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SAR ice charting demonstration and validation

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EXECUTIVE SUMMARY

The overall objective of the Ice Routes project is to demonstrate the feasibility of using satellite data in ice charting and routing for safer and more efficient ship transport in ice-covered waters. The specific objectives of the SAR ice charting demonstration and validation activities are:

1. To acquire for the first time a large amount of RADARSAT ScanSAR data (more than 30 scenes) for analysis and interpretation of ice conditions in the NSR
2. To demonstrate Artificial Intelligence technologies in generating high-resolution ice classification charts for ship routing using RADARSAT ScanSAR data
3. To evaluate the benefits of using ScanSAR data in support of ice navigation

The main activities have therefore been to

- plan and acquire RADARSAT ScanSAR data for the NSR during 1997-1998
- formulate 'ice-rules' for use in the Artificial Intelligence (AI) system
- perform ice expert analysis of SAR data for preparation of training and validation data
- acquire *in situ* ice observations coincident with the SAR data in a demonstration expedition
- validate the final AI ice classification results, using field data from the expedition

In April-May 1998 RADARSAT ScanSAR images were for the first time used in a winter expedition in the NSR. With a mosaic of RADARSAT ScanSAR data (as seen in Figure 1) it is possible to map sea ice with SAR images over much larger areas than is possible with ERS SAR. The first set of RADARSAT data acquired in this project were 22 ScanSAR scenes processed at Gatineau in Canada, covering the Svalbard area, Barents, Pechora, and Kara Seas. The images were obtained between September 1996 and September 1997, and were primarily used to prepare training and validation data for the computer-based classification system. Two expeditions with Russian icebreakers have been organised within the frame of the ICE ROUTES project, first a pilot summer expedition during August-September 1997, followed by a more extensive winter expedition involving several cargo vessels and icebreakers in April-May 1998. During the expedition RADARSAT ScanSAR data were provided in near real time and procedures for digitally data transmission to the icebreaker were tested and evaluated. Four ScanSAR scenes were acquired during the summer expedition, and additionally six scenes were acquired during the winter expedition. All these scenes were processed at Tromsø Satellite Station, in order to get the data in near real time. The expeditions provided considerable amounts of ground truth validation data for interpretation of the SAR signatures, such as visual ice observations, photographs, and video recordings. Also ship performance data was collected for assessment of the routing models.

Training and validation data for the first set of images were prepared by ice experts at NERSC, with support from MSC and NIERSC, by using a specially developed software system called Ice Class Editor (ICE). A main function of ICE is to segment the images, in order to define polygons with uniform image pixel characteristics. Attributes such as ice type, degree of deformation, and special features (i.e. lead, ridge etc.) were manually interpreted and assigned to each image segment. The training data set used to train the Fuzzy Expert System (FES) consisted of several hundred classified segments. The first output of the FES classifier was discussed at a validation workshop in Bergen, 18-19 March 1998. The conclusion from the workshop was that the main features of the classification results were reasonable, although several errors in the classification needed to be improved. So far, the SAR data receiving stations do not provide any calibration for the RADARSAT images. This makes it difficult to perform classification based on radar backscatter data (expressed in σ^0-values), and compare ice signatures from image to image. Due to different processing procedures at Gatineau and TSS, the SAR images first processed at TSS had to be reprocessed at Gatineau in order to match the data used for training of the FES.

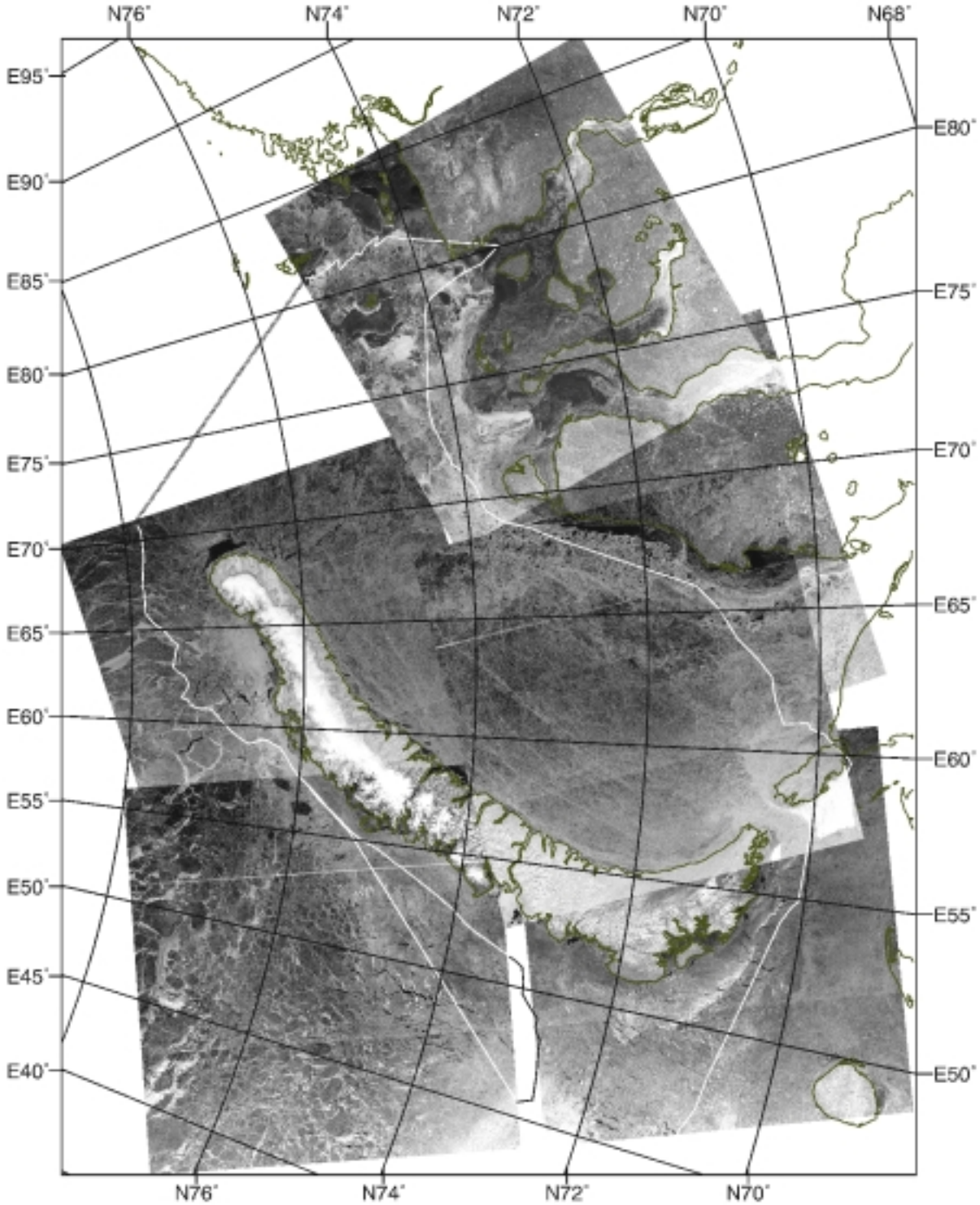


Figure 1. A mosaic of the six RADARSAT ScanSAR scenes obtained during the winter validation expedition April-May, 1998. The sailing route of Sovetsky Soyuz is superimposed.

The main effort of the validation work was planning and implementation of a winter expedition with two MSC icebreakers during April-May 1998. The ICE ROUTES expedition with Sovetsky Soyuz took place prior to and during the ARCDEV Expedition with Kapitan Dranitsyn. A total of 6 RADARSAT ScanSAR and 11 ERS-2 SAR images were received in near-real time onboard both Sovetsky Soyuz and Kapitan Dranitsyn during the expedition period. Also automatically FES classified ice charts were received and validated onboard the icebreakers.

The sea ice conditions in the Kara Sea during the winter 1998 were the most severe in 30 years. During the expedition thick first-year ice (ice thickness more than 120 cm) prevailed in the Kara Sea, due to very low temperatures during the preceding period. The ice navigation conditions in the traditional near-coastal routes through the Pechora Sea, Kara Gate and south-western Kara Sea were very difficult, as heavily ridged ice was formed in the area near the Kara Gate. During late April easterly and north-easterly winds dominated in the western Arctic, causing shore and flaw polynyas a few tens of km wide to form west of Novaya Zemlya, Vaigach Island, the Yamal Coast, and near Dixon.

The high latitude route north of Novaya Zemlya was selected, and from the ice edge in the Barents Sea the voyage went along the Novozemelskayas coastal polynya up to the northernmost point of Novaya Zemlya. Then the convoy headed south-eastwards to Dixon via a polynya west of Arctic Institute island. The traditional near-coastal route along the Yamal Coast, through the south-western Kara Sea, via Yugorsky Strait and into the Pechora Sea was selected for the return voyage in early May. The icebreaker escorting of the convoy is usually done by leading and towing of the cargo vessels. In difficult areas where the cargo vessels could not move independently, each vessel was closely towed by an icebreaker. In more easy ice conditions the convoy of vessels sailed behind the leading icebreaker. Particular difficult fast ice conditions occurred in the Ob estuary. ERS SAR images transferred to the ARCDEV expedition and other MSC icebreakers were used to select the actual course through the estuary and into an artificial harbour on the ice outside a gas-drilling station in Sabeta (Tambey). The Vaygach prepared the channel prior to the arrival of the ARCDEV convoy.

The main tasks of the demonstration and validation expedition were to use near real time RADARSAT ScanSAR data for navigation support, obtain *in situ* observation of different ice types observed in the SAR images, and to validate the automatic classification results. After downloading and processing at TSS, the SAR images were transmitted to the Nansen Centre in Bergen for antenna gain-correction, geo-location, and file-size compression to the JPG-format. The processed data products were digitally transmitted to the icebreakers via the INMARSAT satellite-communication system. The low-resolution version of the ScanSAR data delivered by TSS in near real time had 250m resolution and a file-size of 4-5Mb. With an image resolution of 250m, the data files transmitted to the icebreaker did not exceed 200Kb. Several ERS-2 SAR scenes with 100m resolution were used to supplement the RADARSAT data. The delay between image acquisition and the onboard reception did not exceed more than a few hours. The 6 RADARSAT ScanSAR scenes received onboard the icebreaker was primary used for solving tactical tasks of ice navigation. The first image obtained covered the sailing route north-northwest of Novaya Zemlya, where the icebreaker operated in thick first-year ice, mixed with relatively easy ice conditions. Leads, fractures and level first-year ice used for the ship route were identified from this image. Later, when the convoy approached Dikson, images covering the southern part of the Kara Sea between Izvestiy TSIK and Belyy islands were obtained. Analysis of these image showed that the convoy could move in a mixture of young and first-year ice near the mainland, by choosing leads and fractures in the thick FY ice cover. The images obtained on April 30 and May 8, were important both for the selection of the near-coastal return route to Murmansk, and for solving tactical problems of navigation underway.

The radar signatures of water and sea ice vary due to different surface conditions (wind, ice age, roughness, wetness, salinity, etc) and radar observation parameters (frequency, incidence angle, polarisation, resolution). RADARSAT data have not been used operationally in this region before. Sub-satellite sea ice observations were carried out continuously while the vessels operated in the ice. The observations were used for the interpretation of the images, and for validation of the automatic sea ice classifications. The joint analysis of RADARSAT sea ice images with synoptic visual observations of the sea ice conditions allowed interpretation of

different ice types and features in the images. Open water SAR signature depends on the wind speed and direction. Hence the ice edge cannot be reliably distinguished in all weather situations. Passive microwave satellite data from the SSM/I sensor is a helpful tool for detecting the ice edge position, though with a coarser resolution. RADARSAT signatures of new and young ice vary depending on the freezing stage and surface roughness (deformation). Nilas is evident as homogenous areas with dark signatures. Grey ice has a light homogenous brightness and is clearly distinguishable from nilas. The brightness of grey-white ice varies from dark to rather light, depending on the thickness and state of the surface. Grey-white ice consisting of small ice floes frozen together, observed near the ice edge, was characterised by a very bright radar signal. The brightness of first-year ice varies from dark to light, depending mainly on the degree of ridging and stage of freezing process. Level first year ice is characterised by a dark tone, while areas of heavily ridged ice has a brighter signal and can only be distinguished from grey ice using differences in the image texture. Individual first-year ice floes can clearly be identified. Rather long and wide individual ridges are recognised by their shape and bright signal. Leads and fractures, both unfrozen and covered with new or young ice, can be identified, which is important for the selection of efficient icebreaker routes. The signature of land-fast ice depends completely on the surface roughness, where level ice is shown with very dark signature, similar to that of calm open waters.

The Fuzzy Expert System (FES) classifier used 8 sea ice classes: Water, New, Nilas/young-level, Nilas/young-deformed, First-year-level, First-year-slightly deformed, First-year-medium to heavy deformed, and Multi-year. The latter was not present in the study area. These terms are not identical with the typical sea ice terminology used in traditional ice chart composition, and may be an error source for the classification results of some of the ice classes. Typical SAR signature levels for different ice types were not taken into account when the classification scheme was formulated, because the RADARSAT images were uncalibrated.

A confusion matrix of the FES classification results for the images of April 30 and May 8 was made after careful comparison with *in situ* observations. Although the field observations only covered a small part of each image, all major sea ice features and conditions were observed from the ships, and later identified in the RADARSAT images. The matrix should give a representative indication of the classification ability of the FES at this stage, which proved to be reasonable good in many cases. The reduced resolution of the FES images (500*500m) caused some problems in identification of both new and young ice, and especially open leads, as these features were mainly observed over smaller areas in-between the FY ice floes. Major parts of the new ice observed from the ships were classified as nilas/young, and only 7% were assigned the New ice class. This is mainly due to unclear definitions of the FES classes. Generally, young ice was well recognised, and the misclassification with FY ice is often due to the coarse resolution. Most ice was classified as FY ice with varying degree of deformation, which is reasonable. Within open leads level Nilas/Young ice is often shown, which also is reasonable, although it is not reasonable that deformed Nilas/Young ice is more or less absent in these situations. The most severe misclassification occurred with the Open water class, which very often was assigned to areas covered by level fast FY ice. For the validation of the open water classification, SSM/I ice concentrations from the same day were used. This sensor is well suited to describe the concentration of water in the ice cover, despite its low spatial resolution of 10-15 km. According to the SSM/I observations, the FES class of "Open Water" is found to correspond up to about 20-25% of water in ice, and the term could well be changed to e.g. "Icy Water". With this definition of the “water” class, the classification accuracy of the “Water” classification seems to increase to about 50%.

Continued research on automatic ice classification is necessary before this system can be implemented in practical use. As documented by the sub-satellite observations, the SAR signatures of different ice classes are overlapping in many cases, such as for young ice and deformed first-year ice. Therefore, in addition to brightness and texture measures, it is necessary to use external sea ice information for improving the automatic classification results.
The ICE ROUTES demonstration experiment showed that RADARSAT images can be effectively used for navigation support in the Northern Sea Route, and particularly during difficult ice conditions encountered in April-May 1998 . The images were useful both in planning of fleet operations, strategic ice route selection, and for supporting tactical decision in ice navigation. Due to limitations of the INMARSAT communication system, today only reduced-resolution RADARSAT images (i.e. 250m resolution) can be transmitted in reasonable time onboard the icebreakers. Navigationally important sea ice parameters can be retrieved from the images, such as different ice types, ridged areas, fractures and polynyas. The ice motion and fast ice areas can be determined from analysis of successive images of the same area. The image interpretation is a very complicated procedure and highly qualified ice and SAR specialist onboard the icebreakers are necessary for selecting an optimal ship route using such information.

The study has showed that ice charts from RADARSAT images can be useful both for the Marine Operations Headquarters and onboard icebreakers, but the automatically derived ice charts need to be corrected and improved by an ice expert before they can be used in navigation. Estimates for usage of space-derived high-resolution images (up to 100 m) predict a 150-200% increase of the operating speed during normal ice conditions. The commercial prices of RADARSAT SAR data are currently far too high for implementation of these data in the Russian ice services. Only commercial users such as oil and shipping companies are expected to use SAR data in the NSR in the near future. Unless there is considerable new funding available, it is not realistic that RADARSAT or other high-cost SAR data can be used on regular basis in the Northern Sea Route.

1 OBJECTIVES

The overall objective of the Ice Routes project is to demonstrate the feasibility of using satellite data in ice charting and routing for safer and more efficient ship transport in ice-covered waters. The specific objectives of the SAR ice charting demonstration and validation activities are:

1. To acquire for the first time a large amount of RADARSAT ScanSAR data (more than 30 scenes) for analysis and interpretation of ice conditions in the NSR
2. To demonstrate Artificial Intelligence technologies in generating high-resolution ice classification charts for ship routing using RADARSAT ScanSAR data
3. To evaluate the benefits of using ScanSAR data in support of ice navigation

The objective of the ice charting validation and assessment is to evaluate the quality of the ice classification generated by the Fuzzy Expert System. The main activities have been to

1. generate appropriate training and validation data sets of satellite and ground truth data
2. ensure that the data is prepared in a form suited for testing of the processing algorithms
3. planning and implementation of field expeditions with icebreakers for field experiments
4. validate the results of the processing algorithms, in order to estimate its accuracy.

The validation experiment was carried out in the Northern Sea Route. During the icebreaker expeditions ground-truth data sets were collected and techniques for practical validation of the ice charts and ice route model were tested, and the final results of the Project were assessed. Digital transfer of ice charts and model results to the icebreaker during the field validation was demonstrated. The quality of the ice charts results was evaluated by expert judgement both during the expedition and after the event.

2 BACKGROUND

The NSR is the sailing route along the coast north of Russia between the Barents Sea and the Bering Strait. Ships traversing the NSR along the Siberian coast need good knowledge of ice conditions from day to day as well as on long term basis for safe and efficient navigation. Oil exploration and production facilities in areas such as the Eastern Barents and Kara Sea areas will require both reliable design statistics and timely monitoring and forecasts of sea ice behaviour. Fishing vessels need accurate ice maps updated daily in order to operate in ice edge regions throughout the year. Finally, monitoring of Arctic sea ice over many years is essential to provide an early indicator of global climate change which is predicted to become most severe in polar regions.

The ice conditions in this region restrict sea transportation which requires ice class vessels as well as icebreaker assistance throughout the year. In summer there is traffic in the whole sailing route, whereas in winter it is mainly the western part which is used serving the ports by the Yenisey River. An extensive ice monitoring and forecasting service has been built up in Russia over the last 50 years to serve the sea transportation and icebreaker operations in the NSR. The service is based on data collection from ice stations, coastal stations, vessels, aircraft and satellites. But use of spaceborne SAR has not been a routine part of this service.

The ERS images demonstrated good capability to distinguish between the main ice types in the NSR such as multiyear ice, first year ice, young ice and new-frozen ice, Johannessen et al. 1997. Different classes, forms and features of ice can also be identified such as fast ice, drifting ice, river ice, shear zones, leads, polynyas, ice topography (ridges and hummocks) and ice edge processes. However, in many cases the SAR backscatter data are ambiguous and it is difficult to

classify ice the types correctly without additional data. This is particularly the problem for identification of various stages of young ice and first year ice, for quantification of surface roughness and to distinguish ice and open water during melt conditions. In spite of some limitations, the ERS SAR has proven to be a very useful instrument which can provide quantitative data on most of the important ice parameters except ice thickness. In the Ice Route project RADARSAT ScanSAR images have been obtained for the western part of the NSR, which has provided the first opportunity to study sea ice by SAR over much larger ice areas than with ERS SAR.

The operational users are first of all Murmansk Shipping Company's icebreaker fleet, other shipping companies operating in ice-covered seas and the Russian HydroMet Service. Oil companies and offshore industry currently need consulting services, but will become operational users when they start offshore operations. Consulting services are also required from engineering companies, consulting companies and transport institutions. Scientific users include universities, marine research institutions and other and environmental research institutes.
The two Classifiers available within the project are based on different algorithms:

- Fuzzy Expert System (FES), by EOS under WP330.
- Neural Network -Growing Neural Gas System (NN-GNG), by RUB under WP320.

As a first step, it is necessary to divide the image into a large number of separate homogeneous regions, in the processing routine called Segmentation. The first version of the segmentation routine, available in fall 1997, was found to generate too many segments. A final version giving fewer segments was available in spring 1998. For the work in this report, the coarser segmentation together with the FES classification system has been used.

