few receiving and processing stations.
- The image files are large and need to be reduced before they can be transferred via computer network.
- The ordering procedure is cumbersome. Data must be ordered several weeks in advance which is a disadvantage in operational ice monitoring.
- The data costs are high, which reduce the number of users who can pay for the data.

The first SAR satellite providing SAR data over sea ice was SEASAT which operated for three months in 1978. Extensive SAR ice observation started with the ERS-1/2 programme which provided tens of thousands of images covering 100 km swaths, which were used primarily for research and development work.

Also, the Japanese JERS-1 and Russian Almaz satellites carried SAR instruments. With RADARSAT from 1996 it has become possible to map large areas with swaths up to 500 km. Also ESA’s ENVISAT will provide wide swath data from 2000.

Other active microwave systems are SLR which are operated on the Okean series and scatterometer data. The SLR system provides images with a resolution of about 1 km which is useful for regional mapping. The SLR images show much less details than SAR images. Scatterometer data from ERS and ADEOS NSCAT provides large-scale ice charts with a resolution down to 12.5 km. These data have a similar role as the SSM/I data, but are not yet included in operational ice monitoring.

6.2 Requirements for future satellite systems

Simple satellite sensor systems

Advanced SAR systems like the ASAR to be launched onboard the ENVISAT will undoubtfully provide very good data for ice observation. For operational ice monitoring it will be sufficient to have a simple SAR system which could operate in one mode with a defined frequency, polarisation, and swath width. Several such SAR systems should be operating to provide frequent observation of the ice cover. The costs would be much lower compared to ENVISAT ASAR.

A major challenge is to handle the high data rates. Only a few minutes of SAR data can be recorded onboard for example RADARSAT. Therefore receiving stations are needed to receive most of the data in real-time, when the satellite is in sight. The data rates are determined by swath width and image resolution. Currently, a compromise must be made between swath width and resolution in order to keep the amount of data at a manageable level. In the future, better data compression and transmission techniques are expected to solve this limitation.

Spatial and temporal coverage of the SAR

Many users at sea need daily information about the ice conditions, which can be obtained by a combination of sufficient swath and number of satellites in orbit. In the case of one SAR with a swath of 500 km and a resolution of 100 m, nearly daily coverage is at latitudes above 70°. But ice areas

(Baltic Sea, southern part of Greenland) below 70° of latitude, would only get SAR coverage every 2-3 days, which is insufficient. A SAR system for operational ice monitoring should therefore consist of at least two satellites.

Combined SAR and passive microwave data

Synergetic use of SAR and passive microwave data on a regular basis is recommended to improve the quality of ice monitoring. For example ice edge and ice concentration estimates by passive microwave data can supplement observations by SAR in cases when it is difficult to distinguish between ice and open water in SAR images.

Choice of SAR frequency and polarisation

Both RADARSAT and ERS SAR operates in C-band using horizontally and vertically polarisation, respectively. ENVISAT ASAR can use alternating polarisation simultaneously which is expected to improve ice classification and feature detection. Frequency and polarisation are not considered to be critical parameters for sea ice monitoring.

Laser and radar altimeters

Laser and radar altimeters are used to define topographical features of the surface. They can therefore be used to measure surface roughness of ice. ESA has performed a study to assess the feasibility of using laser altimeter to measure surface height and roughness of sea ice, (ITOS, 1996), but it is a question if a laser system can provide enough good measurements in areas with frequent cloud cover. NASA plans to launch the GLAS (Geoscience Laser Altimeter System) instrument on EOS LAM-1 in 2001, which will primarily observe ice sheet topography by laser altimeter. These data can also be tested over sea ice. Radar altimeter data has shown good capability to detect the ice edge, but since this data type is only obtained along profiles, it is less useful compared to data from imaging instruments.

Very high resolution optical images

Data from Very High Resolution Optical Sensors (SPOT, Landsat, etc.) with a spatial resolution of 2-20 meters are less useful in operational monitoring because of the cloud cover and the long periods of darkness during the winter. But in ideal weather conditions they can be very useful for detailed studies of sea ice.

Medium resolution optical data

Medium resolution optical data could give useful information, but the winter at the Baltic and the Arctic area limits the use of such instruments due to the long periods of darkness, and frequent cloud cover. The trend is to use active microwave instruments because of their capability to function independent of the weather conditions.

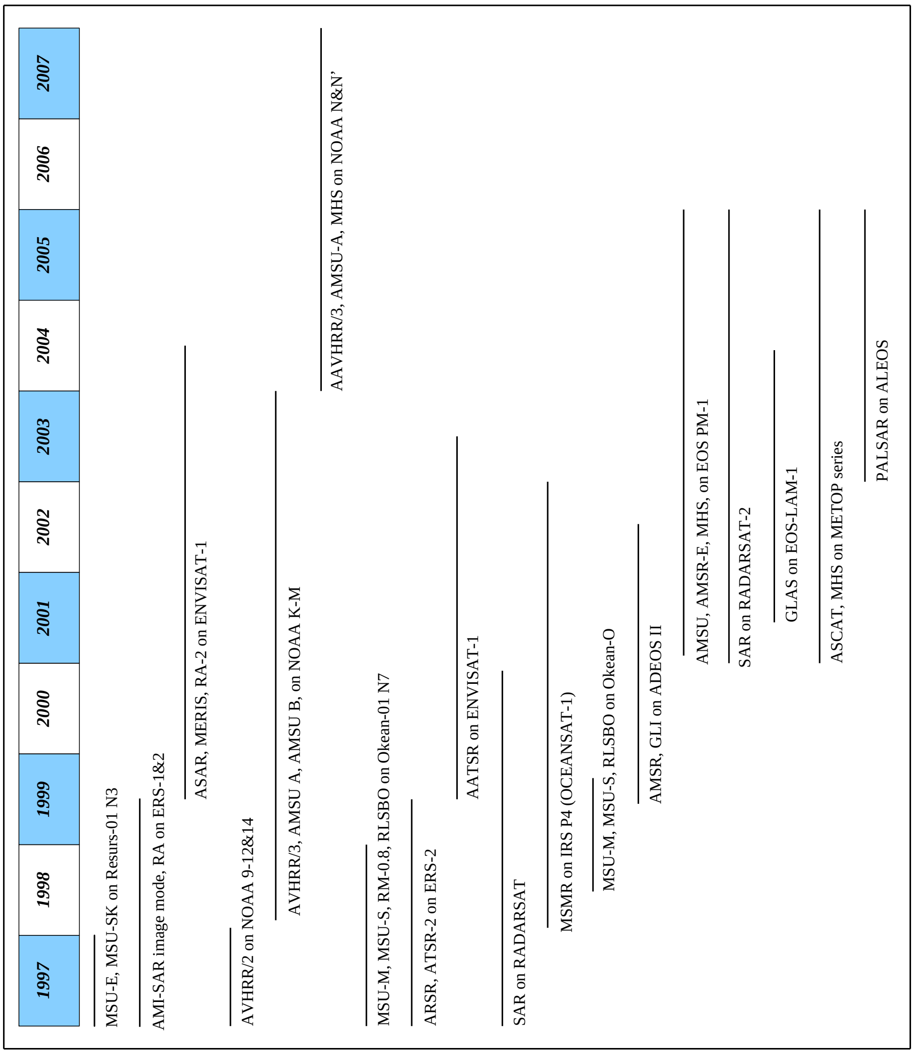


Figure 25. Time schedule for operational and future satellite sensors suitable for detecting and monitoring sea ice (*CEOS, 1997*).

6.3 Ground stations and data distribution

Today, data network has made it possible to transfer satellite data in near real-time from receiving stations to ice centres and other users. SAR data requires more extensive and complex data reception and processing than AVHRR data and other satellite data. A few SAR receiving stations are sufficient to cover the ice areas in the Northern Hemisphere. At present, three SAR stations cover the European ice areas (Fig. 26). Tromsø Satellite Station in Norway covers the western part of the Northern Sea Route, the Barents Sea, Greenland Sea and the Baltic Sea. West Freugh in UK covers East Greenland and the Cape Farewell area, while Gatineau in Canada covers the Baltic Bay and the west coast of Greenland. The processing of raw SAR data to images and distribution of images to user normally takes a few hours.

Full resolution SAR images from ERS are about 65 Mb and from RADARSAT up to 130 Mb. These image files are distributed on CD-ROMs. Before the images can be distributed via Internet, the images are averaged to a coarser resolution, typically 100 - 500 m pixels, to bring the file size down to an order of magnitude of 1 Mb. These files can be sent to ice centres and other users in near real-time. For operational ice monitoring it is usually sufficient to use averaged SAR images.

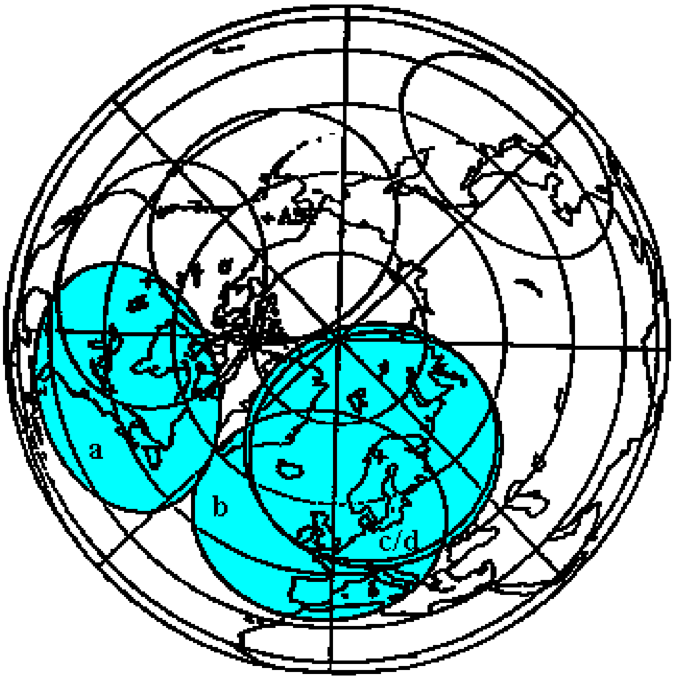


Figure 26. Station masks for SAR receiving stations in the Arctic; a: Gatineau, b: West Freugh, c: Tromsø, d: Kiruna.

In 1998 operational use of RADARSAT images has been tested in the Barents Sea and in the Greenland Sea. The ice centres have received SAR images within a few hours after reception. Data communication lines has been established between the ice centres in Finland, Sweden and Denmark and the receiving stations (Tromsø, West Freugh and Gatineau). Tromsø Satellite Station has demonstrated that it can process RADARSAT images within 2 - 3 hours.

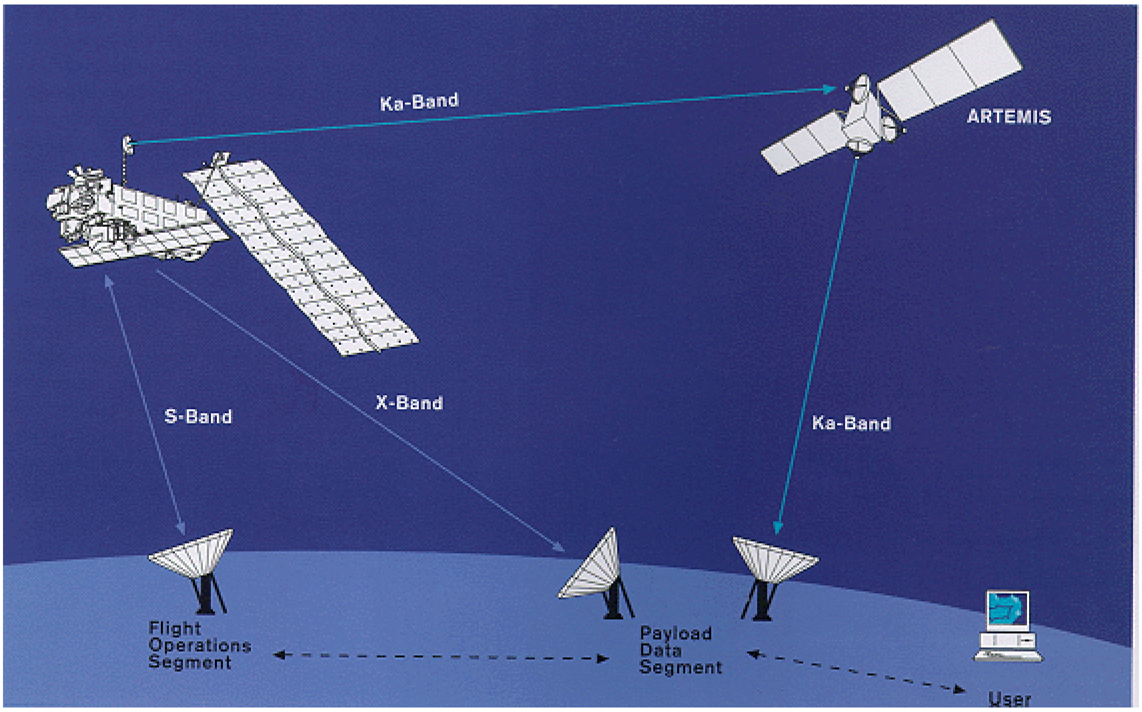


Figure 27. The ARTEMIS data distribution system for ENVISAT.

To make data transmission more efficient it is recommended to investigate data compression schemes, that will minimise the amount of data that needs to be transferred from the supplier to the ice centres without loosing important information in the images.

Some areas like the Laptev Sea area, which is in the middle part of the Northern Sea Route, are not covered by any existing ground stations. This means that it is not possible to get SAR data from this region, except by use of the onboard storing capability of RADARSAT. In areas not covered by the ground stations, it is possible to use direct downlink of satellite data to ships. Such direct downlink is possible for AVHRR, SSM/I and Okean SLR data, but not for SAR data. The feasibility of onboard data processing and direct downlink of SAR images to users is investigated by (*Gudmandsen et al., 1998*), and it is foreseen that such distribution system can become a reality in future SAR satellites. For ENVISAT it is planned to test data transmission from satellite to ground station via ARTEMIS, a data communication satellite, (Fig. 27), If this concept proves to be useful, there is another alternative for real-time data acquisition in areas without ground stations.

Mobile receiving station

There is an interesting development of small, mobile SAR-receiving stations which can easily be moved from one place to another. These mobile receiving stations includes a PC-system for processing raw SAR data to images. The idea of the PC-based transportable ground station is to meet national and/or local needs for satellite SAR data in remote areas without permanent SAR receiving stations. Mobile SAR stations, which can be offered at a lower price than large, permanent SAR stations, open up interesting possibilities to produce SAR images at a lower cost than what is possible today.

6.4 Ordering of SAR data

Due to power requirements of the SAR system it is not possible to obtain SAR data continuously from the satellite. For ERS it is possible to have the SAR system on for about 10 % of each orbit, which takes 100 minutes. For RADARSAT, this percentage is somewhat higher, making it possible to have SAR coverage for about 20 minutes for each orbit. This limitation in data acquisition requires an order procedure, where users request SAR imagery for given areas 2-3 weeks in advance. For operational ice monitoring, this advance ordering procedure can be cumbersome and impractical, because it is often impossible to know 2-3 weeks in advance where SAR images of sea ice are needed.

In future SAR satellites dedicated for ice monitoring, it will be important to have enough power supply to let the SAR be turned on over all sea ice areas. This will simplify the ordering procedure and secure SAR data acquisition over sea ice, allowing the users to select images of interest based on day-to-day needs.

