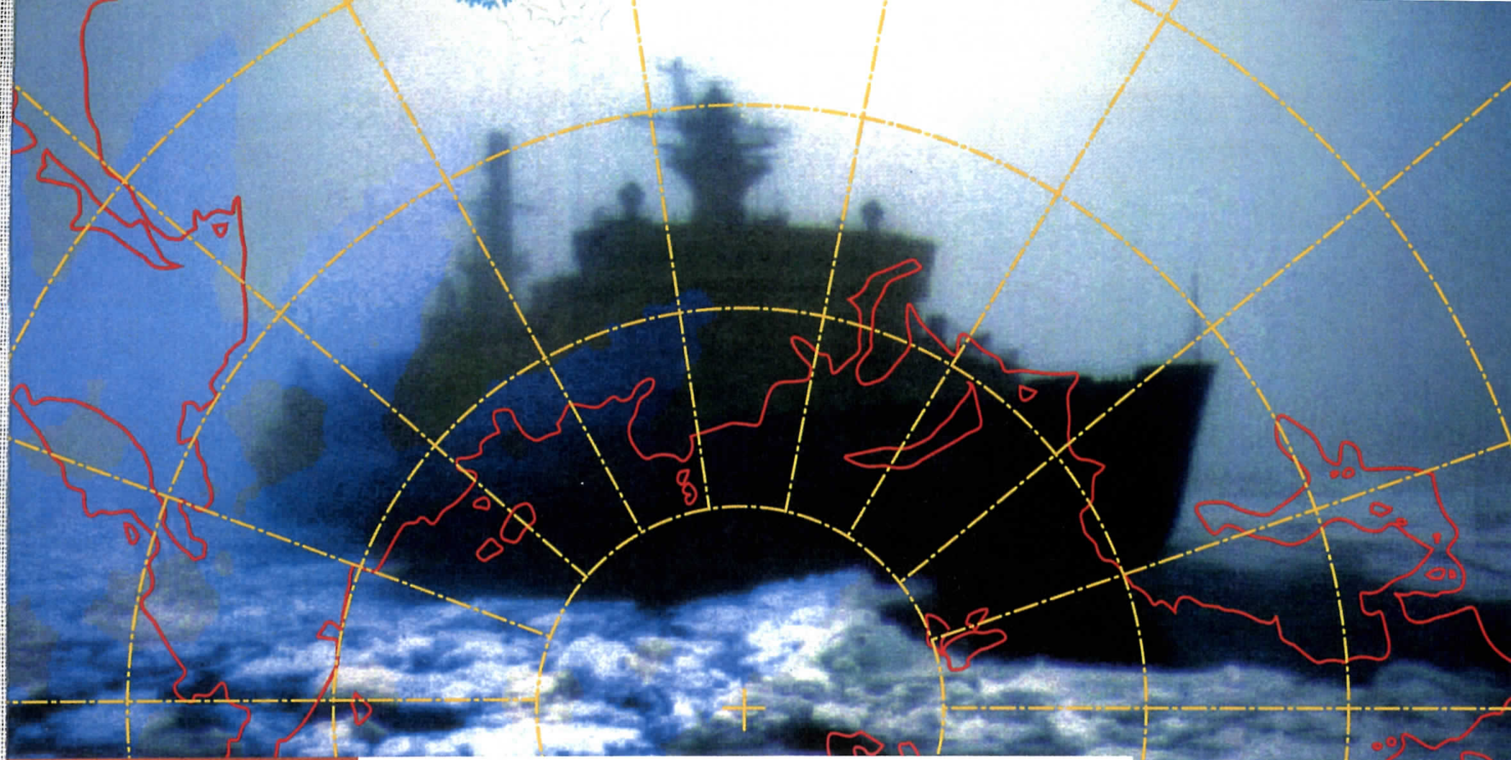
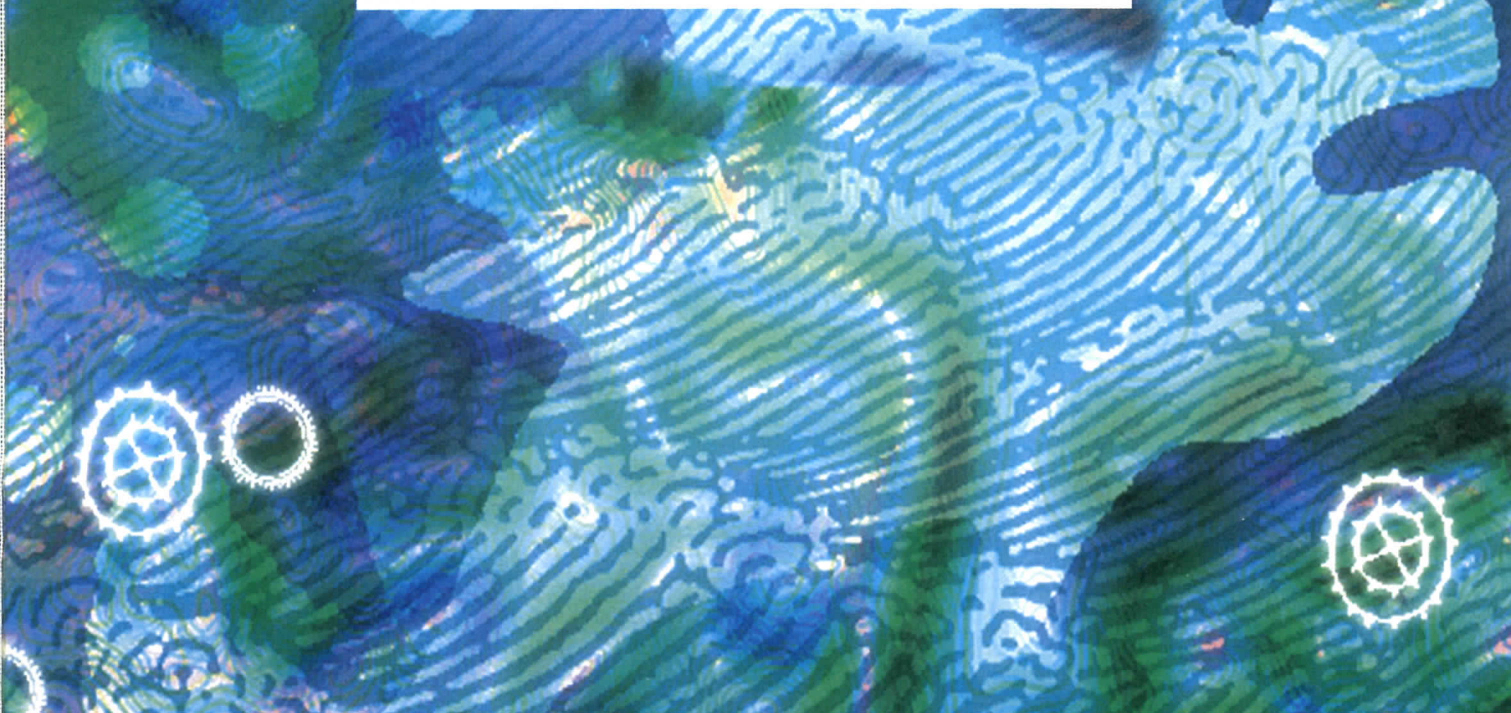


INSROP WORKING PAPER
NO. 38-1996, I.4.2

# Ice Monitoring by non-Russian Satellite Data. Phase 2: Pilot Demonstration.

Ola M. Johannesen, Stein Sandven, Kjell Kloster, Vladimir V. Melentyev and Leonid Bobylev



**INSROP International Northern Sea Route Programme**

Central Marine Research & Design Institute, Russia

The Fridtjof Nansen Institute, Norway

Ship and Ocean Foundation, Japan

International Northern Sea Route Programme (INSROP)

Central Marine Research & Design Institute, Russia

The Fridtjof Nansen Institute, Norway

Ship & Ocean Foundation, Japan

# INSROP WORKING PAPER NO. 38-1996

Sub-programme I: Natural Conditions and Ice Navigation.

Project I.4.2: Ice Monitoring by non-Russian Satellite Data.
Phase 2: Pilot Demonstration.

By: Ola M. Johannesen*, Stein Sandven (supervisor)*, Kjell Kloster*, Vladimir Melentyev** and Leonid Bobylev**.

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## *What is an INSROP Working Paper and how to handle it:*

This publication forms part of a Working Paper series from the **International Northern Sea Route Programme - INSROP**. This Working Paper has been evaluated by a reviewer and can be circulated for comments both within and outside the INSROP team, as well as be published in parallel by the researching institution. A Working Paper will in some cases be the final documentation of a technical part of a project, and it can also sometimes be published as part of a more comprehensive INSROP Report. For any comments, please contact the authors of this Working Paper.

## FOREWORD - INSROP WORKING PAPER

INSROP is a five-year multidisciplinary and multilateral research programme, the main phase of which commenced in June 1993. The three principal cooperating partners are **Central Marine Research & Design Institute (CNIIMF)**, St. Petersburg, Russia; **Ship and Ocean Foundation (SOF)**, Tokyo, Japan; and **Fridtjof Nansen Institute (FNI)**, Lysaker, Norway. The INSROP Secretariat is shared between CNIIMF and FNI and is located at FNI.

INSROP is split into four main projects: 1) Natural Conditions and Ice Navigation; 2) Environmental Factors; 3) Trade and Commercial Shipping Aspects of the NSR; and 4) Political, Legal and Strategic Factors. The aim of INSROP is to build up a knowledge base adequate to provide a foundation for long-term planning and decision-making by state agencies as well as private companies etc., for purposes of promoting rational decisionmaking concerning the use of the Northern Sea Route for transit and regional development.

INSROP is a direct result of the normalization of the international situation and the Murmansk initiatives of the former Soviet Union in 1987, when the readiness of the USSR to open the NSR for international shipping was officially declared. The Murmansk Initiatives enabled the continuation, expansion and intensification of traditional collaboration between the states in the Arctic, including safety and efficiency of shipping. Russia, being the successor state to the USSR, supports the Murmansk Initiatives. The initiatives stimulated contact and cooperation between CNIIMF and FNI in 1988 and resulted in a pilot study of the NSR in 1991. In 1992 SOF entered INSROP as a third partner on an equal basis with CNIIMF and FNI.

The complete series of publications may be obtained from the Fridtjof Nansen Institute.

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# Project I.4.2: Ice Monitoring by non-Russian satellite data

## Phase 2: Pilot demonstration

by

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Bergen, January 1996

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# Summary

Use of Synthetic Aperture Radar (SAR) images from satellites is a technology which is playing an increasingly important role in operational sea ice monitoring. SAR images, with a resolution of 100 m, can distinguish different ice types and map leads, polynyas, shear zones, landfast ice, drifting ice and location of the ice edge. The SAR is the only instrument which provides high resolution images under different cloud and light conditions. The ERS-1 satellite, launched by the European Space Agency in 1991, is the first satellite which has provided extensive SAR coverage in most of the ice-covered areas in the world.

The Russian Arctic Ocean is one of the most important areas for ice monitoring, because the ice conditions off the Siberian coast impose severe restrictions on sea transportation, ice navigation and offshore operations. The Russian icebreaker fleet, which assists all sea transportation in the area, uses an extensive ice monitoring and forecasting service in the navigation.

In several demonstration projects the Nansen Centers in Bergen and St. Petersburg have used ERS-1 SAR images to monitor sea ice conditions in near realtime at different times of the year. The demonstrations have been performed in cooperation with Murmansk Shipping Company onboard icebreakers sailing mainly in the western part of the Northern Sea Route. The SAR images are used in combination with passive microwave data (SSM/I data) which provide large scale maps of ice extent and concentration at a resolution of about 30 km. The SAR images have shown good capability to map ice features which are important in ice navigation such as multiyear ice, firstyear ice, landfast ice, thin ice, leads/polynyas and areas of ridges. The demonstration projects have been supported by Norwegian Research Council, Norwegian Space Centre, European Space Agency, Murmansk Shipping Company and INSROP. From 1995 SAR ice monitoring in the Northern Sea Route is performed in a cooperation between the European Space Agency and the Russian Space Agency, with participation from NPO Planeta and Arctic and Antarctic Research Instititute.

The expected result of the SAR demonstration projects is that SAR data from several satellites can be made available for operational use in ice monitoring of the Northern Sea Route.

# Objectives

The overall objective of this project is to demonstrate the usefulness of ice monitoring by ERS-1 SAR for ice navigation in the Northern Sea Route (NSR). The specific objectives are to:

- demonstrate and familiarize the icebreaker crews and Russian operational ice monitoring service with the use of ERS-1 SAR data to assist sea ice mapping and navigation
- receive first-hand experience on the actual information needs and requirements for the operational use of satellite radar data in icebreaker operations along the Siberian coast
- evaluate and gain experience with data communication to vessels operating in the high-latitude regions off the Siberian coast
- collect seasonal information for the validation of SAR image signatures of various ice types and conditions, to assist the development of automatic ice classification routines
- prepare use of satellite SAR data in the operational Russian ice service

# Introduction

The Northern Sea Route is the sailing route along the coast north of Russia (Fig. 1). Ice conditions can be very severe and icebreaker assistance is required for parts of the route at all times of the year. It can be used in full length between the Barents Sea and the Bering Sea only in summer. In winter, its western part is used for transportation to and from Russian harbours along the Yenisei River. Ice monitoring is of great importance to the Russian icebreakers escorting other vessels. Especially important is accurate ice mapping, though ice forecasting is also of fundamental importance.

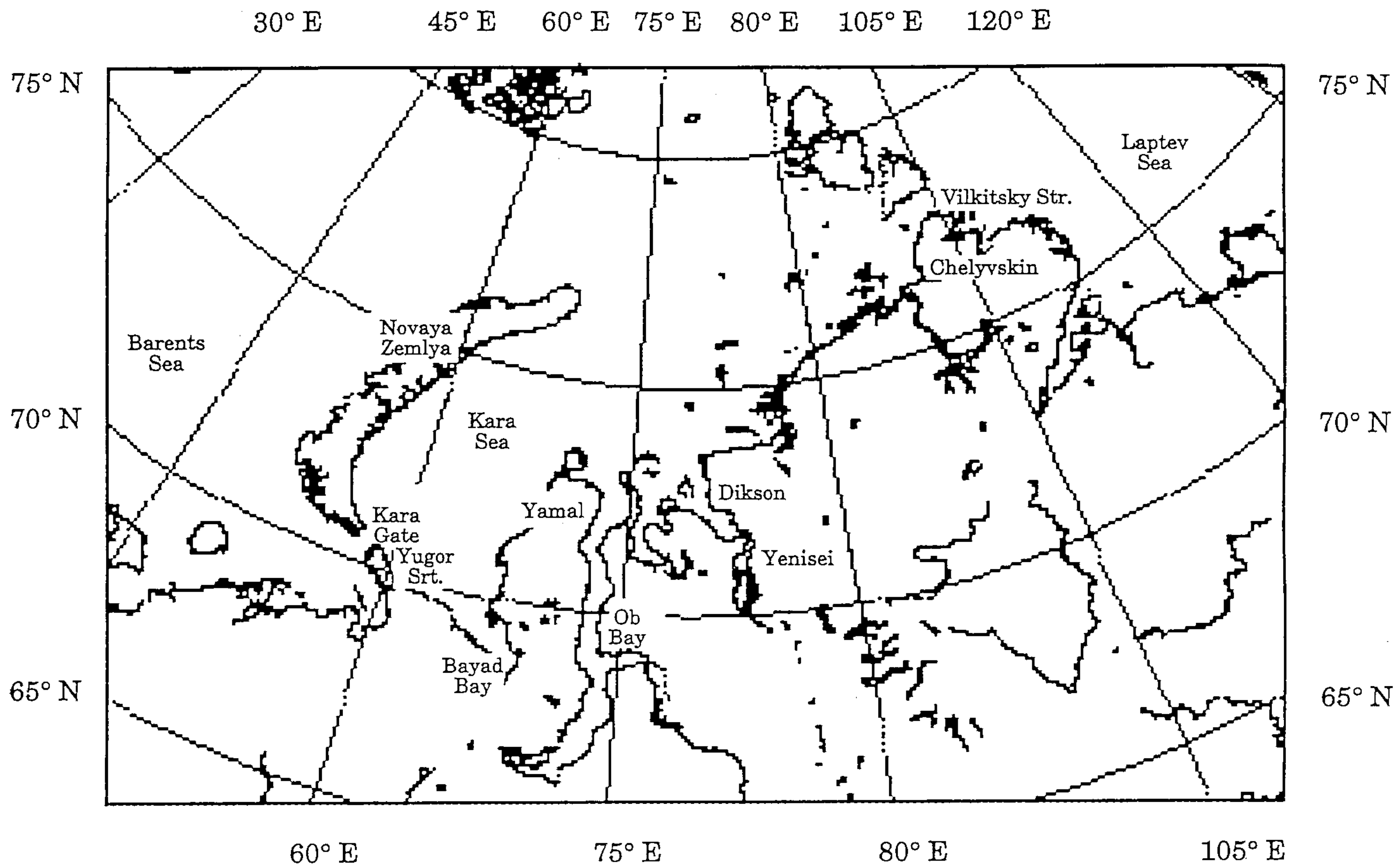


Fig. 1. Map of the Kara Sea region, the western part of the Northern Sea Route.

The possibility to monitor sea ice independent of daylight and cloud cover has improved considerably since the launch of the ERS-1 satellite in July 1991 [Sandven *et al.*, 1994 a]. The ERS-1 has proved that SAR is an excellent instrument for detection, classification and monitoring of the sea ice distribution in many areas. The Nansen Environmental and Remote Sensing Center, Bergen (NERSC) and the Tromsø Satellite Station (TSS) of the Norwegian Space Centre provide SAR data for real-time sea ice monitoring in the European sector of the Arctic including the Kara Sea [Sandven *et al.*, 1994 b]. ERS-1 SAR images are down-linked and processed at TSS. Then the images are transmitted to NERSC for further processing, analysis, production of interpreted maps and distribution to end users [Sandven *et al.*, 1993]. In addition, the SAR data can be coupled with near-real-time passive microwave data from the Special Sensor Microwave Imager (SSM/I) of the U.S. Defense Meteorological Satellite Program to resolve the larger-scale ice coverage.

NERSC first demonstrated use of ERS-1 SAR data for near real-time ice mapping of the Northern Sea Route in August 1991, only a few weeks after the launch of the ERS-1 satellite. SAR derived sea ice maps were then sent by telefax to the French polar vessel *L'Astrolabe* during her voyage through the Northeast Passage from Norway to Japan [Johannessen *et al.*, 1992 a,b,c]. This demonstration was evaluated as very interesting by the captains and sea ice experts onboard the Russian icebreakers which escorted *L'Astrolabe* through the ice-covered parts of the route.

A second and more extensive demonstration was carried out in November 1993 using the

Russian nuclear icebreaker *Sovetsky Soyuz* [Johannessen *et al.*, 1994 a,b]. In this demonstration, a scientist from Nansen International Environmental and Remote Sensing Center, St. Petersburg (NIERSC), stayed onboard the icebreaker and analyzed the SAR images in cooperation with the ice pilot. In addition to the navigational aspects this experiment also had scientific objectives such as improved understanding of sea ice phenomena in the Kara Sea and their SAR signatures.

The 1994 validation/demonstration campaigns in the Northern Sea Route, which will be dealt with in this report, were carried out in February-March (winter) and September-October (summer). During these campaigns, a scientist from NIERSC was onboard the icebreakers and an icebreaking freighter. ERS-1 SAR images were obtained along the route, and the images were analyzed to obtain detailed maps of the ice conditions in the Kara Sea and the Pechora Sea.

In this report the main results from the 1994 campaigns are described, and a recommendation for future use of SAR data in tactical ice monitoring is outlined. When more experience is gained with use of SAR data, it will be possible to study ship performance and assess risks of ship damage in ice navigation in relation to ice information from satellite data.

# Part 1.Validation of sea ice parameters derived from ERS SAR data

In this chapter we first describe the acquisition and processing of SAR data in the Northern Sea Route. Second, the retrieval of sea ice parameters from SAR data is discussed. Third, we present results from the two validation/demonstration campaigns carried out during 1994. In these campaigns, SAR images and near-concurrent *in situ* ice observations were obtained and analyzed. Finally, a preliminary assessment of these campaigns is given.