3 WORK PERFORMED DURING THE PROJECT

The SAR data used in the project needed to be prepared in a form suitable for the classifiers used. Two classifiers were tested in the project:

- Fuzzy Expert System (FES), developed by EOS under WP330
- Neural Network–Growing Neural Gas System (NN-GNG), developed by RUB under WP320

The first step in the data preparation was to divide each ScanSAR scene into four quadrants in order to have reasonably sized files to work with. Then each image quadrant was segmented, in order to define polygons with uniform pixel characteristics. The first version of the segmentation routine, tested in autumn 1997, was found to define to many polygons, up to several thousands pr quadrant. A second version of the segmentation algorithm, available spring 1998 was more appropriate, and used for the preparation of training and test data.

3.1 ACQUISITION OF RADARSAT SCENES FOR TRAINING AND VALIDATION

The first set of RADARSAT data acquired in the project consisted of 22 ScanSAR scenes, covering Svalbard waters, Barents, Pechora, and Kara Seas. The images were acquired between September 1996 and September 1997, by Gatineau in Canada. In addition four scenes were also made available by NERSC, acquired for Vilkitsky Strait and West Laptev Sea, between 14 August and 7 September 1997, processed at TSS. Table 1 gives an overview of this first data set and how it was divided into training and validation data.

No.	Area	Date	Multi-year ice	First-year ice	New/ Young ice	Water	Training# %	Validation %	Supporting data
1	North Kara Sea	29.03.97	Expected, not seen	Dominant	a little	no	100	0	SSM/I for MY
2	South Kara Sea Yamal coast	21.02.97	no	Dominant	a little	no	0	possible	
3	South Kara Sea Yamal coast	24.03.97	no	Dominant	a little	no	0	possible	ERS SAR data
4	Pechora Sea	03.02.97	no	Dominant	a little	yes	0	100	ERS SAR data
5	North Kara Sea Novaya Zemlya	21.02.97	expected, not seen	dominant	a little	no	50	50	
6	Dikson coast	13.12.96	no	dominant	10 %	no	0	100	ERS SAR data
7	North Kara Sea	24.01.97	yes, 10 - 20 %	dominant	5 - 10 %	no	50	50	
8	North Kara Sea	26.10.96	expected	dominant	a little	no	0	possible	ERS SAR data
9	North Kara Sea / Severnaya Zemlya	24.03.97	expected	dominant	a little	no	50	50	
10	Barents Sea	20.04.97	no	dominant	a little	dominant	0	possible	
11	Barents Sea	07.02.97	no	dominant	a little	dominant	0	possible	
12	NE Svalbard	27.01.97	50 %	50 %	a little	a little	50	50	
13	NE Svalbard	16.11.96	30 %	70 %	a little	yes	0	possible	
14	Barents Sea	21.12.96	no	dominant	a little	dominant	0	possible	
15	NE Svalbard	12.03.97	60 - 70 %	30 - 40 %	a little	a little	100		
16	Fram Strait	27.04.97	70 - 80 %	20 - 30 %	a little	yes, strong wind	0	100	ULS data
17	Fram Strait	14.02.97	80 %	20 %	a little	yes	50	50	ULS data
18	NE Svalbard /SUMMER	25.09.96	80 %	10 - 20%	10 - 20 %	yes	0	0	
19	Fram Strait /SUMMER	01.09.97	dominant	a little	a little	dominant	50	50	ULS and ship observations by R/V Lance
20	Pechora Sea	02.05.97	no	dominant	a little	a little	0	possible	
21	North Kara Sea – Franz Josef Land	04.05.97	expected	dominant	a little	a little	0	possible	
22	NE Svalbard	26.10.96	50 %	50 %	a little	a little	0	possible	
A1	Laptev Sea / Vilkitsky Strait	14.08.97	not seen in SAR image	expected	a little	yes	0	100	Ship observations from Yamal, ERS SAR data
A2	Laptev Sea / Vilkitsky Strait	15.08.97	not seen in SAR image	expected	a little	yes	100	0	
A3	Laptev Sea / Vilkitsky Strait	31.08.97	not seen in SAR image	expected	a little	yes	50	50	Ship observations from Yamal 4 - 5 days before
A4	Laptev Sea / Vilkitsky Strait	07.09.97	not seen in SAR image	expected	a little	yes	50	50	Ship observations from icebreakers

the column indicates if the whole image, half of the image or no part of the image is used for training data

Table 1. Overview of the RADARSAT ScanSAR images acquired during the project, divided into training and validation data.

The first 22 scenes were ordered by EOS, and processed at the Gatineau receiving station. The last four scenes were acquired under summer conditions, and ordered by NERSC from the Tromsø Satellite Station, in order to receive the data in near real time.

3.2 TRAINING AND VALIDATION DATA FOR DIFFERENT ICE CLASSES AND SEASONS

Each image in Table 1 was first divided into four quadrants, and then the quadrants were grouped into training data sets and a validation data sets, both representing all the important ice types and ice conditions. The segmentation process attempted to define a large number of sub-areas with uniform properties in the SAR image, but this process is not easy to perform by automatic algorithms. Many segments were not defined in a sensible way, like an ice expert would have done. Nevertheless, the segmentation procedure is a necessarily step in the automatic classification system.

In the preparation of training and validation data about 4 scenes, several thousand segments all together, were classified manually into ice type, deformation level, and feature type. The training data were then used by EOS and RUB to train the FES and GNG classifiers.

In order to have a consistent data set, with representative SAR ice signatures only winter data (December to April) were used, since summer data differ significantly from winter signatures. When the classifiers had been established and tuned according to the signature levels of winter data, a classification of the test data was performed. The results of the automatic classification could then be compared with an independent data set classified by ice experts. The preparation of training and test data sets lasted for several months, and was the most labour intensive activity in the project, except for the field expedition.

3.3 INSTALLING AND USE OF THE ICE CLASS EDITOR

The Ice Class Editor (ICE), which defined segments, estimated several segment attributes, and allowed an sea ice interpreter to classify the segments, was developed as a tool to be used in ice analysis of SAR images. ICE allowed the ice expert to manually assign three attributes for each segment:

1. Ice-age or Water (5 choices): unclassified, water, new ice, first-year ice, and multi-year ice.
2. Ice-deformation (4 choices): Level, slight, moderate, heavy
3. Feature type (7 choices): Unknown, lead, ridge, floe, band, fast ice, other.

Attributes 1 and 2 are closely related, since both are related to the radiometric signature. Attribute 3 is the geometric signature. ICE was used by ice experts at NIERSC and NERSC on 20 training-quadrants and 22 validation-quadrants. Attribute files were generated by ICE for each quadrant.

3.4 COMMENTS TO THE FES CLASSIFICATION TERMINOLOGY USED

The ice attributes defined in the ICE differ from the standard terminology used in ice chart composition. A standard ice terminology is described by the Word Meteorological Organisation (WMO) in the publication "Sea-Ice Nomenclature" (WMO, 1970). About 170 terms for various sea-ice features and their development are described. The terminology forms the basis for all *in situ* observations of sea ice undertaken during the field expeditions of the project. The most frequently used terms relevant for sea ice in the Kara Sea, are shown in Table 2.

Name	Thickness [cm]	Comments
Open water		wind speed determine the backscatter value
New ice	<10	ice crystals only weakly frozen together, dark signature
Nilas	5-10	elastic surface who bends easily under pressure, dark signature, larger areas of broken pieces will give a brighter signature
Pancake ice	up till 10	formed either on a slight swell from new ice, or a breaking up of nilas or grey ice, very bright signature
Young ice (or Grey-Grey/white)	10-30	breaks under swell, either ridge or raft under pressure, medium signature
First year ice	30-200	developed from young ice, medium signature, thickness and deformation will influence on the brightness
Fast ice	various	sea ice that remains fast along a coast or other fixed object, brightness value depending on salinity and pressure.
River ice	various	ice formed in a river, can be a significant part of the ice mass just outside an estuary, the absence of salt gives a bright signature
Floe	various	a relatively flat piece of sea ice, also used for an area of the ice pack which moves as a rigid element

Table 2. The most important sea ice types observed in the Kara Sea region, according to the WMO Sea Ice Terminology

WMO defined ice type	FES defined ice type
New ice	New ice
Nilas Grey ice Grey/white ice	Nilas and young ice, level Nilas and young ice, deformed
First year ice - thin - medium - thick	First year ice - level - slight -medium to heavy
Old ice - second year ice - multi-year ice	Multi-year ice

Table 3. Links between WMO and FES defined ice classes

In Table 3, the correspondence between the WMO terminology and the FES classes is shown, with WMO ice types on the left side, and FES classes on the right. New and young ice are characterized by their specific radar signatures and can in our opinion be identified by WMO classes. In view of SAR backscatter values the FES term Nilas & Young ice is confusing, as these appear quite different in a SAR image. A better combination would be to include Nilas in the New ice class, and have Young ice as a separate class. This makes more sense for the ice navigation as well. A separate class for Pancake ice could also be considered. Alternatively, Pancake ice can be viewed as deformed Young ice. It is impossible to distinguish between thin, medium and thick first-year ice from radar images. Their radar signatures mainly depend on degree of ridging and surface compression. For ice navigation, the deformation terms are misleading, as deformed ice will notify either an area with broken pieces of ice (which can imply easy ice condition) or an area with ridges, hummocks and compressed ice. Correspondingly, the first alternative will be a preferred sailing area, while the latter should be avoided. A division of first-year ice according to the degree of ridging into level, slight and medium (heavy) could be considered as an alternative. Now, the value of the FES classification will depend on how one chooses to interpret the deformation terminology. Also for ice forms the FES classes need to be simpler than the WMO classes, because the SAR sensor is not capable to distinguish all ice forms. The correspondence between WMO and FES ice forms is shown below in Table 4.

WMO defined ice form	FES defined ice form
Pancake ice Brash ice Ice cakes Small floe Medium floe Big floe Vast floe Giant floe	Floe
Fast ice	Fast ice
Iceberg	Other
Ice in stripes	Band Lead Ridge Unknown

Table 4. Comparison of WMO and FES defined ice forms

3.5 PLANNING AND IMPLEMENTATION OF A SUMMER VALIDATION EXPEDITION

The first validation of RADARSAT ScanSAR for summer ice conditions was carried out on an expedition with the nuclear icebreaker Sovetsky Soyuz to the Laptev Sea in September 1997, with support from the IMSI project, (Sandven *et al*. 1998). During this expedition, RADARSAT ScanSAR images were used to investigate first-year and newly formed sea ice (Sandven *et al*, 1998b). Ice observations from the icebreaker and helicopter were used to validate the SAR images, and assess the capability of RADARSAT to discriminate open water and different ice types during summer and early fall conditions. The expedition was carried out in the western part of the Laptev Sea and the Vilkitsky Strait. The strait is usually ice-covered throughout the year and can be one of the most difficult ice navigation areas in the Northern Sea Route with temporary inflow of thick multiyear ice. In the summer and fall of 1997, the ice conditions were easy with much open water, some newly frozen ice and areas with 80-90% first-year ice of 2-3 m thickness. The Vilkitsky strait was also covered by ERS SAR images that could be compared with the RADARSAT images.

The SAR images were processed at Tromsø Satellite Station and analyzed at the Nansen Center within a few hours after the satellite overpass. Averaged ScanSAR scenes with pixel size of 500 by 500 m were transmitted to the icebreaker for use in navigation and validation. The plan was to transmit images in near real time to the icebreaker, but due to delay in the sailing schedule the ship arrived in the area 3 days after the satellite overpass. For the validation work this delay was not critical because the ice and weather conditions were quite stable in this period, with wind speed of typically 4 - 8 m/s and air temperature of about -3°C.

Although the RADARSAT images had no absolute calibration, it was straightforward to distinguish first-year ice from open water, because the open water showed dark signature in contrast to the bright signature from the first-year ice. Comparison with SSM/I ice concentration showed good agreement between ice edge observed from SAR and SSM/I-derived ice edge. For newly formed ice (grease ice and nilas) had dark signature in the SAR images, similar to the signature of open water. At first approximation, it was therefore difficult to distinguish open water from newly formed ice. With more accurate calibration of the SAR images, the possibilities to separate the two classes will be further investigated. Also a comparison between ERS-2 SAR and RADARSAT SAR will be studied in more detail to assess the capability of ice classification.

This summer expedition was a useful pilot demonstration of RADARSAT ScanSAR data for ice monitoring, and the experience from this expedition was very important for the planning and implementation of a more extensive winter expedition in April-May, 1998.

3.6 THE VALIDATION PLAN

Before the winter expedition to the Kara Sea was implemented, a validation plan defining the main work tasks was made. This was necessarily because validation of automatic classification of SAR sea ice images is complicated. The fundament for the validation work in this project, was experience from many previous SAR ice validation studies, as well as field expeditions, especially the expedition with Sovetsky Soyuz in September 1997.

The most important background data are look-up tables indicating statistical relations between different ice types and the configuration of the SAR instrument. Such look-up tables have been developed from many field and laboratory experiments over the last two decades. The lookup tables indicates what sigma-naught values the main ice types have as a function of SAR parameter (frequency, polarisation, incidence angle) and season, (Onstott, 1992).

SAR images need to be calibrated with sufficient accuracy, in order to give σ^0 values (dB) that can be used distinguish between the major ice types.

There were no calibration provided for RADARSAT images used in the ICE ROUTES project. Therefore, the SAR images need to be inter-calibrated so that different ice types and ice conditions will have comparable signatures from one image to another. An absolute calibration providing σ^0 values with ±1 dB accuracy is preferred. But, if this accuracy cannot be obtained it will still be important to have a relative calibration that makes comparison between images possible. *A priori* correction attempting to obtain uniform illumination in the across-track direction has been made at NERSC, and this antenna gain correction applied to all images used during the two field expeditions.

Availability of validation data is always limited, especially from field experiments. In situ observation of ice conditions can only be obtained in a very small part of an image, usually along the track of a ship or helicopter flight line. It is therefore not sufficient to use only in situ data for validation. Ice experts' judgement of the classification results is also an important method of validation. This approach is useful to get an overall assessment of the quality of the classification, especially large scale features, but it cannot replace in situ observations. Although the ice expert has detailed knowledge about ice types, ice deformation, ice thickness and other ice parameters, it will not be possible for him to identify and classify many of the smaller features in the SAR image such as leads, ridges, different stages of new /young ice, etc. Other data for validation can be SSM/I data and ERS SAR data. SSM/I data can provide fairly reliable distinction between open water and ice, and between first-year and multiyear ice excluding the summer season. ERS SAR data can be used to some extent, because these data have been validated in several previous experiments, with an accuracy of 1-2 dB (Sandven *et al*, 1998). Previous studies show that at low incidence angles VV-polarised SAR images (such as ERS SAR) perform better that HH-polarised SAR (such as RADARSAT) in distinguishing grease ice from open water and other ice types. But for other ice classification HH- polarisation is considered to be better than VV-polarisation, especially at high incidence angles.

The main steps in the validation procedure are:

1. Obtain SAR data coincident with ice data from field experiments or other satellite data
2. Perform inter-calibration between the SAR images to enable comparison between images
3. Split available data (both SAR data and validation data) into two sets, one set for training and one for validation. The sets should be selected to include all main ice types and ice conditions, for different seasons. A minimum distinction is between winter and summer data
4. For the validation data, extract sub-image or profiles where in situ data is available. Define a sub-area for each case where a comparison can be done. The in situ data should be taken with smallest possible time difference relative to the SAR image, to avoid that the temperature and ice conditions change too much. All validation data must have position and time. Wind and temperature data should be available for each case.
5. Comparison between SAR image/classified image and *in situ* observations needs to be done. The procedure is repeated for each image where in situ data are available. At the end the overall results of the validation is discussed. It is important that there is representative validation data for as many ice types, ice concentrations, and ice deformations as possible.
6. If in situ data is only available for validation of a limited set of ice parameters, it is useful to complement the validation with other satellite data. For example the SSM/I data can be used to validate ice concentration and ice types (FY versus MY). ERS SAR data can be used to define open water boundaries on a larger scale, and classify new/young ice. Aerial photographs or video recordings can be used to estimate ice concentration, ice types, etc.

7. The results of the validation must be quantitative estimates of the main ice parameters:
   - ice concentration: 0, 10, 20 ...100 % (all ice types)
   - ice types: FY, MY, New/Young ice, open water expresses in concentration
   - ice thickness: resolved with 10 cm accuracy (only nominal thickness for each type can be derived from SAR)
   - ice deformation: height and frequency of ridges
   - Other parameters: width of leads, size of floes, etc.
8. Expert assessment. After comparison with *in situ* and other data, the SAR-derived ice parameters should be assessed by one or more ice experts as the final step in the validation process.

3.7 CALIBRATION OF RADARSAT DATA

Since SAR data delivered by different ground stations, such as Gatineau and TSS, are processed differently, it is not feasible to use these in a common classification system before they have been inter-calibrated.

A difficulty for classification is the inherent variation of backscatter in range-direction, which is different for ice and water. To minimise this effect, Gatineau use a range-varying calibration factor. This may have one of several different forms depending on application. The "Ice-LUT" is the most frequently used for processing of images over sea ice. Pixel scaling at Gatineau is by amplitude (square root of power), while the pixel scaling at TSS is by logarithm of power, with no range-varying LUT applied. An equation for converting TSS-values to Gatineau-values using the ice-LUT was developed and used during the ARCDEV experiment. TSS changed their calibration parameters shortly before cruise start, this complicated the work and made the possible conversion error greater, about 3-4 dB. The difference between Gatineau and TSS images was too large for the classifier, therefore it was decided to use only Gatineau processed data in the FES classification.

3.8 VALIDATION WORKSHOP IN BERGEN 18 - 19 MARCH 1998

The training data and the first output from the Classifiers were discussed at the first validation workshop in Bergen on 18-19 March 1998, were 6-8 project scientists participated. Automatic generated output from EOS and from RUB Classifiers were presented and discussed, and also the performance of the segmentation algorithms was also discussed. The conclusion from the workshop was that main features of the classification results were reasonable, but there were several errors that need to be improved.

3.9 THE WINTER VALIDATION EXPEDITION WITH MSC ICEBREAKER

A major task during the winter and spring of 1998 was planning and implementation of a winter validation expedition with the MSC nuclear icebreaker Sovetsky Soyuz, in co-ordination with the ARCDEV Expedition with Kapitan Dranitsyn (ARCDEV, 1997). During the expedition in April-May 1998, a total of 6 RADARSAT ScanSAR and 11 ERS-2 SAR images were received in near-real time onboard the two icebreakers. This was the first winter validation experiment for RADARSAT SAR data in the Northern Sea Route A few of the RADARSAT ScanSAR images were classified in near-real time during the expedition, and then received onboard as colour coded "class maps". The results of the expedition provided the most important validation data for assessment of the ice classification results.

3.9.1 Objectives of field validation expedition

The objective of this task was to obtain *in situ* ice observations coincident with SAR images, in order to validate the automatic ice classification results. Digital transfer of SAR images and ice chart results to the icebreaker was tested. The quality of the ice chart results was evaluated by expert judgement both during the expedition and after the event. The ice conditions in the Kara Sea were the most severe in 30 years, so the expedition provided a unique possibility to study the use of SAR data for navigation in difficult ice conditions.

3.9.2 Description of the ice situation along the route

The sea ice conditions in the winter of 1998 were considerably more severe than average winter conditions. During the expedition thick first-year ice (ice thickness more than 120 cm) prevailed in the Kara Sea, due to very low temperatures in the preceding weeks and months. The navigation conditions in the traditional near-coastal routes through the Pechora Sea, Kara Gate and south-western Kara Sea were very difficult, as heavily ridged ice was formed in the area near the Kara Gate. In this period eastern and north-eastern winds dominated in the Western Arctic. Shore and flaw polynyas a few tens of km wide were formed to the west of Novaya Zemlya, Vaigach Island, Yamal Coast, near Dixon.

The high sea route was selected, and from the ice edge in the Barents Sea the voyage moved along the Novozemelskayas coastal polynya up to the north of Novaya Zemlya, before heading south-eastwards to Dixon via a polynya west of Arctic Institute island. The traditional near-coastal route along the Yamal Coast, through the south-western Kara Sea, via Yugorsky Strait and into the Pechora Sea was selected for the return voyage.

In the Barents Sea, a mixture of new, young, and thin-first year ice was observed from the ice edge to the coast of Novaya Zemlya. The shore polynya west of Novaya Zemlya was partially unfrozen or covered with new and young ice. In young ice the convoy could proceed almost as in open water, with a speed of 11-12 knots. Thick and medium first-year ice was observed to the north and east of Novaya Zemlya, and the icebreaker moved by using leads and fractures. In the cases of compact ice cover, level first-year ice was chosen for navigation.