6.5 Data handling at ice centres

When satellite data have arrived at the ice centres, there is a number of data processing steps to be performed to come up with the final product. Normally, the ice centres produce ice charts, interpreted images or special ice reports which are sent out to the end users. The main processing steps includes:

- geolocation and transformation of the image to a map projection (for example polar stereographic projection with insertion of latitudes, longitudes and coastline).

- radiometric correction of calibration of pixel values, especially for SAR data where backscatter intensity in sigma-nought is the standard unit.
- use of algorithms to derive ice parameters, where several channels of data can be used. For example, for SSM/I data, ice concentration is estimated, for AVHRR data, separation of clouds from ice is useful, SAR ice classification and several types of data can be used to calculate ice motion from consecutive images.
- integration of satellite data with other ice data (aircraft observation, ship observation, etc.), meteorological data, and oceanographical data. This is usually done in a GIS - system.
- image interpretation and production of ice charts.

The Finnish, Swedish and the German ice services use a software package developed by the Technical Research Centre of Finland called IceMap (*IceMap, 1995*) for data handling, interpretation and analysis of space-borne and in situ data, and for ice chart production. Digital ice charts could be exchanged between ice services, also using IceMap. Digital ice charts could also be sent to icebreakers via IRIS, where the charts could be superimposed on satellite images thus helping the interpretation.

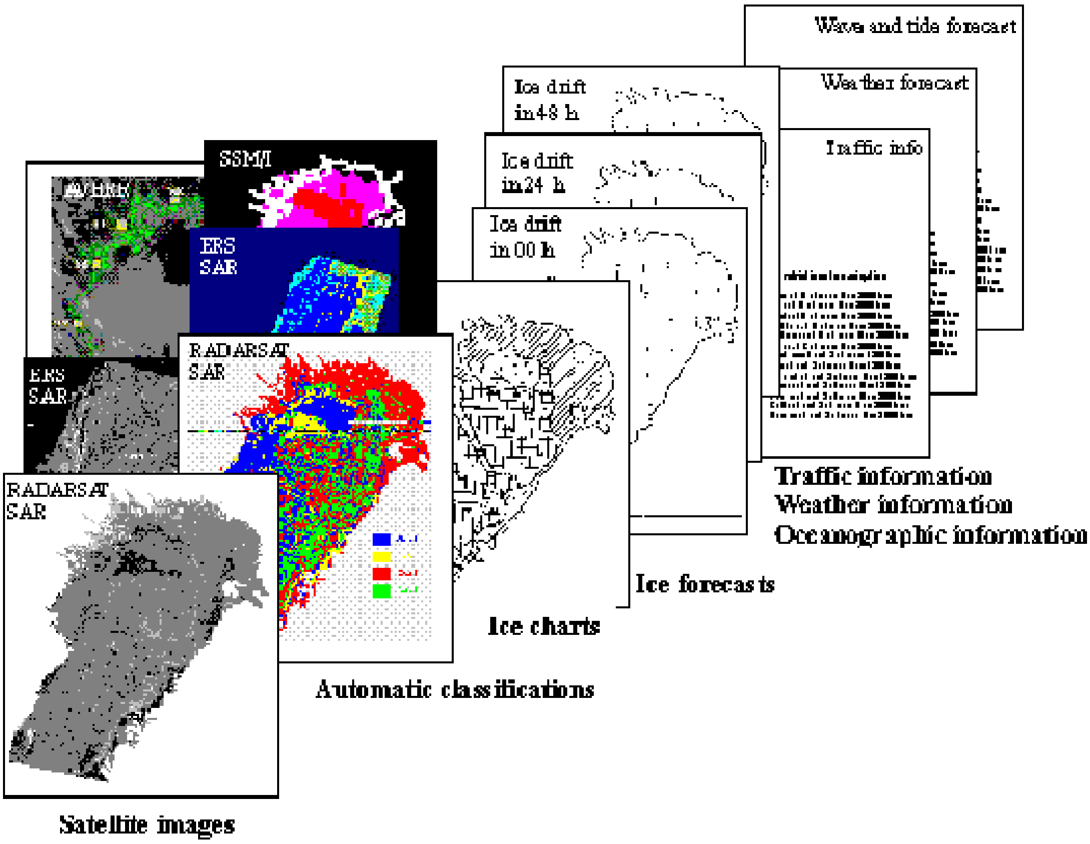


Figure 28. Example of potential sea ice information presentation on ship's computer. Original RADARSAT data © Canadian Space Agency/Agency spatiale canadienne, classification © FIMR, 1997; original ERS data © ESA, classification © FIMR 1997; AVHRR data © NOAA 1997; original SSM/I data © NASA/MSFC, classification © TUD 1998.

In Europe digital ice charts and satellite data are regularly available at sea only at the Finnish and Swedish icebreakers. On experimental basis digital charts and images are tested onboard ships in Greenland, in the Northern Sea Route and on merchant vessels in the Baltic Sea. Finnish and Swedish icebreakers are receiving AVHRR and SAR data via their national ice services. The data is compressed to 2 km (AVHRR), 150-200 m (ERS SAR) or 250-800 m (RADARSAT SAR, Figure 29). By using better compression technique image resolution could be increased.

The Ice Service at DMI is presently using an ice charting system dedicated to the use of AVHRR data. A new GIS-based system is developed for use of RADARSAT data.

The Canadian Ice Service uses a system called ISIS to process, display and analyse the various satellite imageries. The total daily throughput is approximately 3 Gbytes.

The National Ice Center in USA uses their Digital Ice Forecast and Analysis System which includes use of ice models, (*Warner and Campbell, 1993*). A suite of environmental data and information visualisation software products have been designed to allow analysis and forecast generation for a very small and cost-effective platform.

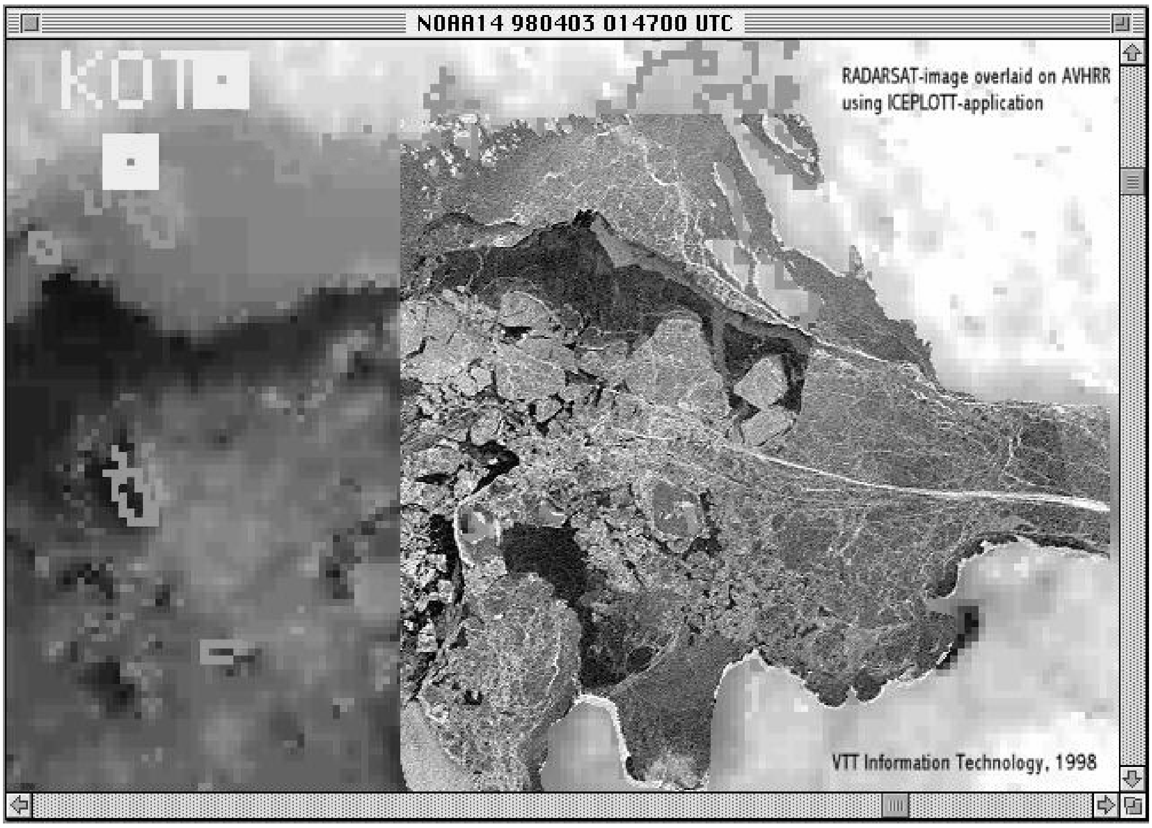


Figure 29. RADARSAT image overlaid on AVHRR using ICEPLOTT application over the eastern Gulf of Finland in The Baltic Sea. Advantages of better resolution of SAR data could be seen very clearly. © VTT Information Technology, 1998.

Automated ice classification

Producing ice type and concentration estimates automatically from SAR has been a long-standing goal of both the operational and scientific communities. Scientists desire a stable long-term data record of ice type and concentration estimates with known accuracy in order to address questions concerning ice mass balance and heat flux. The most feasible way to analyse the volume of SAR imagery required for a climatology of ice characteristics is to use the automated algorithms.

Requirements are that the algorithms must run quickly (NIC anticipates receiving about 3 GB RADARSAT imagery per day), and data cannot be analysed retrospectively. Operational algorithm development is focused on rapid segmentation of an image so that each pixel is accurately assigned to an ice type or to water. Another area which promises operationally useful results is automatically extracting and labelling features such as floes, leads and ridges, data blending, or comparing SAR with other satellites and meteorological analysis to assess ice condition.

RADARSAT makes it possible to accomplish both Arctic-wide and regional analysis with the same high level of detail. A successful operational algorithm, however will quickly process imagery from the central Arctic using averaged data for a less accurate but fast analysis. At the operationally important ice margins, a more sophisticated classifier, such as an expert system, or an experienced human ice expert, will take over.

6.6 Transmission of data and products to users

The traditional method to send ice charts to ships is radio frequency faximile. Today’s digital ice products, which include large image files from SAR, can only be transferred to ships via Inmarsat, mobile telephones or other communication systems which allow digital data transmission. Ice products delivered by ice centres can easily be distributed to users on land who have equipment for file transmission.

Users at sea, however, cannot receive digital ice products unless special systems are installed on the ships, such as in the Baltic Sea region (Table 11). Currently, with large image files such as RADARSAT SAR images, the distribution to users at sea is a bottleneck. Only the Baltic Sea has an operational distribution system for digital data to users onboard ships which operate with acceptable time delay. In other areas of Europe, ad hoc systems have been tested, but problems arise as soon as data files are larger than 1 Mb or so.

One of the main challenges in operational sea ice monitoring is therefore to improve the distribution of products in digital form, utilising new satellite communication systems which will soon be available (Table 12).

Table 11. Time delay of space-borne data transferred to users onboard ships in the Baltic Sea using mobile telephone.

Satellite data	**Area**	**Ice services**	**Users at sea** *
AVHRR	Baltic Sea	10 min- 2 h	30 min-2 h
Meteor	Baltic Sea	<2h	
ERS SAR**	Baltic Sea	<2h	2-5h
RADARSAT***	Baltic Sea	3.5 4 h	4 - 7 h

* Digital space-borne data are only delivered to the Finnish and Swedish icebreakers and some Finnish merchant vessels.

** Used in 1992-97 only in Finland and Sweden. In 1998 used in Germany.

*** Situation in 1998 both in Finland and Sweden. The data processing takes 2 h at the TSS and transmission by Internet and reprocessing takes 1.5 - 2 h. Ideal image sending to the icebreakers is 3 - 4 min.

The SAR derived sea ice information can be used both as image products transferred in hard-copy or in digital format. For transfer to operational ice going units in the Russian Arctic, satellite telephone has been used for both telefax and digital file transfer. There are technical limitations in the high latitude use of this INMARSAT system. There is a need for a more sophisticated and efficient way for near real-time transfer of digital data to the ships, alternatives to the INMARSAT system should be investigated.

In order to use the sea ice information derived from SAR data regularly in operational monitoring, it is essential to have access in the future. Several ice centres have introduced electronic ordering and distribution of ice products. However, users at sea and in the Arctic cannot yet fully utilise these services.

A digital, efficient and cost-effective transmission system requires that:

- infrastructure and telecommunication is available to the users
- several communication channels should be available to secure regular transmission
- the costs of data transmission through different channels must be acceptable for the users
- formats of products suitable for transmission to users must be defined
- ordering and distribution methods must be user friendly
- the distribution must be adapted to end user equipment
- invoicing and payment must be simple

Terrestrial Cellular networks

Mobile telephones usually communicate with terrestrial stations. Dual-mode handsets are coming, and these are able to use a cellular network where there is coverage for this and switch to satellite mode when outside the cellular network. But no dual-mode system is in use yet. Cellular phones like NMT (Nordic Mobile Telephone) and GSM are good working systems and are used in the Baltic Sea region, but the coverage is not good enough leaving parts of the high sea areas of the Baltic Sea uncovered such as mid-Bothnian Sea. In general the coverage is good and after continuos construction of new land stations the coverage is improving. However, there will still be technical problems to make the Baltic Sea totally covered.

Satellite networks

INMARSAT

The INMARSAT communication is quite reliable in latitudes up to 75° - 78° N. Communication is also possible at higher latitudes, but will then depend on longitude and the visibility towards the southern horizon. The provision of SAR images to icebreakers can be done in near real-time, within 2 - 3 hours. The time delay includes reception and processing of SAR images at Tromsø Satellite station, the image file transfer to NERSC, analysis and interpretation at NERSC and transmission to the users. SAR images have also been transmitted to Dikson for use in chart composition.

The transmission of one page SAR image takes 3 - 6 minutes. The relatively poor quality of the SAR images after telefax transmission reduced the possibility for interpretation onboard the icebreaker. Therefore, interpreted ice maps were also transmitted by telefax, but the fine image details were not included in these maps. File transmission using modem with the INMARSAT telephone line was tested as an alternative method. The user onboard the ship calls the computer at NERSC, log in and transfers the image file using ftp. The transferred image file is already reduced by compression techniques, so the size of one file is typically 100 - 200 kbyte. It is expected that marine communications, including data transmission will improve and become less expensive in the next few years. Thus, the transmission of SAR images, preferably in compressed format, will become a routine operation.

- Any new communication application (for reception and display of ice information onboard the ship) must be simple, robust and with a carefully designed user interface.
- It should be made possible for the users to order a specific ice chart through either a BBS or fax.
- Communication of ice information to ships is generally difficult to archive at an equal level for all Greenland waters. It is therefore advised that communication issues must be investigated further.
- Distribution of ice information, ice charts, satellite images, ice reports etc., through Internet should be investigated further. Internet solutions should primarily be made available to users at land: sea ice information providers, harbour authorities, shipping companies and others which are in close contact (telephone and VHF) with the ships at sea.
- Distribution of ice charts and ice reports by INMARSAT-C (e-mail) should be made possible.
- RADARSAT should be transmitted to the Ice Service at DMI with a minimum of delay, 1-2 hours after overpass of satellite, using standard communication lines.

IRIS (Intercontinental retrieval of Information via Satellite)

In the frame of an ESA program named LLMS (Little LEO Messaging System), SAIT as prime contractor, together with Belgian and German partners, is developing a messaging and data transmission system based on LEO satellites. The goal is to provide a world-wide messaging and data transmission system service that is not limited to short massages, with low transmission costs, and with delivery delays that, depending on the latitude of the mobile, can add up to some 12 hours.

