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Integrated use of new microwave satellite data for improved sea ice observation

IMSI

Final Report

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Executive Summary

The **overall goal of IMSI** is to explore and test methods for use of new satellite earth observation data in sea ice monitoring and improve the utilisation of these observations in a wider user community. To reach these objectives IMSI consists of four major tasks:

1. Study of user requirements to define which new satellite products should be developed for use in ice monitoring.

2. Development of new ice products, derived from EO data covering three spatial scales: global scale, regional scale and local scale. The data used are synthetic aperture radar (SAR), passive microwave, scatterometer and side-looking radar (SLR) data. The products are developed for the Northern Sea Route, the Baltic Sea region, the Greenland waters, and for the whole Arctic and Antarctic region. Integrated products, which make use of several types of satellite data, are also developed.

3. User demonstration and product dissemination. The data products developed in Task 2 are disseminated to many users in several countries of Europe where sea ice is relevant. Specific demonstrations are carried out during field expeditions where in situ observations are obtained for validation of the satellite data products.

4. User assessment, evaluation and recommendation. The users who have received satellite data and data products have assessed the usefulness of the information which can be retrieved from satellite data. The benefits for the users have been studied and recommendations have been suggested for future use of satellite data in ice monitoring.

***Why is sea ice monitoring important*?** Because it is

- of national importance in countries where sea ice occurs;
- of considerable economic importance in sea transportation;
- one of the most important and appropriate applications of satellite data with potential to increased use as new satellite data become available;
- an established and organised activity in many countries where sea ice has impact on sea transportation, fisheries, offshore operations, and other marine activities;
- important for weather forecasting;
- important for climate change detection.

Sea ice monitoring is an application of satellite data where:

- some data (AVHRR and SSM/I data) have been used operationally for many years, whereas many newer types of satellite data are not well utilised, such as SAR, scatterometer, SLR, and others;
- introduction of spaceborne SAR data represents a major improvement in the quality and accuracy of ice observations;
- synergy with other data (aircraft, in situ observations, etc.) is essential;
- only satellites can provide useful data in many regions, because other methods are unfeasible or very expensive;
- the market for data and services is expected to grow as a result of increased activities in regions with sea ice;
- considerable improvements of products and services are needed to satisfy user requirements.

What are the main results of IMSI?

- The user requirement study has identified clear needs for new satellite data ice products, because traditional products are not good enough for many users. The most important new products developed in IMSI are:
- IFREMER has developed global ice cover and ice type maps from scatterometer data (ERS AMI and ADEOS NSCAT).
- FIMR and HUT have improved the ice classification and ice charting in the Baltic Sea using SAR, airborne scatterometer and passive microwave data. An IMSI field experiment and data dissemination campaign was carried out in the northern Baltic Sea in March 1997. During IMSI AVHRR and SAR data, SAR classifications and digital ice charts have been distributed operationally to Finnish icebreakers and ships. IMSI has contributed to establish operational use of RADARSAT SAR data in the Baltic Sea from 1998.
- DMI has tested and evaluated RADARSAT ScanSAR data for use in monitoring of sea ice and demonstrations and validations including underflights have been carried out during 1997 and 1998. From 1999, DMI has started to use RADARSAT data in operational ice monitoring in Greenland, replacing the traditional aircraft surveillance with EO data.
- DCRS / DTU has improved the resolution of the SSM/I ice concentration maps by including the 85 GHz channel. DCRS is also developing an efficient data and ice chart dissemination system for SSM/I data products on Internet.
- NERSC in co-operation with Russian icebreakers, has demonstrated use of RADARSAT ScanSAR images for ice charting and ice navigation in the Northern Sea Route. Also other satellite data such as ERS SAR, SSM/I, Okean SLR data are used to improve the ice charting in the area. Data dissemination and product demonstration have been performed for more than a dozen of users in the Northern Sea Route.

Who are the customers who will use the results of this project?

- national weather forecasting and ice monitoring centres use satellite data as input data and will include more satellite data as new products become available;
- national sea transport authorities need state-of-the-art ice information from satellites in transport management and regulations;
- shipping companies and merchant vessels in Arctic areas are interested to use satellite data in planning of transport voyages;
- icebreakers and icebreaker companies are the major users of ice data in operational ice navigation;
- oil and gas companies operating in Arctic areas need detailed and accurate ice information in their offshore operations;
- fishing vessels working in ice edge regions need accurate ice maps to avoid dangerous situations;
- scientists in many polar research disciplines need satellite ice data as part of their environmental data sets.

Benefits for End-Users

The benefits for end users such as ships, icebreakers, offshore operations and other practical users working at sea are two-fold:

- improved ice information by use of satellite data can reduce the operating costs, especially by saving time, for example for a vessel which sails through an ice-covered area;
- improved safety by operating in ice, reducing the risk for accidents and damage.

The benefit for other users such as transport companies, sea traffic management and ice/climate scientists is access to data and information, which would not have been possible to obtain from other sources. For example, global monitoring of changes in sea ice extent over the last two decades can only be done by use satellite data such as passive microwave data.

National sea transport authorities, environmental authorities, industries and other institutions can benefit from satellite data to provide statistical ice information for planning or regulation of activities in ice-covered seas. Weather and ice forecasting centres also need satellite data to provide sea ice information products as input to forecasting models.

1 Introduction

1.1 Overall objective

The overall objective of the IMSI project is to explore and test methods for use of new satellite earth observation data in sea ice monitoring and improve utilisation of these observations in a wider user community.

1.2 Specific objectives

There are four specific objectives of IMSI which define the main tasks of the study:
1. To identify gaps between current satellite ice information products and user requirements
2. To improve the satellite data products using SAR, scatterometer and other microwave data, and synergy between several types of satellite data
3. To demonstrate the new satellite products to selected user groups
4. To assess and recommend satellite products for future operational use

1.3 How the project contributed to the objectives of CEO

IMSI has contributed to
- better utilisation of existing satellite data in a practical application such as sea ice monitoring
- improved and developed satellite data products for use in operational services
- strengthen the co-operation between European sea ice research and operational institutes, including Russian institutions
- establish better links between users and providers of sea ice data
- help the project participants to strengthen their role in a market which is expected to grow in the next decade

IMSI has also helped the customers by
- directly supporting the establishment of operational use of SAR data in ice monitoring
- demonstrating ice information products potentially important for new customers
- improving the quality of existing ice information products used by experienced customers
- facilitating access to satellite data and data products

1.4 Thematic background

Sea ice observations by polar orbiting satellites using optical/infrared and passive microwave data is an established method which has been used for many years. But both of these satellite systems have severe limitations which is the main reason why many users do not yet benefit from satellite data in ice monitoring.

With spaceborne SAR data, which combines high spatial resolution with independence of cloud cover and light conditions, it is possible to observe sea ice with much better accuracy. ERS-1 represents the first milestone in satellite SAR remote sensing of sea ice, while the RADARSAT and ENVISAT systems with wide swath, multi-mode, dual polarisation represent improvements in the technology. In addition, other microwave systems such as scatterometer and side-looking radar (SLR) data have shown promising results in sea ice observations on large and regional scale.

In order for SAR and other microwave data from satellites to become central elements in ice observation, products useful for a wide range of users, interpretation techniques and algorithms must be improved and streamlined. The data products must be developed based on requirements from established users.

Sea ice monitoring takes place on three different scales - each of which have characteristic users and role for satellite data, as shown in Table 1.1.

Table 1.1 ***Summary of sea ice monitoring scales, user groups and role of satellite data.***

Scale	**Geographical regions**	**Applications - user groups**	**Role of satellite data**
Global	Northern and Southern Hemisphere	Climate monitoring Weather forecasting Ocean - atmospheric research	Satellite data is the most important source of information (SSM/I and AVHRR are established data, Scatterometer data are new)
Regional	Baltic Sea, Barents Sea, Kara Sea, Greenland Coast, etc.	Ship traffic planning Offshore planning Weather/ice forecasting Strategic navigation Safety at sea Ice research	Satellite data essential (AVHRR and SAR) Wide swath SAR data will become the most important data source. Aircraft, ship data and coastal observations are also necessary
Local	Straits, Sailing routes, Entrance to harbours, Near offshore operations	Tactical navigation Ship traffic control Support to offshore operations Input data to construction, ship-building, etc.	Ship, aircraft, helicopters and coast stations data are the most important sources of data. Satellite data will play a more important role as SAR data become operational

1.5 Involvement of customers in the study

The following customers have been selected to be involved in IMSI to represent key user-groups of satellite ice information:

- National ice services in Finland and Denmark with responsibility for operational ice monitoring are active partners in the project
- Murmansk Shipping Company is a key user of ice information in the Russian Arctic, because they operate the Russian icebreaker fleet in the western part of Northern Sea Route
- Other users who have received and evaluated new ice products are:
  - National ice services in Norway, Sweden, Germany, and Iceland
  - Icebreakers and icebreaker companies in Finland and Russia
  - Arctic oil and gas companies (Statoil, Nunaoil, Fortum Oil, Gazprom, Lukoil)
  - Fishing vessels
  - Shipping companies and merchant vessels in the Baltic Sea and Greenland
  - Ice Central in Greenland
  - Sea transport authorities: Finnish Maritime Administration
  - Scientist at Arctic research institutes

The role of ice information from satellites is primarily to produce ice maps with better regularity, quality and higher spatial resolution than what is possible without satellite data. Timely ice information is essential in planning and implementation of marine operations in ice-covered seas. The ice information products, which need to be adapted to different user requirements, will contribute to safer and more cost-effective marine operations. Also, ice information on large scale is important in climate studies and strategic planning, because changes in sea ice extent and concentration, which are expected as a result of the global warming predicted for the next century, can only be observed by satellite data which are systematically collected over several decades.

2 Results of user requirement investigation (Task 1)

The main objective of this user requirement investigation is to identify the main gaps between the current capability of satellites to provide sea ice information and the requirements from a selection of key users in Europe. To identify what should be done to improve the quality of ice monitoring, a user workshop was arranged in the beginning of the study with about 20 participants from 5 countries. The discussion of user requirements was focused on four selected regions: the Baltic Sea, Greenland waters, the Northern Sea Route, and Antarctica. The first priority was to identify what is needed for users involved in sea transportation (icebreakers, convoys, cargo ships, transportation planning) and in offshore exploration (seismic surveys, installation of oil terminals and platforms, transportation of oil/gas). Other user requirements, related to global ice monitoring, weather forecast, climate change studies, ice research, statistical information from historical data and ice forecasting were discussed but not as first priority.

2.1 The Baltic Sea

The Baltic Sea has a seasonal ice cover lasting between weeks to half a year. The maximum extent of ice cover varies: as a minimum the ice covers the Gulfs of Bothnia and Finland, as an average north of 59° N and as a maximum the total area of Baltic Sea. This means that sea ice makes navigation difficult at least in Finland, Sweden, Russia, and Estonia. During average and severe ice seasons sea traffic difficulties occur in all Baltic Sea countries, in Norway and the Netherlands. The sea transportation represents normally 70-90% of the total transportation, which of some 40% occur during winter. These conditions are forcing the Baltic Sea countries to keep icebreaker fleets and merchant vessels suitable to ice-navigation.

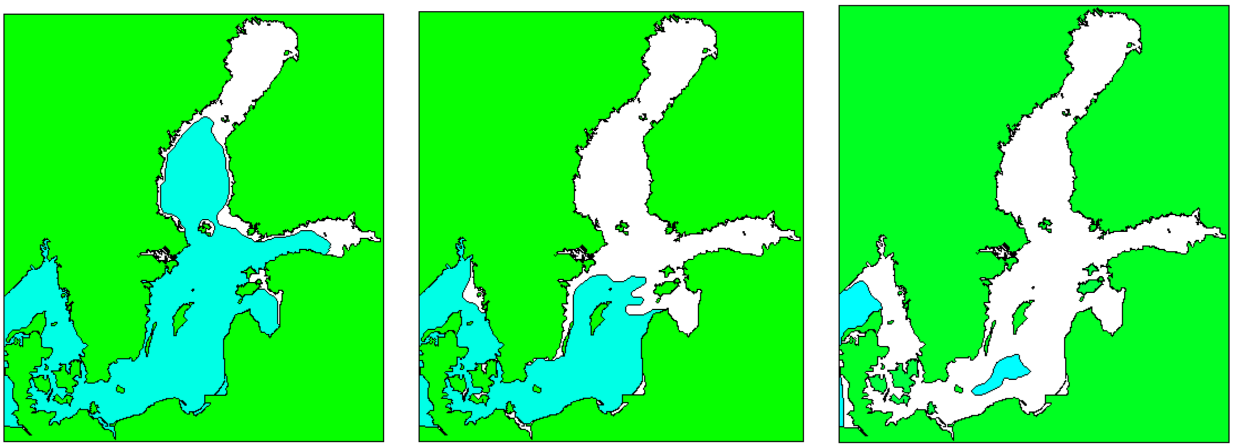


Figure 2.1 ***Classification of ice seasons in the Baltic Sea. Examples of extremely mild (1994/95 with 68 000 km²), average (1993/94 with 206 000 km²) and extremely severe (1986/87 with 405 000 km²) ice seasons. © Finnish Institute of Marine Research. Finnish Ice Service 1996.***

User categories

The sea ice information users in the Baltic Sea area could be divided into three major categories:
User category 1: Ice navigation;
User category 2: Planning and administration of ship traffic;
User category 3: Export and import companies and producers and manufacturers.

Table 2.1 ***Summary of user requirements for the Baltic Sea area.***

	User category 1: Ice navigation	**User category 2: Planning and administration of ship traffic**	**User category 3: Export and import companies and producers and manufacturers**
Users	Vessels	Vessels, NMA, coast guard, navy	NMA, Companies
Coverage	Local	Regional	Regional
Spatial resolution	100-1000m	1-10 km	> 10 km
Time delay	< 2 h	2-24 h	> 24 h
Type of data	In situ/forecasts	In situ/forecasts/statistical	Forecasts/statistical
Ice products	Charts, satellite images, forecasts	Charts, satellite images, forecasts, statistical analysis	Charts, forecasts, statistical analysis
Delivery	Fax, net	Fax, net	Fax, telephone
Satellite data	AVHRR, SAR	AVHRR, SAR / no need	No need
Ice drift	Forecasts +5 d Hindcasts -12 h	Forecasts +5 d - +14 d	Forecasts +5 d - +14 d

Ice navigation: users working at sea who need sea ice information for optimal ice navigation. The typical users of this kind of information are merchant vessels, icebreakers, pilots, coast guard and military. These users need sea ice information which is:

- up-to-date (based on information which is some hours old);
- accurate enough in order to be used in ice navigation (resolution of 50-1000 m);
- contains information on ice conditions which is relevant for ice navigation (information of how to find an optimal route from the ice-edge to the harbour or vice versa);
- sea ice information must be delivered to the user in short time (by fax or in digital form).

The time-scale of needed information is typically the present ice conditions and forecast for next two days. Providers of sea ice information such as the national ice services are also part of this category.

Planning and administration of ship traffic: important user-groups on land are national and international institutions responsible for administration of ship traffic. National users are National Maritime Administrations, normally responsible for winter navigation and icebreaker activities, coast guard and navy. These users need more general information for strategic planning, thus they need information up-to-date of ice conditions and forecasts of how ice conditions will change. The time-scale of needed information is typically the present ice conditions and forecast for next week or two.

Export and import companies, including manufacturers: users consist of national and international companies, which need to transport products by sea. National users are shipping companies, export and import companies, harbour authorities, and factories. International users are shipping companies, export and import companies, service institutes, research institutes and various ice related organisations and companies. They need information on ice conditions for planning their shipments - what kind of vessels could be used and information for planning their shipment time-tables. The time-scale of these kinds of users is typically several weeks.

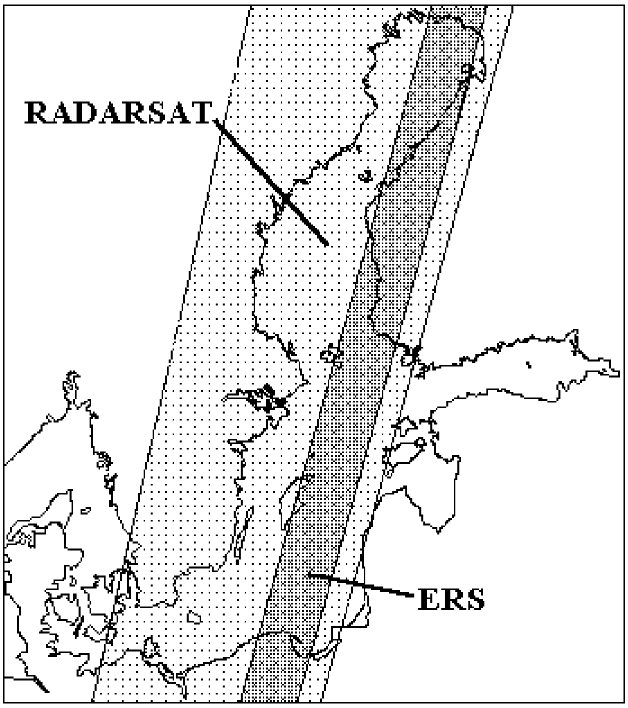


Figure 2.2 ***An example of RADARSAT in WideScan mode (500 km) and ERS (100 km) SAR coverage in the Baltic Sea. One ScanSAR mode swath can cover most of the Baltic Sea every 2-3 days.***

Table 2.2 ***Key factors in ice monitoring using satellite data in the Baltic Sea.***

Factor	**Requirement**
Good coverage	Total Baltic Sea should be monitored daily in the ice season
Fresh	Data should be less than 2 hours old when delivered to users
Suitable format	Data should be in format that is ready to use in applications Image interpretation and classification must be readily available
Longevity	Uniform data sets from satellites should be obtainable on permanent basis
Sensors	Data should be cloud and darkness independent Spatial resolution good enough for ice navigation (i.e. at least 100 m)
Economy	Data costs should be related to quality of data and the benefits obtained from the data

Table 2.3 ***Summary of gaps between user requirements and satellite capability.***

Sensor	**User category 1: Ice navigation**	**User category 2: Planning and administration of ship traffic**	**User category 3: Export and import companies, and producers and manufacturers**	**Notes**
SSM/I	Too poor spatial resolution	Too poor spatial resolution	Poor spatial resolution	Not in use in the Baltic Sea
Visible /IR (NOAA, Meteor)	Useful, giving general view if cloud-free	Useful giving general view if cloud-free	Satisfy requirements if cloud-free	Limited by clouds and vis., poor resolution
ERS SAR	Very useful if the area of interest is covered and data are transmitted to vessels in real-time	Improving mapping in selected areas	Improving mapping in selected areas	Cloud independent, good resolution, too narrow swath
RADARSAT SAR	Very useful if the area of interest is covered and data are transmitted to vessels in real-time	Improving mapping	Improving mapping	Cloud independent, good resolution, expensive, large file size

2.2 The Greenland waters

The coastal waters of Greenland are severely influenced by drifting sea ice and icebergs throughout the year. Especially the ship traffic to and from Greenland is restricted by the ice. The wreckage of the passenger ship ‘Hans Hedtoft’ in 1959 led to the establishment of the Ice Central Narsarsuaq (IC), an airborne ice patrol service, located at Narsarsuaq Airport and administered by DMI. The service is responsible for the operational ice mapping in the Greenland waters for the safety of shipping. Throughout the year three ship navigators, on loan from Greenland Trade Company (KNI), are stationed at the IC as ice observers. The observers all have several years of navigational experience in Greenland. For ice reconnaissance, the IC has at their disposal an aircraft equipped with a 360° radar as well as a helicopter.

The primary ice reconnaissance area is the coastal waters of Southern Greenland and in particular Cape Farewell, which has to be passed by nearly all ships to and from Greenland.

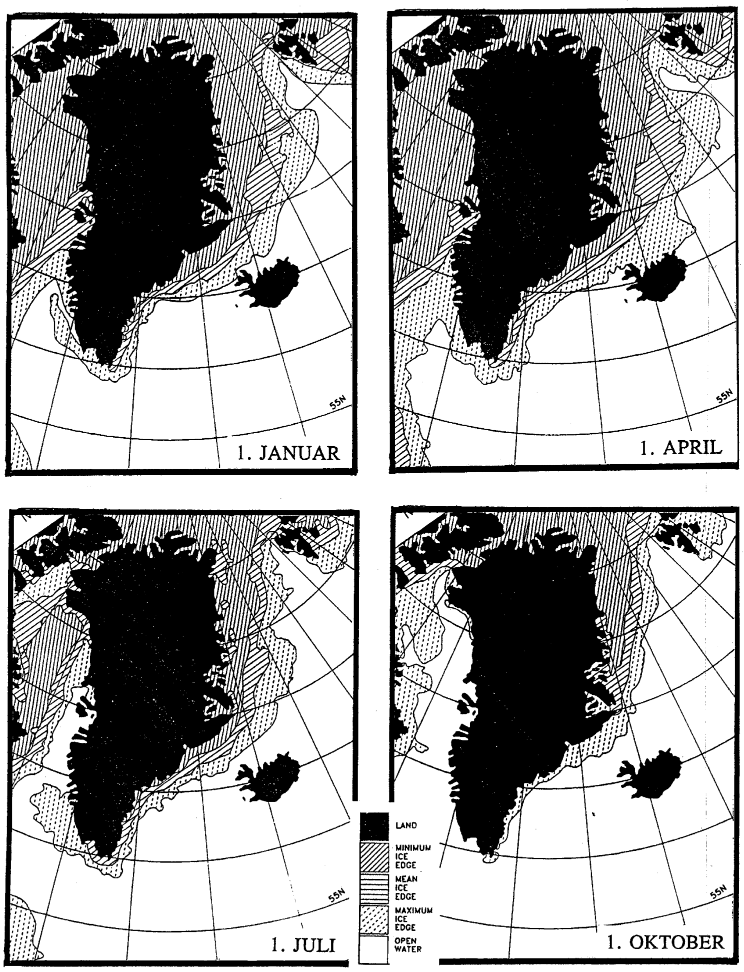


Figure 2.3 ***Ice coverage around Greenland at the beginning of January, April, July and October. Ice distribution with a concentration of 4/10 or more (Naturens Verden 1993).***

Since 1889, the Danish Meteorological Institute (DMI) has been collecting information on sea ice in Greenland. From 1923, a telegraphic information system giving information from coastal stations and ships was initiated, systematic air reconnaissance started in 1959, and satellite based mapping was initiated on an experimental basis in 1966, becoming operational from 1991.

The user groups

Traditionally, the main user groups of ice maps in Greenland have been merchant ships. Recently, also multinational scientific projects and hydrocarbon/mineral exploration companies have become important users of ice information. If offshore oil and gas production starts on the Greenland shelf, oil companies will require specific ice information of higher quality than what is offered today. Additionally, weather services and scientific users benefit tremendously from ice products that are different from the ones demanded by navigation etc., but may yet be useful in the planning phases.

Ship traffic: this group includes merchant ships, fishing vessels and in later years cruise ships, some of them large, carrying up to 1200 passengers each. In numbers, this group of users has traditionally been one of the main users for ice mapping. The users require ice information mainly in order to avoid ice infested areas and in some cases to navigate safely through the ice. It is important to realise that the conditions are different from e.g. the situation in the Baltic. First, the ice typically consists of highly dynamic and hazardous thick floes and growlers, that yield ice breaking is useless since the ice tends to close immediately behind the icebreaker. Secondly, the ship traffic in Greenland most often has the opportunity of choosing an ice free route. Therefore, the ships attempt to avoid navigating ice infested waters. As mentioned, geographically the traffic is concentrated in the southern parts around Cape Farewell and the ice free harbours (approx. 500 passings per year). Since no inter-urban roads exist in Greenland, all traffic has to go by air or sea and consequently the local freight traffic carried out by ships is large compared to the number of inhabitants. Often this traffic takes place along the inshore route from Pamiut to Cape Farewell and requires detailed ice information and guidance, presently supplied by the IC helicopter. In addition, fishing vessels (mainly 20 Royal Greenland Trawlers), primarily in the area from Cape Farewell northward to the Denmark Strait on the east and Baffin Bay on the west, use ice information and occasionally seek shelter inshore. Besides for safety purposes, fishing vessels often use ice information to get as close to the ice edge as possible, since abundant fish stocks are found there. During summer (approx. June-November), merchant ships call harbours as far north as Danmarkshavn on the east coast and Qaanaaq (Thule) on the west coast. During such voyages, ice information is crucial and, especially along the east coast, the ships most often carry their own helicopter. Some important users in this category are Royal Arctic Line and KNI.

Exploration and expedition logistics: for the use of the present work, this group differs from ordinary ship traffic as they operate in areas that are normally outside the ordinary sailing routes. In addition they may manoeuvre in ways that differ from ordinary transport navigation.

Currently, in Greenland waters this group almost exclusively consists of seismic sounding campaigns. Seismic soundings are performed by research vessels towing a line several kilometres long with expensive recording instruments that may be damaged by sea ice. The ships course is only allowed to vary very little (less than 10°) during the operation. Recently, the northern sea areas off East and West Greenland have been extensively explored in the years from 1990 till 1995. This work is ongoing and is foreseen to require extensive specialised ice information in the future. A growing field is the transport required by landbased expeditions, e.g. scientific field experiments or mineral exploration. There are currently approximately 50 licences related to mineral exploration. Since the activities in this category are often restricted to very specific areas, they rely heavily on specialised ice mapping both for the assessment of the feasibility of sailing along a given transect, but also for navigation. In the pre-operational phase statistical information is of great value. The group involves oil and mineral companies, government and scientific institutions.

Table 2.4 ***Summary of user requirements for satellite data.***

	Ship traffic	**Exploration, etc.**	**Offshore activities**	**Weather serv., etc.**
Coverage	Local - regional	Local - regional	Very local	Global
Spatial resolution	100 m - 1 km	100 m - 1 km	<100 m	10 km
Time delay	2-3 hours	2-3 hours	None	< 24 hours
Requirement for archived data	Not important	Important	Important	Varies with the application
Requirement for real time data	Important	Important	Important	Important
Satellite data	SAR, AVHRR	SAR, AVHRR, passive microwave	Not optimal	Passive microwave, scatterometer, AVHRR

Table 2.5 ***Summary of gaps between user requirements and satellite capacity in the Greenland waters.***

	Ship traffic	**Exploration**	**Offshore activities**	**Weather serv., etc.**
Flight Reconnaissance	High resolution and flexibility, but low area coverage and very high cost.	As for Ship Traffic, but often the only source of information that meets the requirements for flexibility and resolution.	Often the only source of information that meets the requirements for flexibility and resolution.	Too low area coverage.
AVHRR	Mostly sufficient, but very vulnerable to clouds.	Mostly sufficient but very vulnerable to clouds.	Good for climatic information.	Very vulnerable to clouds, no commonly accepted ice algorithms.
Passive Microwave	Mostly insufficient, but cloud independent. Unreliable in the melt season.	Unreliable in the melt season. Although basically insufficient, it may be the only source of information in some areas.	Low resolution, may be used for climatic information.	Very useful, but problematic in the melt season.
ERS	Too low coverage for Greenland waters and very hard to interpret. Very vulnerable to wind.	Too low coverage for Greenland waters and very hard to interpret. Very vulnerable to wind.	May be useful, but hard to interpret.	Useful for verification, but hard to interpret, no commonly accepted ice algorithms.
RADARSAT	Very useful, but expensive. Vulnerable to wind. Must prove its worth in melt season.	Very useful, but expensive. Vulnerable to wind. Must prove its worth in melt season.	Probably useful, but expensive.	Useful for verification, no commonly accepted ice algorithms.

Offshore operations: Greenland is rich in natural resources and although experimental drilling campaigns off central West Greenland have been disappointing. However, the Fylla area off the west coast of Greenland has shown encouraging potential for hydrocarbon exploitation. There is presently no offshore operations in progress, but the group of users form a strong potential demand for ice mapping. Drilling platforms and other offshore structures in operation require high resolution ice mapping in a limited area to avoid disasters with possible ecological and human implications. In the pre-operational phase long term statistical information is of the greatest value. These activities are often following exploration efforts and the potential users therefore involve the same economic interests as the preceding group of users.

Weather services and geophysical research: operational sea ice mapping in fixed grids is of great interest to many geophysical disciplines e.g. as input to numerical models. The fluxes between ocean and atmosphere are greatly influenced by even the thinnest layer of sea ice and reliable ice observations will increase the quality of today's weather models. Although for the European weather forecasts as a whole, the improvement is only estimated as second order, it provides improved means of correcting the atmospheric influence in remotely sensed information of the sea at high latitudes as well as significantly improved forecasts in the North Atlantic region. The Greenland Sea is of great interest in climatic studies, as well as in general oceanographic and ice science applications. Users include weather services and various research institutions involved in geophysical sciences.

2.3 The Northern Sea Route

The Northern Sea Route (NSR) is the main sea transport line in the Russian Arctic. The NSR includes those sailing routes suitable for ice navigation between the Barents Sea and the Bering Strait. Its administration is performed by the NSR Administration (NSRA) of the Russian Federation Ministry of Transport. The NSRA executes its functions both directly and through navigation services of the Murmansk and Far-East Shipping Companies, representing the Marine Operations Headquarters (MOH) of the Western and Eastern regions of the Arctic, respectively. The MOH directly carries out all sea ice operations along the NSR. To ensure safe and efficient navigation, the ships need accurate and timely hydrometeorological information. Special demands on information about distribution, conditions and dynamics of the ice cover and on sea ice forecasts must be taken into consideration. All forms of this ice information are combined under a general name: navigational ice information.

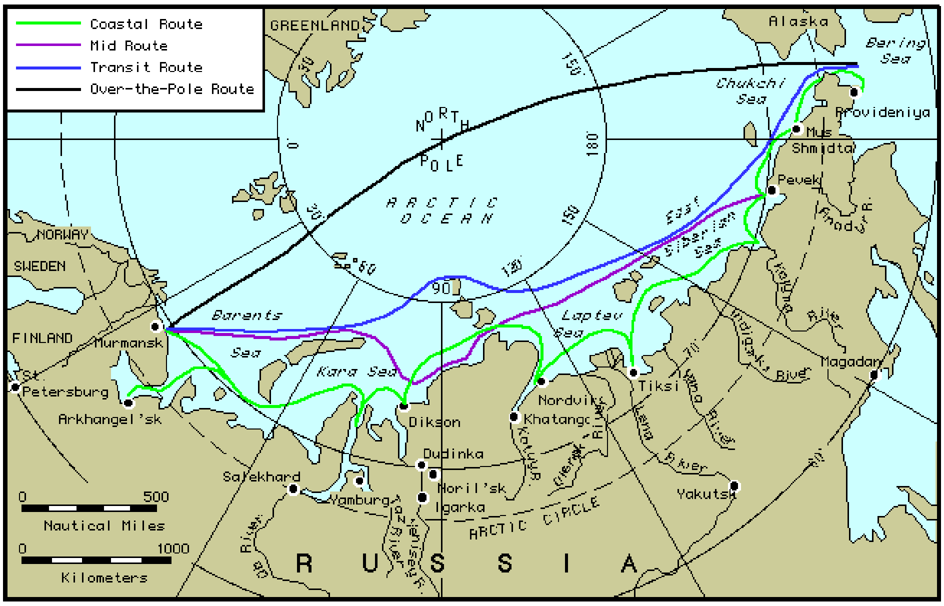


Figure 2.4 ***Map of the Northern Sea Route with the main sailing routes.***

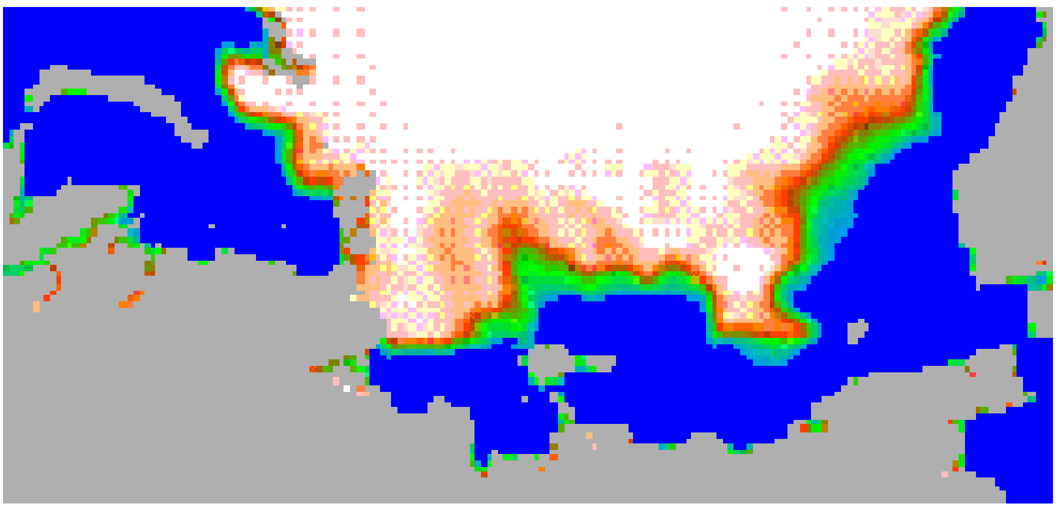


Figure 2.5 ***Northern Sea Route ice concentration map from SSM/I data can be used in strategic ice mapping. This map shows the average ice concentration for September. The colour index is: dark blue: open water; light blue to green: 20 - 50 %; red to orange: 50 - 90%; light orange to white: 90 - 100%.***

The system of hydrometeorological navigation support was formed in USSR at the end of 1932 after establishment of the NSRA. A Polar Aviation group was established for navigational air reconnaissance and the net of existing polar stations was widened. In 1938 a considerable part of the Arctic seas was covered with visual air reconnaissance. The western part of the Northern Sea Route is used for year round ice navigation because of the transport of nickel from Dudinka to Murmansk. The whole NSR, from Murmansk to the Bering Strait, is used mainly in the summer navigation season from July to November.

Several major technological improvements of the ice observation capability occurred in the 1960s when airborne and satellite remote sensing were developed. In 1968 the Side-Looking Airborne Radar (SLAR) ‘Toros’ was made especially for ice surveys. The wide swath-width (approximately 60 km), independence on light and weather conditions and possibility to compose ice charts onboard the aircraft made it possible to use SLAR regularly for ice reconnaissance and for ice research. Use of a special communication link for transmission of radar imagery to icebreakers was very useful for supporting tactical navigation.

Images from meteorological satellites have been used for ice charting since 1967, when the experimental system Meteor became operative. In 1967 - 1969 a net of autonomous centres for receiving satellite information was established in the Arctic and Antarctic Research Institute in St. Petersburg and in all regional Arctic centres. Since then information from meteorological satellites has been used in composition of ice maps for navigation support in the Arctic.

Since the 1980s data from the Meteor, Okean and NOAA satellites are used in ice chart composition. The first satellite of the Okean series was launched in USSR in September 1983. From 1983 the Okean satellites provided regular sea ice information in the Arctic and Antarctic which are widely used for ice chart composition.

High-resolution information from Synthetic Aperture Radar (SAR) had not been used in ice chart composition until the 1990s. Spaceborne SAR instruments, operating at a wavelength of 9.6 cm with 20 m resolution, were installed onboard the Russian satellites Kosmos-1870 and Almaz. Their images were used primarily in ice research and not in regular ice monitoring. SAR data were used in emergency situations, for example, to map sea ice conditions in the area where the research vessel ‘M. Somov’ was beset in ice in the Antarctic.

In July 1991, the ERS-1 satellite capable of providing high-resolution SAR images was launched, and in August the first SAR derived sea ice maps were sent by telefax to the French polar vessel ‘L’Astrolabe’ during her voyage through the Northeast Passage from Norway to Japan. Since autumn 1993, several such demonstration campaigns have been carried out by the Nansen Centres in Bergen and St. Petersburg in co-operation with Murmansk Shipping Company. These campaigns showed the importance of high-resolution SAR images for navigation support in the NSR. As a result of these successful demonstrations, a joint project between the European Space Agency and the Russian Space Agency started in 1995. The purpose of this project is to establish a satellite radar monitoring system for the western Arctic ice cover using Okean SLR and ERS-1 SAR images.

Users of sea ice information

There are several ways to classify users of sea ice information in the Northern Sea Route. One approach is to divide them into practical and scientific users. The practical users can again be divided into a group which primarily needs statistical information for planning purposes, and another group which need first of all near real time information for operations in ice. A second method is to divide the users according to type of organisation. Following the second approach, the three most important user categories are listed below.

Table 2.6 ***Users of sea ice information in the Northern Sea Route.***

User category	User characterisation	Example of users
Russian national institutions	Experienced users in ice monitoring including intercontinental waters and permafrost.	HydroMet Service (AARI, NPO Planeta) Russian Academy of Science (Water Problem Institute, RAS); Ministry of Geology (VNIIKAM, Arkhangelsk GEOLOGIYA)
Shipping companies working with ice navigation	Some are experienced users in ice and some are new users.	Murmansk Shipping Co. Far Eastern Shipping Co. White Sea/Onega Shipping Co.
Engineering companies	New users both in marine and terrestrial applications.	Norilsk Nikel Arctic Marine Engineering Geological Expedition
Oil, gas and offshore industry	Important potential users with capability to pay for high quality service (several commercial SAR ice projects have been implemented).	GAZPROM, PeterGAZ, AMOCO, Norsk Hydro, Heerema B.V., Shell International, Nordeco Inc.
Consulting and service companies	New users.	Eco-Systema Ltd Institute of Water Transport Engineers
Environmental research: water/ice, biosphere, climate	Several experienced users and many potential users.	PINRO, Murmansk Marine Biological Research Institute, Institute of Geography (Siberian Department RAS)

National institutions: their main responsibility is related to hydrometeorological services and administration of ship and icebreaker traffic in the Northern Sea Route. The HydroMet Service (AARI and NPO Planeta), Northern Sea Route Administration, and Marine Operation Headquarter of Murmansk Shipping Company are the main users. These users need mainly statistical information based on historical data, forecasts for planning purposes, and to a lesser degree real-time information.

Shipping companies: ship navigation in ice with different kind of vessels is the primary task of these users. Icebreaker captains and captains of other ships working in the Northern Sea Route as well as the Marine Operation Headquarters are the key users in this category. These users need first of all real-time information which needs to be updated frequently, typically every 2 - 3 days for operational navigation and several times per day for tactical navigation.

Oil, gas and offshore industry: the primary task is to plan and construct offshore pipelines and terminals for transport of oil and gas out of the production areas. Oil companies, construction companies and transport companies are involved in the planning and building of such constructions. These users need first of all historical information for statistical estimates of extreme ice events to assess construction criteria and security factors. They need specific ice information, for example for penetrating ice keels into the seabed for deployment of pipelines in the seabed. Such information is not so important for many other users.There are also other user-categories, such as research institutes, engineering companies, consulting companies, environmental organisations and authorities, and industries such as mining, lumber and fisheries that need ice information. These users are not described separately, but specific requirements will be addressed.

The mapping of sea ice in the Northern Sea Route is defined at three different levels:

- strategic ice reconnaissance; (large scale)
- operative ice reconnaissance; (regional scale)
- tactical ice reconnaissance; (local scale)

which serve different objectives and tasks for the users. The difference between the three types of ice reconnaissance is summarised in Table 2.7 and 2.8.

Table 2.7 ***Summary of requirements to sea ice information for ice navigation in the Northern Sea Route.***

	Strategic	**Operative**	**Tactical**
Users	NSRA MOH	MOH, icebreaker captains	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	2 - 3 hours
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

Table 2.8 ***Use of satellite images for obtaining strategic, operative and tactical sea ice information.***

Sensor	**Strategic**	**Operative**	**Tactical**	**Notes**
SSM/I	Satisfy requirements	Poor spatial resolution	Can be used if there is no other possibility	Can be used only in the cold season
Visible / IR (NOAA, Meteor)	Satisfy requirements when available	Satisfy requirements when available	Can be useful when received onboard ship	These images are used frequently because the data are easily accessible and free of charge for users with their own receiving equipment. The disadvantage is the limitation due to clouds.
Okean (SLR + RM0.8)	Satisfy requirements when available	Satisfy requirements when available	Can be useful when received onboard ship	Can be used independent of cloud and light conditions. Are most useful in the cold season.
ERS SAR	Can be used if large areas are covered regularly	Can be very useful if sufficient coverage is supplied	Satisfy requirements if transmitted to icebreaker in near real-time	Can be used to observe many important details of the ice cover independent of clouds and light conditions. The main limitation is the narrow swath of 100 km.
RADARSAT SAR	ScanSAR satisfies all requirements	ScanSAR satisfies all requirements	Satisfy most requirements if transmitted to icebreaker in near real-time	The most promising and expensive satellite data for ice observations. Cost-benefits need to be assessed.

2.4 Global sea ice monitoring

Sea ice monitoring on global scale is important for climate studies and detection of global climate change. Within global climate research there is a diverse user community ranging from scientist to engineers, consultants and policy makers who can utilise results from passive microwave satellite data (SSMR and SSM/I) to study changes in sea ice extent and concentration.

Several large scientific programs are currently using global sea ice data as important elements in their research. These user requirements are for the most part met by the continuously updated data availability on CD-ROM. Examples of such science programs are: Arctic Climate System Study (ACSYS), the Arctic and Antarctic Sea Ice Thickness Monitoring Programs (AITMP, AnITMP), the Global Ocean Observing System (GOOS) with its European component EuroGOOS, the International Programme for Antarctic Buoys (IPAB), and the European Subpolar Ocean Program (ESOP).

In addition to global monitoring, there is also a need to provide ice information to expeditions in Arctic and Antarctic regions. For this purpose NOAA AVHRR and CRS/RADARSAT satellite data are used in addition to SSM/I data.

2.5 Conclusion of requirement study

The user requirement study for new sea ice products shows that there is a clear demand for improved ice maps and a broader spectrum of products and services compared to what is currently available. The availability of new satellite data, especially SAR data which can be delivered in near real time, have increased the expectations for improved ice products in the user community.

The requirements for ice products can broadly be classified in two categories: 1) Strategic needs and 2) Tactical needs.

Strategic ice information is needed for planning of all marine activities in ice-covered waters and for environmental impact studies. The strategic ice information can to a large extent be based on historical data and statistical analysis of many years of ice observations. The strategic ice information contains mainly large scale and regional ice parameters such as ice extent, ice concentration, ice thickness, iceberg probability, etc. Real-time data and long term forecasting are also needed as part of the strategic ice information to plan sailing routes for cargo vessels and icebreaker convoys. In the Northern Sea Route the Russian users of ice data, primarily the icebreakers, distinguish between strategic and operative ice information. Strategic information covers the whole Russian part of the Arctic Ocean between the Barents Sea and the Bering Strait. It is sufficient with a spatial resolution of about 10 km and a repeat cycle of 10 days. Operative ice information is also used for planning of transports, but it covers regions such as the Kara Sea and it needs to be updated every 2 - 3 days to resolve the variability of the ice cover due to the passage of low pressure systems and subsequent changes in wind conditions. Satellite data, primarily NOAA AVHRR data, DMSP SSM/I data and several types of Russian satellite data already plays an important role to provide strategic ice information. The main requirement from the users is include other data such as scatterometer data and make better quality ice classification and ice concentration maps, and to facilitate the access to these products.

Tactical ice information is used by captains of icebreaker, ice strengthened vessels and other commanders of marine operations in an area of typical 100 km surrounding the vessel. The tactical information needs to be of high resolution, typical 50 m, and it must have the possibility to be updated every 2 - 3 hours in cases when the ice conditions changes rapidly. The requirement for real-time delivery is essential and there are often specific ice parameters, which are important such as location of leads, ridges and multiyear floes. The tactical ice information is usually obtained from aircraft and helicopters. Satellite data can become important as high-resolution SAR data are available and can be transferred to the vessels in near real time. But there are several problems to be solved before SAR data can be used regular in tactical ice mapping: the classification of navigationally important parameters such as ridges and ridged areas must become more reliable, the transmission of images products to users at sea must be facilitated, primarily in high-latitude areas, and the temporal coverage of SAR must be improved.

Recommendations for product development in IMSI:

- Ice maps based on SAR data with ice type classification, leads, polynyas and ridges in the Northern Sea Route (NERSC and Russian partners).
- Maps of ice deformation including ridges in the Baltic Sea (FIMR and HUT). In some regions, there is a need for high resolution images or maps, which shows leads, ridges and areas of deformed ice. SAR data from ERS and RADARSAT will provide the main source of information.
- Improved mapping of ice in Greenland waters using SAR and passive microwave data. The capability of RADARSAT images to locate multiyear floes and icebergs will be investigated (DMI and TDU).
- Global maps of ice extent and classification using satellite scatterometer data (IFREMER).

Table 2.9 ***Summary of gaps for global sea ice cover monitoring from satellites.***

Sensor	Strategic information	Tactical information	Comments
NOAA AVHRR	Vulnerable to clouds, consistent time series impossible to obtain in European ice-covered areas.	Vulnerable to clouds, but very useful under favourable conditions. Can be down-linked in real-time to ships.	Lack of commonly accepted ice algorithms. Most commonly used data, as they are available free of charge.
SSM/I	Independent of clouds/darkness. Continuous time series since 1978 (SMMR). Good for trend analyses of global ice cover changes.	Independent of clouds/darkness. Coarse resolution, vulnerable to land-effects. Useful for ice navigation when received on-board in near real-time.	Several well documented ice algorithms. Make 20 years time series when combined with SMMR data. Unreliable during the melt season.
ERS Scatterometer	Independent of clouds/darkness. Promising results for ice type detection.	Near real-time services are under development in Europe.	Short time series for climate studies (~7 years), but important complementary data to SSM/I for improved ice classification.
RADARSAT	ScanSAR mode provides information on ice coverage, ice types, and ice kinematics. Should be compared to SSM/I and ERS Scatterometer.	Provide excellent temporal and spatial coverage of regions of interest. Near real-time data delivery possible for all ice areas.	Expensive data for use in monitoring. Not realistic to use in global monitoring without governmental support.

3 Development of new ice products (Task 2)

Sea ice observations by polar orbiting satellites using optical/infrared and passive microwave data is an established method which has been used for many years. However, both of these satellite systems have severe limitations, which is the main reason why many users do not yet benefit from satellite data.

With spaceborne SAR data, which combines high spatial resolution with independence of cloud cover and light conditions, it is possible to observe sea ice with much better accuracy. ERS-1 represents the first milestone in satellite SAR remote sensing of sea ice, but there are and will be several improvements in the technology with RADARSAT and ENVISAT systems: wide swath, multi-mode, dual polarisation. Also other microwave systems such as scatterometer and side-looking radar (SLR) data have shown promising results in sea ice observations.

In the IMSI project, state-of-art methods in microwave ice observation techniques, including use of SAR, SLR, Scatterometer and passive microwave radiometer data will be applied to improve sea ice products.

In order for SAR and other microwave data from satellites to become central elements in ice observation, products useful for a wide range of users, interpretation techniques and algorithms must be improved and streamlined. The data products must be developed based on requirements from established users.

The main results of Task 2: Development of new satellite ice data products are shown below. The products are divided into three groups:

1: regional and local scale products for the Northern Sea Route, Greenland waters and Baltic Sea, using mainly SAR data
2: large-scale products: Global scatterometer maps, Arctic radar maps using Okean SLR data and MWR maps Greenland waters and other regions using SSM/I data
3: integrated products: Joint scatterometer products, SAR-MWR products, SAR-SLR products, etc.

The product development is guided by the user requirement investigation in Task 1 (IMSI report no. 1) and each of the six partners contributes to this work. FIMR, NERSC and DMI are emphasising regional and local ice products based on SAR data, especially RADARSAT data. IFREMER and DTU work with large-scale and global ice products using scatterometer and MWR data, respectively. HUT works with multi-sensor data (SAR and radiometer data) from aircraft and satellite SAR investigations in the Baltic Sea.

Most of the new product development has focused on interpretation and classification of RADARSAT images, performed with methods, which are assumed to most optimal for the three regions. In the Baltic Sea it is most important to classify ice roughness including ridges, in Greenland identification of ice edge and detection of icebergs is of first priority, while in the Northern Sea Route identification of ice types, leads, polynyas and ridge areas is equally important. In the Baltic Sea ScanSAR Narrow Mode (SN1 and SN2) with 300 km swath width is most suitable because it will cover most of the ice areas. In Greenland and Northern Sea Route, where the ice areas are much larger, it will be necessary to use ScanSAR Wide Mode with 500 km swath. In addition, it can be necessary to use Standard or Fine resolution modes in smaller areas where more detailed mapping is needed. In the Northern Sea Route some comparisons between Okean SLR data and ERS SAR have been done, suggesting that the two types of data complement each other and both have an important role in Arctic ice mapping.

The first evaluation of the RADARSAT ice products have been done during demonstration campaigns in all the three study regions. Field experiments with icebreakers and helicopters were performed in the Baltic Sea and Northern Sea Route, while aircraft surveys co-ordinated with the satellite overpass were used in Greenland. In the Baltic Sea airborne radiometer and scatterometer data have provided valuable information for interpretation of RADARSAT images. Validation has also been done by comparing RADARSAT data with AVHRR and SSM/I data. The quality of the RADARSAT products seems to be very good in all regions, with some exceptions during summer conditions. There is still a wealth of information in the SAR images, which remains to be investigated.

Large scale ice maps of the Arctic and Antarctic have been developed from scatterometer data from ERS and ADEOS NSCAT using C- and Ku-band, respectively. With NSCAT data, it is possible to increase the resolution of the scatterometer ice maps to 12.5 km. The first comparisons of scatterometer ice maps with RADARSAT and passive microwave data show general good agreement, but more studies are needed to determine the accuracy of the ice classes which can be derived from the scatterometer data.

3.1 Ice classes, concentration and motion from SAR in Northern Sea Route

The main effort of the Nansen Center's product development work is to test and validate ice maps from SAR data, both ERS and RADARSAT. Ice type classification using the Wackerman algorithm (Wackerman and Miller, 1996) has been tested on SAR images from the Barents Sea and the Kara Sea. A challenge for all ice classification methods is to include the differences in ice regimes between the marginal ice zone and the interior of the Arctic pack ice. In the Kara Sea region, which is dominated by first year ice, the main problem is to discriminate between different stages of new and young ice and to separate different degrees of ice deformation. The quality of the automated algorithm depends on how well the training data are selected and specified.

3.1.1 ERS-1 SAR classification in the Barents Sea

An example of automatic ice classification of one of the SIZEX92 SAR images using the Wackerman algorithm is shown in Fig. 3.1. Three scenes from the SAR swath of March 5 from the Barents Sea were selected because these scenes covered all the different ice types, which were investigated. Before the classification could be done, the knowledge of the characteristic ice types was used to pick a few training areas for each class. In this example we selected six classes: open water and five ice classes: multi-year ice, undeformed first-year ice, deformed first-year ice, pancake ice and grease ice. For technical description of the algorithm, we refer to (Wackerman and Miller, 1996). Here, we will just describe the results of the classification. The overall result looks reasonable, but there are some incorrect classifications. The most obvious error is the mixture of pancake ice and multi-year ice classification in the interior of the ice pack. In addition, some multi-year classification is found in the new ice area. Another suspicious result is the occurrence of open water inside the new ice area. It is more likely that this is pancake ice, but there were no *in situ* observations to confirm this. The occurrence of undeformed first-year ice in the new ice area is also incorrect, as was documented by ships in the area. In spite of the errors, it is promising that both the deformed first-year ice, the open water area and the grease ice are very well classified, considered that this example is very difficult to classify. In a further development of the classification technique, the probability of ice types, which can occur in each zone, could be included. Introduction of such knowledge would remove some of the errors evident in Fig. 3.1.