## 1.1 SAR data acquisition and processing

### 1.1.1 The ERS-1 SAR instrument

The SAR instrument onboard the ERS satellites has the ability of giving detailed weather- and daylight-independent imagery over the region south of 84°N. The resolution and noise is variable from about 15m and high noise, to some hundred meters and very low noise. After the backscattered signal has been processed to an image with the chosen resolution, about 200m for general ice imagery, these may be suitably geographically annotated and displayed. Experience is needed for the task of making an annotated image. In a second step, the interpreted radar image can be drawn as an ice map. The image and/or the ice map can then be made available for ships navigating at the ice edge and in the ice.

The relatively narrow swath width of 100 km determines the maximum area covered each day, actual coverage is smaller since the instrument is switched on only over pre-selected areas. The covered area is smaller than desired for sufficient coverage for many applications, including the one described in the current report.

### 1.1.2 SAR data for the Northern Sea Route campaigns

Through ESA's application-oriented pilot project in the Kara Sea [Johannessen and Sandven 1992] SAR data were obtained from the Kara Sea region. In February and March 1994 the ERS-1 satellite was in a three-day repeat cycle, where each SAR swath is repeated every third day. The areas between each SAR swath are not covered at all in this repeat cycle. The data needed in near real-time were obtained from TSS, whereas off-line data were obtained from the ESA archive at ESRIN, ESA's research centre in Frascati, Italy.. Both TSS and the ESA ground station in Kiruna can downlink and process SAR data from the Northern Sea Route west of Cape Chelyuskin (107°E).

The data delivered from TSS were images with 100 m pixel size - "low resolution images" (LRIs) - which were readily transmitted by computer network to NERSC. The transmission time is about 8 minutes per scene. TSS can thus deliver up to several scenes within 1 hour of the ERS-1 overpass. At NERSC the following image analysis steps are carried out:

1) reduction of data by averaging each scene to 8 bit and 200 m pixel size,
2) normalization of values across-track (correction of antenna-gain etc.)
3) two or more consecutive scenes are merged into one image,
4) marking of 0.5° lat. by 2° long. gridlines,
5) annotation of land/islands and interesting ice/ocean features,
6) digital contrast enhancement of the image before printing to hardcopy in A4 format,
7) print of annotated ice map separated from the image,
8) production of a compressed image for file transmission, and
9) transmission of images and maps to the ship by telefax.

This is the basic procedure necessary to enhance and compress the most important ice information in the SAR images, and send it out to the icebreaker. Further interpretation and classification of the images were also done onboard the icebreaker.

## 1.2 Derivation of sea ice parameters from SAR

The key problem of converting SAR data into ice parameters, including the use of consistent ice terminology and symbols, is discussed in this section. The parameters of the SAR imaging system that are of greatest importance for the characterization of ice and water are first described. The basic classes of ice/water variables which can be extracted from SAR are then defined. Then, a description of the signal from the water and ice under various conditions is given.

### 1.2.1 Parameters of the SAR imagery

*Spatial resolution and speckle noise.* Unlike optical imagery, SAR images have a strong noise component called "speckle noise" when the imagery is processed to high resolution. In the case of ERS-1, the highest standard resolution used is about 25 -30m, in this case the noise component is very prominent. This noise has a large effect on the SAR high-resolution imagery. The noise decreases and the size of the resolution cell increases when spatial filtering is done by averaging several pixels. Averaging to 100m or 200m resolution has been found optimal for many general ice mapping tasks. The noise component is then so small as to not affect the analysis of the image. Only in the case of the mapping of small, localized and high-contrast objects, is it advantageous to use images with a resolution down to 25m and with the unavoidable large speckle noise.

*Noise floor.* The minimum detectable backscatter signal is determined by the level of signal in the image in areas with no return from the surface. This level called the "noise-floor" has a fixed value of approximately -25.8dB. This is a value well below the signal from most surface types, only very calm water and grease ice may have a backscatter approaching this value. These two types of surface are also very difficult to separate.

### 1.2.2 Classes of ice/water variables.

Ice and water surface variables to be extracted from SAR can be characterized to be in one of the following three general classes:

*Boundaries and features.* Detection is made using mainly the signal variation (the gradients) within the image. Examples are features at the ice edge, and also leads and floes in the ice pack that are significantly larger than the image resolution. They are generally visible due to a more or less sharp contrast between the feature and the adjacent areas. The detection requires a good backscatter signal gradient in the area of interest. Gradients can be optimized by image processing techniques such as histogram equalization or other digital grayscale-adjustments. Figure 2 is an example of feature definition seen in a digitally- enhaced SAR image from the Yenesei River estuary.

*Measuring the motion of features.* This is measured as the displacement of the same ice feature as seen in two images taken hours or days apart. Displacement of a few large objects can easily be measured by manual methods. Methods using spatial correlation between images can be used to automatically extract the field of many displacement vectors within the overlapping area of the two images. [Kloster *et al.* , 1992]. Figure 3 shows the results of an automated ice motion algorithm applied to SAR data in the ice-covered Ob River estuary, northern Siberia.

*Determination of the type of surface.* The surface can be either ice-free water, unresolved icefloes in water, very thin ice, or thicker ice usually with a layer of snow on the top. There are many ambiguities in the backscatter signal from these surface types, requiring expertise


Figure 2. ERS-1 SAR image of the Yenesei River estuary, obtained in March 1994 when the river is frozen.

The image is contrast-enhanced to show different ice types and ice structures. The bright lines are the icebreaker tracks.

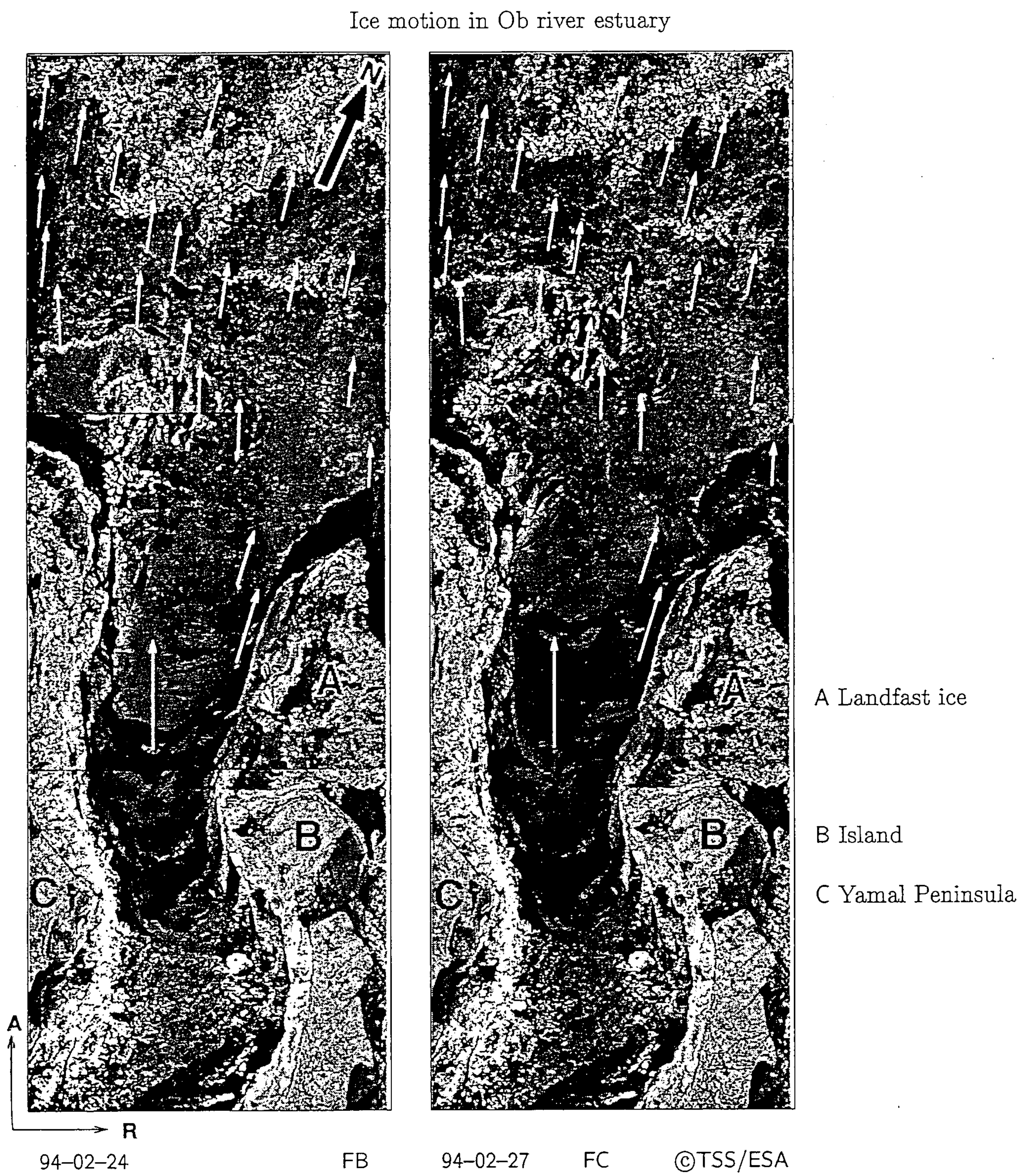



Figure 3. Ice motion vectors derived from an automated ice motion algorithm applied to sequential SAR images of the Ob River estuary. From Hamre [1995].

in the intepretation. Figure 4 depicts the typical SAR backscatter ranges for various open-water wind conditions and various ice types. The backscatter ranges are obtained from numerous coincident SAR and in situ observations of ice types in validation experiments such as SIZEX 92 (Sandven et al., 1994). The results from the two first demonstration experiments, with L'Astrolabe in 1991 (Johannessen et al., 1992 a, b and c). and Sovetsky Soyuz in 1993 (Johannessen et al., 1994) are also included in Fig. 4.

In order to reduce the ambiguities in the backscatter, four different surface regimes are defined, as indicated at the bottom of Fig. 4. For correct determination of surface type based on backscatter, the general surface regime needs to be known, as: a) open ocean, b) ice-edge region, winter, c) summer ice, or d) interior of the pack ice, winter. Open water may be identified using texture, since it generally has a homogeneous appearance. The correct ice regime is determined from knowledge of large-scale ice extent, and the winter versus summer is distinguished via temperature.

Within each regime, some ambiguities still remain. The uncertainties must be solved using various methods, mainly based on a combination of image texture and knowledge of ice types generally expected in a region. Surface type determination is usually done manually, while the possibilities for automated classification are explored.

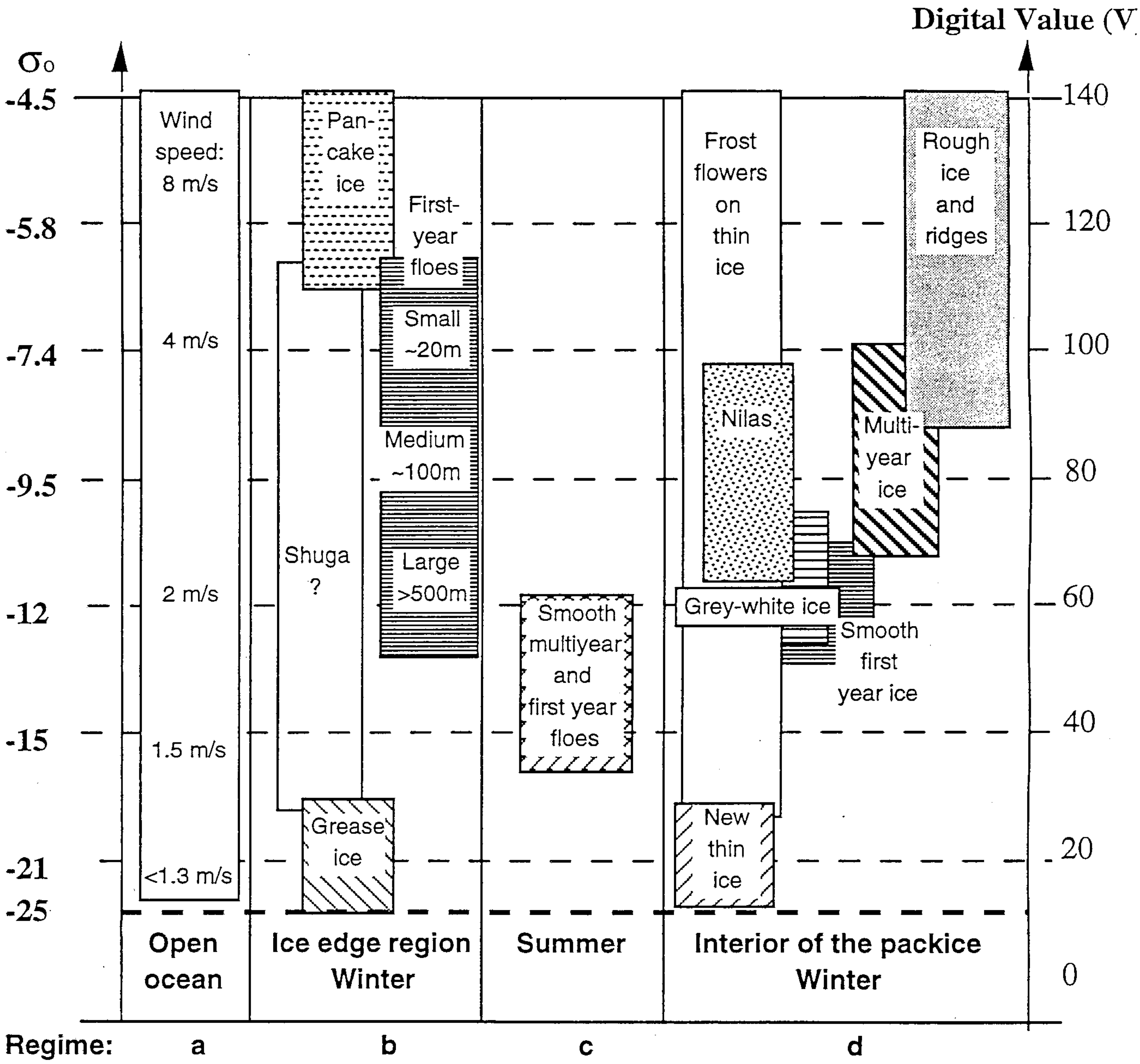



Figure 4. SAR backscatter ranges associated with various ice types and open water conditions in the marginal ice zone and in the interior of the ice pack. The bold dashed line is the ERS-1 SAR noise floor. The backscatter values are based on several coincident SAR and in situ ice type observations in field experiments 1991 - 1993

### 1.2.3 Description of open water backscatter

Open water backscatter is mainly determined by surface wind speed (see Fig. 4), and also to some degree by the wind direction relative to the SAR range direction. Radar incidence angle is also an important parameter - its influence can normally be determined since its value (20°-26°) is known across the swath. The algorithm "CMOD4", developed for the ERS scatterometer, can be used for estimating the SAR signal when the wind speed and direction is known. Therefore, it can be used inversely as an indication of the wind speed over open water, derived from the SAR signal.

### 1.2.4 Description of ice types and associated backscatter

The main ice types in an image and their SAR backscatter depend to a great extent on the surface roughness characteristics, which are influenced by past and present: 1) temperature and 2) motion by waves, wind and currents.

Conditions determined by temperature can be divided into two main groups as follows:

- New-formed and old ice in freezing conditions ("winter").
- Old ice in melting conditions ("summer").

Conditions can also be determined by dividing into three main groups as follows:

- The ice is in relatively undisturbed waters conditions ("calm").
- The ice is broken into pieces by wave/wind action conditions ("agitated").
- The ice is ridged or rafted.

The main ice types and their backscatter signal under the combinations of temperature and motion conditions are described below:

*Ice freezing under calm conditions (e.g. winter in the ice interior, regime (d) in Fig. 4).*

- New Thin ice and Dark Nilas (e.g., smooth refrozen leads) gives a low signal (σ_= -25 to -15 dB).
- New ice with Frostflowers (e.g., rough refrozen leads) on top gives a high signal (σ_= -10 to -4 dB).
- Gray-white ice (Young ice) and First-year ice gives a middle signal (σ_= -13 to -10 dB).
- Multi-year ice (Old ice) gives a somewhat higher signal than FY ice (σ_= -11 to -7 dB).

*Ice freezing under agitated conditions (e.g.,winter at the ice edge, regime (b) in Fig. 4).*

- Grease ice and Frazil ice dampens the waves and gives a low signal (σ_= -25 to -15 dB).
- Shuga and Pancake ice are small ice lumps that give a very high signal, due to edge effects (σ_= -10 to -4 dB)
- Small Floes give a variable signal, high for smaller floes and decreasing with increasing size (σ_= -13 to -6 dB).

*Ice melting under calm conditions (e.g. summer in the ice interior, regime (c) in Fig. 4).*

- Large Floes. The signal is uniformly low. It is only weakly dependent on the ice age, since the the backscatter is mainly determined by the wet snow /ice layer on top (σ_= -16 to -12 dB).

*Ice melting under agitated conditions (e.g., summer at the ice edge, regime (c) in Fig. 4).*

- Fields of Small and Medium size Floes . The signal will increase with decreasing floe size, but to a lesser degree than under winter conditions ($\sigma\_$= -15 to -12 dB).

*Ridged and rafted ice forms (e.g. winter in the ice interior, regime (d) in Fig. 4).*

Ridged and rafted ice is formed when layers of ice are piled up one upon another under pressure. This may take place under both cold and warm conditions. Ridged and rafted ice will give a significantly higher signal than undeformed ice both in winter and summer conditions ($\sigma\_$= -8 to -4 dB).

*Landfast ice.*

This is first-year ice attached to the coast. It will generally give the same low signal as ice formed in calm waters far from the coast. It is often quite smooth and reaches out to the so-called "flaw line", the boundary of the moving ice ($\sigma\_$= -13 to -11 dB).

*River ice.*

Ice formed during the winter resembles landfast ice ($\sigma\_$= -13 to -11 dB). In the spring (generally during May in Siberia) the ice will be carried out to sea in a strong current and the many ice blocks can give a higher signal.

### 1.2.5 Practical classification of ice types using SAR images

It is clear from the analysis of backscatter values for different ice types described in 1.2.4 that several ice types cannot be uniquely identified based on pixel values alone. In addition, pattern information in the image, or textural information, is an essential factor in ice classification. Optimal classification can be done using a combination of several image statistics and texture measures (Wackermann, 1991). However, in practical classification it is useful to identify simple ice features such as floes and leads from the image and combine these with backscatter statistics (Fig. 4), met-ocean data such as air temperature, wind and current. In addition it is also important to have good general knowledge about the ice conditions in the region concerned.

### 1.2.6 Conversion of SAR data into annotated image-maps

The process is conducted in the following steps, and an example is given in Fig 5 a,b:

1. Drawing of the SAR features of interest on an image overlay, to be separated when finished. Line features (edge, narrow leads) are drawn directly. Small-scale features (floes, polynyas) may be outlined and shaded. Uniform areas consisting of many complex small-scale features (floe-fields, ice-fields) are marked by their approximate boundaries.

2. Recognition of large features and areas and annotation of the image, either by text only or by text and arrows. In the latter case, the text may be written outside the image.

## 1.3 The winter and summer campaigns during 1994

A previous validation/demonstration campaign was carried out in the Northern Sea Route in late fall (November-early December) 1993 [see Johannessen *et al.*, 1994]. However, in order to cover other seasons, two campaigns were carried out in 1994: winter (February-March) and summer (September-October). As with the previous campaign, emphasis is placed on the Kara Sea. During these campaigns, SAR-derived ice information products were compared with *in situ* observations and Russian ice maps.

There are two general ice description codes that are relevant for the analysis of the SAR data. The first describes the ice concentration and the second describes ice type (based primarily on its age). The codes used in ice observations are given in Tables 1 and 2.