SAIT is also promoting the commercial venture related to the technological program. Such a venture will take its first steps in the beginning of 1998 with pre-operational trials with potential clients. Real commercial operations are scheduled for mid 1998. The system will be extended and upgraded according to the commercial success. The full plan foresees a deployed constellation of five satellite, if the market demand will be in line with forecasts.

- LLMS is the name of the technological program, IRIS (Intercontinental Retrieval of Information via Satellite) the name of the commercial service.
- The first satellite will be launched during the first two weeks of November from the Baikonur base (Kazachstan) by Zenit, pre-operational trials with potential clients are scheduled for mid-January 1998.
- Usage cost will be 0.4 USD per messages up to 160 bytes and 1.2 USD per additional kilobyte. Special tariffs for massive usage will be negotiated case by case. Current price of the terminals is in the range of 2000 USD, target price for next year is 700 USD.
- Due to polar orbit, the best served areas of the globe will be high latitudes that will benefit from more frequent passages and higher elevation. At 80° latitude the 14 (uniformly distributed in time; each 100 minutes) passages per day of which 7 with an elevation of more than 40°.
- Terminal to satellite 1200 bps user rate, satellite to terminal 4800 bps user data rate, practical maximum transfer volume some 50 Kbytes.

ORBCOMM:

For the use near the polar regions there are very few systems at the moment that can be used. There is a system from USA called ORBCOMM, which is intended for short messages. In principle this could be used for larger files also, by dividing the files into small messages, but the design of the system was for small messages, so the use of this system for image files is uncertain. ORBCOMM has at the moment 2 satellites in orbit and there will be 4 more this year.

IRIDIUM

The IRIDIUM project initially started by Motorola. If their plans will hold, commercial satellite services will be available in 1998. Their idea is to have a handhold dual mode portable telephone which will use cellular system where available and satellite communication elsewhere. The data transmission rate with 2400 bits/s sets a practical limit to the size of the file to be transmitted. IRIDIUM will consist of 66 satellites in low earth orbits.

ICO-P

Another project is driven by the company ICO Global Communication. This system was formerly called INMARSAT-P and is based on MEO (Medium Earth Orbit) satellites. ICO-P service is scheduled to begin in mid 2000, so this system will not be of much use until three years from now.

Globestar

The Globestar system is the third of the largest upcoming satellite communications initiatives. It is, however, limited in latitude from 70° S to 70° N, and is therefore not of much use in polar area.

Teledesic

A network based on 840 geostationary, low earth-orbit satellites is planned to be taken in use during 2002. Teledesic links will support services running from 16 kbps up to 2 Mbps on the uplink up to 28 Mbps on the downlink, and in special cases data rates of 1.24 Gbps can be achieved. At any one time, the network is able to support 20,000 simultaneous T1 (1.544 Mbps) connections, and the coverage is expected to be world-wide.

Satcom COURIER

In Germany there is a company Satcom Gmbh that has launched one satellite in 1993. They claim that the system COURIER consisting of 72 LEO satellites will become operational between 1998 and 2001.

At the moment, considering a time scale between 1998 - 2000, the most potential system for sea ice purpose seems to be the IRIDIUM system, and the ORBCOMM system can be considered in the case of small amounts of data. The IRIS initiative is, however, worth a follow-up, as this is an European project.

Table 12. Overview of satellite networks.

Satellite Networks	Operational	Coverage	Transmission rate
INMARSAT	present	global up to 80 N	SAR image 3 - 6 min 100 - 200 kbyte
IRIS	1998	world wide + polar regions	1200 bps
ORBCOM	present	polar regions	short messages
IRIDIUM	1999	global	2400 bits/s
ICO-P	2000	global	
Globestar	1998/1999	70 S - 70 N	
Teledesic	2001	world wide	2 Mbps
Satcom COURIER	1998/2000		

Direct downlinks from satellites to ships

AVHRR data has been downlinked e.g. to ships for many years. Resolution have been much coarser (about 4 km) than more advanced land-based stations.

A direct downlink of SAR data to ships, or platforms such as an oil rig, will ensure that the user has full control of the data reception and processing chain and data readily available when transmitted from the satellites.

This applies also to stations in remote areas such as the Greenland Sea and the Northern Sea Route. However, in cases where many ships work in an enclosed area such as the Gulf of Bothnian, it can be more efficient to use one receiving station and distribution via cellular network. Such a distribution works well in the Baltic Sea.

7. Proposed concepts for optimal ice monitoring systems

The concepts for optimal ice monitoring need to distinguish between the role of the public and the private sector because their roles can overlap, and there is growing demand to cut public budgets and generate more user financing of public services. In ice monitoring it is useful to define public and private services as:

- **Public service**. A public service is a baseline, general ice service which is the responsibility of the national ice centres in each country, financed by the governments. The public service should in principle be free-of-charge for all customers or available at a reasonable fee.
- **Private service.** Private services will be commercial driven, financed by the users and provided according to their specifications. Commercial services are normally an extension of the public services in cases where the customer needs more detailed and extensive ice monitoring and forecasting. The public and private services can complement each other from the customers' point of view.

The objectives of public and private ice monitoring services should be clarified, for example as:

The public services
- have national obligations to ensure the safety of marine transportation in sea ice waters,
- need ice information for public weather forecasts,
- must provide ice information for navigation to make sea transportation economically feasible,
- must provide regular, operational ice service throughout the year or for the duration of the ice season.

The private services
- should complement the public services in cases where there is demand for special services offered by the public services,
- should provide special services which consist of more detailed and extensive ice observations including forecasting required by the customer,
- could be operational only temporarily, during offshore operations, expeditions, etc.,
- should have commercial interest to sell sea ice information.

Both the public and private services could use the similar input data, analysis methods and communication. In many cases, the special ice services need to use methods which are not regularly used, such as dedicated aircraft/helicopter flights, deployment of automated buoys, use of fixed radars, use of SPOT or other high resolution optical images in combination with standard ice data in order to satisfy the needs of customers.

The basic concept of any sea ice monitoring system is to combine space-borne data, airborne data and ground data. The ice information product is normally a combination of all these data sources. However, to keep all data sources available there is a need for long-term agreements and a network witch is capable to produce regular information for in situ monitoring, statistical analysis and forecasts.

Receiving stations for satellite data, data distribution systems, processing of data, integration of data, production capability and distribution systems need to function in near real-time. Considerable public investments are needed to collect and distribute sea ice data, and it is therefore necessary that the baseline ice service is financed by the governments also in the future. However, commercial services can have a market and compete with the public service in cases where there is offshore oil/gas industry, heavy ship traffic or other commercial activities and the public services are unable to satisfy the demand for ice information.

The basic concept which includes all marine elements, is illustrated in Figure 30, and will be the baseline also in future operational ice monitoring services. Not all the elements need to be implemented in all real ice services. For example, it is possible to use either aircraft or satellite data as the main source of input data. Use of oceanographic models and automatic classification will enhance the quality of the services, but are not mandatory to run an operational service.

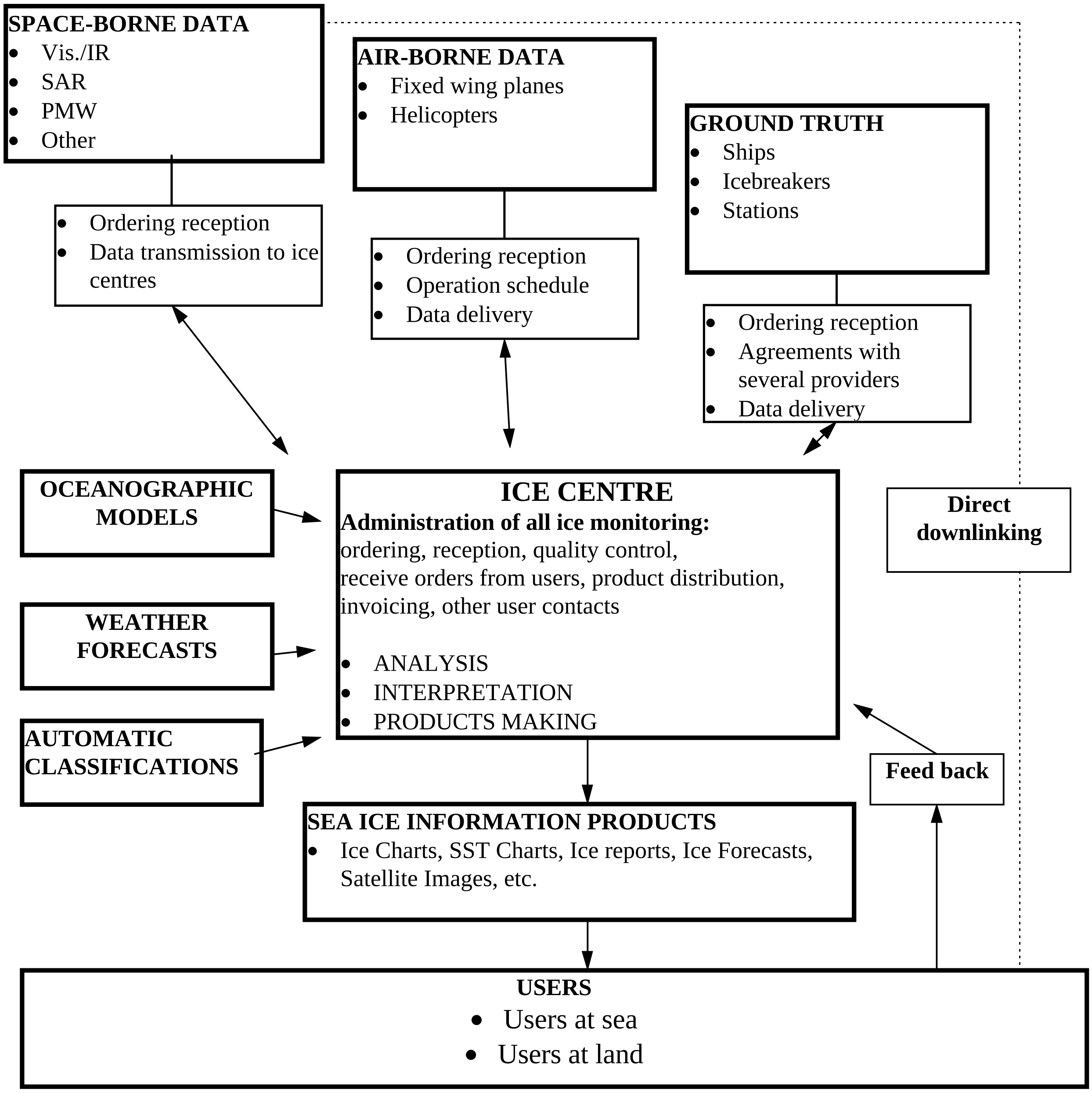


Figure 30. General concept for all ice monitoring systems built around the ice centre.

There are many elements in operational ice monitoring, which will change as a consequence of new satellite data, improved computer systems for data analysis and the revolution in telecommunication. The most significant change is the transition to digital ice data and computer analysis of all data used in ice monitoring. Satellite data will play an increasingly important role in operational sea ice monitoring, because use of aircraft surveys has decreased.

New concepts for ice monitoring must allow use of state-of-art computer technology and be adapted to the local infrastructure. The concepts should allow several data and service providers to deliver ice information to customers. With computer network as the basic element, all types of providers and users of ice information can in principle deliver and retrieve data via the network. An alternative concept for ice monitoring is therefore the network as the main element with all providers and users linked together in the network (Fig. 31). Such network which will make regional co-operation more feasible, in cases where several ice centres need to use the same data. Computer networks and fully digitised data will make exchange of sea ice data much easier. The private sector will play a more important role than before, but operational ice monitoring will still be funded mainly by governmental budgets.

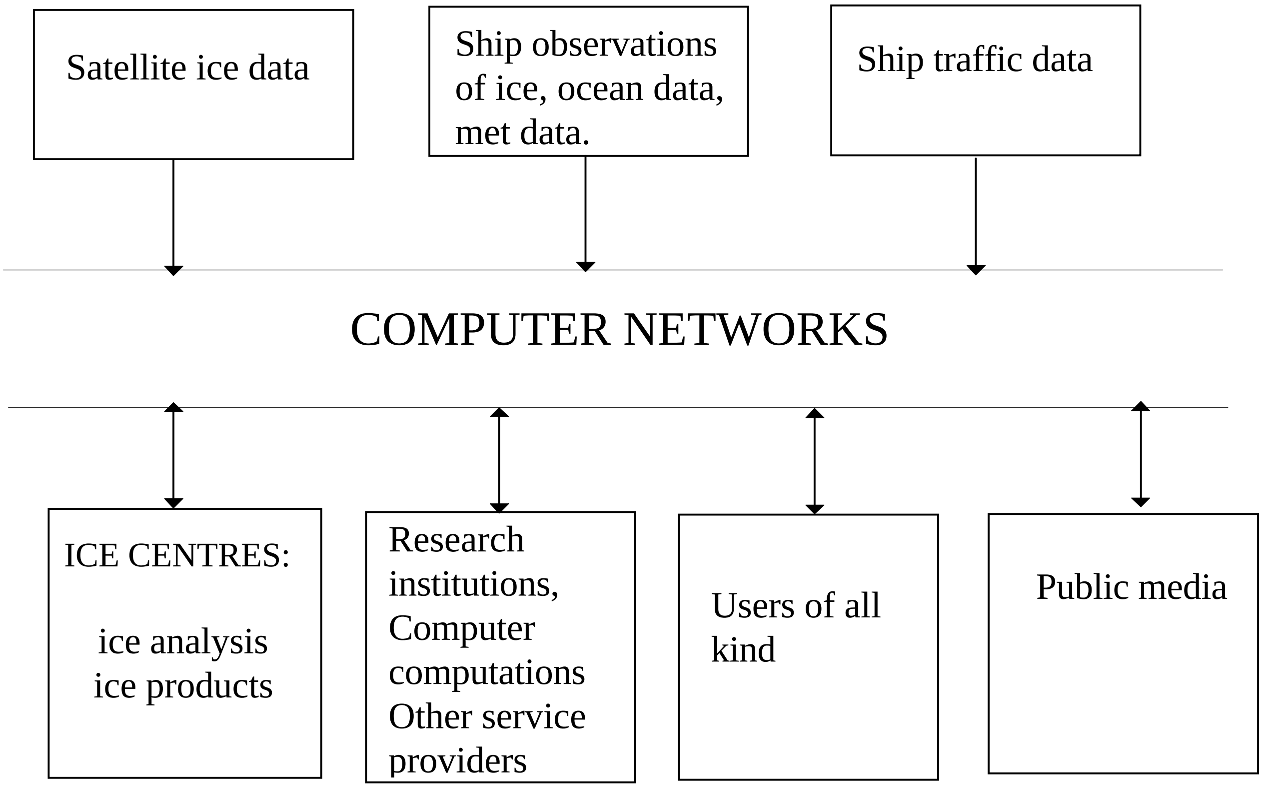


Figure 31. Concept of ice information built around computer networks.

An ideal system must include possibilities to combine different satellite data. To facilitate use of several types of satellite data, receiving stations and other data providers need to standardise their products and streamline data delivery via computer networks. A marine user who work for example onboard a ship, should only need to contact one address/agency to get sea ice data and other environmental data, such as weather and sea state, for a given area. The user should specify area, required parameters and which product he needs. Then the products should be delivered soon after an order has been sent. Before orders are effectuated the probable price including transmission should automatically be displayed to the user, enabling him to change or cancel the order.