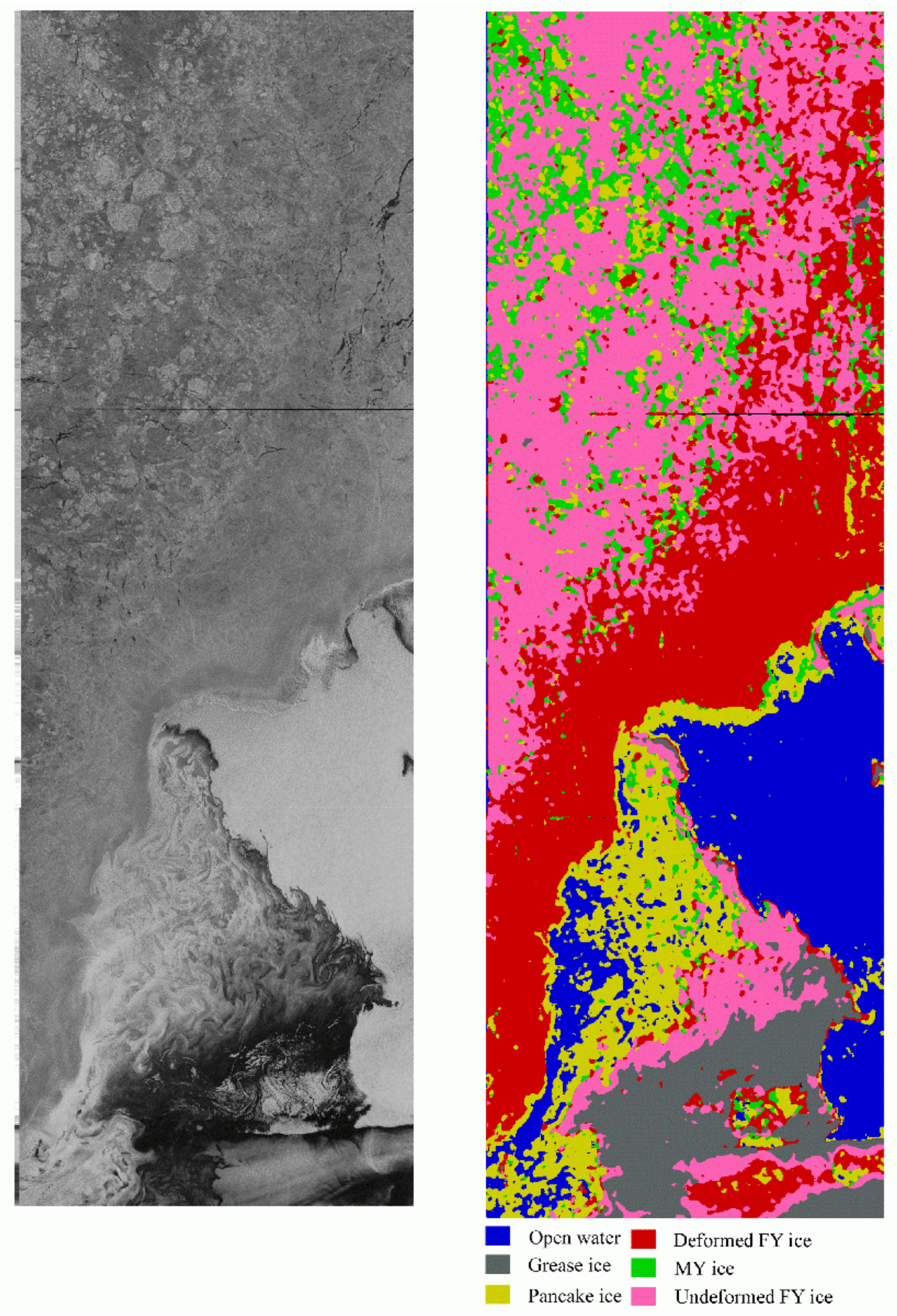


Figure 3.1 ***Classification of ERS-1 SAR images in the Barents Sea 5 March 1992. Image Data © ESA 1992.***

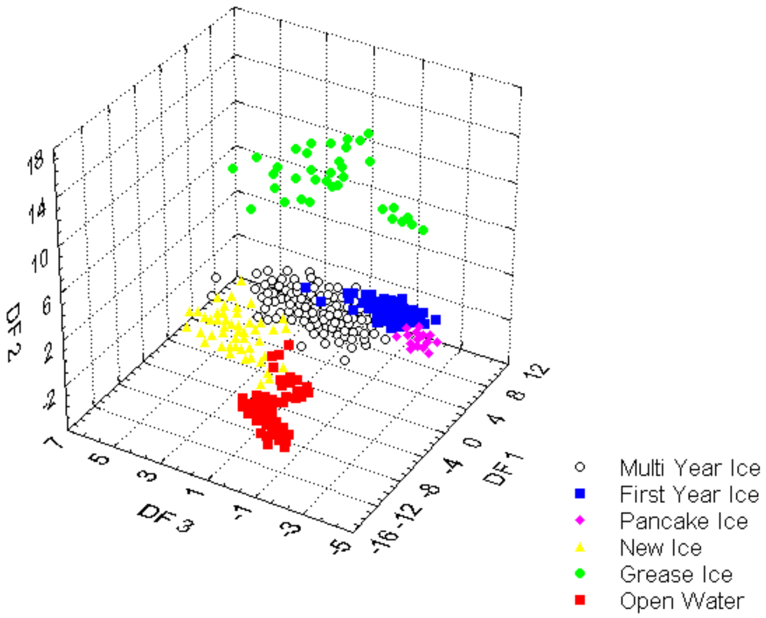


Figure 3.2 ***Scattering diagram in reduced dimensionality space computed for three ERS-1 SAR images acquired during SIZEX92 experiment.***

3.1.2 RADARSAT classification of winter ice in the Kara Sea

RADARSAT SAR images provided for this project were un-calibrated. A calibration procedure for RADARSAT SAR has therefore been described where the effects of different beams, incidence angles and other SAR parameters are taken into account. This procedure has been used for absolute calibration of the SAR images, where sigma-nought values can be estimated to an accuracy of ±2.3 dB, while ERS SAR images are routinely delivered with accuracy in sigma-nought of ± 1.5 dB. The calibration of the RADARSAT images has not been sufficient accurate to use in classification based on look-up tables. Therefore, techniques to classify un-calibrated images have been explored.

Visual comparison of low-resolution RADARSAT images received onboard the icebreaker and the original high-resolution images, showed that many sea ice features important for navigation were lost due to reduction of data files for transmission. One way to reduce the size of the data files, can be to manually or automatically classify the radar images, and then transmit them to the icebreakers. Manual classification by ice experts provides high quality sea ice maps, but it is time consuming. Automatic algorithms can be used for sea ice classification, if the results of classification meet the user requirements to quality and processing time. In our experiment we trained and assessed the performance of two automatic sea ice classification algorithms, based on Linear Discriminant Analysis (LDA) and backpropagation neural network (BNN) algorithms.

Case studies

Two RADARSAT Scan SAR images acquired 25 April and 8 May 1998 were selected for training of the sea ice classification algorithms. Dominant types of drifting sea ice were grouped into 6 classes for training. These classes include first year level ice, deformed and very deformed first year ice, and young ice. Due to high variability of the backscatter coefficients for open water and new ice types, we separated this class into two ones with high (OW&new ice) and low (OW&nilas) brightness in the SAR images. Multi-year ice was not found in any of 6

RADARSAT SAR, images and was not investigated here. There was lack of training regions for the OW&nilas class, and some regions were reserved for validation. Only four squares with the size of 30 by 30 pixels were selected from the coastal polynya to the North of Cape Zhelanya for training of this class. The LDA algorithm was also trained for level fast ice, deformed fast ice and river ice, separate of the training for drifting ice. The boundary between the drifting and fast ice was determined manually using bathymetry data, *in situ* data and successive SAR images. This manually drawn boundary was used in the classification procedure to separate drifting ice and fast ice. Such simplification prevented errors caused by misclassification of level fast ice as open water, because these classes have smooth surfaces and near the same brightness values in the SAR images. Homogeneous regions corresponding to the above mentioned sea ice types, were used for training, to avoid mixtures of different sea ice types. For classification, we used the whole images. This allowed us to assess the performance of the algorithms on mixtures of different sea ice types, which were not used for training.

The methods of sea ice classification

Both the LDA and BNN algorithm needs local statistical and texture parameters from the radar images as input features. Textural features in addition to the mean value of the backscatter coefficients can improve the accuracy of the classification (*Shokr*, 1991, *Barber et al.*, 1993). Standard texture parameters based on the Gray Level Co-occurrence Matrix (GLCM) were used in our case studies (*Haralick et al. 1973*). The set of texture parameters includes contrast, cluster shade, cluster prominence, inverse difference moment, homogeneity and entropy. Local statistical parameters were found useful for automatic classification and were found to be better than texture parameters in separation of sea ice types (*Wackerman and Miller, 1996, Nystuen and Garcia,* 1992*).* Therefore we used the mean value of the brightness values, second, third and fourth statistical moments together with texture parameters. All features were computed with a window size of 9 by 9 pixels, which was chosen to be large enough to describe texture and to provide necessary inputs to GLCM. The window size was supposed to be small enough to decrease the influence of mixtures of different sea ice types.

The first algorithm uses a conventional statistical classification approach, based on Linear Discriminant Analysis (LDA algorithm). It is assumed that the probability distribution for each class is multivariate normal. Classification functions are linear combinations of features of the form $\boldsymbol{\lambda}^{\mathbf{T}}\mathbf{x}$, where $\mathbf{x}$ denotes a data vector whose elements are texture and local statistical features, and $\boldsymbol{\lambda}$ is a vector of adjustable parameters. Decision boundaries are planes in feature space. The pixel in center of the local window is classified as class c if vector $\mathbf{x}$ falls into the region of feature space corresponding to class c. The class boundaries are determined during the training procedure on condition of maximum separability of the sea ice classes. The Fisher criterion of separation is $\gamma = \frac{\boldsymbol{\lambda}^{\mathrm{T}}\mathbf{B}\boldsymbol{\lambda}}{\boldsymbol{\lambda}^{\mathrm{T}}\mathbf{W}\boldsymbol{\lambda}}$ where **B** is *between-class* covariance matrix and **W** is *within-class* covariance matrix. The detailed description of the classification procedure can be found in *Wackerman and Miller, 1992.*

The second approach uses fully connected, multi-layer, feed forward, backpropagation neural network - BNN algorithm (Bishop, 1997). The information propagates in one direction from input processing units to output processing units. The input to a processing unit is weighted sum of the outputs from the previous layer:

$$net_j = \sum_i w_{ji} o_i$$

This sum is transformed by a sigmoid activation function of the processing unit:

$$o_j = \frac{1}{1+\exp\left(-net_j+\theta_j\right)}$$

During iterative training procedure, we adjust the weights between the processing units. The well-known back-propagation method was used for training. The complex form decision boundaries can be constructed during the training procedure. This is especially valuable, if the clusters in feature space corresponding to different sea ice types, have complex form and are interlocked. The form of the clusters in feature space is not fully understood. This may be due to the limited number of images usually used for investigations and large variability of sea ice properties under natural conditions. For three ERS-1 SAR images from SIZEX-92 experiment (Fig. 3.1) all above mentioned texture and statistical parameters were computed and dimensionality of feature space were reduced using Linear Discriminant Analysis. The clusters corresponding to 6 sea ice types in the reduced dimensionality feature space are presented in Fig. 3.2. Three of the most powerful separation discriminant functions (DF) are shown. It is seen that clusters for some sea ice types have rather simple form and can be separated by linear discriminants. However, the result obtained for the SIZEX92 ERS-1 SAR images can be different from results for the RADARSAT radar images acquired for Northern Sea Route.

Classification results: 8 May 1998

The RADARSAT ScanSAR image from 8 May 1998 and results of automatic classification by LDA and BNN algorithms are presented in Fig. 3.3, 3.4, and 3.5. Fast and river ice is classified by LDA algorithm in both cases. Training regions for new ice with high brightness, level and very rough first year ice are taken from this image, therefore this is not a fully independent image. Nevertheless, it is still interesting to see where the border separating different sea ice types is located because rectangular regions were used for training. Heavily ridged ice in the Kara Gate (region A in Fig. 3.5), rough first year ice along Eastern Coast of Novaya Zemlya (region B in Fig. 3.5), and along Yamal Coast (regions C in Fig. 3.5) is better classified by BNN algorithm. Separate ridges of first year ice (regions D in Fig. 3.5) are also better delineated in case of BNN classification. As expected the BNN algorithm is more sensitive to the lack of training data due to better adjustment of decision boundaries compared to the LDA algorithm. Flaw polynya along Yamal Coast was mis-classified as level first year ice by the BNN algorithm and a part of it was correctly classified by the LDA algorithm (regions E in Fig. 3.4 and 3.5). The comparison between the two algorithms is summarized in Table 3.1.

Table 3.1 ***Results of classification of 8 May 1998.***

Sea ice class	Performance assessment	Examples and comments
Very deformed FY ice	BNN algorithm performs better	Region A in Fig. 3.5. Very ridged FY ice in regions D is mis-classified as deformed FY ice
Deformed FY ice	BNN algorithm performs better	Regions B and C in Fig. 3.5
Level FY ice	BNN algorithm performs better	Some regions in the central part of the classified image in Fig. 3.5
Young ice	Not found by both algorithms	Some young ice is expected to be in the mixture with deformed FY ice along Yamal coast.
OW&new ice.	Correctly classified by both algorithms	Region to the West of Vaygach Island
OW&nilas	LDA algorithm performs better	Regions E in Fig. 3.4

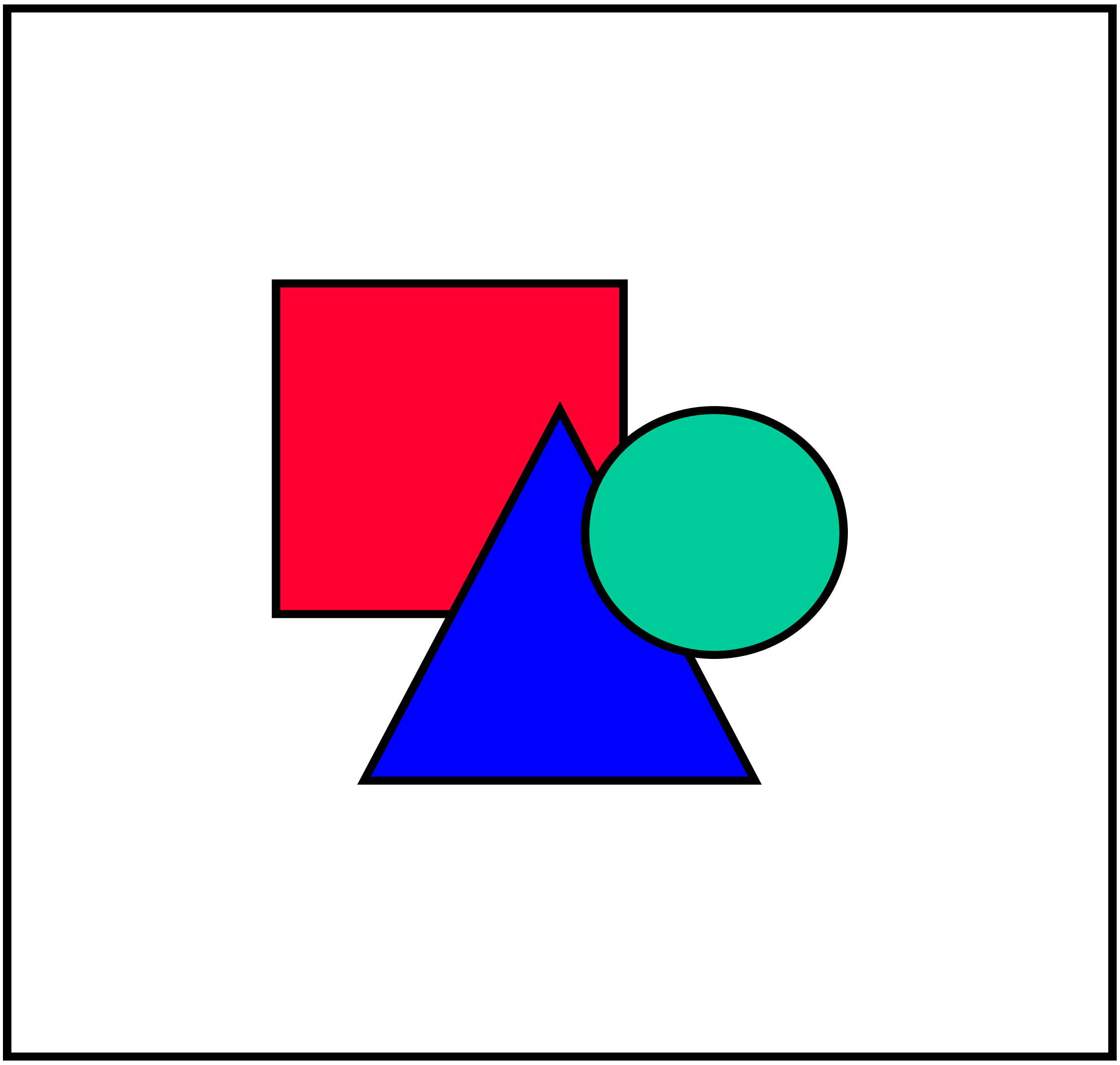
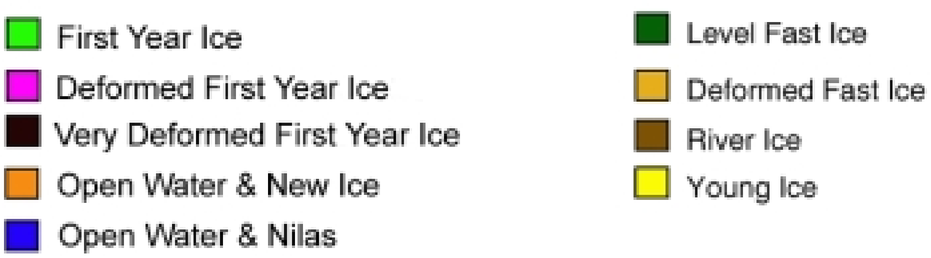


Figure 3.3 ***RADARSAT Scan Wide SAR image acquired of May 8, 1998. Canadian Space Agency.***



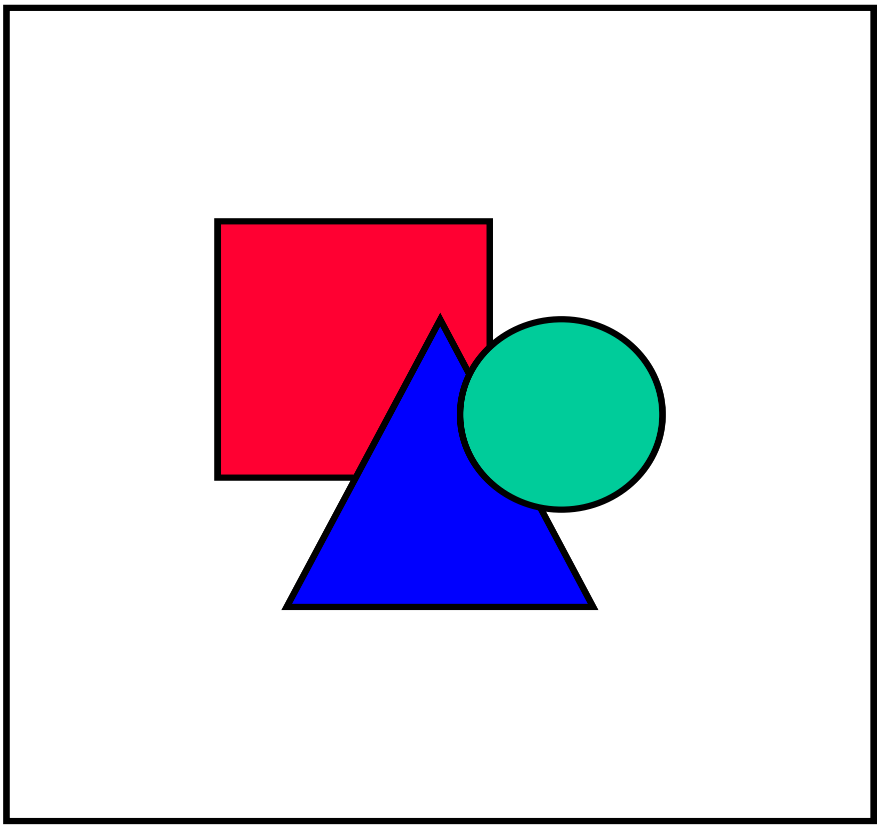


Figure 3.4 ***RADARSAT Scan Wide SAR image acquired of May 8, 1998 classified by algorithm based on Linear Discriminant Analysis.***

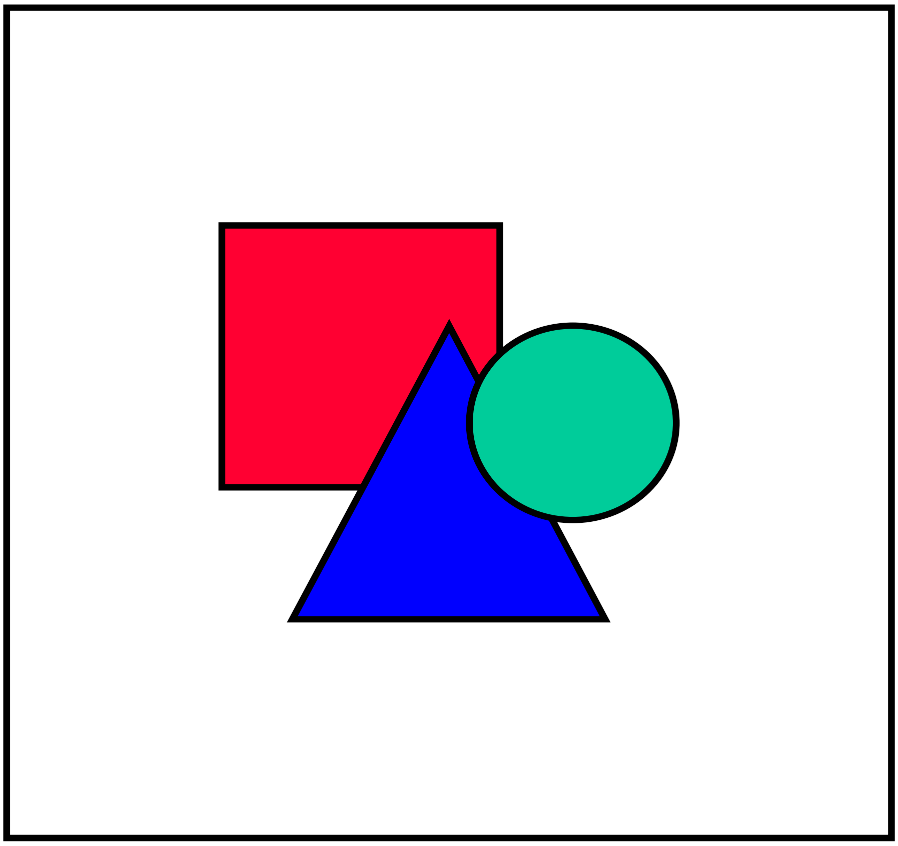


Figure 3.5 ***RADARSAT Scan Wide SAR image acquired of May 8, 1998 classified by backpropagation neural network algorithm with topology 10-70-50-6.***

Classification results: 30 April 1998

The RADARSAT ScanSAR image from 30 April 1998 and results of the automatic classification by the LDA and BNN algorithms are presented in Fig. 3.6 to 3.8 accordingly. This is a fully independent image of drifting ice, although training regions for fast and river ice were taken from this image. Most of the young ice in regions A and B and deformed FY ice in regions C, D and H (Fig. 3.7 and 3.8), is correctly classified by both algorithms. The BNN and LDA algorithms failed to classify to different degrees deformed first year ice to the North of Belyi Island in region E (Fig. 3.7 and 3.8). The main classification mistake, is that flaw polynyas near Sverdrup Island and Dixon (regions F and G in Fig. 3.8 accordingly) were classified as first year ice by BNN algorithm. Some parts of the polynyas were correctly classified by LDA algorithm as OW&nilas class (regions F and G in Fig. 3.7). There may be two reasons for this misclassification:

- the lack of training data
- weak ability of the texture parameters to separate these classes

The latter argument is supported by Shokr, (1991) who found large variability of the texture parameters for regions with smooth texture.
These results of classification are summarized in Table 3.2.

Table 3.2 ***Results of classification of 30 April 1998.***

Sea ice class	Performance assessment	Examples and comments
Very deformed FY ice	Badly delineated by both algorithms	Appears as speckle on young ice in Fig. 3.8.
Deformed FY ice	LDA algorithm performs better	Regions C, D and H in Fig. 3.7
Level FY ice	LDA algorithm performs better	There is not much level FY ice in the image. Some floes of level FY ice were correctly classified by LDA algorithm (Fig 3.7).
Young ice	LDA algorithm performs better	Regions A and B in Fig. 3.7
OW&new ice.	Not found by both algorithms	Flaw polynya covered by new ice in region I in Fig. 3.7, 3.8 was mis-classified by both algorithms
OW&nilas	LDA algorithm performs better	Regions F and G in Fig. 3.7

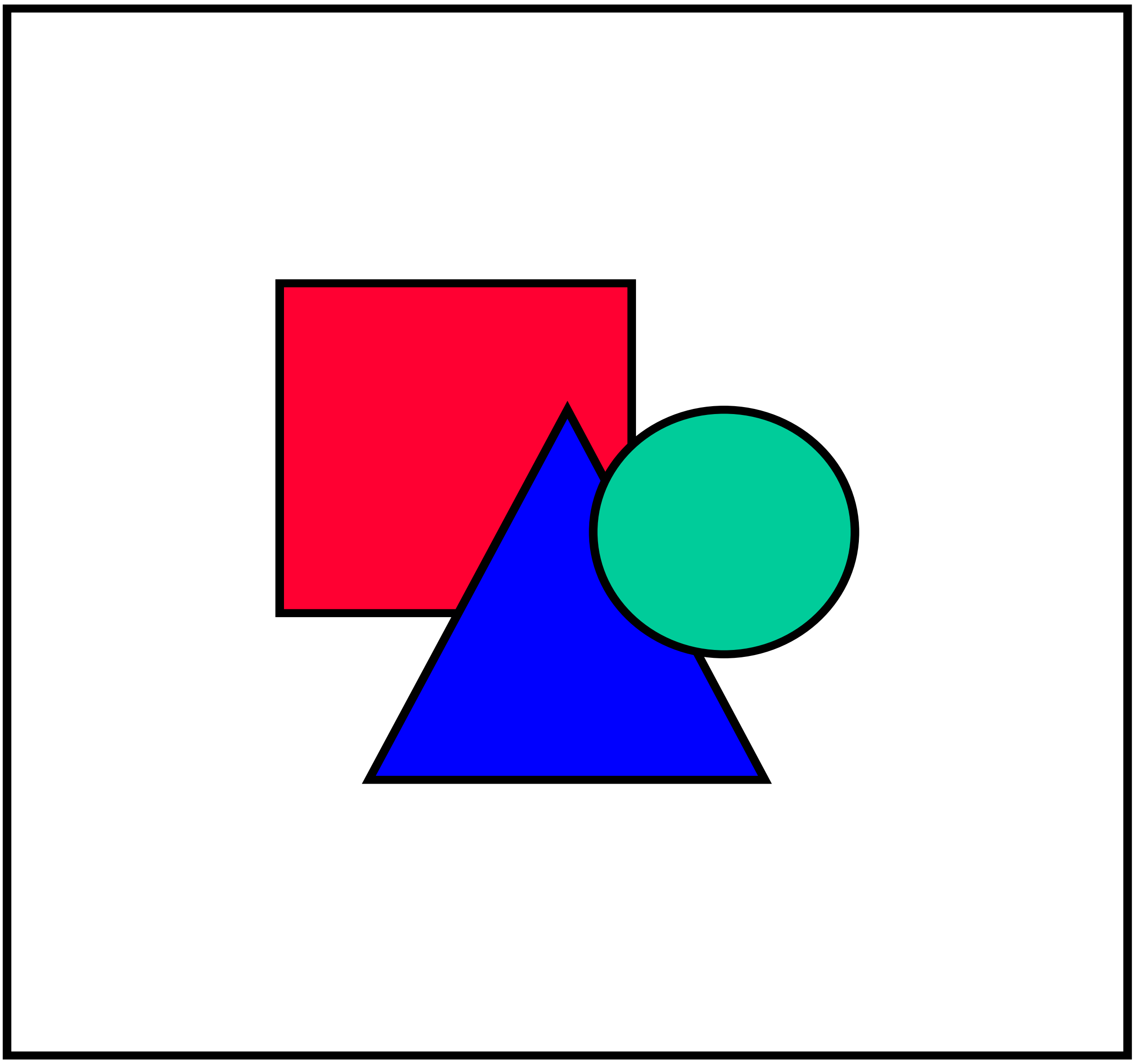
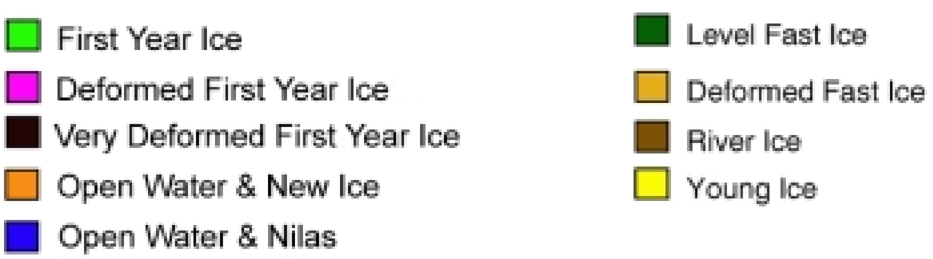


Figure 3.6 ***RADARSAT Scan Wide SAR image acquired of April 30, 1998. Canadian Space Agency.***



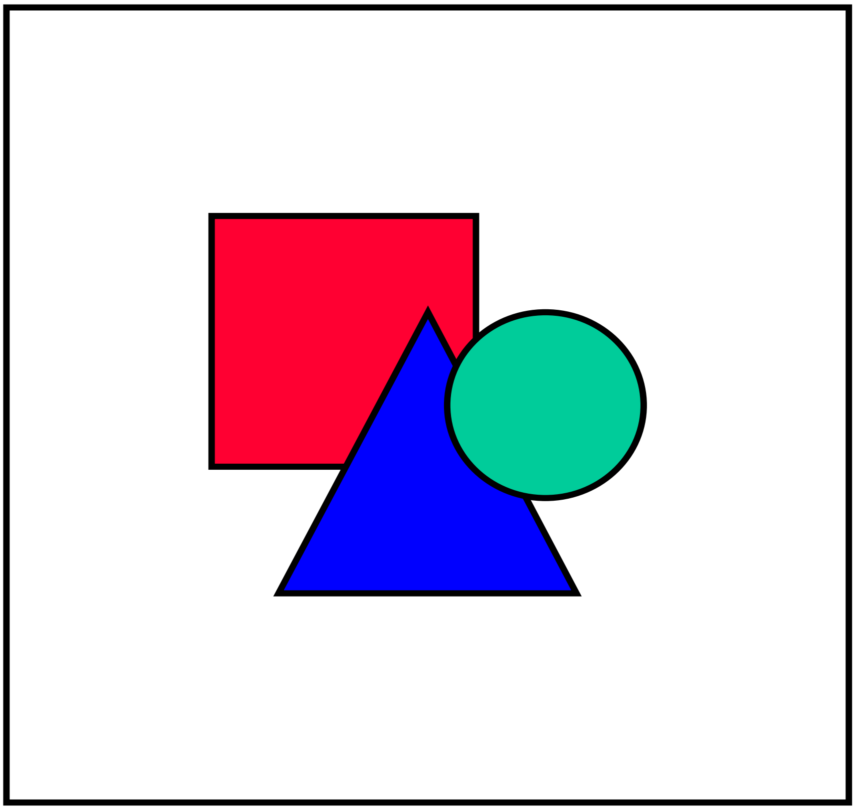


Figure 3.7 ***RADARSAT Scan Wide SAR image acquired of April 30, 1998 classified by algorithm based on Linear Discriminant Analysis.***

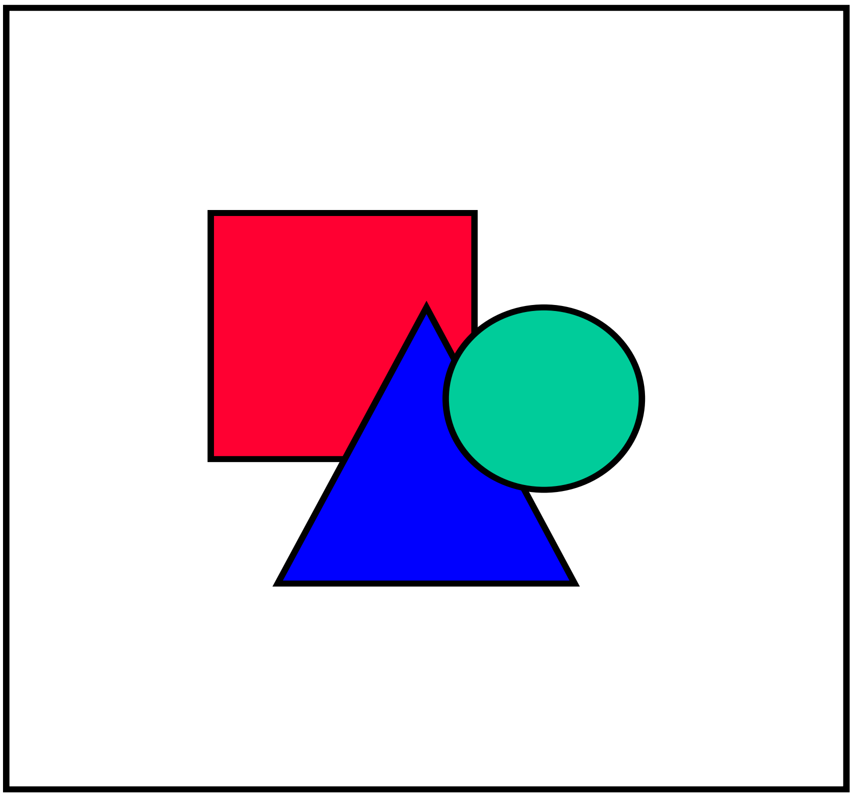


Figure 3.8 ***RADARSAT Scan Wide SAR image acquired of April 30, 1998 classified by backpropagation neural network algorithm with topology 10-70-50-6.***

3.1.3 Ice concentration and velocity in the Laptev Sea

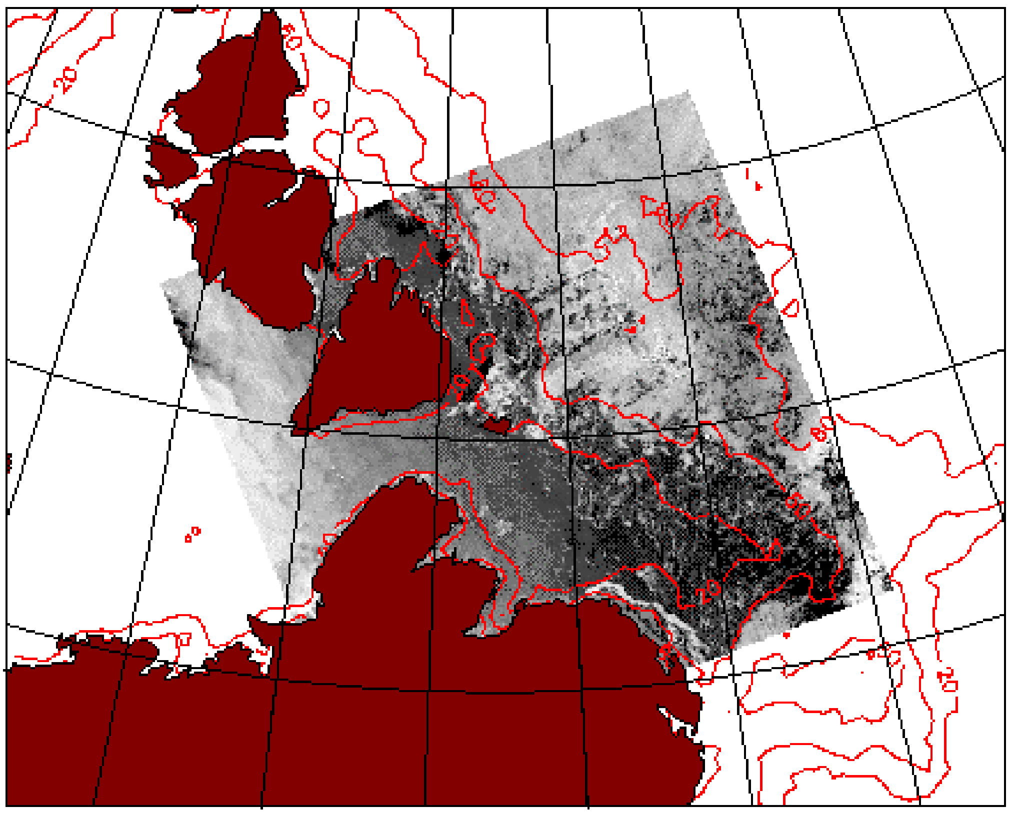


Figure 3.9 ***Joint RADARSAT and SSM/I ice product for 7 September 1997. The SSM/I ice concentration iso-lines for 20%, 50 % and 80 % are shown. Image Data © Canadian Space Agency 1997.***

The first RADARSAT ScanSAR images in the Laptev Sea region were obtained in during the 'Sovetsky Soyuz' expedition in September 1997. This was the first demonstration campaign for RADARSAT data in the Northern Sea Route. The first RADARSAT products which were developed and tested are: 1) geo-coded and contrast enhanced images with landmask and latitude/longitudes, 2) combined RADARSAT image and SSM/I ice concentration map (Fig. 3.9), 3) ice velocity estimates from consecutive SAR images.

To try to get a better estimate of the ice concentration in late summer conditions, RADARSAT and SSM/I data were combined with *in situ* observations in the Laptev Sea region. The principal idea was; all RADARSAT pixels were separated into either open water or thin ice (nilas) with relatively low backscatter (digital value 0) and thick ice, (digital value 100), using a threshold value. The ice concentration for a given area was computed by averaging all ice/water pixels within that area.

To compute the most appropriate threshold value, a profile with in situ observations along a ship track in the RADARSAT image, (Fig. 3.10), was compared with a similar profile from an SSM/I ice concentration image from the same day. The threshold value was computed using a least-mean-squares (LMS) fit between the two profiles, (Fig. 3.11). For this approach, the digital value 109 gave the best fit.

When applying this threshold value to the whole RADARSAT image, the ice edge was correctly positioned, though the ice concentration became too high in the interior of the ice massif north of 78º N. An alternative method is to estimate the histogram for the RADARSAT image. If a local minimum in a bimodal distribution can be found, this is used to define the threshold. In this case, a digital value of 166 was found, resulting in a lower ice concentration, and an ice edge which was displaced too far to the east (compared to the SSM/I data).

In conclusion, this example shows the importance of accurately calibrated images, so that the same type of ice appears similar within a single SAR image and between different SAR images.

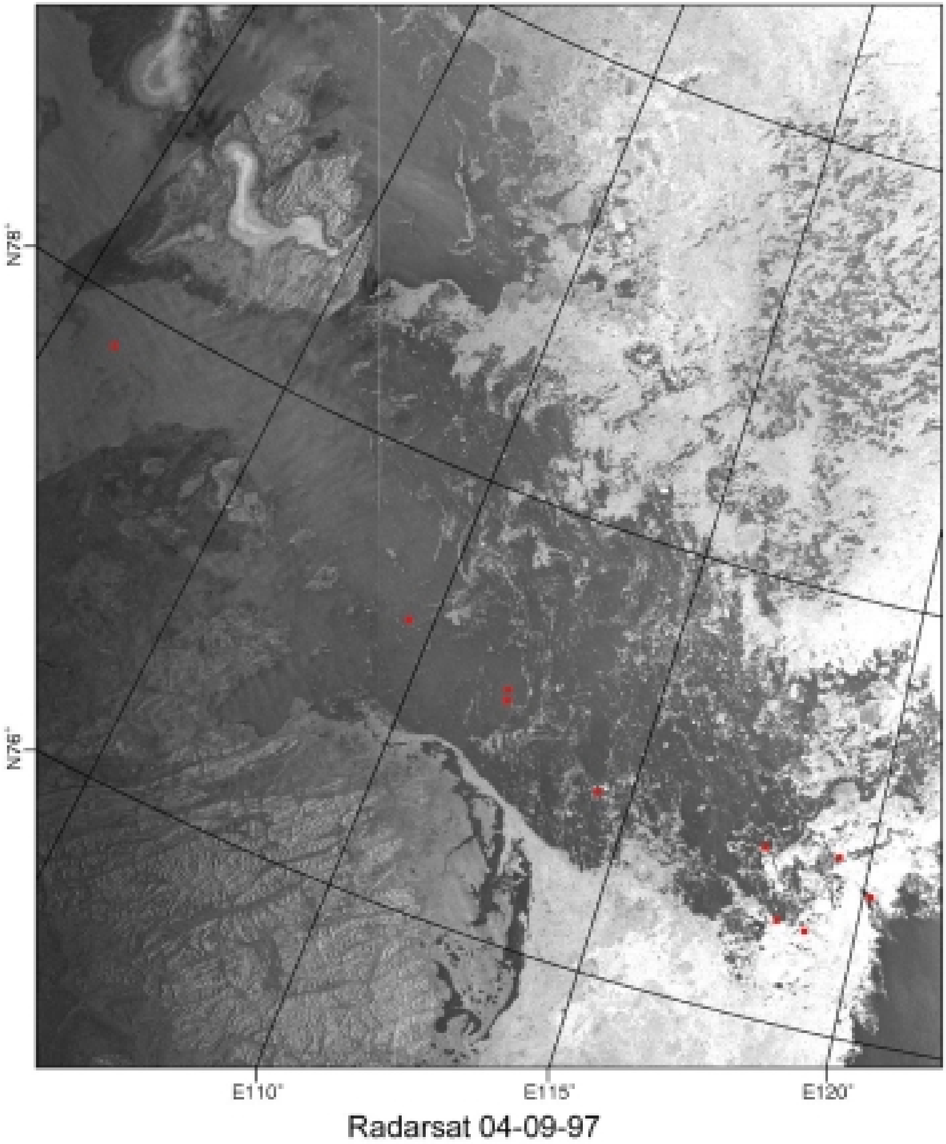


Figure 3.10 ***The resolution is 400 by 400 m, and the red points mark the in situ ice observations (concentrations). The profile used to compute the threshold values is obtained along these points.***

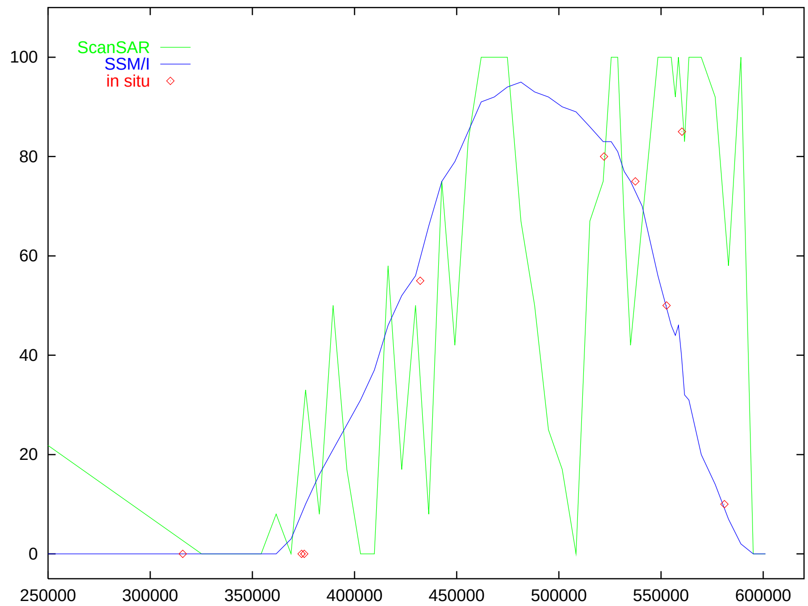


Figure 3.11 ***Comparison of RADARSAT and SSM/I derived ice concentrations using the threshold found using a LMS fit.***

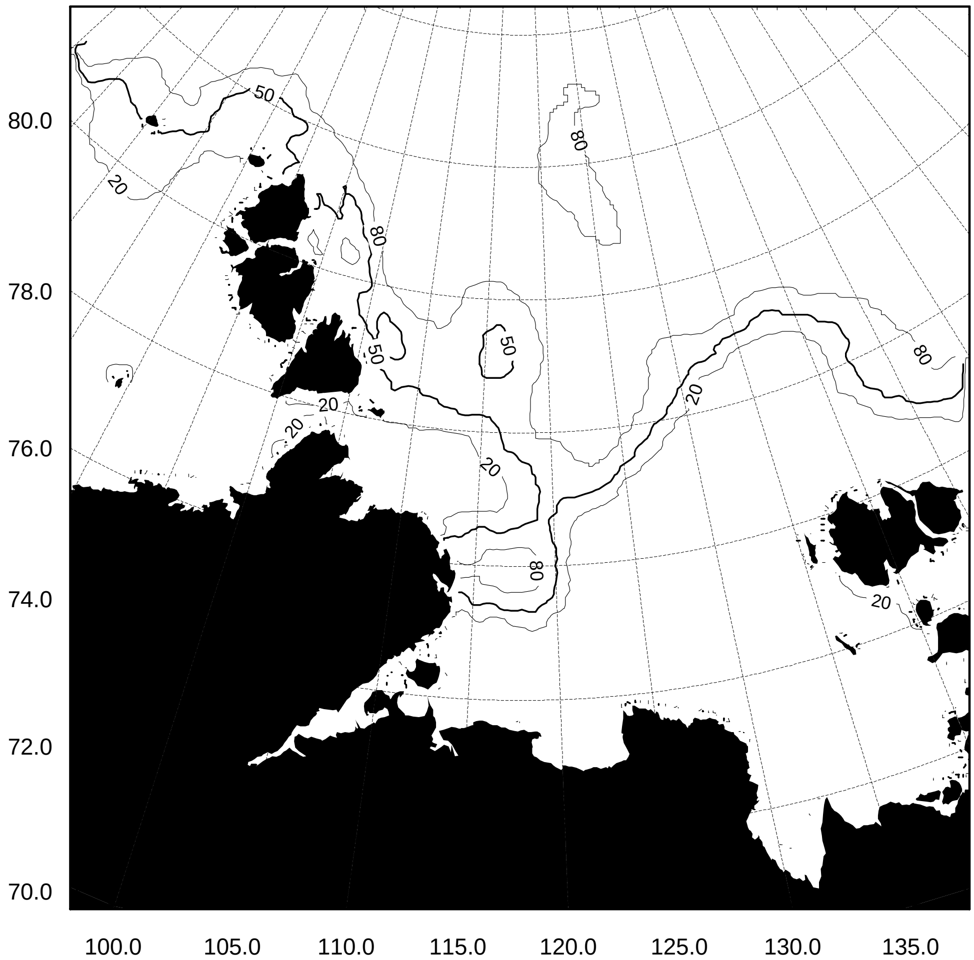


Figure 3.12 ***Ice concentration derived from SSM/I data from 4 September 1997.***

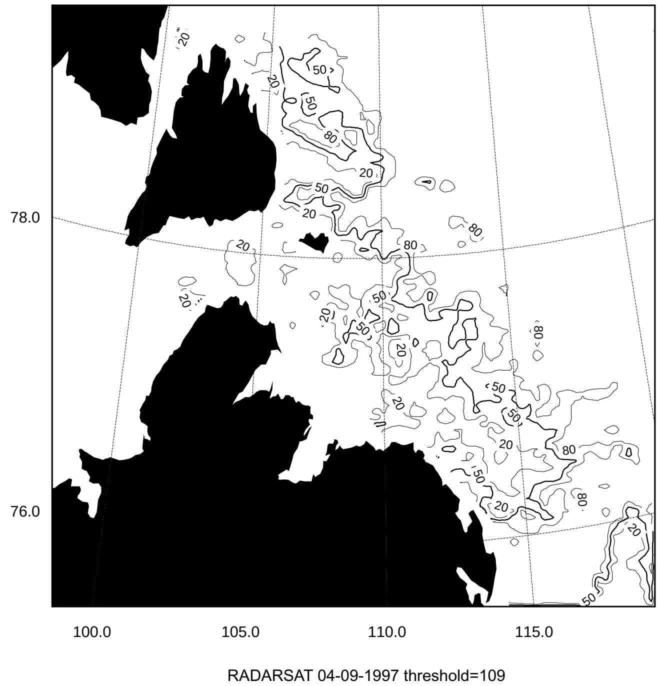


Figure 3.13 ***Ice concentration derived from RADARSAT ScanSAR from 4 September 1997 using threshold value 109.***

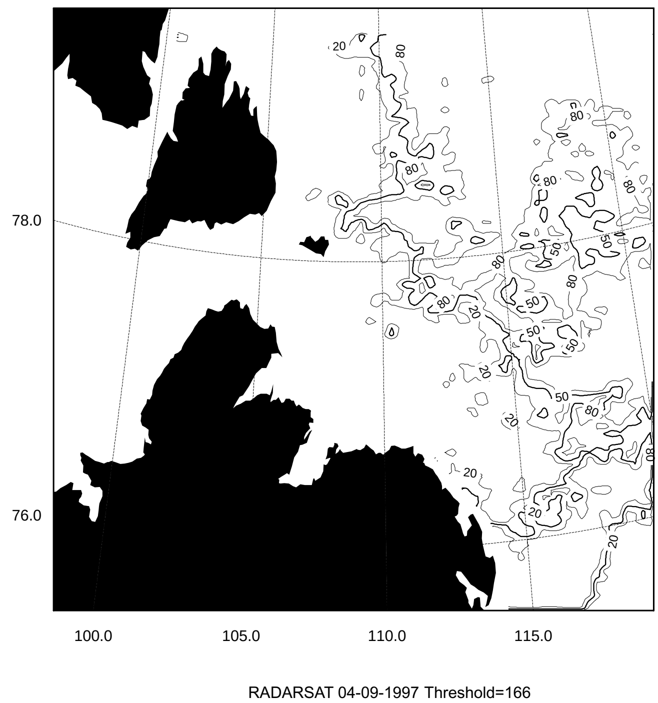


Figure 3.14 ***Ice concentration derived from RADARSAT ScanSAR from 4 September 1997 using threshold value 166.***

For the first time, RADARSAT ScanSAR data were used to estimate sea ice motion in the Laptev Sea, near the Vilkitsky Strait. The 500 km wide swath covered by a ScanSAR image, improve the time and spatial resolutions of the ice displacement calculation compared to ERS SAR images. With RADARSAT ScanSAR, and ENVISAT ASAR from 2000, it will be possible to cover the whole Arctic Sea ice with SAR data every day.

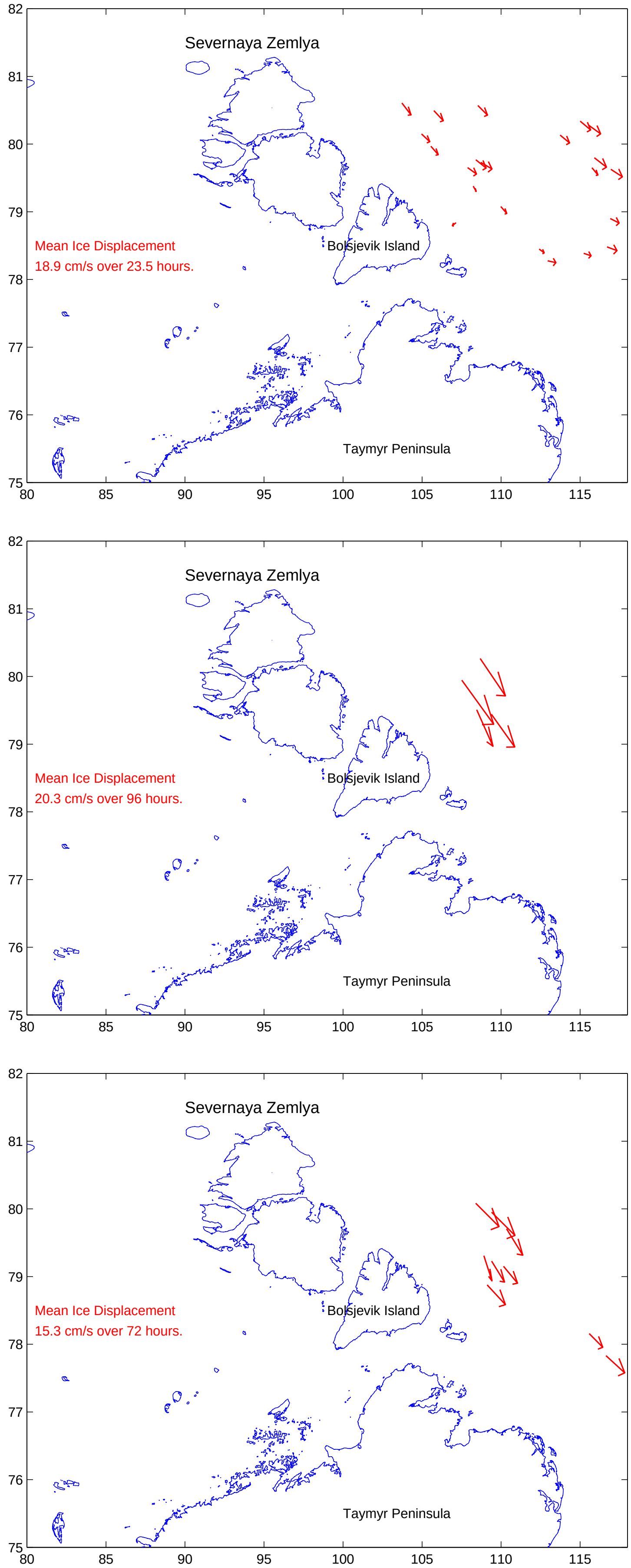


Figure 3.15 ***Sea ice displacement 14 to 15 August, 31 August to 4 September and 4 to 7 September 1997.***

This example shows that sea ice displacement can be calculated from successive RADARSAT images during summer conditions. The time resolution of the ice displacement calculation is better than for ERS SAR images. Images obtained in about 24 hours can resolve the temporal variability of the drift better than images obtained every 72 hours, because the velocity is then averaged over a longer period of time. The capability of RADARSAT ScanSAR images, to cover large areas is important for providing better synoptic velocity fields.

3.2 Neural network classification for SAR data in the Baltic Sea

3.2.1 Introduction to SAR ice classification

The information in the SAR image consists of two components: the intensity value describing the backscattering strength in a target area and the texture of several nearby pixels describing the local variations in the backscattering. The major problems in the SAR based sea ice mapping concern the utilisation of the texture information.

The sea ice fields are continuously moving due to currents and winds. The relatively thin ice cover in the Baltic Sea is in a constant state of deformation. This highly dynamic nature of ice fields is reflected in the irregular appearance of an ice field in a SAR image. It is difficult to determine features that could well characterise an ice type as it can be seen in the SAR image. The complexity of the texture determination task is acknowledged by the researchers by using mostly only intensity values in the sea ice classification, (e.g. Fetterer et al., 1994). However, as soon as one is interested in a more detailed ice information than only the separation between multi-year and first-year, sea ice problems with the sufficient classification accuracy are encountered (Rignot and Drinkwater, 1994).

In the Baltic Sea the most important sea ice product is the daily ice chart produced by the national Ice Services. The main deficiency in the ice chart is its poor spatial resolution. During the IMSI project, the research at FIMR has been focused to investigate the usability of the Pulse-Coupled Neural Network (PCNN) for the sea ice mapping. The objectives have been to improve the accuracy of the description of the spatial distribution of the different ice fields, which can be seen in the ice chart, and the identification of the most deformed ice areas.