The icebreaker escorting of the convoy was usually done by leading and towing of the cargo vessels. In difficult areas where the cargo ships could not move independently, each ship was towed by an icebreaker. In more easy ice conditions the convoy of ships sailed behind the icebreaker. Between the shore polynyas west of Arktichesky Institute and Izvestiy TSIK islands, and the flaw polynya near the mainland, the convoy moved in ice isthmuses consisting of heavily ridged thick and medium first-year ice. In this case, one icebreaker made a channel in the ice and the second towed a ship, resulting in a convoy speed as low as 1.2 knots. Near Dikson, level fast ice approximately 150 cm thick was observed. The sailing route from Dixon to Belyy island was characterised by a mixture of different ice types: new and young ice, interleaved with medium and thick first-year ice. The icebreaker often had to change its heading in order to find more easy ice conditions. Near the Yamal peninsula the icebreaker moved in a wide flaw polynya covered with a mixture of young and first-year ice cakes, allowing a speed of approximately 12 knots. Between Cape of Kharasavey and Vaigach island in the south-western part of the Kara Sea, medium and thick first-year ice was observed. Nevertheless, the navigation conditions were quite easy in this area, due to frequent occurrence of leads and fractures. Some heavily ridged first-year ice east of the Vaigach island and in some parts of the Pechora Sea decreased the ship speed, and the convoy moved using fractures and diverging areas.

3.9.3 WORK PERFORMED DURING THE EXPEDITION

It was decided by MSC that the expedition should take place onboard Sovetsky Soyuz in the Barents, Pechora and Kara seas in April-May 1998. The expedition went from Murmansk to the North of Novaya Zemlya and then to Dikson. On the return voyage, ice observations were carried out in the south-western Kara Sea and the Pechora Sea. In addition, Kapitan Dranitsyn spend several days in the Ob Gulf as part of the ARCDEV expedition. A number of RADARSAT ScanSAR and ERS SAR scenes were ordered synchronously with the planned route. Equipment for digital transmission of SAR images onboard the icebreaker through INMARSAT communication system was installed and tested while the icebreakers were in Murmansk. Special software for digital processing of satellite images (ERmapper) was also installed. Onboard Sovetsky Soyuz, three scientists from NIERSC: V. Yu. Alexandrov, L. V.Zaitsev and A. V. Bogdanov participated, while Ø. Dalen (NERSC) and V. V. Melentyev (NIERSC) stayed onboard Kapitan Dranitsyn. All RADARSAT and ERS SAR scenes were ordered, acquired and processed by NERSC and faxed in near real time to the icebreakers. All these scenes were also received onboard the icebreakers in digital form. The acquisition of SAR data was co-ordinated with the ARCDEV-expedition, which took place about a week after the start of the Sovetsky Soyuz expedition. The RADARSAT scene for April 5 was received in Murmansk before the expedition start, and was used for planning of icebreaker operations. The following RADARSAT ScanSAR scenes were received onboard the icebreakers in near real time:

3.9.4 SATELLITE SAR COVERAGE OF THE SAILING ROUTE

The SAR images were received onboard the icebreaker both by fax, and in digital form using the INMARSAT tele-communication system. The delay between image acquisition and its reception onboard the icebreaker usually did not exceed few hours. At the Nansen Center in Bergen, the SAR images were compressed and presented in JPG-format for digital transmission by INMARSAT. The volume of transmitted data did not exceed 200 Kb, which made it possible to transmit the data in a few minutes. The resolution of the images obtained onboard was 250m for RADARSAT and 100m for ERS. Images obtained in real time were used for solving tactical problems in navigation and selection of the optimum sailing route of the icebreaker. The following RADARSAT ScanSAR scenes were received on board the icebreaker in near real time:

April 23,	NW Novaya Zemlya	April 23,	S Novaya Zemlya, Pechora Sea
April 25,	North Novaya Zemlya	April 25,	Yamal Coast
April 30,	Ob-Yenisey	May 8,	Yamal coast

Table 5 RADARSAT ScanSAR scenes received onboard the icebreakers.

1. 23 April 1998, Northern scene, southern half. The northern half of the scene was only available later from TSS, and thus not included in the classification. The classified part covers a large part of the NW coast of Novaya Zemlya including the icebreaker routes along this coast.
2. The Southern scene from 23 April was ordered for later comparison by Sovetsky Soyuz, and not classified.
3. 25 April 1998, Northern scene. The scene covers the northern part of Novaya Zemlya. A large part of the icebreaker routes is inside this scene.
4. 25 April 1998, Southern scene. The scene covers the South Kara Sea and the Ob Bay area.
5. 30 April 1998. The scene covers the south-eastern part of the Kara Sea, including the Ob and Yenisey Bays.
6. 8 May 1998. The scene covers the area between the west coast of Yamal and the Kara Gate.

The RADARSAT ScanSAR scene of May 8, was only received onboard Kapitan Dranitsyn. Sub satellite observations for all scenes, except April 25 (Yamal Coast) were carried out synchronously with satellite overpass, as long as the icebreakers were inside the areas covered by the satellite.

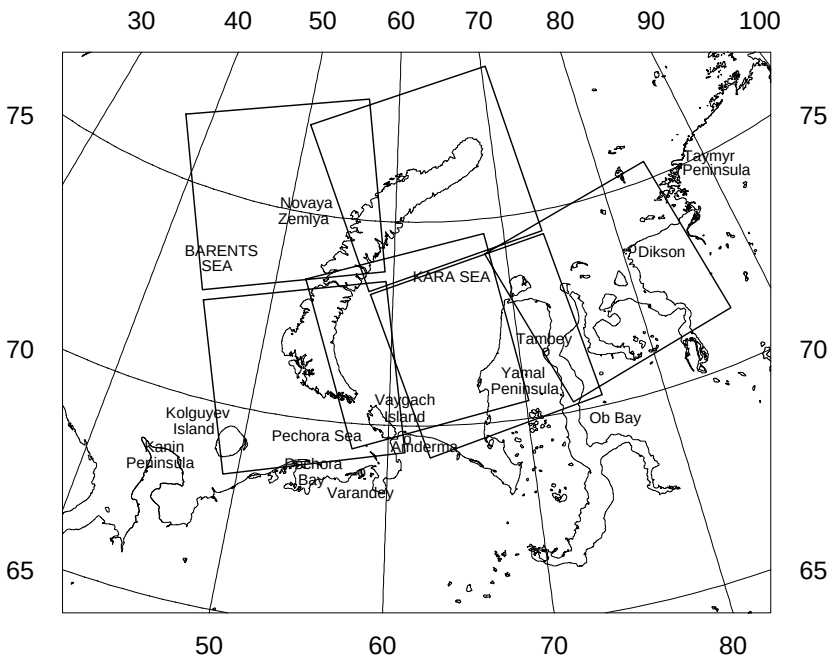


Figure 2 Coverage of the RADARSAT ScanSAR scenes from April 23 to May 8 1998.

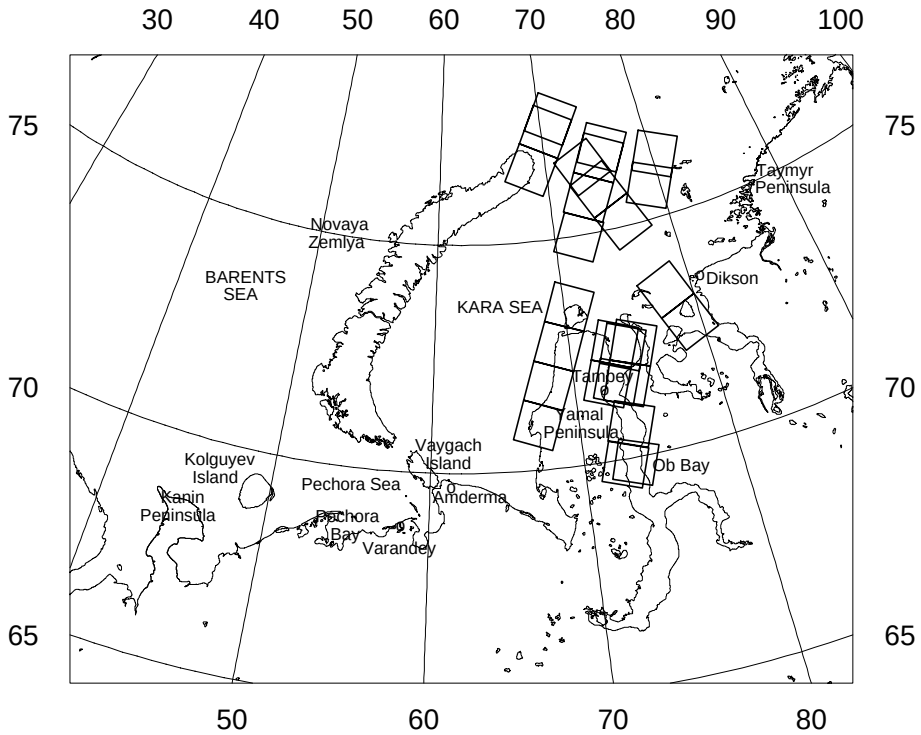


Figure 3 Coverage of the ERS-2 SAR scenes from April 10 to May 6 1998.

Table 6 and Figure 3 displays the ERS-2 SAR scenes ordered and received onboard the icebreaker in near real time. The data was received both by fax and digitally through INMARSAT communication. Synchronous sub satellite sea ice observations were carried out for image 4), 6), 7), 8), 10) and 11).

1) April 10, Yamal	5) April 17, Ob Gulf/Tambey	9) April 30, middle of Ob Bay
2) April 12, Ob	6) April 25, Cape Zhelaniya	10) May 3, Ob-Tambey
3) April 14, Yenisey Bay	7) April 28, 76N/74E	11) May 6, Ob-Tambey
4) April 17, North Kara Sea	8) April 29, 76N/74E	

Table 6. ERS-2 SAR scenes received onboard the icebreaker in near real time

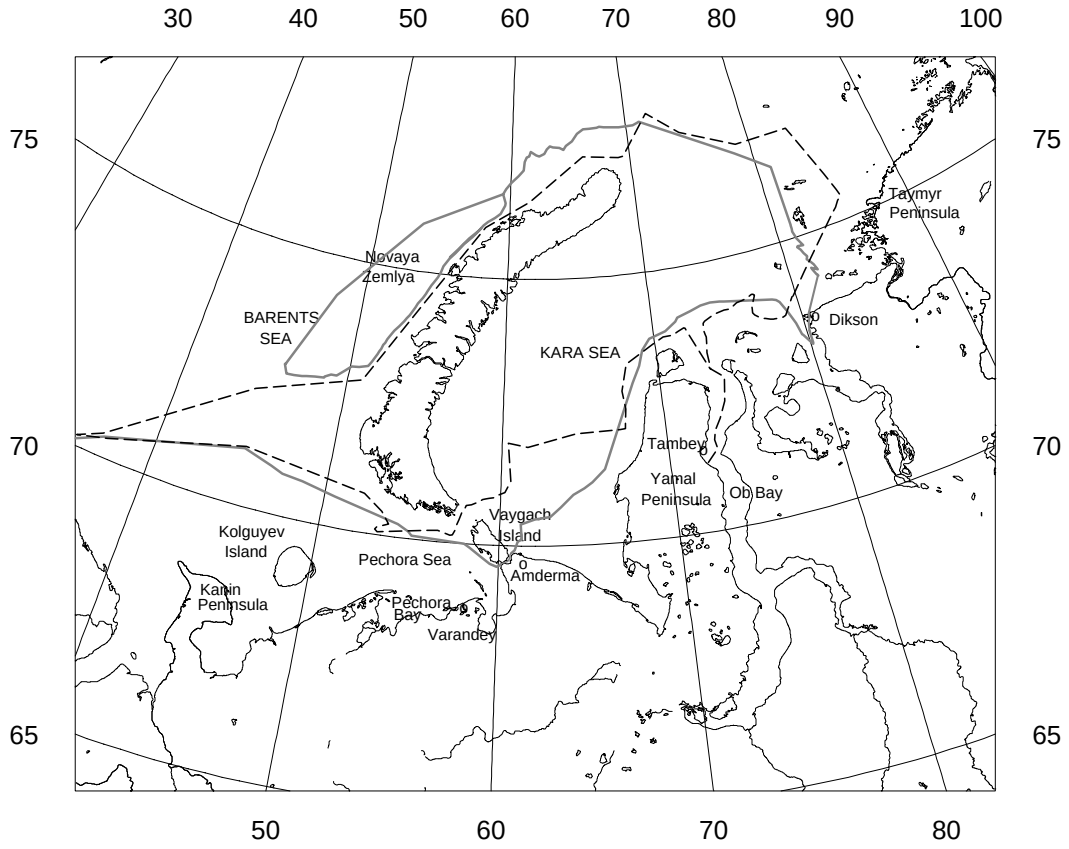


Figure 4. Ship track for Sovetsky Soyuz (grey) and Kapitan Dranitsyn (dashed) during the field survey April-May 1998.

3.9.5 SUB-SATELLITE SEA ICE OBSERVATIONS

Sub-satellite sea ice observations were obtained continuously, when icebreaker Sovetsky Soyuz operated in sea ice. These observations included visual estimate of sea ice parameters from the bridge, photographs and video recordings. When the icebreaker operated in an area covered with SAR images, these observations were carried out 24 hours per day. All significant changes in sea ice conditions have been recorded. On average, sea ice observations were carried out every 15 minutes. Approximately 300 photos and 6 hours of video-recordings were obtained. In areas, which were not covered with satellite images, sea ice observations were carried out every 1 - 2 hours. During the expedition, ice charts automatically composed from RADARSAT images, were received onboard icebreaker Sovetsky Soyuz. Comments and remarks were prepared and sent to the Nansen Center in Bergen. Conducted sea ice observations were used for detailed validation of ice charts. In our opinion, this validation should be done, using the ICE software. Delineated segments will be marked with corresponding sea ice parameters, estimated during the field campaign. Information for validation of Ice Routing was collected during the expedition. This information included icebreaker speed and heading, for different sea ice conditions with correspondingly power levels of icebreaker and different ways of convoy routing in concrete ice conditions.

4 RESULTS OF THE FES CLASSIFICATION

4.1 ICE CLASSES USED BY THE FES

A FES ice classification has been performed for some of the RADARSAT scenes. The ice classification results are discussed in detail for the images of April 30 and May 8, while the image of April 25 is described more briefly, as the area covered in the image is outside the areas explored by the icebreakers. A total of 8 classes were selected for the FES classification, and a colour code was assigned to each class, as can be seen in Figure 5. The selection of the classes was discussed extensively during the project, and especially the deformation levels are debatable. However, a first selection had to be made, bearing in mind that improvements would be needed.

Feature	Deformation	Color
Open Water		
Nilas & Young	Level	
Nilas & Young	Deformed	
New Ice		
First Year	Level	
First Year	Slight	
First Year	Medium & heavy	
Multi Year		

Figure 5. The colour code used for the FES ice classification results.

4.2 NORTHERN PART OF RADARSAT SCANSAR IMAGE OF APRIL 25, 1998

The image displays the ice situation around the northern part of Novaya Zemlya (Figure 6). Major parts of the image is covered by FY ice with various degree of deformation, together with a vast polynya all along the western coast of Novaya Zemlya, covered mainly be new and young ice. At Cape Zhelaya another open polynya is present, consisting of open water and/or very new ice (nilas and grease ice). Several cracks can be seen south-eastwards from Cape Zhelaniya and into the Kara Sea ice massif. First-year ice floes are shown with low signature brightness and their shape can be determined. Cracks and fractures covered either with grey and grey/white ice or nilas can be discriminated from the surrounding first-year ice. Grey and grey/white ice is shown with a significant higher backscatter signature, and nilas with a distinct darker signature, than the average backscatter signature of first-year ice. It can be difficult to separate ridged first-year ice from grey ice, for some occasions.

The characteristic features of the classified image, shown in Figure 7, can be summarised as:

1. The large bright region along the north-west coast of Novaya Zemlya covered by grey and grey-white ice, should have been assigned to the Nilas/Young-level class, but was misclassified as:
   - FY slight ice at approximately 75°-76°N
   - FY medium and heavy ice at approximately 63°30-65°E, and some smaller regions farther south-west
   - open water at approximately 62°15-62°50E
2. The flaw polynya outside Cape Zhelaniya is classified correctly as open water

3. Some leads in FY ice cover, covered by grey and grey-white ice (New Young-level ice class) to the North of Novaya Zemlya (bright elongated features on the image) are misclassified as FY medium and heavy ice. Leads in FY ice covered by nilas (dark elongated features on the image) are classified better.
4. The region covered by FY ice north-east of Cape Zhelaniya is misclassified as open water
5. Some regions of FY medium and heavy ice south-east of Novaya Zemlya (bright areas on the image) are misclassified as FY level ice.

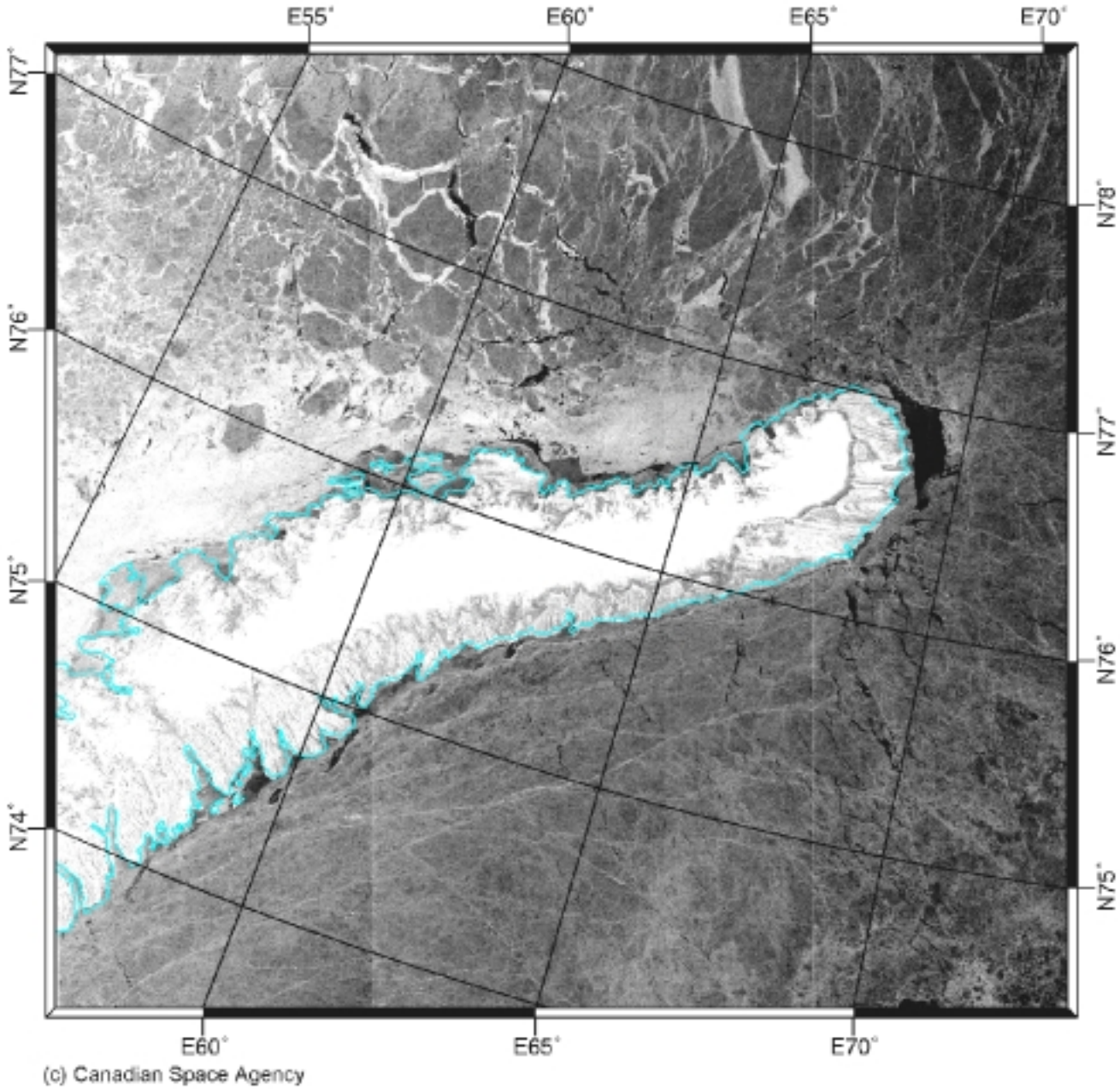


Figure 6. RADARSAT ScanSAR image of April 25, 1998, overlaid grid and coastline. © Canadian Space Agency.