Products should be further developed to include more accurate ice classification and forecasting of the ice situation. The products should not only be ice charts but also images with annotations, optionally with drift vectors and weather information. The products should be easily interchangeable between national ice services to secure optimal use of public data.

The change from predominant aircraft surveys to use of more satellite data represents a certain risk for operational ice services. Today, only RADARSAT provides SAR coverage which is sufficient for operational monitoring. If the satellite fails, it will take time to launch a new SAR satellite. However, the ice centres must have a guarantee from satellite service providers, that the series will be continued for a long period before they can make themselves dependent on satellite data. A summary of the new technologies which are important for ice monitoring are shown in Table 13.

Table 13. New technologies which are important for operational sea ice monitoring.

	Changes in technology and user demands
Satellites and ground stations	• satellite SAR-systems: wide swath covering most ice areas • several satellites in operation • near real-time delivery of data • SAR receiving stations which cover most sea ice areas • low-cost mobile SAR receiving stations
Access to data and processing of data.	• improved data communication on land and at sea • fully digitised data • analysis tools on computers are improved • direct downlink of SAR data to users • wide range of products • use of electronic charts onboard ships • use of Internet for distribution
Users	• budget cuts in the public sector • increased role of private sector: shipping, oil industry, fisheries • requirement to cost effective information • the user community is growing • training and education is needed to enable new users to use data

7.1 European versus regional systems

Sea ice monitoring in Europe is of regional character, involving countries in the northern part of Europe including Russia. Further development of ice monitoring services will require more co-operation between the regions. First of all, in the Baltic region, more co-operation between the countries can be expected within data collection, use of satellite data, electronic exchange of data, common analysis and display systems, etc. In the Greenland area, DMI’s service could benefit from more co-operation with the Canadian Ice Service and the International Ice Patrol, as well as with the Icelandic and Norwegian Ice Services. The ice centres can benefit from more co-operation in issues such as SAR receiving stations, data acquisition and analysis tools, and product development. In the Svalbard area and Barents Sea the Norwegian Ice monitoring service partly overlaps with DMI service in the Greenland Sea and the Russian service in the Barents Sea. Further east, in the Kara Sea and other parts of the Northern Sea Route, the ice is mainly a Russian responsibility. However, it is beneficial with more international co-operation also in the Northern Sea Route, especially in use of satellite data, ground stations and in communications.

A European ice forum, including all institutions and users of sea ice data, could be useful to solve common problems, such as data standardisation, optimal data acquisition from SAR satellites, bulk data orders from satellite data providers, and design of new missions needed in operational sea ice monitoring in the future. But the concepts for ice monitoring should first of all be implemented regionally, because much of the practical co-operation take place between ice institutions in neighbour countries.

7.2 Baltic region

All the Baltic countries have their national ice services: Finland, Russia, Estonia, Latvia, Lithuania, Poland, Germany, Denmark and Sweden. The services have been established during 1910-20's, when most data were in situ data from coastal observation stations and communication means were limited. With EO data it is possible to observe the total Baltic Sea in a single satellite image and ice conditions in all national areas can be observed in high resolution. The evolution of communication technology has been very rapid: today high resolution digital data can be sent to users at sea in reasonable time and at moderate costs by using cellular network. A question could be posed, if there is a need for the national ice services in every country which do the same work. Technically, one ice centre could produce all ice information for the whole Baltic Sea. But national requirements and interests could make the establishment of a centralised Baltic Ice Service difficult. Comparison with meteorology shows that there is a need for national institutions even if the service is dependent on strong international co-operation. The countries in the southern Baltic Sea are not ice bound annually and their ice season is shorter compared to Finland, for example. The increased competition has forced the national meteorological institutes to develop finer scale and other special products.

In ice chart production, there is a standardisation of ice analysis tools. The same software called IceMap, is used in the Finnish, Swedish and German ice services. This system makes it easy to exchange ice information in digital format.

The ship traffic is predicted to increase steadily in the Baltic region, also in the ice season. The number of icebreakers however will stay at the same level. This means, that the icebreakers must be used more effectively in order to solve their tasks. The solution will be to use more and better information of the ice conditions, and this could be achieved by using more SAR data. The SAR data, however, need to be accessible every day over all the ice areas, which require minimum two wide swath SAR satellites.

7.3 Greenland region

The responsibility and governmental support for DMI's public ice service in Greenland is not expected to change in foreseeable future. Information about the sea ice and iceberg conditions for the Cape Farewell area and other parts of the Greenland coast which is essential for all ship traffic in the area, are gathered. Regular ice monitoring service is therefore maintained throughout the year. This service is part of the general safety for navigation in Greenland, and the ice information products are consequently made available to the users free-of-charge.

It is, on the other hand, anticipated that the function of the ice service and its ice products will change according to user requirements, in particular those of the offshore industry. Technical improvements regarding use of satellites for data acquisition and analysis and distribution to users will change the way the ice centre operates. The following points need to be included in the future ice monitoring concept:

- RADARSAT ScanSAR images will become the most import data source for production of ice charts. Use of aircraft reconnaissance flights will be minimised. A helicopter will be used for inshore reconnaissance flights and backup in case data from the satellites are not accessible.
- Due to the complex and rapidly changing ice conditions, visual interpretation of satellite images combined with ancillary information will be the most important tool for production of ice charts. However, automatic image enhancement and classification methods should be investigated to extract ice information from SAR data more efficiently.
- Ice charts will be available both in paper format and as fully vector based digital products for computer based presentation and distribution. Digital ice charts will facilitate the construction of synthesis and composite ice charts and prepare assimilation of ice products into weather prediction models etc.
- Ice products are expected to be increasingly integrated with auxiliary information, e.g. weather data and ocean current data.
- New ways of transmitting the ice information will be introduced, for example digital products will be accessible via INMARSAT and Internet.
- Historic ice charts should be transferred to digital format and to facilitate the construction of a Greenland sea ice climatology for the benefit of strategic planning and research. A time series of digital ice charts should be constructed to enable statistical analysis of ice conditions.
- New product presentation methods, which may be used by both sea and land based users, will be established. In most cases this will imply that dedicated computer and software must be installed on the ships.
- Improved analysis and data handling techniques should be developed for the benefit of the ice analyst who consequently should be able to include a broad range of data sources simultaneously during standard ice chart production. This is also important for optimum utilisation of satellite images, and for production of special ice information requested by e.g. oil exploration companies.

7.4 Northern Sea Route

The main problem in the Northern Sea Route is that the Russian Hydrometeorological and Sea Ice Service has been reduced in recent years. There is now severe lack of sea ice information, but the governmental support to the services has been drastically reduced. This opens up new possibilities to offer new concepts in ice monitoring, and to use more data from satellites. However, new services can only be established with support from the private sector, especially oil industry and shipping companies operating in the Northern Sea Route. New services will therefore be more user-driven and less governmental driven.

It is suggested to implement an operational radar ice monitoring system which will be included in the general Russian operational system. It will use NOAA AVHRR data and Okean SLR data for large scale surveying and ERS/RADARSAT SAR data for detailed observations in specific key areas, which are identified as difficult for the navigation (seasonal variation of their location).

With 500 km swath width the Kara Sea region can be covered by 3 swaths every 2 - 3 days. The commercial price of RADARSAT data makes it unrealistic for use in the operational ice monitoring service. It is more realistic that RADARSAT data will be used in specific areas as requested by customers who can pay for the data.

From 1999, with wide-swath ENVISAT ASAR data available, and possibly also the new Russian SAR satellite - RESURS-ARCTICA - a fully operational system using SAR data every day is possible. Then the desired weekly, or more frequent, coverage of the prioritised areas can be realised.

The planned system will provide SAR and SLR products which will be distributed to a selection of users in near real-time: icebreakers, the headquarters of Murmansk Shipping Company, and the ice centre at AARI. Off-line products will be made available for offshore industry and environmental agencies. The system will be open to include also other users who need radar ice information.

The core activities of the operational system will be:

- acquisition of ERS SAR and Okean SLR data for key areas in the Northern Sea Route,
- near real-time preparation of SAR and SLR data products,
- production of ice maps using WMO ice nomenclature,
- near real-time transmission of SAR and SLR data products from ground stations to icebreakers, Murmansk Shipping Company Headquarters.

The focus will be on streamlining the procedure for acquisition, image product preparation, ice map production and distribution of ice images and maps.

Supporting activities for the operational system will be marketing, user feedback and user requirement investigations, improvement of the EO based ice products, and use of off-line satellite data. These activities are important for involvement of new users and the future development of a fully operational service for parts of the Arctic Oceans.

A satellite based communication system for transmission of SAR images to Marine Operations Headquarters of Murmansk Shipping Company needs to be established. Other users which will be approached in the operational system are oil companies and environmental institutions. For the time being, these users primarily need off-line SAR data for detailed studies of ice conditions in specific locations. Real-time data will be needed for offshore operations and in emergency situations such as during oil spill events and other accidents. The end users will provide necessary feedback to the operational system for improvement of operational ice monitoring routines and sea ice information data products.

The market for ice monitoring is growing due to increased ship traffic and more exploitation of oil, gas and other arctic resources. With new users there will be demand for more ice services. It is foreseen that existing ice centres will reorganise their activities and that there will be opportunities for other service providers to establish new services.

7.5 Standardisation of data exchange

Today, regular exchange of digital data is mainly taking place in the Baltic region. In Greenland and the Northern Sea Route exchange of digital data have only occurred occasionally, during expeditions. When exchange of digital data becomes more established, there will be a need to define standard formats for the files to be transferred.

Data exchange between ice services and users

In the Baltic Sea digital products from national ice service are received only by Finnish and Swedish icebreakers and some Finnish merchant vessels. To use the system, a special agreement is made between data suppliers and users. The data which are exchanged consists of digital ice charts, satellite images and automatically classified satellite images.

It is foreseen that digital sea charts (ECDIS) will have impact on the standardisation of digital ice charts concerning resolution, scale, use of symbols, nomenclature, formats of vector and raster files etc.

Data exchange between ice services

Today the data is mostly exchanged in hardcopies by fax. In the Baltic Sea in the Finnish, Swedish and German ice services a standard IceMap software system is used, which produce Postscript formatted charts. This format makes it easy to copy and paste ice information from one chart to another. Also other standard GIS and image file formats can be used.

8. Synthesis of projects results

8.1 Current ice monitoring systems and the role of satellite data

Current sea ice monitoring activities in most countries where sea ice is a relevant problem have been analysed. The most important areas for ice monitoring in Europe are the Baltic Sea region, the Barents Sea and Svalbard area, the Russian Arctic, and the waters surrounding Greenland and Iceland. Outside of Europe there are extensive ice monitoring activities in Canada and USA. Ice monitoring is also important in eastern Asia (Russia, Japan and China) and in the entire oceans of the Arctic and Antarctic. The organisation of sea ice monitoring and the main users of sea ice information have also been reviewed.

Sea ice monitoring is a well-established and organised activity in countries where sea ice occur, because sea ice has important impact on sea transportation, climate, the biosphere and settlements. Data are obtained by several methods, aircraft/helicopter surveys, ship observations, reports from coastal stations, data from drifting buoys and satellite data. The role of satellite data has increased steadily over the last 10-20 years because new and better satellite instruments have been available. Sea ice monitoring is therefore one of the most important applications of satellite data, since satellites have clear advantages compared to other methods (aircraft, ships, etc.), which are expensive and not practical for observation of large areas. The most useful satellite data until recently has been NOAA AVHRR data (optical and infrared data) and DMSP data (passive microwave data). AVHRR data are used by most ice centres because the data can be received by simple equipment and are free-of-charge. Also, SSM/I data can be obtained free-of-charge, but the usefulness of these data in regional monitoring is limited because of the coarse resolution.

Since 1991 ERS-1 SAR data have been introduced in ice monitoring in many research and demonstration projects around the world. The SAR has proven to be a very powerful instrument for sea ice observations and is at the stage to become the main instrument in operational sea ice monitoring. Ice monitoring in Canada and USA entered a new era, by introducing wide swath SAR data from RADARSAT, which is the first satellite providing sufficient SAR coverage for use by operational ice centres. For other ice centres the cost-benefit of using RADARSAT data must be demonstrated before the data will be used operationally. At the moment several European ice centres are negotiating with Radarsat International for a price on SAR data which is acceptable for use in operational ice monitoring. It is only in specific ice monitoring projects, financed by shipping companies, oil companies and other users which have a strong need for high quality ice information, that SAR data have been purchased at the commercial price.

In general, use of satellite data have demonstrated promising capability to improve the quality of all types of ice charts needed for safe and cost-effective operation in ice areas. Systematic use of satellite SAR data, can bring the quality of local and regional ice charts to a higher level and reduce the risks of damage and accidents caused by sea ice.

It is foreseen that SAR images can be received directly by customers working at sea provided that the images are processed onboard the satellite, and derived products can be transmitted to the vessels and platforms in near real-time. The benefits of using SAR data onboard ships are not only related to safety but also to improve efficiency and time saving which has considerable economic importance.

SAR data can also contribute to better knowledge of the ice conditions which will be useful in making better ice analysis and forecast. The benefits will be:

- both the ice services and the users will receive more exact data on sea ice parameters which increase the knowledge of sea ice behaviour. This will help produce better analysis necessary for safe and cost-effective operations.
- the ice forecasting will be improved which is necessary for short-term as well as long-term planning of operations.

8.2 Outcome of user requirement study

Users of ice information can be classified into three types: 1) people working in the ice environment such as captains on icebreakers and other vessels, oil platform managers and other personnel responsible for operations in ice-covered areas; 2) people responsible for planning and implementation of sea transportation, icebreaker activities, offshore operations and other marine activities, and 3) institutions responsible for data collection and provision of ice charts and other ice products, such as national ice centres and weather forecasting centres. The three types of users need to some extent different ice information products with different repeat cycles.

The users which have been contacted in the study are representatives for shipping companies (Murmansk Shipping Company, Royal Arctic Line), oil companies and offshore industry (Nunaoil, Statoil and Neste), shipbuilding industry (Kvaerner Masa Yard), national ice centres and weather centres (Denmark, Finland, Germany), national maritime administrations (Finland) and other user groups such as marine research and the coast guard. Ice transportation and operations have great economic importance in many regions. For example, in Finland there are more than 20000 port-calls transporting over 30 mill. tons of cargo in the winter season, and it is estimated that with improved ice monitoring cost savings of 10 - 25 mill. ECU is possible per year due to shorter sailing times and more effective cargo logistics.

Technical requirements to sea ice monitoring can be divided into the following categories:

Mission requirements: The most fundamental requirement is to have satellite systems in continuous operation which can provide sea ice data. Current satellite data such as NOAA AVHRR, DMSP SSM/I and SAR play an important role in existing ice monitoring services, although they are not optimised for operational monitoring of ice. The ERS SAR system represents a major technological improvement, providing a large number of high resolution SAR ice images to many ice centres for testing and development in operational ice monitoring systems. Repeat cycle, area coverage, resolution and all weather capability are essential parameters which must satisfy user specifications for satellites used in operational ice monitoring. RADARSAT is the first SAR satellite which fulfils most of the requirements for ice monitoring, but the data policy and price level is currently a main barrier for wide use of RADARSAT data in Europe.