In the studies by Karvonen and Similä, (1998a, 1998b), and Similä and Karvonen (1999), the texture problem was approached by using a large classification unit with a ground resolution of 500 m computed from 25 RADARSAT ScanSAR Narrow image pixels with a resolution of 100 m. In the decision rules used the main emphasis was in the backscattering intensity averaged over a classification unit although the local correlation structure, the local variation, and the contextual information have also been taken into account to some degree. For comparison, we note that the Geophysical Processor System by the Alaska SAR Facility used for classification purposes a ground resolution of 240 m with 64 full resolution ERS SAR pixels, (Fetterer et al., 1994). In the paper by Karvonen and Similä, (1999), the PCNN approach was extended to process the full resolution data by using reparametrization and simplification of the original PCNN equations.

3.2.2 Intensity based sea ice classification

The specification of first-year ice classes in the connection of C-band SAR data is a difficult problem because the ice field structure can be seen only partially in the C-band satellite SAR image. Much of the backscatter variation caused by the variation in the ice surface topography is averaged away at the low resolution (100 m) satellite SAR data. One can find interesting results on the backscatter distributions of different ice types in the Baltic Sea in the Section 3.3.

According to the measurements of HUT, on average the backscatter increases as a function of ice thickness. The deformed ice areas represent the thickest ice. However, there is much overlap between the backscatter signatures of different ice types. When one moves to the coarser resolution, it often happens that level ice as well as deformed ice occurs inside one resolution cell. This complicates the ice type identification. In this kind of cases the total mean intensity usually remains closer to the less deformed ice type, which is due to the sparse nature of ridging. Characteristic to the ice ridges is, that they are thin, long accumulations of ice blocks. Hence, the resulting pixel in SAR image indicates less deformed and thinner ice than what the ice field actually is. The direction of the bias in the ice type determination is mostly that we underrate the ice deformation.

Due to the considerations presented above and due to our own experiences we have selected to use the following ice types: open water, new ice/thin ice (ice thickness on average less than 10-20 cm), thick ice (level ice with ice thickness on average over 10-20 cm), slightly and highly deformed ice. All these ice types are meaningful from the point of view of the winter shipping. We are also aware of the fact that to be able to detect the deformed ice the deformed ice, fields must appear in large patches. To improve the ice type identification we have utilised the contextual information as well as the local variation statistics. The first step in our classification procedure is performed by PCNN. This classification result is then modified with the aid of local statistics.

Our objective in the segmentation can be expressed in the following way. As the scatterometer measurements illustrate, if one takes a large sample of pixels from the same ice type the mean intensity increases as a function of ice deformation. The segments produced by PCNN are an attempt to provide this large sample. To this end, the segmentation methods utilise the spatial continuity property, which holds for the ice types.

We employed the spatial continuity property by assigning to a large pixel block (25 pixels) one class label in our first PCNN applications. This approach is not optimal because the distribution of the backscattering intensity inside one pixel block was not taken into account in the preliminary segmentation phase. This automatically leads to a rather coarse representation of the sea ice field where the smaller scale sea ice field structure can not be detected anymore.

3.2.3 Pulse-Coupled Neural Network and Segmentation Network

Pulse-Coupled Neural Network (PCNN) algorithm, Eckhorn, (1990), Rybak, (1992), Johnson, (1994), Lindblad and Kinser, (1998), is an iterative algorithm in which a binary output image is produced at each iteration. The output images at different iterations typically represent some segments or edges of the input image. The PCNN has a neuron corresponding to each pixel of the input image. One PCNN processing element corresponding to one image pixel consists of sub-elements: the feeding element F, the linking element L, the internal activation element U and the output element O. The input stimulus is received by the feeding element and the internal activation element combines the feeding element with the linking element. The value of internal activation element is compared to a dynamic threshold, which gradually decreases at each iteration. The internal activation element accumulates the signals until it surpasses the dynamic threshold and then fires the output element and the dynamic threshold increases simultaneously strongly. The output Y of the output neuron is then iteratively fed back to the element with a delay of one iteration, see Fig. 3.16. The network can be implemented by iterating the equations 1-5, Johnson, (1994) and Lindblad and Kinser, (1998).

$$F_{ij}[n] = e^{-\alpha_F \Delta t} F_{ij}[n-1] + V_F \quad m_{ijkl} Y_{kl}[n-1] + S_{ij}$$

$$L_{ij}[n] = e^{-\alpha_F \Delta t} L_{ij}[n-1] + V_L \quad w_{ijkl} Y_{kl}[n-1]$$

$$U_{ij}[n] = F_{ij}[n](1 + \beta L_{ij}[n])$$

$$Y_{ij}[n] = \begin{matrix} 1, U_{ij}[n] > T_{ij}[n] \\ 0, \text{ otherwise} \end{matrix}$$

$$T_{ij}[n] = e^{-\alpha_T \Delta t} T_{ij}[n-1] + V_T Y_{ij}[n-1]$$

Equations 1 to 5.

S is the stimulus input (the pixel intensity), F is the feeding portion of the neuron, L is the linking, U is the internal activity, Y is the output and T is the dynamic threshold, the indexes i and j refer to the pixel row and column co-ordinates. m and w refer to two weight functions, which are typically decreasing functions of the distance from the pixel at location (I, j). These functions are called the PCNN kernels. We have used a similar Gaussian shapes with standard deviations s_m and s_w for m and w. There are three potentials V and decay constants a associated with F, L and T. The firing in the binary images produced by the PCNN mainly due to the primary inputs is called the natural firing. Second type of firing which occurs mainly due to the neighbourhood firing at the preceding iterations, we call the secondary firing.

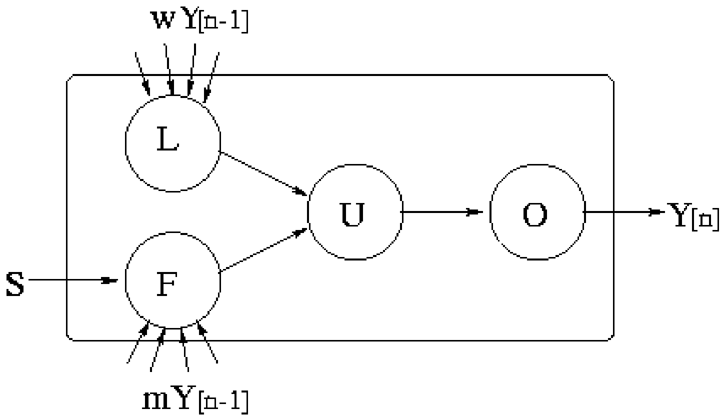


Figure 3.16 ***A simplified PCNN neuron model***.

Three of PCNN-equations above include a contextual component, namely the equations 1-3. All these equations describe a different source mechanism for the contextual information. However, the multitude of the contextual parameters in practice complicates the determination of the parameter values, i.e. the training of the network. Hence, one is tempted to simplify the PCNN equations 1-3 by grouping together the contextual parameters. This reparametrization and simplification of the PCNN equations was done e.g. by Ranganath and Kundimad, (1994). In their model the PCNN equations are given in the following form

$$L_{ij}[n] = \quad w_{ijkl} Y_{kl}[n-1]$$

$$U_{ij}[n] = S_{ij}[n](1+\beta L_{ij}[n])$$

$$Y_{ij}[n] = \begin{cases} 1, U_{ij}[n] > T_{ij}[n] \\ 0, \text{ otherwise} \end{cases}$$ Equations 6 to 9.

$$T_{ij}[n] = \begin{cases} e^{-\alpha_T \Delta t} T_{ij}[n-1], & Y_{ij}[n]=0 \\ V_T, Y_{ij}[n]=1 \end{cases}$$

Ranganath et al. called their PCNN network the segmentation network, and this was the model we used for the full resolution SAR images.

Segmentation Using Primary Firing

In the first version of our algorithm, Karvonen and Similä, (1998a), we have used four PCNN segmentation images selected from binary image sequences produced by three PCNNs with different sets of parameters. Additionally, we used a simple filtering, in which the class boundary pixels are mode filtered and edge pixels are linked together, for the binary segmentation images. The pixels left unmapped by the PCNN are mapped to the segment classes according to the nearby pixels classes and the original intensity values. The class decisions for the pixels are mainly based on the PCNN primary firing. The parameters of the four PCNN segmentation images we used are tabulated in Table 3.3. Three different PCNN iterative processes must be run to produce these images, only two images are from the same PCNN binary image sequence. The parameters were selected by trial and error for a small subset of 100 RADARSAT images. Then the same parameters were applied to all the images.

Table 3.3 ***PCNN Parameters for the four PCNN images used for segmentation.***

V_F	V_L	V_T	α_F	α_L	α_T	β	R_m	R_w	σ_m	σ_w	N
30	20	5500	1	1	1	0.3	2	2	0.75	0.75	5
30	20	5500	1	1	1	0.3	2	2	0.75	0.75	6
30	20	5500	1	1	0.8	0.5	2	2	1.4	1.4	2
30	20	5500	1	1	0.7	0.3	2	2	0.7	0.7	8

According to our experiences with RADARSAT ScanSAR images, this approach seems to work well for low-resolution images that are low-pass filtered and down-sampled versions of the original data. The resolution of these images was 500x500 m^2 corresponding to a downsampling rate of five in both vertical and horizontal directions. To obtain the final ice chart these preliminary classification results were then improved by taking into account the local correlation structure, the local intensity fluctuation as well as some syntactic rules for fast ice detection, for details see Karvonen and Similä, (1998a).

Segmentation Using Tree-Structured Segmentation Networks

This method uses several Ranganath segmentation networks described by the equations 6-9. The networks are applied in a tree structure, which is three nodes deep. The terminal nodes of this tree form the desired segmentation. The tree structure of our algorithm is presented in Figure 3.17. At each node, the pixels at that node are splitted into two classes, the activated neurons and the not-activated neurons (see Fig. 3.17), using two iterations of the Ranganath network. At the first node at the first iteration only the primary firing of neurons takes place, i.e. a set of pixels with an intensity value on a fixed interval is extracted. At the second iteration the neighbour pixels of the first pixel set are fired if their intensity values are close enough to those pixels, which were activated at the former iteration. In addition, at the lower nodes, PCNN2 and PCNN3 (see Fig. 3.17), the PCNN computation uses the contextual information of the neighbouring pixels even if the neighbouring pixels were fired already at a higher node. The only parameter we are changing is the threshold value V_T in the equation 9. This is done according to Table 3.4. The parameters in Table 3.4 were selected by trial and error for one of our test image. Then the same parameters were applied to all the test images. This variant can be implemented in a fast and efficient way, so that the computer memory problems encountered with our previous approach can be avoided.

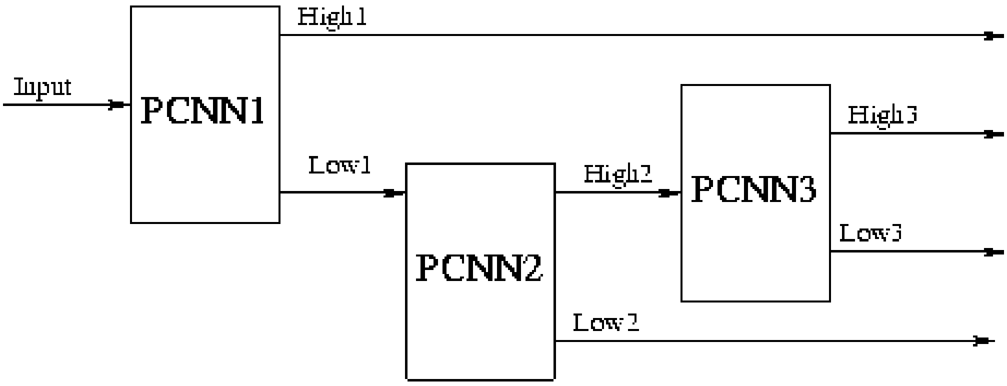


Figure 3.17 ***The tree structure of the three segmentation networks (PCNN1-PCNN3) used to produce four segmentation classes. The word low refers to the neurons that are not activated at that node.***

Table 3.4 ***Parameters for the three segmentation networks to divide a full resolution SAR image into four classes.***

V_T	$_T$		R_w	iterations
1800	0.5	0.7	3	2, 3
1400	0.5	0.7	3	2, 3
1550	0.5	0.7	3	2, 3

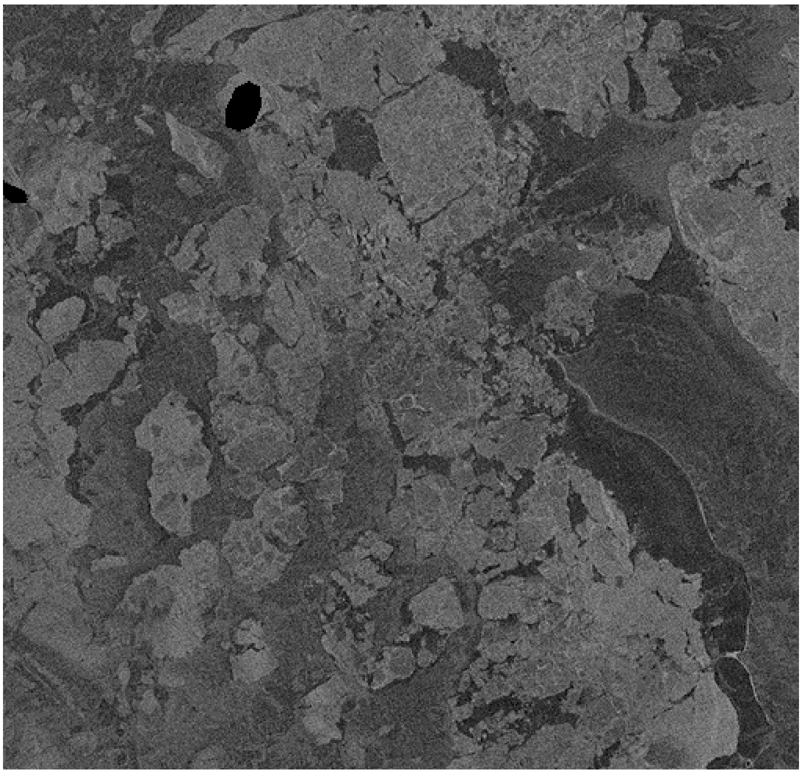


Figure 3.18 ***A RADARSAT SAR test image detail (image test1).***

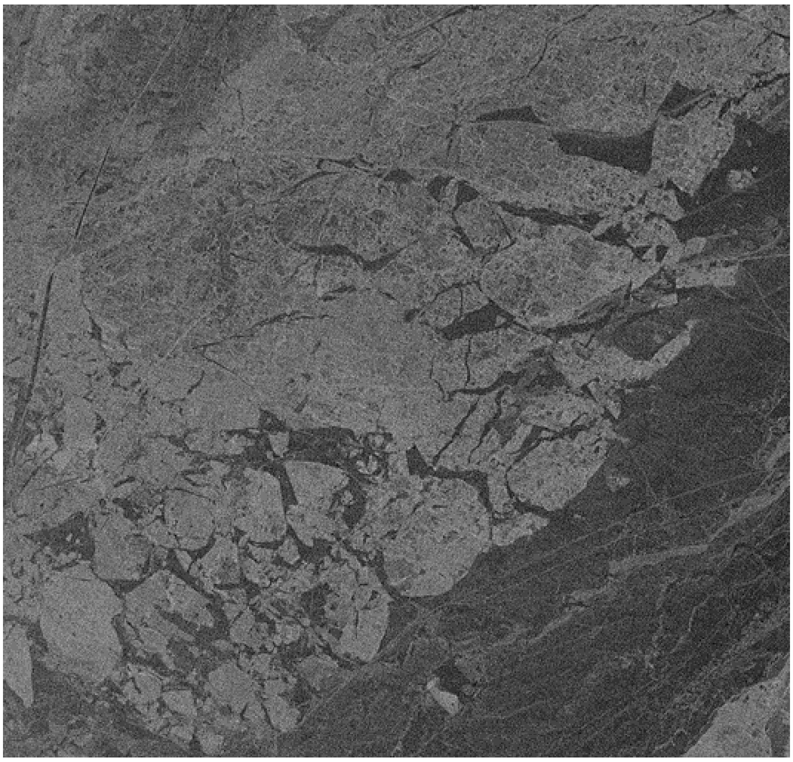


Figure 3.19 ***A RADARSAT SAR test image detail (image test2).***

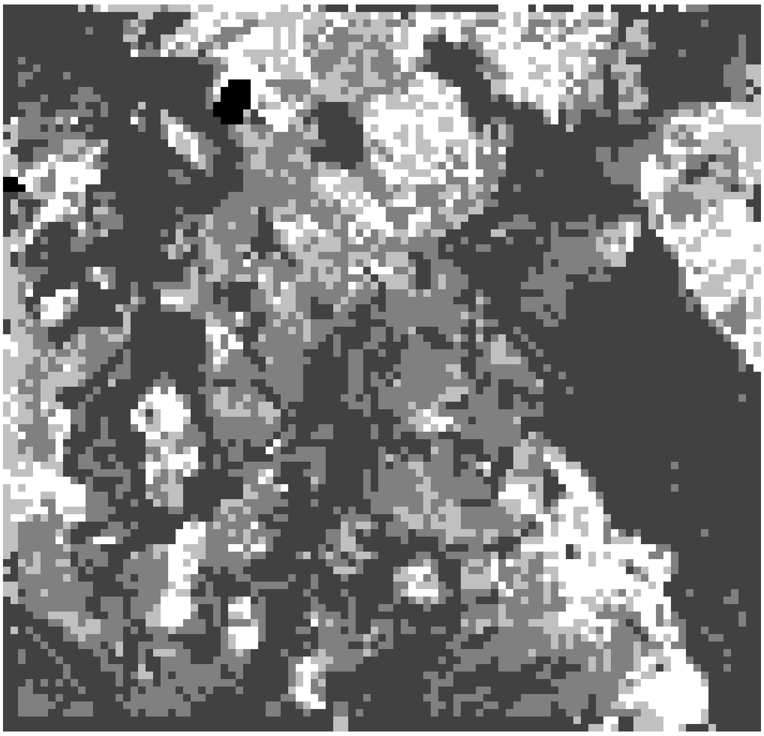


Figure 3.20 ***Segmentation of the test image test1 of Fig. 3.18 into four segment classes based on the low resolution PCNN method.***

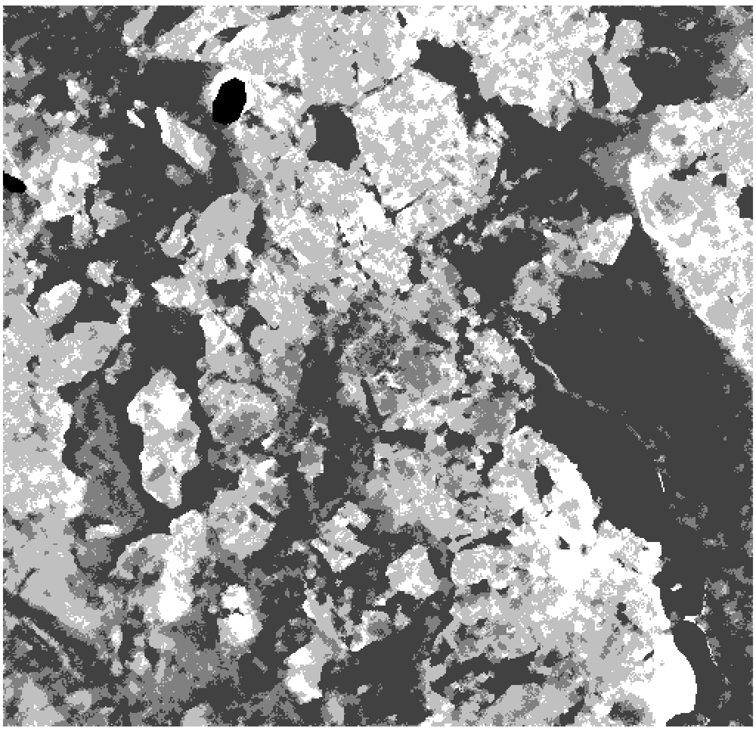


Figure 3.21 ***Segmentation of the test image test1 of Fig. 3.18 into four segment classes based on the segmentation network tree method. The post-processing (filtering) described in the text has been applied to the segmentation.***

Figure 3.22 ***Segmentation of the test image test2 of Fig. 3.19 into four segment classes based on the low resolution PCNN method.***

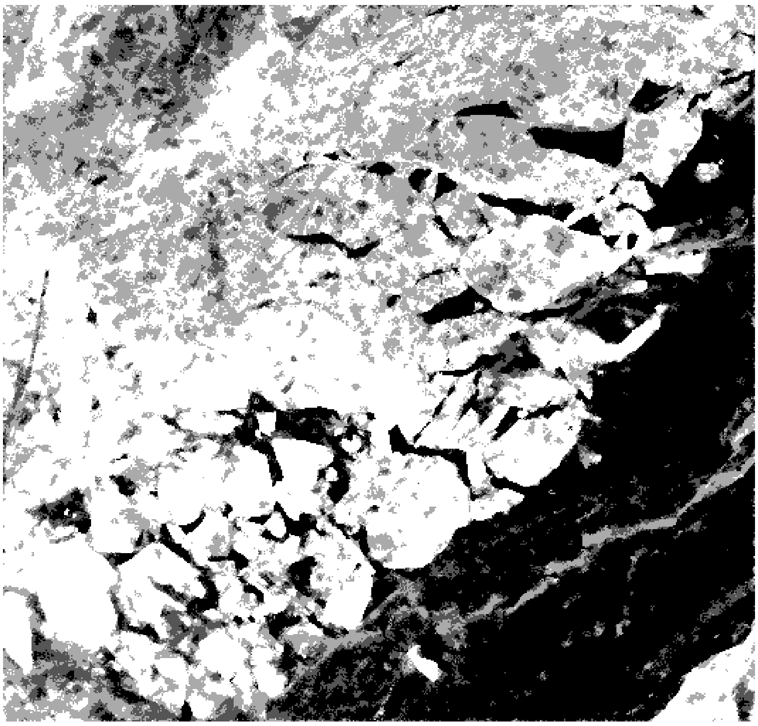


Figure 3.23 ***Segmentation of the test image test2 of Fig. 3.19 into four segment classes based on the segmentation network tree method with post-processing.***

We also used a simple filter to modify the segmentations produced by the segmentation network tree method. The filter mode filters those pixel values in the segmentation image whose NxN square neighbourhood has less than a threshold value T pixels of the same class as the window mid-pixel (with N=5, T=5). The classification results for Fig. 3.18 and 3.19 using Ranganath segmentation network are displayed as Fig. 3.21 and 3.23.

Ice type classification algorithm

The first version of our algorithm processes data in two scales: the full image scale and the downsampled scale. Most of the classification is performed in the downsampled scale and the classification result is also given in the downsampled scale. The major reason to use the downsampled image in the classification and in connection with the PCNN algorithm was the memory and computing capacity limitations due to the huge size of RADARSAT images (c. 6 million pixels per image). As the application of the Ranganath segmentation demonstrates, the full resolution image would have improved the classification results.

A block diagram of the algorithm is given in Fig. 3.25. We do not perform any normalisation for the incidence angle due to the lack of knowledge of RADARSAT SAR calibration. The incidence angle varies at most 20 degrees in one scene but the variation is usually essentially smaller. However, this variation often has very significant consequences, see e.g. the contribution by HUT in this same Task, see e.g. Section 3.3.2.

The quality of a SAR image is highly dependent on the amount of the wetness that is present in the snow layer and in the ice surface. This fact is illustrated in Figure 3.24, where the image contrast is plotted together with the mean air temperature.

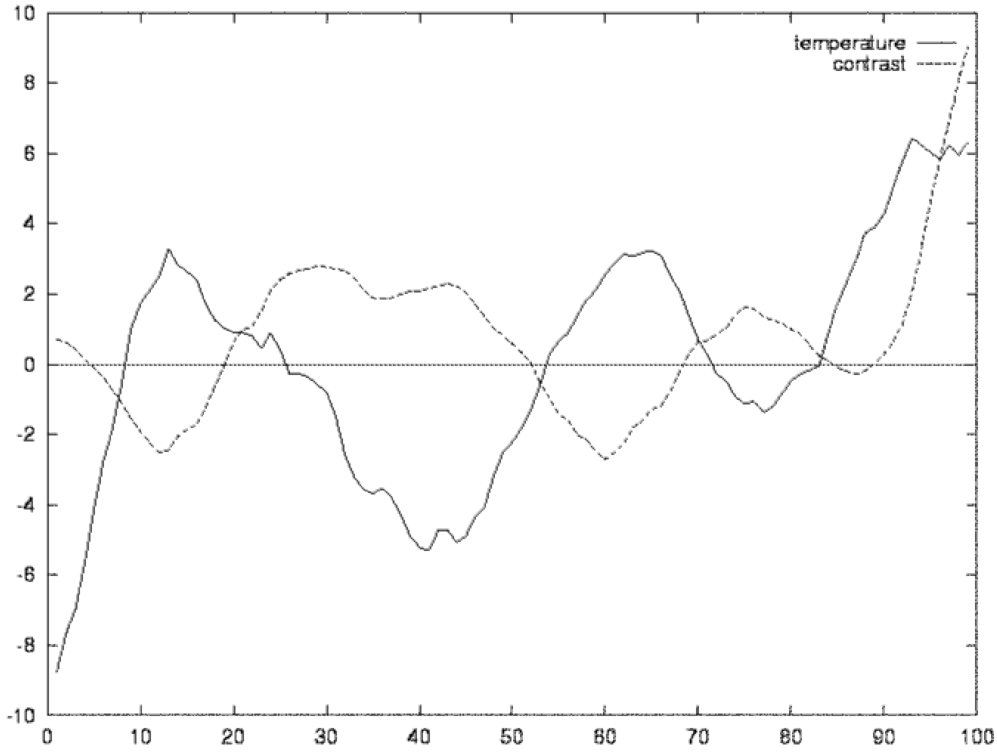


Figure 3.24 ***The three (previous) day average temperatures and the contrast value plots for our test period. Both the time series are low-pass filtered to get the trend even better visible. A strong negative***

correlation is obvious. At the end of the time series the ice started to melt and the majority of the data represents open sea, explaining the different behaviour of the curves from about image number 85.

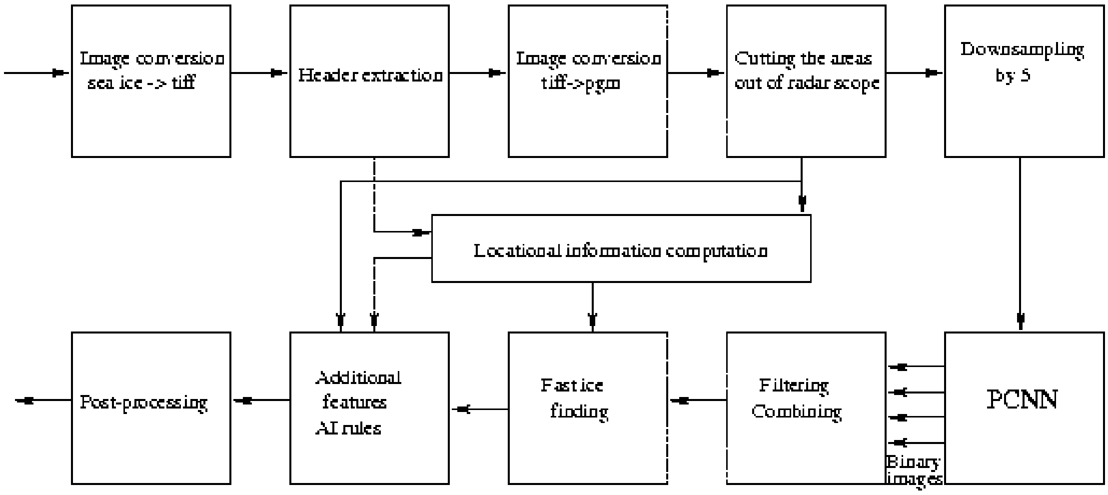


Figure 3.25 ***Block diagram of the algorithm. The pre-processing stages are in the upper row. The input to the system is a SAR-image and the output is a classification colour image.***

The use of the PCNN for the downsampled data was described in the section "Segmentation using primary firing". It is our experience that for the SAR images at our disposal the described use of PCNN algorithm gives a relatively robust preliminary classification result which constitutes a good base for a more refined analysis with additional features. These four binary images produced by PCNN are post-processed with a mode filter in a 5x5 window around each pixel with the same threshold value (70 %) for each separate PCNN image. To avoid blurring the edges at the filtering phase it is also tested if the pixel is in the edge of a segment. This is done by dividing the 5x5 window in two halves in four ways corresponding to edges in the row and column directions and in the diagonal directions. Then the pixels are counted in the halves, and if the count is greater than a threshold in the other half and less than a threshold in the other half then the pixel is an edge pixel. If the pixel then already has value one, the pixel is set to one. Another test is to test if the pixel is on a (smooth) curve. We study this by examining the four lines through the mid-pixel in the window in the row, column and diagonal directions, and if the pixel has value one and some of these lines has more pixels than a threshold the pixel is allowed to keep the value one. After the post-processing, the PCNN images are combined to produce a preliminary classification image with four classes.

The next step in our algorithm is to identify the following important ice categories: open water, deformed ice field and fast ice. The identification of each ice type requires additional analysis with new features. The identification of fast ice area is performed first. The fast ice area requires a separate identification because the backscattering intensity varies strongly in this ice class inside one image and from one image to another due to many factors, e.g. the incidence angle and the wetness of snow. The fast ice represents the oldest ice appearing in the Baltic Sea. Probably one reason to its textureless appearance in the SAR image is that this ice field has undergone many melting and refreezing periods. Another likely reason to the peculiar backscatter behaviour from fast ice may be that backscattering includes in this case a significant volume scattering component. The thick snow cover over the fast ice may cause that important part of the backscattering takes place in the frozen parts inside the snow pack and hence this part of backscattering is totally independent on the ice.

Anyway, the fast ice areas do not possess even by visual inspection many features in a C-band SAR image.

The fast ice identification requires the knowledge of exact location of shoreline. To this end, the image location is improved by comparing it to a digitised map of the Baltic Sea. Some fixed control points, which are distributed along the shoreline of the Baltic Sea, are used at this phase. It is known that fast ice can appear near shoreline only if the sea is shallow or in the archipelago. Using this prior information, we can define the areas where it is possible for fast ice to appear. These areas are drawn in a map of the Baltic Sea and the corresponding parts in a SAR image are computed by utilising the geographical information available. We say that these possible fast ice areas are in the zone, i.e. the image pixel may be in the zone or not. In addition, the shoreline pixels are located by performing a search in the neighbourhood of each non-background pixel adjacent to background pixel(s). If the pixel is adjacent to a pixel representing land in the Baltic Sea map, then the pixel is a shoreline pixel, else not. Because of inaccuracies in the fitting of the map and image together, we need to search a small (larger than one) neighbourhood of each shoreline candidate pixel.

The zone information is used in our adaptive fast ice algorithm. The class distribution for the shoreline pixels adjacent to the zone pixels is computed. According to this distribution is decided which classes of the preliminary classification may belong to the fast ice class. The algorithm assumes that there can be two classes for each image that may belong to the fast ice class. The possible pairs are thicker ice - thick ice or thick ice - thickest ice. Then the fast ice is found by starting from all the shoreline pixels and advancing into eight basic directions, i.e. in the directions of the coordinate axes and diagonals, until some other class or background pixel is reached. This result is then filtered by using a nxn (n=3) mode filter and removing 1% of pixels that have advanced furthest from the edges. Additionally a morphological filtering to create a connected area is performed. In the morphological filtering, first a closure with a small rounded block is computed and then an opening with the same object is computed.

To extract open water areas and deformed ice fields from an image, two additional features are computed. The features used were selected because they are robust to the gradual changes in the intensity level due to the incidence angle effect. These features are autocorrelation mean, Similä, 1994, and the signal-to-noise ratio (SNR). The autocorrelation (mean) value is threshold to locate possible open sea areas and SNR to locate deformed (rough) ice and level (even) ice. These two features are computed from the original image using a window size of 11x11 pixels. The sampling rate is five in both directions thus producing images of similar size as the downsampling process does. The 2-D autocorrelation is computed as

$$R_{xx}(k,l) = \frac{1}{N_{in}} \sum_{i} \sum_{j} X(i,j)\,X(i-k,j-l) \qquad (10)$$

The sum is computed for those pixels x(i,j) for which both x(i,j) and x(i-k,j-l) are in the window and N_{in} is the number of these pixels. We used the mean of the four autocorrelation values with lag values (k,l) = { (0,1), (1,0), (1,1), (1,-1) }. This mean computation is performed to eliminate the directional information, i.e. to achieve rotation invariance.

The SNR was computed in a window (m = E(x), s^2 = Var(x))

$$\mu = \frac{1}{N}\sum_{i=1}^{N} X_i \qquad (11)$$

$$\sigma = \sqrt{\frac{\sum_{i=1}^{N}(x_i-\mu)^2}{N-1}} \qquad (12)$$

$$SNR = \frac{\mu}{\sigma} \qquad (13)$$

The sums are over the pixels in the window, containing N pixels. The SNR based classes are derived simply by thresholding: if SNR value around a pixel is less than a threshold then the pixel is classified to deformed ice class and if the SNR value exceeds another (the thresholds are not the same, and all ice is not either deformed or level ice) threshold the pixel is classified to level ice.

The identification of open water areas is a difficult task. The dominating scattering mechanism from open water at the incidence angles, where RADARSAT operates, is the Bragg resonance that is due to the capillary waves (the length of these waves is of order one mm). However, the wind field, its speed and direction, can modify the waves and their appearance in a SAR image also by other means than through the capillary waves. Hence, it may happen that some parts of open water area may appear very dark in a SAR image and some parts very bright. There does not exist any simple, single rule that would identify open water areas. In addition, by visual inspection the identification of open water areas is in some cases difficult. The randomness assumption, which is behind the use of the autocorrelation feature, is compatible with Bragg resonance but a wide variety of different wave field situations contradict it. Hence, we have resorted to a multitude of different rules, which together are used to identify open water areas.

The autocorrelation value is used in the following way. The value is thresholded in a 7x7 window around the pixel (in the downsampled scale) and if there are more than a threshold number of pixels with autocorrelation values less than an autocorrelation threshold (lower ac-threshold) and additionally less than another threshold number of pixels with autocorrelation values more than another autocorrelation threshold (upper ac-threshold), the pixel is preliminary classified to open sea. Then segments smaller than a threshold size are filtered because very small open sea segments are typically errors. After this, a filling procedure is performed for the open sea areas. If the autocorrelation values in the neighbourhood of the open sea areas are less than a threshold, the pixels are filled with open sea. This filling is done only in areas restricted to an area of the bounding box of the open sea segment extended by a number of pixels in each four directions. Here an extension limit of 30 pixels is used. Then we further analyse the classification result by studying some shape features and location information of the open sea segments still left. We compute the following values for the open sea segments: segment size (area), bounding box dimensions, ratio of the bounding box longer dimension to the shorter one, area divided by bounding box area, mean number of changes to open water in row and column directions inside the bounding box, proportional amount of edges of the segment and proportional amount of the segment in the zone. These values are used to generate evidence if the segment really is open sea or not. The most significant single rule is that the segment is regarded as open water if the size of the segment is large enough. However, many other rules are also utilised. The purpose of these rules is to prune some unlike open water segments. For example, small scattered segments in or near the zone areas are typically erroneous. The open water identification phase is ended with a similar morphological filtering as with the fast ice class. However, the order of the morphological operations is reversed, now an opening is performed first and then a closure.

Based on the backscattering behaviour of radar signals and the visual interpretation of the segmented SAR scenes vs. ice charts provided by the Finnish Ice Service the following ice type classification is performed. The four preliminary ice classes produced by the PCNN that were described earlier are augmented by the ice types provided by fast ice identification, SNR-analysis and autocorrelation feature. The used ice types are summarised in Table 3.5.

Table 3.5 ***The classes produced by the algorithm.***

Class	Properties	Produced by
Thin ice	Low backscattering	PCNN
Thick ice 1 and 2	Varying backscattering	PCNN and SNR
Slightly deformed ice (def. ice 1)	Large deviation in backscattering	SNR
Deformed ice (def. ice 2)	High backscattering	PCNN
Open sea	Low autocorrelation	Autocorrelation threshold

Figure 3.26 ***A sample SAR image from the winter 1998***.

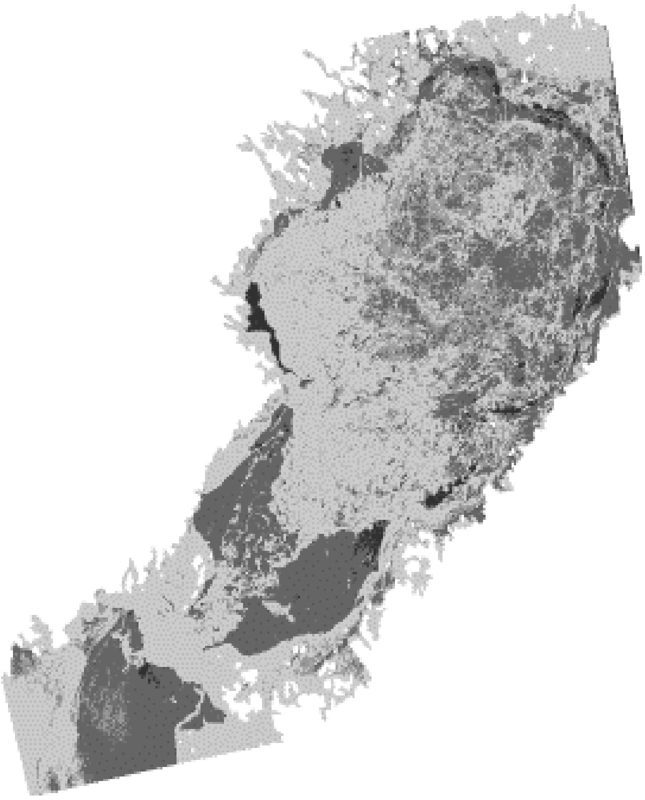


Figure 3.27 ***The PCNN produced preliminary classification into four classes. The darker areas are areas with lower backscattering.***

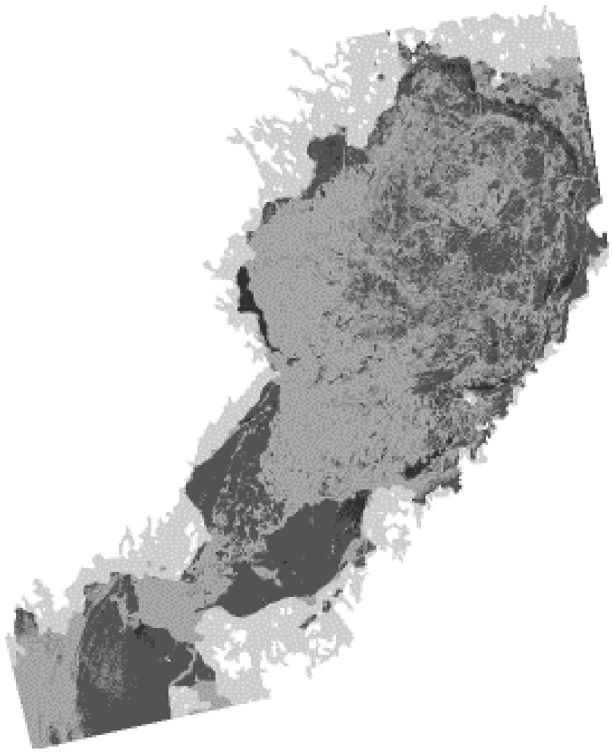


Figure 3.28 ***The fast ice algorithm applied to the PCNN preliminary classification of Fig. 3.27. The fast ice class is the lightest (non-background) grey tone.***

Figure 3.29 ***The autocorrelation image. The values are computed in 11x11 windows. The values are scaled in such a way that white corresponds to an autocorrelation value of one and black to a value of zero.***

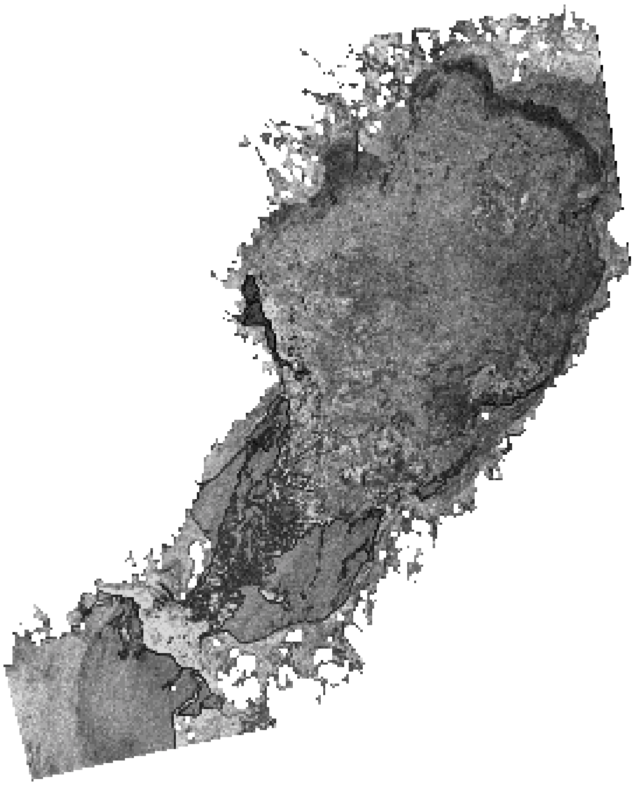


Figure 3.30 ***The SNR image. The SNR is computed in 11x11 windows and linearly scaled and saturated from 1.2 to 12.***

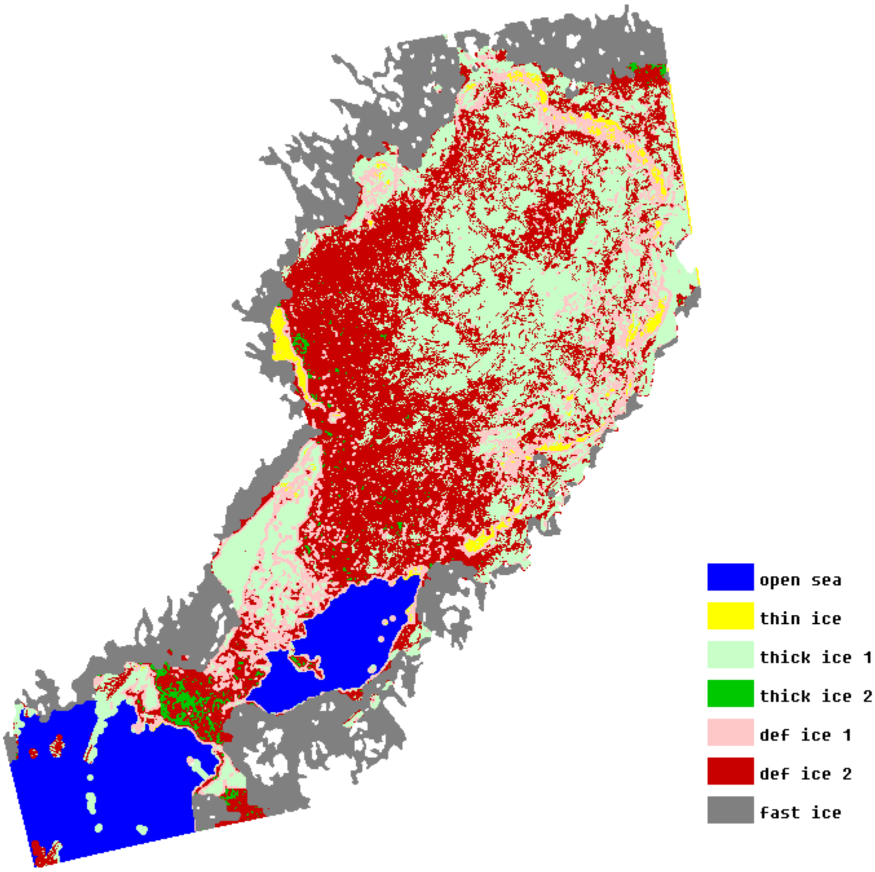


Figure 3.31 ***The resulting classification image for the image in Fig. 3.26.***

After this the resulting grey tone image is post-processed to produce a visually more readable ice chart, a legend is added to the image and it is converted to a colour image using a predefined colour map. The different classification steps are illustrated in Fig. 3.26 to 3.31.

3.3 Ice classification techniques for SAR and MWR data in the Baltic Sea

HUT investigated in co-operation with Finnish Marine Research Institute (FIMR) combined use of SAR and passive microwave radiometer (MWR) data for classification of open water and various ice types in the Baltic Sea. HUT also aided FIMR in the development of the RADARSAT and ERS-2 SAR sea ice classification algorithms by studying C-band backscattering signatures of various Baltic Sea ice types.

3.3.1 Combined use of SAR and MWR data in the Baltic Sea

Single-channel ERS-2 or RADARSAT SAR data may not be adequate to discriminate open water from sea ice and deformed areas from level ice areas regardless of ice and snow cover conditions. However, with the supplementation of the SAR data with only a single-channel low-frequency MWR data the discrimination of open water from sea ice would be more certain due to the high brightness temperature contrast between sea ice and water. Use of multi-frequency MWR data together with SAR data could also help to discriminate deformed areas from level ice areas, due to different surface roughness and ice characteristics of these two ice classes.

Combined use of SAR and MWR data in the Baltic Sea was studied using:

(a) airborne MWR (6.8-34 GHz) and SAR (ESAR and EMISAR) data from the ESA EMAC-95 (European Multisensor Airborne Campaign) sea ice campaign,

(b) airborne MWR (18.7-36.5 GHz) and RADARSAT ScanSAR wide data from the IMSI-97 Baltic Sea ice campaign.

EMISAR is an L- and C-band polarimetric SAR, (Dall et. al., 1997) and ESAR is P/L/C/X-band SAR with HH- and VV-polarisation, (Horn, 1997). MWR measurements were conducted with profiling (non-imaging) HUT radiometer system, (Hallikainen et al., 1998). The nominal incidence angle of the radiometers was 50°, but the actual incidence angle depended slightly on the pitch angle of the aircraft. Airborne MWR data was used instead of SSM/I data because its resolution is comparable to SAR data. The data sets covered a variety of ice conditions, ranging from winter ice (dry snow cover) to spring ice (partly melted ice and wet snow cover). MWR and SAR data were classified by video imagery to open water and different ice types, (Table 3.8).

The ground truth measurements provided classification of the MWR and SAR data into the following snow cover categories: (1) dry snow, (2) moist snow (volumetric wetness < 1%) and (3) wet snow (wetness > 1%). According to a previous study by (Hallikainen et al., 1986), the penetration depth in snow cover decreases rapidly as a function of snow wetness when the wetness is below 1%. The decrease is noticeably slower, when the wetness is above 1%.

The study consisted of the following steps:

1) classification of open water and ice types with MWR and SAR data only,
2) using combined sets of MWR and SAR data as in task 1), and
3) comparison of classification results obtained using approaches 1) and 2).

Classification of the Baltic Sea surface types with MWR data

Open water leads are distinguished from all sea ice types except from very young new ice using single-channel MWR data in the frequency range 6.8-36.5 GHz, either V- or H- polarisation, regardless of the wetness of the snow cover. This is due to the high brightness temperature contrast between water and ice. The sea surface on leads was calm and foam-free. Typically, the leads were from a few hundred meters to a few kilometres wide.

Classification was studied using various two-dimensional combinations of polarisation (PR) and gradient ratios (GR):

$$PR = \frac{T_B(f_1,V) - T_B(f_1,H)}{T_B(f_1,V) + T_B(f_1,H)}, \tag{14}$$

$$GR = \frac{T_B(f_2,P) - T_B(f_1,P)}{T_B(f_2,P) + T_B(f_1,P)}, \tag{15}$$

where T_B is brightness temperature, f_1 and f_2 are frequencies ($f_1 < f_2$) and P is either H- or V-polarisation. The principal component analysis indicated that the MWR data sets are mainly one- or two-dimensional (contain 90% of the variance of the data set). The classification results are summarised in Table 3.6. Discrimination between the ice types was determined with the 90% confidence ellipses. The best ice type classification result is achieved under dry snow condition, although the frequency range of the data is only 6.8-18.7 GHz. Only in the partial dry snow cover case was the data amount so large that the results can be considered statistically reliable.

Table 3.6 ***Classification of the Baltic Sea ice types using airborne profiling MWR data.***

Snow Class	Data Source	Frequency Range [GHz]	No of Ice Types	Best Algorithm [GHz]	Classification Results
Partial dry snow cover	IMSI-97 20, 23 Mar	18.7 - 36.5	6	PR 18.7 and GR 18.7/36.5 V-pol	Ice types are not distinguished.
Dry snow cover	EMAC-95 22 Mar	6.8 - 18.7	4	PR 10.65 and GR 10.65/18.7 V-pol	Ice types are distinguished reliably.
Moist snow	EMAC-95 5 Apr	6.8 - 24	4	None	Ice types are not distinguished. NI was not measured.
Wet snow	EMAC-95 3 May	6.8 - 34	2	PR 6.8 and GR 6.8/34 V-pol	Only RLI and HDI were measured. They are distinguished reliably.

Capability of the NASA Team and Bootstrap algorithms for the Baltic Sea ice mapping

The large separation between the signatures of open water leads and various ice types suggests that it is possible to use spaceborne MWR data to derive sea ice concentration at least within the ice pack. Applicability of the SSM/I data and the NASA Team, (Cavalieri et al., 1991) and Bootstrap, (Comiso et al., 1997), algorithms for the Baltic Sea ice mapping was estimated using the partial snow cover data.

A scatter plot using the PR and GR ratios of the NASA Team algorithm is presented in Figure 3.32. The NASA Team algorithm triangle using the Arctic, (Cavalieri et al., 1991) and Baltic Sea tie points (Grandell and Hallikainen, 1994) is also shown. The data were averaged to a resolution of 100 m. Most of the open water measurements were conducted at an incidence angle of 45°. The Baltic Sea tie points agree better with the airborne PR-GR signatures than the Arctic tie points. However, the airborne PR-GR signatures for various ice types are scattered over a large area and they even extend to the multiyear ice tie point. This does not necessarily mean that the NASA Team algorithm is not applicable in the Baltic Sea because at the 100 m resolution of the airborne data the signatures of various ice types are probably always quite variable whereas at the resolution of the gridded SSM/I data, 25 km, the fine scale emissivity variations average out, and the signatures of the same ice types are very close to each other.

The poor resolution of the SSM/I data was simulated by representing each surface type with the mean and standard deviation of the PR-GR values, Figure 3.32b. The mean PR-GR values are very close to the Baltic Sea first-year ice tie point and the standard deviations are quite small. This suggests that it is not possible to modify the NASA Team algorithm to map concentrations of new ice and all other ice types together in the Baltic Sea as has been done in the Arctic seasonal ice areas, (Cavalieri, 1994). Further, this means that the formulation of the algorithm, in general, may not be applicable for the Baltic Sea. The algorithm triangle should be replaced with a single line connecting the open water and 100% ice concentration tie points. In this case, the ice concentration can be obtained using only PR or both PR and GR for greater dynamic range.

Applicability of the Bootstrap algorithm was studied in a similar way, Figure 3.33. The results suggest that it is possible to use it to map total ice concentration, but the line AD in the algorithm passing through the clusters of various ice types should be very short or even be replaced by a single point.