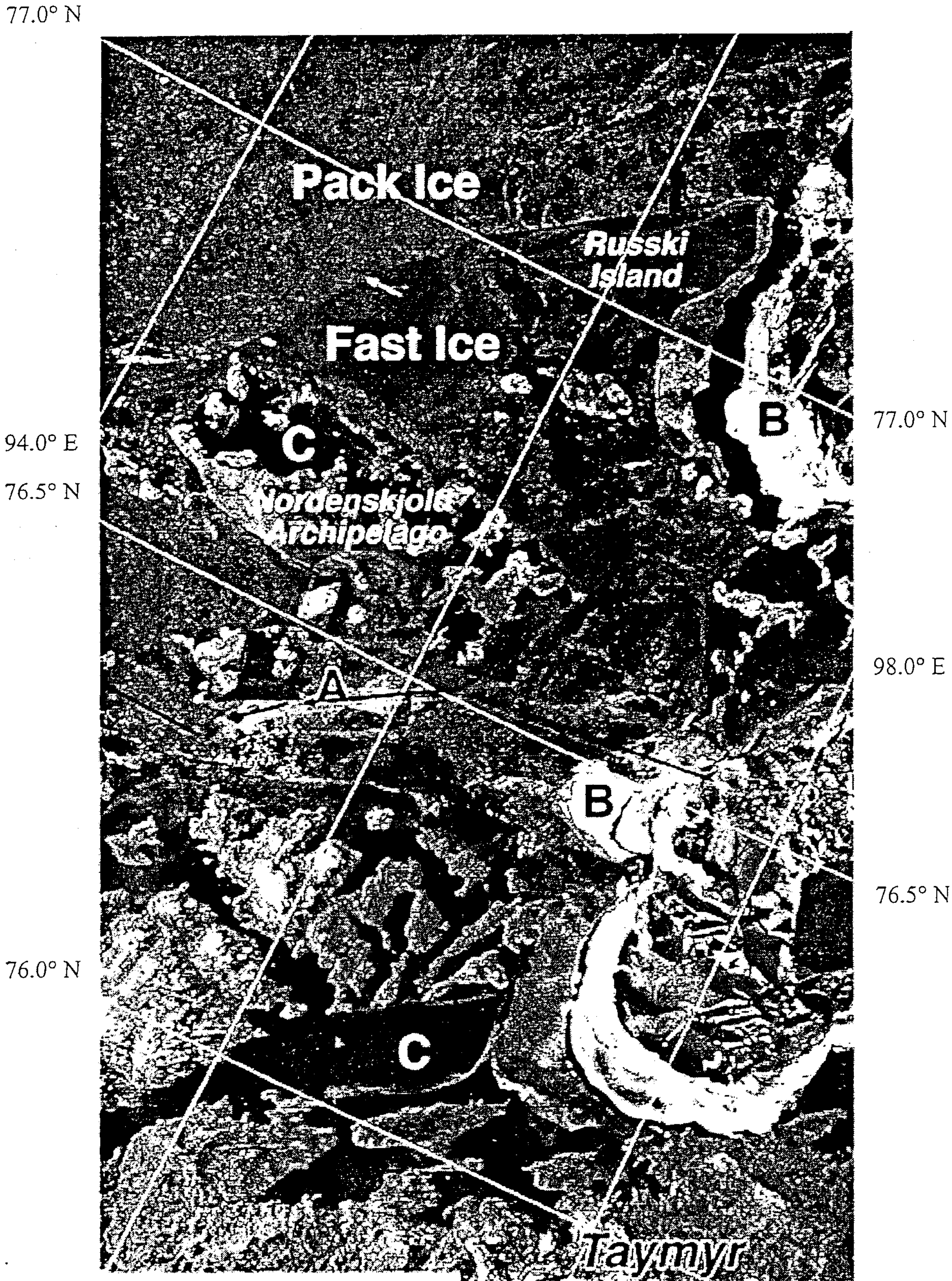



Fig. 5a. ERS-1 SAR image from the Nordenskjold Archipelago region, 28 November 1993.

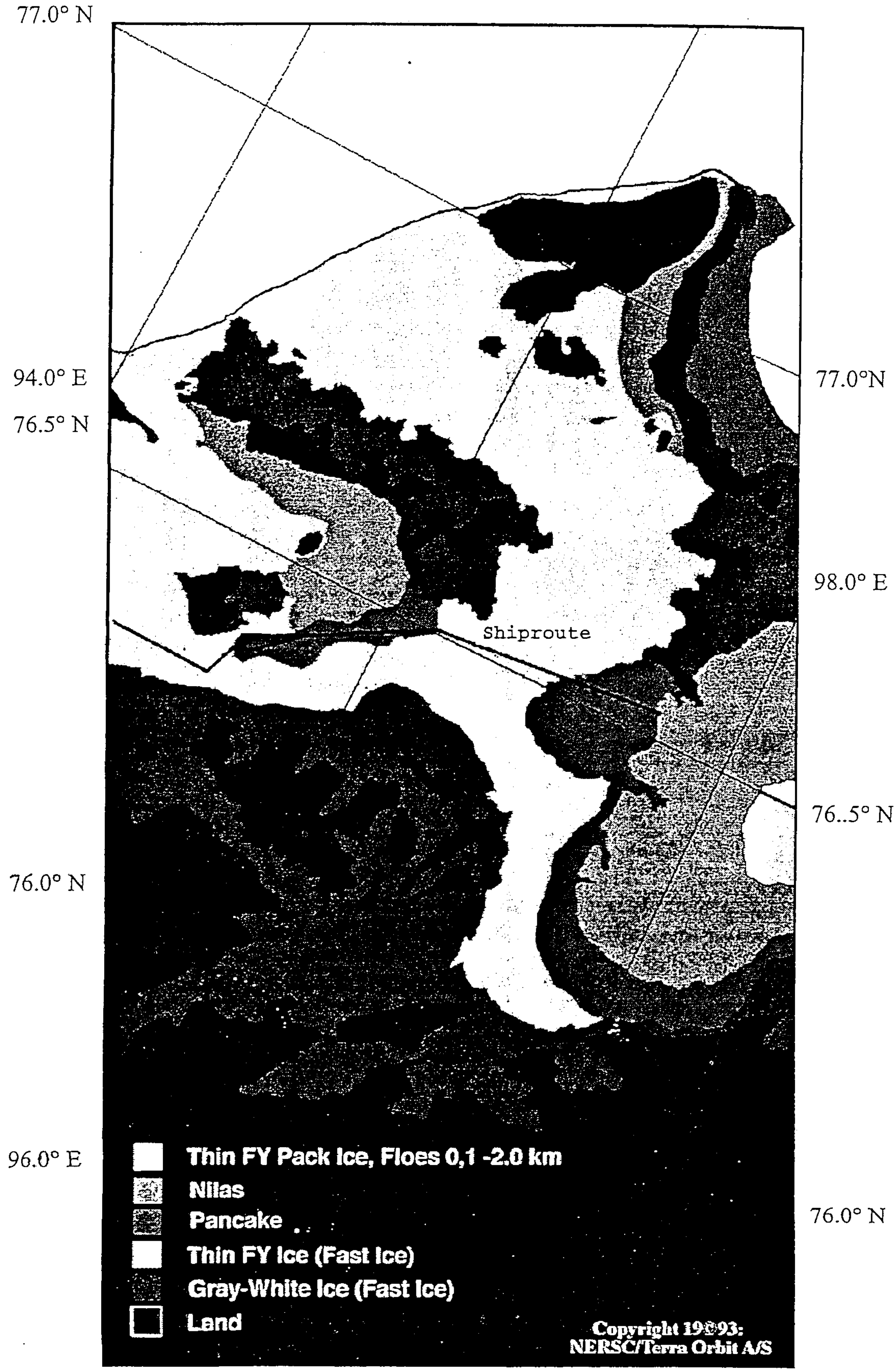



Fig. 5b. Ice map derived from SAR image (Fig 5a) from the Nordenskjold Archipelago region, 28 November 1993.

Table 1. Ice concentration codes

| Code | Description of ice concentration |
|---|---|
| 0 | Sea ice is absent (in field of view) |
| 1 | Ship is in an open water of width more than 1 naut. mile, or the ice is out of sight. |
| 2 | Separate ice floes, very open pack ice of concentration from 1 to 3 tenths |
| 3 | Open pack ice with concentration from 4 to 6 tenths |
| 4 | Close pack ice with concentration from 7 to 8 tenths |
| 5 | Very close pack ice with concentration from 9 to 10 tenths |
| 6 | Strips and patches of pack ice with separate ice floes between them |
| 7 | Strips and patches of closed pack ice or very close pack ice with separate regions of ice with lower concentrations |
| 8 | Fast ice with separate ice floes, very open pack ice or open pack ice at far distance |
| 9 | Fast ice, close pack ice or very close pack ice at far distance |
| / | no observation |

Table 2. Ice type codes

| Code | Description of ice type |
|---|---|
| 0 | New ice (frazil ice, grease ice, slush, shuga) |
| 1 | Nilas type (ice rind, dark nilas, light nilas, pancake ice), thickness < 10 cm |
| 2 | Young ice (grey ice, grey-white ice), thickness 10-30 cm |
| 3 | Predominance of young ice and/or of new ice with inclusion of first-year ice |
| 4 | Predominance of first-year ice with inclusion of young ice and/or of new ice. |
| 5 | Thin first-year ice, thickness30-70 cm |
| 6 | Predominance of medium first-year ice (70-120 cm), thick first-year ice (thickness >120 cm) with inclusion of thinner (younger) first-year ice |
| 7 | Medium first-year ice and thick first-year ice |
| 8 | Predominance of medium first-year ice and thick first-year ice with inclusion of old ice (thickness > 200 cm) |
| 9 | Predominance of old ice |
| / | no observation |

### 1.3.1 The winter validation/demonstration campaign February-March

*Ice and weather conditions.* The weather in February 1994 was characterized by a normal winter situation with a strong high pressure over eastern Siberia which directed southerly and southeasterly winds into the Kara Sea rigion. The air temperature is usually in the range from -20° to -40° C. From 8 to 16 March, the wind changed to southwesterly and warmer air masses with temperature from 0° C to -10° C entered the Kara Sea. From 17 to 25 March the wind was again southeasterly with temperatures from -15° to -25°C.

With winds blowing from land to ocean, polynyas between the landfast ice and the pack ice are formed several places in the Kara Sea: the Amderma Polynya in the southwestern part of the Kara Sea, the Yamal Polynya, the Dikson Polynya and the Severnaya Zemlya Polynya.

The latter is the largest one and extends from near Dikson to the northernmost islands of Severnaya Zemlya, nearly 1000 km.

The polynyas open up and refreeze many times during the winter. The polynyas are therefore important sailing routes since the ice in the polynyas is thinner and easier to penetrate than the surrounding landfast ice and the packice.

The ice conditions in February and March 1994 were typical for this time of the year, as shown in the Russian ice map (Fig. 6a,b). The ice edge was located west of Kolguyev Island, close to the entrance to the White Sea. Most of the ice in the Pechora and Kara Seas was easy to penetrate by the icebreakers.

In general there are two main problems concerning the ice navigation: one is the entrance to the Kara Sea through the Kara Gate or the Jugor Strait. Difficult ice conditions occur frequently due to the strong currents in these straits. The icebreakers will select the strait with most favorable ice conditions. Accurate ice maps are particularly important in this region. The second difficult area is the Yenisei Gulf and Yenisei River. In this area, the navigation is restricted to fixed channels where the bottom depths allow the icebreakers to sail. The tidal range and river discharge are particularly critical factors for the navigation, in addition to the ice conditions.

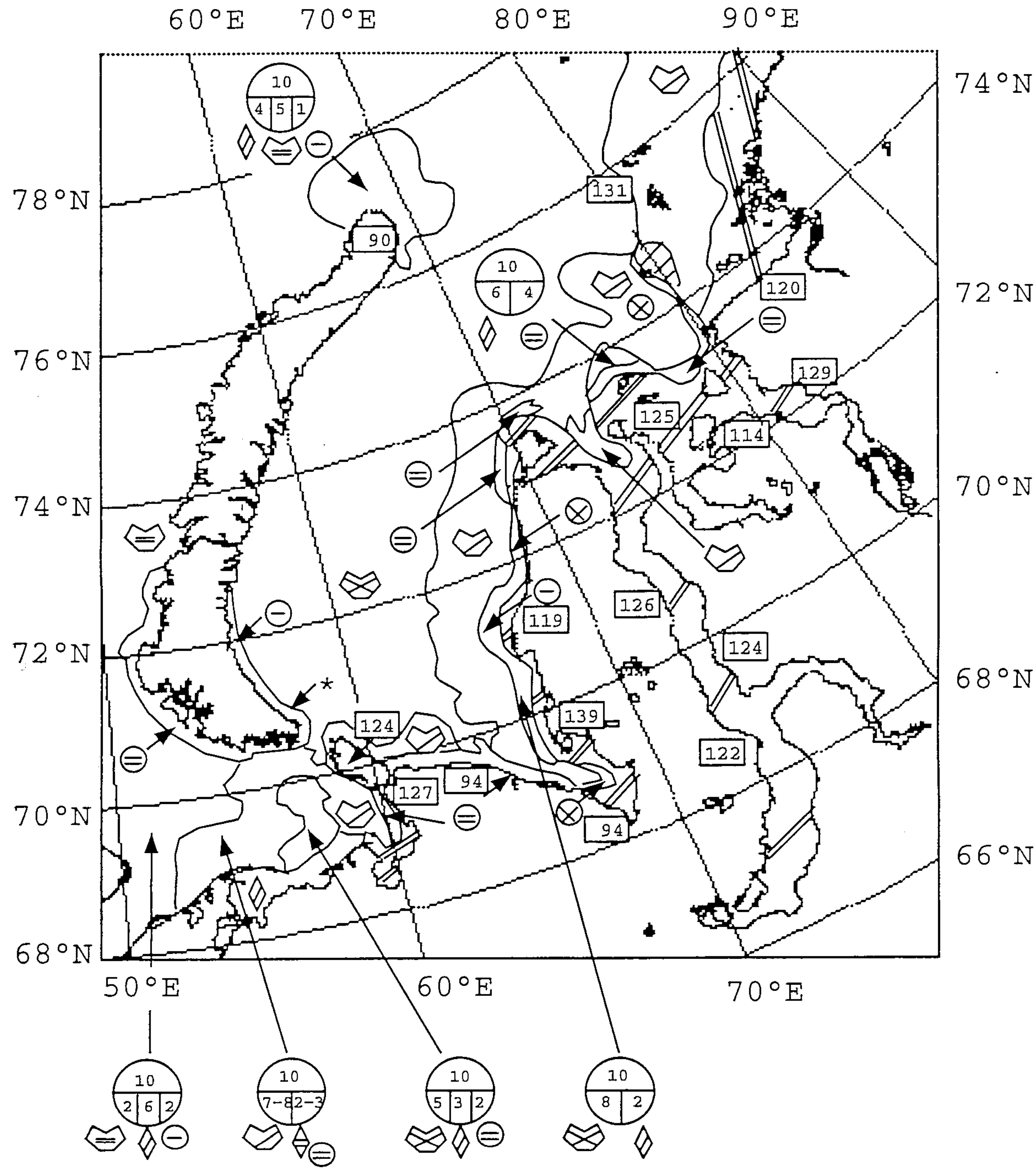



Figure 6a. Russian ice map (reproduced digitally at NERSC) from 19-21 February 1994.
The codes and symbols are explained in Fig 6b.

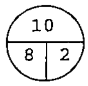
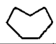
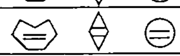
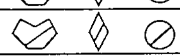
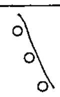
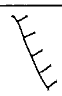
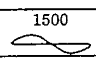
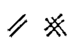
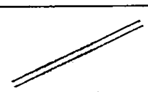
| Symbols | Ice parameters | |
|---|---|---|
|  | ice concentration (tenths)<br>thick ice conc. (tenths) I thin ice conc. (tenths) | |
| | **Floe size** | **Horizontal sizes** |
|  | vast floe | 2 – 10 km |
|  | big floe | 0.5 – 2 km |
|  | medium floe | 100 –500 m |
|  | small floe | 20 – 100 m |
| | **Age of ice** | **Thickness** |
|  | grey ice | 10 –15 cm |
|  | grey white ice | 15 –30 cm |
|  | thin first year ice | 30 –70 cm |
|  | medium first year ice | 70 –120 cm |
|  | thick first year ice | > 120 cm |
| | **Miscellaneous features** | |
|  | compressed ice | |
|  | compressed ice edge | |
|  | diffuse ice edge | |
|  | open water | |
|  | width of fracture | |
|  | ridges | |
|  | hummocking | |
|  | floeberg | |
|  | small ice cake | > 2 m |
|  | brash ice, flaw | |
| 124 | ice thickness (measured) | in centimeters |
| * | nilas | |
|  | fast ice | |

Figure 6b. Codes and symbols used in Russian ice maps (Fig. 6a)

*The icebreaker transits.* The validation/demonstration project started a the scientist from NIERSC went onboard the icebreaking freighter *Sevmorput* in Murmansk on 24 February. *Sevmorput* is a 260 m long freighter with nuclear engines of 40000 horsepower. During the next month, four transits were made between the Pechora Sea and Dudinka on the Yenisei River:

| | |
|---|---|
| 24 - 28 February: | eastward transit |
| 8 - 12 March: | westward transit |
| 14 - 19 March: | eastward transit |
| 23 - 25 March: | westward transit |

In addition to the *Sevmorput*, the icebreakers *Vaygach* and *Taymyr* participated in the transits. The *Vaygach* and *Taymyr* are shallow-water icebreakers with a draft of 9 m, and thus can operate on the Yenisei River. As an example, the positions of the *Sevmorput* are plotted every six hours for the 24-28 February transit is shown in Fig. 7.

*Ice and meteorological observations.* Observations of wind, temperature, pressure and ice parameters were made by the hydrologists onboard icebreakers every six hours during the transits. These data are important for the monitoring and forecasting of the ice conditions at the Marine Operational Headquarters in Dikson. These data are also important for interpretation of the SAR images obtained during the campaigns.

*Description of ice conditions.* A selection of SAR images from four different areas will be presented: the Kara Gate/Jugor Strait, Cape Kharasavey, Ob Gulf, and Yenisei Gulf. Each of these areas were covered by SAR repeatedly every three days. The ice conditions in each image will be briefly described, using *in situ* observations from the icebreakers.

Case 1. The Jugor Strait. In each of the transits, the Jugor Strait was used because the ice conditions were estimated to be more difficult in the Kara Gate.

The first image of the Jugor Strait was obtained on 25 February (Fig. 8a) a few hours before the icebreakers passed through the strait. In the Pechora Sea the ice concentration in the sailing route was high (9-10 tenths) with thickness 30-70 cm. The Jugor Strait itself was fully ice-covered as seen in the image, apart from the northern part. The wind was southeasterly 11-16 m/s.

The second image is from 12 March (Fig. 8 b) when the icebreaker was sailing westwards. Southwesterly winds had opened up the Amderma Polynya. The strait is again clogged with ice, and the Pechora Sea has very close packice (9 - 10 tenths) consisting of first-year ice with inclusion of young and new ice.

In a later image, taken on 24 March after a period of northeasterly wind, the Amderma Polynya had disappeared and the ice west of the Jugor Strait had opened up.

Case 2. Cape Kharasavey. When *Vaygach* passed Cape Kharasavey, located on the west coast of Yamal Peninsula, on February 26 the wind was easterly 5-12 m/s with temperatures below -30° C. In the SAR image (Fig. 9) from this day, various stages of young ice were observed in the Yamal Polynya. As the ice is advected from the coast and open water is exposed to the cold air, new ice is immediately formed. During southerly and easterly winds, which dominated in February and March 1994, the ice conditions were favourable for navigation along the coast.

When the icebreaker was sailing westwards in this area on 10 March, the ice conditions had not changed. SAR images obtained on 10 and 16 March showed that the ice moved slowly northwards, at a speed of 1-3 km per day. This ice motion is caused by the current regime.