Product requirements: The data products from satellites must provide necessary ice information with sufficient resolution and quality. Ice parameters such as ice edge, ice concentration, ice type classification, iceberg positions, ice motion, and detection of leads and deformed ice are the most important. SAR images with resolution of 100 m or better are the most appropriate type of satellite data which provide data on most of these parameters. It is, however, necessary to have algorithms which can translate SAR images into ice parameters such as ice types, ice motion, etc. Algorithms which run more or less automatically have been developed, but they need to be tested, quality controlled and streamlined for use in operational sea ice monitoring.

Infrastructure and communication requirements: It is of primary importance that satellite data can be readily transferred from the receiving stations to the ice centres, and from the ice centres to the end users. Computer lines, telephone lines and satellite communication systems are not equally well developed in all regions where users of ice information need to receive data. For large data files, such as SAR image files, the communication can be a real bottleneck. In cases where use of satellite systems such as INMARSAT is the only solution, the cost of transferring data can be very expensive. The ice regions in Europe should therefore allow different solutions for data transmission. With the rapid development in satellite communication, it is expected that the possibility to transmit data will improve significantly in the next years.

Information requirements: In spite of many pilot and demonstration projects over the last years using ERS data, there are many users of ice information who are not aware of the possibilities which can be offered by new satellites. With increasing amount of satellite data, many data and service providers, and a variety of different products and processing algorithms, there is a strong need to organise all relevant information and make it readily available to the users.

8.3 Economic framework

The economic aspects of using satellite data in ice monitoring can be discussed from different perspectives:

- space agency perspective,
- national economy perspective,
- ice centre perspective,
- end user perspective.

The current study has foreseen mainly on the two latter perspectives.

Ice monitoring is traditionally a public service financed by the governments through their national ice centres. Users of ice information consider standard ice information products to be free-of-charge or available at a low cost. As the need for more specialised ice information develops, first of all due to requirements from the offshore industry, financing of specialised products by the customers increases. This development is clearly seen in many European ice services.

Today the ice services have the basic governmental funding supplemented by customer funding of up to 50 % of the total budget of the ice centres. However, many of the customers are other governmental institutions, so it is a question of how public funding is channelled. There is also varying degree of financing from industry and private funding sources. The exact figures for how much public and private customers contribute to the financing is difficult to assess because expenses of the ice services are also part of for example the coast guard air surveillance, public rescue services and the general meteorological services.

It is foreseen that the trend of decreasing public funding and increasing private funding will continue. The specialised needs from different customers, the availability of better space-borne data, the improvements in global communication, and last but not least the importance of computer technology to produce new ice products will stimulate a market where several companies and institutes will offer data and services related to ice monitoring.

There has also been a change in governmental policy towards reducing the free-of-charge public services. Therefore some of the products, which were formerly free-of-charge or very cheap, have been re-priced, including the products and services delivered to the other governmental institutions. The ice services have been able to sell their products to a larger number of customers and thus the funding by customers has increased. However, the market is limited by the number of driving users such as ship traffic and offshore oil activities.

The shipping companies are not fully aware of possibilities of operating ships more economically in ice-covered areas by using more high resolution satellite data. On the other hand, public ice services cannot and are not willing to finance the use of expensive SAR data alone, since it is the private sector which will benefit from improved ice information. If ice navigation could be made more efficient, it is the shipping companies which will save costs and the price per transported ton would decrease. The overall result of this cost saving is to the benefit of the whole national economy.

The user investigations suggest that the major component of the ice services will also be a public responsibility in the future, but it will be supplemented by the private financing. The questionnaire sent to the users in the private sector suggest that the ice services could be funded 3/4 from public sector and 1/4 from the private sector.

The cost-benefits of using satellite data is totally determined by the data policy of the space agencies (ESA, NASA, CSA, NASDA, etc.) or national space programmes (NOAA, SPOT, IRS, etc.). The member states of these organisations decide the data policy which regulates prices of satellite data or determine if some data should be free-of-charge. Satellite systems for earth observation are usually financed by national governments through the space agencies, space programmes or through organisations such as WMO. Commercial space programmes using more dedicated and low-cost satellite systems are expected to become more important in the future.

The national ice services/centres are the main customers of satellite data for ice monitoring, although they are not the end user of the ice product. The cost-benefit of satellite data from their point of view are mainly determined by the price they have to pay for the data compared to the price of other sources of information. In many cases, there is a trade-off between use of aircraft surveys and satellite data, especially SAR data. The ice centres have limited budgets and there is often a demand to reduce costs as well as to increase the quality of the ice monitoring service. User payment for the ice information has been introduced for some services, but since basic ice information is a part of the public service it should be available free-of-charge or at a modest cost. It would not be possible to provide a basic ice service without considerable funding from the national governments. A full commercial ice service would only be possible for specific customers such as shipping companies, oil companies and other offshore industry which need more extensive and focused ice information than the basic public service can provide.

The most important economic aspects are those from the end users point of view. It is the end users who are the driving force for the national ice services, and it is the benefit and cost-savings for the end users which determine the acceptable cost of ice monitoring. If there is a large number of end users, who need ice information and are willing to share the costs, it is possible to increase the quality of the ice service by introducing more expensive satellite data. On the other hand, if there are only a limited number of users and they expect the ice service to be free-of-charge, it is not realistic to introduce additional satellite data on fully commercial terms to improve the ice service.

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8.4 The role of the public and private sectors

The general view among the users is that the organisation of ice monitoring services is best taken care of by public institutions such as national ice centres or weather forecasting centres also in the future. The public sector will continue to play the main role in financing of basic ice services, including use of satellite data. But there is also an increasing interest among many users to strengthen the role of the private sector in the financing of special ice services. With growing ship traffic, oil and gas exploitation, fisheries and other economic activities in ice covered regions, there will be a growing demand for dedicated, specific ice products which are more extensive or more advanced then the standard ice charts delivered by the national ice centres. This will enable existing ice centres or other service providers to develop and deliver commercial ice information products which will be a supplement to the standard ice charts which are free-of-charge or have a low price.

The main arguments for financing a public ice service can be summarised as follows:

- Provision of basic safety series at sea is a public responsibility.
- Support to ice navigation for transport of passengers and goods is a public responsibility.
- Monitoring and combat of pollution at sea is public matter, which can be co-organised with an ice monitoring service.
- Regional planning and development in Arctic areas are a public responsibility which requires ice information.
- Weather forecasting is a public responsibility which require ice information.

Justification of commercial services can be the following:

- Ship routing in ice. Detailed ice information beyond the public ice charts should be provided for environmental safety and economy of the ship transportation in specific situations. This information should be financed by the customer, i.e. the ship operator/owner.
- Offshore activities. Oil and gas exploration and production usually require specific ice information to design installations, operate platforms and other installations, and for protection of the environment. Operators often require more accurate ice prediction products than most other users. This apply particularly to iceberg monitoring and prediction.
- Fisheries in ice-covered regions. Ice information supporting the fishing industry beyond the public ice charts needs to be financed by the industry itself.
- Other industrial activities: Mining, timber industry, etc. also need to finance special ice information.
- Expeditions in Arctic and Antarctic sea ice areas. The public basic ice services may not cover the areas of such expeditions, so there is a need for additional services to support such expeditions.

It is foreseen that the trend of decreasing public funding and increasing private funding will continue. The specialised needs from different customers, the availability of better space-borne data, the improvements in global communication, and last but not least the importance of computer technology to produce new ice products will stimulate a market where several companies and institutes will offer data and services related to ice monitoring.

8.5 Regional solutions for future ice monitoring systems

New concepts for ice monitoring will most likely be further development of the present ice services. The availability of new technologies (new satellite data, computer systems and satellite communication) are already changing the working routines at the ice centres quite significantly. There are several new institutions other than the ice services which offer special products or services related to ice monitoring. This indicate that there is a development from pure public services to a mixture of public and private institutions which partly compete with and partly complement each other.

The discussion of new concepts is done regionally, because there is a number of elements which make the Baltic Sea, the Greenland region, and the Northern Sea Route different from each other:

- the quality and types of users,
- the existing ice services (icebreakers, aircraft, etc.),
- the communication services,
- the infrastructure including satellite receiving stations,
- the ice conditions.

The Baltic Sea
In the Baltic Sea area, nine national ice services are operating and producing more or less similar products, the quality depending on the available ice monitoring data. One concept would be to establish a single centralised ice service, the Baltic Sea Ice Information centre, which will be a service for the whole region. For example, a wider range of EO data could be used in more effective ways by a centralised ice centre than many different national ice centres. Also development and testing of automatic classification algorithms for EO data and more effective sea ice models could be implemented by a single ice centre. A centralised ice centre could distribute the products to the users more effectively and the users could get all sea ice information from a single place. The total cost-effectiveness could be much better. However, there are many national requirements which would make it difficult to establish a such centre. A first step would be to establish more co-operation between the national ice centres, such as data acquisition and exchange of data, standardisation of products, etc. The main elements in future Baltic Sea ice monitoring will be:

- Strengthen the co-operation between countries other than Sweden and Finland, to secure good quality ice information every day from SAR images. This is especially important in more severe ice years when the ice extend to the central and southern part of the Baltic Sea.
- More than one SAR satellite is needed to provide daily SAR coverage. With ENVISAT ASAR, combined with RADARSAT ScanSAR, it will be possible to obtain daily coverage from 2000. A resolution of about 100 m in the SAR image would be sufficient.
- Requirement of better quality ice charts. The ship traffic in the Baltic Sea will grow in the future, but number of icebreaker will not grow correspondingly. This means that the ships must navigate more independently inside the ice covered areas. This will be possible only by the extensive use of better EO data.
- Improved data transmission from SAR receiving stations to the ice centres, and from ice centres to end users.
- More efficient data handling and analysis methods.
- A wider range of ice information products.
- More integration of ice information with traffic information, weather data and oceanographic data. This also includes electronic ice charts.
- Need for education and training of captains and mates as well as other new users in satellite ice monitoring and other aspects of ice navigation to secure safe operations in the future.

Greenland region

In Greenland, the main limitation in use of SAR data is the lack of ground station which covers the whole Greenland area. Today, it is necessary to use SAR data from three different ground stations (Norway, United Kingdom and Canada) which is cumbersome. Requirements for better ice products can quickly come up as the offshore industry plan to start drilling on the Greenland shelf in the summer of 1999. If oil and gas production becomes a reality, this will have significant impact on the ice service.

The following issues are important for the Greenland area:

- A new SAR receiving and processing station is needed which covers the important ice areas, possibly in co-operation with Iceland and/or Canada. This will help access SAR data in near real-time.
- Direct downlink of SAR data to the Ice Central in Greenland would be an optimal solution, avoiding unnecessary delays and data transmission problems.
- Use of more than one SAR satellite and back-up aircraft as security measures if one SAR satellite is out of operation.
- Tailored ice information products for the offshore industry which includes ice forecasting.
- Specific techniques to observe icebergs and growlers, including radar observations from ships and coastal stations.
- Improved communication between data providers and the ice centres (Ice Central and DMI), and between the ice centres and the users.

Northern Sea Route

The situation in the Northern Sea Route is very special, because this region had the most advanced ice monitoring system during the 1980's. After the disintegration of the Soviet Union in 1991, the ice services were significantly reduced due to the lack of governmental support. No SAR data from satellites were included in the system. Therefore, when services are re-established they should include SAR data from ERS, RADARSAT, ENVISAT, etc.

Some of the most severe problems to be solved are:

- Facilitate access of SAR data for Russian users. Today both organisational, financial and technical barriers make use of SAR data difficult for Russian users.
- Improve the utilisation of Russian satellite data, which require improved data communication and financing.
- A new SAR receiving station is needed in Siberia which can cover the whole Northern Sea Route.
- Involvement from key end users (shipping companies, oil companies) to re-establish a cost-efficient ice service for the Northern Sea Route.
- Strengthen the hydrometeorological data acquisition and distribution necessary to provide ice analysis and forecasts.
- Support new Russian satellites which can contribute to ice monitoring.

8.6 Cost benefit considerations

The project has not conducted a full cost-benefit analysis of using satellite data in ice monitoring. The reason is that it has been difficult to quantify the benefits, and to find figures which are representative for cost and values of the different elements of ice monitoring. Much of costs are integral parts of other activities, such as coast guard operations, public weather forecast and pollution monitoring. The benefits are not only economical, but in many cases primarily for safety. Regulations for safety are imposed by authorities. Also other regulations such as harbour fees, icebreaker support and other services such as insurance premiums represents costs which do no change as a result of improved ice monitoring.

A main issue is who will benefit from economic savings or better safety, and will they have an incentive to improve the ice monitoring by use of satellite data? The end users such as the shipping companies, the ice service, industries responsible for import/export or the nation (i.e. the government) can benefit, but it is difficult to identify exactly who experience a benefit in each case. It is very difficult to calculate actual savings correctly, because there are always some assumptions in the calculations which can be disputed.

We have, however, collected some figures and pointed out factors which are important:

- Ice class requirements for vessel sailing in different ice areas are main cost factor for ship owners and operators. The requirements are usually fixed by authorities, but if better ice information can show that a lower ice class vessel can sail a given route, it represents a considerable saving for the operator.
- Environmental regulations with impact on technical standards on vessels operating in ice areas. The same argument applies for environmental regulations. However, the safety aspect can be dominant, making it difficult for the operator to use lower technical standard on the vessels.
- The fairway due in Finland is very high which means that the ship owners expect all costs associated with bringing ships to Finnish harbours to be included here. It is not clear for the ship owners if they save costs by paying for the ice information. Normally, they consider better service to be a part of public service. Better quality ice information should be financed by the government because it helps operate the icebreakers and the ice navigation in general more efficiently.
- In the Northern Sea Route icebreaker support is mandatory and this support has a price range per ton of cargo to be transported. Currently, Murmansk Shipping Company uses a price of 6-15 USD per ton. The cost savings of better ice information are not reflected in this price.
- Use of larger cargo vessels can reduce the need for icebreaker support, but the need for accurate ice information will increase. But reduced icebreaker costs do no necessarily mean that more money can be spent on satellite data.
- Public and private ice services will have different cost-benefit estimates. The public services will have a responsibility for the overall safety at sea, which is difficult to cost-estimate. The private services are commercially oriented and the products must reflect a value which customers are willing to pay for. Should a public service become commercialised or should it be free-of-charge or included in other costs such as the fairway due?
- The mixture of public and private responsibilities makes it difficult to visualise who will save costs and how much if the quality of ice information improves.
- On national scale improved ice service (including icebreaker service and ice charting) is cost-beneficial if a large number of ships can sail more efficiently. For example, the number of port calls to Finland during the winter season has increased from 14000 to 23000 during the last ten years. The number of icebreakers have been unchanged, which shows that it has been possible to handle a much larger ship traffic with an ice service at the same cost level as ten years ago. This can be explained by improved quality of the ice charts, and better ice management attributed to more use of satellite data, better communication of satellite data transport system from ice services to the ships and traffic control system, which makes it possible for the icebreakers and the merchant vessels to operate more efficiently.
- In Canada, cost-benefit studies have been used to assess if satellite data should replace aircraft surveys in ice monitoring (*Watkins, 1992*). The decision to launch RADARSAT was primarily political. Economic benefits have been assessed for many applications of SAR, but expensive

satellite programs like RADARSAT would not be implemented without heavy governmental support.

- Estimates made by Murmansk Shipping Company indicates that use of RADARSAT in the whole Northern Sea Route can increase the productivity of the icebreaker fleet by a factor of two. This would have significant impact on the costs of operating the icebreaker fleet. But it does not mean that the icebreaker fleet could be reduced by the same factor and the savings could be used to purchase SAR data. The icebreaker fleet is financed by the government and it would be kept operational because of national interests.