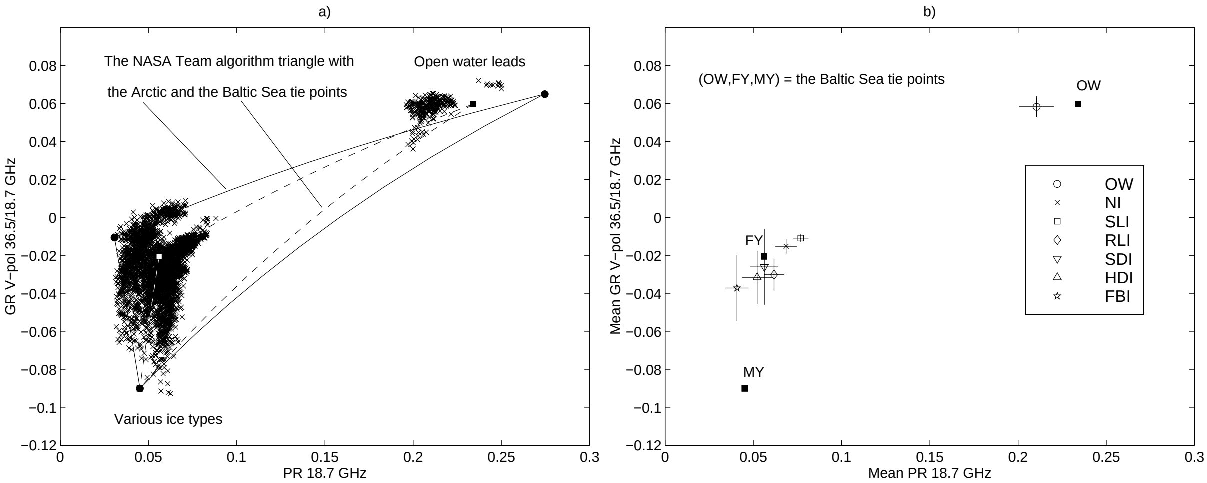


Figure 3.32 ***a) A scatter plot and b) mean and ±1 standard deviation confidence limits of PR 18.7 GHz versus GR V-polarisation 36.5/18.7 GHz using the partial dry snow cover MWR data. The data were averaged to correspond to a resolution of 100 m.***

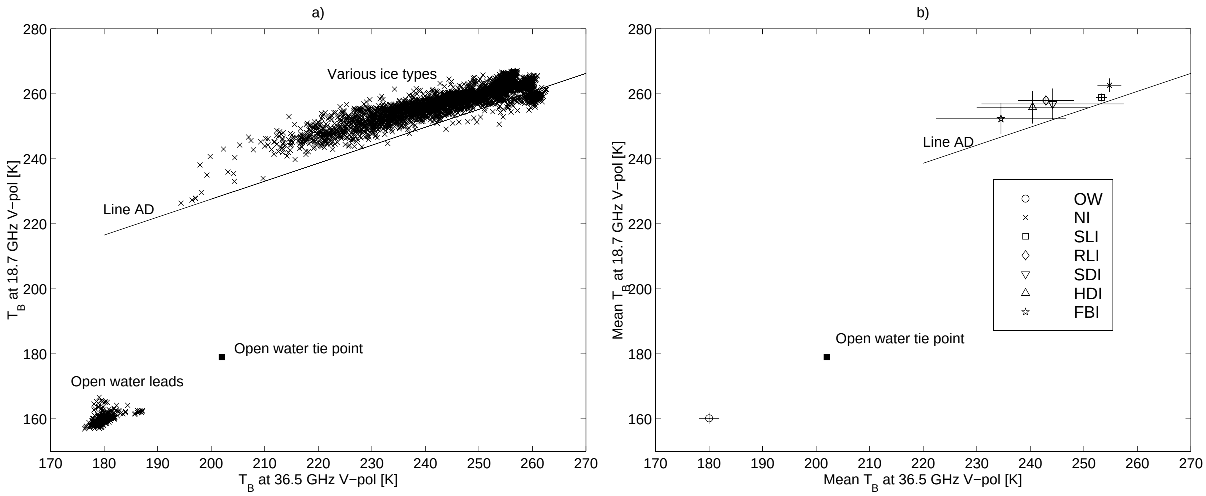


Figure 3.33 ***a) A scatter plot and b) mean and ±1 standard deviation confidence limits of 36.5 GHz V-polarisation versus 18.7 GHz V-polarisation brightness temperatures using the partial dry snow cover MWR data. The data were averaged to correspond to a resolution of 100 m.***

Classification of the Baltic Sea surface types with combined MWR and SAR data

The MWR and SAR data were combined by extracting strips from the SAR images equivalent to those of the MWR measurement flights. The pixels of the ESAR and EMISAR strips were averaged in 100 by 50 m blocks and the pixels of the RADARSAT strips in 1000 by 100 m blocks. The MWR data were averaged to the corresponding SAR resolutions. The RADARSAT data was absolutely calibrated with the aid of the HUTSCAT scatterometer data. The accuracy of pixelwise matching of MWR and SAR strips is unknown but it is probably not very good as the correlation between different MWR and SAR channels was usually surprisingly low. Classification of ice types was tested using various combinations of MWR polarisation and V-polarisation gradient ratios and SAR channels and co- ($\sigma°_{HH}/\sigma°_{VV}$) and cross-polarisation ($\sigma°_{HH}/\sigma°_{HV}$) ratios. Unsupervised or supervised classifiers were not developed due to the small data amount. Ice type discrimination with the SAR data only (i.e. backscatter coefficients) was also investigated. The combined data sets and the classification results are presented in Table 3.7.

Table 3.7 ***Classification of the Baltic Sea ice types with the combined MWR and SAR data.***

Snow Class	SAR Data, Inc. Angle	MWR Data [GHz]	No of Ice Types	Classification Results
Partial dry snow cover	RADARSAT 32°	23.8 36.5	5	Ice types are not discriminated using either the MWR or SAR data alone or both of them together.
Partial dry snow cover	RADARSAT 45°	18.7 23.8 36.5	3	Ice types are not discriminated using either the MWR or SAR data alone or both of them together.
Dry snow	EMISAR L-band 53°	10.65 18.7	4	Ice types are discriminated with the MWR data but not with the SAR alone. The combination MWR and SAR data increases the ice type discriminations.
Moist snow	ESAR: L_{VV}, $C_{HH/VV}$, $X_{HH/VV}$ 48°	6.8 18.7 24 V	3	Small data amount and the small number of different ice types prevent making any reliable conclusions.

The classification results cannot be considered statistically very reliably as the data amount and number of different ice types were very small. To fully conclude the classification capability of the combined MWR and SAR data, much more data with different SAR incidence angles, wider MWR frequency range and different snow cover wetness should be acquired. A high-frequency MWR channel, like 94 GHz, could improve the classification results due to higher sensitivity to snow cover characteristics. It is also noted that in this study, only one-dimensional MWR and SAR data were used, and it is possible that better classification results are obtained with two-dimensional data, when also second order texture parameters can be utilised.

Comparison of the classification results obtained by the combined MWR and SAR data and by the SAR data alone (i.e. the results of FIMR) was not considered to be meaningful due to the small amount of the combined data.

The current (SSM/I) and near future (e.g. EOS PM-1 AMSR) spaceborne MWR data are not useful alone for monitoring the Baltic Sea ice for ship navigation purposes due to their very poor spatial resolution. In the Baltic Sea, spaceborne MWR data are mainly useful for helping to develop SAR classification algorithms. The SAR algorithms could be adjusted for example by comparing MWR and SAR derived ice concentrations to each other. The determination of the applicability of the NASA Team and Bootstrap algorithms in the Baltic Sea or development of a new better ice concentration algorithm requires further studies using both airborne and spaceborne MWR data. Particularly, the effect of snow cover wetness needs to be investigated.

3.3.2 C-band backscattering signatures of the Baltic Sea ice

Identification of different ice types and open water in ERS-2 and RADARSAT SAR images has been studied by FIMR using several classification algorithms, including co-occurrence matrix based clustering and pulse-coupled neural networks. Interpretation of the classification results is often difficult because the classification algorithms utilise mainly the image structure and only in a very general level physical reasoning. The algorithms do not employ information on backscattering signatures of different ice types under different snow and ice conditions. The classification results could very likely improve if this kind of physical information is utilised.

The development of the sea ice classification algorithms for the RADARSAT and ERS-2 SAR and forthcoming ENVISAT ASAR (Advanced SAR) images is supported by analysis of C-band backscatter measurements of different Baltic Sea surface types. The measurements were conducted with the helicopter-borne C- and X-band (5.4 and 9.8 GHz) non-imaging HUTSCAT scatterometer, Hallikainen et al., 1993, during six ice research campaigns in 1992-1997. In 1992-1995, the measurements were conducted at incidence angles of 23 and 45 degrees. During the IMSI-97 campaign, also an incidence angle of 34 degrees was used. The HUTSCAT data were assigned by video imagery to different ice types, (Table 3.8). The ground truth data provided classification of the data into different snow wetness classes. HUTSCAT data were used to investigate:

1) variation of the backscattering coefficients as a function of incidence angle,
2) statistical properties of the backscattering coefficients, and
3) the effect of snow cover wetness on previous studies.

Accuracy and noise floor of the HUTSCAT scatterometer

Relative accuracy is ±0.3 dB at all channels. Absolute accuracy is ±0.8 dB at 5.4 GHz HH- and ±0.5 dB at VV- and VH-polarisation (90% confidence intervals). The noise equivalent $\sigma°$ at incidence angle of 23 degrees is around -25 dB at 5.4 GHz HH- and -28 dB at VV-polarisation. The noise $\sigma°$ depends slightly on measurement distance and incidence angle.

Table 3.8 ***Baltic Sea ice type classes assigned for MWR, SAR and HUTSCAT data.***

Main group	Sub groups	Abbr.	Effect to ship navigation
Open water leads	None	OW	None
New ice	None	NI	None
Level ice	Smooth level ice Rough level ice	SLI RLI	Depends on thickness
Deformed ice	Slightly deformed ice Highly deformed ice	SDI HDI	Slows down or blocks navigation Usually blocks navigation
Brash ice	Loose brash ice Frozen brash ice	LBI FBI	Depends on thickness

Variation of 5.4 GHz HH- and VV-polarisation $\sigma°$ as a function of incidence angle

Average differences between mean HUTSCAT 5.4 GHz HH- and VV-polarisation $\sigma°$ (equivalent to RADARSAT and ENVISAT) at incidence angles of 23 and 45 degrees for different ice types are presented in Table 3.9. The mean $\sigma°$ was calculated from the HUTSCAT data averaged in 25 m intervals. This resolution is four times better than the resolution of the fast delivery RADARSAT ScanSAR narrow images used in the Baltic Sea ice mapping by FIMR. However, the average difference does not depend on the resolution of the HUTSCAT data.

Table 3.9. ***Differences between 5.4 GHz HH- and VV-polarisation mean backscattering coefficients of incidence angles of 23 and 45 degrees.***

Difference	NI		SLI		RLI		SDI		HDI		LBI		FBI	
	HH	VV	HH	VV	HH	VV	HH	VV	HH	VV	HH	VV	HH	VV
Max	5.5	6.4	7.3	5.6	5.0	6.3	5.9	5.4	4.9	5.5			3.4	3.6
Min	1.5	2.3	2.6	3.5	3.6	4.5	2.3	2.4	1.4	2.0			1.4	1.4
Mean	3.9	4.0	4.9	4.7	4.4	5.1	4.1	4.1	2.9	3.4	-	-	2.7	3.0

The difference between the values at the two incidence angles depends on ice type and on measurement date, i.e. on specific ice condition. No clear relationships between the difference and snow wetness were observed. On average, the difference is the smallest for HDI and brash ice types. The mean differences for other ice types are within an interval of 1 dB and higher than the means for HDI and brash ice types. However, for NI it is probably not possible to define general mean difference, as here NI is a common definition for all different new ice types less than 10 cm thick. It is noticeable that the mean difference is smaller for HDI than for SDI indicating that when the degree of deformation increases, the difference decreases. This is probably caused by the weaker incidence angle dependence of ridge σ° compared to level ice σ°.

The HUTSCAT derived incidence angle dependencies of σ° can be used to remove the incidence angle variation in the RADARSAT ScanSAR and ENVISAT wide swath SAR images. The variation of the incidence angle in the RADARSAT SAR images has been observed to complicate their classification. The variation of the incidence angle in the RADARSAT SAR images over the Bay of Bothnia and the Sea of Bothnia is less than 10 and 15 degrees, respectively. Over the Gulf of Finland it can be over 15 degrees due to the east-west elongated geometry of the area. The range of the incidence angle values in the RADARSAT SAR images over a same sea area is very variable because it depends on the incident angle range of the whole image and the imaging geometry. Removal of the incidence angle variation in the SAR images may improve classification results. The exact removal is, however, quite impossible because the incidence angle dependence is different for various ice types. In practice, uniform linear scaling (in dB scale) of the whole image to a certain incidence angle is probably the only possible method. The basis for the scaling could be like around 4 dB mean difference between the angles of 23 and 45 degrees (corresponds to 0.182 dB/deg). This scaling would be on average correct for SDI, less than 0.06 dB/deg too high for HDI and brash ice types and less 0.05 dB/deg too small for SLI and RLI. When the incidence angle to which all σ° in a SAR image are scaled is chosen to be the mean angle over some sea area, the accuracy of the uniform scaling is quite good as the maximum angle shift is always less than 10 degrees.

Statistical parameters of 5.4 GHz backscattering coefficients

Various basic statistical parameters of σ° were used to study discrimination of open water from sea ice and classification of different ice types. The statistical parameters were calculated both for the large HUTSCAT data sets and for the small parts of these data sets. A large data set consists typically of all measurements conducted during a same day. Small parts of these data sets are for example sets of nine consecutive values of σ°. Before calculating the statistical parameters the HUTSCAT data were averaged to a resolution of 25 m. At this resolution the fading in a single σ° is negligible and, thus, the consecutive σ° values represent true spatial variation of target σ°.

Mean and 90% confidence limits of HH- and VV-polarisation σ° of large data sets

The mean σ° usually increases with increasing ice deformation (Figure 3.34). The mean σ° for open water leads is varying variable as it depends on the wind speed and direction. The variation of mean σ° as a function of ice type is the largest under dry snow and the smallest under wet snow condition. Moist and wet snow attenuate or even block totally backscatter from underlying sea ice, and, thus, probably reduce the spatial variation of mean σ° from one ice type to another. The variation of mean σ° is around 0.5-3.0 dB larger at an incidence angle of 45 degrees than at 23 degrees because σ° of NI and level ice types decreases more with increasing incidence angle than σ° of deformed ice types. Under every snow wetness condition, the 90% limits of both VV- and HH-polarisation σ° are so large that discrimination of open water from sea ice and unambiguous classification of different ice types is not possible with only σ° values. Usually the 90% limits of open water leads at 23 degrees are within the 90% limits of the most of ice types whereas at 45 degrees they are only within the limits of NI.

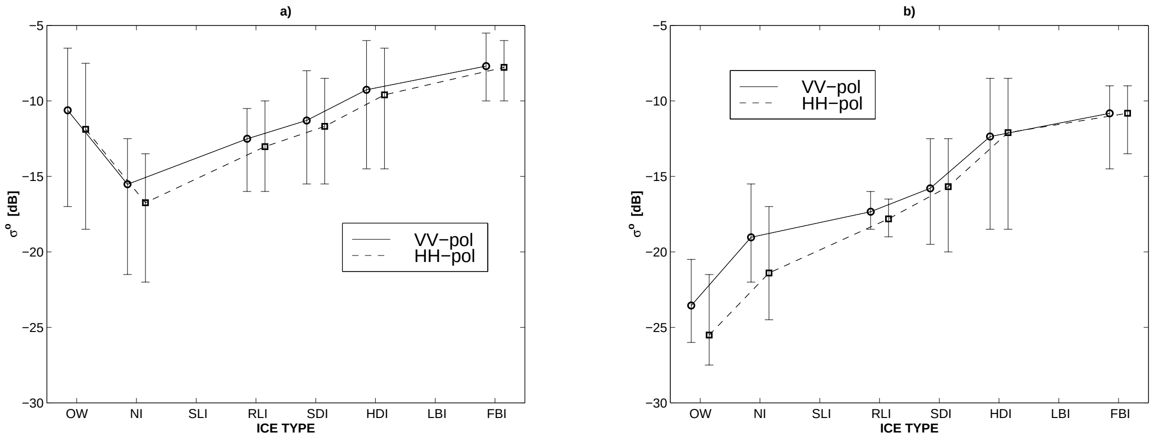


Figure 3.34 ***Mean and 90% confidence limits of 5.4 GHz VV- and HH-polarisation σ° of different ice types using the moist snow data measured on 26 March 1994. The data were averaged to the resolution of 25 m. The incidence angles are a) 23 and b) 45 degrees.***

Probability density functions (PDFs) and Maximum-likelihood classification of HH- and VV-polarisation σ° of large data sets

PDFs of the 5.4 GHz HH- and VV-polarisation σ° were estimated with the Parzen method using a Gaussian kernel function (Figures 3.35. and 3.36.). The PDFs of the VV- and HH-polarisation are very similar in shape. Under dry snow condition separation between the PDFs of different ice types is roughly equal at incidence angles of 23 and 45 degrees. Under moist and wet snow condition the PDFs are, on the contrary, wider apart at 45 degrees than at 23 degrees.

After the estimation of the PDFs a Maximum-likelihood classification of σ° was conducted, to study the accuracy of the intensity based classification. Same data were used in the classification and in the estimation of the PDFs. The mean accuracy of the classification is in all cases quite poor, only between 43-68%. This indicates that it is not possible to classify different surface types only by their backscatter level. On average, there are no differences between discrimination capabilities of HH- and VV-polarisation. Under moist and wet snow condition, the mean accuracies are 8-20% better at 45 degrees than at 23 degrees. Under dry snow condition there are, on the contrary, no large differences between these two incidence angles. It was always possible to determine a cut-off level for σ° below which an ice type is most likely not one of the deformed and brash ice types. This level is also quite equal in different data sets of moist snow condition. The determination of the cut-off level above which ice type belongs to deformed or brash ice types was not always possible at 23 degrees due to the location of the open water PDF.

The results suggests that at least under moist and wet snow condition SAR images with high incidence angle range (e.g. 40-50 degrees) are better for classification of different surface types than images with low incidence angle range (e.g. 20-30 degrees). The accuracy of Maximum-likelihood classification was so poor that probably just visual interpretation of SAR images gives better results than automatic only intensity based classification. The cut-off levels could be useful in automatic classification algorithms to help to determine the ice type.

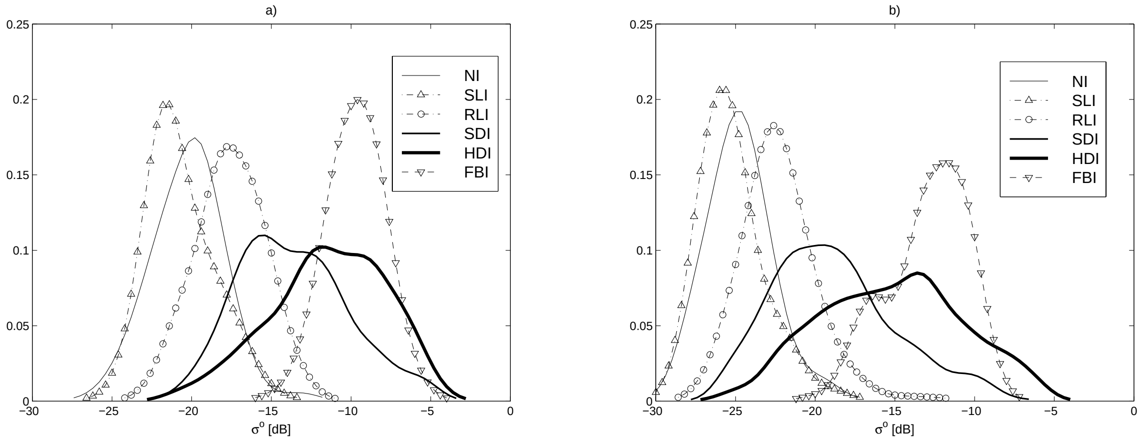


Figure 3.35 ***PDFs of the 5.4 GHz HH-polarisation σ° of different ice types using the IMSI-97 dry snow data averaged to the resolution of 25 m. The incidence angles are: a) 23 and b) 45 degrees.***

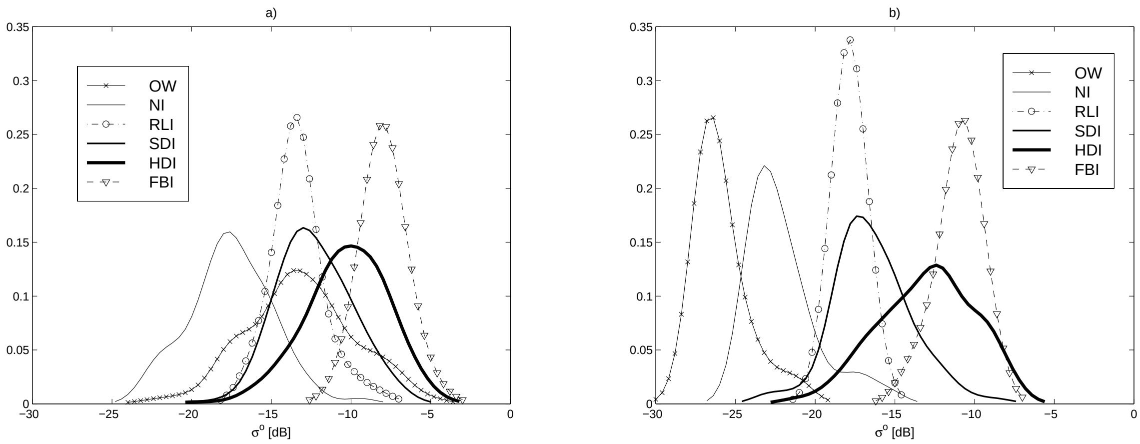


Figure 3.36 ***PDFs of the 5.4 GHz HH-polarisation σ° of different ice types using the moist snow data measured on 26 March 1994. The data were averaged to the resolution of 25 m. The incidence angles are: a) 23 and b) 45 degrees.***

Mean and standard deviation of small sets of HH- and VV-polarisation σ°

Mean and standard deviation were calculated for sets of nine consecutive 5.4 GHz HH- and VV-polarisation σ° averaged to a resolution of 25 m. The interval of nine σ° was moved step by step over the averaged data. Mean and standard deviation of these nine σ° can be considered to be equivalent to the mean and standard deviation of a 3 times 3 pixels window in the SAR image.

Unambiguous discrimination of surface types only with the mean or standard deviation is not possible under any snow cover condition. The standard deviation alone is poorer for surface type discrimination than mean or single σ° alone. Mean standard deviations at HH- and VV-polarisation are under all snow cover conditions very close to each other (difference < 0.5 dB). The 90% limits of standard deviations are also on average equal. This means that the magnitudes of the textural variations of HH- and VV- polarisation σ° are roughly equal. The mean standard deviation is usually the largest for deformed ice types and NI and the smallest for brash ice types. The standard deviation depends slightly on incidence angle (less than 1 dB). In general, the standard deviation depends on incidence angle, ice type and specific ice condition.

An example of the means and standard deviations at HH-polarisation is presented in Figure 3.37. The ellipses represent 90% confidence limits calculated by principal component analysis. Combined use mean and standard deviation does not either make possible unambiguous discrimination of all surface types. The difference between HH- and VV-polarisation in the discrimination of surface types is very small. In some cases, the combination of mean and standard deviation increases discrimination of the surface types compared to using only mean or single $\sigma°$. In Figure 3.37 where FBI is partially discriminated from deformed ice types and RLI is further separated from SDI with the aid of the standard deviation. It is usually possible to determine in the mean-standard deviation coordinates areas where the ice type is most likely one of deformed, brash or level ice types, or NI. This kind of information could be useful in the automatic classification algorithms of the SAR images.

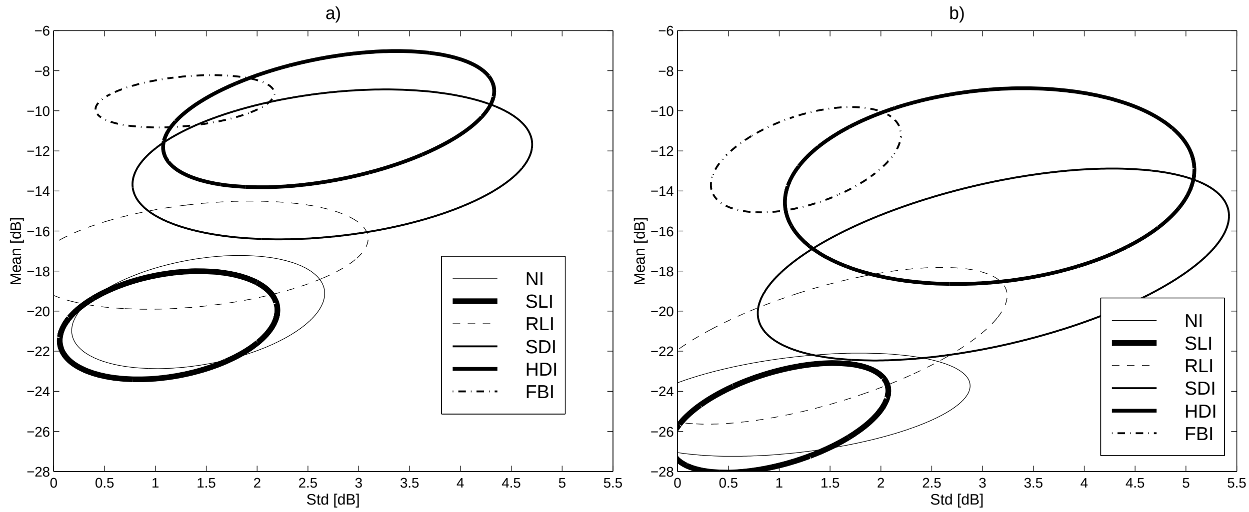


Figure 3.37 ***Mean and standard deviation of nine $\sigma°$ of different ice types at 5.4 GHz HH-polarisation using the IMSI-97 dry snow data averaged to the resolution of 25 m. The ellipses represent 90% confidence limits. The incidence angles are a) 23 and b) 45 degrees.***

Cross-polarisation $\sigma°$, co- and cross-polarisation ratios of large data sets

The operation modes of the ENVISAT ASAR include an alternating polarisation mode, which produces two images at either HH- and VV-, HH- and HV- or VV- and VH-polarisation. Only intensity based discrimination capabilities (i.e. no textural information) of these images were estimated by studying statistical properties of the 5.4 GHz cross polarisation $\sigma°$, co-polarisation ratio ($\sigma°_{HH}/\sigma°_{VV}$) and cross-polarisation ratio ($\sigma°_{HH}/\sigma°_{VH}$). Unambiguous discrimination of surface types is not possible either with these variables. The mean accuracy of the Maximum-likelihood classification using any one of the three variables is in all cases quite poor, only between 24-68%. The mean accuracy is in all cases the largest for the cross polarisation $\sigma°$ and around 6-32% and 10-29% smaller for the cross- and co-polarisation ratios, respectively. The mean accuracy is usually the smallest for the co-polarisation ratio. The accuracy of open water leads identification is very variable for all three variables, e.g. even from 0% to 96% for cross polarisation $\sigma°$. On average, the cross-pol ratio is the best of the three variables for open water leads identification.

The mean accuracies for C-band (5.4 GHz) HH-, VV- and cross polarisation are so close to each other that it is not possible determine which of these polarisation's is the best one for surface type classification. For open water leads identification, the cross-polarisation ratio is the best of the five C-band variables.

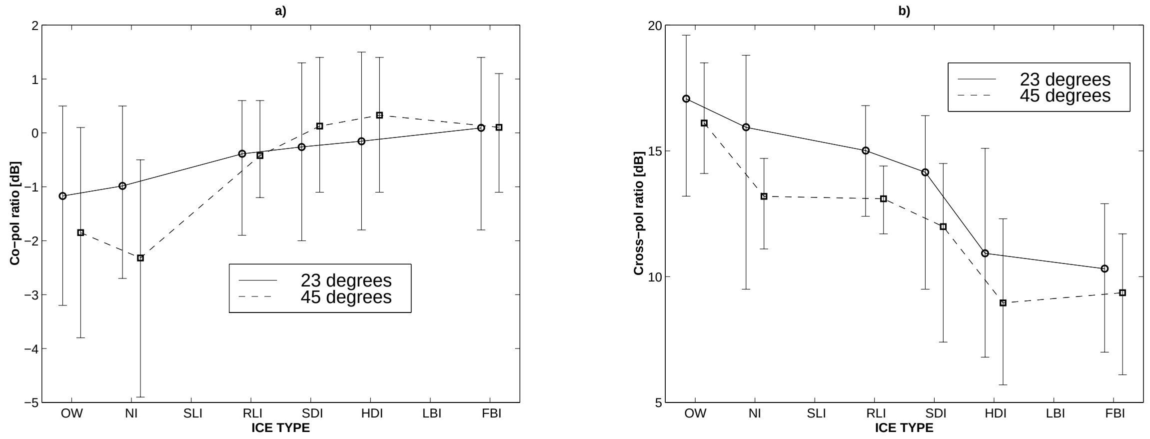


Figure 3.38 ***Mean and 90% confidence limits of 5.4 GHz a) co-polarisation ratio and b) cross-polarisation ratio of different ice types using the moist snow data measured on 26 March 1994. The data were averaged to the resolution of 25 m.***

3.4 Ice charting methods for Greenland waters using RADARSAT data

During product development and geophysical validation work, the effort has been concentrated on tree main tasks and objectives:

- Investigation of operational set-up for using RADARSAT.
- Geophysical validation with simultaneous underflights.
- Development of enhancement filters for ice features.

The main interest of the Danish Meteorological Institute (DMI) in evaluating the data from the Canadian RADARSAT is to determine whether the quality of the data and the temporal coverage of the relevant waters are sufficient for its operational sea ice mapping service. An equally important factor is whether this can be carried out cost effectively so that the need for aerial observations in the navigationally most important waters, those around Cape Farewell, can be eliminated or greatly reduced. The latter waters have until now been mapped using aerial reconnaissance 2-3 times per week or according to navigation needs by the Danish Ice Patrol based in Nassarssuaq, Greenland. To aid and optimise the use of aerial reconnaissance's, DMI has, for the last 6-7 years, been mapping the ice, on a daily operational basis, using the AVHRR - NOAA images. However, given the weather conditions around Greenland i.e. extensive cloud cover, it is only possible to map the sea ice along the east and the west coasts using the AVHRR images if they are sufficiently cloud free. Within the last couple of years, we have started to incorporate the DMSP SSM/I data into the ice charting operations. Our main conclusions, so far, are that they are very helpful along the east and west coasts and complement the AVHRR images quite well. However, in the waters around Cape Farewell, because of poor resolution and frequent rain cloud cover, they are of very little or no use at all.

Since 1994 DMI has been involved with extensive evaluation of the sunlight and cloud independent SAR sensors on board the ESA's ERS-1 and -2 satellites (Nielsen et al., 1994, Gill et al., 1995a, 1995b, 1996). The main conclusions of these evaluations were that the C-band, VV-polarisation and the steep incidence angles of the ERS-SAR are very sensitive to ocean surface winds. The latter (and the seasonal ice surface melting), are in many cases responsible for making many of the images practically useless for mapping the ice, because the ice edge the most important ice parameter for navigation in the Greenland waters, could not be estimated with the required certainty. Further, given the small swath width (≈ 100km) of the SAR sensor it was concluded that the spatial coverage of the Cape Farewell waters using ERS-SAR alone was inadequate to meet the operational needs off Cape Farewell. However, the data from this satellite are still very useful when combined with and as support to the interpretation from other (primary) sources of data.

The Canadian RADARSAT was launched in November 1995. The main difference between this satellite and its predecessors is that the RADARSAT was especially designed for the remote sensing of the sea ice in the Canadian waters. The satellite has only one instrument on board, namely a SAR (C band HH polarisation and incidence angles from ≈ 20° - 50°). An attractive feature of this SAR for ice mapping around Greenland, is that it is possible to operate the SAR in a number of different modes. The main modes that are of interest to DMI for sea ice mapping around Greenland are the ScanSAR wide (SCW) and Narrow (SCN). The SCW mode has pixel size of 50 m and image swath width of 500 km when the data is direct down loaded and 450 km when the data is recorded on board the satellite. SCN product has pixel size of 25 m and the swath width is 300 km. At DMI we have mainly concentrated on the evaluation of the data from the SCW mode (Gill and Valeur, 1996, Gill et al., 1997), because it offers the best possible spatial and temporal coverage with RADARSAT. This is an important parameter, because any operational sea ice mapping service based on satellites alone must meet the requirements of the navigational community in terms of having sufficient temporal coverage.

The data set consisted of the SCW images and the aerial validation data from the Danish Ice Patrol. In particular, the former consists of 45 SCW mode images from the months of March - July. Of these 45 images 7 were from the west coast from Disko and Baffin Bays with latitudes from 65°N - 72°N from March and April. The remainders were from the Cape Farewell region. More specifically, there were 15 images from March to June and 23 from July.

The underflight validation data consisted of aerial photographs taken from both side of the aircraft and the ice charts made by the Ice Patrol using both visual observations and the ice edge deduced using the 360° mapping radar on board the aircraft. In particular, the Ice Patrol carried out 20 such dedicated underflights in 1997 for the evaluation of the RADARSAT images. It should be mentioned that these dedicated flights were separate from the normal ice reconnaissance flights carried out by the Ice Patrol. Of these 19 were from the Cape Farewell region and 1 from the Disko Bay.

Furthermore, the surface wind vectors and air temperatures, as those measured by the nearest weather stations along the coasts and the forecasts made by the HIRLAM and ECMWF numerical weather models, were also used in the evaluation. These data were particularly used to estimate the extent to which the weather conditions influenced the quality of the RADARSAT images for sea ice mapping.

The evaluation of the RADARSAT images was carried out using the following main steps:

1. ice charts were drawn using only the RADARSAT images and, when ever useful, the grey tone images of the texture parameters such as the Power-to-mean Ratio (PMR) for ice edge and icebergs detection (Gill et al. 1996, 1997) which were derived from the RADARSAT images were also used,

2. when all the RADARSAT ice charts had been drawn then they were compared with those produced by the Danish Ice Patrol using aerial reconnaissance's and the NOAA-AVHRR ice charts (if available),
3. if there were serious inconsistencies between these two sets of ice charts for a particular date then the aerial photographs taken during the underflight were studied to determine the true extent of the discrepancies.

Taken as a whole, the ice charts made using RADARSAT alone are of very high quality. This is surprising because the size of the floes in the Cape Farewell waters is < 50- 60 m, which is below the resolution of the SCW mode. With the exception of few times in the month of July, there was very good agreement between the ice charts made using aerial observations and those based on RADARSAT. In general, there was practically no problem in interpreting the images for the months of March, April, May and parts of June and July.

To give a quantitative measure of the quality of the images for sea ice mapping all the images from the Cape Farewell region were split into 5 categories. The 5 categories defined were:

1) excellent
2) good
3) acceptable
4) unacceptable
5) useless

Category 1 defines those images that were totally problem free i. e., there were no problems at distinguishing between the open water and ice regions and at determining the various ice conditions. Our evaluation showed that from all the SCW mode images from the Cape Farewell region evaluated in 1997 there were none in this category. Category 2 included those images that could be used for making detailed ice charts. However, in some regions there were some radar backscatter ambiguities which meant that there might be small errors in the estimated ice concentration. It was found that 25% of the images belonged to this category. Category 3, which included 42% of all, the images from the Cape Farewell region were acceptable for mapping the sea ice. There was practically no problem in detecting the ice edge. However, the estimated ice concentration should not be totally relied upon. Category 4 includes those RADARSAT images when used alone were unacceptable for mapping sea ice. In particular, some of the estimated ice edges were in error and the concentrations could not be estimated. 25% of the images belonged to this class. These images should only be used in conjunction with data from other satellites and, if available, to use ice charts from the previous days. Finally, category 5 included those images that contained very little information for mapping the sea ice. 8% of all the images from the Cape Farewell region belonged to this category.

In order to compare the quality of the ice charts drawn using RADARSAT alone with those based on aerial observations, all the RADARSAT ice charts were separated into 3 categories:

1. the first class included those RADARSAT Ice Charts (RIC) which were considered to be better than Aerial reconnaissance Ice Charts (AIC),
2. the second class included those RICs which were as good as AICs, and
3. the third class included those RICs that were considered worse than AICs.

The overall results of the comparison for the Cape Farewell waters, for 1997, showed that 46% of the time when RICs were made there were no corresponding AICs for comparison. For the remaining 54% of the RICs which could be directly compared with AICs it was found that 47% of these RICs belonged to category 1, 33% to category 2 and finally, 20% (at the very most) belonged to category 3.

Just as it is important to determine whether the RADARSAT SCW images are of sufficient quality to map the sea around Greenland, an equally important requirement for our operational ice mapping is to determine whether the spatial coverage of the relevant waters is sufficient. This means whether the relevant waters, for example those off Cape Farewell, are mapped at the frequency required by the vessels navigating in them. Currently, as stated above, the sea ice in the Cape Farewell waters is mapped on average 2-3 times per week using aerial observations. Therefore, as a rule of thumb, we should require at least similar frequency of coverage from a satellite based system.

The repeat cycle of RADARSAT is 24 days. The RADARSAT SPA (Swath Planning Application s/w) was used to estimate the possible coverage of the Greenland waters from (40°W - 55°W). A rough estimate of the possible daily coverage of the Cape Farewell waters from approximately (42°W - 50°W) and (59°N - 62°N) over a 24-day period can be estimated. There is no coverage at all for 5 of the 24 days, for 4 days the coverage is less than 50% for 3 days the coverage is less than 70% and there is full coverage (≈ 100%) on the remaining 12 days. More specifically, if we were mapping the sea ice around Cape Farewell using RADARSAT from 1st -24th of July we could not map the ice on the 3rd, 10th, 13th, 17th and 20th of July. On the 6th, 7th, 14th and 24th of July the coverage would have been less than 50%. On the 16th, 21st and 23rd of July it would have been less than 70%. Only on the 1st, 2nd, 4th, 5th, 8th, 9th, 11th, 12th, 15th, 18th, 19th, and 22nd we would have full coverage. Furthermore, there will be a gap of one day before these waters could be imaged fully again. However on 3 occasions, from 6th-7th, 13th-14th and 23rd-24th of July for example, in a 24-day period, there will be inadequate coverage over 2 consecutive days.

For an operational sea ice service such as that of DMI’s it is important to receive the data in real time or in near real time i. e., within hours of the overhead pass of the satellite. Since DMI does not have its own RADARSAT receiving station on Greenland, then these data have to be received from the satellite receiving stations in UK (West Freugh) and in Canada (Gatineau). To image the Cape Farewell region in both the ascending and descending passes then it is necessary to receive data from West Freugh and Gatineau. The data from the passes that are in the mornings ≈ 9.30-9.50 UTC, will be received at West Freugh. The ascending passes are in the evenings ≈ 20.30 -20.50 UTC, and the data will be received at Gatineau. Then the question arises as to the most cost-effective method of transferring these data from these two stations to DMI in Copenhagen for Interpretation.

The relative costs of the data transfer to DMI via satellite lease of a fast line and using Internet were investigated. As a no great surprise, the cheapest solution was found to be via Internet. Trials were carried out with data transfer via Internet in near real time i.e., the times at which the data are expected to be transferred in an operational phase, from Gatineau (Canada) and West Freugh (UK) to Copenhagen. With today’s operational Internet connection one scene (≈100 Mbytes) is from either Gatineau or West Freugh transferred in 20 - 60 minutes. That is sufficient for the operational service at DMI.

The main commercial users of ice information in Greenland waters can be divided into two categories:

A. shipping companies carrying goods, passengers and tourists, and
B. those companies involved in offshore explorations and conducting, for example seismic soundings.

The needs for both groups were identified in Task 1 (Chapter 2) and it transpired that they were very similar. The main difference being is that a user from group B might require more frequent ice information, such as high resolution imagettes of a specified region, than a user from group A. Both groups required information on the following ice parameters:

1. Ice edge, essentially delineating ice/no ice boundaries,
2. ice concentration,
3. floe sizes,
4. major iceberg concentration,
5. ice thickness,
6. full resolution imagettes of selected regions such as inland waters if it is category A user, and if the user is from group B then an imagette could be of a particular area that is being explored.

Concerning the satellite(s) system(s) to be used to obtain the relevant ice information it was stated by the users that foremost they require a system that has (i) all weather capability, (ii) sufficient resolution to identify the small ice floes, and (iii) adequate temporal coverage. Currently, the satellite that can meet these requirements is the Canadian RADARSAT launched in November 1995. This satellite has a number of modes of operations (see, for example Parashar et al., 1993). The modes that are important for the above users are essentially the ScanSAR Narrow (SCN) and Wide. This is because (due to the very large size of Greenland), only satellite with large swath widths have the adequate temporal coverage. For this reason ESA ERS-1/2 satellites, because of their rather small swath widths (100 km), have inadequate spatial and temporal coverage and therefore cannot alone be used for operational ship navigation.

Image texture parameters
As is well known the main problems with SAR (Synthetic Aperture Radar) images, as far as imaging sea ice is concerned, are (i) image speckle, (ii) the large backscatter from wind infested waters and (iii) surface melting. These effects can make it very difficult if not impossible, to identify the ice features such as ice edge, ice concentration or the location of major icebergs. For this reason, effort has been spent in the research community to reduce, by way of filtering for example, these effects in the SAR images. DMI has also been active in this endeavour (Gill et al. 1995a, 1995b, 1996, 1997, Gill 1996). The approach employed at DMI involves determining some useful image texture parameters that could be used to delineate the ice edge or the position of major icebergs, for example.

In particular to distinguish between regions of ice and water the grey tone values (after appropriate scaling) of the second (Power-to-Mean-Ratio = PMR), third (Skewness) and fourth (Kurtosis) moment of the probability density function, and the shape parameter of the Gamma function used to model texture variations in the k-pdf model, were manually interpreted (Gill, 1996). It was found that the PMR values were useful at detecting the ice edge. The higher order moments and the parameters of the k-pdf contained essentially no extra information. The PMR parameter is now used routinely at distinguishing between the regions of ice and open water and for detecting icebergs. PMR values are computed using the following expression:

$$PMR = E<X^2>/E<X>^2$$

Where E<X> is the expectation value and subscript X denotes pixel amplitude or intensity. For ice edge and icebergs detection, the values of PMR were computed using moving windows of different sizes. It was found that for window size of ≈ 20*20 pixels and inter window spacing also of ≈ 20*20 pixels produced the best results for the ice edge detection. Similarly, for icebergs detection the optimal values were found to be ≈ 20*20 pixels for window size and ≈ 5*5 pixels for inter window spacing.

Second order texture parameters derived from the grey-level co-occurence matrix (GLCM) (Haralick et al., 1973; Shokr, 1991; Skriver, 1994; Gill et al., 1997) have also evaluated to determine their usefulness at distinguishing between sea ice and open water. Following Shokr (1991) and Skriver (1994) five parameters were selected: entropy, inverse difference moment, uniformity, inertia and correlation. These parameters are computed from the square matrix P_{ij} which is the count of the number of occurrence of two neighbouring pixels, at two different locations within a square window of size W*W which have grey values i and j. P_{ij} was computed along directions 0°, 90°, 45° and 135° within the window and its normalised average value was calculated along the method outlined by Shokr (1991). Further, to reduce the computation time the number of grey values of the original image were reduced from 8 bits to 4-7 bits by examining the image histogram and then reducing to fewer bits using either linear stretch or histogram equalisation. Comparing the values of the above five parameters computed from a 4-7 bits images it was found that to distinguish between the open water and the ice regions at least 6 bits data values are required. Further it was found that entropy (ENT) (followed by inverse difference method and uniformity) was the most useful at discriminating between the open water and the ice regions. ENT is defined as follows

$$ENT = \Sigma_j \Sigma_i -P_{ij} \log(P_{ij})$$

As for the PMR parameter, computation of the ENT for a window size of ≈ 20*20 pixels and interpixel window spacing of ≈ 20*20 pixel produced the best results for ice edge detection.

The image in Figure 3.39 shows a ScanSAR scene of Scorresby Sound filtered with the PMR iceberg filter. The Sound is filled with icebergs and growlers, the positions are shown as bright spots in the image.

Figure 3.39 ***PMR grey values for iceberg detection from the RADARSAT image.***

Based on the RADARSAT evaluations carried out during Task 2 of the IMSI project it can be concluded that overall, the results are, surprisingly good (given that the size of ice floes in the Cape Farewell waters is < 50-60m which is below the resolution of the SCW mode). There was practically no problem in interpreting the images for the month of March, April, May and parts of June and July. However, there were occasions when there were serious uncertainties in interpreting the images for the months of June and July. This was mainly in regions where the ice had severe surface melting. Occasionally, in the latter regions ice with concentrations as high as 4/10 - 6/10 was difficult to identify in the RADARSAT images.

Bearing in mind the nature of the ice service DMI is entrusted to provide in the Greenland waters which is foremost for the safety of ship navigation, it has been concluded for the time being at least, that it would be unwise to rely solely on RADARSAT for the mapping of the ice in the summer melt season. The latter is approximately from the month of June - August. The main reasons for this conclusion are: (i) not being able to identify the ice edge in some of the images and, equally important, (ii) there was a general feeling of uncertainty when identifying the position of the ice edge (the most important parameter for ship navigation in the Greenland Waters) during the melt season. It is felt that in some cases we guessed correctly the ice edge. A guess is not adequate for the safety of ship navigation. However, the above conclusions are based on interpreting just one ice melt season of RADARSAT data. It is very strongly felt that RADARSAT derived sea ice maps will become much more reliable, including in the ice melt season, as experience is gained in interpreting

RADARSAT data. This was in fact also the experience of the Canadian CIS (Canadian Ice Services).

The classification certainty using RADARSAT along the east and west coasts of Greenland is very high. During the Kista Arctica project (described in chapter 4 and IMSI report no. 10) the ice mapping was validated along the route of the freighter sailing in the ice infested. The ship had a helicopter onboard, which was both used for reconnaissance, discarding, and loading of the ship. Both oral and written reports and digital photographs were communicated from the navigators to DMI in order to validate the information derived from RADARSAT, NOAA-AVHRR and SSM/I. This validation showed that the information on the ice in this area on the east coast is very reliable. It is however very important that the information is received onboard the ship with short time delays from the overhead pass of the satellite for the information to be of any value.

RADARSAT is now used operationally at DMI except for the melt season where the Cape Farewell is covered with aerial reconnaissance. Further investigations of RADARSAT during the melt season are carried out during the summer 1999 with underflights and aerial photography.

3.5 Improved resolution of SSM/I ice charts and distribution service on Internet

The product development done by DTU is focused on two problems: Improvement of the spatial resolution of the passive microwave (SSM/I) products and combination of SAR, AVHRR and SSM/I data for distribution on Internet.

Improved spatial resolution of the passive microwave (SSM/I) products can be obtained using 85 GHz channels. DTU has developed a prototype of an algorithm that is currently being tested. The algorithm uses a standard Comiso bootstrap algorithm to determine coarse resolution ice concentration almost independent of weather conditions. If the coarse resolution algorithm gives above zero ice concentration, the 85 GHz polarisation difference is used to split the pixel with ice in four sub-cells according to a linear conversion of the polarisation difference to ice concentration, whereas if the coarse resolution algorithm gives zero (or less) ice concentration, this value and the coarse resolution is maintained.

Combination of SAR, AVHRR and SSM/I data can be done at spatial resolutions from 300 m (ERS-1) through 1-4 km (AVHRR) to 15-50 km (SSM/I), and distribution is currently carried out through our *Java* based Internet tool. The tool allows display of images at very different spatial resolution, and overlays of vector graphics such as ice concentration contours of SSM/I based ice maps (same day), ice concentration contours of SSM/I based ice maps (earlier days), contours of bathymetry, coastlines, latitude-longitude grid lines at different grid spacing, and outline frames of high resolution images (ERS-1 SAR). This approach allows the user of the ice data to examine all the different data on his/her screen using Netscape or Internet Explorer software with Java. Data sets from several regions (Greenland, Baltic Sea and Kara Sea) are now available on this system.

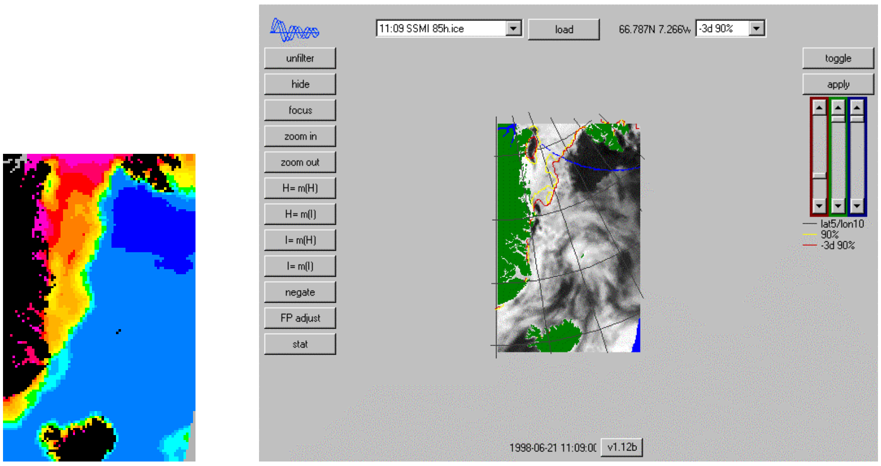


Figure 3.40 ***Examples of ice concentration products from the Java based Internet tool from 21 June 1998 in the Greenland area.***

Necessary satellite data have been obtained in due time for the project:

Table 3.10 ***Satellite data sources and typical delay times from satellite pass to the data are available to end users.***

Satellite data and source	**Approx. delay**
SSM/I data received from Marshall Space Flight Center, NASA, USA	8-14 hours
NOAA AVHRR quick-look data received from Tromsø Satellite Station, Norway	4-6 hours
NOAA AVHRR full resolution data received from DMI, Copenhagen	3-6 hours
NOAA AVHRR full resolution data received from DMI, Sønderstrømfjord, Greenland	3-6 hours
RADARSAT data received from DMI	6-9 hours when available
Digital Ice-charts received from DMI	6-9 hours when available

The Defence Meteorological Satellite Programme (DMSP) passive microwave sensor (SSM/I) has been the primary data source for the work, and in particular the use of the 85 GHz channels have been assessed. The SSM/I instruments measure the thermal microwave emission from the surface of the Earth at four different microwave frequencies, i.e. 19, 22, 37 and 85 GHz. The spatial resolution ranges from approximately 60 kilometres at the lowest frequency to approximately 15 kilometres at the highest (85 GHz) frequency, However, the atmospheric influence is larger at the higher frequency. Therefore, traditional ice mapping using these data has primarily utilised the lower frequency channels in order to prevent atmospheric influence. The only low cost alternative to the SSM/I data is the NOAA AVHRR visual and infrared data that are received world-wide at a large number of receiving stations including one at the DMI in Denmark, one operated by the DMI in Sønderstrømfjord, Greenland, and one operated by the Tromsø Satellite Station in Tromsø, Norway.

A number of new products have been developed using the SSM/I data

- Simple histogram equalised horizontally polarised brightness temperature map at 85 GHz.
- 85 GHz. polarisation difference maps
- Special resolution enhanced ice maps based on a combination of the 85 GHz polarisation difference maps, and ice maps derived from the lower frequency channels.

Examples of the various microwave radiometer based sea ice products available from DCRS through the World Wide Web.

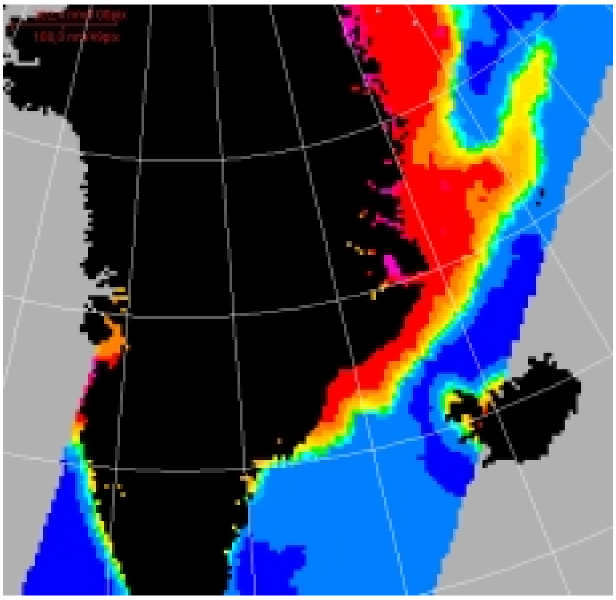


Figure 3.41 ***a) Traditional 19/37 GHz ice concentrations at 50 km resolution, February 21,1998.***

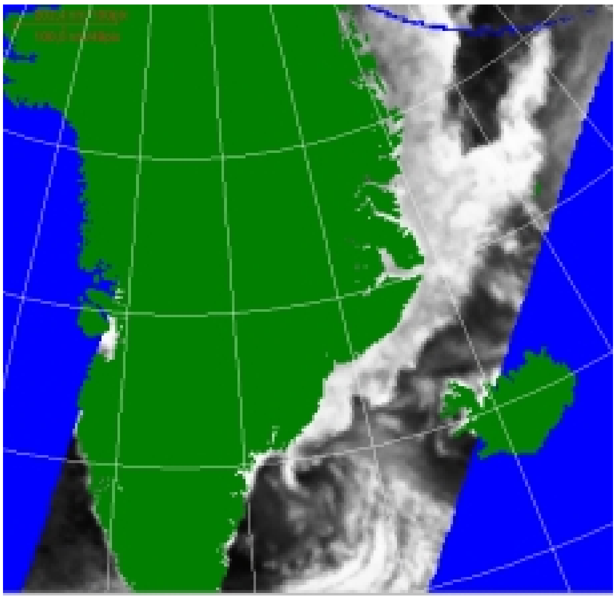


Figure 3.42 ***b) 85 GHz Horizontally polarised SSM/I image, February 21, 1998.***

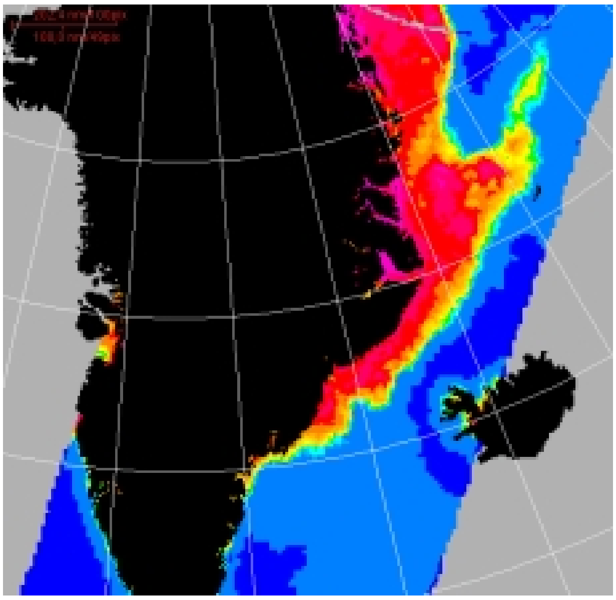


Figure 3.43 ***c) Resolution enhanced SSM/I image from February 21, 1998.***

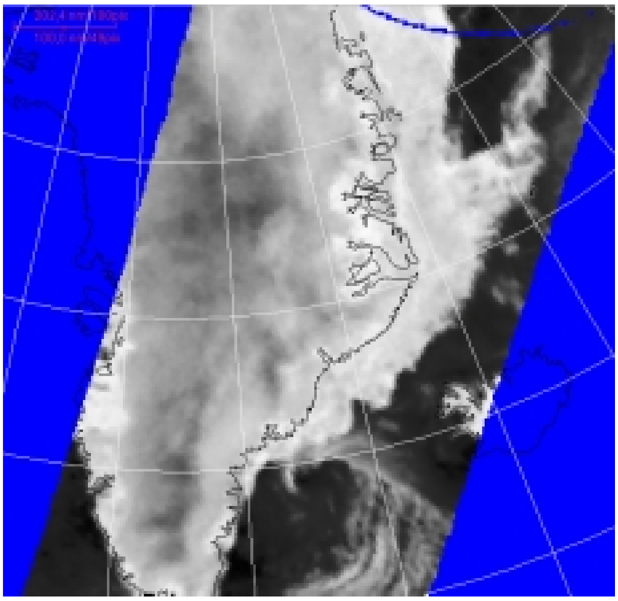


Figure 3.44 ***d) 85 GHz polarisation difference, February 21, 1998.***

3.6 Large scale ice mapping by scatterometer data for the Arctic and Antarctic

Scatterometer ice maps

Software necessary to produce Ku band backscatter maps over both polar oceans from NSCAT level 1.5 data has been developed and tested. It is important to note that the backscatter maps have a 25 km spatial resolution and are constructed using three consecutive days of data.