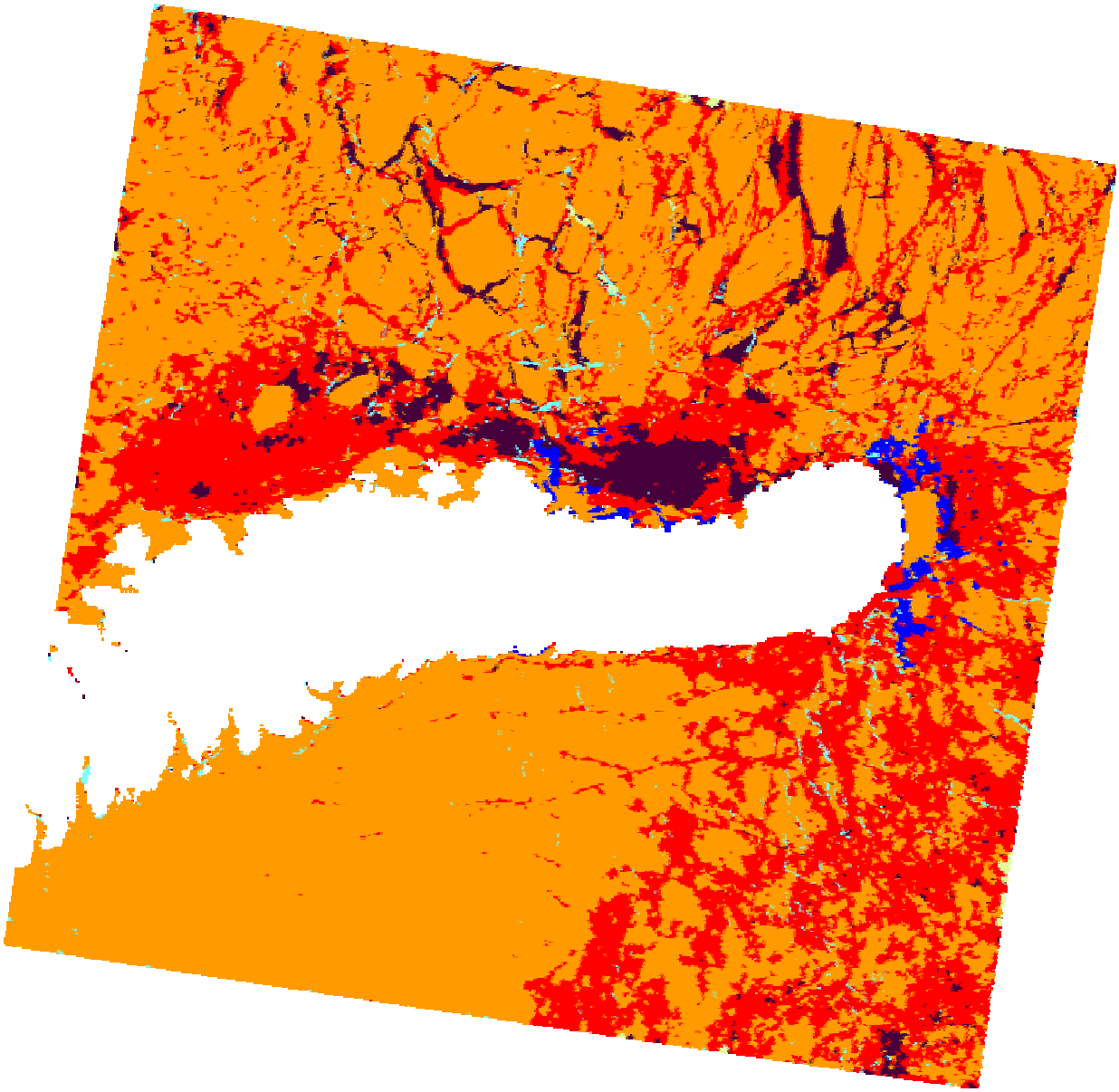


Figure 7 RADARSAT ScanSAR classified image of April 25, 1998.

4.3 RADARSAT SCANSAR IMAGE OF APRIL 30, 1998

The SAR image displays the very complex ice situation outside the Ob and Yenisei estuaries in the southern part of the Kara Sea (Figure 8). In this image, all typical sea ice features are present, except for multiyear ice. The estuaries are covered by fast FY ice with various degree of compression and surface roughness, with flaw polynyas developed at the edge. Flaw polynyas are also found westward of islands between 74-75°N and 78-80°E. The drift ice mainly consisted of medium and thick FY ice with different roughness. Comparison with *in situ* observations confirmed that grey ice have a higher brightness signal than both nilas and first-year ice, and can therefor be quite easily distinguished. Areas covered with heavily ridged first-year ice also have high brightness values, but the texture is different from the textures of grey and grey/white ice. The radar signatures of new ice in the shore polynya near the mainland vary considerably. Level fast ice is characterised by very low signal values, and can in many cases not be separated from calm open waters. Single large and giant first-year ice floes can be recognised in the image. The classification results of this image are also discussed in more detail in Chapter 5.

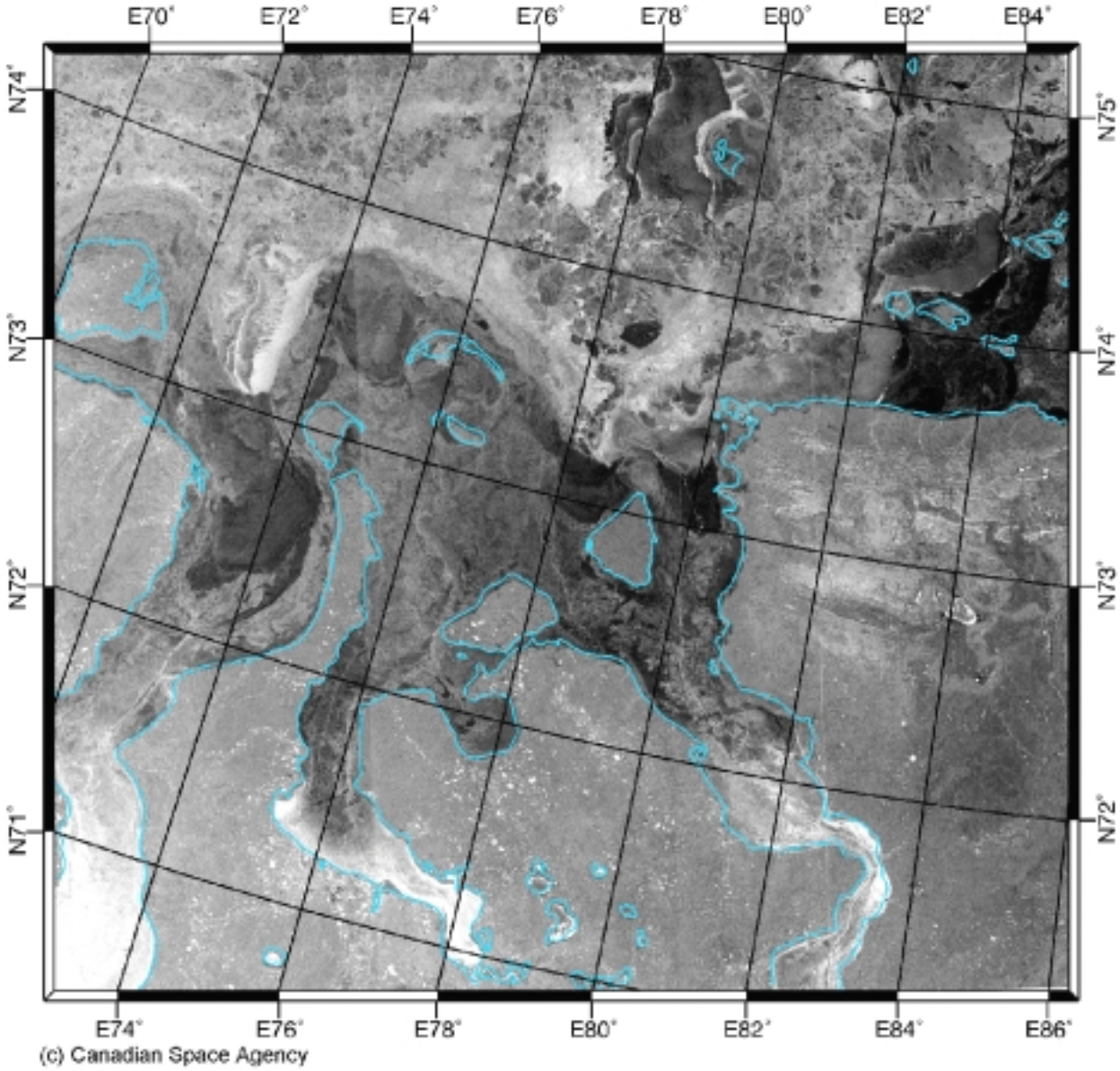


Figure 8. RADARSAT ScanSAR image of April 30 1998, overlaid grid and coastline. © Canadian Space Agency.

The characteristic features of the classified image, shown in Figure 9, can be summarised as:

1. First-year ice areas are mainly classified correctly; there is some difference with in-situ data concerning degree of deformation
2. Regions of fast ice and drifting FY ice in the upper right of the image are misclassified as open water, while the ice tongue coming down from the corner is classified correctly.
3. Some regions of young ice (bright areas in the image) are classified as:
   - FY medium and heavy ice, at 73°50N/79°12E, 74°25N/77°02E, and 74°05N/81°32E
   - FY slight ice, at 73°24N/73°20E and 73°49N/76°14E
4. The regions of fast ice (dark areas on the image) to the North and West of the Shokalskogo Island, to the East of the Sibiriakov Island and to the West of the Belyy Island are misclassified as open water
5. The regions of FY and young ice at approximately 73°59N, 73°43E are misclassified as open water
6. Some of the river ice in Yenisey River, Ob and Gidanskaya Bay are misclassified as FY medium and heavy ice
7. Areas marked with green (deformed nilas and young ice) are mainly classified correctly except area in the Yenisey mouth and small area between Sverdrup Island and Arkticheski Institute Island
8. Fast ice is mainly classified as FY ice. Some fast ice areas near Dikson and near Shokalskogo and Belyy Island are marked as open water.
9. Areas marked with brown, (FY moderate deformed) are partially classified correctly, except some areas near Dikson.
10. In the Kara Sea there is no multiyear ice present at all.

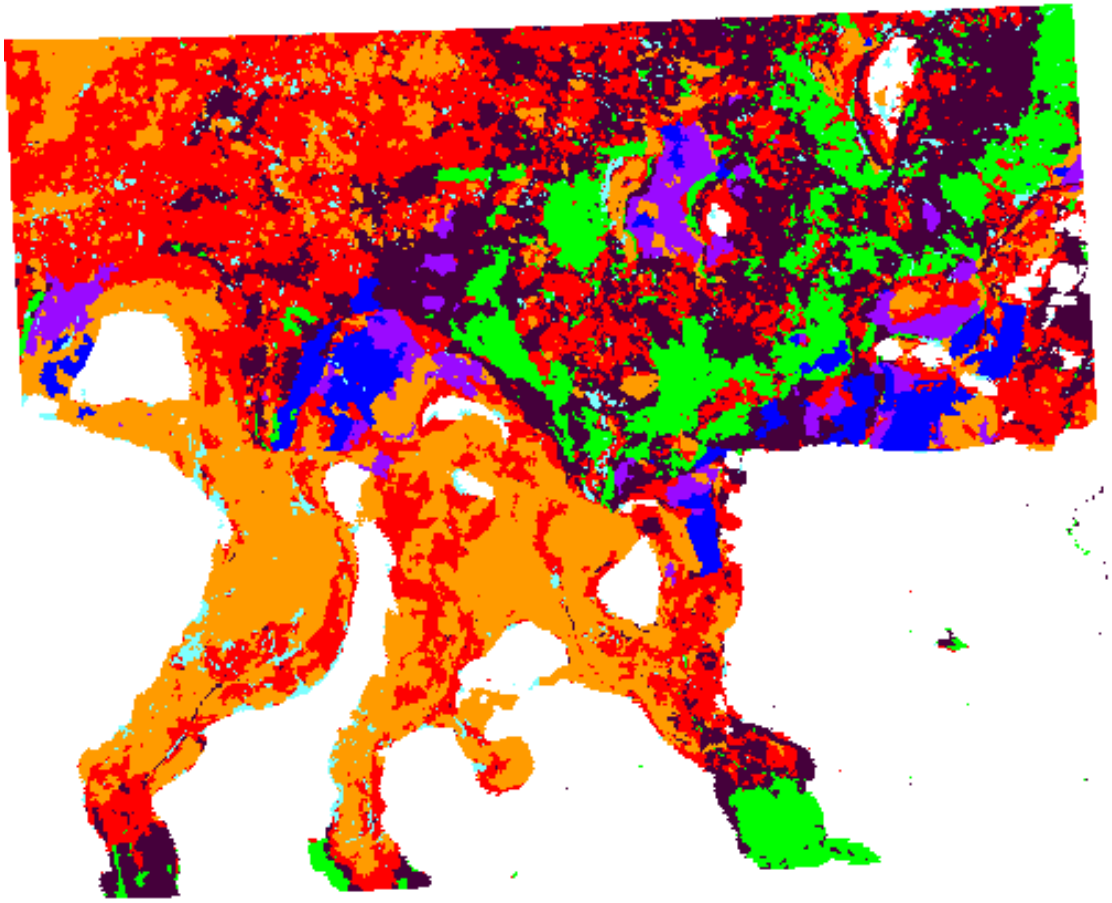


Figure 9 RADARSAT ScanSAR classified image of April 30, 1998.

4.4 RADARSAT SCANSAR IMAGE OF MAY 08, 1998

The SAR image shows the south-western part of the Kara Sea, which is mainly covered by medium and thick first-year ice (Figure 10). A vast open polynya south-west of Vaygach island contained mainly open water and new ice. The image was obtained two days after Sovetsky Soyuz left the area, and primary supported the ARCDEV expedition. The wide shore polynya west of the Yamal peninsula was covered with a mixture of first-year and young ice. Single level first-year ice floes in this area can be discriminated due to their low brightness, as opposed to the higher signal values from young ice. Fractures covered with grey ice care evident in the south-western part of the Kara Sea. Large areas with heavily ridged ice east of the Vaigach island can be separated from the more level first-year ice due to the higher brightness. A large unfrozen shore polynya west Vaigach is shown with a very high brightness signal. The results of the classification of this image is discussed in more detail in Chapter 5.

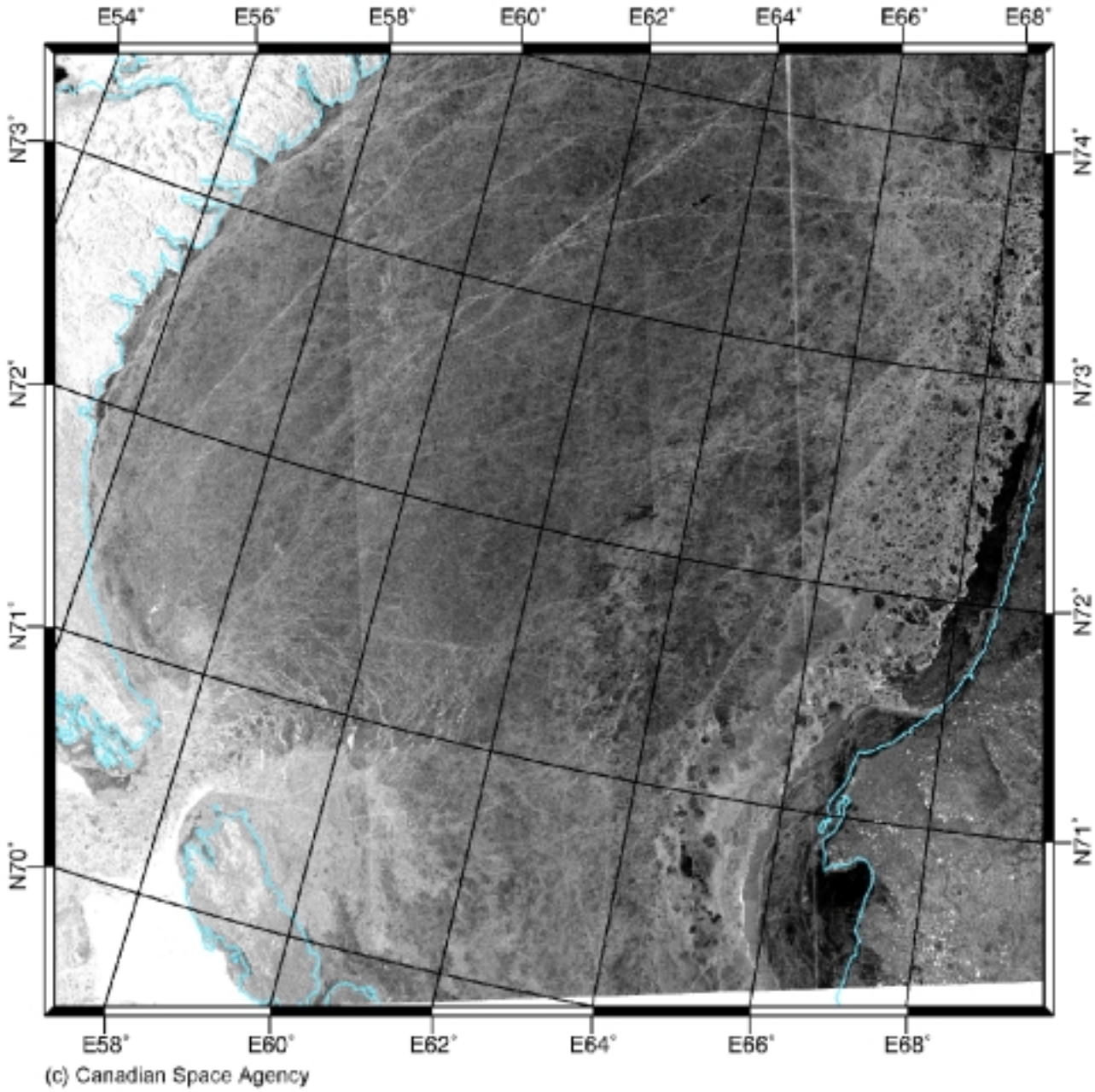


Figure 10. RADARSAT ScanSAR image of May 08, 1998, overlaid grid and coastline. © Canadian Space Agency.