9. Recommendations

9.1 The need for a sea ice monitoring mission

In near future SAR based operational satellite system should be established to satisfy the needs of European ice monitoring both in the Arctic and the Baltic Sea area. SAR data should be supplemented by other types of data (optical, IR, passive microwave data) and be provided at a lower cost than today in order to be cost-effective. The following factors must be taken into account:

- Technical specifications to a future sea ice monitoring mission must be determined by the fundamental user requirements on temporal and spatial coverage, resolution, data distribution and cost-effectiveness.
- ESA's ENVISAT with ASAR with dual polarisation, multimodes including a global monitoring mode with 1 km resolution is a very interesting concept for operational ice monitoring, which will be demonstrated from 2000.
- NASA's LightSAR is a proposed mission for launch in two-three years, which will offer multi-channel, multi-polarisation SAR which operates in several modes, which would be very useful for sea ice monitoring. The LightSAR will represent another milestone in advanced SAR technology, but for operational sea ice monitoring a simpler SAR concept may be sufficient.
- Sea ice monitoring requires new cost-effective satellite systems with frequent revisit time and high spatial resolution. A study by Alenia Aerospazio (*Mura et al., 1998*) suggests that a constellation of 5 - 10 small satellites (each not exceeding 300 kg) carrying both SAR and optical sensors, can be implemented within 5 - 10 years. This system will meet the requirements from sea ice monitoring as well as from many other marine and terrestrial applications.
- Satellite ice is listed among the parameters required to be observed in ongoing or planned ocean monitoring programmes such as GOOS/CGOS (*Allison and Moritz, 1995*), EuroGOOS (*EuroGOOS, 1997*), and IGOSS (Integrated Global Ocean Services System) which is planned, developed and co-ordinated jointly by Intergovernmental Oceanographic Commission (IOC) of the United Nations Educational, Scientific and Cultural Organisation (UNESCO) and by the World Meteorological Organisation (WMO). See IGOSS Plan and Implementation Programme 1996 - 2003 (*UNESCO, 1996*).

9.2 Improved ground segment and more efficient data delivery to ice centres

There are several bottlenecks in the ground segment which need improvement before SAR data can be fully used:

- New SAR receiving stations are needed to cover all the important sea ice areas with near real-time data.
- Efficient computer networks are needed to facilitate distribution of high-resolution satellite images to the ice centres. Today transfer rates of Internet are low, and transfer of large SAR files take too long time.

9.3 Streamlining of analysis and interpretation of SAR data

The ice centres which are responsible for operational ice monitoring need to develop fast routines for extracting ice information from SAR data.

- Improved knowledge and analysis techniques must be developed to interpret SAR ice data and derive ice parameters for use in ice charts. The high resolution of SAR images demands new interpretation methods, and ice nomenclature and symbols must be adjusted to include detailed information from SAR images.
- Existing scattering models which relate physical ice parameters to SAR parameters are not good enough. Further research is needed to clarify SAR imaging of different ice types and ice conditions.
- Improved automatic ice classification algorithms for SAR images need to be developed to be able to utilise SAR ice information in an operational ice monitoring system.

9.4 More efficient distribution to end users

The data and derived data products from the ice centres to end users must be made more effective to satisfy the requirements for near real-time ice information. In many cases, when the ice changes fast, the delivery time should be reduced to 2-3 hours.

- Data must be distributed to users at sea, which should not be more than 6 hours old.
- Processing times of SAR data at most of the existing receiving stations must be reduced.
- Direct downlink of SAR images to ships and other users in remote areas would be of great advantage in sea ice monitoring. Therefore, the concept of onboard SAR processing and direct dissemination via simple user stations, has been studied by ESA where navigation in sea ice would be a prime application of the system (*Marelli et al., 1998*). The study has shown that the concept is feasible on a small or medium satellite. The revisit time determines the number of satellites which need to be in operation.

9.5 Secure long-term access to SAR and other satellite data

Users of sea ice information should be confident that EO data will be available daily over the relevant areas and that the delivery of data are fast and convenient. For operational ice monitoring it is essential to be confident that data will be available in the future.

- The data providers should guarantee delivery of satellite data for several years ahead. Because there are risks associated with the satellite systems, several SAR satellites providing SAR data must be in operation and conflict between different instruments onboard the satellite, which is the case for the ERS system must be avoided.
- The ordering procedure of SAR data today is not satisfactory for operational ice monitoring. The data must be ordered weeks beforehand and is difficult to change on short notice.

9.6 Towards fully digitised information system onboard ships

The development in digital information systems on ships, including digital sea charts (ECDIS) and sea ice maps, will have impact on the products delivered by the ice centres.

- Systems for digital data delivery to vessels should be improved to include ice information products, such as ice charts, satellite data and ice forecasts. It is expected that meteorological and oceanographical data and forecasts will be available in digital information systems in near future.

9.7 Benefits from new communication systems

- New communication satellites able to transfer high data rates at reasonable prices are expected in a few years. Providers of sea ice information products should take advantage of new communication technology to secure efficient data distribution to the users at sea and in the Arctic areas.

9.8 Strengthening of regional co-operation

Today the ice services are mainly operating on national basis supported by national governments. The concept of regional ice centres instead of national ice centres should be further investigated.

- In the Baltic Sea area where many countries perform ice monitoring in the same region it is a question if there is a need for nine national ice services. Alternatively, a single Baltic Sea ice information centre could be established. Also in other regions, more co-operation should be established between ice centres working in the same area. In the Greenland area for example more co-operation between DMI, Canadian and Icelandic ice services should be considered.
- Improved information service should be established on Internet, where all sea ice monitoring information providers could be accessed, through one entry-print. Data receiving and delivery should be established in this service.
- A European forum of sea ice information users cold be useful; to take care of interests which are common for users and service providers. The forum could represent the sea ice community towards ESA, EU and other entities which can play important roles in establishing future operational sea ice monitoring satellites.
- In Russia, strengthening of the ice services is of high priority and the use of all available satellite data, not only Russian data, should be implemented. Russia should participate actively in the international co-operation between the ice services in the Baltic region.

9.9 Summary of recommendations

The recommendations for operational sea ice monitoring by satellites can be summarised as follows:

- A combination of SAR, optical and passive microwave data from satellites is required.
- Long-term access to satellite data must be secured.
- The number of satellites in orbit must be sufficient to ensure coverage of the ice areas at least once per day.
- There must be SAR receiving stations which can process and deliver SAR data from all ice areas in near real-time.
- High speed computer links between receiving stations, ice centres and other major users of satellite data must be established.
- The analysis and interpretation of SAR images at the ice centres must be streamlined.
- Digital distribution of ice products to ships must be established in all relevant regions.
- The concept of onboard processing and direct downlink of SAR data to users should be further developed.
- The possibility of including ice information in ECDIS and/or other information systems onboard ships should be investigated.
- Standardisation of digital ice products is needed.
- New satellite communication systems should be tested for distribution of ice products to ships.

- Increased co-operation between ice centres to ensure optimal data handling and distribution should be encouraged.
- Training and education of users in satellite ice monitoring should be strengthened.

10. Acknowledged institutions

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Vitaly Alexandrov (Nansen International Environmental and Remote Sensing Centre, Russia)
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- Canadian Space Agency
- Danish Meteorological Institute
- EUMETSAT
- European Space Agency
- Finnish Institute of Marine Research / Finnish Ice Service
- Finnish Maritime Administration
- Murmansk Shipping Company, Russia
- National Ice Centre, USA
- National Snow and Ice Data Centre, USA
- NIERSC, Russia
- Norwegian Meteorological Institute
- NPO Planeta, Russia
- Swedish Meteorological and Hydrological Institute

11. Acronyms

The following acronyms are used in the report:

AARI	**A**rctic and **A**ntarctic **R**esearch **I**nstitute, St. Petersburg, Russia
ADEOS	**Ad**vanced **E**arth **O**bservation **S**atellite
ADF	**A**dmiral **D**anish **F**leet
AES	**A**tmospheric **E**nvironmental **S**ervice
AMSR	**A**dvanced **M**icrowave **S**canning **R**adiometer
APT	**A**utomatic **P**icture **T**ransmission
ASAR	**A**dvanced **S**ynthetic **A**perture **R**adar
AVHRR	**A**dvanced **V**ery **H**igh **R**esolution **R**adiometer
AVNIR	**A**dvanced **V**isible and **N**ear-**I**nfrared **R**adiometer
BSH	**B**udesamts fur **S**eeschiffahrt und **H**ydrographie
BSHIS	**B**udesamts fur **S**eeschiffahrt und **H**ydrographie **I**ce **S**ervice
CAD	**Ca**nadian **D**ollars
CCG	**C**anadian **C**oast **G**uard
CCRS	**C**anadian **C**entre for **R**emote **S**ensing
CEOS	**C**ommittee of **E**arth **O**bservation **S**atellites
CIM	**C**omprehensive **I**ce **M**aps
CIS	**C**anadian **I**ce **S**ervice
CSA	**C**anadian **S**pace **A**gency
DIS	**D**anish **I**ce **S**ervice, Copenhagen, Denmark
DMI	**D**anish **M**eteorological **I**nstitute, Copenhagen, Denmark
DMSP	**D**efence **M**eteorological **S**atellite **P**rogram
DNMI	The **N**orwegian **M**eteorological **I**nstitute
ECDIS	**E**lectronic **C**hart **D**isplay and **I**nformation **S**ystem
ECU	**E**uropean **C**urrency **U**nit
EMHI	**E**stonian **M**eteorological and **H**ydrological **I**nstitute, Tallinn, Estonia
ENVISAT	**Envi**ronmental **Sat**ellite
EO	**E**arth **O**bservation (normally meaning the use of space-borne data)
EOS	**E**arth **O**bservation **S**ystem
ERS	**E**uropean **R**emote Sensing **S**atellite
ESA	**E**uropean **S**pace **A**gency
ESSA	**E**nvironmental **S**cience **S**ervice **A**dministration
EUMETSAT	**Eu**ropean Organisation for the Exploitation of **Met**eorological **Sat**ellites
Eurimage	European Commercial Data Distribution Service
EuroGOOS	**Euro**pean Association of Agencies to Promote the **G**lobal **O**cean **O**bserving **S**ystem **(GOOS)**
FIMR	**F**innish **I**nstitute of **M**arine **R**esearch, Helsinki, Finland
FIS	**F**innish **I**ce **S**ervice, Helsinki, Finland
FMA	**F**innish **M**aritime **A**dministration, Helsinki, Finland
FMI	**F**innish **M**eteorological **I**nstitute, Helsinki, Finland
GLK	**G**reenland's **C**ommand, **K**angilinnquit, Greenland
GMS	**G**eostationary **M**eteorological **S**atellite
GPS	**G**lobal **P**ositioning **S**ystem
GTS	**G**lobal **T**elecommunications **S**ervice
HRPT	**H**igh **R**esolution **P**icture **T**ransmission

HRV sensors	**H**igh **R**esolution **V**isible sensors
IC	**I**ce **C**entral **N**arsarsuaq, Greenland
IIP	**I**nternational **I**ce **P**atrol, Canada
ILAS	**I**mproved **L**imb **A**tmospheric **S**pectrometer
IMG	**I**nterferometric **M**onitor of **G**reenhouse **G**ases
INMARSAT	**In**ternational **Mar**itime **Sat**ellite
IR	**I**nfra-**R**ed
ISIS	**I**ce **S**ervices **I**ntegrated **S**ystem
ITOS	**I**mproved **T**IROS **O**perational **S**atellite
JAMSTEC	**Ja**panese **M**arine **S**cience and **Te**chnology **C**enter
JERS	**J**apan **E**arth **R**emote-Sensing **S**atellite
JMA	**J**apan **M**eteorological **A**gency
LHMA	**L**atvian **H**ydro**m**eteorological **A**gency, Riga, Latvia
LRI	**L**ow **R**esolution **I**mage
MESSR	**M**ultispectral **E**lectronic **S**elf-**S**canning **R**adiometer
Meteor	**Meteor**ological Satellite
MIMR	**M**ulti-frequency **I**maging **M**icrowave **R**adiometer
MOH	**M**arine **O**perations **H**eadquarters, Russia
MOS	**M**arine **O**bservation **S**atellite, Japan
MSC	**M**urmansk **S**hipping **C**ompany, Murmansk, Russia
MSR	**M**icrowave **S**canning **R**adiometer
MSS	**M**ulti Spectral **S**canner
NASDA	**Na**tional **S**pace **D**evelopment **A**gency, Japan
NAVICECEN	**Nav**al **Ice** **Cen**tre, USA
NAVOCEANO	**Nav**al **Ocean**ographic **O**ffice, USA
NERSC	**N**ansen **E**nvironmental and **R**emote **S**ensing **C**enter, Bergen, Norway
NESDIS	**N**ational **E**nvironmental **S**atellite **D**ata **I**nformation **S**ervice, USA
NIC	**N**ational **I**ce **C**entre, USA
NOAA	**N**ational **O**ceanic and **A**tmospheric **A**dministration, USA
NPO Planeta	Research and Production Association "Planeta", Moscow, Russia
NRCMEF	**N**ational **R**esearch **C**enter for **M**arine **E**nvironment **F**orecasts, Beijing, P.R. China
NSCAT	NASA **Scat**terometer
NSR	**N**orthern **S**ea **R**oute
NWS	**N**ational **W**eather **S**ervice, USA
O/OI	Ice and Remote Sensing Division, Canada
OCTS	**O**cean **C**olour and **T**emperature **S**canner
POLDER	**Pol**arisation and **D**irectionality of **E**arth's **R**eflectance’s
RAR	**R**eal **A**perture **R**adar
RDAF	**R**oyal **D**anish **A**ir**f**orce
RIS	**R**egional **I**nformation **S**ervice
SAR	**S**ynthetic **A**perture **R**adar
SLAR	**S**ide-**L**ooking **A**irborne **R**adar
SLR	**S**ide-**L**ooking **R**adar
SMHI	**S**wedish **M**eteorological and **H**ydrological **I**nstitute, Norrköping, Sweden
SMMR	**S**canning **M**ulti-channel **M**icrowave **R**adiometer
SOA	**S**tate **O**ceanic **A**dministration , Beijing, P.R. China
SOD	**S**econd **O**ceanographic **D**ivision, Beijing, P.R. China
SOG	**S**pecial **O**peration **G**roup, Russia

SPOT	**S**ysteme **P**our l' **O**bservation de la **T**erre
SSM/I	**S**pecial **S**ensor **M**icrowave **I**mager
SST	**S**ea **S**urface **T**emperature
TM	**T**hematic **M**apper
TOMS	**T**otal **O**zone **M**apping **S**pectrometer
TSS	**T**ethered **S**atellite **S**ystem
TSS	**Tr**omsø **S**atellite **S**tation
USCG	**U**nited **S**tates **C**oast **G**uard
UTP	**U**niversal **T**opographic **P**rojector
VHRR	**V**ery **H**igh **R**esolution **R**adiometer
VISSR	**Vi**sible and **I**nfrared **S**pin-**S**can **R**adiometer
VNN	National Meteorological Institute for North of Norway
VTIR	**V**isible and **T**hermal **I**nfrared **R**adiometer
WMO	**W**ord **M**eteorological **O**rganisation

12. References

AES (Atmospheric Environmental Service, Canada), 1991: Second WMO Operational Ice Remote Sensing Workshop, 10 - 13 September 1991, Ottawa, Canada, 253 pp.