The 25 km resolution software is now being employed to generate backscatter maps systematically over the period of NSCAT operation, every three days consecutively.

The possibility of generating Ku-band backscatter maps over the Arctic Ocean at 12.5 km resolution, based on only one day of NSCAT level 1.5 data has also been studied. Such maps require, as prerequisite, information acquired in the course of generating the 25 km resolution maps produced from three days of data.

ERS-2 AMI-Wind C-band maps over both polar oceans continue to be produced on a weekly basis, and are placed on the WWW server within two to three weeks after satellite acquisition.

Joint scatterometer products

Comparisons between C-band backscatter maps, produced on a weekly basis from ERS-2 AMI-Wind level 1.5 data, and NSCAT three day products has been undertaken. Ku band offers a larger range of values between first year and multi year ice than C-band, probably because cavities, created by the downward drift of saltwater droplets in multi year ice, resonate more efficiently at the smaller wavelengths. Moreover, in the Ku backscatter vs. C band backscatter plane, the cloud of points corresponding to smooth first year ice is distinguishable from the larger, rough first year and multi year cloud.

Since 1991, weekly backscatter maps over both polar oceans have been produced by the CERSAT, using the C band data of the AMI in wind mode on ESA satellites ERS-1 and ERS-2.

In 1997, the software necessary to produce Ku band backscatter maps over both polar oceans from NSCAT level 1.5 data was developed and tested. For full details, IMSI Report No. 4 should be consulted. It is important to note that these maps have a 25 km pixel size, and are projected on the corresponding NSIDC SSM/I grid. An elaborate screening procedure is used to detect and eliminate open water regions. Over sea ice, the value of backscatter at 40° incidence angle, given by these digital maps, is obtained assuming a linear relationship between backscatter and incidence angle. This relationship is determined by a least squares fit through the set of measurements made in each pixel individually; here, use is made of the fact that backscatter over sea ice regions of large extent (on the order of 1000 km^2) is isotropic in azimuth. Figures 3.45 and 3.46 show examples of such maps over the Arctic and Antarctic oceans respectively. Such maps were produced consecutively every three days over the lifetime of NSCAT (September 1996 to June 1997) and placed with the C band maps on the IMSI server in January 1998. Comparison of these maps shows that backscatter at Ku band has a significantly greater sensitivity to ice type than C band backscatter (results to be published in an NSCAT JGR Special Issue in 1999).

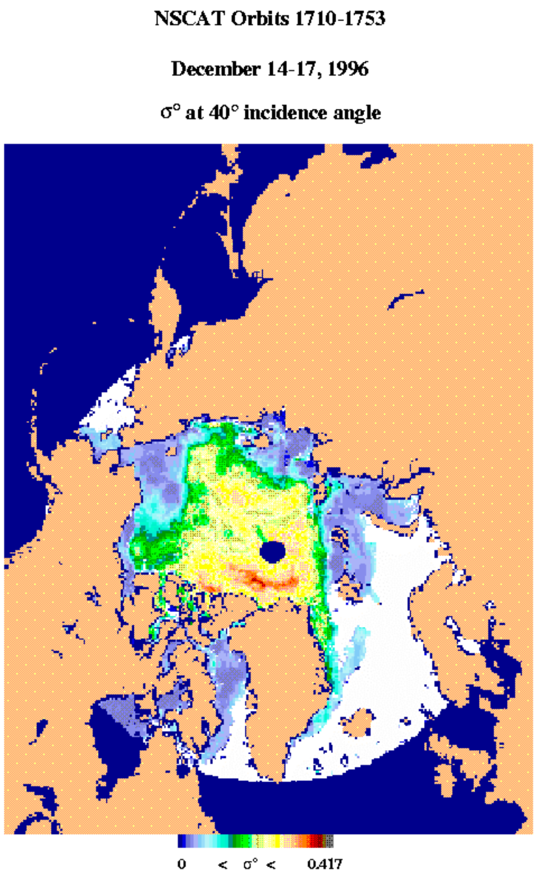


Figure 3.45 ***Backscatter at 40° incidence angle over the Arctic Ocean.***

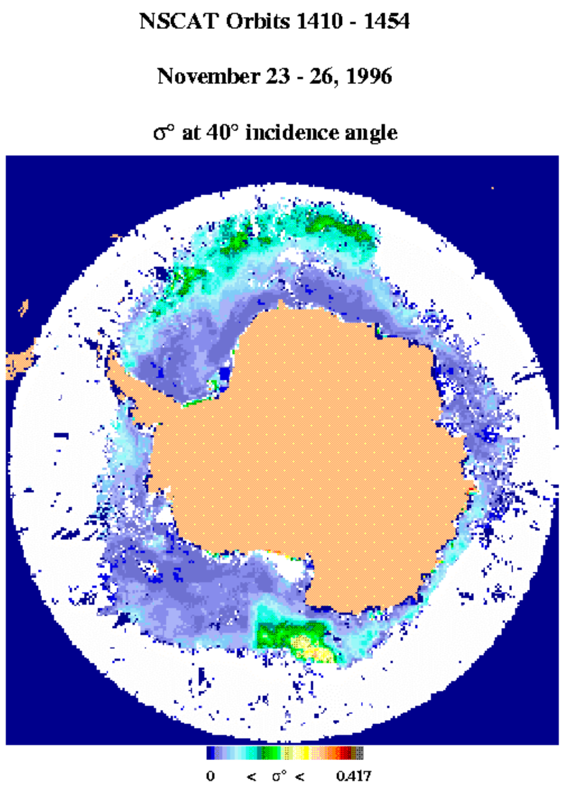


Figure 3.46 Backscatter at 40° incidence angle over the Antarctic Ocean.

As an experimental mode, backscatter maps have been generated from NSCAT data on the NSIDC SSM/I 12.5 km pixel grid over the Arctic Ocean. Full details of the procedure will be available in an article accepted for publication in a future issue of the 'IEEE Transactions on Geoscience and Remote Sensing'. Here, it is only necessary to say that it was shown that the derivative of Ku band backscatter as a function of incidence angle fits very closely a straight line relationship to backscatter at 40° incidence angle, that is:

$$d\sigma°/d\theta = \alpha + \beta\, \sigma°_{40}$$

Table 3.11 ***Values of α and β at different times of the year are given in the following table.***

SEASON	Intercept : α	Slope : β
Late Autumn (November)	$-1.41\ 10^{-5}$	$-2.77\ 10^{-2}$
Late Winter (March)	$-1.43\ 10^{-5}$	$-2.84\ 10^{-2}$
Late Spring (May)	$-1.07\ 10^{-5}$	$-2.86\ 10^{-2}$
Early Summer (June)	$-2.57\ 10^{-6}$	$-3.55\ 10^{-2}$

This relationship holds in the incidence angle range between 21° and 60°, outside of the summer period, when melting and ponding at the ice surface create regional variations that are not manageable. In fact, the values of α are so low that in the construction of the backscatter maps, this parameter was simply set to zero. Such an approximation leads to express backscatter at 40° directly as a function of backscatter measured at any incidence angle θ:

$$\sigma°_{40} = \sigma°_{\theta} /[(1-\beta)(40.- \theta)]$$

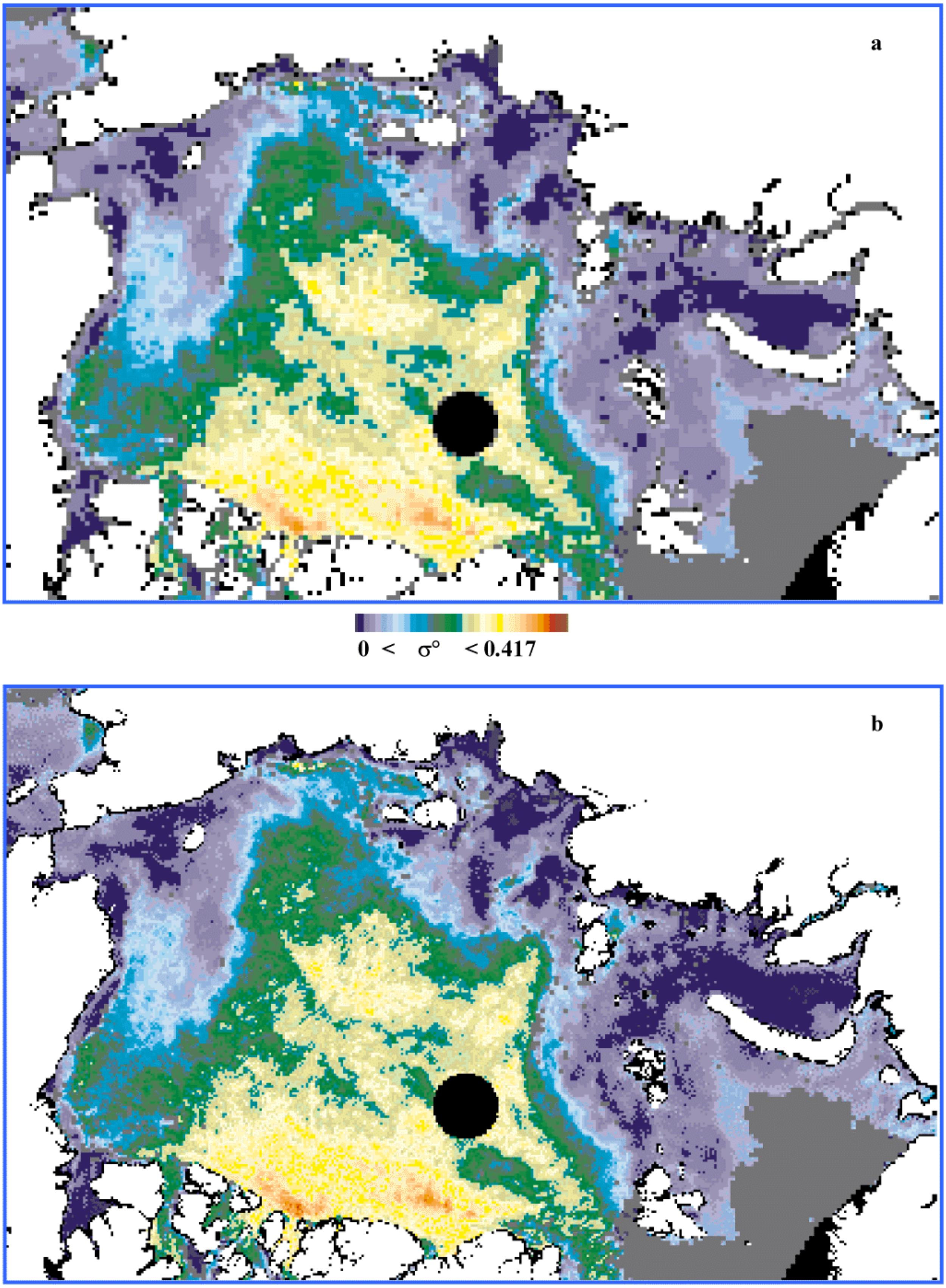
Maps of $\sigma°_{40}$ can readily be constructed using this relationship on the SSM/I 12.5 km pixel grid, using data from three consecutive days, one day or even a single swath, values of individual estimations of $\sigma°_{40}$ falling within a given pixel being averaged. However, it proved impossible to produce a reliable ice/water mask at this resolution from NSCAT data alone, so that the ice limit continues to be determined from the 25 km, three day product. Figure 3.47 show a comparison of the 25 km and 12.5 km images thus produced, using the winter value of β. Clearly, some information is gained by using the higher resolution.

As a further example, consider the Kara Sea ice situation as described by the two RADARSAT images on February 21, 1997, furnished by ICE ROUTES. At the lower left hand corner of Figure 3.48, the passage between Novaya Zemlya to the North-west and Vaygach Island to the south-east is clearly distinguished by the zone of first year ice, broken and modified by the influence of tidal and, to some extent, wind driven currents. A general drift from the Barents to the Kara Sea produces the fan shaped area of high backscatter first year ice north of the passage. Further north, in the inner part of the Kara Sea, the first year ice has low backscatter values, while complicated structures are visible, roughly parallel to the coast. Figure 3.49 shows the northern part of Novaya Zemlya and of the Kara Sea on the same day. Higher values of backscatter occur around the island than on the right side of the image, to the southeast. A zone of particularly high backscatter, with well defined texture, is seen to the north-east of the island's northern tip, while an elongated fuzzy zone of fairly strong backscatter is visible some thirty kilometres to the south of the island.

Figure 3.50 presents the NSCAT 12.5 km resolution backscatter map produced from data of the 21st to the 23rd of February 1997, as well as two zooms which each cover the RADARSAT images previously described. The false colour scale of the Arctic Ocean image is well adapted to the dynamics of the ocean ice as a whole, including the very high backscatter of multi-year ice. However, it is not suitable to illustrate the fine details in backscatter between different first year ice types. Therefore, the false colour scale of the zooms has been increased by a factor of seven, clearly improving their visibility. As previously noticed, the interior of the Kara Sea is a region of low backscatter, corresponding to smooth first year ice. Only the region to the east of the passage between Novaya Zemlya and Vaygach Island shows relatively high backscatter, already set in evidence on the RADARSAT image. Around the northern part of Novaya Zemlya, the elongated fuzzy zone is again detectable and the high backscatter region to the north of the island as well. In fact, high backscatter is seen to extend almost continuously near the Barents Sea shore of Novaya Zemlya, probably because of the combined influence of wind and tidal currents, as well as wave action during the initial phases of ice formation.

Figure 3.51 is a Ku band 12.5 km pixel image produced from the NSCAT data of a single day (March 10, 1997). Overlaid on the image are the isolines of ice concentration as determined at DTU from the SSM/I 85 GHz algorithm. The image covers part of the East Greenland current and shows the transient ice extension known as the Odden. It is to be noted that the two sources of information are complementary. The concentrations given by the SSM/I eliminate open water areas which might be interpreted as sea ice because of their relatively high backscatter, while the higher backscatter value in the northern part of the East Greenland current indicate a higher concentration in multi-year ice.

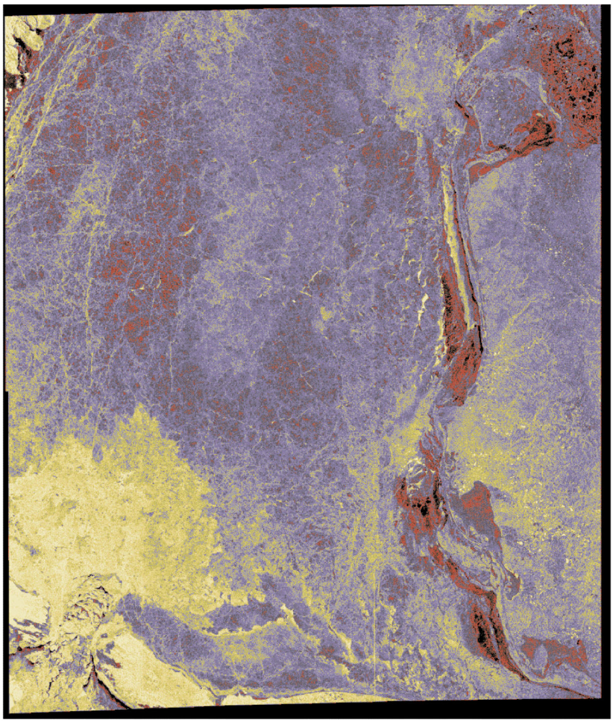
In the spring of 1999, a rotating antenna Ku band scatterometer with an exterior swath width of 1500 km (QUIKSCAT) will be launched. The effort made to understand and use the NSCAT data will be directly applicable to this instrument. With this instrument, the 12.5 km resolution maps will pass from an experimental to a standard mode of processing.



NSCAT backscatter maps at 40° incidence angle on March 25-27, 1997
Resolution a: 25 km , b: 12.5 km

Figure 3.47

74.928ºN , 59.024ºE 73.624ºN, 74.218ºE

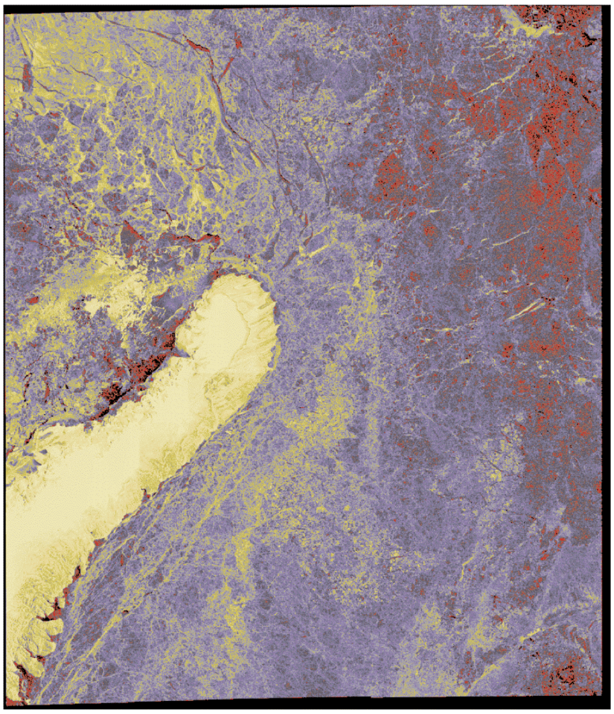


69.836ºN, 56.170ºE © Canadian Space Agency, 1997 Image Courtesy : Ice Routes/EOS 68.770ºN, 67.997ºE

False color RADARSAT image on February 21, 1997. Kara Sea
Color scale ranges from red to white as backscatter increases.

Figure 3.48

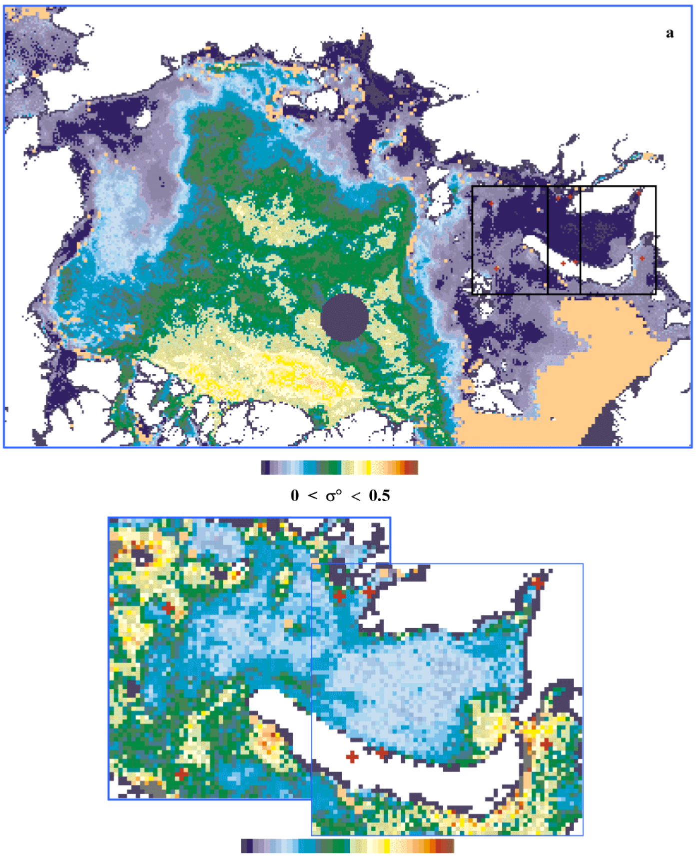
79.254ºN, 63.003ºE 77.570ºN, 82.873ºE



74.194ºN, 58.507ºE © Canadian Space Agency Image courtesy : Ice Routes/EOS 72.936ºN, 73.107ºE

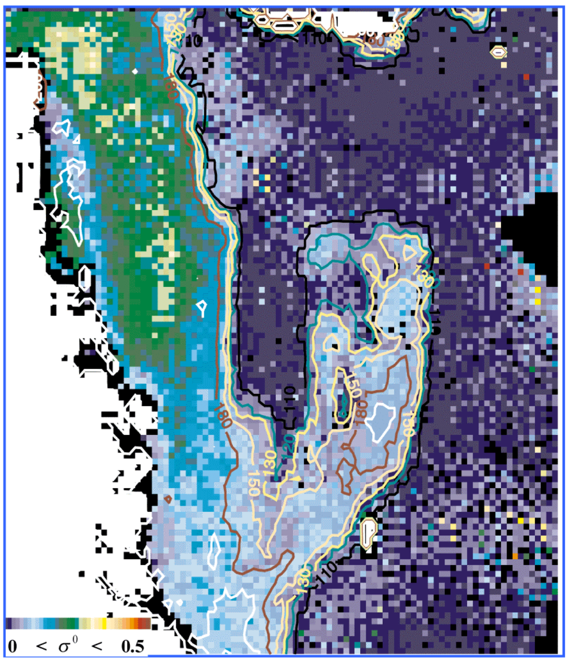
False color RADARSAT image on February 21, 1997. Kara Sea, East of Novaya Zemlya.
Color scale ranges from red to white as backscatter increases.

Figure 3.49



NSCAT 12.5 km grid backscatter maps, 21-23 February 1997
The 25 km grid water mask is added; red crosses define the corners of the RADARSAT scenes.
a : Central Arctic, black frames define the zoomed areas
b : Mosaic of the two zooms

Figure 3.50



East Greenland sea ice extension, 10 March 1997
NSCAT, 12.5 km grid resolution
SSM/I, 85 GHz, sea ice concentration(%)+100

Figure 3.51

4 User demonstrations and product dissemination (Task 3)

4.1 Northern Sea Route and Svalbard area

Dissemination to users in the Northern Sea Route
During 1997 about 250 ERS SAR images, 6 RADARSAT ScanSAR images and about 20 SSM/I ice concentration maps were distributed from the Nansen Center in Bergen to users in the Northern Sea Route, the White Sea, Ladoga and Onega lakes, and the Bay of Finland. Most of this data dissemination has been co-ordinated by the Nansen International Environmental and Remote Sensing Center in St. Petersburg.

The majority of the data was obtained in different parts of the Northern Sea Route between Pechora Sea in west and Laptev Sea in east. The ERS SAR data have been provided by ESA as a continuation of the ICEWATCH project, while the RADARSAT data has been obtained in co-operation with the ICE ROUTE project co-ordinated by EOS. The SSM/I ice concentration maps have been obtained to support ship expeditions with regional ice information and for comparison with SAR data. Most of the SAR images have been interpreted and sent to the users as annotated images by telefax. In some cases, digital transfer of images has been done to users who have computer and telephone connection with NERSC.

The users who have received satellite data and data products from NERSC are:

A German oil transport company
Rigel Schiffahrts GmbH c/o Gefo Gesellschaft für Oeltransport mbH in Hamburg had a transport voyage by MT ‘Rheinstern’ from Kathanga in the White Sea to Tiksi in the Laptev Sea during September. This ship received about 10 SSM/I maps, which were used to map areas of open water to find the fastest and safest sailing route.

Marine Operations Headquarters in Dikson
The operational ice monitoring centre for the western part of the Northern Sea Route is located at the Marine Operations Headquarters in Dikson. They received many of the ERS SAR images and used them in their production of ice charts.

Murmansk Shipping Company headquarters in Murmansk
SAR images have been transmitted to the headquarters of the Icebreaker Fleet of Murmansk Shipping Company for use in planning of icebreaker operations. Data have been transmitted both digitally and by fax.

Icebreaker expeditions
SAR and SSM/I data have been transmitted to icebreakers during voyages in the Northern Sea Route.

North Pole expedition with ‘Sovetsky Soyuz’ in July
SAR images from the Franz Josef area were used by ‘Sovetsky Soyuz’ to find the best sailing route to the North Pole.

The first RADARSAT demonstration expedition to the Laptev Sea

The first demonstration of near real-time ice monitoring by RADARSAT SAR was done during an expedition with ‘Sovetsky Soyuz’ to the Laptev Sea in September 1997. Several RADARSAT ScanSAR scenes were ordered in the period from 14 August to 7 September covering the northern Kara Sea and the western part of the Laptev Sea. Most of the Kara Sea was ice-free and the main ice edge was located east of Vilkitsky Strait. The SAR data were ordered for the area where dense ice could be expected. The SAR data were downlinked and distributed from Tromsø Satellite Station within a few hours after the satellite overpass. The western part of the Laptev Sea is just at the margin of the coverage area for Tromsø Satellite Station. SAR data acquisition or the central and southern part of the Laptev Sea cannot be obtained by direct downlink to any existing ground stations. Therefore, SSM/I data, which cover the whole Kara and Laptev Seas, were obtained in near real time for mapping of ice edge and ice concentration.

Onboard ‘Sovetsky Soyuz’ a PC and modem were installed and connected to the INMARSAT A station before the icebreaker left Murmansk. Personnel from NIERSC participated in the expedition which lasted from 7 to 20 September. Due to delays in the departure of ‘Sovetsky Soyuz’ from Murmansk, the SAR data acquisition in the Vilkitsky Strait and the western part of the Laptev Sea was ordered a few days before the icebreaker came to the ice area. Another problem was that RADARSAT was turned off after 9 September, so it was not possible to order additional images. Therefore, the SAR images could not be used directly in ice navigation. However, the transmission of satellite data to the icebreaker was successfully tested, using SSM/I ice maps and compressed SAR images. The transmission could be done while the icebreaker was within range of INMARSAT in the Kara Sea, but when the ship came into the Laptev Sea this transmission could not be done. The SAR images provided very detailed information about ice concentration, ice types and ice motion. In situ ice observations from ship and helicopter were collected for validation of the SAR images.

PINRO expedition to the White Sea

The Polar Research Institute of Marine Fisheries and Oceanography (PINRO) in Murmansk has used ERS SAR data in combination with aircraft surveys to features of the White Sea ice regime and its impact on ecology, especially the behaviour of sharp seals and their springtime migration.

Arctic and Antarctic Research Institute

Some SAR images were used by Arctic and Antarctic Research Institute for ice research and support to field expeditions.

Oil companies: Statoil and Shell

The oil companies Statoil and Shell have received hardcopies of SAR ice images in the specific areas where they plan to build oil terminals for shipment of oil by tankers.

NIERSC: demonstration data for marketing towards new customers

NIERSC has received several images for use in marketing towards new customers in Russia.

Users in the Svalbard region

NERSC delivered two ERS SAR scenes to the University of Svalbard for use in education. The scenes were used to plan a field expedition north and west of Svalbard in April, and to study different ice types and ice conditions.

ERS SAR data were also used to support a research expedition by R/V ‘Håkon Mosby’ north of Svalbard in September 1997. About 20 scenes were used during a two-week period to map the exact location of the ice edge and plan the ship tracks of the vessel. Accurate ice information is of particular importance for R/V ‘Håkon Mosby’ when she works near the ice edge, because the vessel is not ice-strengthened. Only SAR data can provide reliable and accurate ice edge position for such operations. SSM/I and NOAA AVHRR data were also used as a supplement to the ERS data.

Demonstration on Norwegian Television

Ice extent maps from SSM/I data have been demonstrated on TV2, the main commercial TV channel in Norway, as part of the weather forecast service the winter of 1998.

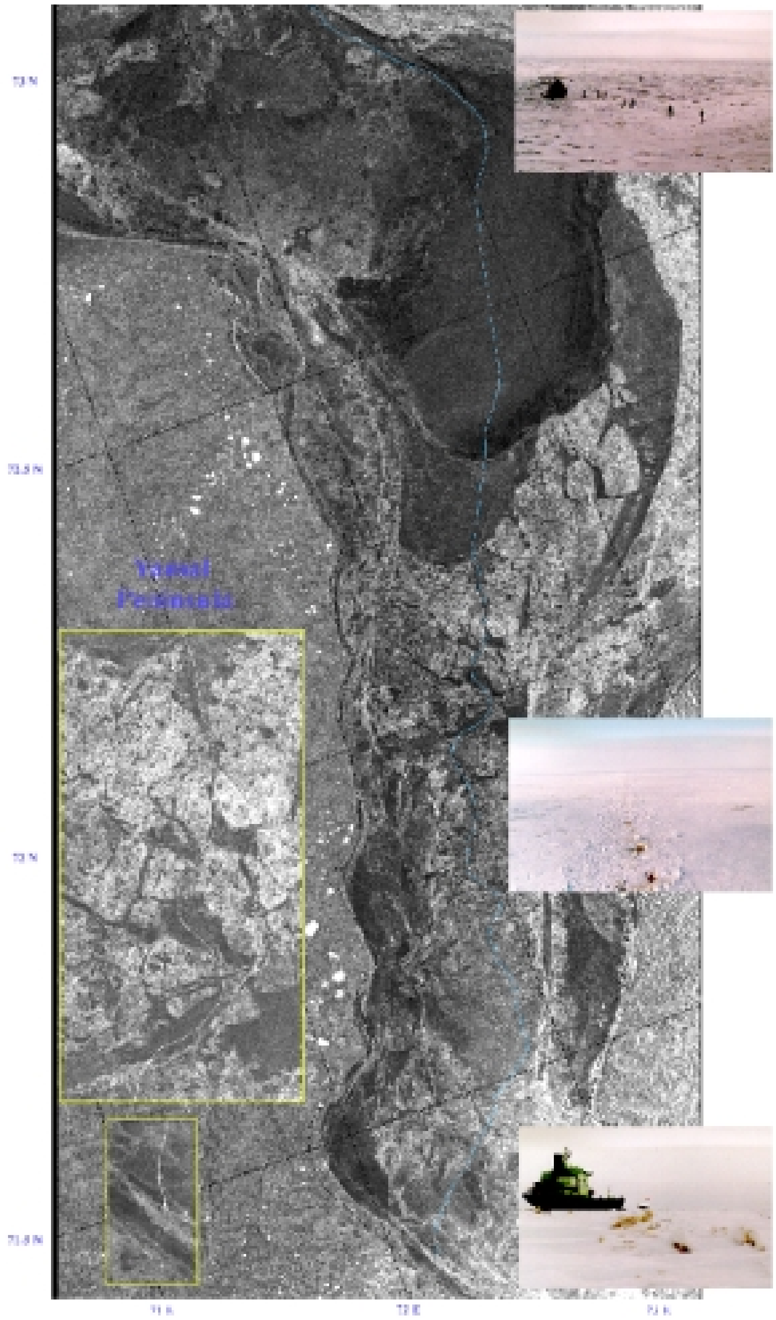


Figure 4.1 ***Expedition to the Ob Gulf April - May 1998. Blue line indicates the icebreaker track. Image Data © ESA/TSS 1998.***

ARCDEV expedition to the Ob Gulf

In April - May 1998 SAR ice monitoring was used before and during an expedition where an ice-strengthened tanker was escorted by several icebreakers to the Ob Gulf (Fig. 4.1). After loading of gas condensate the tanker was escorted back to Murmansk. The whole expedition, which was carried out under severe winter ice conditions, took about three weeks. With systematic use of satellite SAR data, the expedition could not have been completed so quickly due to very difficult ice conditions with high risk for damage and delays (Pettersson et al., 1999)

Demonstration for the Norwegian Meteorological Institute's Ice Service

In January - February 1999 a test was carried out using SAR data from ERS-2 and RADARSAT SAR images in the ice maps produced by the Norwegian Meteorological Institute in Tromsø. SAR data were obtained over a period of 2 - 3 weeks in the Hinlopen Strait in Northern Svalbard where shrimp trawling is an important activity. The pilot study demonstrated how SAR images can improve the quality of the ice maps considerably.

4.2 Baltic Sea

During the winter of 1997 several IMSI activities were launched in the Baltic Sea. One of them was ICEPILOT-97, an experiment in delivering digital ice information products and space-borne data to merchant vessels at sea. During this experiment automatic classified SAR data were also delivered to the ICEPILOT-98 and to the Finnish icebreakers. In addition, ice drift forecasts, whose initial stage was based on remote sensing, were delivered between January and April to Estonian, German, Russian and Swedish ice services.

ICEPILOT-97 was conducted between 13 January and 28 April 1997. Three vessels participate the experiment: the m/s Kemira sailing between Germany and various harbours in Finland, the M/S Fennia, a ferry sailing daily between Finland and Sweden in the Quark area and the M/S Containership III sailing mostly between Central European ports and St. Petersburg. The data delivered in digital format consists of 76 ice forecasts, 132 AVHRR images, 18 ERS images, 20 ice charts, 21 messages and 13 automatic classified ERS SAR images.

The ice season of 1996/97 was rather mild and only 30% of the total Baltic Sea area was ice covered. The mild ice conditions hampered the usefulness of satellite data delivered. Ice conditions in the Gulf of Finland were especially mild and the need for extra sea ice information was very small. However, the experiment gave valuable information on the possibilities that this kind of technique could offer for merchant vessels, (Seinä et al., 1998). The technical bottlenecks were also identified and they have been removed for the season of 1997/98.

For the ice season of 1998 two and half day ice drift forecasts have been expanded into five days by taking into operational use the 5-day wind forecasts of the ECMWF (European Centre of Medium Range Weather Forecasts). The wind fields are in a 50 by 50 km grid, which are interpolated into ice model’s 15 by 15 nautical miles grid.

The beginning of the ice season of 1997/98 was very mild and the need for special sea ice information was small. Maybe this was the reason, that during the ice season of 1997/98 only CONTAINERSHIPS Oy Ltd participated the ICEPILOT-98 experiment with three vessels sailing between the Central European ports and St. Petersburg. The experiment started on 19 December 1997, delivering AVHRR and RADARSAT SAR data over the Gulf of Finland to the vessels, (Fig. 4.2).

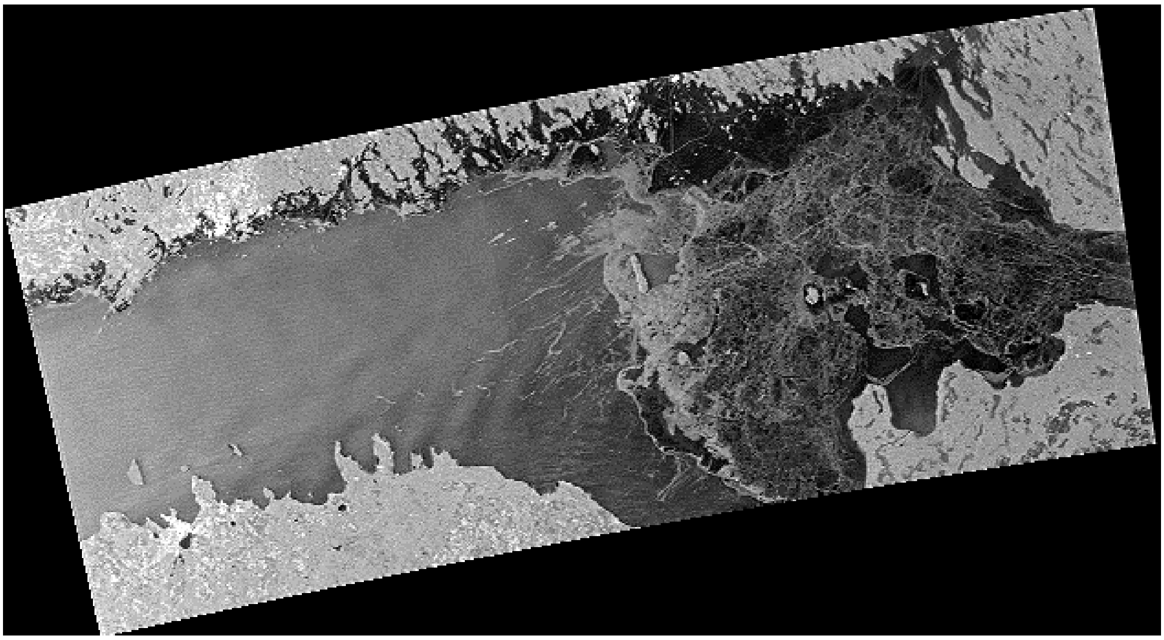


Figure 4.2 ***RADARSAT screen (26 February 1998 15:55 SCN.FAR) processed into 800 m resolution. © Canadian Space Agency / Agency spatiale canadienne, 1998. Processed by TSS and FIMR, 1998.***

Simplified ice chart on FIMR's web pages

A simplified version of the Finnish ice chart was developed and available on the Finnish Ice Service's web pages from the winter of 1997, http://ice.fmi.fi/tilanne.html. The chart was updated once a week or fortnightly depending on the changes in ice conditions. The users comments of the chart were positive, and the chart was simplified to satisfy the needs for just looking the extent of ice cover. The charts became very popular, and in 1998 there were 18,867 logins to the web pages. Most of the visitors were from Finland (13,714 or 73%), (Fig. 4.4). In January-April 1999 the number of visitors went up to 17,377 of which 70% were from Finland.

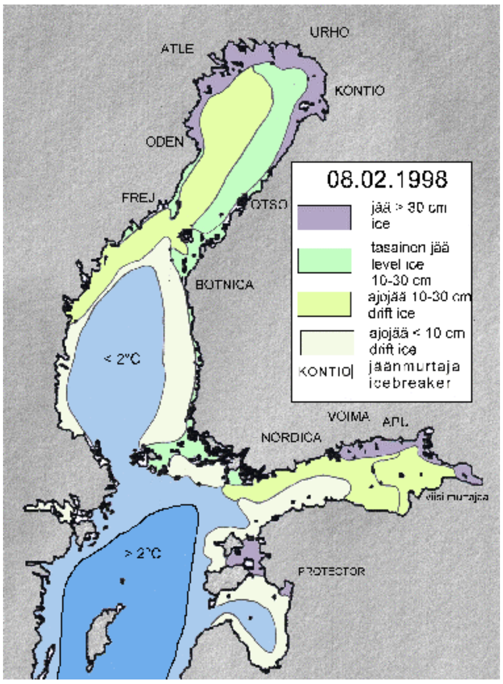


Figure 4.3 ***An example of the Finnish ice service simplified ice chart at the web pages.***

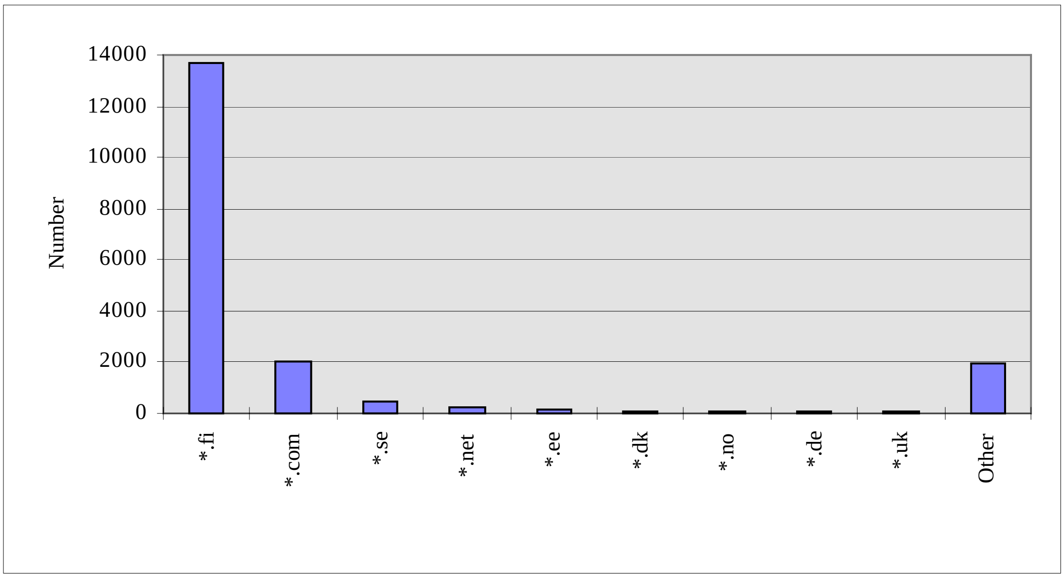


Figure 4.4 ***Visitors at the Finnish ice service's simplified ice chart web pages in 1998 according to server.***

Digital data to the Finnish icebreakers and merchant vessels

During the IMSI project digital sea ice data was sent to several users at sea, as shown in Table 4.1. These users were the Finnish icebreakers and various merchant vessels. For the icebreaker, the Ice Service put the data into the server of the Finnish Maritime Administration (FMA) from where it was automatically delivered to the icebreakers via cellular telephone network or via communication satellites. For the merchant vessels the data were put on a server from where the ships could pick up the needed information via cellular telephone network. In 1999 the data was sent in attached files on e-mail.

Digital data were also sent to some merchant vessels; in 1997 to three vessels of three shipping company, in 1998 also to three vessels of one shipping company and in 1999 to six vessels of one shipping company. In 1997 the technology was developed and tested, in 1998 and 1999 the production became operational (Seinä et al. 1998).

Table 4.1 ***Digital data delivered to the Finnish icebreakers and merchant vessels during IMSI in 1997-1999.***

	No of users			Digital ice charts			AVHRR data		
	1997	1998	1999	1997	1998	1999	1997	1998	1999
Icebreakers	5	6	8			x	x	x	x
Merchant vessels	3	3	6	x		x	x	x	x
	ERS SAR data			RADARSAT SAR data			SAR classifications		
	1997	1998	1999	1997	1998	1999	1997	1998	1999
Icebreakers	x				x	x	x	x	x
Merchant vessels	x				x	x	x	x	x

In the season of 1997, the data sent to the icebreakers consist of EO data of NOAA AVHRR and ERS SAR, plain language ice drift forecasts, and automatic ERS SAR image classifications. In 1998, AVHRR and RADARSAT SAR and plain language ice drift forecasts were transmitted. In

1999 the data were expanded covering also digital routine and special ice charts, plain language ice drift forecasts, and automatic RADARSAT SAR image classifications.

The data sent to the ships in 1997 consisted of EO data from AVHRR and ERS SAR, routine and special ice charts, plain language ice drift forecasts, and automatic ERS SAR image classifications. In 1998, AVHRR and RADARSAT SAR and plain language ice drift forecasts were transmitted. In 1999 the data was EO data from AVHRR and RADARSAT SAR, digital routine and special ice charts, plain language ice drift forecasts, and automatic RADARSAT SAR image classifications.

NOAA AVHRR data are used in the ice service in full 1.1 km resolution. By using image compression the file sizes were reduced, implying a poorer resolution. The AVHRR transmitted to icebreakers and ships had a resolution of 1.5-2 km.

Use of RADARSAT data in the Finnish ice service

In 1998, a contract was made between a consortium consisting of the Finnish Institute of Marine Research, Finnish Maritime Administration, Swedish Meteorological and Hydrological Institute, and Swedish Maritime Administration, and on the data provider’s side the RADARSAT International and the Tromsø Satellite Station (TSS) to deliver RADARSAT data for operational testing. For a fixed price, TSS made available 150 RADARSAT ScanSAR Narrow screens of which the consortium was allowed to download 100 screens. It should be mentioned, that this was the first time in Europe, that RADARSAT data were used in operational sea ice monitoring. In 1999 a similar contract was agreed between the same consortium and the data providers.

The RADARSAT data (covering 300 by 300 km) were delivered to the Finnish ice service in 100 by 100 m resolution in order to keep file size small and save transmission time. TSS sent to the Finnish and Swedish ice services a list of satellite orbits, from which the ice services selected required screens and sent orders to TSS 10-14 days before satellite overpass in 1998. This period was reduced to 7 days in 1999.

In the Baltic Sea area there are two useful RADARSAT orbits covering the ice monitoring areas: one in the morning and another in the late afternoon. The data from the morning passes could be used for updating the ice charts of the same day, but the data of evening passes were available in the next morning. In 1998 it took at least 4-5 hours before the data were ready for use in the ice service. In 1999 after faster and more efficient work station was installed in the Finnish Ice Service combined with faster delivering from TSS, made it possible to reduce this time to about three hours.

The RADARSAT SAR data have proved to be essential for monitoring the rapidly changing Baltic Sea ice conditions, where dense marine traffic demands updated and correct ice information under all circumstances. Since rapid changes in ice conditions normally are related to low pressure activities and thick cloud cover, SAR is the only method to provide reliable and high-resolution sea ice data.

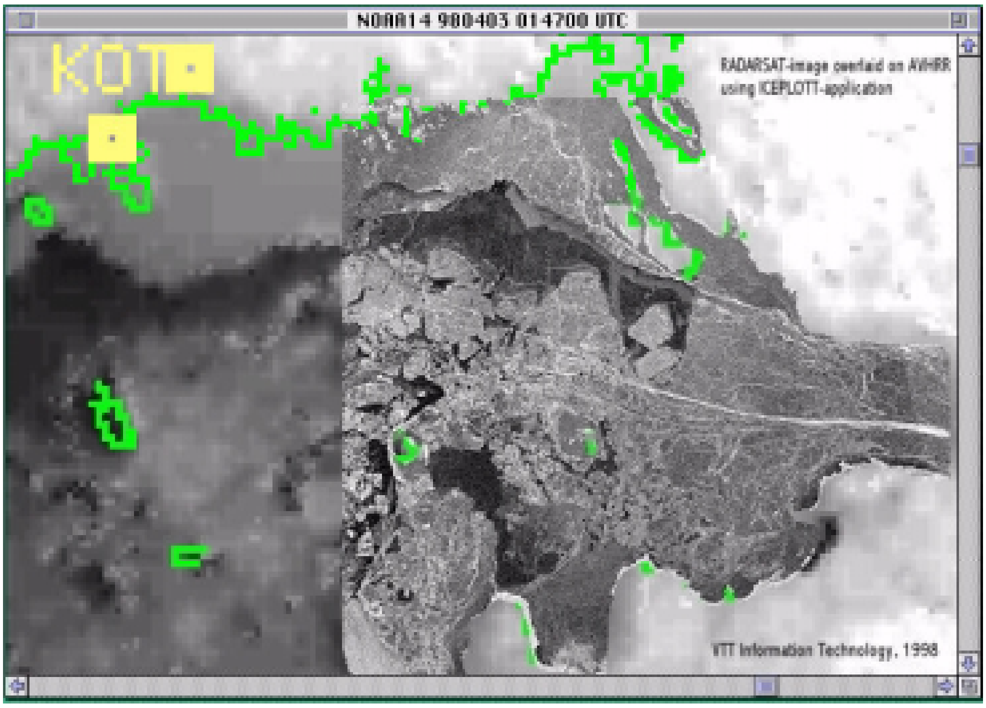


Figure 4.5 ***An example of the AVHRR and SAR data combination in the eastern Gulf of Finland as seen over the presentation environment used by the Finnish icebreakers and some merchant vessels on board.***

4.3 Greenland waters

The aim of the demonstrations by DMI in Greenland was to provide better and more concise ice information using satellites and in particular the SAR satellite RADARSAT. It was also important to evaluate the products, which were developed in an operational context, and distribute the improved ice information product to some end users.

The ice conditions along the east coast of Greenland are severe. Throughout the year, sea ice from the Arctic drifts southwards with the East Greenland Current. In the late winter until mid - summer, the ice extends all the way to Cape Farewell, round the Cape, and further north into the Julianehåb Bay and along the west coast. The ice is concentrated along the north east coast in a wide belt and is drifting with the current and the general winds. Even in the months of August and September which is the only time of year where navigation is possible off the east coast, the belt of sea ice is often more than 200 km wide, with floe sizes often reaching 50 km in diameter. The ice consists mainly of multiyear polar ice several meters thick, which is impossible to break even for large ice strengthened ships like KA and most ice breakers. *En route* KA is able to break 0.5 m of ice and during actual ice breaking 1-1.5 m. The continuously changing ice conditions does not support the use of icebreakers and there are no icebreakers in Greenland. Therefore, the only possible way of navigating in these waters is to avoid areas with high ice concentrations.

From year to year the total amount of ice varies considerably depending on: (1) inflow from the polar basin (2) local formation of ice (3) weather induced breaking of the ice (which accelerates melting) and (4) finally of course weather conditions. On a tactical/operational time scale (hours-days) the most important factor is the wind forcing and related variability of the ice. The ice conditions can change from a wide belt with fairly low overall concentrations, to being very closely packed near the coast. The process of complete change between the two situations may under certain wind conditions occur in less than a week. Navigation in packed multiyear ice is nearly impossible for supply ships like KA and very time consuming.

For the field demonstration in 1998, a PC was installed onboard the Royal Arctic Line (RAL) shipping company's 'Kista Arctica' (KA), for receiving and displaying ice information in near real time. KA is a 4200 ton freighter sailing in Greenland and capable of operating in ice. During the test period ice information based on RADARSAT, SSM/I and NOAA-AVHRR was sent to the ship via Inmarsat and HF -radio.

The KA project was carried out in co-operation with the Electromagnetics Institute at the Technical University of Denmark (DTU) which supplied the presentation browser for the computer on board the ship. Using the new type of data from DMI and the presentation system developed at DTU, it was possible for the navigators on the ship to receive vector-based ice charts, satellite image subsections and even do simple interpretation of images on board the ship. The navigators on the ship described the value of the information they received for navigation and evaluated the new products in general.

'Kista Arctica', performed two trips to the east coast of Greenland with Mogens Nørgaard as captain during the first trip (26/6-9/7 1998). Fritz Ploug was captain during the second, longer trip (14/7-29/8 1998) calling ports from Danmarkshavn to Tasilaq. The most important issue in the operational test was to supply the navigator with the best available ice information for sailing the ship safely through the ice. By this demonstration DMI was able to (1) test the operational use of RADARSAT, (2) test operationally the new ice mapping system SIKU (the Greenlandic word for sea ice) and finally (3) test extensively the reliability of satellites for data communication. During the second trip the ship covered 2000 nautical miles (20-30 days) in ice infested waters, plus the 1500 nautical miles back and forth to Aalborg in Denmark. Ice infested ports were called 9 times from Danmarkshavn in North to Tasilaq in South. KA also went to Nuuk on the west coast, but this area has little or no sea ice in summer.

Weather and ice conditions can seriously hamper navigation, and even though this trip is planned every year it is usually only successfully completed every second year. Under these conditions it is important to have detailed, reliable and up-to-date ice information of the area, in order to optimise the route.

During the 1998 season ice conditions with respect to navigation were average. The ice was in a belt close to the coast and ice information was necessary for navigating in the ice. In the northernmost waters (north of 74°N) the ice conditions were favourable for ship navigation. In some of the fjords navigation was very difficult due to large amounts of advected sea ice. From the beginning of August the ice started to pack, starting near Scoresbysund and later also further North. The packing close to the coast made the coast inaccessible from 74°N to Scoresbysund. A week later also the entrance to Scoresbysund fjord was closed. From the 13th of August until the beginning of September there were at least 90% ice cover near the coast over the entire area. That situation is not unusual in the area but it makes navigation difficult.

In advance DMI had ordered 48 RADARSAT ScanSAR - wide scenes to cover the route of KA and to further investigate the ice in the Cape Farewell area. 39 images were ordered from the east coast to cover the route of KA and 9 from Cape Farewell, for further validation of RADARSAT in this area. As a supplement to the RADARSAT data other satellite data and satellite data based charts were sent to KA. When ever the area was cloud and fog free NOAA AVHRR images (combination of channel 1, 2 and 3) were analysed. Both the image and the corresponding ice chart were then transmitted to KA. The data was sent to DTU where all available SSM/I images from the area were included. The data was at DTU packaged and transmitted to the ship.

The Kista Arctica project is described in detail in IMSI report no. 10, (Tonboe and Rosengreen, 1998). For DMI it was the operational test for the use of RADARSAT as an integrated part of the ice service. RADARSAT showed its strength in providing visually appealing and precise ice information so that KA could follow the optimal route. DMI was able to test important issues in connection with the use of RADARSAT: 1) time delay from the overhead pass of the satellite to the navigator receives the information onboard; 2) planning the scenes with respect to the navigational plan when the ship is operating in ice; 3) investigating the areal and temporal coverage; 4) the performance of RADARSAT for ice mapping on the East coast of Greenland; 5) the use of satellites for data communication and 6) the operational application of RADARSAT and the new products.

The analysis was done by an experienced ice analysts in a Geographical Information System (GIS) environment, specifically customised and further developed at the DMI for ice analysis purposes. Each individual area is during the analysis assigned its particular characteristics, such as concentration, floe size, thickness etc., before the topology is created. From this initial analysis, the digitised ice information can either be further prepared in a graphic design system to produce hard copy ice charts, or sent directly to the end user in a standard GIS format together with a degraded sub-image of the original data. Figure 4.6 shows a typical RADARSAT image from the east coast of Greenland with segmentation of uniform ice areas by the ice interpreter. This procedure is part of the new ice mapping system SIKU. The result of the ice analysis is usually the ice chart shown in Figure 4.7. Prior to SIKU only hard copy ice charts were produced and transmitted to the ships.