In situations with northerly and westerly winds, the ice is pushed towards the coasts and the Yamal Polynya can disappear. Heavy ridging can occur if such winds prevail for several

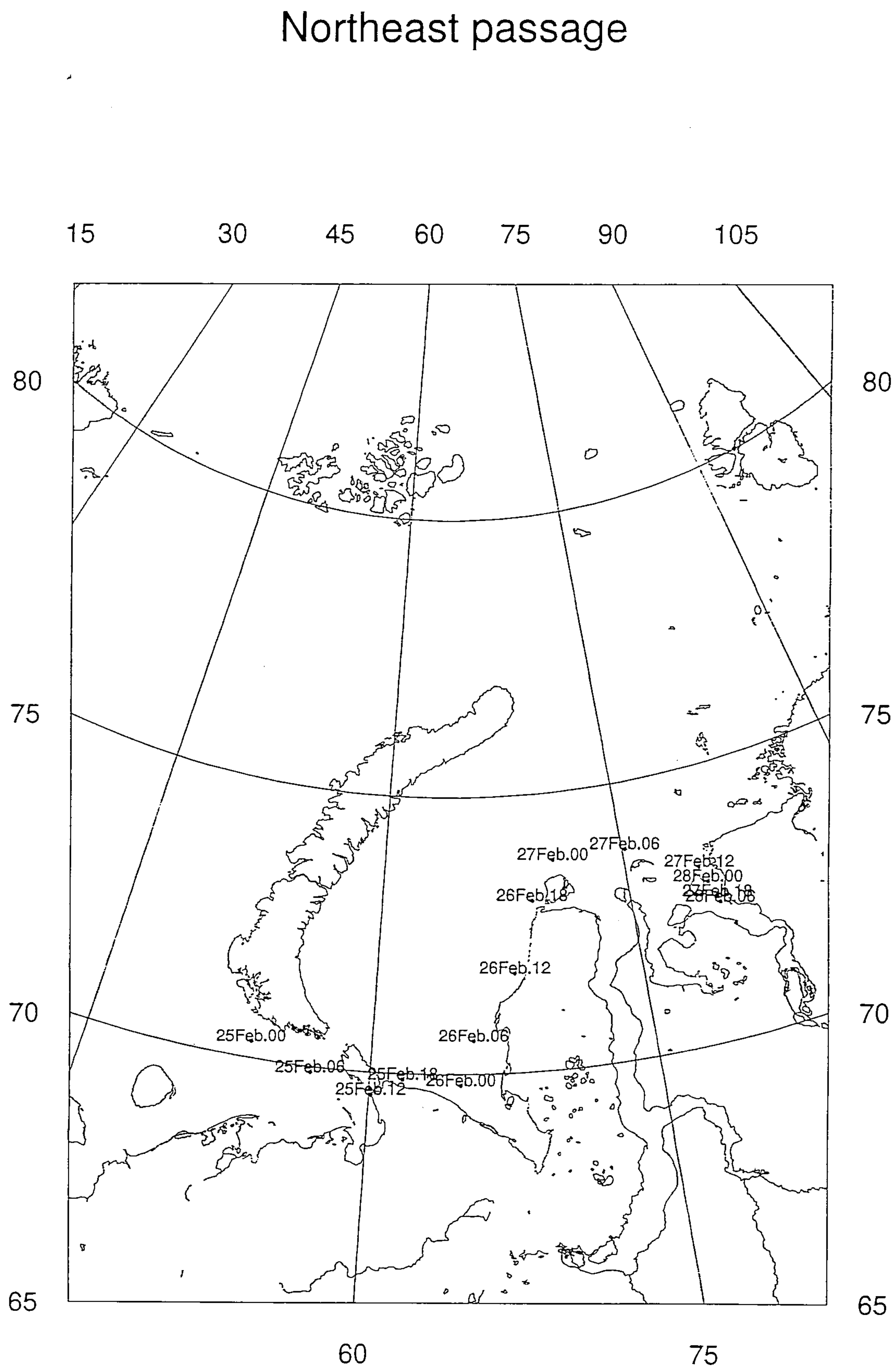



Figure 7. The position of the Sevmorput plotted every 6 hours for the first transit.

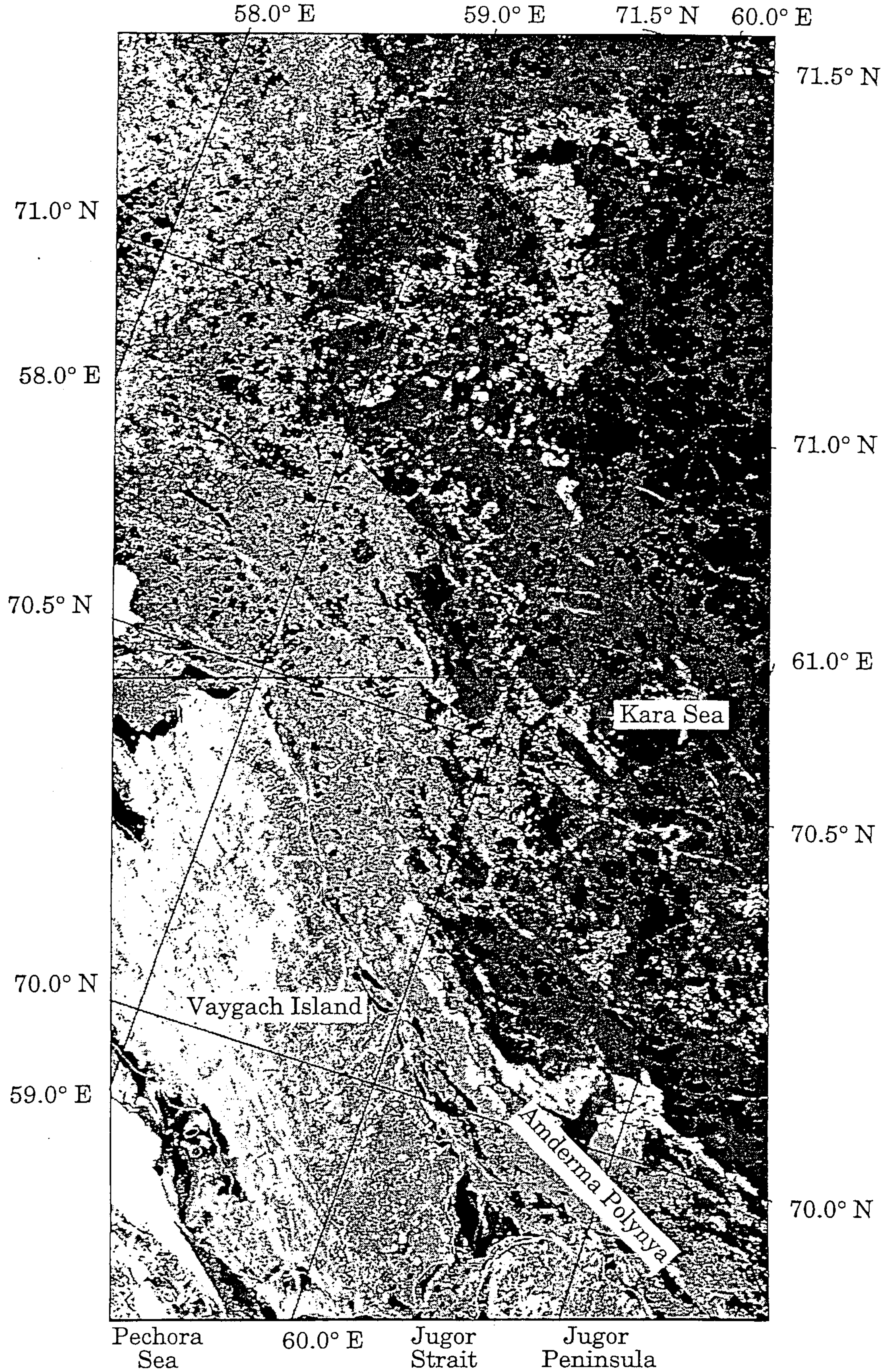



Figure 8a. ERS-1 SAR image from the Southwestern Kara Sea 25 February 1994.

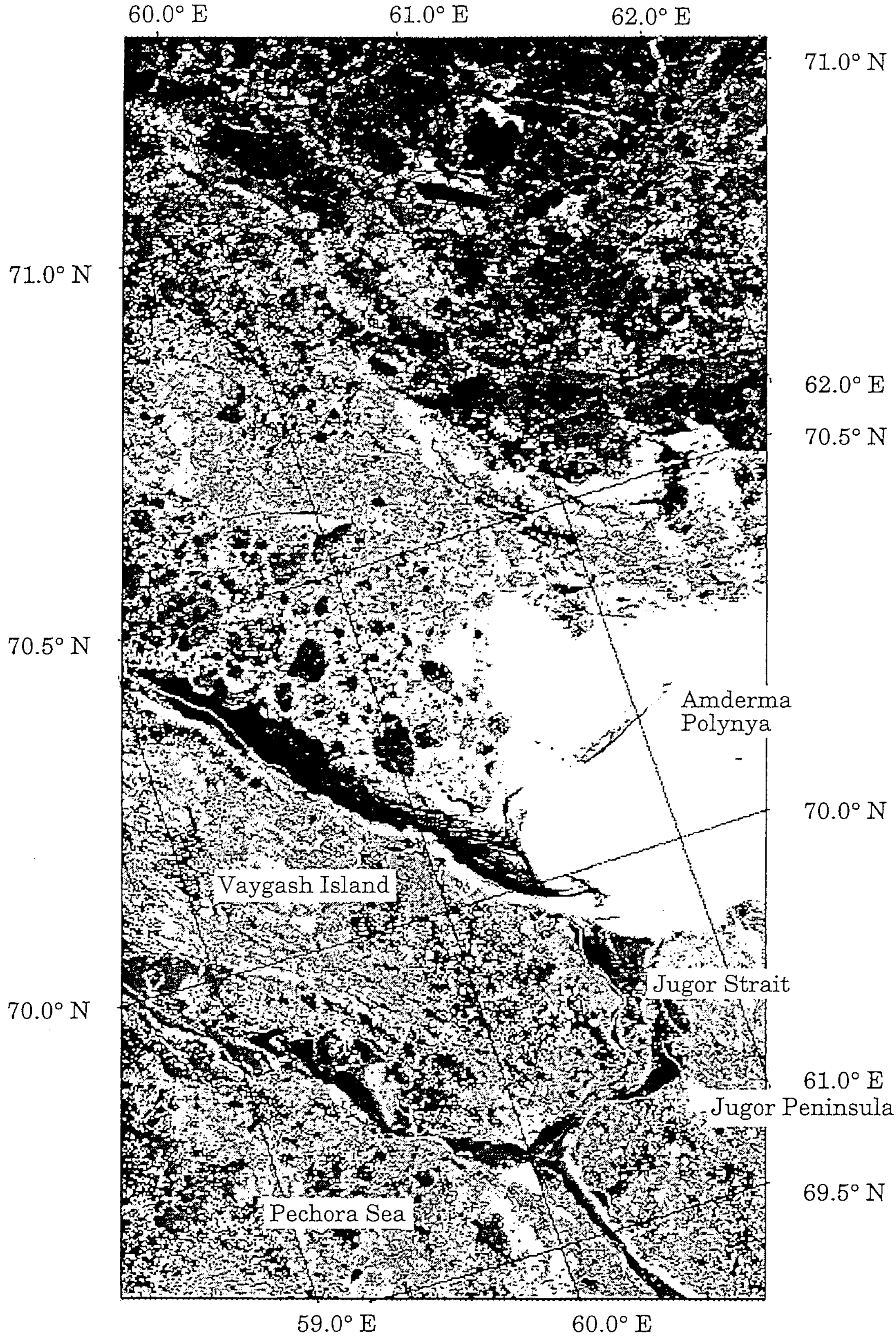



Figure 8b. ERS-1 SAR image from the Southwestern Kara Sea12 March 1994.

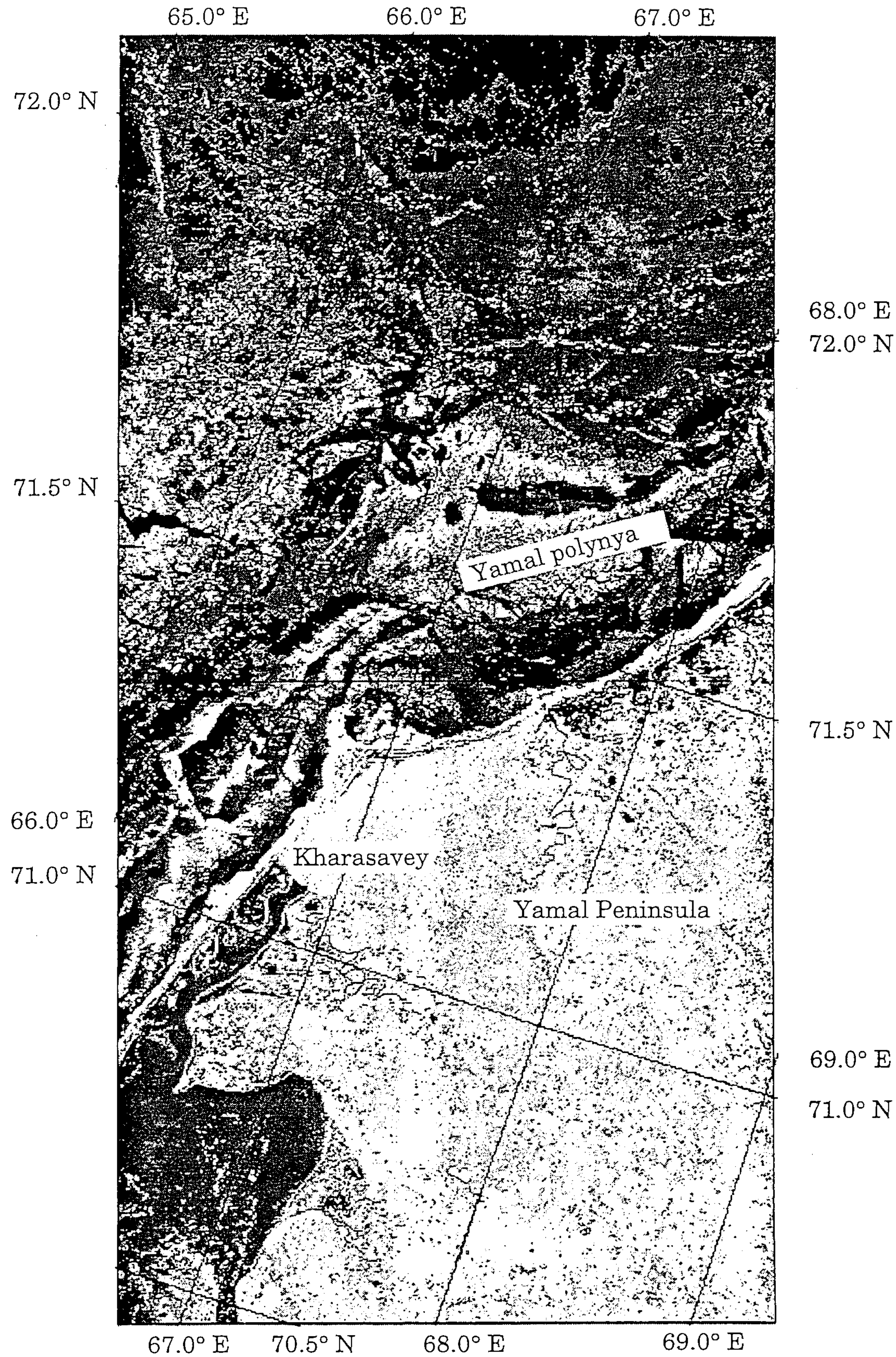



Figure 9. ERS-1 SAR image of 26 February off the Yamal Coast. The image was obtained a few hours after the *Vaygach* passed through the area.

weeks. In such conditions the icebreakers have the option of choosing another route, from the Belyi Island towards the northeast coast of Novaya Zemlya, and along the coast of this island where a polynya opens up during northwesterly winds.

Case 3. Ob Gulf. The Ob River releases large amounts of fresh water into the Kara Sea which freezes in the winter. Some of this ice is landfast along the coasts or stuck to the bottom in shallow areas. The icebreaker transit passed the Ob Gulf north of Belyi Island (at about 73° 50') where no ice problems were encountered. The ice was 1-2 m thick first-year ice without strong ridges which could cause difficulties for the navigation. However, the ice in the area can be difficult to penetrate if there is much freshwater ice from the rivers. The SAR image from 27 February (Fig. 10) shows the shear zones between landfast ice or ice which is stuck to the bottom, and the drifting ice. The dark signature of the ice indicates that it is undeformed. The ice velocity vectors, which have been estimated by the ice kinematics algorithm [Sandven *et al.*, 1991], show that the ice moves northwards at an average speed of 6 cm/s.

Case 4. Yenisei Gulf. The ice conditions in the Yenisei Gulf in the winter time are usually stable and dominated by 1-2 m thick fast ice. Much of the ship traffic in this period is to the ports in Dudinka and Igarka on the Yenisei river where sea transportation is important throughout the year. The icebreakers have fixed sailing routes which are determined by the bathymetry. The shipmaster sailing route to be used is dependent on ice conditions. With SAR images available in near real-time it is possible for the captain to select the most favourable route. The SAR mosaic presented in Fig. 11 is composed of 5 scenes obtained between 18 and 23 March 1994. The most important information from the SAR images is the location of thin, undeformed ice (dark signature) and areas of deformed ice which can be several meters thick due to ice keels and ridges (bright signature).

### 1.3.2 Summer validation / demonstration campaign September-October 1994

This section presents the results of the summer campaign. The presentation style used here is different to the winter results (section 1.3.1). The style used here serves to better demonstrate how the icebreakers actually operate during such a period.

*Schedule of events.*

| Date | Event |
| --- | --- |
| 07. Sep. | First attempt to send SAR (6/9) to the *Taymyr*. No contact. |
| 08 " | Departure of V.M. from Archangelsk onboard Capt.Archenevsky. |
| 09. " | Transfer of V.M. to the *Taymyr*. at 95°E. |
| 09. " | Start of 1st eastward voyage through Vilkitskogo Strait to 115°E. |
| 11. " | Start of return voyage from the Laptev Sea. |
| 13. " | Start of 2nd eastward.voyage through Vilkitskogo Strait to 105°E and return. |
| 13. " | Telephone conversation with V.M. |
| 15 " | Start of 3rd eastw. voyage through Vilkitskogo Strait to 118°E. |
| 21. " | Start of the return voyage from Laptev Sea through Vilkitskogo Strait to 100°E. |
| 23. " | Start of 4th eastward voyage to the east end of Vilkitskogo Strait at 107°E. |
| 24. " | Telephone conversation with V.M. |
| 25. " | Start of waiting period in Nordenskjold Archipelago at 95°E |
| 29. " | Start of 5th eastw. voyage through Vilkitskogo Strait. |
| 30. " | Transfer of V.M. to the *Vaygash* at 115°E |
| 30 " | Start of return voyage through Vilkitskogo Strait to 97°E. |
| 02. Oct. | Short voyage to Vilkitskogo Strait at 102°E and return to 95°E. |
| 03. " | Another short voyage to 102°E. |
| 04. " | Start of final return westward voyage. |

V.M.: Dr. Vladimir Melentyev (NIERSC)

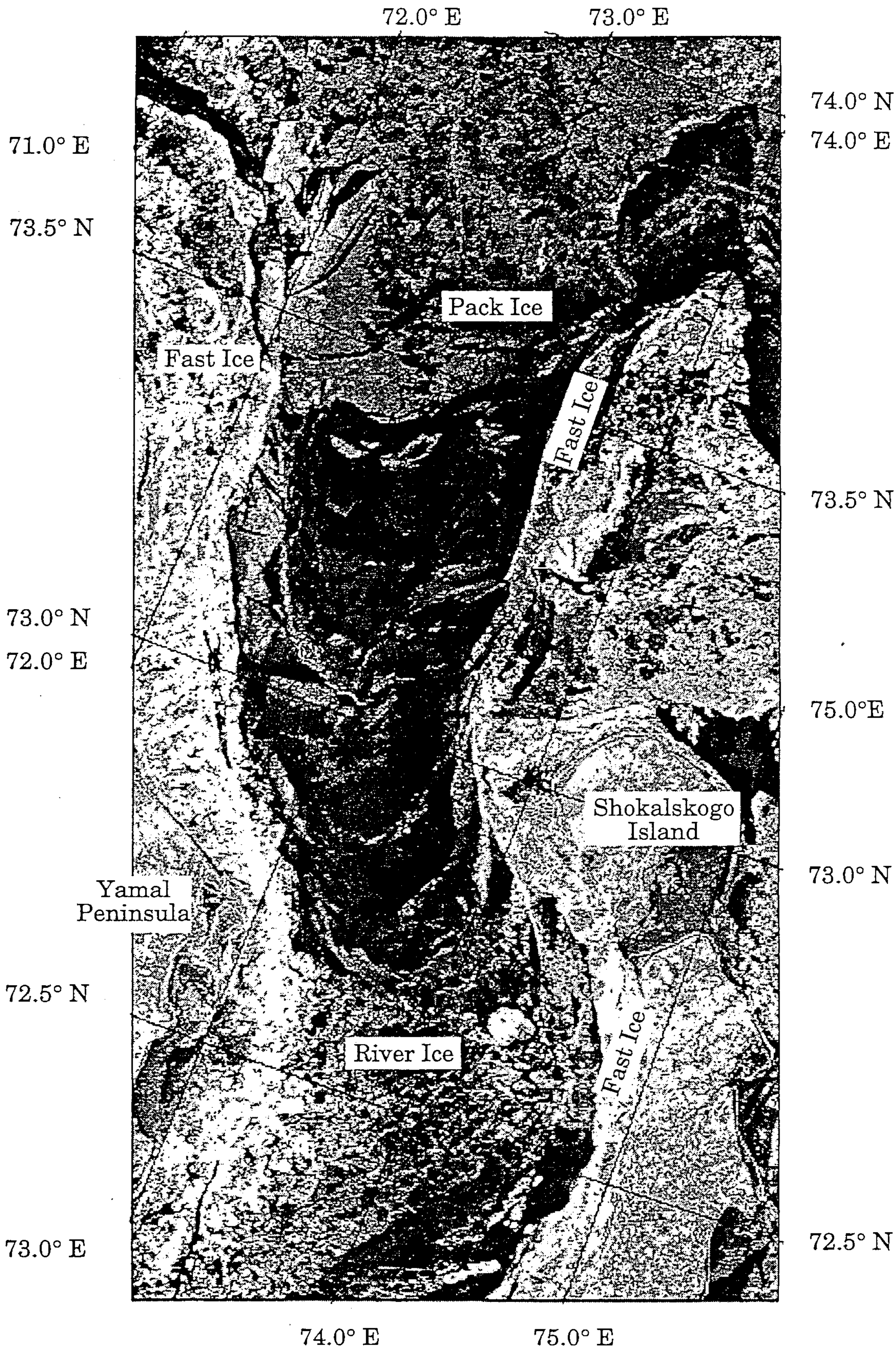



Figure 10. ERS-1 SAR image of the Ob Gulf, 27 February 1994.