Allison, I and R. E. Moritz. Sea Ice in the Global Climate System: Requirements for an Ocean Observing System. OOSDP background Report no. 7, April 1995, 28 pp.

Arctic Pollution Issues: A State of the Arctic Environment Report, 188 pp, AMAP, 1997.

Bjørgo, E., O. M. Johannessen and M. W. Miles. Analysis of merged SMMR-SSM/I time series of Arctic and Antarctic sea ice parameters 1978-1995. Geophysical Research Letters, vol. 24, no. 4, pp. 413-416, Feb. 15, 1997.

Breivik, L.-A., Ø. Godøy, H. Schyberg, S. Andersen, 1998. SAF Ocean and Sea Ice. In Proceedings from 27th International Symposium on Remote Sensing of Environment, June 8-12, 1998, Tromsø, Norway.

Brigham, L. W. (editor). The Soviet Maritime Arctic. Naval Institute Press. ©Woods Hole Oceanographic Institution, 1991, 336 pp.

Committee on Earth Observation Satellites: Towards an Integrated Global Observing Strategy (1997 CEOS Yearbook), 1997. Published by Smith System Engineering Limited, UK.

Efthimerou M., and Ketselidis M., 1997. Satellite Communication Survey. Joint Research Center, EC, March 1997. EUR 17302 EN.

Gronvall, H., Seina, A, & Simila, M. 1996. The Finnish ice service and real-time automatic classification of SAR data. Nordic Space Activities, Vol. 4. No 4/96, pp. 28-29, 32-35.

Haykin, S., Lewis, E.O., Raney, R.K., Rossiter, J.R., 1994. Remote Sensing of sea ice and icebergs. Wiley series in remote sensing.

Håkansson, B. and M. Moberg. Potentials of SAR for sea ice ship routing based on experiences obtained with ERS-a SAR in the Baltic Sea. Proceedings of the Second ERS Applications Workshop, London, UK, 6 - 8 December 1995, ESA SP-383, February 1996, pp 317 - 321.

Håkansson, B., M. Moberg and T. Thompson. Real-time use of ERS-1 SAR imagery for ice service and icebreaking operations in the Baltic Sea. Int. J. Remote Sensing, Vol. 16, no. 17, pp. 3441 - 3458, 1995.

IceMap User’s Manual, version 1.4, 21.12. 1995. M. Kylänpää, VTT - Technical Research Centre of Finland, Information Technology.

ICE ROUTES, Final Report, 1998. Contract: WA-96-AM-1136. Project founded by the European Commission under the transport RTD programme of the 4th Framework Programme.

IGOSS Plan and Implementation Programme 1996 -2003. IOC report no 43, 1996, 56 pp.

ITOS report. Mission study of an Ice Topography Observation System. Final report. ESTEC Contract No. 11613/95/NL/CN. September 1996.

Johannessen, O. M., A. M. Volkov, V. D. Grischenko, L. P. Bobylev, S. Sandven, K. Kloster, T. Hamre, V. Asmus, V. G. Smirnov, V. V. Melentyev and L. Zaitsev. ICEWATCH - Ice SAR monitoring of the Northern

Sea Route. In “Operational Oceanography. The Challenge for European Co-operation” (Editor in Chief: J. H. Stel). Proceedings of the First International Conference on EuroGOOS, 7 -11 October 1996, The Hague, The Netherlands. Elsevier Oceanography Series, No. 62, 1997 a, pp. 224 - 233.

Johannessen, O. M., S. Sandven, K. Kloster, L. H. Pettersson, V. V. Melentyev, L. P. Bobylev and K. Ya. Kondratyev. ERS-1/2 SAR monitoring of dangerous ice phenomena along the western part of the Northern Sea Route. Int. J. Remote Sensing, Vol. 18, No. 12, 2477-2481, 1997 b.

Johannessen, O. M., S. Sandven, L. H. Pettersson, M. Miles, K. Kloster, V. V. Melentyev, L. P. Bobylev and K. Ya. Kondratyev. Near-real time sea ice monitoring in the Northern Sea Route using ERS-1 SAR and DMSP SSM/I microwave data. *Acta Astronautica, Vol. 38*, No. 4-8, pp. 457 - 465, 1996.

Kwok, R., J. C. Curlander, R. McConnel and S. S. Pang, 1990: An ice motion tracking system at the Alaska SAR Facility. IEEE J. Oceanic Eng., 15, pp. 44-54.

Kwok, R., A. Schweiger, D. A. Rothrock, S. Pang, and C. Kottmeier. Sea ice motion from satellite passive microwave imagery assessed with ERS SAR and buoy motions. Journal of Geophysical Research, Vol. 103, No. C4, pp. 8191-8214, April 15, 1998.

Marelli, E., P. Gudmandsen and J. Rosello-Guasch.. New mission concepts based on on-board SAR processing. In Future Trends in Remote Sensing. Proceedings of the 17th EARSeL Symposium on future trends in remote sensing, Lyngby, Denmark, 17 - 19 June 1997 (Ed. P. Gudmandsen), p. 15 - 33, Balkema, 1998.

Massom, R. 1994. Satellite remote sensing of polar snow and ice: present status and future direction. Polar Record, Vol. 31, No 177, pp 99-114.

Mulherin, N.D., 1996. The Northern Sea Route. Its development and evolving state operations in the 1990s. US Army Engineer District, Alaska. CRREL Report 96-3.

Mulherin, N. D., D. T. Eppler, T. O. Proshutinsky, A. Yu Proshutinsky, L. D. Farmer and O. P. Smith. Development and Results of a Northern Sea Route Transit Model. CREEL Report 96-5, May 1996, 105 pp.

Mura, F., C. Dionosio and D. Oricchio. Future remote sensing systems. In Future Trends in Remote Sensing Proceedings of the 17th EARSeL Symposium on future trends in remote sensing, Lyngby, Denmark, 17 - 19 June 1997 (Ed. P. Gudmandsen), p. 17 - 24, Balkema, 1998.

Naturens Verden, 1993. Rhodos Internationalt Forlag for videnskab og kunst. Danish Journal.

Raney, R. K. and J. C. Falkingham. RADARSAT and operational ice information. In "Remote Sensing of Sea Ice and Icebergs" (Eds. S. Haykin, E. O. Lewis, R. K. Raney, J. R. Rossiter) John Wiley & Sons, 1994, pp. 611 - 657.

Sandven, S. & Grönvall, H. & Seinä, A. & Valeur, H. H. & Nizovsky, M. & Gill, R. & Andersen, H. S. & Jensen, V. & Kloster, K. 1997: Operational Sea Ice Monitoring by Satellites in Europe: *OSIMS Report* No. 1: WP1: Description of the ice monitoring systems and their users, and WP2: analysis of satellite data used in ice monitoring. -European Commission Environmental and Climate Programme 1994-1998, Theme 3, Area 3.2. Contract No. ENV4-CT96-0329. - NERSC Technical Report No. 124. Bergen, 23 May 1997.

Sandven, S. & Seinä, A. & Grönvall, H. & Valeur, H. H. & Andersen, H. Steen & Pettersson, L. H. & Alexandrov, V. & Nizovsky, M. & Jensen, V. E. 1997: Operational Sea Ice Monitoring by Satellites in Europe: *OSIMS Report* No. 2. WP3: Investigation of user requirements and cost benefits of using satellite data in ice monitoring. -European Commission Environmental and Climate Programme 1994-1998, Theme 3, Area 3.2. Contract No. ENV4-CT96-0329. - NERSC Technical Report No. 129. Bergen, 13 October 1997.

Sandven, S., Grönvall, H., Seinä, A., Valeur, H., H., Nizovsky, M., Gill, R., Andersen, H. S. & Haugen, V. E. J. 1998: Operational Sea Ice Monitoring by Satellites in Europe: *OSIMS Report* No. 3. WP 4. technical feasibility of sensors, instruments and ground structure. WP 5. Proposed concepts for optimal ice monitoring systems -European Commission Environmental and Climate Programme 1994-1998, Theme 3, Area 3.2. Contract No. ENV4-CT96-0329. - NERSC Technical Report No 142. Bergen, 1 April 1998.

Sandven, S., Makynen, M., Hallikainen, M., Similä, M., Grönvall, H., Seinä, A., Cavanie, A., Ezraty, R., Maroni, C., Gill, R., Valeur, H. H., Pedersen, L. T., Alexandrov, V., Andersen, S., Lundhaug, M., Bjørgo, E, Dalen, Ø., Kloster, K. 1998: Integrated use of new microwave satellite data for improvement sea ice observation -*IMSI Report* No. 8: Development of new satellite ice data products. -European Commission Environmental and Climate Programme 1994-1998, Theme 3, Area 3.3.3. Contract No. ENV4-CT96-0361. - NERSC Technical Report No. 145. Bergen, 27 February 1998.

Seinä, A. & Grönvall, H.& Nizovsky, M. & Vainio, J. 1998: Integrated use of new microwave satellite data for improvement sea ice observation -*IMSI Report* No. 3: Dissemination of test products to selected users in the Baltic Sea. Report on activities in the winter of 1997. -European Commission Environmental and Climate Programme 1994-1998, Theme 3, Area 3.3.3. Contract No. ENV4-CT96-0361.- Meri - Report series of the Finnish Institute of Marine Research No 33. Helsinki.

Smirnov, V., A. V. Bushuev, V. S. Loschilov, Yu. D. Bychenkov, O. S. Devyatayev, Yu. A. Shcherbakov, V. D. Grischenko, E. D. Yakshevich, A. R. Shigbutdinov and S. Sandven. Review of Russian Satellite Data for the Northern Sea Route. INSROP Discussion Paper, I.2.3.1998.

Strübing, K. 100 JAHRE EISDIENST - Vergangenheit - Gegenwart - Zukunft. Jahresbericht 1996, Bundesamt für Seeschiffahrt und Hydrographie, Hamburg und Rostock, 1997, 73-80.

Strübing, K., 1996: The Ice Winter of 1995/96 on the German Coasts between Ems and Oder, with a Survey of the Entire Baltic Area.(Dt. Hydrogr. Z. 48, 1996, 73-87).

The EuroGOOS Plan. EuroGOOS Publication No. 3, February 1997, 28 pp.

The Polar Code, 1997. The International Code of safety for ships in polar waters (Polar Code). Sub-Committee on ship design and equipment - 41 St session, Agenda Item 10. Submitted by Canada on behalf of the outside working group.

Warner R. A. and W. B. Campbell, 1993. Ice application requirements. In: Satellite Remote Sensing of the Oceanic Environment, I. S. F. Jones, Y. Sugimori and R. W. Stewart (Eds.). Seibutsu Kenkyusha, pp. 330-340.

Watkins, G., 1992. Use of Satellite Data in Operational Monitoring and Forecasting of Sea Ice Conditions. The Canadian Experience. Norwegian Space Centre (NRC). NRC-report(92)10.

Weir, L., 1996. RADARSAT Near Real Time Imagery Analysis In Support of the Canadian Coast Guard Arctic Icebreaking Program. In: RADARSAT for Ice and Oceans. The 6th Workshop of the Canadian Ice working Group. November 19-21, 1996. Ottawa, Canada.

Yu, Y., and Rothrock, D. A. 1996: Thin ice thickness from satellite thermal imagery. J. of Geophysical Res., Vol 101, no C11, pp. 25753-25776.

Appendix A. Results of the user workshop in Helsinki

A.1 Introduction

The OSIMS (Operational Sea Ice Monitoring by Satellites in Europe) was hosted by FIMR in Helsinki onboard the icebreaker Urho. A selection of users were invited to the workshop to discuss topics important for operational sea ice monitoring:

- Use of new satellite data,
- Data collection,
- Data integration and analysis,
- Distribution to users.

Agenda:

5. Feb. 1998

14.00: Opening of Workshop: What is OSIMS? Better sea ice monitoring in the Northern Sea Route, the Greenland Waters and the Baltic Sea (Stein Sandven, NERSC, Ari Seina, FIMR, Henrik Andersen, DMI).
15.30: Short tour at IB Urho emphasising communication systems (Captain Rintala)
16.30: Dinner onboard hosted by the FMA
18.00: Closing the first day

6. Feb. 1998

09.00: Workshop continues with plenary discussion: Solutions for better sea ice monitoring in the Northern Sea Route, the Greenland Waters and the Baltic Sea - round table discussion
12.00: Lunch
13.00: Workshop continues with plenary discussion
15.30: Preliminary results of OSIMS Workshop (Stein Sandven, NERSC)
16.00: Closing the workshop

List of participants

Stein Sandven, NERSC, Norway
Pekka Jarvilehto, CEC DG XII
Henrik S. Andersen, Danish Meteorological Institute, Denmark
Anders Moller, Chief of Denmark Icebreaking Service, Århus, Denmark
Hans Jorgen Roed Jensen, Captain and chief Ice Central Narssarssuaq, Denmark
Klaus Strübing, BSH, Germany (on 6 Feb.)
Hannu Gronvall, FIMR, Finland
Ari Seina, FIMR, Finland
Mikael Nizovsky, FIMR, Finland
Lennart Hagerstam, FMA, Finland (on 5 Feb.)
Bjoern Sjoman, FMA, Finland
Raimo Rintala, FMA, Finland
Robin Berglund, VTT, Finland (on 6 Feb.)
Nikolai Babich, MSC, Russia
Vitaly Alexandrov, NIERSC, Russia
Lawson Bringham, SPRI/US Coast Guard, USA

A.2 Results

A.2.1 Presentations of key issues in each region

1. Ice service in the Baltic region: Ari Seina, FIMR.

- Good quality and fast delivery ice mapping is essential for winter traffic in the Baltic Sea.
- Finland and Sweden started the first use of RADARSAT ScanSAR narrow mode data in operational ice monitoring in the winter of 1998. 100 screens will be available.
- RADARSAT data are transferred in near real-time from Tromsø Satellite Station via Internet. Transmission time is 25 min for one scene in optimal cases.
- Averaged ScanSAR scenes (800 m pixel size) are transferred to the icebreakers.
- Evaluation of the benefits of RADARSAT data after the end of the ice season.
- There is a need for cloud and daylight independent digital data onboard to be used in ice navigation. This kind of data will make the traffic smoother and increased security.

2. Greenland: Henrik Steen Andersen

- The potential use of RADARSAT data for sea ice monitoring in the Greenland waters has been tested and evaluated.
- The plan is to use RADARSAT operationally and thereby reduce the number of aircraft reconnaissance flights. Most likely the aircraft will only be used during June and July because RADARSAT is least reliable to detect ice in the Cape Farewell area during that period. The helicopter service will be maintained.
- It is estimated that approximately 600 RADARSAT scenes (ScanSAR Wide) are needed per year. About 50 % of these will cover the Cape Farewell area.
- Practical preparations are needed before operational use of RADARSAT data may commence. In particular: an efficient data transmission from data supplier (receiving station) to DMI, adequate processing and analysis system must be established at DMI, etc.
- New products are expected: e.g. vector based ice charts, ice drift information and weekly sea ice status ice charts for the Greenland waters.

3. Northern Sea Route: Vitaly Alexandrov (NIERSC) and Nikolai Babich (Murmansk Shipping Company)

- Sea ice and hydrometeorological service is essential for sea transportation in the Northern Sea Route throughout the year
- Reduction in operational ice monitoring service has been significant over the last 10 years
- Satellite data becomes more important as use of aircraft has been severely reduced
- Existing satellites (both Russian and non-Russian) are not used systematically, except NOAA AVHRR data
- SAR data have been demonstrated to be very useful, but operational SAR ice monitoring is not yet possible due to lack of financing.