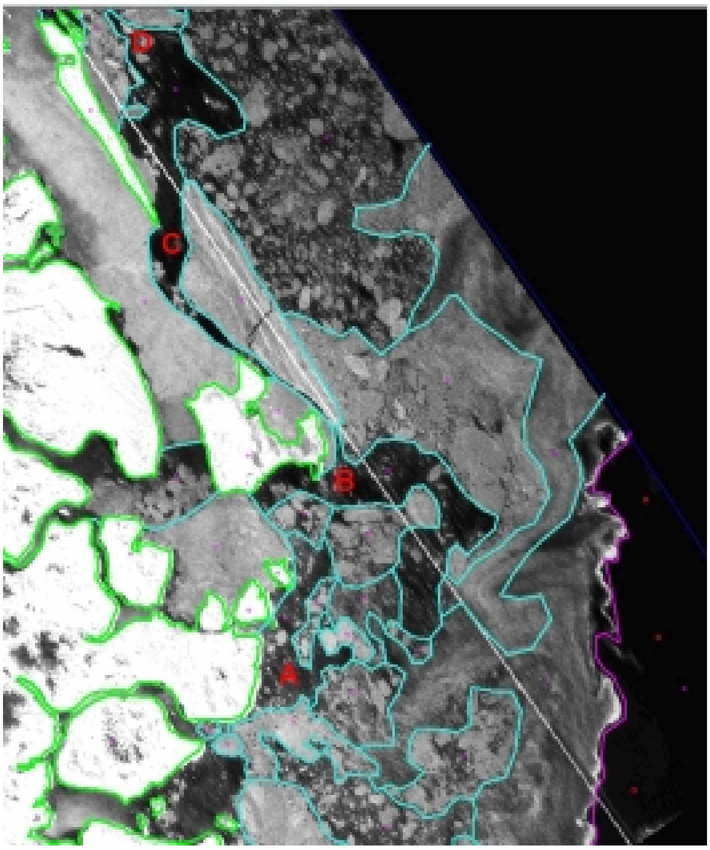


Figure 4.6 ***RADARSAT image from 8th of August 1998. © DMI and RADARSAT International.***

Figure 4.6 is part of a RADARSAT image acquired the 8th of August 1826 UTC, showing approximately 400 km of the east coast from 73° 50' N to 76° 45' N with Store Koldewey Island in the top left corner. As can be seen in the image it shows a variety of ice types and floe sizes. In the ice analysis, the shore is outlined with green and the outer ice-ocean boundary with purple (bottom right). The areas marked with cyan have different ice concentrations -floe sizes and types. Just above the 'B' is an area with approximately 9/10 ice coverage, and floe sizes ranging from a few hundred meters to 40 km, all consisting of polar ice. It is unlikely that a ship could navigate through this area without detailed ice information. This area is bordered to the west by a 111 km. long ice floe of first year winter ice about 1 m. thick. KA's route was at this time from Daneborg marked with the letter 'A' to Danmarkshavn indicated by 'D', which was possible given the right ice information. The direct course goes either directly north from 'B' through dense ice or out into open water and back into the ice again. Instead KA followed the lead to the west of the big elongated ice floe, and had no problems, despite the visibility was less than 100 meters due to heavy fog, which made the helicopter on board useless. The ship radar has a range of a few kilometres, so that the ice in the vicinity can be seen, but it cannot provide any large scale overview. The bright features at the eastern edge of the ice are not, as it might seem, dense ice, but highly irregular ice, broken to small pieces by wind and waves. In the above example it was fairly simple to interpret the image, other scenes were more difficult.

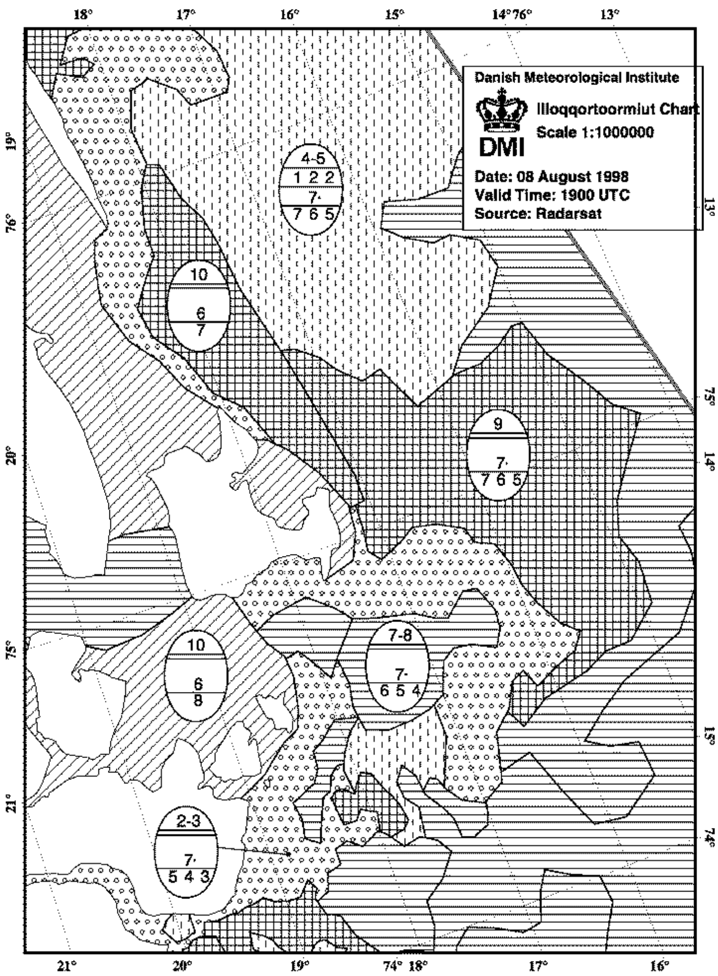


Figure 4.7 ***RADARSAT based ice chart of the same area as figure 4.6. Note that for clarity reasons not all the areas are shown with egg codes. Because this particular ice analysis is intended for electronic displaying, it has greater detail than is usual for hard copy ice charts. The ice information is given in the standard WMO 'Egg code', including hatching of the various areas. Dry land has no hatching.***

The ice situation on the east coast of Greenland can vary rapidly under certain conditions and it is essential for the value of the information that it is relayed to the navigator fast. The existing products based on aerial reconnaissance could be distributed with short time delay of 2 hours after the aircraft had returned to the base and if there were ships in the area of the reconnaissance the observations were relayed directly to the navigator from the aircraft in real time. The time delay concerning information based on NOAA-AVHRR can be distributed to the navigator within 1-2 hours from the pass of the satellite, this is possible because DMI has its own receiving and processing facilities for this type of satellite data.

On the other hand, the navigators onboard KA could usually receive the RADARSAT based information within 5-6 hours after the satellite overpass, which is sufficient for navigation in the area. This delay includes processing of the data either at Gatineau or West Freugh ground station (~2.5 hours), transmission via Internet from the processing facility to DMI in Copenhagen (~1.5 hours), interpretation and analysis of the data and production of the ice chart (~1.5 hours), transmission of the product to the navigator (~minutes).

Under the current RADARSAT acquisition plans the images must be ordered at least 2 weeks in advance. Under special circumstances it can be reduced to one week, but then no guarantee for the acquisition is offered. This is a relatively inflexible procedure which potentially reduces the feasibility of using RADARSAT data for tactical ice piloting. Ships are operated with careful planning and route optimising, but in ice infested waters this planning is frequently revised during a trip. This poses some difficulties to the planning of data acquisition. In order to ensure data coverage of the area where the ship is located at a specific time, difficult navigational areas along the route should be foreseen to make the navigational time schedules as realistic as possible. It is technically possible to cover very large areas frequently at high latitudes and thereby ensure the coverage of the route, but the cost of RADARSAT data allowed only a limited number of scenes to be ordered.

The most critical part of KA east coast journey was limited to an area of approximately 700 by 200 km. The entire area could most often be covered by two ScanSAR Wide (SCW) scenes in combination (one scene is 500 by 500 km), so that any re-routing of the ship could be covered by the same data. The average cruise speed was relatively low when the ship was sailing through ice. Therefore a delay of e.g. 24 hours only meant a displacement of the target area of approximately 200-300 km. That was often within the same area covered by the two SCW - scenes.

Because of the large geographical coverage no significant problems concerning coverage were experienced during the test period. A total of 39 scenes were ordered to cover approximately 30 days of sailing, incorporating the whole area approximately every second day. The scenes were ordered specifically to allow for adjustments in the navigational plan and the data coverage turned out to be fully satisfactory. It was demonstrated on several occasions during the test that RADARSAT can provide both detailed and large scale ice information. The detailed information was usually communicated to the navigator through sub-images so that a particular area could be studied down to the individual floes and leads. The overview was provided by the ice charts and with a reduced image layer.

The quality of the RADARSAT data for use in ice mapping was excellent along the east coast. None of the images were difficult to interpret, and ice edges were clearly distinguishable. There were no problems concerning melt water on the ice or low ice concentration disguised by ‘sea clutter’ as earlier seen in the Cape Farewell area (see IMSI report no. 7). The navigators on KA had during the journey on two occasions taken digital photographs from helicopter of the ice situation in the area they were sailing through. These photographs were returned to DMI together with written comments on the ice charts. The pictures were very valuable for the interpreters at DMI because the ice charts could be validated with the in situ information and the future charts could be mapped in greater detail when the signatures on the RADARSAT image could be related to the exact ice type and concentration. There were no significant differences between the reported in situ observations and the ice conditions derived from the RADARSAT-images.

SIKU the new ice mapping system was tested operationally. During the test there were two immediate advantages using the new system: 1) the ice mapper was able to include different types of information in the analysis of the RADARSAT images, and 2) vectorised ice charts could now be transmitted directly to the ship which meant that the ice could be mapped with greater detail not being graphically limited to a fax sheet. The navigator received the data via Inmarsat. The Inmarsat system relays the data to a geostationary satellite over equator. Communication with Inmarsat above 70°N sometimes causes problems, because the satellite is below the horizon, but in spite of the physical set up of the Inmarsat system, it was possible to transfer data to the ship while it was operating north of 70°N on several occasions during the test.

During Task 3 RADARSAT showed its strength in providing visually appealing and precise ice information so that KA could follow the optimal route. DMI had the opportunity to test their new products operationally and now these products based on for example RADARSAT are an integrated part of the service.

4.4 Regional SSM/I ice charts on Internet

DTU has developed an Internet-based Java World Wide Web browser for disseminating sea ice products to the user-community, http://www.dcrs.dtu.dk/sea-ice/archive.html. The main target users of this system are land-based, with medium to high-speed data transfer lines. Ice products are now available from several regions: Greenland and Iceland Seas, Baffin bay and Davis Strait area, South Greenland, Kara and Barents region and the Baltic Sea.

Our development JAVA browser, which by the end of 1997 is only available for the East Greenland area was requested by a total of 49 users over the period October 29 to December 31, 1997. We have received very positive feedback from the Icelandic Meteorological Office who are a major professional user of our ice information on a daily basis. We consider these results a confirmation that there is a need for the type of ice information we are providing. It should be noted that the information this far has not been advertised to any major extent. By the end of the IMSI project the number of users had increased dramatically, as shown in Table 4.2.

A large user community has been established, ranging from the occasional personal user over university users working on projects related to the Arctic to commercial users in shipping companies and operational ice centres. The major users of the information are listed in the table below which shows users from all categories.

The primary target user group for the Internet ice service was universities working with sea ice or polar research. We have been in close contact with a number of these groups and the feedback has been very positive. We even had feed back from some groups we did not know. This happened when the service was for some reason out of operation for a shorter period. Also, the users at ice centers in Northern Europe (Iceland, Denmark and Greenland) have been very positive and found the service of very good use. These users were not anticipated originally, but they turned out to be by far the major ones (see Table 4.2)

Table 4.2 ***Major users of the DCRS/IMSI Internet based sea ice information service sorted by total number of ice products downloaded.***

Total	%	Name	Country
2841	10,0	Icelandic Meteorologic Institute	Iceland
2562	9,0	GEOMAR Research center for Marine Geosciences	Germany
2438	8,6	Icecenter Narsarsuaq	Greenland
2275	8,0	Danish Meteorological Institute	Denmark
717	2,5	Internet service provider (dialup.online.no)	Norway
620	2,2	The Icelandic Maritime Administration	Iceland
616	2,2	Internet service provider (194.25.201.xxx)	Germany
603	2,1	German climate computing center (DKRZ)	Germany
603	2,1	Institute for Meteorology, FU Berlin	Germany
568	2,0	Scott Polar Research Institute, Cambridge	UK
554	1,9	Højskolen i Bodø, Research Institute	Norway
503	1,8	Arctic Net (relay.an.ru)	Russia
500	1,8	Finnish University Network	Finland
498	1,7	Kiel University	Germany
477	1,7	National Oceanic and Atmospheric Administration (NOAA)	US
431	1,5	Ministry of Environment and Energy	Denmark
410	1,4	Japanese Broadcasting Corporation	Japan
353	1,2	Helsinki University Of Technology	Finland
340	1,2	Mapmakers Group Ltd. (meteorological software company)	Russia
333	1,2	Internet service provider (isnet.is)	Iceland
311	1,1	Internet service provider (t-online.de)	Germany
293	1,0	Natural Environmental Research Council	UK
255	0,9	Nansen Environmental and Remote Seaning Center	Norway
236	0,8	Norwegian Polar Institute	Norway
234	0,8	Federal Maritime and Hydrographic Agency og Germany	Germany
234	0,8	Canadian Government, Fisheries & Ocean	Canada
231	0,8	Copenhagen University	Denmark
210	0,7	Finish Meteorological Institute	FInland
193	0,7	Internet service provider (America On-line)	
175	0,6	Geophysical Institute, Polish Academi of Science	Poland
165	0,6	Hamburg University	Germany
155	0,5	Duesseldorf University	Germany
153	0,5	Internet Service Provider (Compuserve)	US
145	0,5	Ocean Tiger	Denmark
138	0,5	Internet service provider (planet.net.uk)	UK
128	0,4	NASA	US
121	0,4	Norwegian Institute of Technology	Norway
119	0,4	Norwegian University of Science and Technology	Norway
93	0,3	Alfred Wegener Institute for Marine and Polar research	Germany
85	0,3	University of Colorado	US
85	0,3	Marine Research Institute	Iceland
83	0,3	Joint research center	Italy
76	0,3	KNI Greenland	Greenland
70	0,2	Princess Cruises	US
57	0,2	IFREMER	France
50	0,2	Environmental Research Institute of Michigan	US
49	0,2	University of Bergen	Norway
46	0,2	UK Met Office	UK
36	0,1	Danish Hydrographic Administration	Denmark
35	0,1	Statoil - Oil company	Norway
31	0,1	The Norwegian Meteorological Institute	Norway
26	0,1	Public Roads Administration	Iceland
21	0,1	University of Bremen	Germany
18	0,1	US coast guard	US
28507	100	TOTAL	

As can be seen from Table 4.2, a large number of new satellite products have been used by ice services in Iceland, Greenland, Denmark and other countries. These ice services did not use passive microwave data for operational ice mapping before.

Most of the users we have been in contact with stresses the importance of good and frequently updated ice information for safety reasons as well as to reduce fuel consumption and find profitable fishing grounds. University users find the daily updated ice information very valuable for the planning of cruises as well as for the understanding of the geophysical processes that interacts with the ice cover. Thanks to primary NASA, the Tromsø Satellite station and the Danish Meteorological Institute, all data products have been distributed without a charge.

Results of the dissemination and exploitation work (Task 3)

An Internet based processing and distribution system for sea ice data has been established and operated for more than 1 year. The system contains daily updates of sea ice information from the European sector of the Arctic covering the Baffin Bay/Davis Strait area between Greenland and Canada, the Kap Farewell area around southern Greenland, the entire Greenland east coast, the Greenland Sea, the Fram Strait, the Barents Sea, the White Sea and the Kara Sea, see Fig. 4.8.

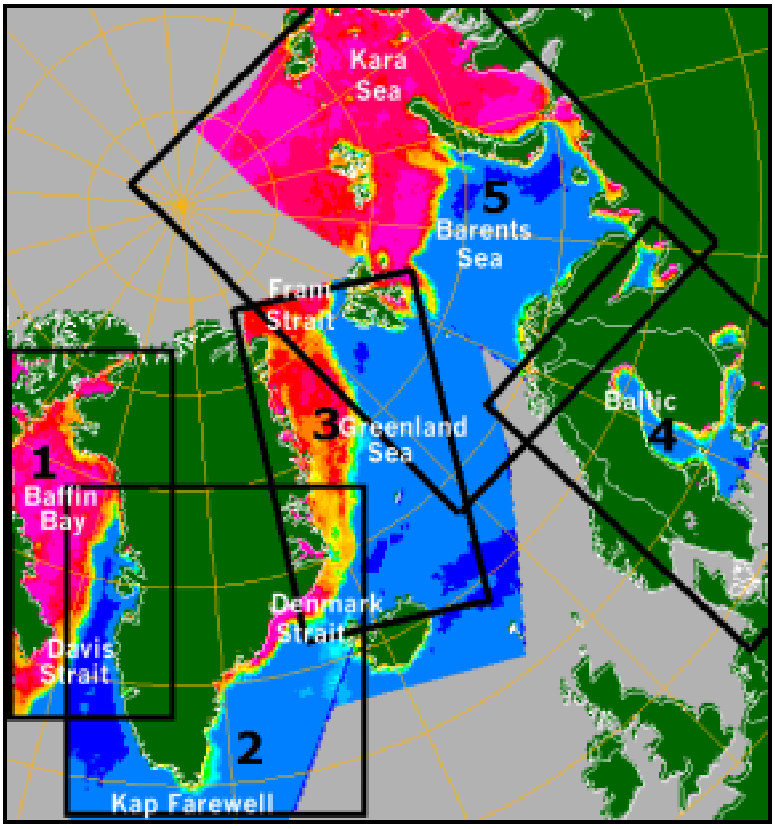


Figure 4.8 ***Outline of the areas covered by the ice data information system at the Danish Center for Remote Sensing (DCRS), Technical University of Denmark. After the production of this map, a 6th area covering the Northern Coast of Greenland and the Fram Strait has been introduced as well.***

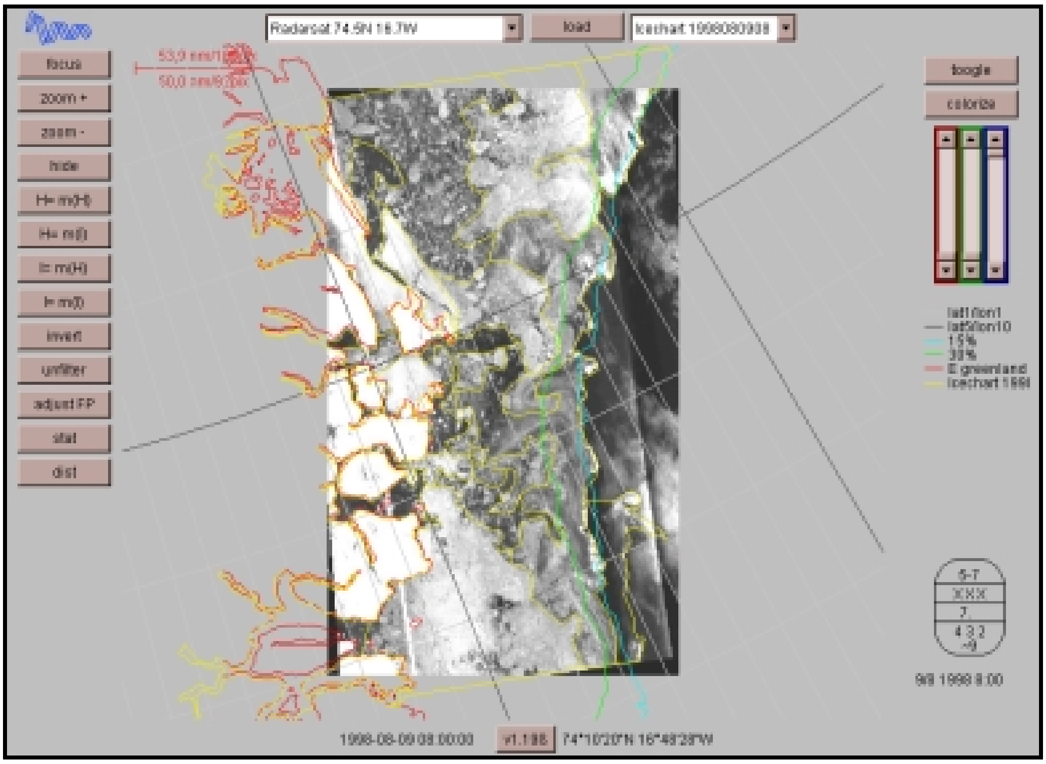


Figure 4.9 ***Example of the Java browser in action, showing a RADARSAT image with overlays of coastline, lat/lon grid, ice concentration contours from SSM/I, and digital clickable ice chart from DMI. When the user clicks in a polygon on the ice chart, the ice egg code is display in the lower right corner of the screen. The egg code is a WMO standard for display of information of ice type, ice thickness, floe sizes etc. © DMI/RADARSAT International.***

Other dissemination activities:

Presentations at various DCRS meetings and seminars, including interactive demonstrations of Java browser.

The source code for the DCRS Java browser has been delivered to the Nansen Environmental and Remote Sensing Center for use in a refugee mapping project.

The DCRS Java browser and archive structure is currently being implemented by the Danish Meteorological Institute for future distribution of ice data.

4.5 Arctic and Antarctic scatterometer ice charts on Internet

Evaluation of IFREMER scatterometer Polar Sea Ice Products

The IFREMER Polar Sea Ice Products (PSI), produced and placed on the Web by the CERSAT (Centre ERS d'Archivage et de Traitement) have only a low resolution (40 to 50 km) but compensate for this by their frequency, produced weekly and every three days over both polar oceans, respectively from the ERS AMI in Wind mode and NSCAT. Users essentially consult the Web pages, only nine users having asked for the numerical files since February 1998.

http://www.ifremer.fr/cersat/SERVICES/BROWSERS/E_BROWSE.HTM

Figure 4.10 shows the number of HTML pages consulted per month from February 1998 to February 1999. After a first surge of interest from February to May 1998, the situation stabilises around 300 consultations a month, outside of an unexplained peak in February 1999. Clearly, most users wish to know what the general sea ice situation is, but have no desire to analyse the data further.

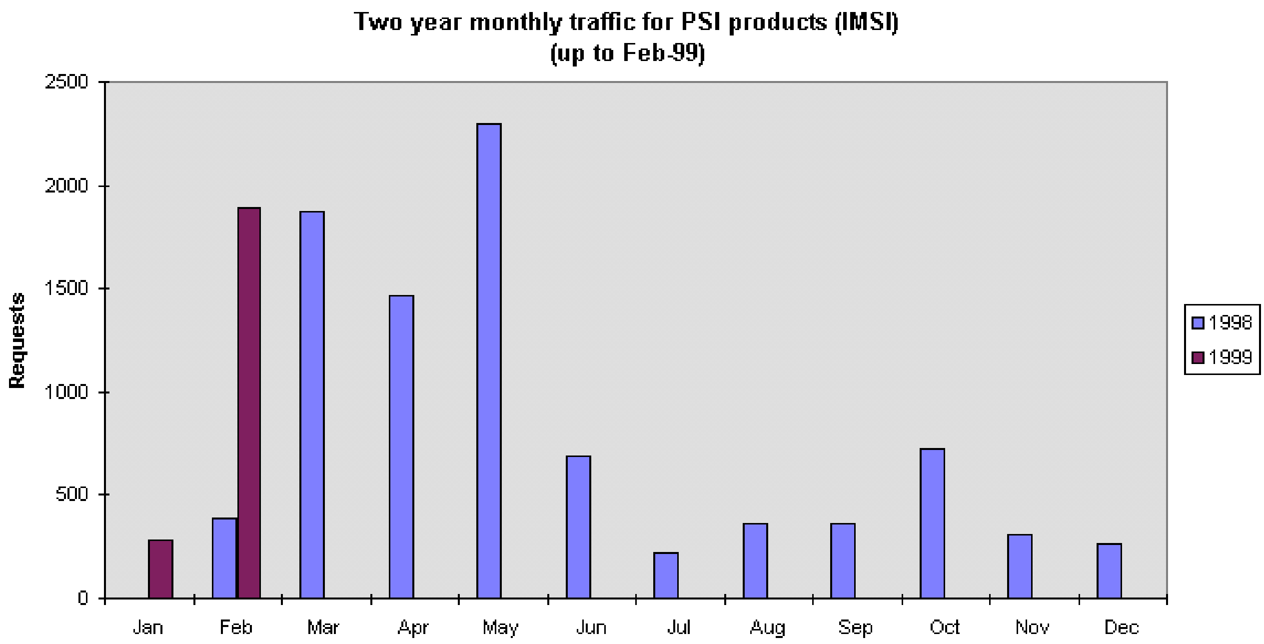


Figure 4.10 ***Number of HTML pages consulted per month from February 1998 to February 1999.***

The number of HTML pages consulted by different countries during this thirteen months period is of some interest. The following table shows that quite a large number of countries are concerned (36 in all), many having placed only a few requests, probably out of simple curiosity. But some stand out as regular users, essentially France, the USA, Denmark, Germany, Finland and Japan, which each register more than one hundred requests during the thirteen month period. The large USA demand is split into four segments: Commercial, Educational, Government and Military, corresponding respectively to 1564, 151, 314 and 4 requests.

Table 4.3 ***The number of HTML pages consulted by different countries.***

Country	Requests	Country	Requests	Country	Requests
Austria	2	Greece	4	Poland	10
Australia	9	Ireland	1	Portugal	4
Belgium	17	Israel	6	Russian Fedn.	10
Canada	29	Italy	59	Singapore	14
Chile	1	Japan	196	Spain	11
China	5	South Korea	8	Sweden	76
Denmark	437	Lebanon	1	Switzerland	7
Estonia	4	Mexico	3	Thailand	2
Finland	118	Malaysia	1	Taiwan	2
France	4166	Netherlands	51	Ukraine	3
Germany	275	Norway	91	USA	2031
Great Britain	37	New Zealand	2	Unresolved	937

5 Validation of products developed in IMSI

5.1 Field validation of SAR ice classification in Northern Sea Route

Of the two algorithms discussed in Chapter 3.1, the LDA algorithm performed better for the independent RADARSAT image that was not used for training. It was possible to assess the performance of LDA algorithm more accurately because the image was acquired at the same time as the icebreaker entered the area covered by the image. Homogeneous regions on the image along the ship route were delineated, and assigned to the sea ice classes according to ship observations. Fragments of the image on 30 April 1998 and the fragments classified by the LDA algorithm with the validation regions overlaid is presented in Fig. 5.1 and 5.2. The number of pixels for each region belonging to certain sea ice classes were counted, and the result together with in situ data is presented in Table 5.1, showing how many pixels were correctly classified by the LDA algorithm.

Table 5.1 ***Classified regions in image of 30 April 1998.***

Region number	**Sea Ice Class**	**Number of pixels in the region**	**Level FY ice** (%)	**Deformed and very deformed FY ice** (%)	**Young ice** (%)	**OW& nilas**(%)
R1	OW&nilas	822	14.6	34	0	**51.2**
R2	OW&nilas	189	16	39	0	**45**
R3	OW&nilas	103	0	24	0	**76**
R4	OW&nilas	120	0	24	0	**76**
R5	OW&nilas	176	0	70	0	**30**
R6	Young ice	323	0	6	**94**	0
R7	OW&nilas	323	2	34	0	**64**
R8	Young ice	984	0	46	**54**	0
R9	Young ice	580	0	29	**70**	0
R10	Young ice	313	0	0	**100**	0
R11	Young ice	702	0	10	**90**	0
R12	Young ice	163	0	10	**90**	0
R13	Deformed FY ice	2725	0	**98**	2	0
R14	Deformed FY ice	9687	0	**75**	25	0
R15	Deformed FY ice	2076	0	**81**	19	0
R16	Young ice	8719	1	65.3	**34**	0
R17	OW&nilas	815	63	30	0	**7**

Classification table for all regions along the ship route for the RADARSAT Scan SAR image on 30 April 1998 is presented in Table 5.2.

Table 5.2 ***Classification table for all regions along the ship route.***

	FY level (%)	Deformed and very deformed FY ice (%)	Young ice (%)	OW&nilas (%)
FY level	**0**	0	0	0
FY rough	3.9	**70.3**	25.8	0
Young ice	1.8	59	**39.2**	0
OW&nilas	51.5	31	0.2	**16**

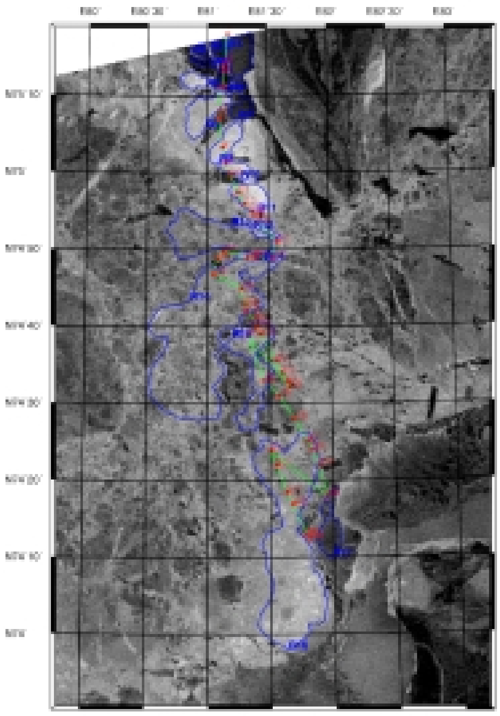


Figure 5.1 ***Fragment of RADARSAT Scan Wide SAR image acquired of April 30, 1998 with the icebreaker route and validation regions overlaid. Canadian Space Agency.***

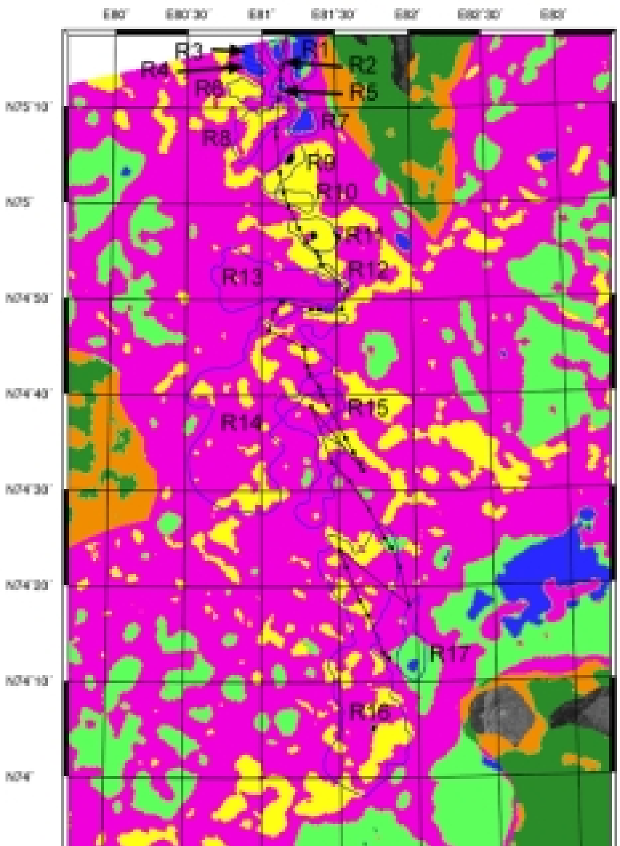


Figure 5.2 ***Fragment of RADARSAT Scan Wide SAR image acquired of April 30, 1998 classified by LDA algorithm with the icebreaker route and validation regions overlaid.***

5.2 Validation of RADARSAT classification in Baltic Sea

The IMSI validation activities in the FIMR were concentrated on the RADARSAT automatic classification development, distribution of EO data and EO data products to the users at sea and distribution of sea ice information to the users at land via web-ice chart.

Status and limitations of the current EO data

The main limitations of current satellite data are:

- AVHRR and other visual/infrared systems are cloud and daylight limited, which means that regular observations of sea ice are not possible every day.
- SAR data from ERS can provide most of the important ice parameters at sufficient resolution, but spatial and temporal resolution is not adequate for regular use in sea ice monitoring.
- SAR from RADARSAT can fulfil most technical requirements for sea ice observations. The main problem is the high cost of data.

The AVHRR data are the basic EO data in ice monitoring, because the data are free of charge, and it is easy to receive by fairly simple equipment. Resolution of 1 km is good enough for general ice mapping. The Baltic Sea is frequently covered by clouds especially during low pressure activities, and as major changes occur during low pressure activities, visible/infrared data has its limitations. It has been estimated, that in the Baltic Sea area some 60% of images are useless because of cloud cover.

SAR data are ideal for ice monitoring, because they are independent of clouds and daylight, assuming the swath is wide enough and the resolution is suitable. SAR data processing is complex and requires more extensive processing at the ground stations compared to other data. Also the file sizes are large and transmission on Internet takes time. This means that there is time delay of several hours before the data are available for use in the ice services. Another disadvantage is that the data must be order 1-2 weeks in advance. The data is also rather expensive to use.

Status and limitations of the current delivery systems

The main limitations of current delivery systems are:

- Cellular telephone systems used in data delivery are slow and it has gaps in coverage in the high sea areas.
- Delivery time of large file size from SAR data receiving station and ice service via Internet is too slow.
- The RADARSAT SAR images delivered to the icebreakers and ships in 1998 had too coarse resolution (800 m) to be used directly in tactical ice navigation.

Terrestrial cellular telephone systems (NMT-450 and GSM) used in data transfer have rather low data transfer capacity. Also the coverage at sea has gaps at the high sea areas. However, the system is inexpensive and has been used for years despite its limitations. In near-future all data transfer at sea should be based on telecommunication satellites with higher data transfer capacities.

One of the RADARSAT data problems is due to the timing of the orbits in the Baltic Sea area. There are two useful orbits, approximately 04:00 and 16:00 UTC (±2 h). The processing takes about 2 h at TSS. After image transmission via Internet, the data were reprocessed into suitable format and geographic corrections are made. The image transmission takes 1.5-2 h including reprocessing, implying that the data were accessible at the ice service 3.5-4 h after reception. Then the local winter time is 09:30-10:00 (21:30-22:00). The data used for analyses of ice charts, must be available before noon. The schedule of the RADARSAT morning passes is optimal, and the screens could be used in ice mapping for the same day. The evening screens were available next morning. This meant that the morning images can be available for the users at sea after 4-5 h, while the evening images after more than 24 h.

In 1999 RADARSAT image resolution sent to the icebreakers and ships was improved to 400-500 m in full size 300 by 300 km image. This was a major improvement compared to 800 m in 1998. The aim is to improve compression applications, so that images could be optimally send in full resolution and the transmission time would be made very short.

Automatic classifications of RADARSAT SAR image in the Baltic Sea

In 1998 a total of 99 ScanSAR Near and ScanSAR Far RADARSAT SAR images were classified. In general, classification results were acceptable, and transmitted operationally and in real-time to Finnish icebreakers and some cargo ships. FIMR will continue these activities during the coming ice seasons. The original data were in the resolution of 100 m, and the classification maps were represented with the resolution of 500 m. The classification results were validated against the standard Finnish ice charts, containing all available ground truth, air-borne and space-borne sea ice information.

The first version of the algorithm was available in early 1998, and the latest in summer 1998. The first validation was done in spring 1998, and the results were used for further development of the algorithms (Sandven et al. 1998a, Karvonen and Similä 1998a and 1998b, Similä and Karvonen 1999, Karvinen and Similä 1999).

The ice parameters which were used in evaluation were: ice-edge, leads, thin level ice, thick level ice, slightly deformed ice, heavily deformed ice and fast ice. Thin level ice was determined as the ice that has a relatively smooth surface and is in average less than 10-20 cm thick, and thick level ice as the ice that has a somewhat rougher surface than thin level ice with a average thickness of more than 10-20 cm. Hence, the ice thickness could vary significantly inside one ice category.

The results were given as discrete distributions, and in this kind of approach there must be enough material to get a reliable result. A classified image can indicate false information because of several different reasons (e.g. air temperature, incidence angle variation, used resolution, algorithm malfunctions, etc.), and therefore, if there were only a couple of images for certain ice conditions the total percentage of successful classifications cannot be considered reliable.

The terms thick and thin were used in determining some of the ice parameters. The ice thickness can not be measured directly with C-band radar instrument, but the surface roughness increases as first year ice ages. The backscatter of a C-band SAR is dominated by surface scattering in the case of first year ice and the strength of the measured scattering increases when the surface roughness increases. Hence, terms thin and thick can be used in describing ice features. Rough and relatively smooth surfaces generate different kinds of backscattering, and these scattering mechanisms are highly dependent on the angle of incidence.

The validation was divided in four sections:

1) All the classified images were included in the first evaluation.
2) The classified images were evaluated due to the area they cover.
3) The classified images were evaluated due to three day minimum and maximum mean temperatures.

4) The impact of incidence angle (ScanSAR near and ScanSAR far).

Effect of incidence angle on SAR classification

In figures 5.3 and 5.4 A-D and E-F, some examples of successful and unsuccessful classifications are shown. The temperature clearly has an effect on the quality of sea ice radar image and, hence, also naturally to the classification results. This is a problem of the measurement system itself. The algorithm cannot provide reliable information if the measurement is unreliable. Wind speed ranged from 2 to 6 m/s and, thus, provides no explanation to the quality difference of the classified images. The RADARSAT SAR looks always to the right. This implies that the same ice areas are illuminated from different directions and at different incidence angles during ascending and descending orbits.

Image A is a classified ScanSAR Far image taken during a descending orbit on 8th of February 1998 covering the Quark and Bothnian Bay, and the classification can be considered successful. The sea from middle high sea towards the Finnish coast was mainly covered by the thick level ice. In the classified image the area is mainly thick level ice (dark green) and in lesser degree thin level ice (light blue) with slightly deformed areas (yellow). From the middle high sea towards the Swedish coast there was mainly deformed very close ice, and in the classified image the heavily deformed areas are seen as brown and slightly deformed as yellow. Fast ice (red) extends near the coasts, and deformations at the fast ice area are seen as yellow and brown.

Image B is a classified ScanSAR Near image taken during a ascending orbit covering the Bothnian Bay and Quark on 9th of February 1998. The classification can be considered successful. There are no considerable changes in the overall ice conditions when compared to image A, but differences due to incidence angle are clearly seen. The level ice region extending from mid high sea towards the Finnish coast is mainly thin level ice (light blue) when in the case of image A it was classified mainly as thick level ice. Deformations at the Swedish side are seen mainly as heavy deformations (brown) when in the case of image A they were seen mainly as slight deformations (yellow).

Image C is a classified ScanSAR Near image taken during a descending orbit on 25th of February 1998 covering the eastern Gulf of Finland. The classification has mostly been successful. The area was quite heavily deformed very close drift ice and fast ice from its middle and eastern parts, going westward there were less deformed areas. Heavy deformations (brown) in the image are in good accordance with the operational Finnish ice chart, and going westward the number of deformations diminish being mostly slight deformations (yellow). The western part was classified mainly as thin level ice which is, also, in good accordance with the ice chart where there exists a area of level ice that is 10 - 30 cm thick. A low concentration area is seen as open sea. The identification of fast ice areas does not function very reliably in area of the Gulf of Finland which is in the contrast with good experiences gained about the Bay of Bothnia.

Image D is a classified ScanSAR Near image taken during a ascending orbit on 26th of February 1998 covering the Eastern Gulf of Finland. The classification has not been successful in the case of detecting deformations. Neither ice nor temperature conditions had changed much from those that prevailed when image C was taken, but the deformed ice areas are seen to concentrate to the western parts of the image. This can be explained by the incidence angle effect because the satellite has passed the area from a different direction. The identification of fast ice does not function either. The area of open water (blue) on the eastern side is either flooded or moist snow.

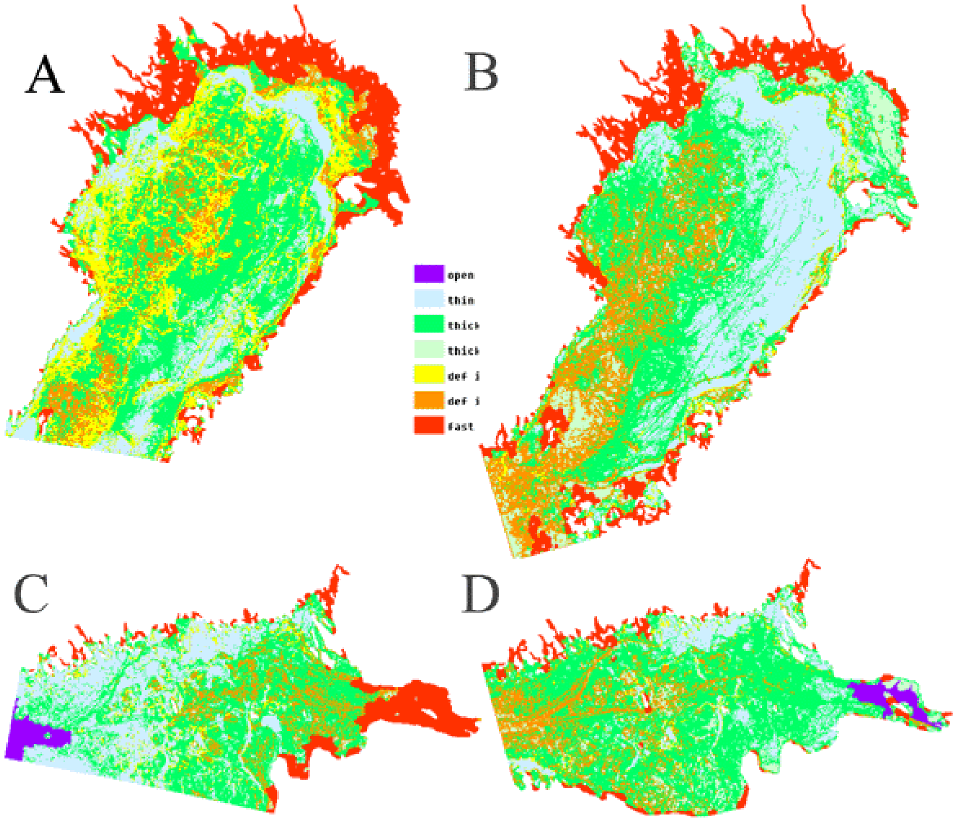


Figure 5.3 ***A-D. Examples of the RADARSAT SAR classifications. The ice parameters in the evaluation given in parameters used by the algorithm are: ice-edge = border between open sea and any ice classification; leads = open sea; thin level ice = mainly thin ice; thick level ice = mainly thick ice 1 and thick ice 2; slightly deformed ice = def ice 1; heavily deformed ice = def ice 2; fast ice = fast ice and locally other classifications.***

Image E is a classified ScanSAR Near image taken during the ascending orbit on 29th of March 1998 covering the Bothnian Bay and Quark. The image gives false information about the overall ice conditions. This was caused by the long warm weather period, when the air temperature was above 0º C. The snow on the ice surface is very moist, and water appears on the ice surface also in snow-free areas. Then the backscattering takes place from the water and does not tell anything about the ice. Even visually it is very difficult to analyse this kind of SAR images and the classification rules developed for dry ice conditions cannot be applied.

At the Quark two wide leads are separated by low concentration ice areas, and according to the classified image most of the area is open sea (blue). This is a successful result taking into consideration that the algorithm is not capable of detecting low ice concentrations. But the results in the Bothnian Bay are not successful. According to the ice chart the coasts are covered by fastice with thickness up to 75 cm, and the high sea area heavily deformed very close drift ice with thickness ranging from 20 to 60 cm is present. According to the classified image there is a large area of open sea (blue) with floes present, and the coasts are mainly thin level ice (light blue). The reason for these false interpretations can be traced back to the preceding air temperatures. The large area of open sea is most likely water that has melted during the warm period, but the reason why the coasts are classified as thin level ice (blue) is harder to explain. It could be asked why is there no flooded water at the fast ice area near the coasts? It can be concluded that the SAR data are temperature dependent by comparing images taken during this warm period. The SAR gives false interpretations about the overall ice conditions, and in consequence the algorithm gives false classifications.

Image F is a classified ScanSAR Far image taken during a descending orbit on 31st of March 1998 covering areas of Quark and Bothnian Bay. The classification is more reliable than in the case of image E, and there has been a decrease in air temperature. In fact the maximum temperature on 31 of March was -3.0 °C, while on 29 of March it was +2.8 °C.

According to the ice chart there was a large lead at the southern Quark that can be clearly seen in the classification map, but the northern Quark was covered mainly by deformed close and very close drift ice. The image classification has been unsuccessful. The ice conditions at the Bothnian Bay had not changed considerably compared to two days earlier when image E was taken. The open sea classification at the southern Bothnian Bay was most likely flooded or very moist snow on top of the ice. Elsewhere the classification functioned rather well, and the reason was most likely related to the decrease in temperature.

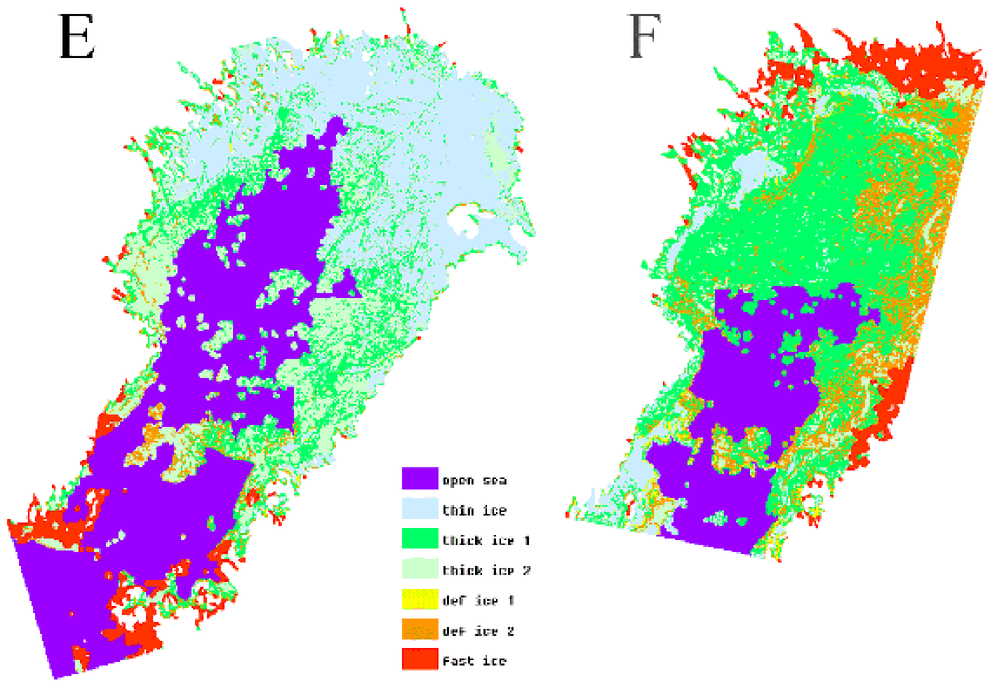


Figure 5.4 ***E-F. Examples of the RADARSAT SAR classifications. The ice parameters in the evaluation given in parameters used by the algorithm are: ice-edge = border between open sea and any ice classification; leads = open sea; thin level ice = mainly thin ice; thick level ice = mainly thick ice 1 and thick ice 2; slightly deformed ice = def ice 1; heavily deformed ice = def ice 2; fast ice = fast ice and locally other classifications.***

No examples of large open water area classification were included. This kind of open water areas are identified correctly in the classification maps. Open water classification problems occur with narrow leads and also sometimes during the cold freezing period when there appear thin ice floes in the sea. A question which demands further investigation is the classification of low ice concentration areas. In these cases, the current algorithm systematically overestimates the extent and thickness of ice floes.

5.3 Use of aircraft and field experiment data in Baltic Sea

HUT investigated in co-operation with FIMR combined use of SAR and passive microwave radiometer (MWR) data for classification of open water and various ice types in the Baltic Sea. HUT also aided FIMR in the development of the RADARSAT and ERS-2 SAR sea ice classification algorithms by studying C-band backscattering signatures of various Baltic Sea ice types.

Combined use of SAR and MWR data was studied using airborne MWR and SAR data and RADARSAT data. The SSM/I data were not used due to their poor spatial resolution. The data were used to study classification of different surface types with MWR data alone and MWR and SAR data together. Additionally, the MWR data were also used to validate applicability of the NASA Team and Bootstrap ice concentration algorithms in the Baltic Sea. The results suggests that it is possible to use both algorithms to map total ice concentration; however, modification of the open water and 100% ice concentration reference signatures is needed. It may not be possible to modify the NASA Team algorithm to resolve concentrations of new ice (i.e. thin ice) vs. all other ice types in the Baltic Sea as has been done for the Arctic seasonal ice areas. User demonstrations have not been conducted as the spatial resolution of currently available spaceborne radiometer data (SSM/I) is too poor for ship navigation purposes in the Baltic Sea.

The development of sea ice classification algorithms for the RADARSAT and ERS-2 SAR and forthcoming ENVISAT ASAR (Advanced SAR) images was supported by analysis of C-band backscatter measurements of different Baltic Sea surface types. The measurements were conducted with the helicopter-borne C- and X-band non-imaging HUTSCAT scatterometer during six ice research campaigns in 1992-1997.

The HUTSCAT derived incidence angle dependency of backscattering coefficient can be used to remove the incidence angle variation in the RADARSAT ScanSAR and ENVISAT wide swath SAR images. This removal is expected to improve the classification results of the SAR images.

The results suggests that at least under moist and wet snow condition SAR images with high incidence angle range (e.g. 40-50 degrees) are better for classification of different surface types than images with low incidence angle range (e.g. 20-30 degrees). The accuracy of Maximum-likelihood classification of backscattering coefficients was so poor that probably just visual interpretation of SAR images gives better results than automatic intensity-based classification. It was usually possible to determine cut-off levels for σ° below which an ice type is most likely not one of the deformed ice types and above which it is. The cut-off levels are useful in automatic classification algorithms to help to determine the ice type.

The mean accuracies of Maximum-likelihood classifications for C-band HH, VV and cross polarization are so close to each other that it is not possible to determine which of these polarizations is the best for surface type classification. For open water lead identification the cross-polarization ratio is the best of the C-band intensity variables.

5.4 Validation of RADARSAT SAR images for ice monitoring in Greenland waters

The aim of the products development at DMI

DMI ice service has the primary purpose of distributing information about the sea ice around Greenland for the safety of navigation. In particular it is the duty of the ice service to cover the navigationally important Cape Farewell region (59 - 61°N, 38 - 48°W).

This puts the following operational requirements on the satellite data:

(1) transfer time from the satellite (via ground processing facility i.e. satellite receiving and processing) to DMI must be acceptable considering the physical conditions and the variability of the sea ice

(2) the product must undergo geophysical validation to determine under which conditions they are valid

(3) the products from DMI e.g. ice charts imagettes etc. must contain the relevant information such as ice edge, ice concentration that are needed for navigation.

(4) the product should be transmitted and presented to the navigator in near real time for them to be of any use (data that is >12 hours old is only of scientific interest). All the above mentioned aspects must be considered in a product validation campaign.

The DMI validation campaign was divided into 2 parts: (1) validation of RADARSAT data quality for mapping the sea ice around Greenland, data transmission coverage and aerial validation (IMSI report no 7), and (2) validation of the operational procedure, satellite transmission of information at high latitudes and user evaluation of the final product (IMSI report no. 10).

Products based on RADARSAT

The RADARSAT was launched in November 1995. Soon after its launch it was used for operational sea ice charting by the Canadian Ice Services, (Ramsay et al., 1997). The satellite has only one instrument on board, namely a SAR (C band HH polarisation and incidence angles from ≈ 20° - 50°). An attractive feature of this SAR for ice mapping is that it is possible to operate the SAR in a number of different modes. The main modes of interest to DMI for its operational ice monitoring service for Greenland is the ScanSAR wide (SCW) mode. The images from this mode have pixel sizes of 50 m and swath widths of 450 km - 500 km. The main focus since 1996 has been on evaluating these data (Gill and Valeur 1996b, Gill et. al., 1997, 1998b). This is simply because, given the size of the region that is to be mapped, it offers the best possible areal and temporal coverage with this satellite.

Transmission of the RADARSAT data from satellite receiving stations to DMI in near real time

To image the Cape Farewell region in both the ascending and the descending passes it is necessary to receive data from the RADARSAT receiving stations West Freugh (UK) and Gatineau (Canada). The data from the descending passes which are in the mornings ≈ 9.30 -9.50 UTC, are received at West Freugh. The Ascending passes are in the evenings ≈ 20.30 - 20.50 UTC, and the data are received at Gatineau. The question arises as to the most cost effective method of transferring these data from these two stations to DMI in Copenhagen for interpretation.

The relative costs of the data transfer to DMI via satellite, lease of a fast line and using Internet were investigated. As a no great surprise, the cheapest solution was found to be via Internet. Trials were carried out with data transfer via Internet in real time i.e., the times at which the data are expected to be transferred in a operational phase, from Gatineau and West Freugh to Copenhagen. The data from West Freugh were transferred ≈ 12.00 - 13.00 UTC (allowing 2 - 3 hours for the SAR processing) and from Gatineau ≈ 23.00 UTC. It was found that with DMI's current 256 Kbits/s connection to the Internet the data transfer rate was on average ≈ 1 Mbytes per minute. Thus it is possible to transfer a full SCW mode image (≈ 100 Mbytes) in about 1 hour 30 minutes which is sufficient for DMI operational ice mapping needs. However it should be pointed out that the transfer times from Gatineau can increase by as much as a factor of 3-4 if the data are transferred during the day time.