The characteristic features of the classified image, shown in Figure 11, can be summarised as:

1. The polynya near the Yamal Coast, covered with new and young ice, was not completely identified. Some areas of the polynya were classified correctly, but some others were classified as moderately deformed ice. This is the main error of the presented automatic classification results.
2. Some leads and fractures important for navigation were recognised, but some other were not recognised
3. The deformation degree of the first-year ice were mainly estimated correctly, except the area near Novaya Zemlya, where too much level ice was identified

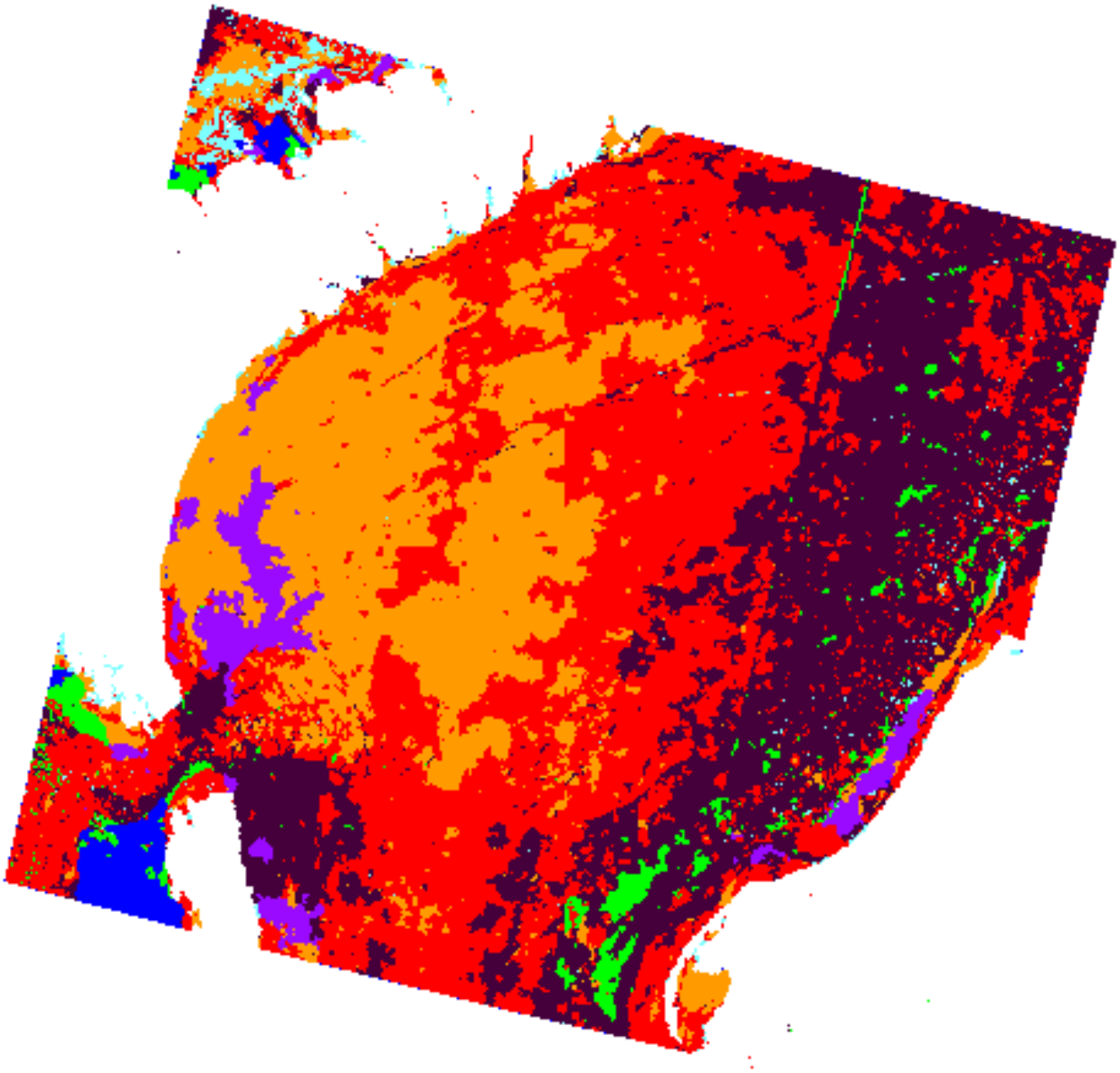


Figure 11 RADARSAT ScanSAR classified image of May 8, 1998.

5 ANALYSIS OF *IN SITU* OBSERVATIONS AND FES CLASSIFICATION RESULTS

Based on *in situ* observations from Sovetsky Soyuz and Kapitan Dranitsyn, a detailed analysis of the FES classification results along the sailing routes has been performed on the RADARSAT ScanSAR images of April 30 and May 08, using data processed Gatineau receiving station. The colour code of the FES classified images follow from Figure 5. The following abbreviation are used in the text and in Table 8, Table 9, Table 10 and Table 11:

Type	Deformation	Abbreviation
Open water		OW
New Ice		New
Nilas&Young,	Level	NYL
Nilas&Young,	Deformed	NIYD
First-Year,	Level	FYL
First-Year,	Slight	FYS
First-Year,	Medium&Heavy	FYH
Multi-Year		MY

Table 7 Abbreviation for the 8 classes used in the FES system and the detailed analysis.

5.1 RADARSAT SCANSAR IMAGE OF 30 APRIL, 1998

In the analysis the image has been separated into two smaller areas, covering the route of Kapitan Dranitsyn and Sovetsky Soyuz along the coast of Taymyr and Yamal peninsula. Sub-image 1 (Figure 12a) displays the ice situation around Dikson and the Yenisei estuary. Kapitan Dranitsyn operated in this area between May 1-3, while Sovetsky Soyuz was inside the sub-image coverage between May 1- 4. Both icebreakers meet both light and very heavy ice navigation situations in this area. All major sea ice features were observed within this sub-image. Observations made from Sovetsky Soyuz are numbered from K to 3, and the observations from Kapitan Dranitsyn are numbered from A to L.

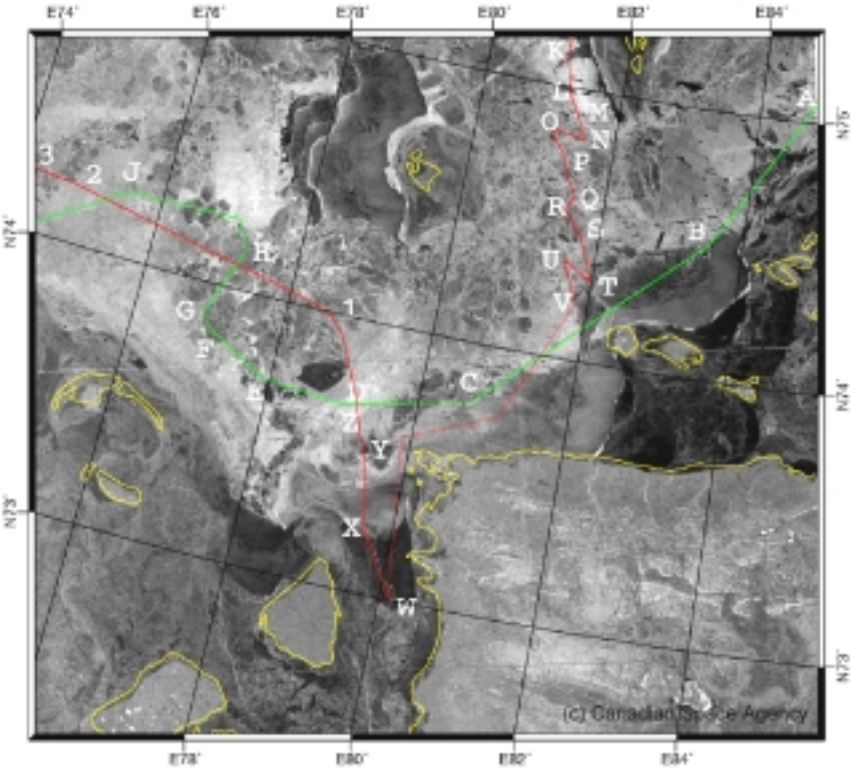


Figure 12a Sub-image 1 of the RADARSAT ScanSAR image of April 30, 1998. © Canadian Space Agency.

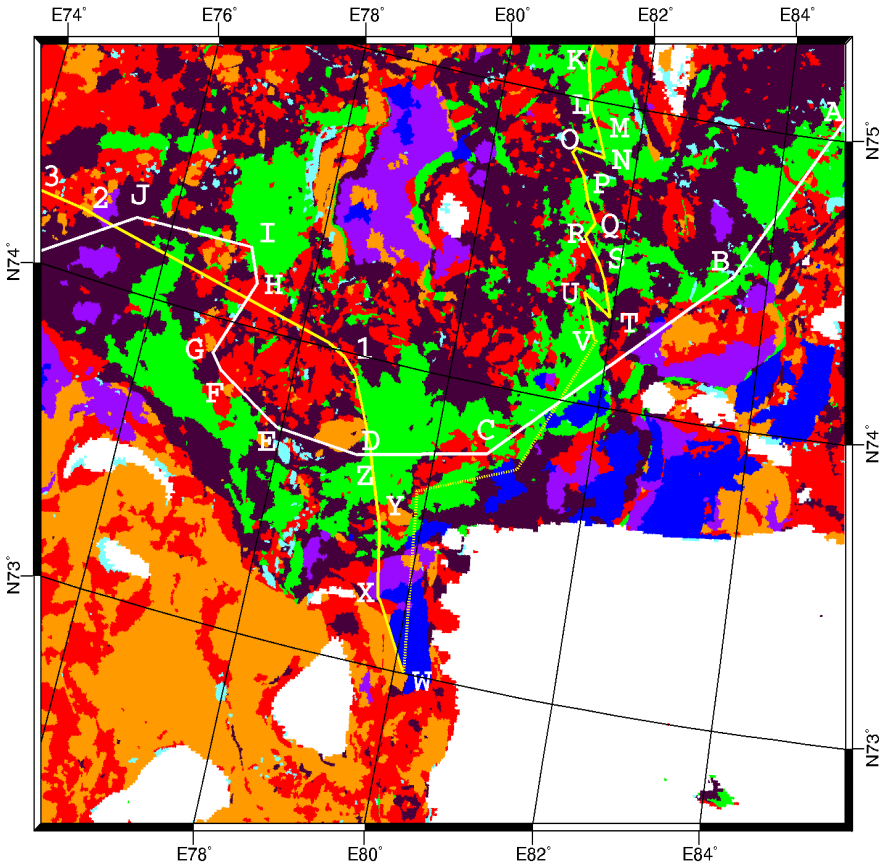


Figure 24b FES classification result of sub-image 1 of the RADARSAT ScanSAR image of April 30, 1998. © Canadian Space Agency.

Table 8. Comparison of FES classification results and in situ data for sub-image 1 of the RADARSAT ScanSAR image of April 30, 1998

Area A: 75°22N/85°25E	**FES**: Ni/YD	**In situ**: C=9-10, G/W (9), Ni (1), hummocks (2)
Comments: Reasonable		
Area B: 74°30N/83°30E	**FES**: Ni/YD, FYH,S, New	**In situ**: C=9-10, G, G/W, Ni(6), FY med (3-4)
Comments: Ni/Y and New ice is reasonable. The FY ice area appears overestimated, and its segment cannot be recognised in the SAR image. Major parts of the Fast ice area at of Pyasinskiy (eastwards from Dikson) have been classified as OW and New ice, which is a crude and serious mistake.		
Area C: 73°47N/80°40E	**FES**: Ni/YD, FYH,S, OW	**In situ**: C=7-8, G, New
Comments: Ni/Y and FY ice is reasonable**.**		
Area D: 73°40N/79°00E	**FES**: Ni/YD	**In situ**: C=8-10, G
Comments: Reasonable		
Area E: 73°42N/77°56E	**FES**: FYH,S, Ni/YL	**In situ**: C=9-10, FY med (5), FY thick (4-5), G, G/W (1-2), heavy ridging
Comments: FY ice with various degree of deformation is reasonable. Ni/Y floes of this size can be correct, but should maybe be deformed.		
Area F: 73°50N/77°03E	**FES**: FYS,H	**In situ**: C=9-10, FY thick (5), FY med (3), G, G/W (1-2), heavy riding
Comments: FY ice is reasonable**.**		

Area G1: 73°53N/76°54E	**FES**: FYH, Ni/YD	**In situ**: C=8-9, G, G/W
Comments: Reasonable result, a FY floe surrounded by Ni/Y.		
Area G2: 73°55N/76°59E	**FES**: FYH	**In situ**: C=8-9, FY thick (8-9), G/W (1), hummocks (2-3)
Comments: A large FY floe the ship moved around, reasonable result.		
Area H: 74°08N/77°16E	**FES**: FYS	**In situ**: C=9-10, FY thick (6), FY med (3), FY thin (1), small parts with river (brown) ice, hummocks (3-4)
Comments: Reasonable with FY.		
Area I: 74°15N/77°07E	**FES**: Ni/YD	**In situ**: C=10, FY thick, med (6), FY thin (4), small parts with river (brown) ice, hummocks (2), close to ice belt
Comments: The ice belt can have moved. The edge between the to ice situations is well detected. Reasonable result.		
Area J: 74°15N/75°30E	**FES**: FYH,S	**In situ**: C=9-10, FY thick (5), G/W (4-5), small parts with river (brown) ice, hummocks (2)
Comments: An area with a mixture of different ice types. Not correct with YH, G/W is the dominating ice feature.		
Area K: 75°10N/81°05E	**FES**: Ni/YL,D, FYL,S	**In situ**: OW, New, Ni, G
Comments: Reasonable result for Ni/Y. Areas consisting of Nilas are wrongly classified as FYL. Fast ice area around AARI island miss-classified as Ni/YL		
Area L: 74°58N/81°15E	**FES**: Ni/YD, FYH,S	**In situ**: G, G/W, strongly rough FY 1 mile to the west
Comments: Reasonable result for Ni/Y. The FY ice areas in west are detected, but the edge is way to far to the west. Areas consisting of Nilas are wrongly classified as FYL.		
Area M: 74°54N/81°24E	**FES**: Ni/YD, FYH	**In situ**: Narrow fracture covered with G, surrounded by strongly rough FY
Comments: FY ice to the west is wrongly classified as Ni/Y. Smaller areas consisting of Nilas are wrongly classified as FYL. The edge of the FY ice is to far to the west.		
Area N: 74°49N/81°32E	**FES**: Ni/YD, FYH	**In situ**: End of ice isthmus, OW fracture
Comments: FES resolution to coarse to capture the ice isthmus, OW not recognised.		
Area O: 74°50N/81°08E	**FES**: FYH	**In situ**: End of fracture, thick FY (7), thin FY (1), Young (1-2), strongly ridged and rough FY
Comments: Reasonable result, but between N and O it is only FYH ice, not Ni/Y. (S.S. was stuck in this area for 3 days.)		
Area P1: 74°45N/81°17E	**FES**: Ni/YD, FYH	**In situ**: Mean, thick FY (7), thin FY (2-3), Young (0-1)
Comments: Ni/YD highly overestimated with respect to the FY ice. Not correct.		
Area P2: 74°40N/81°24E	**FES**: FYH, Ni/YD	**In situ**: Thick FY (8), mean FY (2), mean roughness, icecake
Comments: Reasonable, but Ni/Y to the west is not correct.		
Area Q: 74°36N/81°33E	**FES**: Ni/YD, FYS,H	**In situ**: Fracture with OW and NI
Comments: Reasonable.		
Area R: 74°33N/81°27E	**FES**: FYS,H	**In situ**: FY (6), G (3), fracture
Comments: Reasonable result		
Area S1: 74°28N/81°42E	**FES**: FYS,H	**In situ**: G, ridged FY to the left and right
Comments: Reasonable result, most important floes detected		
Area S2: 74°25N/81°48E	**FES**: Ni/YD, FYS,H	**In situ**: Fracture with OW and Ni
Comments: Reasonable with Ni/Y. Between S and T it should be Ni/Y.		
Area T: 74°18N/81°57E	**FES**: Ni/YD, FYH	**In situ**: Beginning of polynya
Comments: Border of polynya well detected, it is reasonable that it can consist of New ice, but FY ice inside is not reasonable.		
Area U1: 74°22N/81°33E	**FES**: Ni/YD, FYS,H	**In situ**: FY (1), G (6), G/W (2), fractures with OW
Comments: Reasonable result		

Area U2: 74°19N/81°38E	**FES**: Ni/YD, FYS,H	**In situ**: G, G/W (2), OW to the west
Comments: Reasonable result, amount of FY is overestimated in this region.		
Area V: 74°13N/81°47E	**FES**: Ni/YD, FYS	**In situ**: Mix of Ni and Pancake near ice edge, close to polynya with OW
Comments: Partly correct, polynya miss-classified as FY ice, while Ni/Y is reasonable.		
Area W: 73°00/80°07E	**FES**: OW, FYL	**In situ**: Level Fast ice.
Comments: Level Fast ice miss-classified as OW, crude and serious mistake.		
Area X: 73°13N/79°40E	**FES**: OW, New, FYS	**In situ**: Unstable Fast ice, FY ice cake frozen together, close to ice edge zone and OW
Comments: Fast ice miss-classified as OW, crude and serious mistake**.**		
Area Y: 73°28N/79°28E	**FES**: FYL,S,H, Ni/YD	**In situ**: Ni (7), G ice cake (3)
Comments: Reasonable results for Ni/Y, but FY ice is not present. Fast ice in the south is miss-classified as OW, and OW is miss-classified as FYS,L. OW classified as New ice is reasonable.		
Area Z1: 73°38N/79°15E	**FES**: Ni/YD	**In situ**: Rafted Ni (3-4)
Comments: Reasonable results		
Area Z2: 73°43N/79°09E	**FES**: Ni/YD	**In situ**: G (5), Ni (4)
Comments: Reasonable results		
Area 1a: 73°56N/78°47E	**FES**: Ni/YD	**In situ**: Young ice, G/W (4), G (4), Ni (1), few ridges
Comments: Reasonable results		
Area 1b: 74°01N/78°21E	**FES**: FYS,H	**In situ**: FY (1-2), G/W (5), G (3)
Comments: Reasonable, difference is due to ice drift.		
Area 2: 74°12N/75°07E	**FES**: FYL,H, New	**In situ**: Thin FY, G/W, close to polynya with G/W
Comments: Not correct, should mainly be Ni/Y. Crude and serious errors outside Gydanskaya estuary, where major parts of the Fast ice area are classified as OW and New ice.		
Area 3: 74°14N/74°08E	**FES**: FYS, L Ni/YL	**In situ**: Thin FY (6), G/W (3), Ni (1), fractures
Comments: Reasonable results, but information about floes/fractures is lost.		

Sub-image 2 (Figure 13) mainly covers the Ob estuary, which was dominated by fast ice with various degree of deformation. The drifting ice consisted mainly of deformed FY ice with young ice in-between. Sovetsky Soyuz was inside the sub-image coverage on May 3, while Kapitan Dranitsyn operated within the area between the May 3-9, spending most of the time stationed outside Sabeta/Tambey in the Ob Gulf.

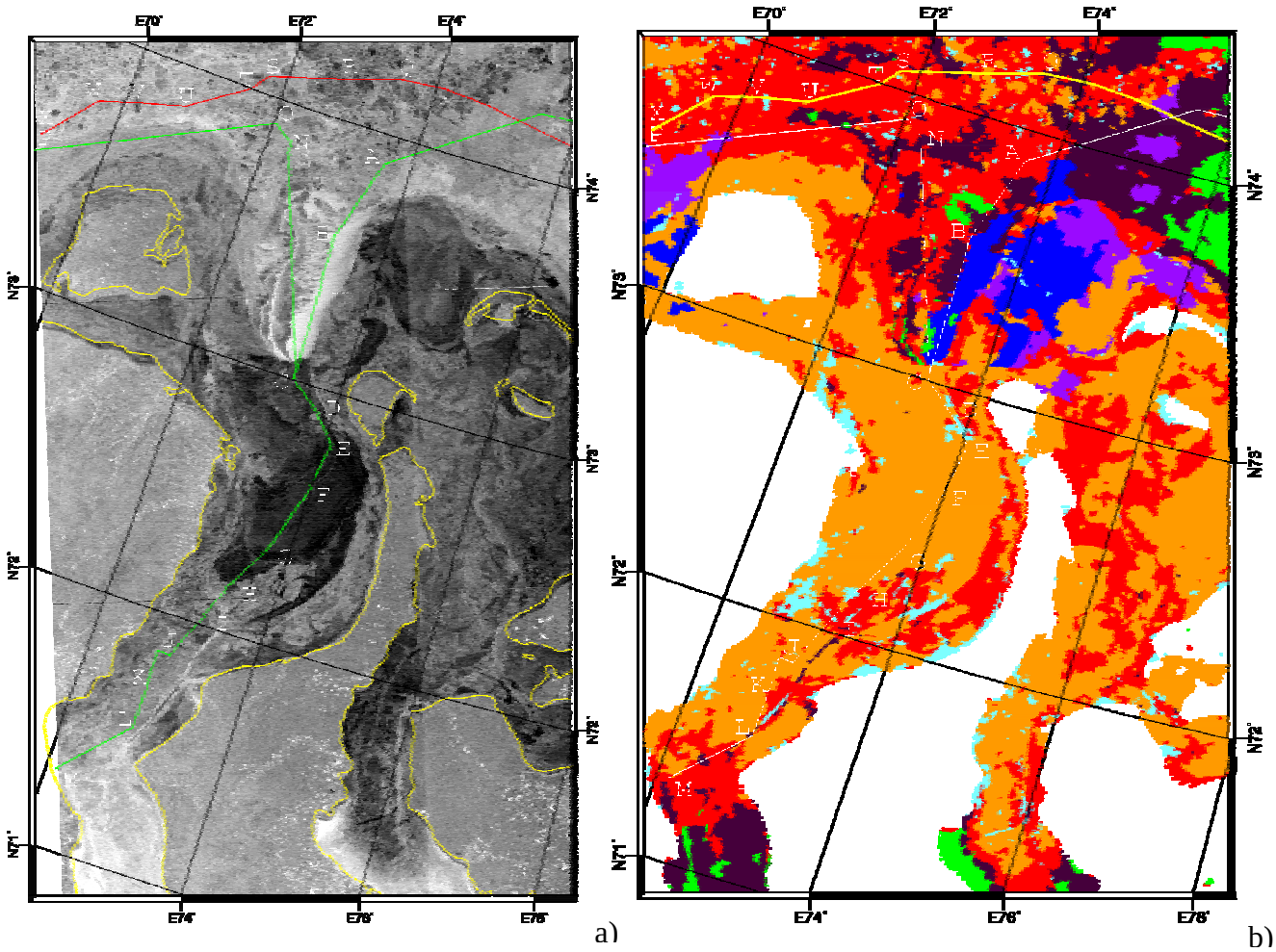


Figure 13. a) SAR and b) FES classification results of sub-image 2 of the RADARSAT ScanSAR image April 30, 1998. © Canadian Space Agency.