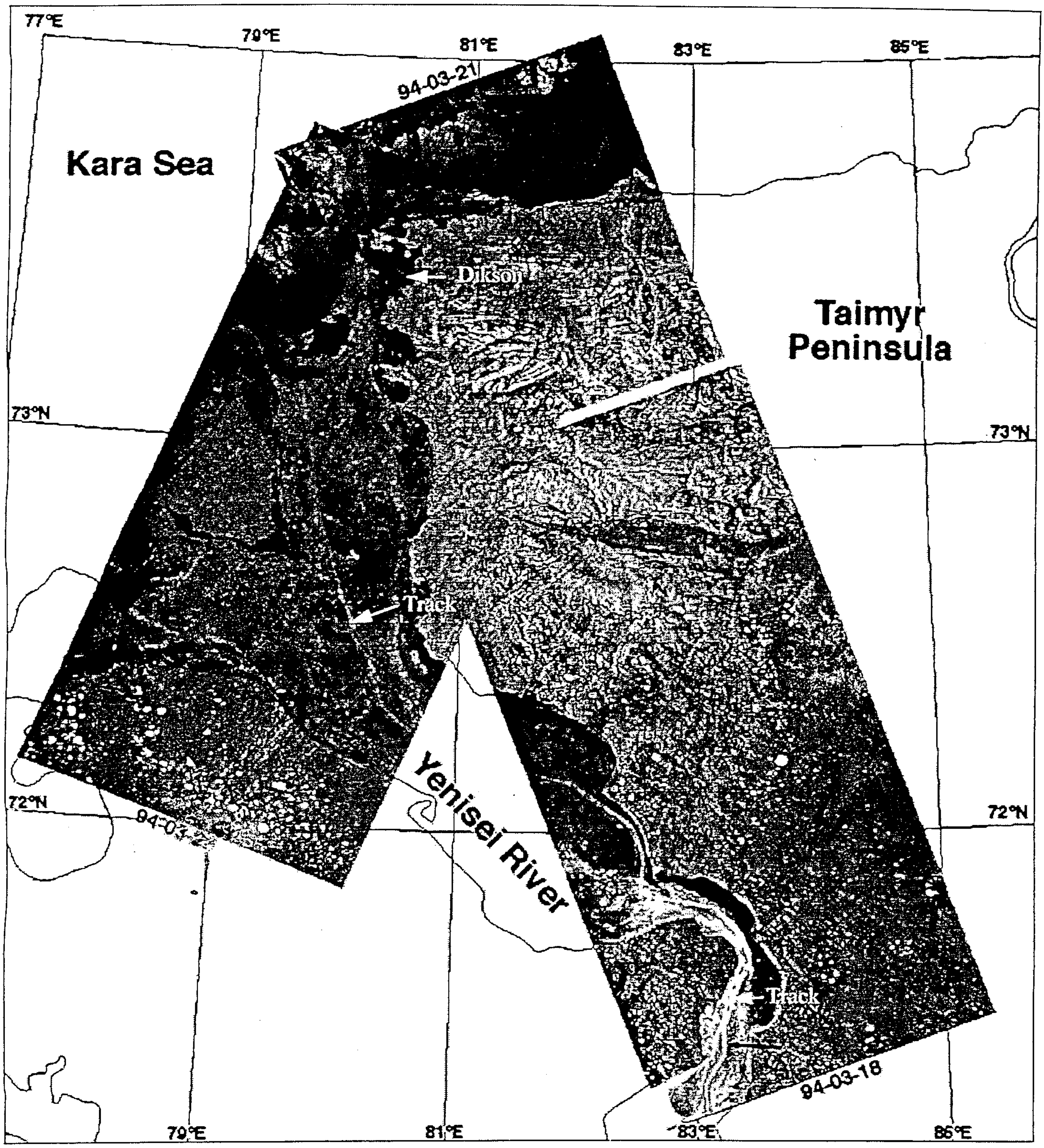



Figure 11. ERS-1 SAR mosaic of the Yenisei Gulf from 18-23 March 1994.

*Description of the experiment.* Following general information on the sailing routes, ice-covered areas from the Siberian coast and about 100 km to the north had priority when selecting SAR scenes. The TSS coverage put an eastern limit at about 105°-107°E. The west and east ice edges were located at approx. 94°E and 115°E in mid-September and were nearly stable during this month. Vladimir Melentyev was onboard the *Taymyr* from 9-30 September; after this date he was on the *Vaygash.*

In all, 22 SAR passes were processed at NERSC between 17 August and 26 September. Of these, 13 SAR images were sent to Dikson by fax. Scenes showing only little ice or the ice edge were not sent. Contact with the *Taymyr* was poor and never possible by fax. The negative result can be caused by a variety of factors: the ship being out of reach of INMARSAT, poor atmospheric conditions, antenna in poor position, etc.

After 26 September, problems with SAR reception at TSS stopped the processing of further scenes until 11 October. Before that date, the operation of TSS was very good. An urgent request was sent to ESA on 12 September for more SAR passes west of Vilkitskogo Strait, 96°-103°E, in the second half of September. Otherwise, the ESA acquisition schedule was good for our purposes. SAR ice imaging continued in October and November, with 5 images sent to Dikson (16 October to 7 November). Thereafter 5 images were sent to the *Sovetsky Soyuz* working in the eastern part of the Kara Sea.

The delay between SAR image time and time the fax was successfully transmitted varied from about 1 day to 3 days, depending on several factors in the processing chain. Because no image was received directly on the ship and the analysts at Dikson used this information in a general way, this delay is not believed to have been critical. Due to system changes in the data distribution service in USA, no SSMI ice concentration maps were available before the beginning of November. No ice analyses (except marking of water, land and possible shiptracks) were made on the images in near-real time.

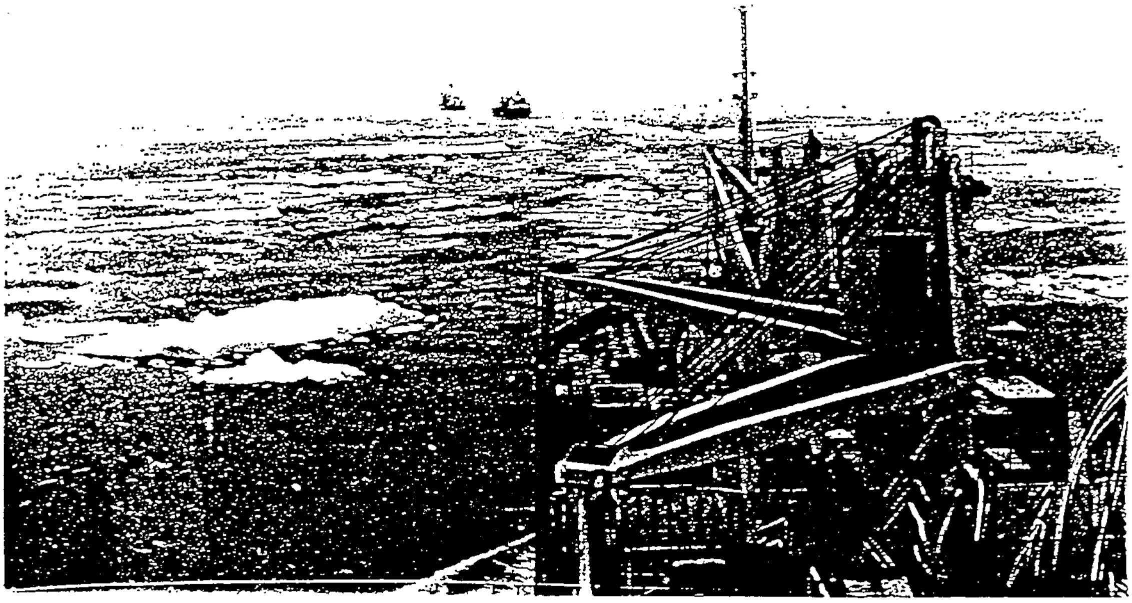
*Comparison between SAR images and photographs.* The following is a description and comparison of 6 selected interesting ice situations in September 1994, taken by VM onboard the *Taymyr* during the 3rd expedition in the Northern Sea Route. Even though none of the photos were taken at exactly any of the SAR overpass times, the difference in time for most of the photographed situations is reasonably small. It can then be assumed that no major change of the ice situation has taken place between the photo time and the SAR overpass time.

Case 1.

Photo no.101: 10 September 02z, 77.1°N, 101°E
Wind: 5 -6 m/s Ice: Open pack 30 -60%, thin FY 30 -60cm thick.
SAR image: 09 September 14z. Time difference: 12 hours.

The convoy is travelling eastward along the Chelyuskin Peninsula toward the Vilkitsky Strait. The photo (Fig. 12 upper) shows scattered ice in water, with more dense ice (or some fog) in the distance to the left of the heading, toward the Taymyr coast.

The SAR image (Fig. 12 lower) at this position shows medium bright backscatter with some darker bands and brighter patches. Since the wind is low, the darker areas correspond to open water and the brighter to denser fields of ice floes. The dense ice seen in the distance in the picture should correspond to a band of ice along the coast as seen in the SAR.



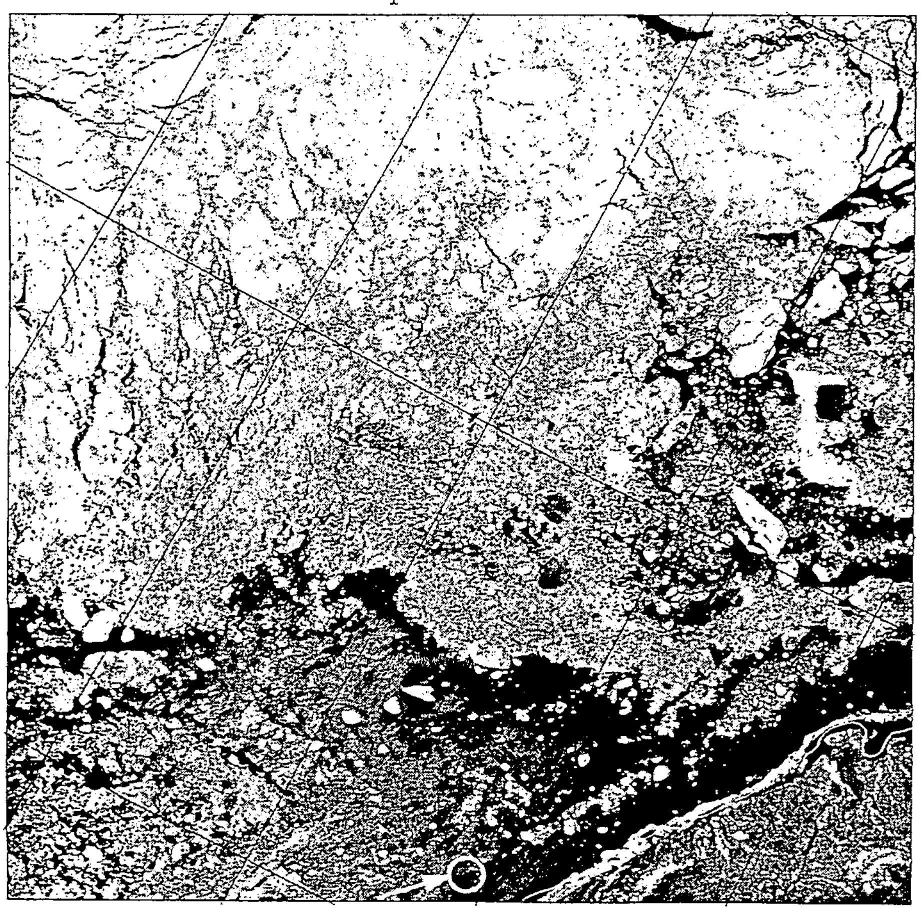



Figure 12. Case 1: Photograph (upper) near the Chelyuskin Peninsula 10 September 1994, and a SAR image from 9 September 1994.

Case 2.

Photo no.119: 10 September 03z, 77.3°N, 102°E
Wind and ice: same as for the previous photo.
SAR image: 09 September 14z. Time difference: 13 hours.

The convoy is travelling eastward along the Chelyuskin Peninsula toward the Vilkitsky Strait. The photo (Fig. 13 upper) shows mostly open water with a few patches of ice. The band of more dense ice (or fog) is also here seen to the left.

The SAR image (Fig. 13 lower) at this position shows low, homogeneous backscatter, as would be expected of open water in low wind.

Case 3.

Photo no.226: 14 September 07z, 77.8°N, 104°E
Wind: 5 -8 m/s Ice: Very close pack ≈90%, thick ice ≈150cm.
SAR image: 15 September 14z. Time difference: 24 hours.

The convoy is travelling westward near Cape Chelyuskin in the Vilkitsky Strait. The photo (Fig. 14 upper) shows the convoy in dense ice, with open water only in the ship-lane. This is a situation with hard ice maneuvering in a stable ice situation.

The SAR image (Fig. 14 lower) at this position has variable, mostly medium backscatter. The signatures of larger floes are both dark and bright, and no sign of large leads or openings in the ice are seen by the SAR.

Case 4.

Photo no.233: 16 September 05z, 77.6°N, 105.5°E
Wind: 5 -8 m/s Ice: Open pack 40 -60%, thin FY 30 -70cm thick.
SAR image: 18 September 14z. Time difference: 2 days, 9 hours.

The convoy is travelling eastward east of Cape Chelyuskin. The photo (Fig. 15 upper) shows many ice floes in open water.

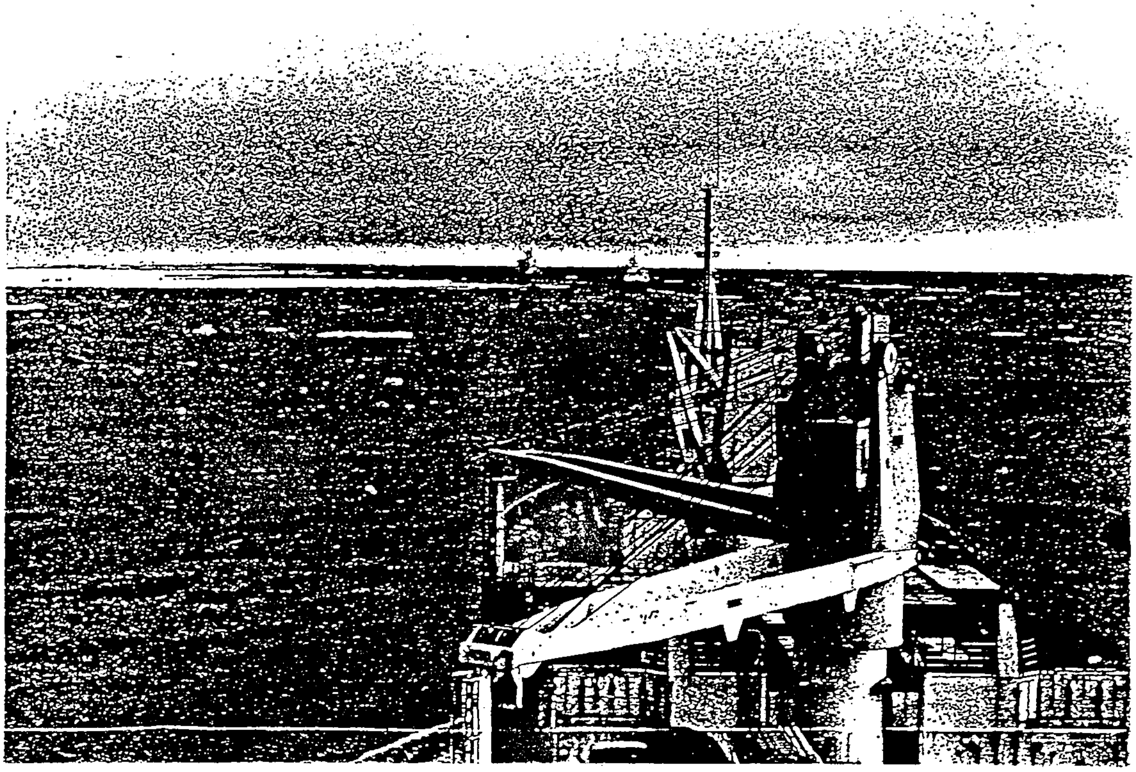
The SAR image (Fig. 15 lower) at this position has a very uniform medium backscatter. The icefloes are not resolved in the image. Evenly distributed small floes in water will give rise to the uniform backscatter seen.

Case 5.

Photo no.401: 22 September 13z, 77.7°N, 106°E
Wind: 10 m/s Ice: Close pack 80 -90%, ≈100cm thick.
SAR-image: 21 September 14z. Time difference: 23 hours.

The convoy is travelling westward east of Cape Chelyuskin. The photo (Fig. 16 upper) shows a ship near a very large floe with a large lead in the foreground.

The SAR image (Fig. 16 lower) at this position has very variable backscatter with both bright and dark large floes, as well as some leads with a medium backscatter signal. The medium lead signature is probably mainly determined by a high wind speed.