Validation of the RADARSAT derived ice products

The data set consisted of 52 SCW images, 7 of which were from 1996 and 45 from 1997. 10 of these, from March and April, were from the Disko and Baffin Bays regions along the west coast (66 - 72 °N, 48 - 56 °W), 1 from Scoresby Sound along the east coast Sound (69 - 72 °N, 20 - 28 °W), and the remainder 41, namely 18 from March - June and 23 from the month of July 1997, were from the Cape Farewell Region (59 - 61 °N, 38 - 48 °W). Emphasis was placed on acquiring data from the month of July because it was anticipated to be the most difficult month to map with RADARSAT as the ice floes contain substantial surface melting and the ice concentration is normally low (< 5/10 in most areas around Cape Farewell). Further, on 6 different days in July both the ascending and descending images were acquired to improve and to check the quality of the RADARSAT deduced ice charts.

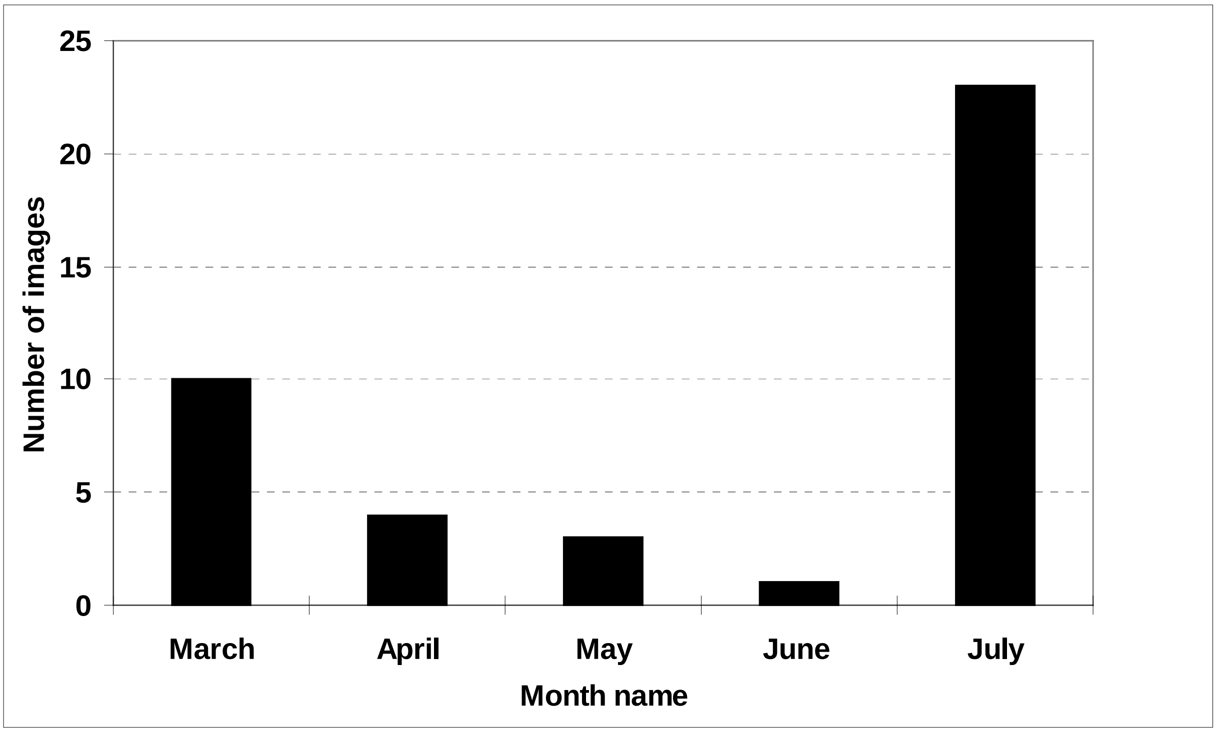


Figure 5.5 ***Total number of RADARSAT images acquired in each month between 1996 - 1997.***

The underflight validation data consists of aerial photographs taken from both side of the aircraft and the ice charts made by the Ice Patrol using both visual observations and the ice edge, deduced using the 360° mapping radar on board the aircraft. In particular, the Ice patrol carried out 20 such dedicated underflights for the evaluation of the RADARSAT images in 1997. Of these 19 were from the Cape Farewell region and 1 from the Disko Bay. Furthermore, meteorological data were also used.

Evaluation procedure

The evaluation of the RADARSAT images was carried out using the following main steps:

1) ice charts were drawn using only the RADARSAT image(s) and, wherever useful, the grey tone images of the texture parameters such as the Power -to -mean Ratio (PMR) for ice edge and icebergs detection (Gill et al., 1996, 1997) which were derived from the RADARSAT images were also used,
2) when all the RADARSAT ice charts had been drawn then they were compared with those produced by the Danish Ice Patrol using aerial reconnaissance's and the NOAA-AVHRR ice charts (if available),
3) if there were serious inconsistencies between these two sets of ice charts for a particular date then the aerial photographs taken during the underflight were studied to determine the true extent of the discrepancies.

To give a quantitative measure of the quantitative measure of the quality of the images for sea ice mapping all the images from the Cape Farewell region were split into 5 categories. The 5 categories defined were:

1. Excellent, 2. Good, 3. Acceptable, 4. Unacceptable and 5. Useless

(The definitions of the categories and further description can be found in IMSI report no. 7.)

In order to compare the quality of the ice charts drawn using RADARSAT alone with those based on aerial observations, all the RADARSAT ice charts were separated into 3 categories:

1. the first class included those RADARSAT Ice Charts (RIC) which were considered to be better than Arial Ice Charts (AIC),
2. the second class included those RICs which were as good as AICs, and
3. the third class included those RICs which were considered to be worse than AICs.

Overall 32 % of the RICs were judged to be better than AICs, 54 % of them were of similar quality to the AICs and while 14 % of them were inferior than then AICs. More significantly, during the summer months June - July, when a substantial surface melting of the ice takes place, there were no occasions when RICs were better than AICs, just more than half (57 %) of them were of similar quality to the AICs and just under half (43 %) were of interior quality than the AICs.

Table 5.3 ***Comparison between the quality of the ice charts drawn using RADARSAT and aircraft for the Cape Farewell region from March - July 1996 - 1997 in percentages.***

	March - May	June - July	Overall from March - July
RADARSAT better than aircraft	47 %	0	32 %
RADARSAT as good as aircraft	53 %	57 %	54 %
RADARSAT worse than aircraft	0	43 %	14 %

Based on the evaluation carried out during the geophysical validation campaign it can be concluded that the results are surprisingly good (given that the size of ice floes in the Cape Farewell waters is < 50 -60m which is below the resolution of the SCW mode). There was practically no problem in interpreting the images for the months of March, April, May and parts of June and July. However, there were occasions when there were serious uncertainties in interpreting the images for the months of June and July. This was mainly in regions where the ice had severe surface melting. Occasionally, in the latter regions ice with concentration as high as 4/10 - 6/10 was difficult to identify in the RADARSAT images.

The development of ice mapping tools for RADARSAT data

The approach employed for developing new ice analysis tools at DMI involves determining some useful image texture parameters that could be used to, for example, delineate the ice edge or position of major icebergs. To distinguish between regions of ice and water the grey tone values (after appropriate scaling) of the second (Power-to Mean- Ratio = PMR), third (skewness) and the fourth (Kurtosis) moment of the probability density function and the shape parameter of the Gamma function used to model texture variations in the k - pdf model, were manually interpreted (Gill, 1996). It was found that the PMR values were useful at detecting the ice edge and icebergs. The higher order moments and the parameters of the k-pdf apart from the skewness contained essentially no extra information. The PMR parameter is now used routinely at distinguishing between the regions of ice and open water and for detecting ice bergs. The PMR is very effective in enhancing features like ice edges and icebergs which can be difficult to detect on the original amplitude image.

Dissemination and test of the new product in co-operation with DTU

The final stage of validating the new sea ice information was done in the Kista Arctica (KA) project described in detail in IMSI report no. 10. Kista Arctica - Royal Arctic Line (RAL) shipping company's 4200 ton freighter capable of operating in ice, was during the summer 1998, sailing along the heavily ice infested east coast of Greenland, calling ports from Danmarkshavn (76° N) to Tasilaq (65° N). DMI supplied the ship with ice information and had at the same time the opportunity to test and validate new products in an operational environment.

During this project DMI was able to (1) test the operational use of RADARSAT along the west coast of Greenland, (2) test operationally the new ice mapping system SIKU (Andersen, 1998) and the entire operational chains of the ice mapping service of DMI based on RADARSAT (3) test extensively the reliability of satellites for data communication to users at high latitudes (4) finally the users had the opportunity to evaluate the products developed by DTU and DMI.

The RADARSAT scenes must be ordered in advance and both the temporal and spatial resolution must be considered in the selection of scenes. If the ship is not following the planned route the coverage area of the RADARSAT scenes can be insufficient. However, this did not become a problem during the test. There were considerable irregularities in the plan but mainly due to the fact that the ship is sailing slowly while operating in ice it was possible to account for the irregularities and cover the route.

Both detailed and large scale ice mapping can be done with RADARSAT. This was demonstrated on several occasions during the test. The detailed mapping was communicated to the navigator as sub-images of a particular area, here the ice conditions could be studied down to the individual floes and leads. The overview was provided by the ice charts and with a reduced image layer. It was possible to enhance the pertinent regions in the image using filters developed at DMI. The PMR filter was used to enhance icebergs and ice edges.

It was demonstrated during the KA project that it is possible with the Inmarsat system to transfer data to a ship operating north of 70°N.

The following new products were demonstrated in the operational test:

1) Vector ice charts
2) Imagettes for display on the ship
2) PMR filters
   a) PMR ice edge enhancement filter
   b) PMR ice berg detection filter

User evaluation of the new products
The navigators at Kista Arctica were very satisfied with RADARSAT sub scenes and the RADARSAT derived ice charts which they received. Captain Fritz Ploug states explicitly: “It is absolutely the best product we have received onboard until now”(Tonboe and Rosengreen, 1998).

Conclusion
The conclusions from the validation campaigns in 1996, 1997 and 1998 has lead to the operational use of RADARSAT data for ice mapping at DMI. The ice charts has mainly been based on RADARSAT data since autumn 1998.

RADARSAT data are of sufficient quality to map the sea ice around Greenland, with the exception of the summer melt season (June-August) in the Cape Farewell region.

The data are downloaded from the receiving stations via Internet and the final product is ready for transmission 5-6 hours after the region has been imaged by the satellite.

The new data products helped optimising the route of ‘Kista Arctica’ during her expeditions in the summer of 1998.

5.5 Validation of scatterometer products

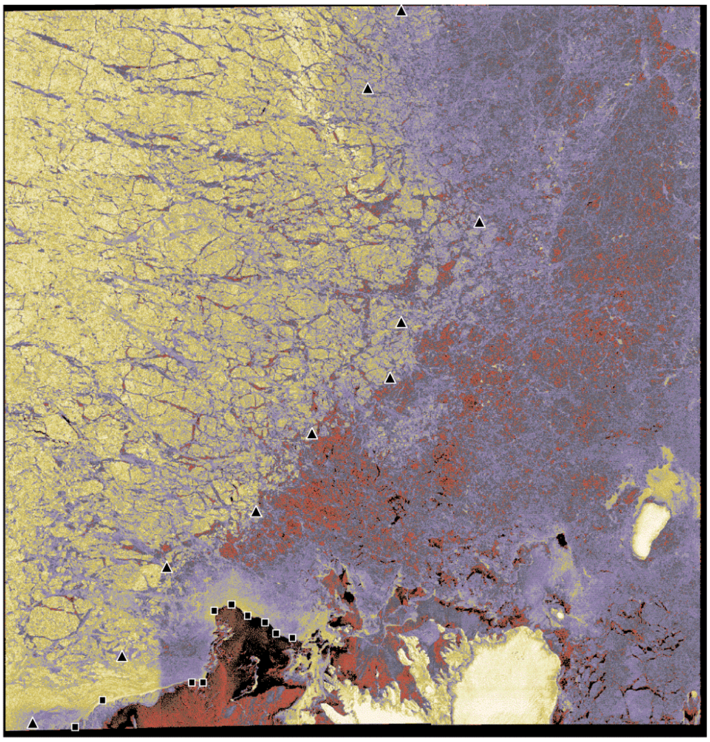
Validation of NSCAT products
In the course of IMSI, an investigation was led in order to evaluate and help in the interpretation of large scale backscatter maps obtained from scatterometer data at Ku band (NSCAT on ADEOS). RADARSAT SAR images, were employed to interpret certain details of the backscatter maps and confirm the positions of limits between open water and sea ice or different ice types. The SAR images used in this study were RADARSAT ScanSAR products, 3x3 matrices of pixels having been regrouped to form images with a pixel size of 150x150 meters. The NSCAT backscatter maps used in the inter-comparison are presented on the NSIDC polar stereographic projection with either a 12.5x12.5 or a 25 x 25 km pixel size. Ice concentration maps produced at DTU from H and V polarized SSM/I 85 GHz data were also used in conjunction with backscatter maps to study their joint potential to estimate the ice limit. A complete description of this work is given in IMSI Report No.9. The present paragraph will present only the essential comparison with a SAR image north of Spitsbergen and SSM/I 85 GHz images over the Barents Sea.

The winter situation north of Svalbard
Figure 5.6 presents the RADARSAT image north of Svalbard on January 27, 1997. A false color scale is used to increase contrasts; backscatter increases as colors evolve from black to red, to blue, yellow and white. The image is 477.5 km wide, the left side (494.99 km) being slightly smaller than the right side (503.00 km) due to the SAR image generating mechanism.

In the lower part of the image, the northern part of Svalbard is easily identified. To the left of Svalbard, an open water area, which corresponds to the northward drift of relatively warm Atlantic water, can be seen. The limit between ice and open water is marked by small black squares, originally positioned on the black and white paper image. In the same way, triangles mark the estimated limit between first year ice to the right and multi-year ice to the left of the image. First year ice has lower backscatter values and less texture than the fractured multi-year ice. It is interesting, and somewhat disappointing, to note that backscatter over open water can have values quite similar to those over first year ice.

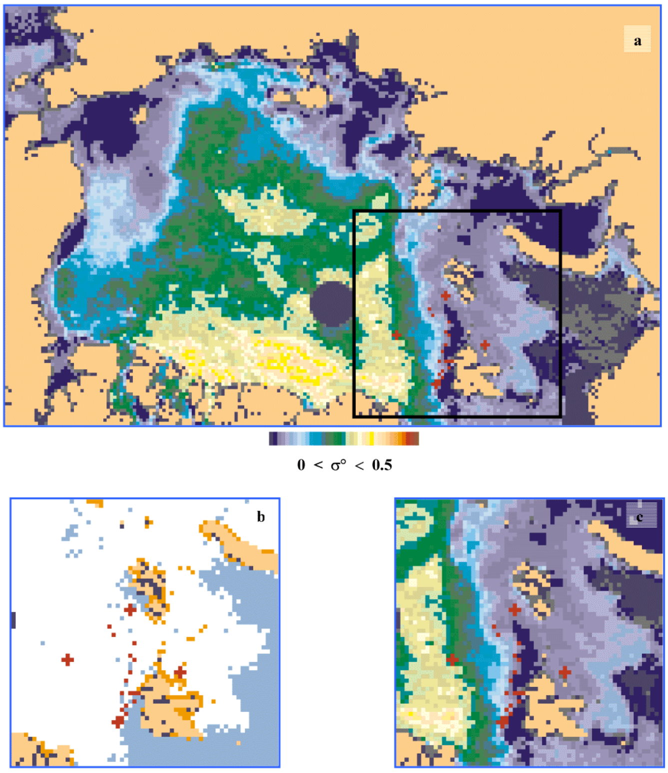
Figure 5.7 shows the NSCAT 25 km pixel backscatter map corresponding to the RADARSAT image whose four corners are represented by red crosses. The limits previously defined on the image are reproduced as small red squares. Their original positions on the RADARSAT black and white paper copy were measured in millimeters vertically and horizontally from the lower left hand corner, with a precision corresponding to roughly 2.5 km. Using a linear interpolation on the left hand border of the image for both latitude and longitude, then spherical trigonometry formula along a great circle segment to reach the horizontal position of the point, these positions were then transformed into geographical coordinates. These could then be marked precisely on the NSCAT maps.

It is encouraging that the points corresponding to the open water limit fit the limit as defined by the sea ice/open water mask to within one pixel. Since the map was constructed from data acquired over three successive days, part of the uncertainty in position may lie in the ice limit's motion. The first year/multi-year ice limit points all lie in the transition zone between light and medium blue on this false color image. Thus the RADARSAT image allows us for the first time to identify clearly this transition zone, and because of its high resolution, to visualize the abruptness of the transition from one type of ice to the other.



False color RADARSAT image on January 27, 1997. North of Spitsbergen.
Color scale ranges from red to white as backscatter increases.
▲: Sea ice boundary ■: Open water boundary

Figure 5.6



NSCAT backscatter maps, 25-27 January 1997 on the 25 km grid
a : Central Arctic, the black frame defines the zoomed area.
b : Sea ice/open water mask ; red crosses define the corners of the RADARSAT scene, red dots mark the sea ice and open water boundaries of the SAR scene
c : backscatter at 40° incidence angle, no water mask

Figure 5.7

The texture of the SAR scene also suggests a possible explanation for the scattered points along this limit on the NSCAT map, evaluated by the ice mask to be open water in the pack. In regions where backscatter varies very rapidly, it is probable that the ratio of HH to VV polarized backscatter, used to detect water, is perturbed by the non-coincidence in space of the two backscatter measurements. Although such points are not frequent, they do appear as spurious on close examination of the SAR scene.

Comparison of NSCAT and SSM/I open water/sea ice discriminations

The sea ice concentration data set was provided by the Danish Center for Remote Sensing (Electromagnetics Institute, Denmark Technical University). The data set consists of daily files of values coded as ice concentration in %+100 and organized according the NSIDC 12.5 km grid.

The algorithm utilizes the 85 GHz polarization difference of brightness temperatures as soon as the ice concentration computed using the Comiso bootstrap algorithm (25km grid, 19 GHz and 37 GHz brightness temperatures) is above 20%. Ice concentration artifacts values (smaller than 0% and greater than 100%) do occur rather frequently, because of inherent noise and because the algorithm, tested in the Greenland Sea, may need tie point adjustments in other areas.

The Barents Sea area was chosen to compare SSM/I and NSCAT ice limits because of the slow evolution of the sea ice edge with time in this area of the Arctic ocean. The times series of the composite map are presented in Figure 5.8. Each of the three rows correspond to a single three day-25 km NSCAT water mask.

The upper row, March 23-25, shows that both sensors perform almost similarly during a period when the ice limit is evolving slowly. On average, the difference is of the order of a NSCAT water mask pixel; but a systematic difference can be observed at the upper left part of the sector. The middle row of the plate, March 26-28, corresponds to a retreating ice limit as can be seen from the SSM/I signature. The NSCAT water mask underestimates the ice extent at the beginning of the period; the map at the end of the period indicates, again, a slight systematic mismatch in the lower left part of the sector. The lower row, March 29-31, corresponds to a short re-freezing period. NSCAT indicates the systematic presence of sea ice in the upper part of the sector while the SSM/I indicates water. As re-freezing occurs, an ice tongue develops in the middle part of the sector as shown by the SSM/I signature and confirms the sea ice detection performed by NSCAT over the three days. Looking at the daily-12.5km NSCAT maps (last two panels), it can be anticipated that the SSM/I misses the presence of the isolated sea ice cluster on March 29; however, the NSCAT water mask does not map the whole ice tongue as can be seen on the NSCAT map of March 31. This last situation clearly shows the benefit of a joint analysis; indeed, it would have been rather difficult to assess the real situation using NSCAT data only.

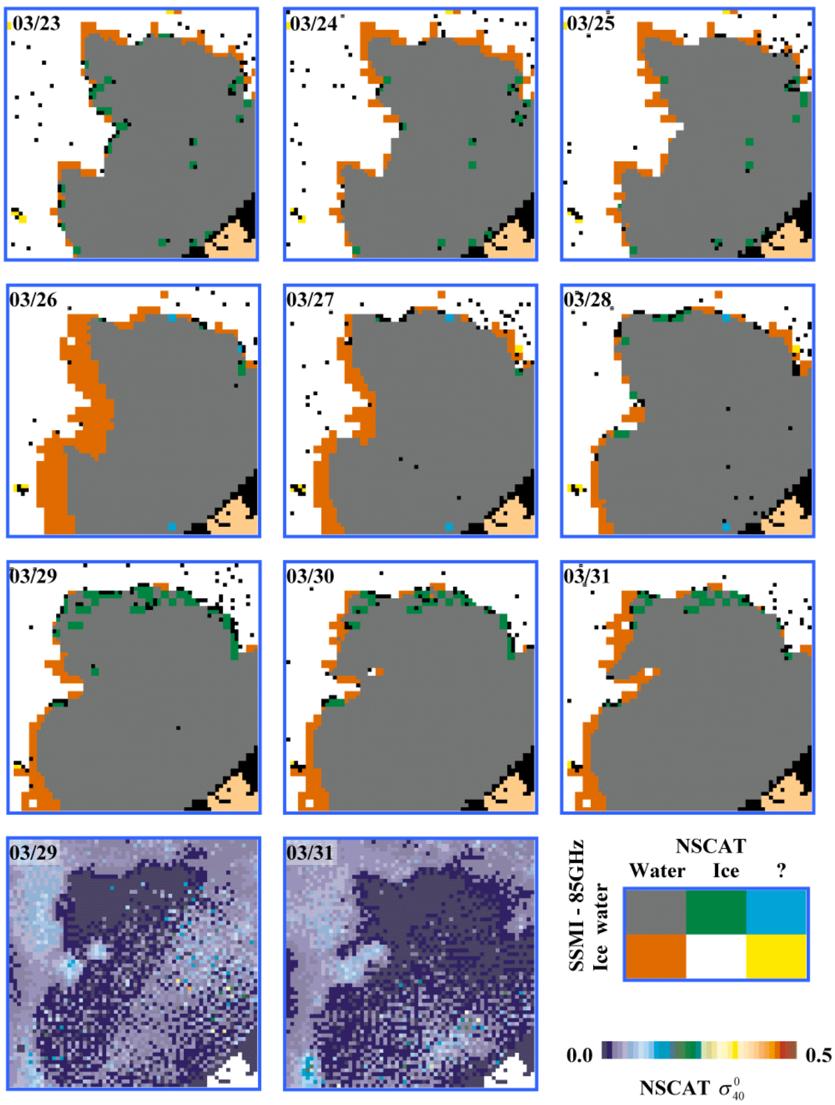


Plate 3: **Open water/sea ice detection**
Merging NSCAT and SSMI – 85 GHz information
Time series of ice edge, Barents Sea, March 23-31, 1997
Bottom row: daily 12.5 km NSCAT σ^0_{40} maps, no water mask

Figure 5.8

6 User assessment, evaluation and recommendations (Task 4)

6.1 Baltic Sea

6.1.1 User assessment, and evaluation of project results

The main result of IMSI for the Baltic Sea is the introduction of RADARSAT data and development of products from these data in ice monitoring. FIMR has used 300 ERS SAR screens and 200 RADARSAT ScanSAR Narrow screens in the period of IMSI. These data have been used in the operational ice service and automatic classification development. Some of these data have been sent in digital format to Finnish icebreakers and a number of merchant vessels, in various resolutions as part of the demonstration and validation activities.

Automatic classification algorithms have been developed for RADARSAT SAR data to discriminate between open water / ice and ice surface deformation degree. The results were in use of the ice service in spring 1998, and they have been validated for the first time in spring 1998. Validation results have been used for further development of the algorithms. During the ice season 1998/99 automatic classifications have also been sent operationally to Finnish icebreakers and some merchant vessels. The evaluation of the usability of RADARSAT SAR image classification from the users was positive. Although the results from the algorithm are partly unreliable during melting periods and when air temperature is above 0º C, this kind of high resolution ice information is very valuable in ice navigation.

In addition to demonstrations onboard ship, evaluation was also done in a user workshop, at icebreaker captains' annual meetings, and in almost daily contacts between icebreaker captains/mates and the Finnish ice service. The usability of EO data for the merchant vessels has been evaluated in personal contacts with the captains, representatives of shipping companies and the Finnish ice service. The evaluation showed that: SAR data, and especially wide swath RADARSAT data, have been proved to be essential for icebreakers at sea. The SAR data have replaced the intensive use of icebreaker based helicopters in ice reconnaissance and selection of optimal routes. With SAR images superimposed on ice charts and automatic classifications, the icebreaker personnel have been able to make interpretations of ice conditions more easily and faster than without use of EO data. The merchant vessels, which received mainly AVHRR data and only a few examples of SAR data, have been able to estimate their time-tables more accurately. This has especially been important for the vessels sailing to St. Petersburg, where availability of sea ice information is more limited than in the Finnish waters.

The consortium of four partners for purchasing RADARSAT data in 1998-99 made it possible to obtain data at realistic costs. The RADARSAT SAR used in the Finnish ice service had 100 m resolution, which have proved to be nearly optimal. On board icebreakers and ships this data have been used in coarser resolution, 800 m in 1998 and 400 m in 1999. In near future we are expecting to be able to deliver data to the users at sea in 100 m resolution by using an algorithm developed at the FIMR for compressing SAR images for visual use.

Since the beginning of IMSI, the use of EO data in the ice service have not increased, because AVHRR data was used extensively. With the introduction of RADARSAT SAR however, the data quality and usability have been increased. New digital sea ice information products have been introduced during IMSI, and the number of operational EO data customers has increased, from three vessels in 1997 into eight vessels in 1999.

6.1.2 Cost-benefit considerations

In the Baltic Sea the seasonal ice cover lasts up to six months per year. This means that 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. The two most heavily marine operated areas in the world, where seasonal sea ice plays an important role in navigation, are the Gulf of St. Lawrence in Canada and the Baltic Sea in Europe. In the Gulf of St. Lawrence some 180 million tons of goods are transported annually. The total cargo turnover in the Baltic Sea in 1995 was about 500 million tons, of which some 40% takes place during winter season.

There are several cost factors which make winter navigation expensive: operation of icebreaker fleets, daily ice monitoring, the merchant vessels must be ice-strengthened, and time delays in transport schedules caused by ice conditions. If ice monitoring and icebreaker assistance could be made optimal for the merchant vessels, considerable potential savings could be achieved. It is estimated, that Finland could save between 10 and 25 million Euro a year. This would demand optimal, satellite-based, high-resolution, and cloud and daylight independent data, such as SAR, and a spectrum of interpretations like digital ice charts and automatic classifications available for the users at sea in near real-time every day.

The ice service itself can also become more cost-effective by using SAR data in ice monitoring, because

1) collection of ice data is more cost-effective using satellite data compared to aircraft,
2) the operations of the icebreakers can be done more optimal.

Finally, the end users such as the merchant vessels can save time by reduced sailing time and less risk for delays due to ice conditions.

6.1.3 Conclusions and recommendations for the future

The economic value of winter navigation in the Baltic Sea is large, and ice navigation is vital for Finland with 500 million tons of goods transported by sea every year. By improving the sea ice monitoring, and high resolution data and information product distribution, considerable savings could be achieved in ice navigation, mostly by reducing sailing times.

One of the activities in the Finnish ice service in the 1990s has been to demonstrate the utilisation of EO data in sea ice monitoring to a wider user community including all of the Finnish icebreakers and a number of merchant vessels.

There is a rapid development towards a fully digitised information system onboard ships, including digital sea ice charts. This will have a strong impact on the development of sea ice monitoring systems.

New communication systems will be available in the near future which can transfer higher data rates at reasonable prices. Providers of sea ice information products should take advantage of the new communication technology by developing high-resolution information products to be used directly in ice navigation.

In cold conditions the classification results were usually good and informative according to the performed evaluations. The effect of incidence angle on the classification results is essential. Most of the classification errors occurred at large incidence angles or during the warm weather conditions. Currently, the automatically produced classification map can be regarded as an important addition to the conventional ice chart. The spatial distributions of different kind ice fields are often more accurately described by the classification map than by the traditional ice chart.

Recommendations for the future

- Satellite observation systems for sea ice monitoring should be developed, which operated SAR in synergy with optical, infrared and passive microwave sensors.
- SAR systems with wide swath (up to 500 km) and acceptable resolution (100 m), with option to provide higher resolution in smaller areas. The SAR system should also have options for polarisation and multi-frequency.
- Technology for transmission of high resolution digital sea ice data, like SAR data, to the users at sea should be developed further so that images can be transmitted in reasonable time.
- Those users at sea, which have been in opportunity to use high resolution EO data in ice navigation, could have been optimise their ice navigation, and thus reduce costs by cutting down the sailing-times. If EO data and all other kind of ice information could be introduced to large number of merchant vessels in the Baltic Sea, considerable savings could be reached.
- For number of users there seems to be psychological barriers towards new technology and computer technology. There also seem to be lack of information about data, products and services. Breaking down these barriers takes a long time and much effort. One of the possibilities for such breaking could be launching campaigns, lasting for years, where suitable data are delivered to users on board ships, similar to what has been done under the IMSI campaigns.
- The determination of the applicability of passive microwave algorithms in the Baltic Sea or development of a new better ice concentration algorithm requires further studies using both airborne and spaceborne MWR data. Particularly, the effect of snow cover wetness needs to be investigated further.
- To fully conclude the capability of the combined MWR and SAR data to classify Baltic Sea ice, much more data with different SAR incidence angles, wider MWR frequency range and different snow cover characteristics should be acquired.

6.2 Northern Sea Route

6.2.1 User assessment, and evaluation of project results

Although satellite ice information products from SAR and SSM/I data have been distributed to many users in the Northern Sea Route, there is one major user whose assessment of the products is of primary interest. This user is Murmansk Shipping Company’s icebreaker fleet which is responsible for escorting and navigation of all sea traffic in the Northern Sea Route. In IMSI, Murmansk Shipping Company has participated in several demonstrations of SAR ice monitoring. The most important demonstrations were carried out in August – September 1997 in the Laptev Sea area and in the Kara Sea in April – May 1998.

The most frequently used sailing route in the western part of the Northern Sea Route is through the Pechora Sea, Kara Gate and south-western Kara Sea which is usually maintained navigable by icebreakers through the winter season. This route is used year-round for transport of nickel from Norilsk, one of the major mining towns in Siberia, via Yenisey River to Murmansk. Because of heavy ice conditions in this route in April 1998, the icebreakers of Murmansk Shipping Company used an alternative sailing route north of Novaya Zemlya to avoid the risk of being stuck in ice in the Kara Gate. Several convoys were escorted in this northern route by three nuclear icebreakers “Rossia”, “Sovetsky Soyuz” and “Arktika” in the period April 12 to May 3 when two eastbound and one westbound convoys were escorted between the ice edge in the Barents Sea and Dikson. The eastbound convoys sailed in easy ice conditions along the coastal polynya west of Novaya Zemlya, through more difficult ice northeast of this island and south-eastwards to Dikson. SAR images from RADARSAT and ERS were transmitted to the icebreakers and were essential in planning of the sailing routes, (Fig.6.1).

The cargo ships were assisted by the icebreakers by leading or towing which are the two basic escorting methods, both of which need tactical ice information which can be provided by SAR data delivered to the ships in near real time, i.e. within 6 hours. Escorting by leading means that one or more cargo ships move by own power behind one icebreaker (simple convoy) or several icebreakers (complex convoy). The other method, which is to tow one ship at the time behind the icebreaker, is used in very difficult ice conditions when ships cannot move by own power. Typical convoy speed in polynyas with mainly young ice is similar to open water speed of 11 - 14 knots. In areas with medium and thick first-year ice the convoys were escorted by the leading method at 4 - 6 knots. In compact first-year ice, navigation is preferred in level ice to avoid ridges. Difficult ice conditions with strong compacting but almost no fractures were encountered to the northeast of Novaya Zemlya. In this area one icebreaker first made a canal and then one ship at the time was towed by another icebreaker through the canal. Another area of difficult ice conditions was found between the coastal polynya southwest of Arctic Institute Islands and the polynya near the mainland where heavily ridged first-year ice dominated. The two icebreakers “Sovetsky Soyuz” and “Arktika” spent approximately 30 hours to tow three cargo ships a distance of 20 nautical miles. SAR images were useful to find the best possible sailing route, but some navigation in difficult ice could not be avoided.

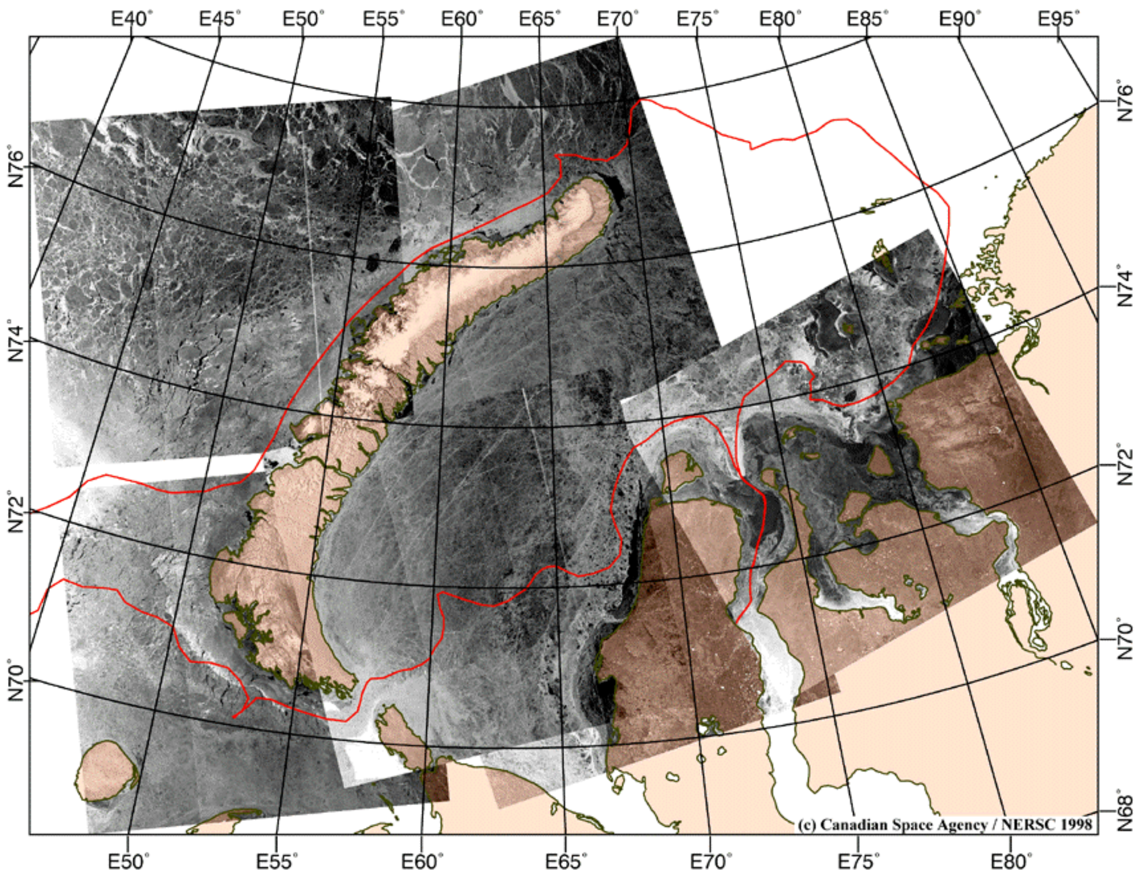


Figure 6.1 ***Mosaic of six RADARSAT ScanSAR scenes each covering 500 by 500 km obtained during the ARCDEV expedition in April-May 1998. The red line shows the sailing route of the expedition between Murmansk and Ob Gulf. © Canadian Space Agency / Agency spatiale canadienne, 1998.***

In the beginning of May, sea ice conditions in the near-coastal route became easier and “Sovetsky Soyuz” escorted another convoy together with “Arktika” from Dikson through the southwestern part of the Kara Sea and the Pechora Sea. This convoy consisted of three cargo ships, including the nuclear cargo vessel “Sevmorput” which is 300 m long and can only be escorted by leading. A RADARSAT image of 8 May was obtained for this area, and was used to plan the west-bound trip of “Sovetsky Soyuz”. Heavy ice conditions were also found in the area near Yugor Strait where the average convoy speed decreased to about 2 knots during a 10 hour period. In the Yugor Strait “Sovetsky Soyuz” made a canal in level fastice where the convoy moved at 7-8 knots. “Sovetsky Soyuz” left Dikson on May 3 and returned to Murmansk on May 8 while “Rosily” and “Arktika” continued their operations in the Kara Sea.

The user assessment of SAR ice monitoring expressed by Nikolai Babich, chief hydrologist at Murmansk Shipping Company, is the following:

“High resolution radar systems, such as RADARSAT, ERS or similar systems are the most useful and promising for strategic, operative and tactical navigational ice reconnaissance. SLR Okean images can be used for composition of survey (strategic) ice maps, but due to low resolution these data does not satisfy user requirements to ice charts of operative and tactical ice reconnaissance. Satellite ice monitoring systems will decide strategic, operative and tactical tasks of ice navigation. Use of NOAA AVHRR data is limited due to their comparatively low resolution and dependence on natural light and visibility conditions (polar night, clouds, and fog). NOAA data is used only for composition of survey (strategic) ice maps.”

There are several advantages of using SAR for navigation. First of all high resolution ice images can be obtained independent of visibility and light conditions. SAR images can be used for regular acquisition of sea ice information for ice chart composition, and for solving navigational tasks at strategic, operative and tactical levels. As a result of using high resolution images in near real-time, the average ship speed in ice can increase by a factor of 1.5-2, according to N. Babich. The safety of ice navigation is increased and the number of emergency situations decreased.

Strategic and operative ice maps can be made on the basis of interpreted SAR images. These ice charts are useful in ice navigation for solving organisational and operative tasks of planning fleet operation. Original images in digital form with special software, providing overlay of images on electronic or paper maps, will be useful onboard icebreakers and ships for solving concrete tactical tasks of navigation – route selection, choice of steering method (towing, leading) and safe manoeuvring in ice. Interpretation of navigationally important sea ice characteristics can be carried out by experienced navigators after special training in image interpretation. For solving tactical tasks the delay between image acquisition and its reception onboard icebreaker should not exceed more than a few hours. Successful use of SAR data in tactical navigation was demonstrated in the icebreaker expeditions in 1997 and 1998.

6.2.2 Cost-benefit considerations

The Marine Operations Headquarters (MOH) which provides ice maps and ice forecasts for the western part of the Northern Sea Route, is partly financed by the Murmansk Shipping Company, which is in turn financed by the Russian government to provide icebreaker service in the area. It is of major importance of MOH to have the best possible ice information for planning of optimal icebreaker operation.

The Northern Sea Route is the longest and most difficult sailing route in sea ice. Lack of adequate ice information can therefore have severe economic impact for ships in terms of damage to ships and time loss due to difficult ice navigation. Satellite data is considered to play an increasingly important role to provide the ice information, first of all because use of aircraft for ice monitoring has decreased in recent years. Satellite data is the only feasible method for ice observation in such large region as the Northern Sea Route, because aircraft surveys would be much more expensive.

NOAA AVHRR data are, in spite of the cloud limitation, the most used remote sensing data in sea ice monitoring in the Northern Sea Route because they are free-of-charge and easy to access. SAR data have proven to be the most powerful tool for ice monitoring, but operational use has not yet been possible to establish due to high cost of data and insufficient coverage. With RADARSAT and ENVISAT, the coverage is significantly improved, if the data cost for SAR data is reduced; it is expected that SAR will be used operationally.

The MOH has limited budgets, and if there is a need for improved quality of the ice monitoring services by use of SAR data, it is expected that the users must pay for this.

Availability of SAR images and derived sea ice information may replace parts of the expensive, and in periods, extensive 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 reduce the sailing time by following the optimal route. With a daily cost of for example $ 50 000 for icebreaker assistance to foreign vessels significant savings can be made by using real-time ice images to select the optimal sailing route.

Accurate and timely sea ice information is important not only for the economy, but also for safe navigation to avoid accidents with loss of human lives and pollution (oils spills, etc.) which harms the Arctic environment. The regulations of ship transport in the Northern Sea Route, which require extensive hydrometeorological and sea ice information, are made to minimise the risks for pollution of the environment. Transport of oil and gas, which is currently performed by pipelines, can be shifted more to tankers in the future as production moves offshore. Also, the prospect of international ship traffic between Europe and East Asia/North America will have impact on the environment and the need for satellite data in ice monitoring.

6.2.3 Conclusions and recommendations for the future

SAR derived ice information has proven to be essential in ice monitoring of the NSR, both for navigation and off-shore operations. Near real-time use of SAR data onboard Russian icebreakers can improve the ice navigability considerably if the data are obtained over the critical areas at the right time. The main limitation of ERS data is that only selected parts of the NSR can be covered. RADARSAT ScanSAR data, however, have proved to be able to cover large enough areas for planning and implementation of expeditions in the Kara Sea region. A synergetic use of ERS SAR, RADARSAT SAR, ENVISAT ASAR and Okean SLR data is considered to be the optimal scheme for real time ice monitoring. The combination of these data will provide SAR coverage of all sea ice areas every day. The SLR data will be used for regional mapping every week, whereas SAR data will be used mainly in the most critical areas where high resolution ice information is needed. ENVISAT ASAR data can be tested for use in operational ice monitoring when these data become available.

For climate and large scale ice monitoring, it is clear that passive microwave data (SSM/I data) in combination with Scatterometer data are useful. Two decades of passive microwave data have proven to be important for detecting trends in ice cover (Bjørgo et al., 1997). SSM/I data are also useful for daily monitoring of sea ice on regional scale when data are obtained in near-real time mode. NOAA AVHRR and other optical/infrared systems are important supplements to active and passive microwave systems.

The future systems of satellite sea ice monitoring for navigation purposes should be based on high resolution remote sensing sensors with resolution not lower than 50-100 m. The method for validation of these data should envisage the possibility of issuing survey and operative charts for the coastal fleet navigation services. A part of operative ice information (ice charts of the navigation area) should be transmitted to icebreakers and ships. The original images without preliminary interpretation can form a base of informational support for solving tactical tasks of navigation. The determination of ice charts needs, frequency of their receiving in the user interests is determined by the services, which plan and organise fleet operations. Ice chart composition should be carried out in specialised ice centres.

In an operational service there is a number of requirements which need to be satisfied before the SAR monitoring technology can become an operational tool, such as: selection of SAR coverage in strategic areas, real-time access to SAR data, data ordering procedure, interpretation of SAR images, quantitative ice parameters from SAR, linking ERS data to the Russian ice monitoring services, transmission of ice maps and images to ships and other end users. An operational radar ice monitoring system should use SSM/I data, NOAA AVHRR, Okean SLR data for large scale surveying and RADARSAT and ERS SAR data for detailed regional observations, especially in areas which are identified as difficult for the navigation. It is recommended to obtain weekly coverage of SLR for the whole Northern Sea Route, and 6 - 10 RADARSAT and ERS SAR stripes of 2-5 scenes per week covering key areas of the Northern Sea Route.

RADARSAT ScanSAR scenes or corresponding ASAR data from ENVISAT, with up to 500 km swath width, can become an important data source in an operational system for the Northern Sea Route if funding of such data becomes available. Real-time SAR monitoring requires a new receiving station in Russia in order to have full SAR coverage of the whole NSR.

The transmission of SAR image stripes as files over the INMARSAT-A connection is recommended as a standard for future operations. The equipment on board should be of high quality, using e.g. a "Saturn" receiver, a Pentium computer, a high-quality printer, etc. The fax connection is useful for transfer of messages, transfer of SAR coverage maps, and also as a backup for transfer of images.

Fax should also be used frequently for reporting back from the ships to the MOH, informing about the reception quality, possible problems and the ships position and immediate sailing plans. Thereby, the optimal selection of SAR scenes and the most efficient processing will be assured.

One option is to send all SAR products to the MSC headquarters in Murmansk, which will forward the information to the icebreakers which are in operation. The state supervision of the NSR is performed by the NSR Administration (NSRA) of the Russian Federation Ministry of Transport. The NSRA executes its functions both directly and through special navigation services of the Murmansk and Far-East Shipping Companies, the Marine Operations Headquarters of the Western and Eastern regions of the Arctic, respectively. The MOHs have direct responsibility for all sea ice operations along the NSR.

Ice monitoring is part of the hydrometeorological service in the Northern Sea Route, which is organised under the ministry of Transport and the Russian Committee on Hydrometeorology. The service was very extensive until the beginning of the 1990's, using a data from many sources: aircraft, satellites, icebreakers, ice stations, coastal stations, etc. Recently, the amount of data used in the ice service has decreased due to lack of public funding. This opens up possibilities for new services based on use of satellite SAR data, especially for the offshore and shipping industry which need high quality ice data.

6.3 Greenland waters

6.3.1 User assessment, and evaluation of project results

During the 'Kista Arctica' demonstration project in 1998, (Fig. 6.2) DMI received 48 RADARSAT ScanSAR scenes for the areas surrounding Greenland. 39 scenes were dedicated to the piloting of 'Kista Arctica' along the east coast of Greenland and the remaining 9 scenes were acquired to further validate ice mapping in the Cape Farewell area. The acquisition of the scenes was carefully planned in accordance with the navigational plan. All the images ordered during the validation campaign arrived in due time and in accordance with the agreement made with RADARSAT International.

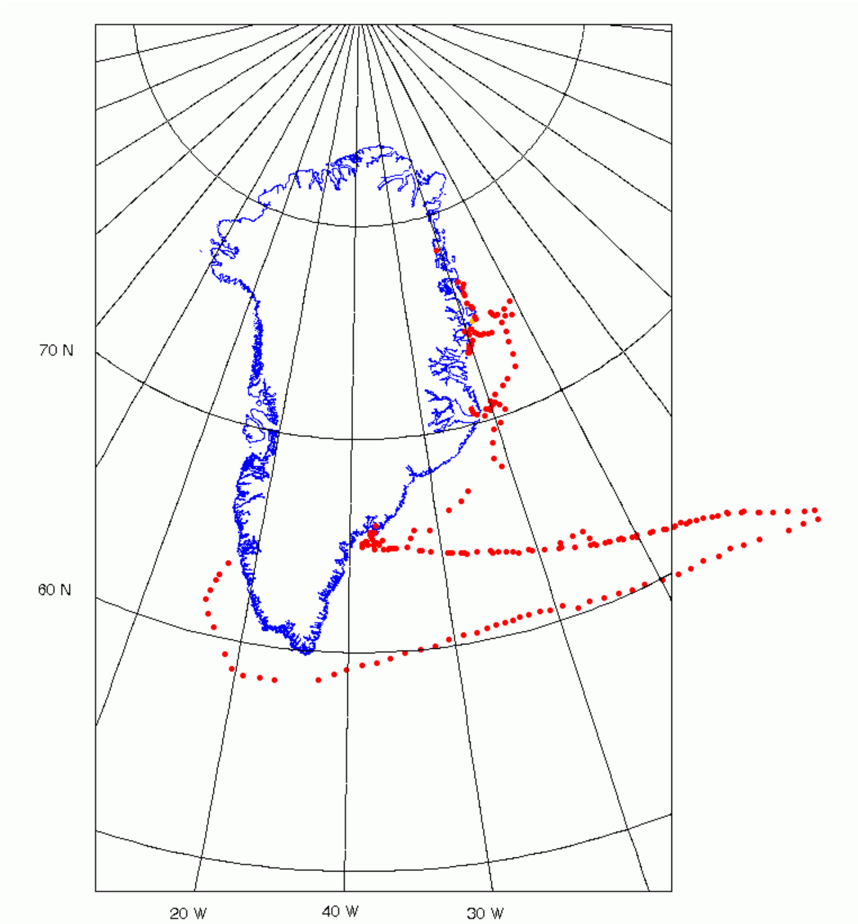


Figure 6.2 ***Reported positions of 'Kista Arctica' during 2. trip. Weather observations are reported every 3 hours. Notice the areas where the dots are very close, indicating slow progress. Positions are not communicated when the ship is at port.***

The broadcast of digital ice information and image subsections to ‘Kista Actica’ was continued in the spring season 1999 in Disko Bay on west Greenland, and will be maintained in the future. SSM/I is not included in the information which KA receives but the broadcast of NOAA-AVHRR and RADARSAT subsections in combination with vectorized ice charts will continue as under the ‘Kista Arctica’ project demonstration.

The different types of data which were received onboard ‘Kista Arctica’ were evaluated by the navigators during the ships voyages. After the first journey, First Mate Benny Skou Mortensen (BSM) provided DMI with a written report on the received ice information products. The main points in his evaluation are:

Passive microwave (SSM/I): The images are received on board ‘Kista Arctica’ 24 hours after the overhead pass of the satellite. The coarseness of the images makes it difficult to retrieve any detailed information. The features in the DTU browser does however make the images more interesting for navigation. The images are used for the large scale route planning.

NOAA images: The images are received on ‘Kista Arctica’ 6 hours after the overhead pass of the satellite. The images are very good. They are however restricted by fog and clouds. During cloud free conditions the images can be used for route planning, even though this does require experience in image interpretation.

RADARSAT: The images are received on ‘Kista Arctica’ 4-12 hours after the overhead pass of the satellite. They are very detailed and presented with an overlay of vector ice charts. The egg code appears by clicking the ice covered area on the map. This type of data does require experience in image interpretation. Wind and waves can make the ice in the image more diffuse and more difficult to see.

Ice charts: These were not commented specifically by BSM during this journey.

During the second journey far more images were transmitted to the ship. Captain Fritz Ploug has evaluated the data. The conclusions of his report are:

SSM/I passive microwave images:
They are not interesting for the ship, since they may be as much as 24 hours old, at the same time the resolution is so coarse that they have no value for navigation.

NOAA-AVHRR:
They are very fine images when there are no clouds. Then they can be used for the large scale route planning. With time it should be desirable to receive them directly on board the ship as the satellite passes. However, in order to use these images great expertise in image interpretation is needed. I don’t believe that we have that expertise, at the moment, on the ships, and it would also be time consuming to do the interpretation. Our opinion is that we have to accept the delay, and have confidence in the product from DMI via fax or via Skamlebæk radio, which is made by experienced image interpreters.

RADARSAT/ice charts:
It is absolutely the best product we have received onboard until now. The RADARSAT images speaks for themselves and in combination with the DMI ice chart overlay they have given us a very

detailed, very precise and a useful product. Together with our experience, this enabled us to optimise the navigation of the ship.

The navigators were very satisfied with the RADARSAT products and in general the possibility for receiving satellite imagery onboard. This among other things has led to the operational use of RADARSAT for ice mapping at DMI since autumn 1998. The ice mapping in the Cape Farewell was before done with aerial reconnaissance. Today the Cape Farewell region, as well as the east and west coasts are mapped primarily with RADARSAT and whenever the cloud cover and daylight allows; NOAA-AVHRR. The ice service is now almost completely based on satellite observations except for the summer months where severe surface melting limits the use of SAR. All the users of ice charts in the Greenlandic area are now indirectly using satellite data. The current contract with Greenland Air involves the use of aircraft for ice monitoring during the summer months June-August. RADARSAT will be used during the rest of the year.

The user assessment of the products developed during IMSI project will continue with the distribution of digital products and sub-images to ‘Kista Arctica’ from the Royal Arctic Line shipping company after the IMSI project has ended. The products and developments are documented in IMSI reports and papers and presented at conferences e.g. Gill and Rosengreen (1998), Tonboe and Rosengreen (1998), Gill et al. (1998) and Gill et al. (1999). The new IMSI products have been recommended by DMI to its end users through actual product dissemination exercises, for example in the Kista Arctica project.