Table 9. Comparison of FES classification results and in situ data for sub-image 2 of the RADARSAT ScanSAR image of April 30, 1998

Area A: 73°53N/73°37E	**FES**: FYS	**In situ**: C=5, G, G/W, large areas with OW
Comments: Reasonable, but should be a mixture of FY and Ni/Y.		
Area B: 73°34N/73°20E	**FES**: OW, FYS	**In situ**: C=9-10, FY thick (6), G/W (3-4), hummocks (2-3)
Comments: Mistake, presumably FY and Grey ice.		
Area C: 73°00N/73°22E	**FES**: FYL	**In situ**: C=10, Fast FY ice (50 cm), River ice, large floes, smooth surface, dusty surface, hummocks (2), snow (2)
Comments: In absence of a Fast ice category, this is to some extent correct. Information about lighter (dark in SAR) as opposed to more difficult ice navigation areas (brighter in SAR) is lost, which makes the classification not useful for the fast ice areas in the Ob estuary.		
Area D: 72°53N/73°52E	**FES**: FYL, Ni/YL	**In situ**: C=10, Fast FY ice, med. thickness
Comments: Same problem as above. Identification of Ni/YL areas is a crude and serious mistake.		
Area E: 72°48N/74°05E	**FES**: FYL	**In situ**: C=10, Fast FY ice
Comments: Same situation and problem as in C.		

Area F: 72°38N/74°00E	**FES**: FYL	**In situ**: C=10, Fast ice, thickness = 1.20m, brackish water, river ice, brown water
Comments: Same situation and problem as in C.		
Area G: 72°27N/73°51E	**FES**: FYL	**In situ**: C=10, Fast FY ice,
Comments: Same situation and problem as in C.		
Area H: 72°11N/73°24E	**FES**: FYS, Ni/YL	**In situ**: C=10, Thick Fast FY ice (1.5m), smooth surface, hummocks
Comments: Beginning of area with more hummocked surface, so FYS is to some extent correct. Identification of Ni/YL areas is a crude and serious mistake.		
Area I: 72°04N/73°15E	**FES**: FYS, Ni/YL	**In situ**: Fast FY ice, smooth surface, hummocks
Comments: Same situation and crude mistake as under H. The very bright line in the SAR image is identified as FYH, which is reasonable (though it is Fast ice)		
Area J: 71°51N/72°52E	**FES**: FYL	**In situ**: C=10, thick Fast ice, hummocks (2-3), snow (2)
Comments: Not correct, and not in agreement with the classification results in H and I.		
Area K: 71°43N/72°51E	**FES**: FYL,S	**In situ**: C=10, Fast FY, mix of smooth and rough surface, hummocks 0.5-1m in height, brackish/ nearly fresh water
Comments: Same situation and problem as in J.		
Area L: 71°33N/72°50E	**FES**: FYL	**In situ**: C=10, smooth Fast FY ice, hummocks/sastrugi
Comments: Same situation and problem as in J.		
Area M: 71°18N/72°09E (Sabeta/Tambey)	**FES**: FYS	**In situ**: C=10, Fast FY ice, thickness >2m, hummocks (2-3) 0.5-1.5 m in height, artificial harbour/loading-station
Comments: Correct to some extent.		
Area N: 73°51N/72°16E	**FES**: FYS,H	**In situ**: C=7-8, Ni, G, G/W, floesize 100-200m
Comments: Reasonable.		
Area O: 73°54N/72°03E	**FES**: FYS	**In situ**: C=8-9, FY, edge between young and FY ice, thickness 1m
Comments: Reasonable.		
Area P: 73°30N/69°07E	**FES**: FYS, New	**In situ**: Thick mean FY (5), Young (4), mean roughness
Comments: FY ice area is reasonable, but New ice is doubtful especially of this large amount. The New ice segment cannot be found in the SAR image.		
Area Q: 74°13N/73°29E	**FES**: FYL,S,H	**In situ**: Thick, mean FY (8-9), Ni (1), strongly rough
Comments: Reasonable, but Ni/Y ice is under-estimated.		
Area R: 74°09N/72°44E	**FES**: FYL,S	**In situ**: FY ice (8), fractures with NI (2)
Comments: Reasonable, but Ni/Y ice is under-estimated.		
Area S: 74°04N/71°45E	**FES**: FYL,S	**In situ**: FY ice isthmus (2-3 miles), then FY(7), New, Young (3)
Comments: Reasonable, but Ni/Y ice is under-estimated.		
Area T: 74°00N/71°34E	**FES**: FYS	**In situ**: Thick, mean FY (6-7), Young (2-3), strongly rough
Comments: Reasonable, but Ni/Y ice is under-estimated.		
Area U: 73°51N/70°48E	**FES**: FYS	**In situ**: Thick, mean FY (7), New, Young (2-3)
Comments: Reasonable, but Ni/Y ice is under-estimated.		
Area V: 73°48N/70°11E	**FES**: Ni/YL, FYS	**In situ**: Thick, mean FY (7), thin FY (3), strongly ridged
Comments: Reasonable, but Ni/Y ice is under-estimated.		
Area W: 73°45N/69°40E	**FES**: FYL,S	**In situ**: Thick, mean FY (6), thin FY (2), G/W (2), strongly ridged
Comments: Reasonable, but Ni/Y ice is under-estimated.		
Area X: 73°33N/69°07E	**FES**: FYS, New	**In situ**: Thick, mean FY (5), Young (4), mean roughness
Comments: Reasonable with FY, amount of New is highly overestimated.		

5.2 RADARSAT SCANSAR IMAGE OF 8 MAY, 1998

The SAR image covers the route of Kapitan Dranitsyn and Sovetsky Soyuz from Cape Skuratova (northern point on Yamal Peninsula) through the Kara Sea, and into the Pechora Sea. Kapitan Dranitsyn operated within the image coverage from May 9-11, and Sovetsky Soyuz from the May 4-6. The ships chose different routes to reach the Pechora Sea, making it possible to validate major parts of the FES classification.

Sub-image 1 (Figure 14) covers the part of Kara Sea from which Kapitan Dranitsyn passed Cape Skuratova and reached the inner of the Kara Sea ice massif at 72°N. The observations from Kapitan Dranitsyn are from May 9-10. Sovetsky Soyuz chose another approach to cross this part of the Kara Sea, and moved farther south along the western shores of Yamal Peninsula between May 4-5, utilising the opening of the vast recurring Yamalskaya Polynya.

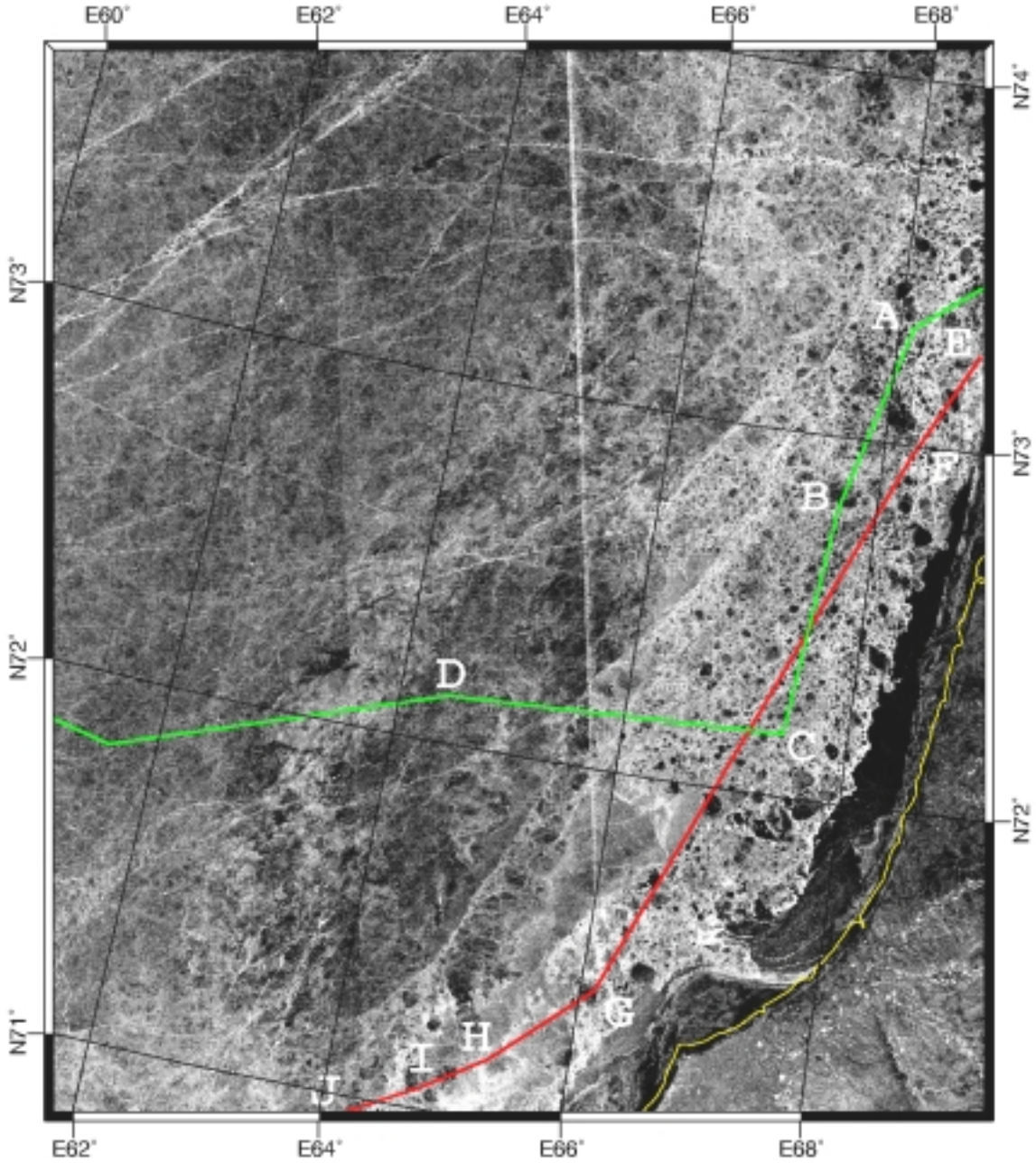


Figure 14a. Sub-image 1 of RADARSAT ScanSAR image of May 8, 1998. © Canadian Space Agency.

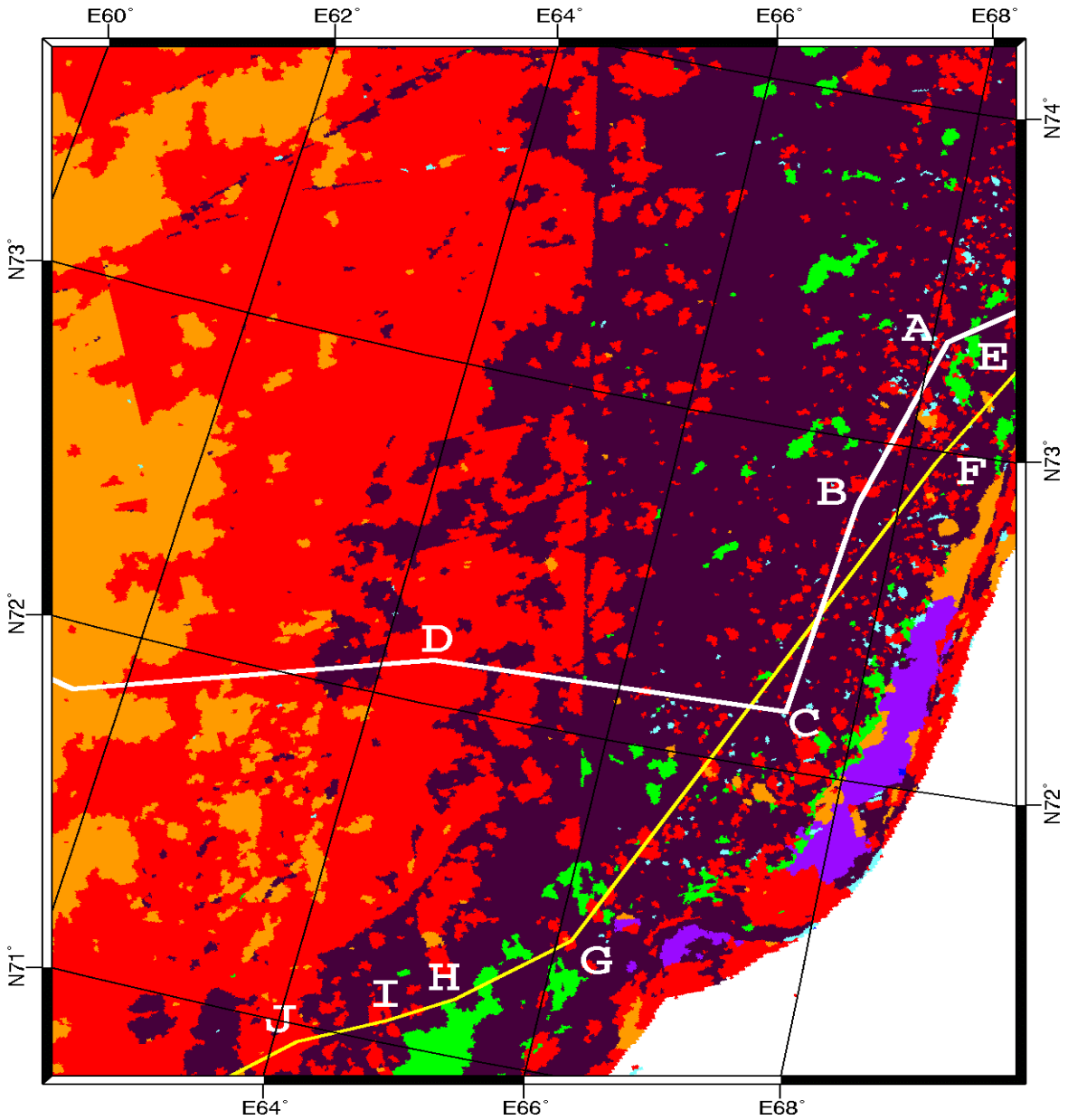


Figure 26b. FES classification result of sub-image 1 of RADARSAT ScanSAR image of May 8, 1998.

Table 10. Comparison of FES classification results and in situ data for sub-image 1 of the RADARSAT ScanSAR image of May 08, 1998

Area A: 73°19N/68°06E	**FES**: FYS,H, Ni/YL,D	**In situ**: Thin FY, Ni, G, G/W (K.D)
Comments: This was an area with small floes and leads, and great variations in the ice types, in which the could move fast. Considering FYH to indicate smaller, broken pieces of FY ice the FES result is reasonable, but information about the edge of the thicker ice massif to the west is lost (ca. 67°30E). A significant amount of the larger floes are detected, though some of the Ni/YL segments cannot be recognised in the SAR image.		
Area B: 72°48N/67°37E	**FES**: FYS,H	**In situ**: thick FY (8), Grey (1-2) (K.D)
Comments: Presumably, the - observation was made within the large floe classified as FYS, the surrounding ice is of the same character as in Area A. Again, the edge of the ice massif is gone, and some of the Ni/YL segments cannot be recognised.		
Area C: 72°10N/67°22E	**FES**: FYH, Ni/YL	**In situ**: Thick FY, ridged (K.D)
Comments: The observation is within a large floe, and the surrounding ice is a mixture of thick FY and Young ice. Reasonable result, considering the above constraint for FYH.		

Area D: 72°07N/64°21E	**FES**: FYS	**In situ**: Thick FY (9-10), Ni (0-1), heavy ridging (1-2m) (K.D)
Comments: This was a very difficult area, where the had trouble getting through. The observation is within a very large segment (close 100km) which can be viewed as one giant floe, appearing with a quite dark signature in the SAR image. Only part of this floe is recognised by the FES, and especially the western edge is lost. The correctness of this area depends on how one interprets the FYS class. Areas of more broken FY ice within this floe is reasonable		
Area E: 73°16N/68°48E	**FES**: FYH,S, Ni/YD	**In situ**: OW, Ni (S.S)
Comments: An area with large variations of ice features, in which the could move fast. Amount of FY ice is high overestimated.		
Area F: 72°58N/68°15E	**FES**: FYH	**In situ**: ice cake, thick mean FY (6), new/young (3) (S.S)
Comments: Reasonable, though extent of FY ice is overestimated		
Area G: 71°24N/66°07E	**FES**: FYH,S	**In situ**: G/W, few ridges (S.S)
Comments: Not correct		
Area H: 71°10N/65°19E	**FES**: FYH, Ni/YD	**In situ**: polynya (1km), mean, rough FY surrounding (S.S)
Comments: Probably correct, given that the polynya is now closing in (2 days separation). Ni/YL is maybe more correct.		
Area I: 71°04N/64°50E	**FES**: FYH,S	**In situ**: thick, mean FY (7), young (2) (S.S)
Comments: Reasonable		
Area J: 70°57N/64°11E	**FES**: FYS	**In situ**: thick, mean FY, mean roughness, fractures (S.S)
Comments: Reasonable.		

Sub-image 2 (Figure 15) displays the ice situation at the inner of the Kara Sea ice massif, around island Vaygach and the Kara Gate, and a small part of the Pechora Sea. The observations onboard Kapitan Dranitsyn were done between the May 10-11, including a six-hour stop from which field measurements on the ice were carried out. While Kapitan Dranitsyn went through the Kara Gate, Sovetsky Soyuz moved through the Yugor Strait south of island Vaygach. Sovetsky Soyuz operated in this region between May 5-6.

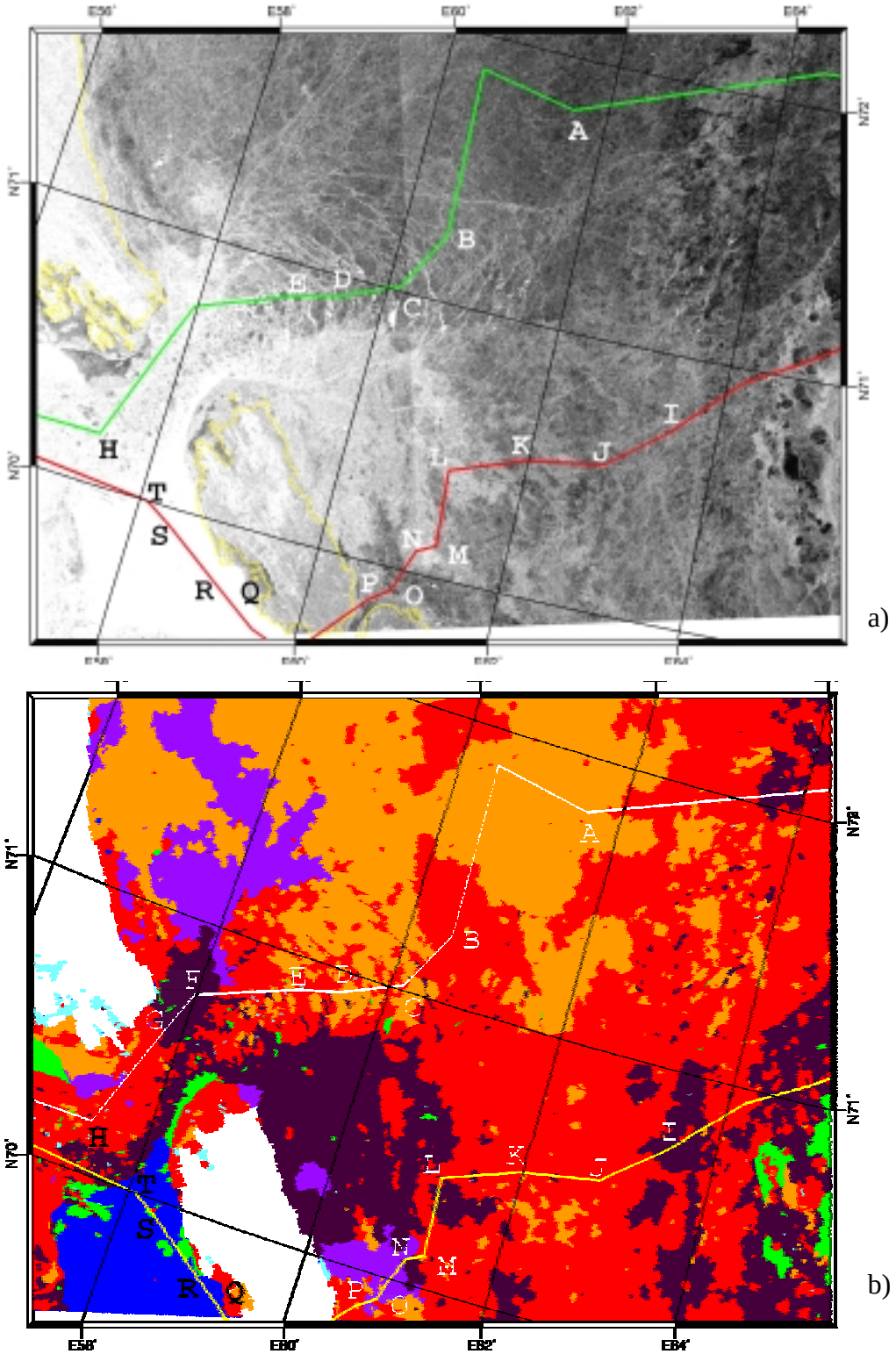


Figure 15. a) SAR and b) FES classification result of sub-image 2 of RADARSAT ScanSAR image of May 08, 1998. © Canadian Space Agency.