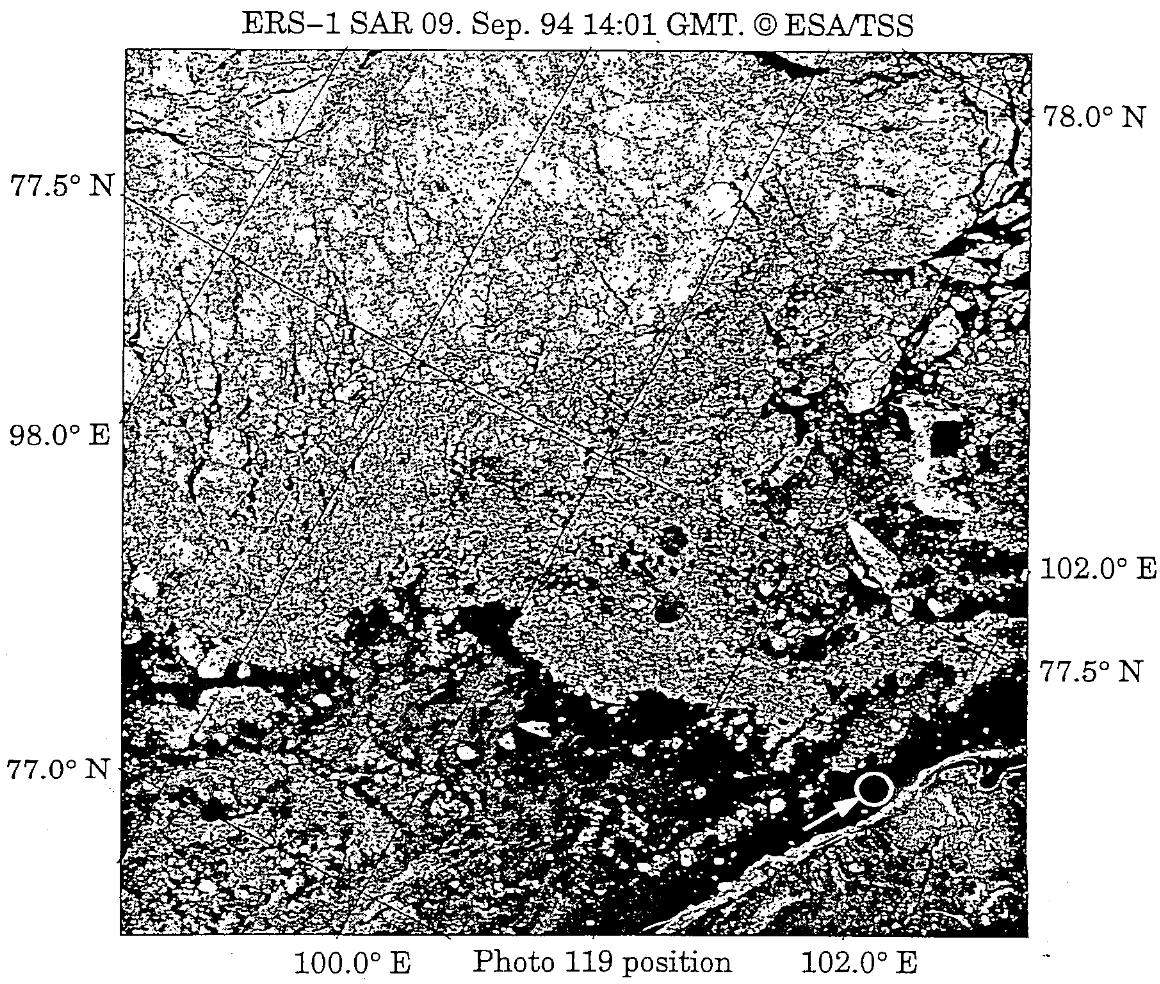
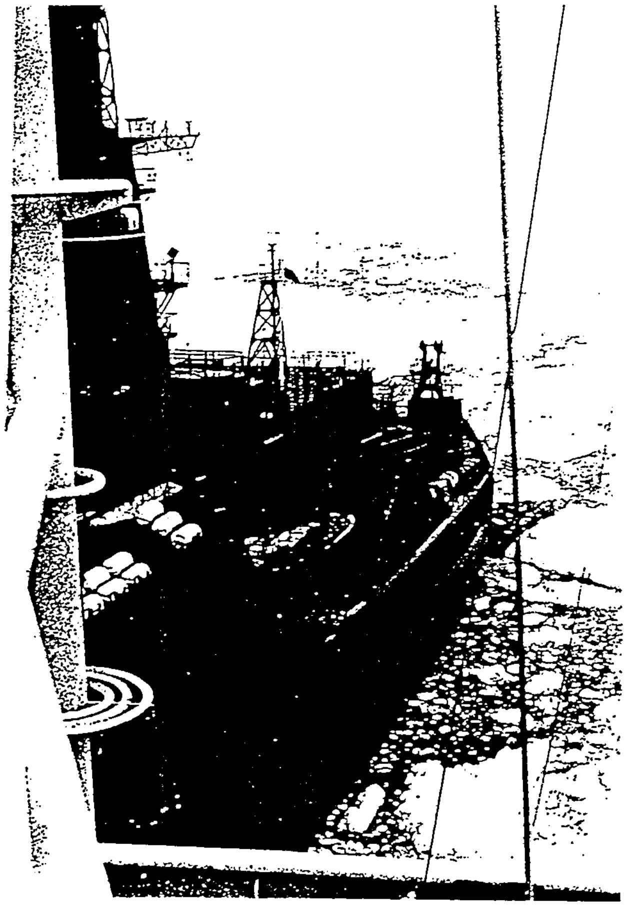



Figure 13. Case 2: Photograph (upper) near the Chelyuskin Peninsula 10 September 1994, and SAR image from 9 September 1994.



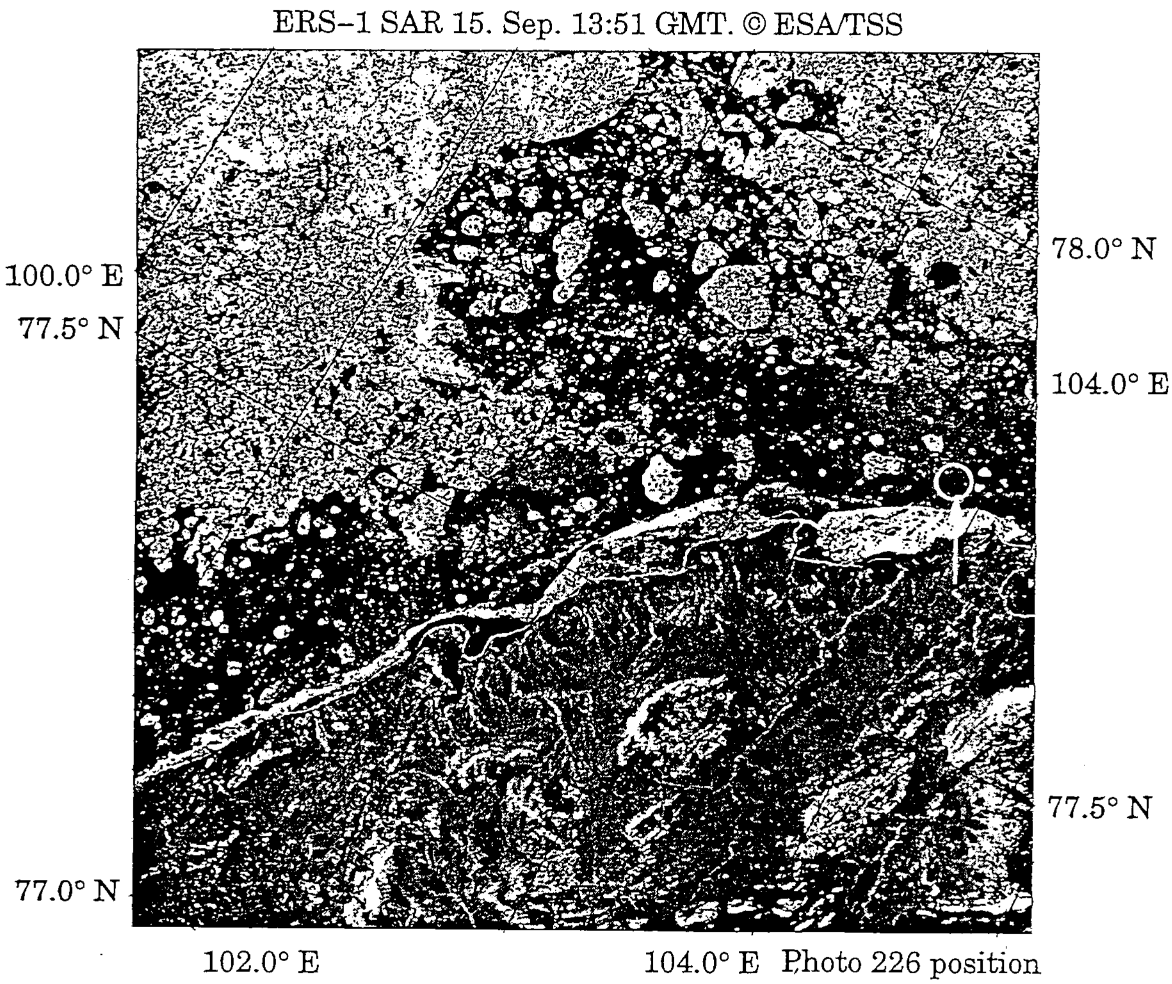



Figure 14. Case 3: Photograph (upper) near the Chelyuskin Peninsula 14 September 1994, and a SAR image from 15 September 1994.

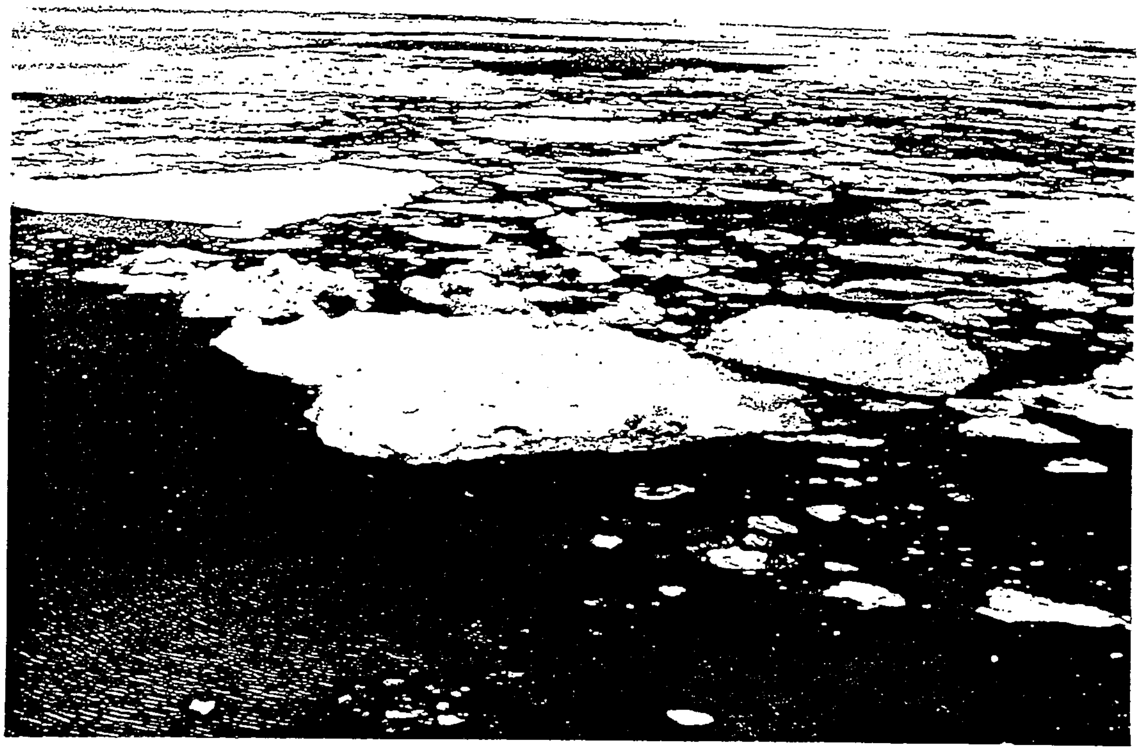
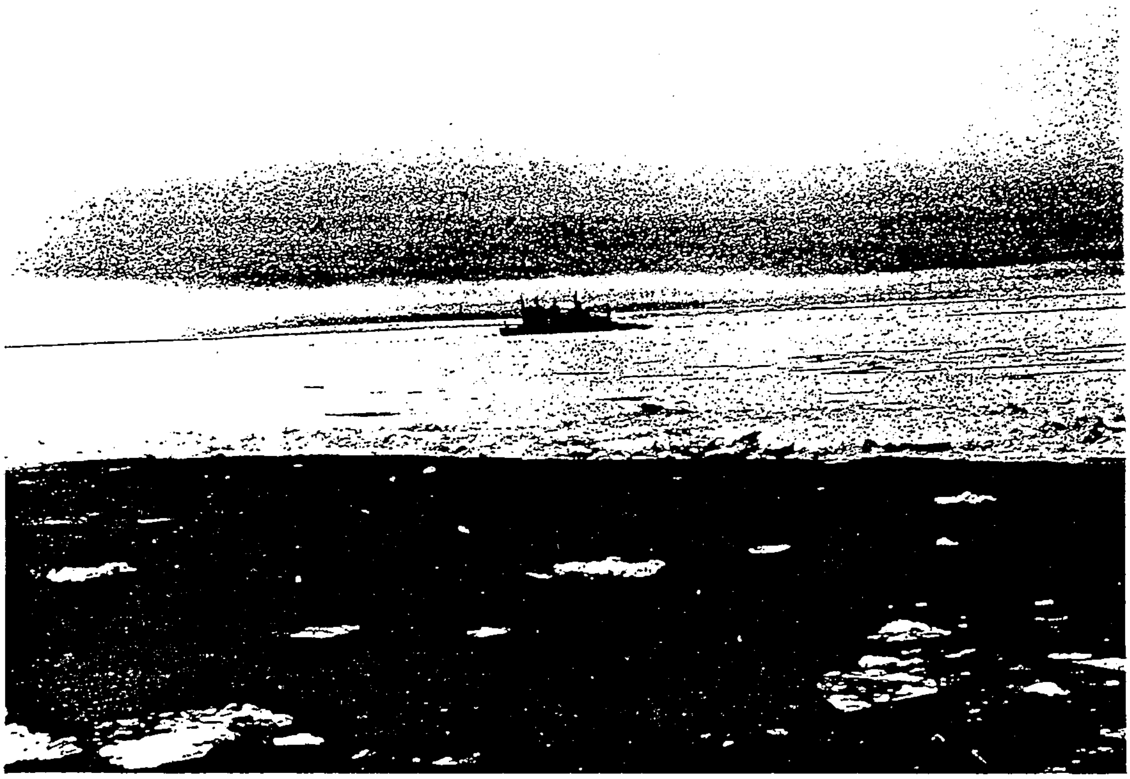



Figure 15. Case 4: Photograph (upper) east of Cape Chelyuskin 16 September 1994, and a SAR image from 18 September 1994.



ERS–1 SAR 21. Sep. 13:40 GMT. © ESA/TSS

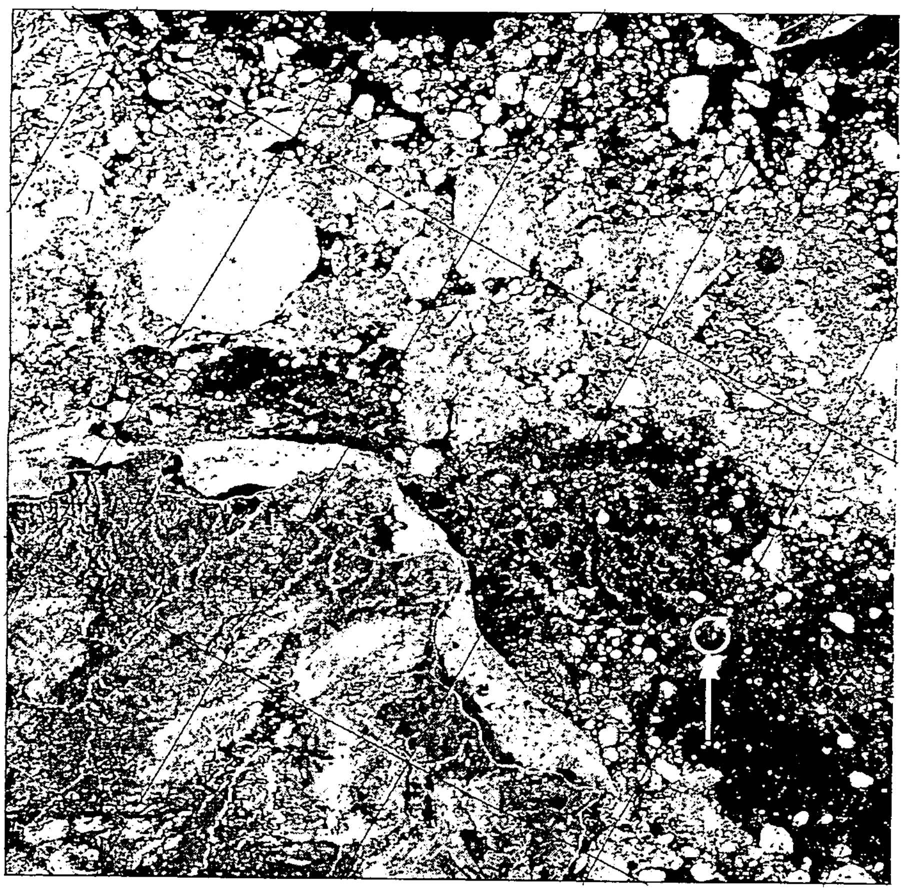



Figure 16. Case 5: Photograph (upper) east of Cape Chelyuskin 22 September 1994, and a SAR image from 21 September 1994.

Case 6.

Photo no.421: 24 September 0z, 77.6N, 106E
Wind: 4 m/s Ice: Very close pack 90%, medium FY and some nilas.
SAR image: 21 September 14z. Time difference: 2 days, 10 hours.

The convoy is travelling westward east of Cape Chelyuskin. The photo (Fig. 17 upper) shows the convoy in a lead in dense ice.

The SAR image (Fig. 17 lower) at this position has the signature as described above. A comparison with the photo is difficult due to the large time difference - no nearer SAR scenes were available for this photo.

## 1.4 Preliminary assessment of the campaigns

### 1.4.1 Communications

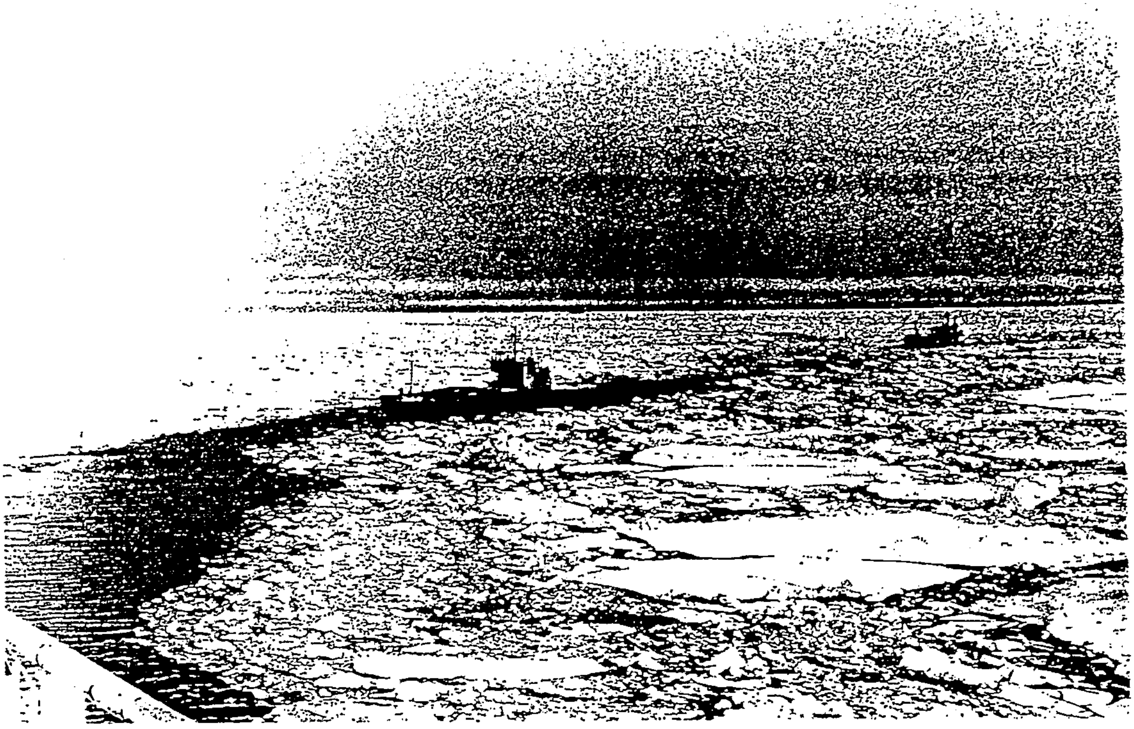
An evaluation of the practical aspects of campaigns, particularly concerning communication, are described below:

a) The delay between SAR time and fax time can, if found necessary, be shortened to a few hours in critical situations when the ship is heading for the imaged area. This requires full operational status of all the links in the processing chain: 1) the SAR antenna and computer at TSS, 2) the Uninett link to NERSC, 3) the NERSC computer access, storage space and hardcopy unit, 4) the personnel at NERSC, 5) the fax sending machine at NERSC, 6) the satellite telephone link to the ship, and 7) the fax receiver onboard the ship.

b) An efficient way of reporting ship position and sailing plans in the nearest future is very desirable in all near-real time ice imaging and mapping. It is important to be able to put priority on the parts of SAR imagery that are of most interest, since making correct ice interpretation is both difficult and time-consuming. This was not practised during the expedition. (We suggest to equip several icebreakers with Argos systems to allow us to know where they are in real-time.)

c) Both the *Taymyr* and *Vaygash* have "shadow zones" for transmission of data via INMARSAT, centered on ship heading in azimuth 182°, 270° and 350°. These are caused by various antenna obscuring parts on the ships. The shadow zones coupled with the low altitude of the satellite are probably the main causes for the poor transmission results. The antenna on the *Sovetsky Soyuz* is better placed, and more reliable transmission to that ship has been experienced. Increase in transmission reliability is considered essential for future service development.

d) Another factor that has made transmission to the *Sovetsky Soyuz* easier is that the telefax and voice communication has separate telephone numbers. On the two other ships, manual switching must be made between voice and fax.