Figure 6.3 ***Cape Brewster seen 33 km away. The picture is taken 29th of July 1998 from helicopter at position 70° 25’ N 21°45’ W direction 195° at 3000 feet. The ice floe in front is approximately 2.5 km in diameter.***

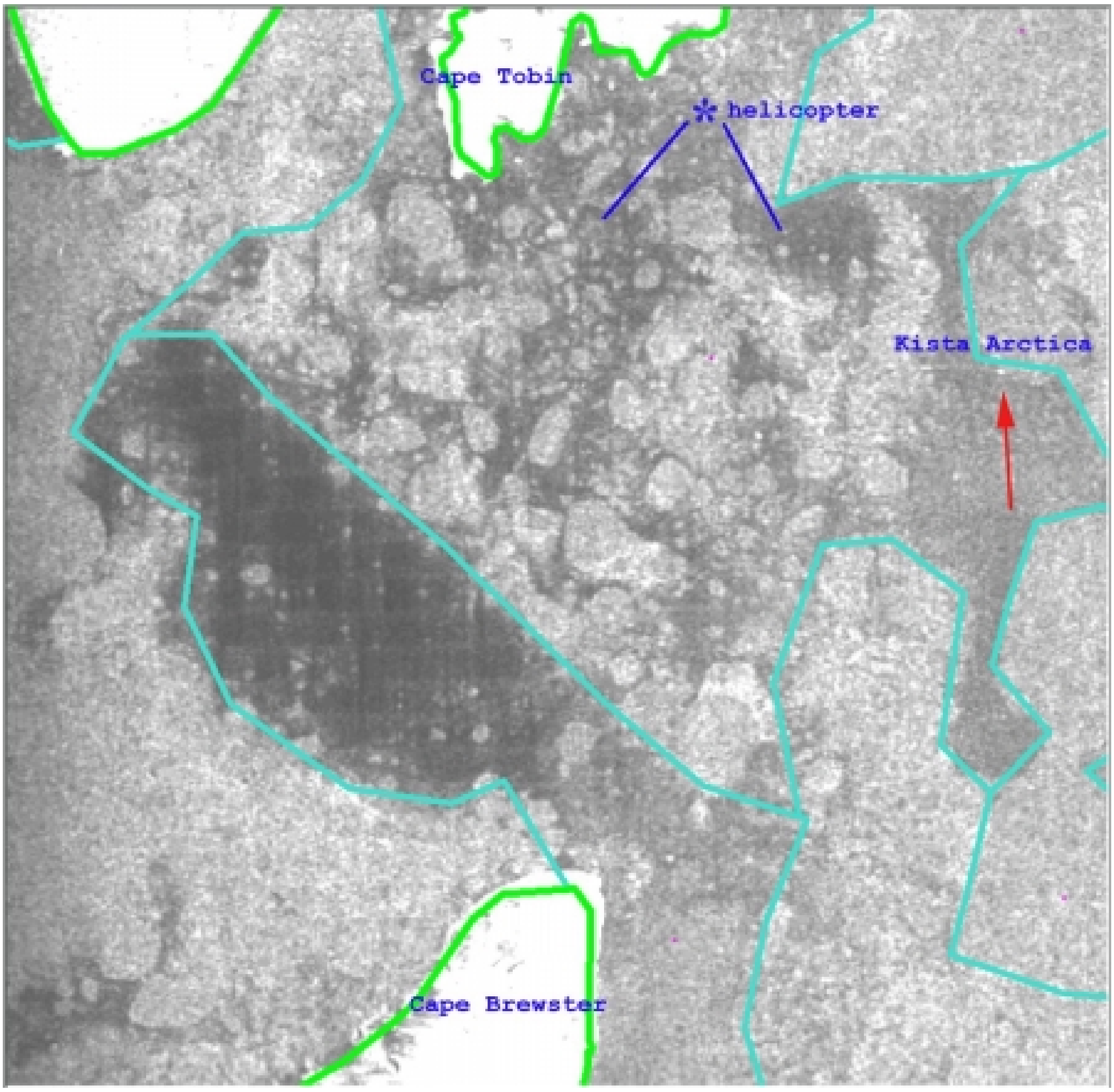


Figure 6.4 ***RADARSAT image 29/7 1998 0822 UTC. The photograph in figure 6.3 taken simultaneously with satellite passage. The land at the bottom of the image is Cape Brewster. The land at the upper part of the image is Cape Tobin. The blue asterisk indicates the position of the helicopter when the photographs were taken, and the red arrow points to the position of 'Kista Arctica' going to Cape Tobin. The image is app. 50 km across. © DMI and RADARSAT International.***

The use of the ice information web pages at DCRS/DTU has increased since the establishment in 1998 (see Fig. 6.5 and 6.6). The archive became operational in January 1998, and obviously the winter months are the ones where most ice information is requested. In 1998 substantial amounts of ice was present in all three areas, whereas in 1999 there has been almost no ice in the Greenland Sea which explains the relatively small number of downloads from this area in 1999. The statistics have been made by excluding downloads from the DCRC/DTU and various search robots etc.

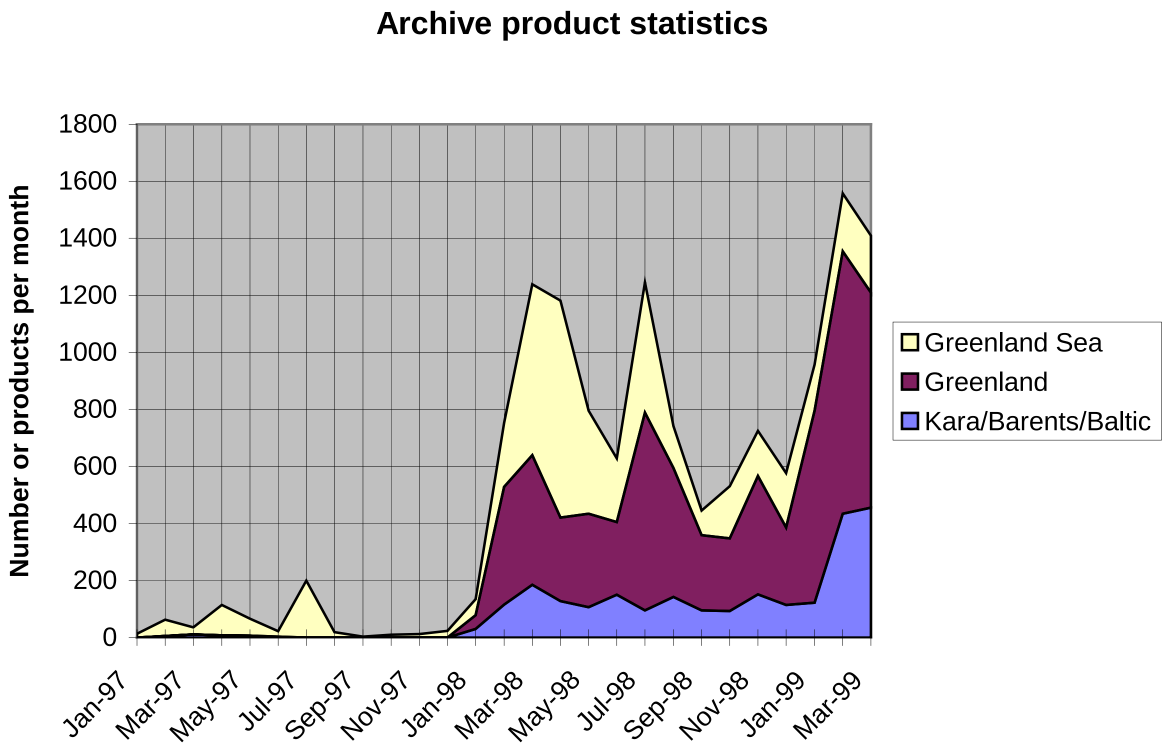


Figure 6.5 ***Number of downloaded products per month from the DCRS/DTU sea information archive.***

The major users of the archive has been the ice services in northern Europe and some university partners from other EU projects (ESOP, PELICON, SEALION). Not included in the statistics are the images emailed of sent via FTP to ships operating in the areas. The two major users in this category was the “Kista Arctica” of the Royal Arctic Line, and the Ocean Tiger” of the Ocean Prawns A/S. The Kista Arctica pilot project was organized by the Danish Meteorological Institute and is described below.

The Captain of the Ocean Tiger called up one day when the Internet service was temporarily out of operation. We had never heard about him, but he asked what had happened to the excellent ice information he had got used to download via the Internet. He informed us that they used the satellite telephone to connect to the Internet via an Internet Service Provider (ISP), and that they found the ice data (primarily the new SSM/I based products) very useful. He also suggested that we should work on a solution that would allow users such as himself to work off-line with the data, and not have to maintain an expensive telephone connection during the work. This information was very important for the preparation of the Kista Arctica pilot project. We have now set up a service where users of this type can have the JAVA software installed on a computer on-board the ship, along with data files with coastlines, latitude/longitude grids, bathymetry contours etc. This pre-installed software will then access a reduced version of our archive on the same computer. The on-board archive can be updated as frequently as necessary by accessing packages of compressed images and auxiliary files via FTP or having them transmitted via email. The Captain emphasised the necessity to reduce transmission times, and we have reduced packet sizes to 25-75 kilobytes with typical transmission times via a 9600 baud satellite telephone connection of 1-2 minutes. This is considered very useful by the Captain, and he now functions as an ice information relay central for other trawlers operating in the same area.

Figure 6.6 shows download statistics for the enhanced resolution SSM/I products that are available through the URL: http://www.dcrs.dtu.dk/ftp/ssmi/icemaps/latest/ice.html. These images are produced directly from the raw data downloaded from the Marshall Space Flight Center (NASA). An example of a South Greenland image can be seen in Fig. 6.7.

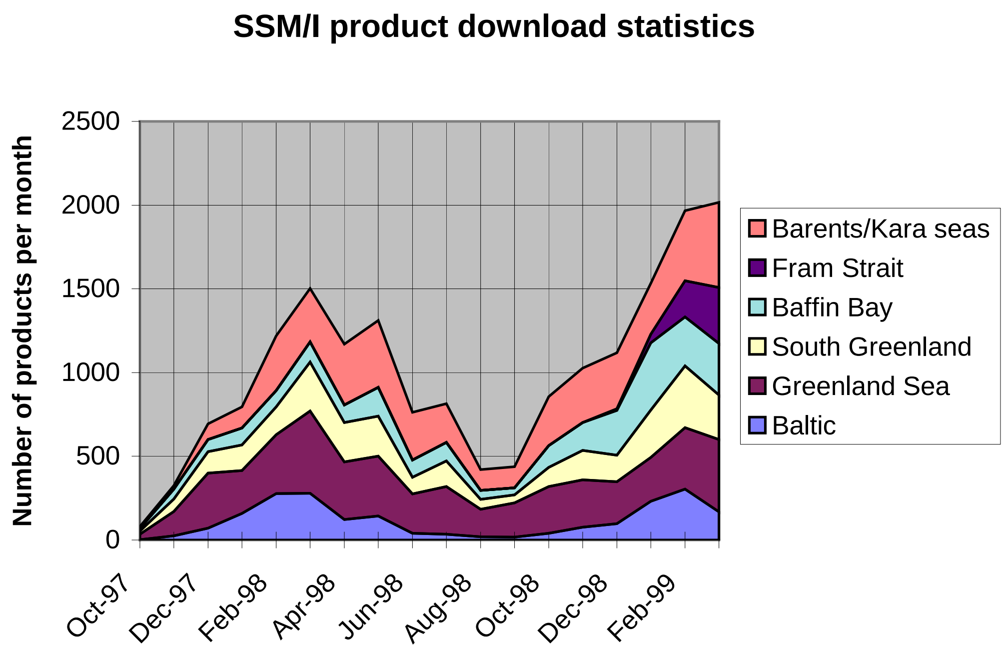


Figure 6.6 ***Download statistics for the daily updated enhanced resolution SSM/I products.***

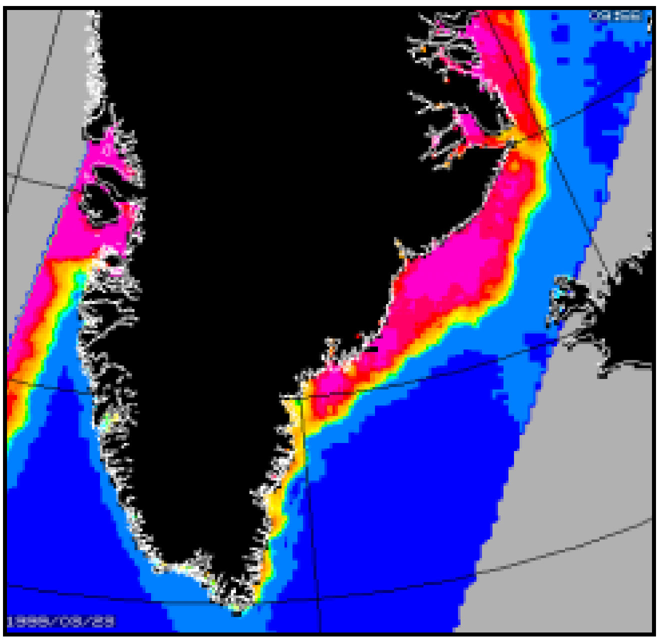


Figure 6.7 ***Example of enhanced resolution SSM/I image of the South Greenland area from March 23, 1999 at 09:56 UTC.***

The data are available through a very simple WWW interface at DCRS. The interface is entirely text-based in order to reduce download times, and the data server at NASA is checked every 30 minutes for new data. Products are available with a typical delay time of 4-12 hours after the satellite pass. The images are masked so land areas are black, and a lat/lon grid is superimposed as well as coastlines. Typical image sizes are 10-25 Kilobytes in gif format, which should ensure quick download times for most users.

6.3.2 Cost-benefit considerations

The overall result of the cost benefit considerations at DMI using RADARSAT data replacing aerial reconnaissance is that the service provided with the RADARSAT ice product is better than aircraft surveillance product inside the same budget. The involved expenses using RADARSAT are comparable to that of using aerial reconnaissance. A subjective analysis by Gill et al. (1999) rates the ice information quality using RADARSAT at least as good as using aerial reconnaissance. The advantages of using RADARSAT are: 1) SAR data can provide both very detailed and large scale overview information 2) the data are independent of sunlight and the operation of the satellite is independent of weather conditions. 3) a more regular coverage can be maintained and 4) the original data can be archived and retrieved. During the coming years it is expected that SAR satellites e.g. lightSAR and Envisat will be launched which will improve the overall spatial and temporal coverage. Thus the reconnaissance using satellites has improved considerably and the potential for further improvement in the next 10 years is very high. In particular, using the data from the upcoming SAR bearing satellites, in combination with the data from the current satellites and ice drift forecast models, it should be possible to provide daily ice monitoring service which is far more complete, precise and detailed than the hitherto aerial reconnaissance. This of course means that the flexibility and the possibility for real-time reports are lost.

The current operational set-up of DMI ice patrol is that RADARSAT will be used during the winter, spring and fall and can be used during the summer. However, during the summer months June-August the aircraft (Twin Otter) will be used as the interpretation of RADARSAT can be problematic due to severe surface melting of ice. The helicopter is used all year for reconnaissance in the straits and fjords. This set-up gives the best possible ice information for the safety of navigation and fulfils the responsibilities of the service inside the frame of the current budget.

6.3.3 Conclusions and recommendations for the future

The conclusions from the work DMI has done in IMSI has among other things led to the operational use of RADARSAT in Greenland. The major conclusions that led to this achievement were: 1) The coverage in the Greenlandic region was sufficient with RADARSAT ScanSAR wide mode imagery 2) The ice could (with very few exceptions) always be mapped with high precision and quality 3) New ice edge /ice berg detection products could be derived 4) the satellite derived products were more useful and contained more information than that from aerial reconnaissance and 5) the cost was comparable to the cost of aerial reconnaissance.

The spatial and temporal coverage of RADARSAT ScanSAR in the navigationally important Cape Farewell area was investigated both through actual experience with images during the geophysical validation campaign and by the use of the RADARSAT swath planner. From these investigations it is concluded that the coverage in the Cape Farewell area is sufficient though less flexible than aerial reconnaissance. At higher latitudes on the east and west coasts of Greenland the coverage of RADARSAT is better than in Cape Farewell. The coverage of the east coast has been investigated during the Kista Arctica project. The result of this project also concludes that the coverage is sufficient using RADARSAT ScanSAR. One of the problems concerning coverage providing a ship with satellite ice information while it is operating in ice infested waters is that the sailing plan can not be kept strictly and the satellite may therefore not cover the actual area when it is needed. The experience gained from this project indicates that because the ship was moving slowly while operating in the heavy ice and because of the large area covered of RADARSAT 'Kista Arcticas' route was covered sufficiently.

The geophysical validation campaign during 1996, 1997 and 1998 delineated the possibilities using RADARSAT for icemapping in the Greenland waters. Along the east and west coasts of Greenland the physical interpretation of the RADARSAT data concerning the ice conditions is clear. The Cape Farewell area is with respect to the geophysical situation special, it is at the same time navigationally the most important area. During most of the year the physical interpretation of the RADARSAT data in Cape Farewell is clear but during the summer months under certain meteorological conditions surface melting and winds from various directions can make the interpretation uncertain.

The amount of detail which can be mapped and included in the new type of ice information developed during the IMSI project is greater than the information from aerial reconnaissance. The position of, for example, individual ice floes or leads can be communicated through image sub-sections.

IMSI has supported DMI's long time strategy of integrating SAR satellite data in the operational service. During the project RADARSAT has replaced most of the tasks which were formerly done with aerial reconnaissance. IMSI has supported the necessary testing and validation of RADARSAT and the development of new products based on satellite observations. The use of RADARSAT has increased the observation frequency and improved the quality of the product. Of course at the same time, the advantages provided by aerial reconnaissance has been lost e. g. flexibility and real time reports.

The following recommendations for the future ice monitoring in Greenland can be formulated:

- The use of RADARSAT or other similar wide-swath SAR data for tactical ice information should be continued in the future.
- NOAA-AVHRR and other types of satellite data are often a very fine supplement or alternative for getting timely ice information. Whenever it is possible these charts should be produced and distributed.
- Vector ice charts produced in SIKU (image processing software operational at DMI) contain detailed information which can be extracted using display software on the ship. Those data presentation systems (e.g. DTU Java browser) provided better ice information than previous systems but should still be developed for better operational use.
- Information which can be extracted from RADARSAT like ice berg distribution density should be included in the ice information.
- Ice drift forecast information should be included in the ice information.
- Sea surface temperatures should be included in the ice information.
- Data communication to a ship at high latitudes is a problem.
- Polar orbiting communication satellites should be used when they become operational.
- Data communication costs should be reduced so even small ships can afford the information.
- Skamlebæk HF-radio should be maintained as a reserve and to the benefit of small ships.

6.4 Large scale ice monitoring in Arctic - Antarctica

6.4.1 User assessment, and evaluation of project results

Since the ice backscatter maps produced over both polar oceans are of low spatial resolution and produced weekly (C band) or every three days (Ku band), they are of no direct use in piloting ships. Although they can serve industrially, when analyzed over several yearly cycles, to plan an operational strategy, they are principally useful to climatologists and ecologists interested in the long term evolution of sea ice, or to modelers wishing to test their sea ice models. Distributed by Internet, they are justified by the number of web pages consulted monthly, which varies around two to three hundred, with an occasional peak when a research institution downloads a large part of the data base. The original data used to produce the maps is obtained free of cost from national (NASA) or international space agencies (ESA), and the products are, by the same token, redistributed freely on the Internet.

6.4.2 Conclusions and recommendations for the future

The production of Ku band maps, in the course of IMSI, showed these maps to be superior to the present C band products, because the frequency band is better adapted to discrimination between different ice types, and the sensor (NSCAT) offers a higher resolution, covers twice the area covered by the AMI in the same amount of time, and is not hampered by a SAR mode which turns off the scatterometer mode. It is unfortunate that NSCAT data was interrupted by the failure of the ADEOS platform after ten months of operation, but the existing data set can serve to anticipate results to be obtained by future sensors.

In the near future, at least until the end of the operational life of ESA's ERS-2, IFREMER will continue to produce C-band maps weekly and distribute them on the Web server. IFREMER will also develop a new Ku band product from NOAA's rotating scatterometer QUIKSCAT, launched in June 1999. In view of the large swath of this instrument and because its measurements are made at two constant incidence angles, it is hoped to decrease the period between successive maps to one or two days. It is expected that, in the beginning of the 21st century, EUMETSAT's Ocean and Sea Ice SAF (Satellite Applications Facility) will produce C band sea ice products from METOP's two-swath ASCAT (Advanced Scatterometer) at a better resolution (25 km) and more frequently than could be produced from the AMI, while in the USA, future Ku band scatterometers (SEAWINDS) will fly. Combining the backscatter data in the two frequency bands with passive microwave data from the SSM/I (Special Sensor Microwave Imager) or from its successor, the AMSR (Advanced Microwave Scanning Radiometer) remains to be accomplished. This combination will allow discrimination of a larger number of ice types, with better resolution both in time and space and greater precision than presently possible. Such near real time products however, which require the facilities of a large meteorological agency, will probably be produced in the USA, but should be considered for a future evolution of the EUMETSAT Ocean and Sea Ice SAF, presently too limited in its possibilities.

7 Concluding remarks

The main **contributions from each partner** to the project have been:

IFREMER has developed global ice cover and ice type maps for the whole Arctic and Antarctic using scatterometer data from ERS AMI and ADEOS NSCAT, the latter providing higher resolution and improved sensitivity than the ERS data. NSCAT data were available for about 9 months during the project period. IFREMER also developed a distribution service for scatterometer ice charts on Internet.

FIMR and **HUT** have developed better ice classification algorithms for the Baltic Sea using SAR, airborne data, as well as field observations. Automated ice classification is used to produce better ice charts in the Baltic Sea. Several user demonstrations were carried out for icebreakers as well as merchant vessels. Use of RADARSAT is now established in operational ice monitoring in Finland and Sweden. Traditional aircraft surveys of sea ice is reduced because use of satellite data is more cost effective and gives better quality of the ice charts.

DMI has established use of RADARSAT data in monitoring of sea ice and icebergs in Greenland waters. Several validation experiments with aircraft surveys and user demonstrations have been carried out. Methodology to map different ice conditions and icebergs from RADARSAT ScanSAR images have been developed. This methodology is used in operational ice monitoring, instead of traditional aircraft surveys throughout the year. Aircraft is only used in the summer months when the information from SAR data can be unreliable.

DTU/DCRS has improved the SSM/I I ice concentration maps by including the 85 GHz channel, resulting in an increased resolution from about 30 km to about 10 km. DTU/DCRS has furthermore developed an efficient data and ice chart dissemination system on Internet for SSM/I-derived ice charts as well as other ice data such as NOAA AVHRR data and SAR data in the Greenland area.

NERSC has been project leader and developed use of SAR and SSM/I for ice monitoring in the Northern Sea Route. SAR ice classification using neural network has been developed for ERS and RADARSAT images. Two validation and demonstrated expedition using RADARSAT ScanSAR images were carried out with Russian icebreakers, one during summer conditions in the Laptev Sea area and the other during severe winter conditions in the Kara Sea. Near real-time transmission of SAR data for tactical ice navigation was demonstrated in these expeditions. Also other satellite data such as ERS SAR, SSM/I, Okean SLR data were used to improve ice monitoring in the area. Data dissemination and product demonstration have been performed for more than a dozen of users.

The **dissemination of project results** has focused on three types of activities:

1. Transmission of EO data and derived products to ships at sea in three different regions: the Baltic Sea, Greenland Sea and Northern Sea Route. The transmission has been demonstrated during field campaigns with icebreakers, other icegoing vessels, cargo vessels and fishing vessels.

2. Dissemination of products via Internet. DTU/DCRS service for SSM/I, AVHRR and SAR data has been most successful with several tens of thousands of log-ins. Also IFREMER's service for Scatterometer data has been very popular, showing that there is a real need for data sea ice information products which can be downloaded free-of-charge from Internet.

3. Other dissemination activities
- promotion activities towards oil companies, other ice centres, by hosting of workshops, distribution of brochures and reports, direct contact and demonstrations
- general presentation at conferences and in scientific publications
- IMSI web-pages

Who are the main users of ice information ? The user requirement study showed that the main users of ice information are:
- national ice centres and weather forecasting centres
- sea transport authorities
- shipping companies, merchant vessels and fishing vessels
- icebreakers and icebreaker companies
- oil companies and other offshore industry operating in the Arctic
- science users and research expeditions

What is the overall benefit of improved ice information?

The benefits for **end users** such as ships, icebreakers, offshore operations and other practical users working at sea are two-fold:

- improved ice information by use of satellite data can reduce the operating costs, especially by saving time, for example for a vessel which sails through an ice-covered area;
- improved safety by operating in ice, reducing the risk for accidents and damage.

The benefit for **intermediate users** such as ice services, weather services, climate researchers and other service providers is access to higher quality data and information which would not have possible to obtain from other sources. Better quality of input data enable them to provide a better quality service for the end users. For example, global monitoring of changes in sea ice extent over the last two decades can only be done by use satellite data such as passive microwave data.

Have the success criteria for the project been fulfilled ?

The following criteria for success was defined for IMSI and the results show that all criteria have been more or less fulfilled.

1. Do existing users require more EO-data ?

Yes: both end users such as icebreakers, and intermediate users such as the ice centres and transport authorities.

2. Have new users responded positively to EO-data demonstrations ?

Yes, cargo ships, oil companies and fishing vessels have responded positively and stated that they will use EO data in the future.

3. Have new EO-based products been developed ?

Yes, SAR (RADARSAT and ERS), scatterometer, and SSM/I products have been developed, as well as better quality of ice charts using these data products.

4. Will use of EO data provide safer and more cost-effective operations in sea ice ?

Yes, all users state that EO data can contribute to both safety and economy in sea ice operations.

5. Will services developed in the project continue in the future ?

Yes, the ice services in the Baltic Sea and in Greenland will continue to use EO data operationally, especially RADARSAT SAR data. In the Northern Sea Route EO data will be used more extensively, but it depends on the amount of economic activity in the region. It has been well documented that EO data are more cost-effective and is gradually replacing traditional aircarft surveys.

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Appendix A: List of IMSI reports

IMSI report no 1:
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IMSI report no. 4:
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IMSI report no. 5:
Gohin, F. and C. Maroni. "ERS Scatterometer polar sea ice grids - User Manual". IFREMER/CERSAT Technical Report: C2-MUT-W-03-IF, V2.0, March 1998.

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IMSI report no. 7:
Gill R. S. and M. K. Rosengren "Evaluation of the Radarsat imagery for the operational mapping of sea ice around Greenland in 1997". DMI Scientific report no. 98 - 5, February 1998.

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IMSI report no. 9:
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IMSI report no. 10:
Tonboe, R. T. and M. K. Rosengreen. Operational test of RADARSAT and data dissemination. DMI report, October 1998.

IMSI report no. 11:
Mäkynen, M., and Hallikainen, M., "Feasibility of microwave remote sensing for classification of the Baltic Sea ice", Helsinki University of Technology, Laboratory of Space Technology, Report 38, November 1999.

IMSI report no. 12:
Stein Sandven, Marko Mäkynen, Martti Hallikainen, Hannu Grönvall, Ari Seinä, Markku Similä, Juha Karvonen, Mikael Nizovsky, Alain Cavanie, Robert Ezraty, Rasphal Gill, Hans H. Valeur, Leif Toudal Pedersen, Vitaly Alexandrov, Andrey Bogdanov, Rasmus Tonboe, Maria Lundhaug, Øyvind Dalen and Kjell Kloster, IMSI Final report, NERSC Technical report no. 170, July 1999.

Appendix B: List of acronyms and abbreviations

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
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
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
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
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
GR	**G**radient **R**atio
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
HUT	**H**elsinki **U**niversity of **T**echnology, Finland
HUTSCAT	**H**elsinki **U**niversity of **T**echnology **Scat**terometer
IC	**I**ce **C**entral **N**arsarsuaq, Greenland
INMARSAT	**In**ternational **Mar**itime **Sat**ellite
IR	**I**nfra-**R**ed
ISIS	**I**ce **S**ervices **I**ntegrated **S**ystem

JERS	**J**apan **E**arth **R**emote-Sensing **S**atellite
LRI	**L**ow **R**esolution **I**mage
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
MWR	**M**icro**w**ave **R**adiometer
NASDA	**Na**tional **S**pace **D**evelopment **A**gency, Japan
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
NSCAT	**N**ASA **Scat**terometer
NSR	**N**orthern **S**ea **R**oute
NWS	**N**ational **W**eather **S**ervice, USA
OCTS	**O**cean **C**olour and **T**emperature **S**canner
PDF	**P**robability **D**ensity **F**unction
POLDER	**Pol**arisation and **D**irectionality of **E**arth's **R**eflectance’s
PR	**P**olarisation **R**atio
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
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
TM	**T**hematic **M**apper
TSS	**Tr**omsø **S**atellite **S**tation
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

Appendix C: IMSI brochure

NERSC

Nansen Environmental and Remote Sensing Center (coordinator)

Danish Meteorological Institute

Technical University Denmark
Electromagnetics Department

Finnish Institute of Marine Research

Helsinki University of Technology

IFREMER, Centre de Brest

IMSI

Integrated use of new microwave satellite data for improved sea ice observation

Objectives

- to explore and test methods for use of new satellite earth observation data in sea ice monitoring, and
- improve the utilisation of these observations in a wider user community

Project period

February 1997 - April 1999

Project support

CEC Environment and Climate Programme 1994-1998

Theme 3: Space Techniques Applied to Environmental Monitoring and Research.

Area 3.3.3: Centre for Earth Observation Application Support

Main tasks

1. Study of user requirements to define new satellite sea ice products

2. Develop new ice products on global, regional and local scale, using SAR, passive microwave, scatterometer and SLR data

3. Field demonstrations and product dissemination to many users

4. User assessment, conclusion and recommendation

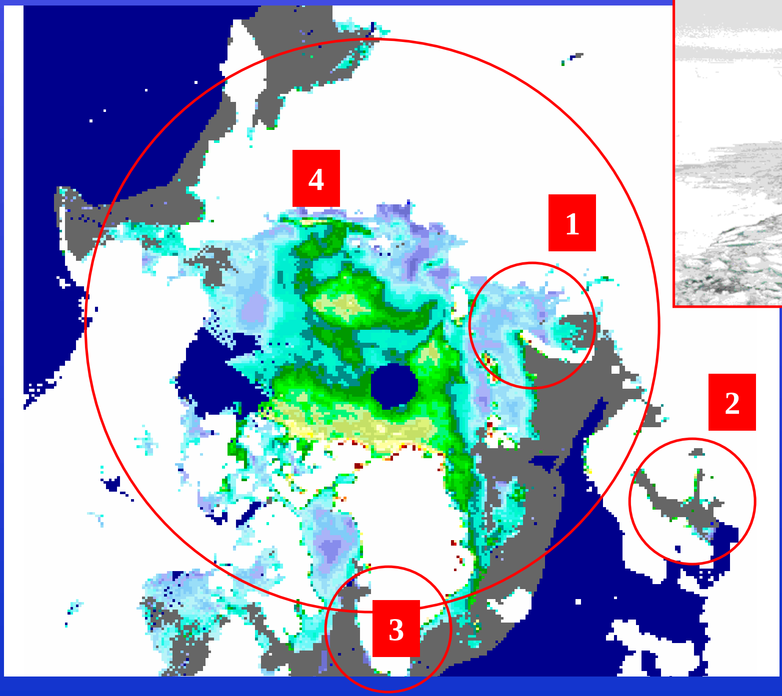
Customers

- national ice centers and weather forecasting centers
- sea transport authorities
- shipping companies, merchant vessels and fishing vessels
- icebreakers and icebreaker companies
- oil companies and other offshore industry operating in the Arctic
- science users and research expeditions

Study areas

The new satellite ice products are developed for the Northern Sea Route (1), the Baltic Sea region (2), Greenland waters (3) and for the whole Arctic Ocean (4).

Russian icebreaker "Yamal"in the Laptev Sea during the first demonstration campaign for use of RADARSAT data in the Northern Sea Route in August - September 1997.



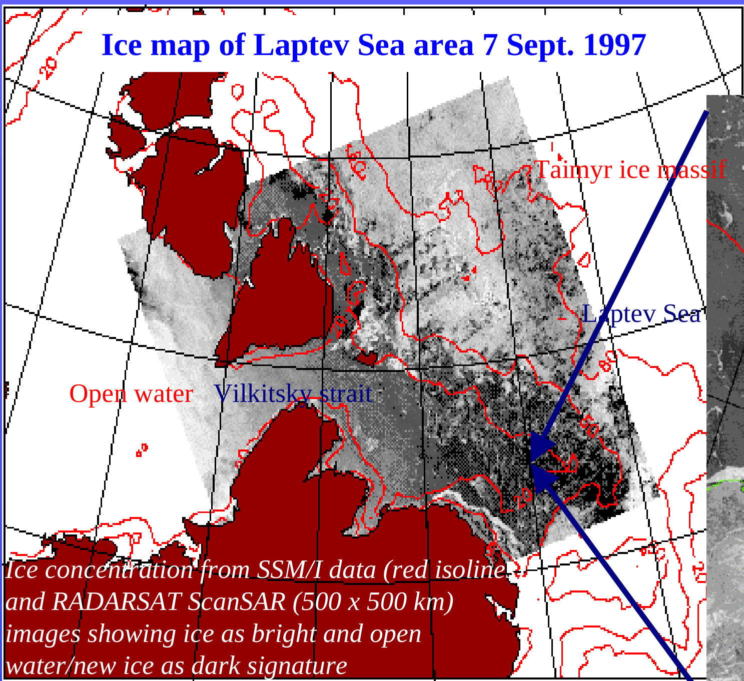
Map of the Arctic area showing sea ice observed by ERS Scatterometer data. The red circles indicate the IMSI study areas. ERS Scatterometer data provided by IFREMER.

NERSC

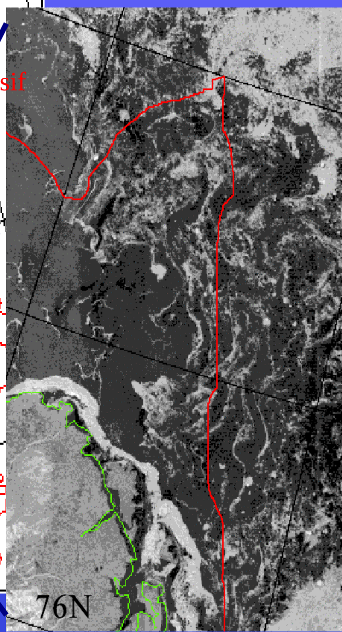
Nansen Environmental and Remote Sensing Center:

- coordinator and leader of Russian contribution to IMSI
- development of SAR ice products for Arctic areas
- synergetic use of SAR, SSM/I and Okean SLR data
- demonstration and validation campaigns with icebreakers
- dissemination of products to users in the Northern Sea Route
- provision of special ice service to oil industry and sea transportation
- establish relations to new users

Address: Edvard Griegsvei 3a
N-5037 Solheimsvik, NORWAY
telephone: + 47 55 29 72 88
fax: + 47 55 20 00 50
contact: Stein Sandven
e-mail: stein.sandven@nrsc.no
http://www.nrsc.no/

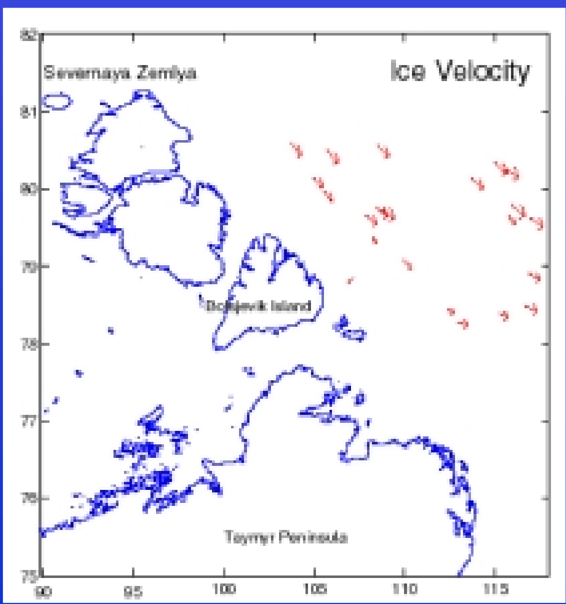


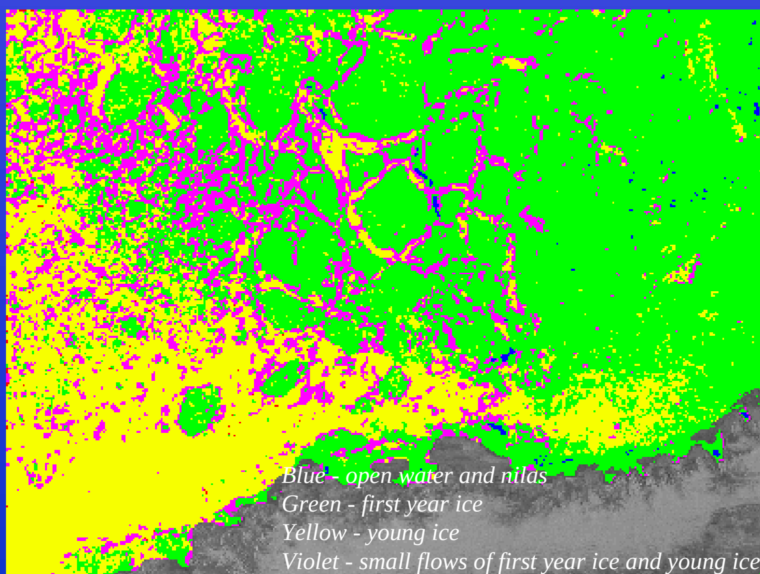
Ice concentration from SSM/I data (red isoline) and RADARSAT ScanSAR (500 x 500 km) images showing ice as bright and open water/new ice as dark signature



Blow-up of the SAR image of a 200 by 100 km area for ice routing of Sovetsky Soyuz (red line)

Subset of RADARSAT ScanSAR image on 25 April 1998 classified using algorithm developed by C. Wackerman and D. Miller for Marginal Ice Zone. Texture and local statistics of the image were used for classification.





Ice velocity can be calculated from consecutive SAR images by estimating the displacement of ice floes, tongues, clusters and other ice features. The example below shows a mean ice velocity of about 20 cm/s in southeasterly direction from 14 to 15 August. Ice velocity is an important parameter in ice forecasting

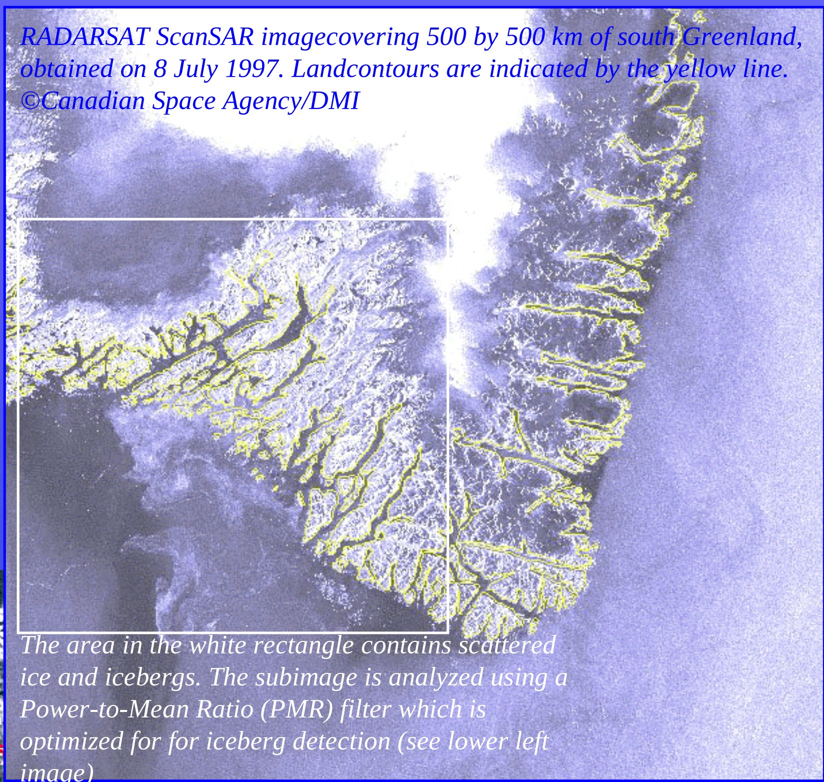
IMSI – Integrated use of new microwave satellite data for sea ice observation. Contract No. ENV4-CT96-0361

Danish Meteorological Institute

- study ice features in Greenland waters by RADARSAT SAR
- ice product development for Greenland waters
- demonstration and validation campaigns in Greenland waters
- dissemination to other users
- evaluation and assessment of ice products in Greenland waters
- identify new users in Greenland waters

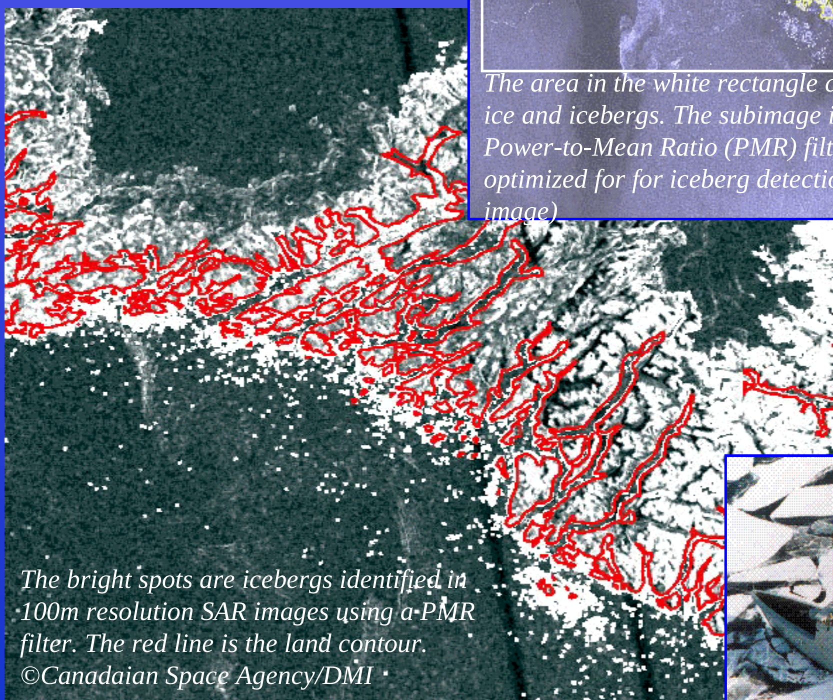
Address: Lyngbyvej 100
DK-2100 Copenhagen
DENMARK
tel: + 45 3915 7500
fax: + 45 1915 7300
contact person
Hans H. Valeur
e-mail: hhv@dmi.min.dk

The most important and dangerous ice features in Greenland waters are small floes of old multiyear ice and icebergs which are often difficult to observe by any remote sensing method. Aircraft surveys have been used as the main observation method, but now RADARSAT SAR will be the main data used in operational monitoring.



RADARSAT ScanSAR imagecovering 500 by 500 km of south Greenland, obtained on 8 July 1997. Landcontours are indicated by the yellow line. ©Canadian Space Agency/DMI

The area in the white rectangle contains scattered ice and icebergs. The subimage is analyzed using a Power-to-Mean Ratio (PMR) filter which is optimized for for iceberg detection (see lower left image)



The bright spots are icebergs identified in 100m resolution SAR images using a PMR filter. The red line is the land contour. ©Canadaian Space Agency/DMI

The Royal Arctic Line freighter 'Kista Arctica' have been involved in demonstration and validation expeditions

The main users of ice information in Greenland waters are transport ships, fishing ships and other vessels such as vessels conducting seismic surveys in ice covered waters.

IMSI – Integrated use of new microwave satellite data for sea ice observation. Contract No. ENV4-CT96-0361

Technical University Denmark, Electromagnetics Institute

Address: Bygning 101A, DK-2800 Lyngby, DENMARK
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telephone: + 45 4525 3791
fax: + 45 4593 1634

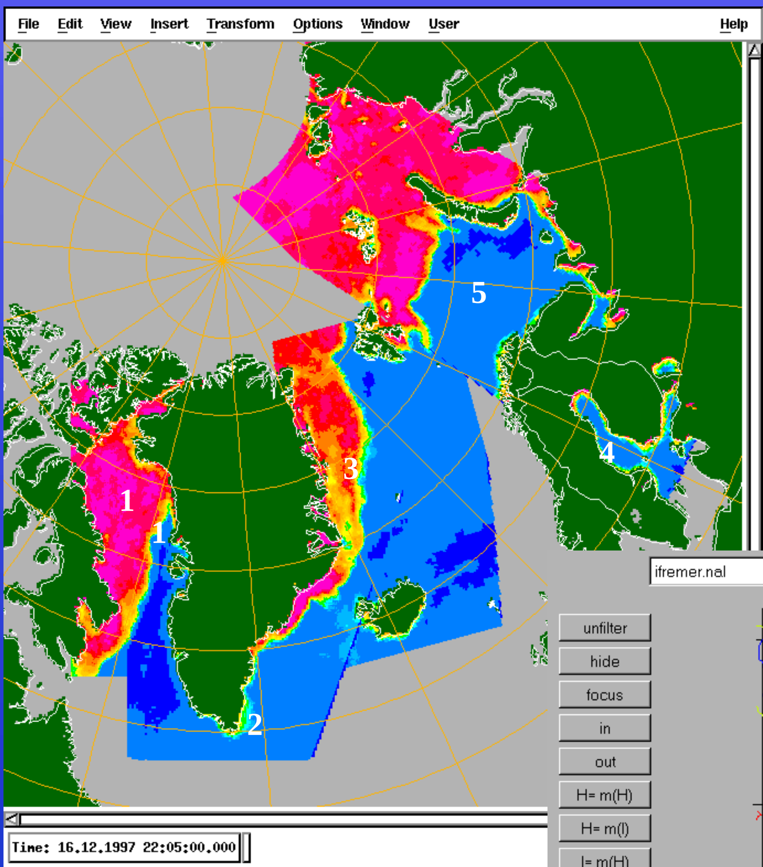
e-mail: ltp@emi.dtu.dk
http://www.dcrs.dtu.dk

- development of methods for handling the geometrical differences between the different datasets, i.e. different scale and orientation.
- development of methods for visualization of information on very different scales, i.e. 10-300 meters of the SAR, 1-2 Km of AVHRR and 10-100 Km of SSM/I.
- extraction of detailed ice edge information from the combined dataset
- characterization and classification of ice using the combined dataset.
- dissemination of data products via Internet

SSM/I data is obtained routinely from NASA and ice concentration maps which include use of the 85 GHz channel are produced every day.

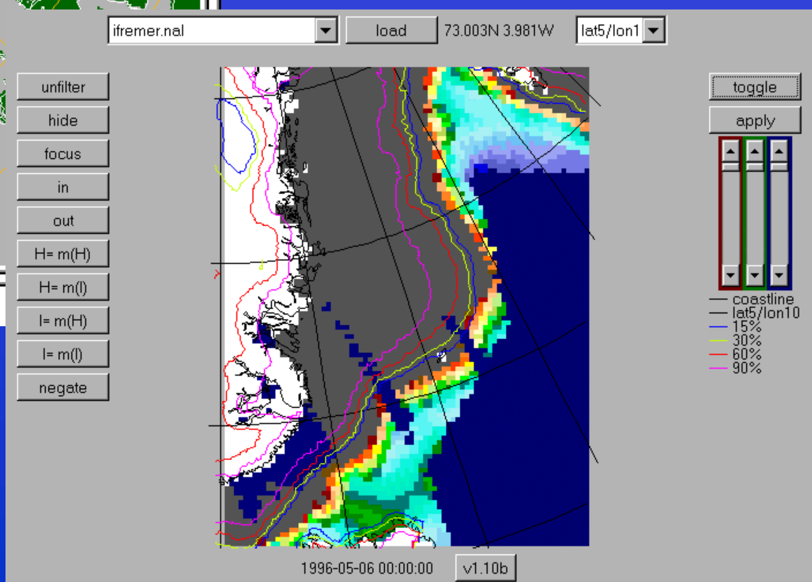
The ice maps which currently cover 5 regions, are distributed via the World Wide Web interface at the Danish Center for Remote Sensing:

http://www.dcrs.dtu.dk/DCRS/latest-ice.html



Map showing the total area covered by our 5 sections of the European Arctic. The sections are: 1) Baffin Bay & Davis Strait, 2) South Greenland, 3) East Greenland, 4) Baltic, 5) Kara & Barents Sea. The colours originate from the combined 85 GHz and Bootstrap algorithm.

The map shows the ice cover (yellow and red) in the beginning of the early winter of 1998 (January). Blue areas indicate ice-free waters.



WWW interface to ice product database showing an ERS Scatterometer product produced at IFREMER, combined with ice concentration contours from SSM/I derived at DCRS and coastline and latitude/longitude grid.

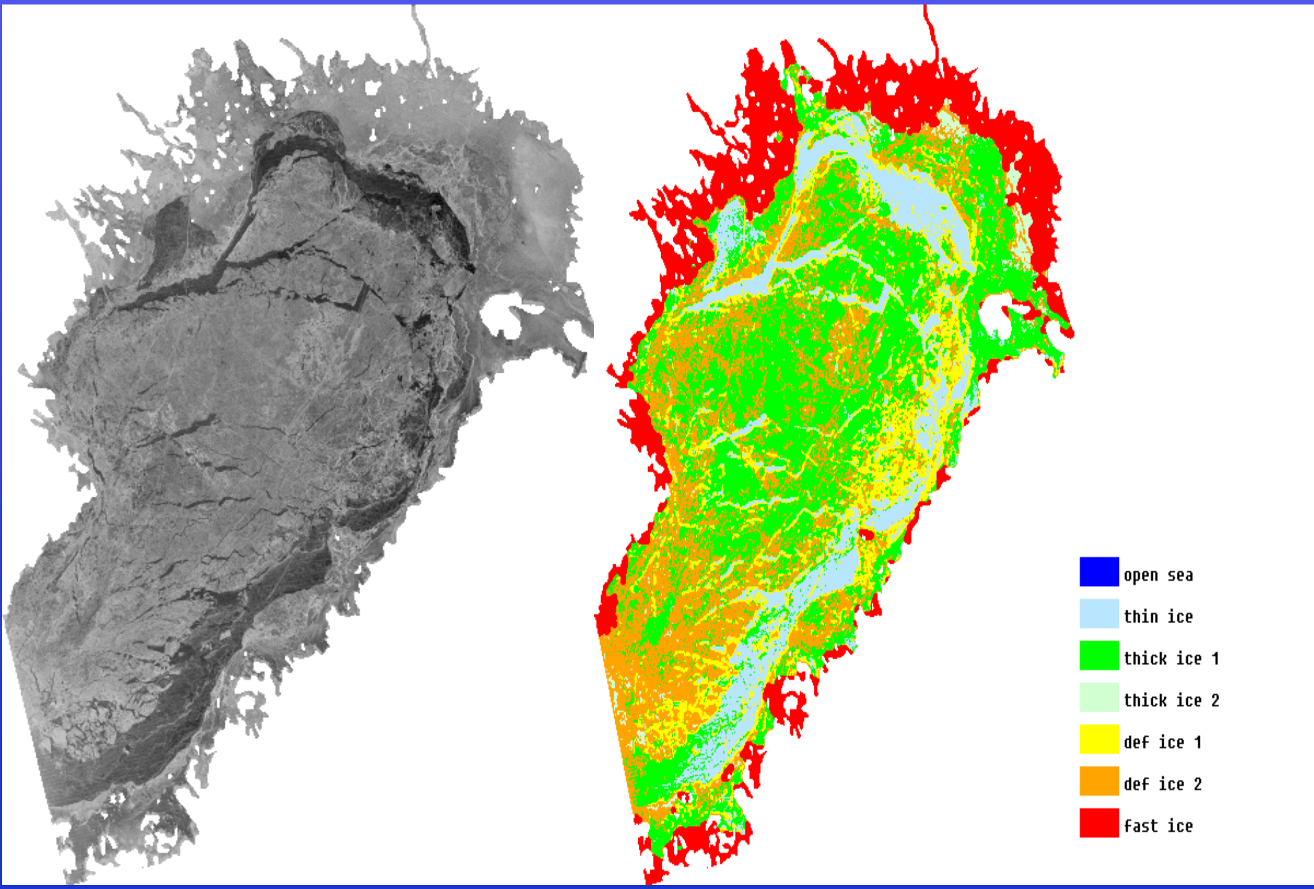
IMSI – Integrated use of new microwave satellite data for sea ice observation. Contract No. ENV4-CT96-0361

Address: Lyypekinkuja 3
FIN-0093 Helsinki, FINLAND
telephone: +358 9 6139 4422
fax: + 358 9 6139 4494
Contact person: Hannu Gronvall
e-mail. hannu.gronvall@fimr.fi

Finnish Institute of Marine Research

- Study of user requirements for ice data products in the Baltic Sea
- development of new satellite ice products from SAR data
- validation and demonstration campaign in the Baltic Sea
- dissemination to users including realtime transfer to icebreakers
- evaluation and assessment of ice products
- responsible for data archives in the Baltic Sea
- responsible for operational ice monitoring in Finland
- identify new users in the Baltic Sea

FIMR is developing operational use of satellite SAR data for ice monitoring in the Baltic Sea. During the winter season of 1998 approximately 100 RADARSAT ScanSAR images were used in the production of ice charts as a joint project between Finland and Sweden. Automatic extraction of the main ice classes is an important element of the SAR data analysis which is necessary for handling large amounts of data every day.



The area covered by this RADARSAT image (left) contains most of the ice types of the Baltic Sea. At the top of the image and at the top on the right are areas of fast ice. The light areas represent deformed areas or fast ice and dark areas new ice and open water. However, not all areas can be directly classified on the basis of local intensity values. In such cases, deduction rules based on the neighbouring areas must be used. The image was obtained on March 15 1998.

IMSI – Integrated use of new microwave satellite data for sea ice observation. Contract No. ENV4-CT96-0361

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- Combined use of SAR and passive microwave radiometer data (MWR) for classification of open water and various ice types in the Baltic Sea.
- Investigation of C-band backscattering signatures of various Baltic Sea ice types to development RADARSAT & ERS-2 SAR sea ice classification algorithms.
- Airborne MWR, SAR and scatterometer data from several field campaigns utilized.

Microwave radiometer measurements of the Baltic Sea ice with the HUT Short SC-7 Skyvan aircraft. The radiometers look backwards along flight track through open cargo door.

- Open water leads are distinguished from sea ice using only single-channel MWR data in the frequency range 6.8-36.5 GHz, regardless of the snow cover wetness. Classification of different ice types is possible only when snow cover on ice is dry.
- In the Baltic Sea spaceborne MWR data are not useful alone for ship navigation purposes due to their very poor spatial resolution. However, the spaceborne MWR data could be utilized in the development of the SAR classification algorithms. The SAR algorithms could be adjusted by comparing MWR and SAR derived ice concentrations to each other.
- C-band scatterometer data were used to investigate:

  1: variation of the backscattering coefficients as a function of incidence angle,

  2: statistical properties of the backscattering coefficients, and

  3: the effect of snow cover wetness on previous parameters.
- The derived incidence angle dependencies of backscattering coefficients can be used to scale the RADARSAT ScanSAR images to a certain incidence angle. The scaling probably improves the classification results of the SAR images.
- SAR images with high incidence angle range (e.g. 40-50 degrees) are better for classification of different surface types than images with low incidence angle range (e.g. 20-30 degrees).

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- develop scatterometer sea ice products
- comparison of scatterometer data with other microwave data for ice observation
- software for dissemination of scatterometer products
- dissemination of scatterometer products to users of global sea ice data using Internet
- evaluation and assessment of products