Table 11. Comparison of FES classification results and in situ data for sub-image 2 of the RADARSAT ScanSAR image of May 08, 1998

Area A: 71°48N/61°35E	**FES:** FYL	**In situ**: Thick FY (1.5m), h. ridges 0.5m, 100m int. (K.D)
Comments: 6-hours stop for K.D. Level to slightly ridged surface, reasonable result, though slightly deformed might be more correct.		
Area B: 71°14N/60°30E	**FES**: FYS	**In situ**: Thick FY (9-10), Ni/OW (0-1), h. ridges 0.5-1m, small floes (K.D)
Comments: Reasonable result. The border of the segment is not very distinct in the SAR image, and the very bright lines appearing in the SAR image is not recognised.		
Area C: 71°01N/60°09E	**FES**: FYL,S	**In situ**: Thick FY, ridges, small floes (K.D)
Comments: Here begins the area of very thick and ridged FY ice, which lasted through the whole Kara Gate. Both ridge height and amount increases towards the Kara Gate. FYL is not reasonable, as more depressed ice were observed. Several segments appearing in the FES image cannot be recognised in the SAR image.		
Area D: 70°55N/59°29E	**FES**: FYL,S	**In situ**: Thick FY (9-10), h. ridges 0.5-1m, int. 100m (K.D)
Comments: Same situation as above, level FY ice is not likely to appear here. The segmentation causes some artifacts.		
Area E: 70°53N/59°03E	**FES**: FYL,S	**In situ**: Thick FY (9), h. ridges 1-2m, floes >100m (K.D)
Comments: Similar situation as above. Medium to heavy deformation is more correct. The segmentation causes some artifacts.		
Area F: 70°44N/57°58E	**FES**: FYH	**In situ**: Thick FY (>2m), very ridged, distr. in all directions, h. 2-3m (K.D)
Comments: Reasonable with FYH, though the areas between E and F classified as slightly deformed should be medium to heavy. For Ni/Y to appear at this amount here, is not reasonable. For New ice to appear north-west of F (the inner of the Kara Sea ice massif) is not likely, and this miss-classification is very crude as this areas most likely consist of some kind of deformed FY ice. The absence of a FES class for fast ice causes crude artifacts all along the shores of Novaya Zemlya and island Vaygach.		
Area G: 70°36N/57°49E	**FES**: FYH	**In situ**: Thick FY (9), very ridged, distr. in all directions, h. 1-3m, small leads (K.D)
Comments: Reasonable with FYH here, though the area between G and H should also be FYH. In general, the amount of FYH through the whole Kara Gate is way to small. The segmentation causes artficats and edges not seen in the SAR image.		
Area H: 70°11N/57°22E	**FES**: FYS	**In situ**: G, G/W, OW (K.D)
Comments: This can be correct, depending on the weather situation and ice drift in-between SAR and *in situ* observations. This was a fairly easy ice navigation area. Area just south of Novaya Zemlya classified as Ni/YD is more likely to consist of OW, maybe pancake ice. Area classified as New ice is wrong, should be FYH. Area classified as FYS is more likely to be Ni/Y. Ni/YL along the shores is a crude mistake, should be fast ice.		
Area I: 70°43N/63°28E	**FES**: FYH	**In situ**: thick, mean FY, mean roughness (S.S)
Comments: Reasonable with FY ice, but the deformation should be slight.		
Area J: 70°33N/62°50E	**FES**: FYS	**In situ**: thick, mean FY, mean roughness, fractures (S.S)
Comments: Reasonable, though there is no major difference in SAR brightness		
Area K: 70°30N/61°58E	**FES**: FYS	**In situ**: Rather level FY (S.S)
Comments: Reasonable		
Area L: 70°24N/61°10E	**FES**: FYS,H	**In situ**: slightly rough FY, fractures (S.S)
Comments: Reasonable, but it should have been more FYH ice in the surroundings.		
Area M: 70°07N/61°14E	**FES**: FYS	**In situ**: thick FY, strongly rough (S.S)
Comments: Not in agreement with above classification, as deformation should have been heavy. The boundary between level and ridged/deformed FY is not well determined.		
Area N: 70°05N/61°02E	**FES**: New	**In situ**: fracture (S.S)
Comments: Consists mainly of FYH ice, the amount of New ice is highly overestimated.		
Area O: 69°55N/60°52E	**FES**: New, FYL	**In situ**: thick, mean FY, ridged (S.S)
Comments: Not reasonable, and not in agreement with surrounding areas		

Area P: 69°52N/60°40E	**FES**: FYS	**In situ**: fast ice boundary (S.S)
Comments: Fast ice is not covered in FES, the edge is not detected		
Area Q: 69°39N/59°32E	**FES**: OW	**In situ**: OW (S.S)
Comments: Reasonable		
Area R: 69°47N/59°00E	**FES**: OW, Ni/YD	**In situ**: G/W (S.S)
Comments: Difficult to judge due to ice drift, but result seems reasonable.		
Area S: 69°56N/58°24E	**FES**: OW, Ni/YD	**In situ**: compressed pancake (S.S)
Comments: Reasonable with OW.		
Area T: 70°00N/58°05E	**FES**: OW	**In situ**: FY (7), Ni (2), very rough (S.S)
Comments: The edge of the polynya can have moved westwards due to wind from the east. It is reasonable with FY ice at the edge. The actual edge is well detected. Fast ice area north-west of Vaygach is wrongly detected as FYS, New ice, and Ni/YL.		

5.3 CONFUSION MATRIX OF FES CLASSIFICATION AND *IN SITU* OBSERVATIONS

Based on the analysis presented in the previous chapter, a confusion matrix of the FES classification results for the images of April 30 and May 8 has been made. Although the field observations only cover a small part of the images, all major sea ice features have been observed in field, and identified in the RADARSAT images. The matrix should give a representative indication of the classification ability of the FES at this stage.

Observed *in situ* / **FES classification**	**Open Water**	**New (grease, nilas)**	**Young (grey, grey/white)**	**First year**	**Fast ice**	**Total no. of cases**	**Percent correct**
Open Water	5	0	1	0	6	12	40%
New ice	2	2	0	7	2	13	15%
Nilas/young	0	14	18	6	6	44	41%
First Year ice	5	13	10	48	11	87	55%
Fast ice	-	-	-	-	-	-	-
Total occasions	12	29	29	61	25	156	
Percent correct	40%	7%	62%	77%	-	-	

Table 12. Confusion matrix for the FES classification results

The main results of this confusion matrix are:

Open water: 50% of the areas classified as open water was observed/analysed to consist of level fast first year ice, which is the most serious mistake of the FES classification. It is good that 40% of the observed water areas were recognised by the FES, the mixture with new ice is a less severe mistake.

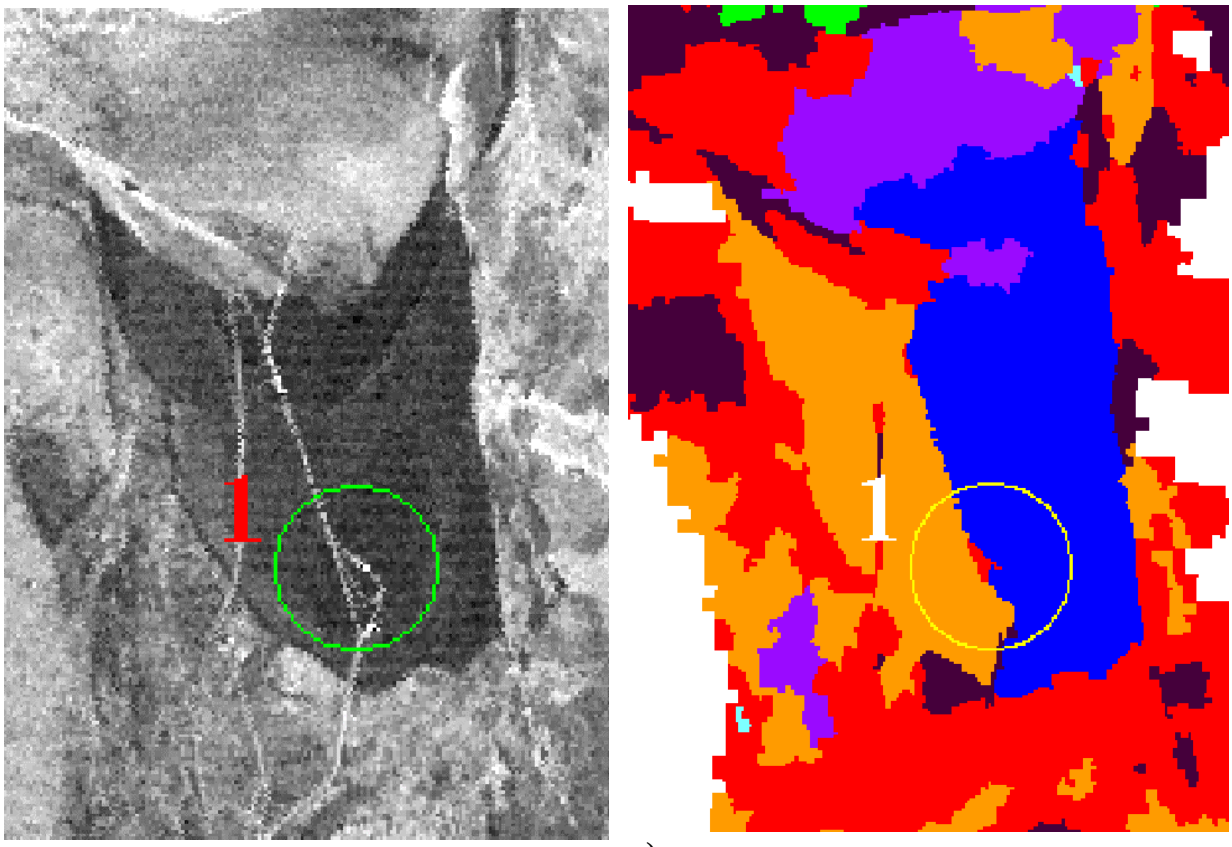
New ice: As mentioned in before, to use Nilas/Young ice as a single class is not a good choice with respect to the SAR backscatter signature, as these two features produce quite distinct and separable backscatter values. Therefore, major parts of the new ice observed in field have been classified as nilas/young, and only 7% were correctly recognised. The confusion with first year ice and fast ice is serious for ice navigation purposes. The reduced resolution (500*500m) may cause problems for identification of new ice, as this feature was mainly observed over smaller areas in-between other ice features.

Nilas/Young: Generally, young ice (grey, grey/white) have been recognised well, and the confusion with FY ice is often due to the coarse resolution, as smaller areas with young ice in-between first year ice is smeared out. Also for this feature fast ice (here more deformed/hummocked) have caused problems.

First year ice: Quite good result, when one chooses to ignore the deformation classes. If fast ice is included in this class, the performance is even better.

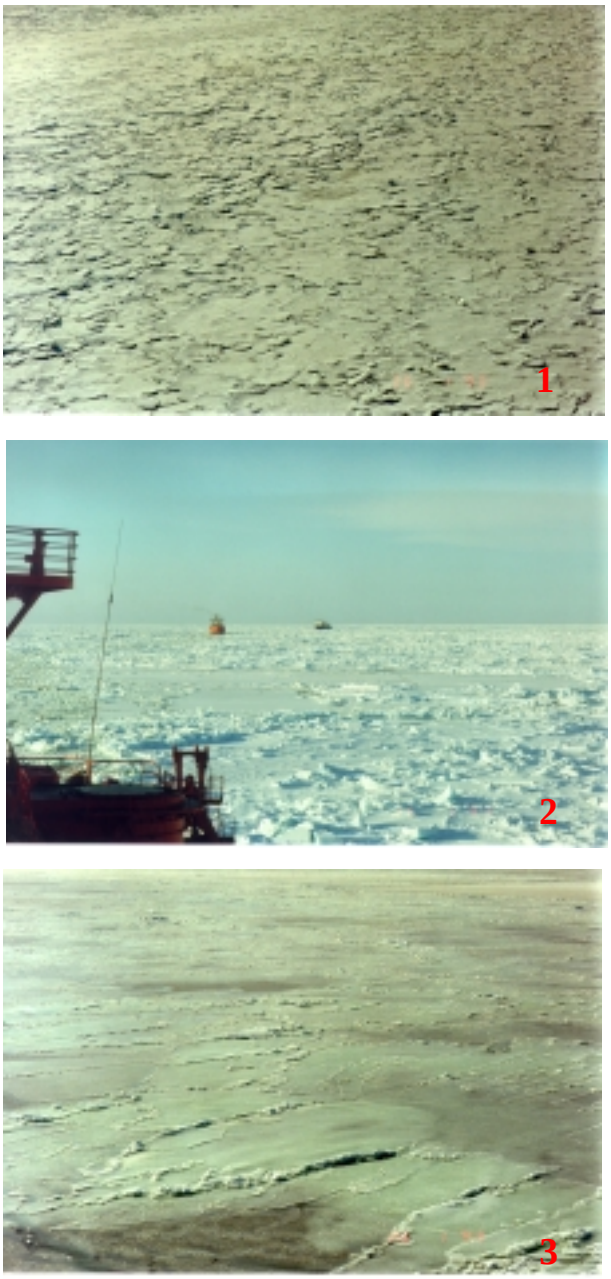
5.4 COMPARISON BETWEEN SAR SIGNATURES AND PHOTOGRAPHS

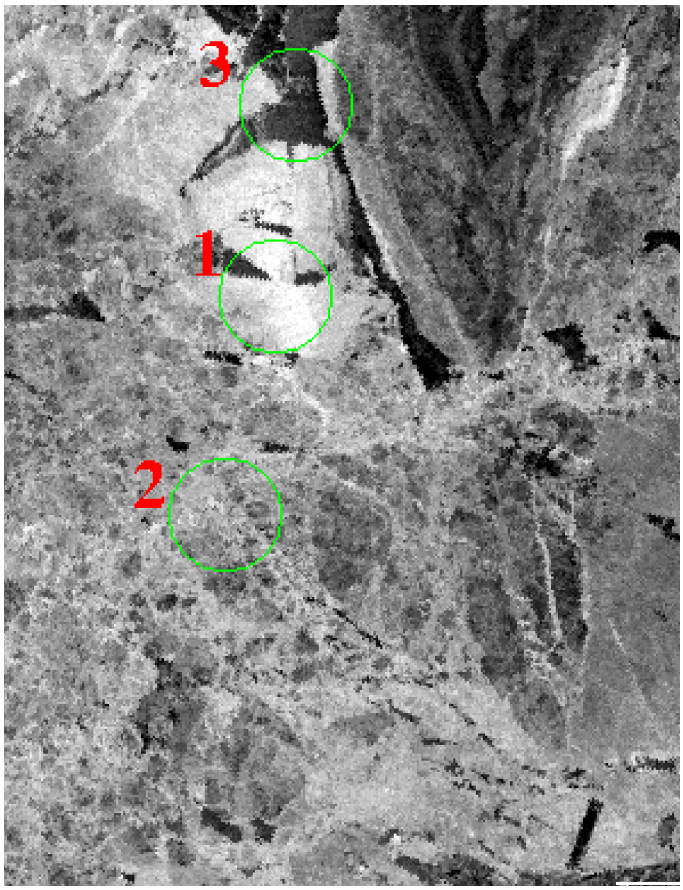
A useful method to validate the SAR classification results is to define small areas where the SAR image, as well as the classified image can be directly compared with *in situ* observations. Photographs of the observed sea ice features were taken all along the route during the two expeditions. Figure 16 provides an example of a test area where both RADARSAT ScanSAR signatures, FES classification results, and photographs of the same area are presented. The pixel-resolution of the RADARSAT image is 250*250m, and the FES-image has a pixel-resolution of 500*500m. The image of April 30 was used for this study. In Figure 17, three test areas are presented.



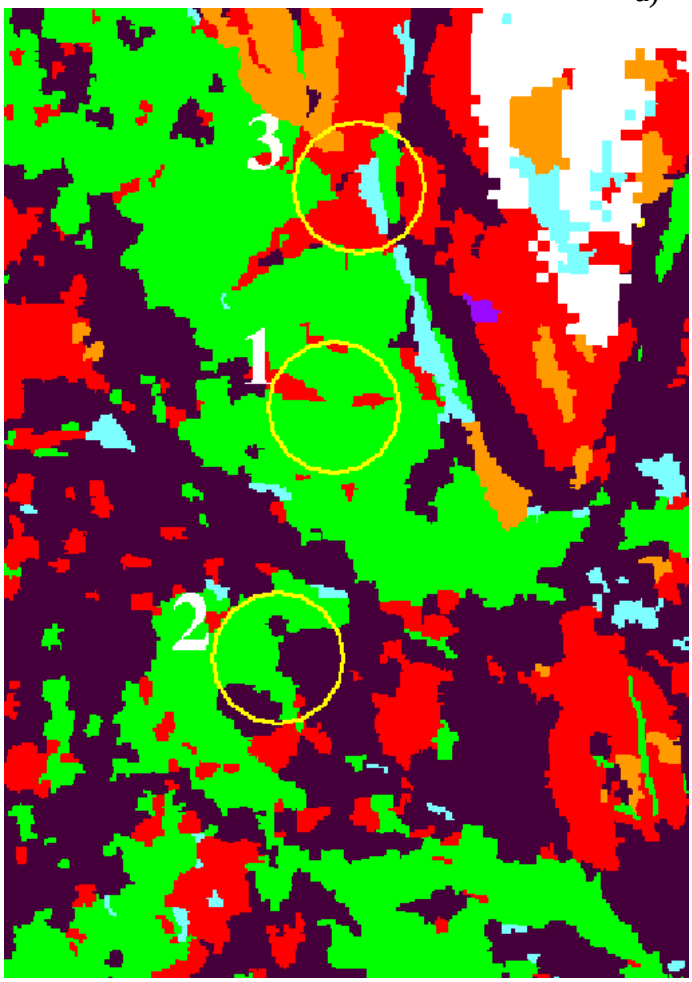
a) b)

Figure 16. a) Radarsat SAR signature for level fast ice in the Yenisei estuary. The test area is marked by a circle, and denoted by "1". The snow layer is approximately 15 cm thick, and covers major parts of the sea ice surface. In the SAR image, two ship-tracks can be seen as very bright lines on the dark level fast ice signature. b) The FES classifier recognises this area to be open water (east of ship-track) which is a crude mistake, and level FY ice (west) which is correctly classified. The areas classified as new ice are also wrong, being either level (south) or unstable (north) fast ice. c) Photograph of the test area.





a)



b)

Figure 17. Three sites at approx. 75°N/82°E are presented, showing photographs of 1) grey/white ice, 2) slightly ridged/deformed FY ice, and 3) nilas, with corresponding a) Radarsat SAR signatures and b) FES classification results. The snow layer was approximately 15 cm thick (except over the nilas where there is only small amounts of snow), and covers major parts of the sea ice surface. The bright signatures of grey/white ice (1) have been well recognised by the FES classifier, while the obviously more darker signatures of the FY ice (2) (also note a different texture) have to some extent been confused with the nilas/young ice category. Major parts of the very dark signatures of nilas, found in the polynya in area 3, have been miss-classified as slightly deformed FY ice.