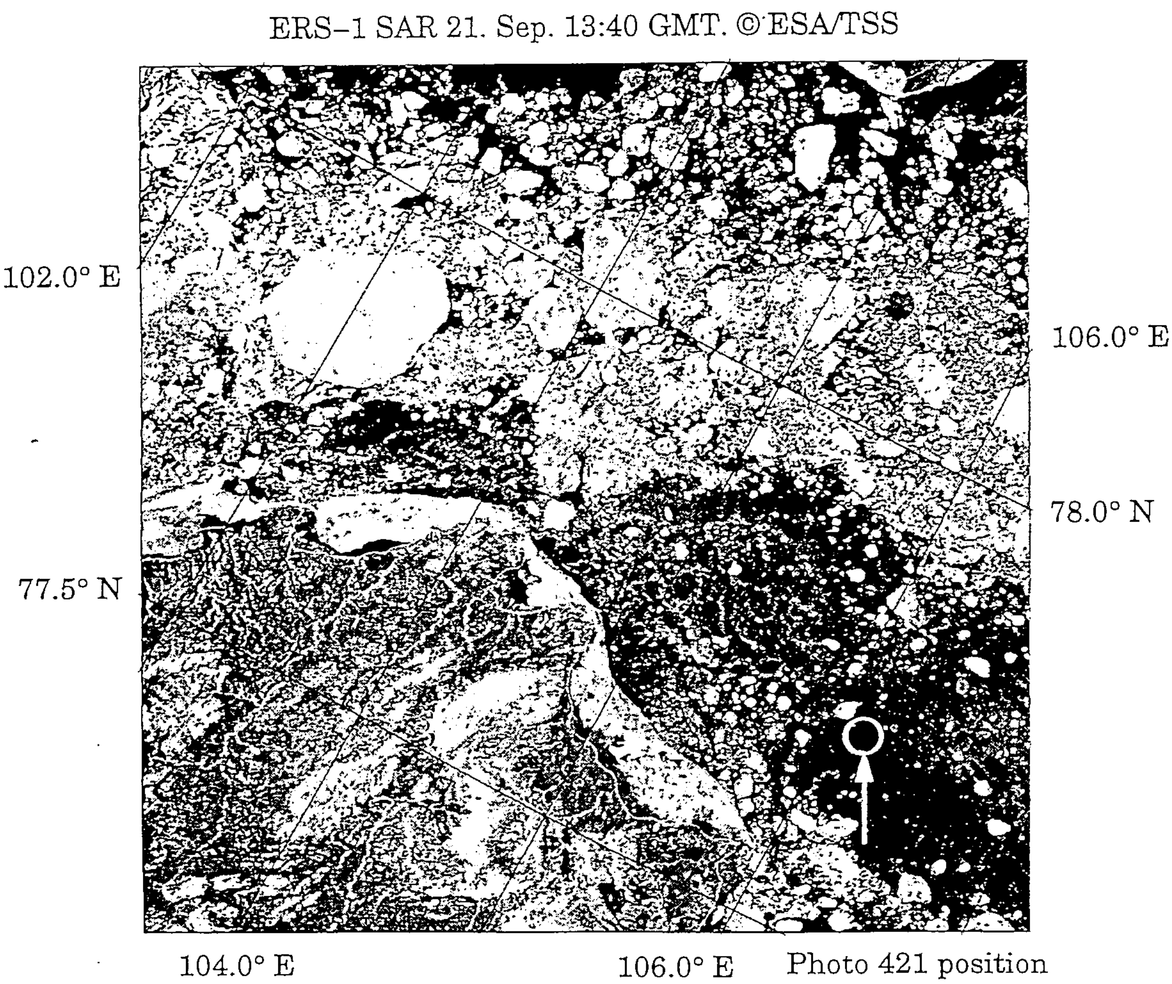



Figure 17. Case 6: Photograph (upper) east of Cape Chelyuskin 24 September 1994, and a SAR image from 21 September 1994.

### 1.4.2 Sea ice parameter validation results

Extraction of ice parameters from SAR images has been demonstrated using both manual and automatic methods.

*Ice edge and ice features.* Mapping of the ice edge and ice features has been successfully achieved. Ice features that can be identified and mapped include fast ice, polynyas, ice "breccia" or compressed ice, large floes, ice tongues and bands at the ice edge. As long as the backscatter contrast is high and the feature dimension is greater than the resolution of the image, ice feature and ice edge mapping present no large problem, and the results have been shown to be reliable. Most of the mapping has been done manually as automatic routines are presently not sufficiently developed.

*Ice motion.* The mean ice motion field between sequential images has been measured and mapped. An automatic algorithm based on spatial correlation has been tested with good results in some areas, e.g., in the Ob River estuary. There the ice features are recognizable and the features do not change too much in 3 days (the usual interval between images). The algorithm is less successful in other regions, e.g. in the area of Vilkitsky Strait. There the features change too much, and only some very large floes can be followed using a manual method.

*Determination of type of surface.* This has been done in an algorithm primarily based on a table of backscatter values. Other available information such as the general temperature and the regime must also be used to minimize the many ambiguities present. Texture is an important parameter, especially in the separation of ice and open water areas. Present algorithms are only semi-automatic, as some of the input information is difficult to quantify and some important ambiguities still exist. The comparisons with *in situ* ice observations and photos have shown that the SAR results are useful and qualitatively correct, although a quantitative evaluation is difficult to make.

### 1.4.3 Usefulness in ice navigation

The experience from using ERS SAR data in the Northern Sea Route is primarily that these data are an important supplement in the mapping of the general ice conditions. SAR data have documented that the ice mapping is improved compared to a situation where only Russian ice maps are used. These maps are based on NOAA AVHRR and other optical/infrared satellite data and observations from ships, coastal stations, etc. The quality of these maps is therefore variable.

The primary role of the SAR data is in general ice mapping needed in the planning of the icebreaker sailing routes. The requirement for real-time data is not very strict, it is sufficient with data coverage 1 - 2 times per week in areas where the most important ice processes occur. In the tactical navigation the icebreakers need real-time data within 2 - 3 hours to find the optimal course during the voyage. For such real-time information SAR data can also play an important role if the data can cover the right areas at the right time. The best example of direct use of a SAR image to choose the best route through the ice pack, was in November 1993 when Sovetsky Soyuz sailed westward through the Mathissen Strait (Fig. 5). The image obtained onboard the ship before entering the strait was used to select a different and safer route through the pack ice. When SAR data from Radarsat are available (from 1996), the temporal and spatial SAR coverage of the Northern Sea Route will become much better than for ERS data. Regular use of SAR data in tactical navigation will become possible.

The possibility to use SAR data to map details of the ice cover, such as ridges, which have direct impact on ship speed and damage risk, remains to be studied. It is not yet clear if current spaceborne SAR systems can provide sufficient detailed information about ridges (height, width, distribution, etc.). This problem will be further investigated using Radarsat data with higher incidence angle which is required for ridge mapping.

# Part 2. Analysis of ERS SAR data requirements

This chapter discusses the pertinent ERS SAR data characteristics and requirements for their use in operational sea ice monitoring along the Northern Sea Route. This analysis is based primarily on the experience from the 1994 winter and summer campaigns. The characteristics and requirements for ERS SAR coverage are presented in Section 2.1. The ordering, acquisition, and processing is discussed in Section 2.2. The transmission of ERS SAR image-maps to the users is discussed in Section 2.3. Finally, we present a summary assessment of the main ERS SAR data requirements.

## 2.1. ERS SAR coverage

The ERS SAR swath imaged is 100 km wide and is situated with its center 300 km to the right of the line directly under the satellite (the satellite subtrack). The instrument is power-limited and thus is switched on for only a short part of each orbit, typically 10 minutes or 10% of the time. Thus large portions of the swath are non-imaged. ESA-ESRIN determines what parts of the swath will be imaged, based on requests from all users. This is done on a priority basis - fortunately the Northern Sea Route project has high priority since it is one of the programs accepted by ESA.

The earth's rotation causes the swath to be displaced 25° westward for each orbit. After 3 days, the swaths will show either an exact repeat or a near repeat. This results in a regular diamond-shaped pattern of ascending and descending swaths during any 3-day period. The distance between swaths in one direction is 8° or approximately 300 km at 70°N. At this latitude, the non-imaged areas between swaths will be twice the total swath areas in any 3-day period, in addition a significant part of the swaths may be non-imaged (SAR turned off). The actual coverage of any larger portion of the Siberian coast during any 3-day period will therefore only be 33% or lower, depending on the acquisition schedule. Coverage increase with latitude to ≈ 50% at 75°N. If swaths in both directions (ascending and descending) are considered, both time and spatial coverage increases. However, usually swaths in only one direction have the SAR turned on.

The diamond-pattern is repeated either exactly or nearly exactly every 3 days, depending on the satellite orbit. In the winter (February-March) 1994 campaign, an exact 3-day repeat was achieved. Then the same areas were imaged (if the SAR was on) every 3 days, while other areas were never imaged. In the summer (September-October) 1994 campaign, the pattern drifted eastward by 1.6° for every 3 days (exact repeat was 168 days) so all areas were imaged sooner or later (again assuming the SAR was on).

Along the Northern Sea Route, Tromsø Satellite Station can read down images limited to the section west of and including Cape Chelyuskin/Vilkitsky Strait (to approx. 107°E). A large gap exists to the section of the Northern Sea Route where the Fairbanks, Alaska read-down station can take over at approximately 135°E. No read-down station is presently operational in this gap. This region includes the entire Laptev Sea, and the need for a receiving station in the area is clearly indicated. An additional limitation is that images near the limit of TSS operation may be noisy due to the low antenna elevation.

As an example, Figure 18 shows 3-day ERS SAR coverage during part of the winter campaign. In this case, approximately 25 scenes were used for the region between the Pechora Sea and the Yenesei River. The geographic gaps in the 3-day coverage are seen to be about 200 km along the route. No scenes were requested east of the Yenisey River

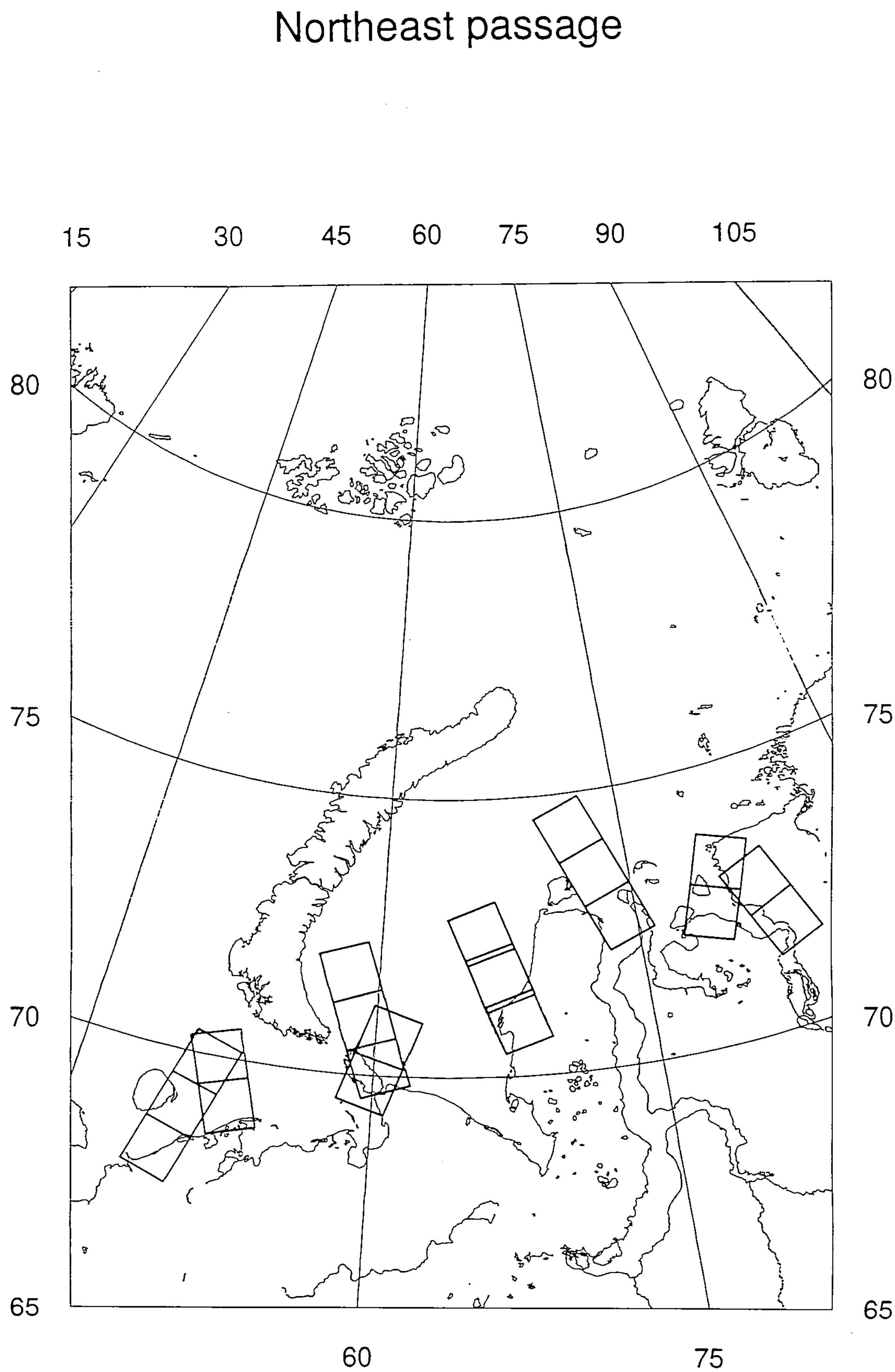



Figure 18. ERS-1 SAR scenes acquired during a 3-day period during the winter campaign. Between the Pechora Sea and the Yenisey River, 25 scenes were acquired.

because there was no icebreaker activity at this time; had there been, approximately 50 scenes would have been requested in a 3-day period to extend the coverage to Cape Chelyuskin.

Considering the icebreaker navigation schedule and the inherent gaps in ERS SAR coverage, it was difficult to best-coordinate the SAR coverage with the icebreaker navigation. The degree of geographic and temporal correspondence achieved between ERS SAR coverage and icebreaker position is shown in Figure 19a,b. In the winter campaign (Figure 19a), about 40-45% of the images were of immediate practical use for icebreaker navigation - that is, the scenes were in the right place at the right time. In the summer campaign (Figure 19b) the corresponding figure was about 60-65%.

Nonetheless, *all* of the SAR scenes are useful to the Marine Operations Headquarters (MOH) in Dikson, by providing an overall impression of the ice conditions in the region. In these and in previous campaigns, the SAR requests were done by NERSC. In the future, using diagrams such as in Figure 19, the MOH and the icebreaker captains themselves should be able to order high-priority SAR data.

## 2.2 Ordering, acquisition, and processing of SAR data to image-maps

The ESA acquisition schedule is the timetable for having the SAR turned on. The schedule is normally determined 3-5 weeks in advance, but may be altered for high-priority projects at as little as 1-week's notice. Following this schedule, the ordering of 2-3 scenes along all the desired swaths is made to TSS. This will give images of 100 km width and 200-300 km length that cover the normal route of the ships, usually including portions of the shore.

Ordering of scenes from TSS can be made at very short notice, right up to the acquisition time, or even afterwards, because the data are archived up to one month. Depending on the stated requirement for real-time and the operational status of all links in the processing chain, processed images can be finished at NERSC with a delay of minimum about 1.5 hours. This delay includes the processing in Tromsø, the data file transfer, plus the processing in Bergen. As described in section 1.1 and 1.2, the standard product from NERSC is a gridded, interpreted, annotated, gray-tone hardcopy suitable for fax transmission.

## 2.3 Transmission of image-maps

The transmission of ERS SAR image maps to the users has proved to be the main bottleneck of the total processing chain. An image on A4 paper is transmitted by normal telefax using the satellite telephone network of INMARSAT. The coast of the Northern Sea Route eastward to the Cape Chelyuskin is within sight of the geostationary communication satellite over the Indian Ocean at 60°E (code 873). However, the elevation of the satellite over the horizon is low and variable at these high northern latitudes, from 10° near the Kara Gate diminishing eastward to zero near Cape Chelyuskin.

Moreover there is a gap in coverage before the Pacific Ocean satellite at 180°E can be used on the Siberian coast for communication westward of approximately 120°E. The low altitude of the communication satellite means that free sight can easily be obscured by hills and ship masts; in addition the atmospheric effects are large. The connection has therefore often been of poor quality, or even impossible east of Cape Chelyuskin. Changes in ship motion and heading direction may have large effects. Imagery has also been sent to Dikson MOH at 73°N, 80°E using INMARSAT. Here the satellite elevation is also low, but the antenna is stationary and the connection is more stable.

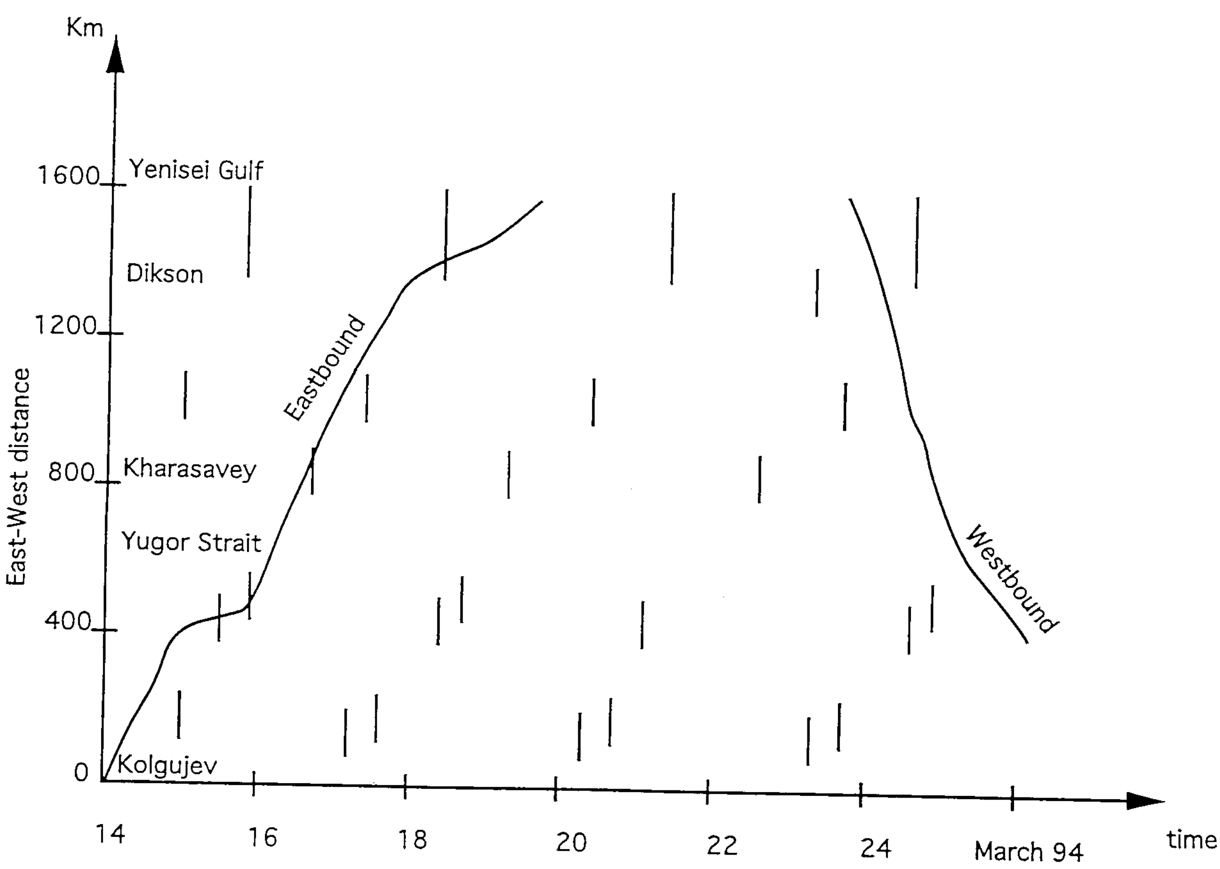



Figure 19. Diagrams indicating the icebreaker's longitude as a function of time (curves) and the SAR scenes (vertical bars) acquired during the winter campaign. To be considered of immediate practical use for navigation, the SAR scenes should be at the proper longitude within 48 hrs. before the icebreaker is there.