A.2.2 Presentations by invited participants

1. Lennart Hagerstam, Finnish Maritime Administration, Head of Traffic Department

- Finland could be compared to an island: 80-90 % of foreign trade is marine based and all harbours are ice-bound, in the north up to seven months
- Sea ice is forcing to restrict sea traffic by closing half of harbours for winter, assisting only vessels suitable for ice navigation and operating an icebreaker fleet

- Traffic has increased: in 1987 there were 14 000 port-calls and 19 mil. tons were transported during winter months, in the winter of 1997 there were 23 000 port-calls and 30 mil. tons were transported.
- Number of icebreakers have not increased, thus the icebreaker fleet was been used more effectively. In future number of icebreakers will not increase, but the traffic will increase considerable. The icebreakers cannot assist all vessels, and therefore they will need more detailed ice information. Only suitable solution for this will be space-borne data
- There is a need for integrating sea ice charts into ECDIS

2. Lawson Brigham, former captain of USCG icebreaker

- operating USCG icebreakers Polar Sea and Polar Star in both hemispheres
- research expeditions, escorting of tankers, etc.
- need direct downlink from satellites to ships (i.e. in the interior of the Arctic)
- use SSM/I in real-time (8 - 10 images per day), resolution about 12 km
- need also processed SAR images onboard for analysis of ice conditions
- need to overlay other data such as bathymetry on top of the images
- the Polar Ice Code defines rules for operations in Arctic and Antarctica which will have implications for ice information in the future. Operational ice monitoring systems should take these rules into account

3. Vitaly Alexandrov, ice scientist at NIERSC, St. Petersburg

- the structure and organisation of the ice service is changing: the Marine Operations Headquarters of MSC is moved from Dikson to Murmansk
- use of satellite data will be more important: essential to establish new services which can provide SAR data from RADARSAT, ERS, and other satellite systems for ice monitoring in the Northern Sea Route
- SSM/I data has proven to be very useful in strategic ice charting
- lack of SAR receiving stations in Laptev Sea is currently a problem for provision of near real-time data. ESA is planning to build a new receiving station in Siberia which will solve the problem
- New satellite systems will be very useful such as ESA’s ENVISAT ASAR, NASA’s LightSAR, and Russian Space Agency’s RESURS ARCTICA

4. Nikolai Babich, chief hydrologist at the Nuclear Icebreaker Fleet of Murmansk Shipping Company

- transport in the Northern Sea Route has declined since 1987: currently there is about 500 ships per year, while it was 1000 per year 10 years ago
- the foreign ship traffic is increasing: now 13 - 17 % of the cargo is transported by foreign ships
- the state-supported hydrometeorological service, which included extensive ice monitoring and forecasting, has been severely reduced.
- the situation for the ice service is unclear and reorganisation is expected
- there is currently severe lack of ice information
- the icebreaker operations and convoy speed can be significantly improved by use of more high resolution ice information from SAR data.

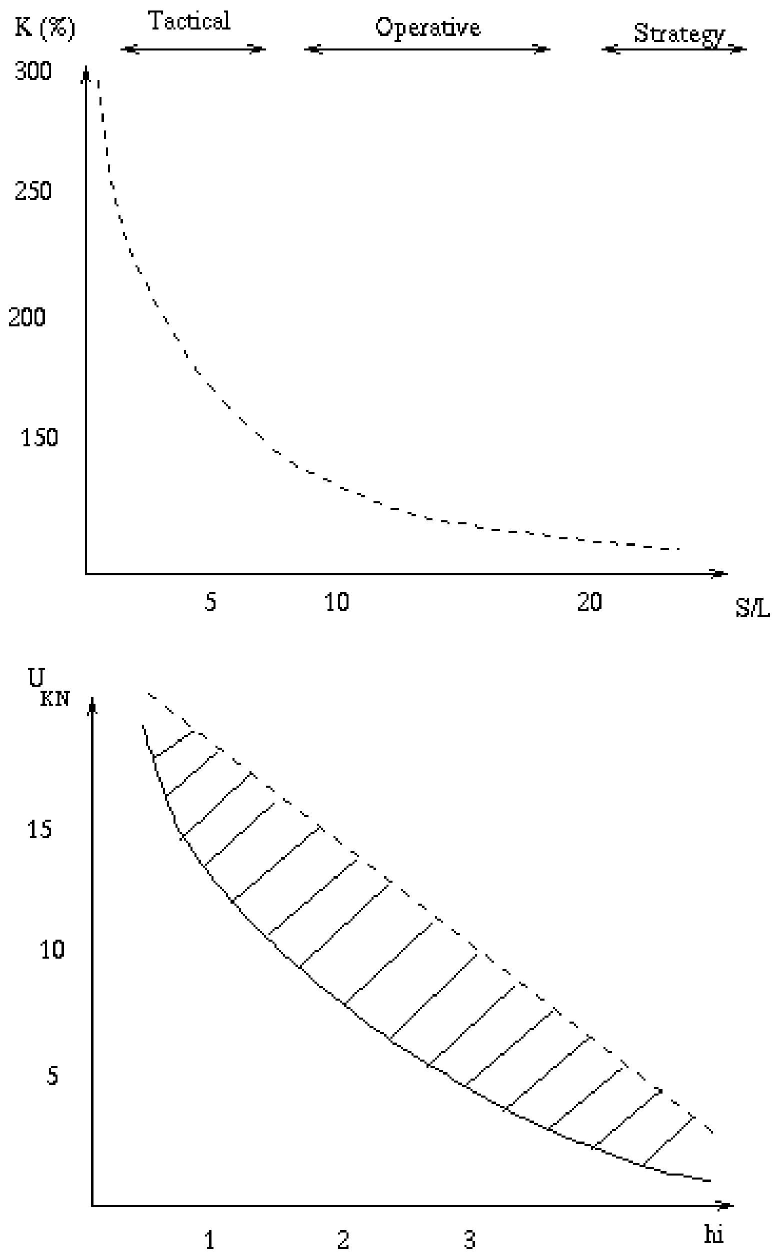

Figure 32. Ship velocity (U) as a function of ice thickness (hi), (*N. Babich, personal communication*).

5. Hans Jørgen Roed Jensen, captain and chief of Ice Central in Narssarssuaq, Greenland

- The ship traffic in the Cape Farewell area consists of one or two cargo vessels per week and inshore route passenger transport.
- Safety is the main issue for the ice service, i.e. to avoid accidents with ships in ice.
- It is believed that the safety will be maintained even when almost all air reconnaissance flights are replaced with operational use of satellite data.
- Relying only on RADARSAT creates a need for a backup system, i.e. use of helicopter and/or air craft.
- Use of RADARSAT data requires efficient data transmission; from data suppliers to DMI and from DMI to Greenland.

6. Anders Møller, chief of Denmark Icebreaking Service

- Formerly Anders Møller served as captain of Thetis, the vessel which performed seismic surveys in the Greenland waters during several summer seasons.
- A seismic survey include towing seismic cables a 4.5 knots in areas where ice may occur.
- Such operations require ice information which may differ from the 'normal' operational ice charts used for navigation. Information from satellite images are commonly supplemented by helicopter ice reconnaissance.
- Real-time ice information to avoid ice areas during a seismic survey.

7. Klaus Strübing, chief of German Ice Service at BSH in Hamburg

- use of ERS SAR data has been established, using near real-time processing and distribution from a German receiving station
- there are many customers of ice information in Arctic and Antarctica, because Hamburg is a major port for polar ship traffic
- SAR data in the Antarctica has been available 2 months per year from the O'Higging receiving station
- ice service is needed in the Antarctica as a consequence of the Antarctic Environmental Treaty.
- ice analysis software is co-ordinated among several ice centres in the Baltic region. The system provided by VTT (IceMap) is used by the German, Swedish and Finnish Ice Service and makes production of ice charts from satellite data and other information sources very efficient.

8. Robin Berglund, VTT Information Technology

- provider of several ice analysis systems used by the ice services and the icebreakers in the Baltic Region:
    - ICEPLOT used onboard icebreakers
    - IceMap used by Ice Centres to produce ice maps
    - IBNET improved system based on IRIS will be in use in the beginning of 1999
- provider of distribution systems for the Baltic Sea using mobile telephone network
- analysis and distribution systems based on state-of-art information technology will play an important role for all partners involved in ice monitoring services: data providers, ice centres and the end users

A.2.3 Plenary discussion of major topics

Data and information requirements

Baltic region
High resolution SAR images from satellites (pixel size of 100 -500 m) are needed daily during the ice season. Minimum acceptable operational resolution needs in ice navigation are under study in Finland. RADARSAT can provide data every 1 - 2 days. Optimal coverage would be twice per day. Higher resolution than 100 m would be needed near harbours.

Greenland
The first priority is to cover the Cape Farewell area with satellite images every day to support ship traffic in the most dangerous ice area. Both SAR and visual images are needed. Resolution should be as high as possible to resolve icebergs and growlers. Oil industry will have specific requirements to support drilling operations and transport.

Northern Sea Route

The data must satisfy strategic, operative and tactical ice charting, which means that data must be available at different spatial and temporal scales. The most challenging requirement is to provide tactical ice information from satellites 2 -3 times per day for each convoy working somewhere in the Northern Sea Route. This would require 3 - 4 satellites, and the resolution of the data should be 100 m or better. Direct downlink to ships will be necessary to avoid time delays.

Global coverage in Arctic and Antarctica

SSM/I data with resolution of order 12.5 km and update every 1 - 2 days is more than sufficient for large scale mapping of sea ice in the whole Arctic and Antarctica. Other data sources such as NOAA AVHRR can be used, but it requires a lot of data processing to mask out clouds and build up a mosaic covering all ice areas.

Requirements for new products

Today only a limited number of ice information products are available from the Ice Centres. It is foreseen that in near future, a wider range of products will be requested, such as

- ice charts in different scales, especially with higher resolution in particular areas such as near harbours, around offshore platforms, etc.
- ice charts of specific ice phenomena: i.e. iceberg charts, ice drift charts
- images with and without annotation from which the users will extract necessary information themselves
- ice forecast presented as predicted ice charts

Communication requirements

- In the Baltic region the cellular telephone system satisfies most of the requirements for data transmission to users at sea
- Presently, HF-facsimile is used to transfer ice charts to ships in the Greenland Waters. INMARSAT can be used for fax and data transmission if needed. It is foreseen that INMARSAT will be used more as prices go down. Internet is being established in Greenland for use on land. With start of oil/gas drilling on east Greenland, it is expected that digital data transmission by INMARSAT and other future communication systems will be used regularly.
- In the Northern Sea Route radiotelex is commonly for transmission of ice charts. INMARSAT can be used in some parts of the Northern Sea Route, but the use is limited due to the high costs. Transmission of compressed SAR images by INMARSAT has been successfully tested on Russian icebreakers in the western part of the Kara Sea.
- Direct downlink of data from satellite to ships can solve some of this problem. AVHRR, SSM/I and Okean SLR can provide direct downlink today. When such service becomes available also for SAR images, the real-time use in ice monitoring will become simpler.

Conclusion: new communication systems, which also include the polar regions, are expected to be available in near future. The communication services will be better, and the main task is to develop digital products which are suitable for quick transfer to ships.

There is an economic aspect and a safety/environmental aspect which has implications beyond pure economics. A main issue is who will experience economic savings by improving ice monitoring by use of satellite data. It can be the end users such as the shipping companies, the ice service, industries responsible for import/export or the nation (i.e. the government). It is very difficult to calculate actual savings correctly, because there are always some assumptions in the calculations which can be disputed.

There is a number of regulations which have impact on the cost-benefit calculations:

- Ice class requirements for vessel sailing in different ice areas.
- Environmental regulations with impact on technical standards on vessels operating in ice areas.
- The fairway due in Finland is very high which means that the ship owners expect all costs associated with bringing ships to Finnish harbours to be included here. It is not clear for the ship owners if they save costs by paying for the ice information. On the other hand it is either clear, that ship owners are willing to pay for such a data, if they consider better service as a part of public service. Better quality ice information should be financed by the government because it helps operate the icebreakers more efficiently.
- In the Northern Sea Route icebreaker support is mandatory and this support has a certain price per ton of cargo to be transported. The cost savings by better ice information are not reflected in this price.
- Use of larger cargo vessels can reduce the need for icebreaker support, but the need for accurate ice information will increase. Does the fairway due reflect this situation?
- The role of a public service versus a private service. Should a public service become commercialised or should it be free-of-charge or included in other costs such as the fairway due ?
- The mixture of public and private responsibilities makes it difficult to visualise who will save costs and how much by improving the ice service
- It is well documented that improved ice service (including icebreaker service and ice charting) is cost-beneficial. For example, the number of port calls to Finland during the winter season has increased from 14000 to 23000 during the last ten years. The number of icebreakers have been unchanged, which shows that it has been possible to handle a much larger ship traffic with an ice service at the same cost level as ten years ago. This can be explained by the quality of the ice charts, attributed to more use of satellite data, which makes it possible for the icebreakers to operate more efficiently.

***Concluding question**: is there a drive for better quality of the ice services which requires use of satellite data ?*

- Yes, because the ice services themselves are actively seeking better quality of ice charts and ice forecast which requires more cost-effective access to information.
- Yes, because there are “heavy” customers who will demand better ice services, especially oil companies involved in oil and gas production in Arctic offshore areas. Also increased sea transportation in the Baltic Sea and the Northern Sea Route will be an important market for ice information
- Yes, because increased interest in environmental questions related to sea ice (global warming, pollution transport) requires data which can only be obtained from satellites.

Table 14. Summary table of satellite data requirements.

Ice parameter	Which satellite data are needed and what temporal/spatial resolution is required				
Region	**Baltic Sea**	**Greenland**			**Northern Sea Route**
		Cape Farewell	North of 62° N	Greenland Waters	
Ice extent	AVHRR: 1 km /daily SAR: 100 m / daily	SAR: 100 m Optical: 30-1000 m Daily	SAR: 100-1000 m Optical: 1000 m When required	SAR: 1000 m PMW: 5-10 km Weekly	SSM/I: 10 km/10 day AVHRR: 1 km/ 3 day Okean SLR: 1 km/ 3 day
Ice edge variability	AVHRR: 1 km /daily SAR: 100 m / daily	SAR: 100 m Optical: 300-1000 m Daily	SAR: 100-1000 m Optical: 500-1000 m When required	SAR: 1000 m PMW: 5-10 km Weekly	AVHRR: 1 km/ 1 day Okean SLR: 1 km/ 1 day SAR: 100 m/ 1 day
Ice type concentration	AVHRR: 1 km /daily SAR: 100 m / daily	SAR: 100 m Optical: 300-1000 m Daily	SAR: 100-1000 m Optical: 500-1000 m When required	SAR: 1000 m PMW: 5-10 km Weekly	SSM/I: 10 km / 3 day Okean SLR: 1 km / 3 day SAR: 1 km / 3 day
Leads	AVHRR: 1 km /daily SAR: 100 m / daily		SAR: 100-1000 m Optical: 500-1000 m When required		SAR: 100 m / 1 day
Deformation/ ridges	AVHRR: 1 km /daily SAR: 100 m / daily				SAR: 100 m / 1 day
Brash ice	AVHRR: 1 km /daily SAR: 100 m / daily				SAR: 1 km / 1 day
Icebergs/ growlers		SAR: 50-100 m Daily			SAR: 100 m / 1 day
Passage		SAR: 50-100 m When required			