5.5 COMPARISON OF FES AND SSM/I WATER CLASSIFICATION

For comparison with the classified images, SSM/I ice concentration available for the same dates have been used. This sensor is well suited to detect the amount of water in ice with a spatial resolution of 10 -15 km. It can also detect multiyear ice in cold weather, but this is not relevant in this study, since no multiyear ice was present in the investigated areas.

The April 30 scene

Comparison between FES water and SSM/I water for 30 April is made for the 10 medium and large areas showing water by the FES classification.

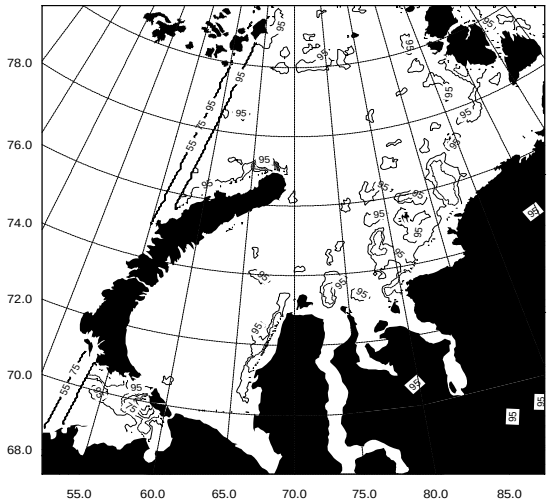


Figure 18 SSM/I ice concentration contours for the 30 April 1998.

The flaw line separating fast ice and pack ice is readily seen by SAR. Some areas outside this line are classified as water, while the SSM/I data show these areas to consist of about 20% water. Also several areas inside the flaw line are classified as water by FES, while the SSM/I shows no water. In the SSM/I there are large areas with considerably lower ice concentration, both east of Sverdrup Island and outside the flaw line north and east of Dikson. Here the FES does not recognise any water.

The May 8 scene

The classification map of May 8, covering the southern Kara Sea and the Kara gate, shows water in a large area west of Vaygach, and in a small area at the west coast of Novaya Zemlya near the Matochkin Strait.

For the area west of Vaygach, the FES water area corresponds to the SSM/I ice concentration isolines of approximately 80%. The lowest SSM/I ice concentration in this area is 50%, close to the Vaygach coast. For the second area, the corresponding SSM/I area shows about 70% water. A stripe with over 15% water in SSM/I within the classified map area runs along the west coast of Yamal. Here, FES shows "new ice" in the typical form of a coastal polynya. This class is not unreasonable here.

Another area of high SSM/I water concentration is in the surroundings of the water area along the west-coast of Novaya Zemlya. Here, FES shows a mixture of FY and level nilas/young ice. This is probably not correct. All the remaining areas that are FES-classified as ice have less than 5% water according to the passive microwave. This is reasonable. The class of "new ice" is also

shown in a large area north of the Kara Gate, but does not correspond to water on SSM/I. The reality of this class is difficult to judge.

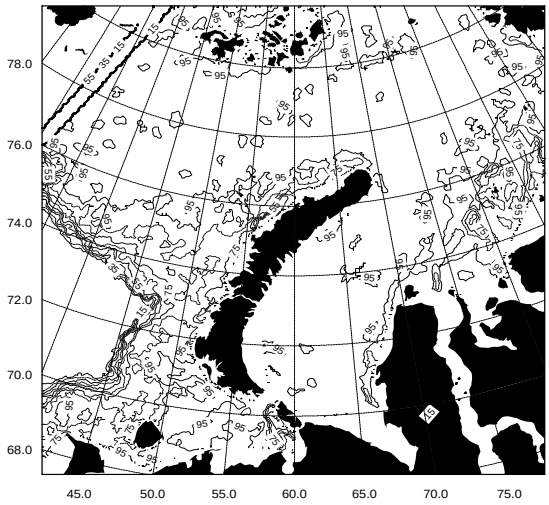


Figure 19 SSM/I ice concentration contours for 8 May 1998.

Summary of open water classification results

The best threshold for what FES classifies as "water" in the areas that correspond to the SSM/I areas, seems to be at about 85% ice concentration. The term could well be changed to e.g. "Icy Water". With this definition of the class, the accuracy of the "Water" classification seems to be around 50%. Note that passive sensor water areas are defined within resolution cells of 10 -15 km size, and that values closer to land than this distances are not reliable. Water areas less than 10 km and close to land can not be reliably compared.

The validity of the ice classes can only be subjectively discussed outside of the ship routes. As before, most ice is also here classified as FY ice with varying deformation, which is reasonable. Within some leads, NY-level is shown, also reasonable. NY-deformed ice is now present in large areas, in many places where FY-medium&heavy ice class was found before. The validity of this is difficult to judge.

A new class called "New ice" is present in the latest class maps. Its definition by WMO is for frazil, grease, slush and shuga, that is: not-consolidated ice crystals in water. It is present in large areas mainly close to the water areas. This does not seem reasonable.

The correspondence for water on April 30 is not too good. Of the areas shown as "water" by FES, about 50% are correct with less than 85% ice concentration in SSM/I. According to SSM/I, several areas not shown as water by FES do contain water above this limit.

6 CONCLUSIONS

SAR signatures of different ice types were documented on the basis of *in situ* observations from icebreakers:

- RADARSAT signatures for new and young ice vary considerably depending on ice type and state of its surface. Nilas is shown as homogenous areas with dark brightness. Grey ice is shown with light homogenous brightness and is clearly distinguished from nilas. Brightness of grey-white ice varies from dark to rather light depending on thickness and state of its surface. Grey-white ice cake, consisting of small ice floes (few meters in diameter) is shown by a very strong signal
- Brightness of first-year ice varies from dark to light depending on degree of ridging. Level ice is characterised with dark tone. Level first-year fast ice is shown with very dark brightness. Single first-year ice floes are clearly identified
- Leads and fractures, both unfrozen and covered with new or young ice, are identified in RADARSAT SAR images. This is very important for selecting optimum route of icebreaker;
- Brightness of areas, consisting of first-year ice and young ice, varies from slightly light to light. These areas can be distinguished by their characteristic texture.

Validation of ice classification results was carried out using *in situ* observations from icebreakers and SSM/I data, and the results of this analysis are presented in the Table 13.

FES classes	Location	Correct classes	Erroneous classes
Open water	Flaw polynyas	Some open water areas were classified correctly	Some fast ice areas were classified as open water
Nilas/young level Nilas/young deformed	Flaw polynyas and fractures	Some areas in polynyas were classified correctly	Some areas were miss-classified as first-year ice
First-year level First-year slight First-year medium/heavy	FY ice dominated in the Kara Sea	Generally reasonable identified	Few areas were misclassified as new ice. Some errors should be mentioned for degree of deformation
Multiyear ice	MY-ice is not present in the investigated region		

Table 13. Validation of automatic ice classification results

The analysis shows that the automatic classification results are reasonable in many cases. The greatest difficulties were found in classification of water, new and young ice. According to the SSM/I sensor, about 50% of the areas shown as water by FES are correct. Since SSM/I is a more reliable water/ice detector than SAR, its use in future system development both for water and multiyear ice is recommended. Continuation of research on automatic classification is necessary for implementation of this system in practical ice charting. The study has shown that radar signatures of different ice types can overlap, for example young ice and deformed first-year ice. Therefore, various texture measures and context information are needed for improving the automatic classification results. The classical approach for visual interpretation of satellite images includes to a large extent use of context information. Among such context data there are: ice history, use of hydrometeorological data, ice drift data, and previous observations by other remote sensing sensors. Physical constraints limit the appearance of some ice types in different seasons and in different regions of the Arctic Seas. River ice could be distinguished using logical features, and the fast ice boundaries from analysis of successive images.

Data on typical convoy speed in different ice conditions were collected during the expedition for validation of the ship routing models, and are presented in Table 14.

Ice conditions	Speed of convoy
Polynya (open water, nilas, grey, grey-white, pancake ice)	11 – 14 knots
Areas with mixture of first-year ice with new and young ice	6 – 13 knots
Thin first-year ice	10 - 11 knots
Level thick and medium first-year ice	2 – 10 knots, stuck in ice
Ridged first-year ice	2 – 5 knots, stuck in ice
Level fast ice (ice thickness 130 – 150 cm)	7 – 8 knots

Table 14. Typical convoy speed in different ice conditions

7 SUGGESTED IMPROVEMENTS OF AUTOMATIC SEA ICE CLASSIFICATION

Automatic sea ice classification of RADARSAT ScanSAR data is an ambitious and complicated task. For RADARSAT ScanSAR data to be operationally useful as ice navigation support, this has to be solved. Analysis of the automatically composed sea ice charts showed that in many cases the obtained results corresponded to real ice conditions as observed by ground truth measurements. Nevertheless, the automatic sea ice classification procedure needs to be improved. The following approaches should be investigated in further development of the methodology:

1. The radar backscatter signals from sea ice vary considerably depending on the different ice parameters, and therefore a continuation of the field observations is necessary in order to improve and broaden the database of RADARSAT SAR sea ice signatures for training and validation of the automatic classifier.
2. The image segmentation procedure delineated large areas with homogenous sea ice conditions, and the automatic classification of these areas appear to have worked well, but should be improved. When a mixture of different ice types were observed within delineated segments the classification results were worse. A continuation of studies on image segmentation, including delineation of smaller single cracks and leads, is necessary.
3. The brightness and texture of different sea ice types overlaps, therefore contextual information such as wind speed and direction, and a priori knowledge of the general sea ice condition in the region, should be considered for improving the classification results.
4. The determination of the fast ice boundary is a very complicated task for an automatic sea ice classifier. This problem could be solved by using analysis of successive images over the same area, and the classifier should only estimate the ice deformation for this area.
5. The segmentation algorithm is a weak point at this stage, and should be improved in order to limit artifacts within relatively homogenous areas.

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10 APPENDIX - *IN SITU* OBSERVATIONS CO-ORDINATED WITH RADARSAT DATA

In situ ice observations obtained from Sovetsky Soyuz synchronously with RADARSAT ScanSAR images are presented below:

APRIL 23, 1998

75.55N; 57.48E - compact grey-grey-white ice
75.45N; 57.12E - grey ice
75.36N; 56.36E - grey-grey-white ice, few fractures
75.25N; 56.01E - grey-white ice
75.18N; 55.39E - grey-white - grey ice, some ridges
75.09N; 55.16E - grey-white, inclusions of grey ice, few fractures and ridges
75.02N; 55.08E - after level grey-white ice in this point some cracks and ridges
74.56N; 54.56E - grey-white ice
74.50N; 54.43E - fracture, covered with nilas, (width = 1 mile)
74.46N; 54.33E - level grey-white ice
74.39N; 54.20E - level grey-white ice, fracture
74.36N; 54.13E - level grey-white ice
74.31N; 54.03E - level grey-white ice, Fracture (700m width), covered with nilas
74.24N; 53.47E - grey-white ice, few ridges
74.19N; 53.37E - polynya (1 x 1 mile) covered with nilas
74.10N; 53.19E - level grey-white ice
74.06N; 53.09E - grey-white ice
74.02N; 53.00E - few fractures with nilas
73.56N; 52.44E - fracture (400-500m) with nilas
73.50N; 52.26E - grey-white ice, some roughness
73.42N; 52.10E - grey-white ice, inclusions of nilas
73.39N; 52.05E - grey-white rough ice, formed from compacted pancake ice
73.35N; 51.59E - fracture, covered with nilas (width 2 miles)
73.32N; 51.53E - area with net of narrow fractures, after that - level grey-white ice
73.27N; 51.46E - predominantly grey-white ice
73.24N; 51.40E - grey-white ice and nilas (20%) grey-white ice with small roughness, formed from compacted pancake ice
73.21N; 51.36E - grey-grey-white ice (60-70%), nilas(30%). Here we exited from the Northern RADARSAT image.

Southern RADARSAT image
73.16N; 51.27E - net of narrow fractures
73.11N; 51.19E - grey-white ice, roughened

April 24

73.06N; 51.08E - grey-white(70%), nilas (20-30%)
73.03N; 50.34E - level grey-white ice
73.02N; 50.06E - thin FY (40%), grey-white(30-40%); nilas(10-20%)
72.56N; 49.43E - thin FY(40%), grey-white(30%), nilas(10-20%)
72.48N; 49.16E - predominantly rough FY ice (60%)
72.48N; 48.54E - predominantly level FY ice (60%)
72.44N; 48.32E - wide polynya, covered with nilas
72.43N; 48.31E - rough FY ice (30 cm ridges)
72.42N; 47.57E - polynya, covered with grey ice And nilas
72.40N; 47.25E - thin FY (60%), grey-white (40%)
72.39N; 47.09E - thin FY, ice cake
72.38N; 46.38E - grey - white ice, ice cake
72.37N; 46.10E - thin FY (30%); grey-white (60%), ice cake
We exited the area, covered with RADARSAT South
RADARSAT NORTH
72.47N; 45.55E - grey-white ice cake, frozen together
72.48N; 45.58E - thin FY (50%), grey-white (40%)ice cake, frozen together

April 25, 1998

75.20N; 55.40E - level grey-white ice
75.30N; 56.14E - grey-white ice, few ridges
75.36N; 56.35E - level grey-white ice

75.43N; 56.57E - grey-white ice, thin FY, few ridges
75.53N; 57.40E - grey-white ice, some fractures
75.59N; 58.00E - grey - grey-white ice
76.03N; 58.19E - grey-white ice, nilas in fractures
76.08N; 58.50E - Grey, grey-white(80%), nilas(10-20%)
76.13N; 59.17E - fracture 700-800m wide
76.22N; 59.36E - open water polynya (300-400m), FY ice around
76.25N; 59.38E - grey ice with rough surface (formed from pancake)
76.35N; 59.24E - mean FY ice
76.41N; 59.38E - mean FY (50%), grey-white (30%), nilas(10%) FY ridged ice
76.48N; 60.00E - rather level FY ice
76.56N; 60.36E - Fracture, open water, nilas and grey ice. FY ice around
77.02N; 61.03E - Fracture, nilas
77.12N; 61.05E - mean FY ice

April 26, 1998
77.17N; 61.16E - fracture, grey ice
77.18N; 61.28E - grey-white ice
71.23N; 61.37E - thin FY, grey-white; turn around
77.19N; 62.04E - fracture, covered with nilas
77.18N; 62.21E - nilas 8-9/10
77.21N; 62.47E - FY ice, strongly ridged
77.26N; 63.00E - level FY ice
77.29N; 63.14E - -wide fracture, covered with grey ice
77.28N; 63.30E - grey ice, FY ice to the left
77.27N; 64.04E - grey, grey-white ice
77.25N; 64.25E - area of grey ice (2 miles), than mean FY ice
77.29N; 64.38E - thin and mean FY ice
77.34N; 65.11E - mean and thick FY ice, average roughness
77.42N; 65.39E - FY ice, average roughness
77.47N; 66.12E - fracture
77.47N; 66.44E - level grey-white ice floe
77.47N; 67.25E - mean and thick FY ice, heavily ridged to the right
77.48N; 67.39E - level mean and thick FY ice
77.47N; 68.04E - FY ice, level to the right and mean roughened to the left
77.45N; 69.22E - thick FY ice, old channel
77.45N; 70.38E - FY ice, fractures
77.47N; 71.03E - thick FY, mean roughness
77.48N; 71.12E - level thick FY ice
WE exited from RADARSAT image.

May 1, 1998
75.15N; 81.09E - open water, new ice to the right
75.14N; 81.08E - nilas
75.11N; 81.07E - begin of grey ice
75.08N; 81.06E - nilas
75.07N; 81.06E - begin of grey ice area
74.58N; 81.15E - grey, grey-white ice, 1 mile to the right - strongly rough FY ice
74.54N; 81.24E - narrow fracture covered with grey ice; strongly rough FY ice around
74.49N; 81.32E - end of ice isthmus, after that - open water fracture
74.50N; 81.08E - end of fracture; after that point - strongly ridged FY ice
74.49N; 81.05E - FY ice (70%), thin FY (10%), young (10-20%) strongly rough
74.45N; 81.17E - mean, thick FY(70%), thin FY (20-30%), young(0-10%)
74.40N; 81.24E - thick FY(80%); mean FY (20%), mean roughness, ice cake
74.36N; 81.33E - fracture with open water and nilas

May 2, 1998
74.33N; 81.27E - FY (60%), grey (30%), fractures
74.28N; 81.42E - grey ice, ridged FY ice to the left and to the right
74.25N; 81.48E - fracture with open water and nilas
74.18N; 81.57E - reached polynya and turn around for escorting another ship.

May 3, 1998

74.22N; 81.33E - FY ice (10%), grey (60%), grey-white (20%), fractures with open water
74.19N; 81.38E - grey, grey-white ice, open water - to the left
74.13N; 81.47E - mixture of nilas and pancake near ice edge
74.13N; 81.49E - polynya with open water
73.00N; 80.07E - level fast ice
73.13N; 79.40E - unstable fast ice; FY ice cake frozen together
73.14N; 79.37E - ice edge zone, open water
73.28N; 79.28E - nilas (70%), grey ice cake (30%)
73.38N; 79.15E - rafted nilas (30-40%)
73.43N; 79.09E - grey ice (50%), nilas (40%)
73.56N; 78.47E - young ice
73.59N; 78.36E - grey-white ice (40%), grey (40%), nilas(10%), few ridges
74.01N; 78.21E - FY ice (10-20%), grey-white (50%), grey (30%)

May 4, 1998

74.12N; 75.07E - thin FY ice, grey-white
74.13N; 74.48E - polynya with grey-white ice
74.14N; 74.08E - thin FY (60%), grey-white (30%), nilas(10%), fractures
74.13N; 73.29E - thick, mean FY (80-90%), nilas(10%), strongly rough
74.09N; 72.44E - FY ice (80%), fractures with nilas(20%)
74.04N; 71.45E - FY ice isthmus (2-3 miles), after that FY ice (70%), new, young ice (30%)
74.00N; 71.34E - thick, mean FY ice (60-70%), young (20-30%) strongly rough
73.51N; 70.48E - thick, mean FY (70%), new, young (20-30%)
73.48N; 70.11E - thick, mean FY (70%), thin FY (30%) strongly ridged
73.45N; 69.40E - thick, mean FY -(60%),thin FY (20%), grey-white(20%), strongly ridged
73.33N; 69.07E - thick, mean FY (50%), young (40%), mean roughness
We exited from RADARSAT image
Return way home:
73.16N; 68.48 E - open water and nilas
72.58N; 68.15E - Ice cake, thick, mean FY(60%), new, young(30%)

May 5, 1998

71.24N; 66.07E - grey-white ice, few ridges
71.10N; 65.19E - polynya (1 km wide), mean rough FY ice around
71.04N; 64.50E - thick, mean FY (70%), young (20%)
70.57N; 64.11E - thick, mean FY ice, mean roughness, fractures
70.43N; 63.28E - thick, mean FY, mean roughness
70.33N; 62.50E - thick, mean FY ice, mean roughness, fractures
70.30N; 61.58E - rather level FY ice
70.24N; 61.10E - slightly rough FY ice, fractures

May 6, 1998

70.07N; 61.14E - thick FY ice, strongly rough
70.05N; 61.02E - fracture
69.55N; 60.52E - thick, mean FY ice, ridged
69.52N; 60.40E - fast ice boundary
69.38N; 60.05E - fast ice boundary (Pechora Sea), after it -pancake
69.36N; 59.55E - nilas, 30% rafting
69.39N; 59.32E - open water
69.47N; 59.00E - grey-white ice
69.56N; 58.24E - compressed pancake ice
70.00N; 58.05E - FY ice (70%). nilas (20%); very rough

May 7, 1998

70.04N; 55.08E - FY ice (60-70%), nilas (10%)
70.08N; 54.57E - FY ice (80%), nilas (10%), mean rough
70.15N; 54.19E - thin FY (70%), grey-white (20%)
70.35N; 50.35E - young (50-60%), nilas (10%)
70.44N; 48.37E - thin FY (50%), nilas (40%)
70.47N; 47.25E - thin FY (60%), young (30%)
70.53N; 46.41E - thin FY (70%), grey (20%)
70.59N; 45.27E - ice edges