## 2.4 Assessment of ERS SAR data requirements

Based on the campaigns carried out, the ERS SAR data requirements for an operational system can be summarized as follows:

- The 100 km swath width of the ERS SAR results in substantial gaps in coverage in the whole Northern Sea Route. A wider swath width is needed to cover all ice areas in say three days.
- There is a data gap in the Laptev Sea because the area is neither covered by the receiving stations in Europe (Tromsø and Kiruna) nor in Alaska (Fairbanks). It is therefore necessary to build a new SAR receiving station in Siberia with sufficient data processing and distribution capability.
- The ESA data request system appears adequate for an operational ice monitoring system, though it would be better to decrease the advance-time needed to request SAR scenes. The TSS ordering, acquisition, and processing procedures satisfy the needs of an operational system.
- There are difficulties in getting geographic and temporal correspondence between the SAR scenes acquired and the icebreakers' practical navigation needs. This could be improved if the icebreaker captains and the Marine Operations Headquarters (MOH) in Dikson ordered high-priority scenes themselves, using diagrams such as in Fig. 19a and Fig. 19b.
- The transmission of ERS-1 SAR image maps to users remains problematic, mostly because of inherent communication problems between Bergen and the icebreakers. One means for improvement might be to use Dikson as the SAR analysis center, since it is much closer to the operations in the Northern Sea Route.

## 2.5 Summary and conclusions

After the first demonstration of operational use of ERS-1 SAR data for ice navigation during the *L'Astrolabe* expedition in August 1991 several demonstrations have been carried out onboard icebreakers in order to test operational use of SAR data. The following table shows the demonstrations which have been carried out from October 1993 to April 1995:

| Stage | Period | Notes |
|---|---|---|
| 1A | October 93 | |
| 1B | October 93 -December 93 | V.M. onboard *Sovetsky Soyuz* |
| 1C | December 93 - January 94 | |
| 2 | February 94 -March 94 | V.M. onboard *Vaygach.* |
| 3A | August 94 - September 94 | |
| 3B | September 94 | V.M. onboard *Taymyr* |
| 4A | October 94 - December 94 | |
| 4B | January 95 - February 95 | N.B. onboard *Vaygach* |
| 5 | February 95 -April 95 | B.P. onboard *Sovetsky Soyuz* |

V.M: Dr. Vladimir Melentyev; N.B.: N. Babich; B.P.: Boris Pachenko.

The purpose of the demonstrations has been to test:

*1. Coverage and repeat cycle of ERS-1 SAR data in the important ice areas of the Northern Sea Route*

*2. The feasibility of obtaining SAR data in real time*

*3. Data ordering procedures*

*4. Interpretation of the images in terms of ice types and ice features that are important ice parameters for navigation*

*5. Which quantitative ice parameters can be derived from SAR data*

*6. What other data are needed to supplement the SAR data.*

*7. Transmission of images or image products to icebreakers*

*8. How SAR data can be used in ice navigation*

*9. Preliminary assessment of the SAR's capability to map ice conditions*

The experience gained from these demonstrations, which is an essential element in the design of an operational SAR ice monitoring system, can be summarized as follows.

*1. The SAR coverage*

The ERS orbits and SAR coverage pattern were discussed in Section 2.1. The experience is that the ERS SAR can provide a very useful temporal and spatial coverage of the important ice areas if the orbits are fully utilized. The main limitation is the gaps between the swaths where no SAR coveage is obtained within a short time frame. Full spatial coverage of the Kara Sea for example can only be obtained if the orbits are "drifting" and mosaics are built up over several days. For a real-time ice monitoring of larger regions this is not sufficient. However, for detailed mapping of critical straits such as the Kara Gate or Vilkitsky Strait, the SAR coverage from ERS-1 has been very useful. Also other straits which can be critical for ice navigation, such as Jugor Strait, Mathissen Strait, Sannikova Strait and Long Strait can be well covered by the ERS-1 SAR data. The ground stations which cover these areas are Kiruna and Tromsø for the western part and Alaska SAR Facility for the eastern part.

*2. Real-time access to SAR data*

The acquisition of SAR scenes in near realtime is an essential part of an operational system. Near real-time is considered to be within 6 hours or so after the satellite overpass. Tromsø Satellite Station has routinely delivered SAR scenes to the Nansen Center within 1-2 hours after the satellite overpass when needed. Analysis and interpretation of the scenes at the Nansen Center take about 1 hour. The delivery to the icebreakers can be done within 2-3 hours if the need for realtime data is urgent and the communication by telefax is working. In other cases analysed images are ready for delivery within 6-12 hours, depending on the time of day for the SAR acquisition. The access to SAR images in near realtime has not been the bottleneck in the demonstrations. In an operational system the time delay should not exceed 2-3 hours. The production of SAR ice maps needs to be streamlined before this can be achieved on a regular basis.

### *3. Data ordering procedure*

Ordering of SAR data is currently a two-step operation. First, request for SAR acquisition over a given area is submitted to ESA ESRIN about a month in advance. Based on this request as well as all other user requests for SAR data, ESA ESRIN sets up the SAR acquisition plan for the next 3 - 4 weeks. This acquisition plan shows which scenes are scheduled for the ice monitoring project. A data order is then submitted to the receiving station 1-7 days in advance. In this order not all of the SAR scenes which are scheduled for the project are included. This is because the scenes which cover the most important ice areas can only be selected a few days in advance. This data ordering procedure should be streamlined in an operational system. The ice center which is in charge of the ice monitoring should have direct contact with ESA ESRIN in order to ensure that the most important SAR scenes are obtained.

### *4. Interpretation of SAR images*

The demonstrations have provided good insight into many of the ice characteristics of the Northern Sea Route and how they are reflected in the SAR images. In situ obervations of ice and meteorological parameters have been useful in the interpretation of the SAR images. Ice edge location, ice concentration, 3-4 ice types, landfast ice, shear zones and leads can be interpreted in the SAR images. However, there are important ice features such as ridges and icebergs which cannot be uniquely identified. It is also difficult to distinguish different stages of young ice because the backscatter changes rapidly as the ice is deformed. Therefore, the interpretation of the ice conditions based on SAR data alone cannot be 100 % correct. More validation studies are needed to be able to interpret the ice types and ice phenomena in SAR images important for the navigation.

### *5. Quantitative ice parameters from SAR*

Classification of multi-year ice, first-year ice, thin ice and open water can usually be derived from the SAR images. In the summer, when the ice and snow is melting, it can be difficult to identify the ice edge and classify ice types. Ice motion and ice concentration can be calculated. Ice edge, leads and polynyas can be accurately mapped. Ice thickness cannot be estimated from SAR images, and methods for localization of ridges are not well developed. Quantitative mapping of ridges cannot be obtained with the current spaceborne SAR systems.

### *6. Other data needed to supplement the SAR data*

Large scale ice maps, obtained from Okean SLR, SSMI or AVHRR data, are useful for general mapping of the ice extent. These data are used to decide where to obtain SAR data, especially to find the ice edge region and major leads. In addition, meteorological observations, especially air temperature, wind speed and direction are important in order to interpret the SAR images. Data on ocean currents, temperature and salinity are also needed for analysis of the ice conditions.

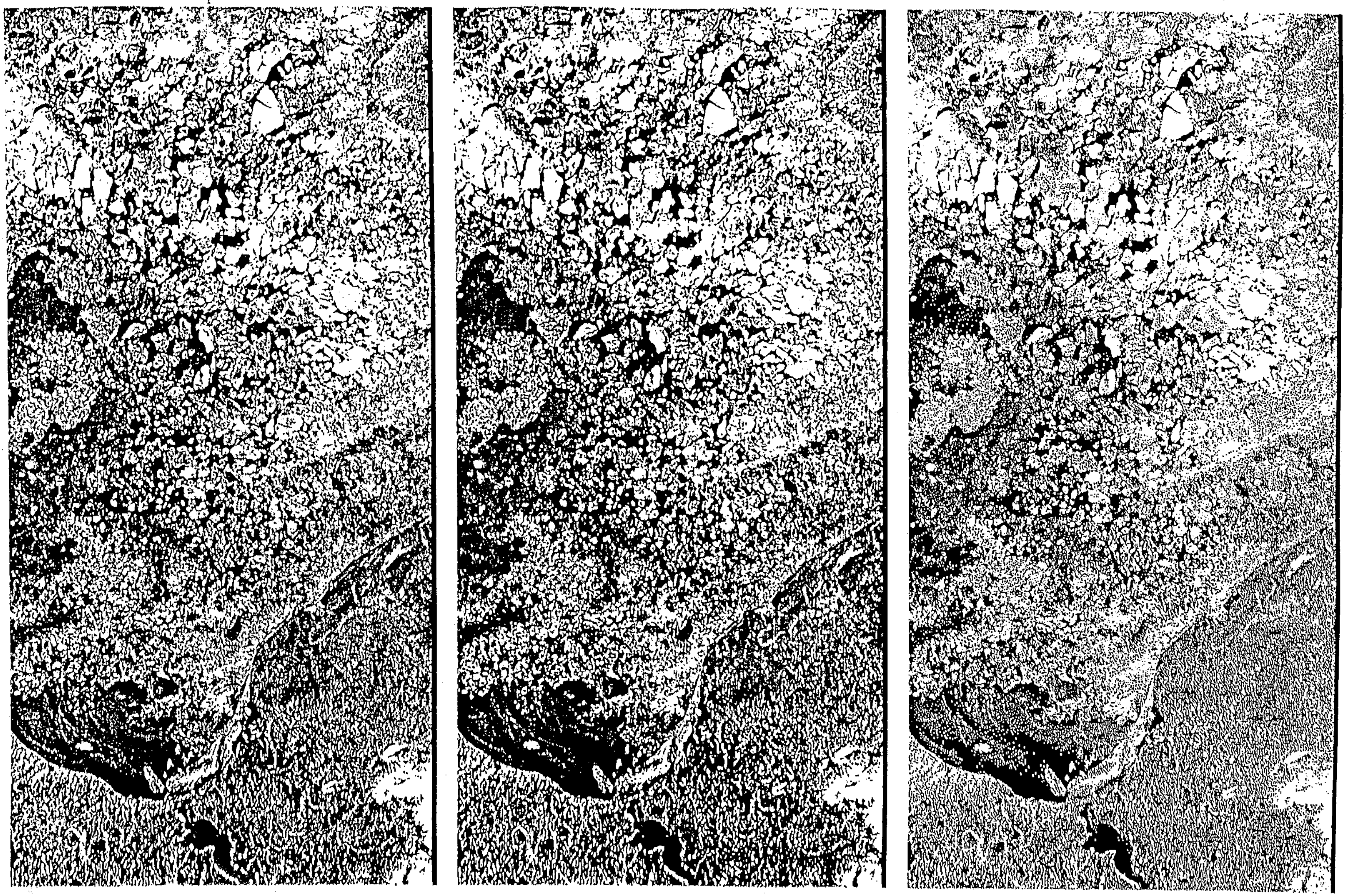
### *7. Transmission of images and image products to icebreakers*

A critical part of a near-real-time ice monitoring service is the transmission of the images or maps to the users onboard ships. INMARSAT-A stations with separate telephone and telefax lines onboard the receiving ships have been used in the demonstration projects. The transmission of a 1-page SAR image normally takes 3-6 minutes. The relatively poor quality of the SAR images after telefax transmission reduced the possibility for interpretation onboard the icebreaker. Therefore, interpreted ice maps were also transmitted by telefax, but the fine image details were not discernible in these maps.

File transmission using modem with the INMARSAT telephone line has been tested as an alternative method. The user onboard the ship calls the computer at NERSC, log in and transfers the image file using "ftp". The transferred image file is already reduced by compression techniques, so the size of one file is typically 100 - 200 kbyte. This method will allow the user to look at the image in detail on a PC, and print out hardcopies in much better quality than a fax product. It is expected that marine communication, including data transmission, will improve and become less expensive in the next few years. Thus, the transmission of SAR images, preferrably in compressed format, should become a routine operation.

In Figure 20 an example of a SAR image from the Northern Sea Routeis shown in three different versions: (a) is the original quality of the image as it is printed on a laser printer, (b) is the compressed file which indicates the quality of the image which is transferred by “ftp” via modem, and (c) is a telefaxed version of the image. Prior to transmission the latter image has been dithered, a processing technique in which the grey tones have been replaced by variable density of black dots. The dithered image has poorer quality than the original image, but it can be telefaxed without further degradation.

Example of low resolution SAR image (8 bit), compressed version (for modem) and dithered version (for fax).



Original Data © ESA/TSS 1995. Image Processing NERSC.

Figure 20. Example of a SAR image of sea ice displayed in three different qualities. The left image is the original image with 200 m pixel size, the image in the middle has been compressed using the JPEG algorithm, and the right image is dithered.

*8. How SAR data can be used in ice navigation*

Users of sea ice information distinguish between strategic and tactical ice information. Strategic information is used for long-range planning and requires ice maps of large areas, while tactical information provides detailed information within the immediate vicinity (150 - 200 nautical miles) of the vessel. In the demonstrations the SAR images have been used for improved mapping of the ice conditions which is necessary information to assist in the navigation through difficult ice conditions. The tactical information requires that the SAR images are obtained daily and can capture the rapid changes in the ice conditions. It is foreseen that ERS SAR can play an important role in tactical ice navigation, especially in straits and other confined regions where ice conditions can be difficult. However, with Radarsat data available in most of the Northern Sea Route every day, it will be possible to use SAR ice information on a regular basis in ice navigation.

***9. Preliminary assessment of the SAR's capability to map ice conditions***

It has been demonstrated that ERS SAR has the capability to map several of the key ice parameters which are important in ice navigation. This mapping capability, in combination with near real-time access to the data, will lead to increased use of SAR in ice monitoring in the future when several SAR satellites are in operation. The SAR system has some weaknesses, i.e. its inability to accurately map ice thickness and ridges, but they are less significant compared to the great advantages offered by the SAR to quantify other ice parameters. When the SAR is supplemented by other satellite data, meteorological data, oceanographical data and ice-ocean simulation models, it is foreseen to play a key role in future ice monitoring and forecasting systems.

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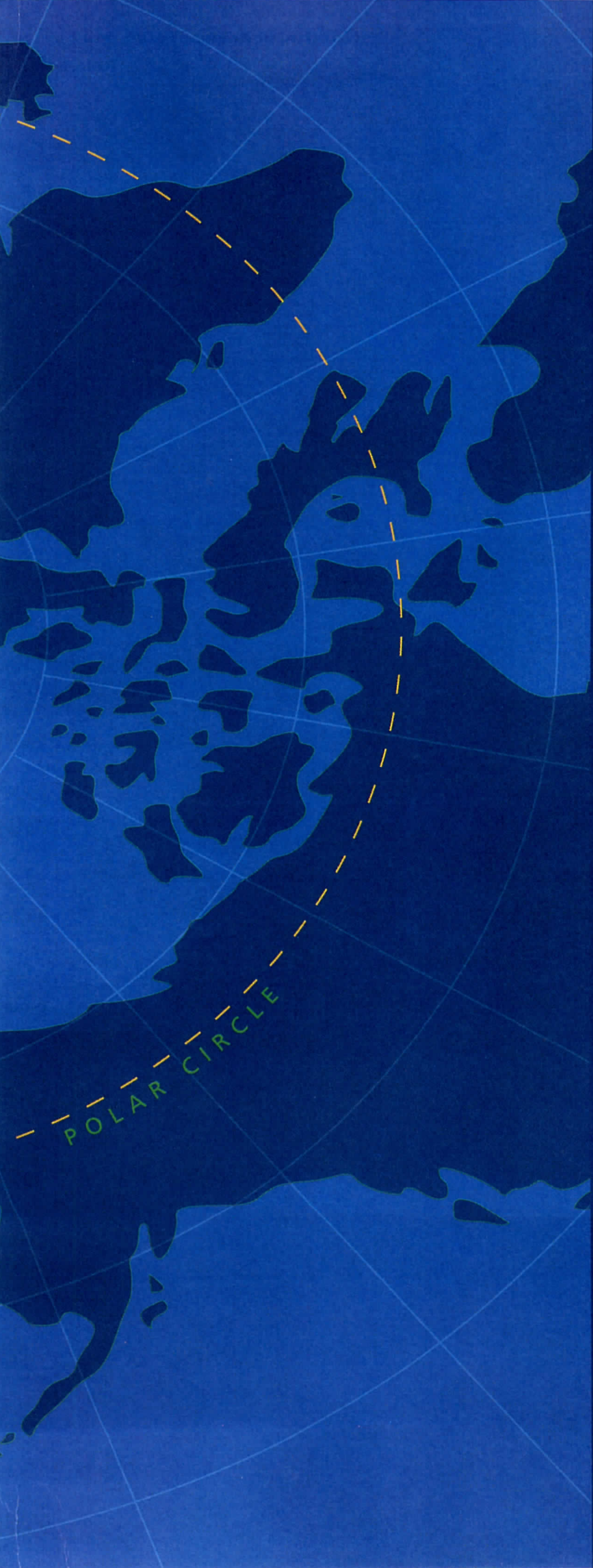


**The three main cooperating institutions of INSROP**

**Ship & Ocean Foundation (SOF), Tokyo, Japan.**

SOF was established in 1975 as a non-profit organization to advance modernization and rationalization of Japan's shipbuilding and related industries, and to give assistance to non-profit organizations associated with these industries. SOF is provided with operation funds by the Sasakawa Foundation, the world's largest foundation operated with revenue from motorboat racing. An integral part of SOF, the Tsukuba Institute, carries out experimental research into ocean environment protection and ocean development.

**Central Marine Research & Design Institute (CNIIMF), St. Petersburg, Russia.**

CNIIMF was founded in 1929. The institute's research focus is applied and technological with four main goals: the improvment of merchant fleet efficiency; shipping safety; technical development of the merchant fleet; and design support for future fleet development. CNIIMF was a Russian state institution up to 1993, when it was converted into a stockholding company.

**The Fridtjof Nansen Institute (FNI), Lysaker, Norway.**

FNI was founded in 1958 and is based at Polhøgda, the home of Fridtjof Nansen, famous Norwegian polar explorer, scientist, humanist and statesman. The institute spesializes in applied social science research, with special focus on international resource and environmental management. In addition to INSROP, the research is organized in six integrated programmes. Typical of FNI research is a multidisciplinary approach, entailing extensive cooperation with other research institutions both at home and abroad. The INSROP Secretariat is located at FNI.