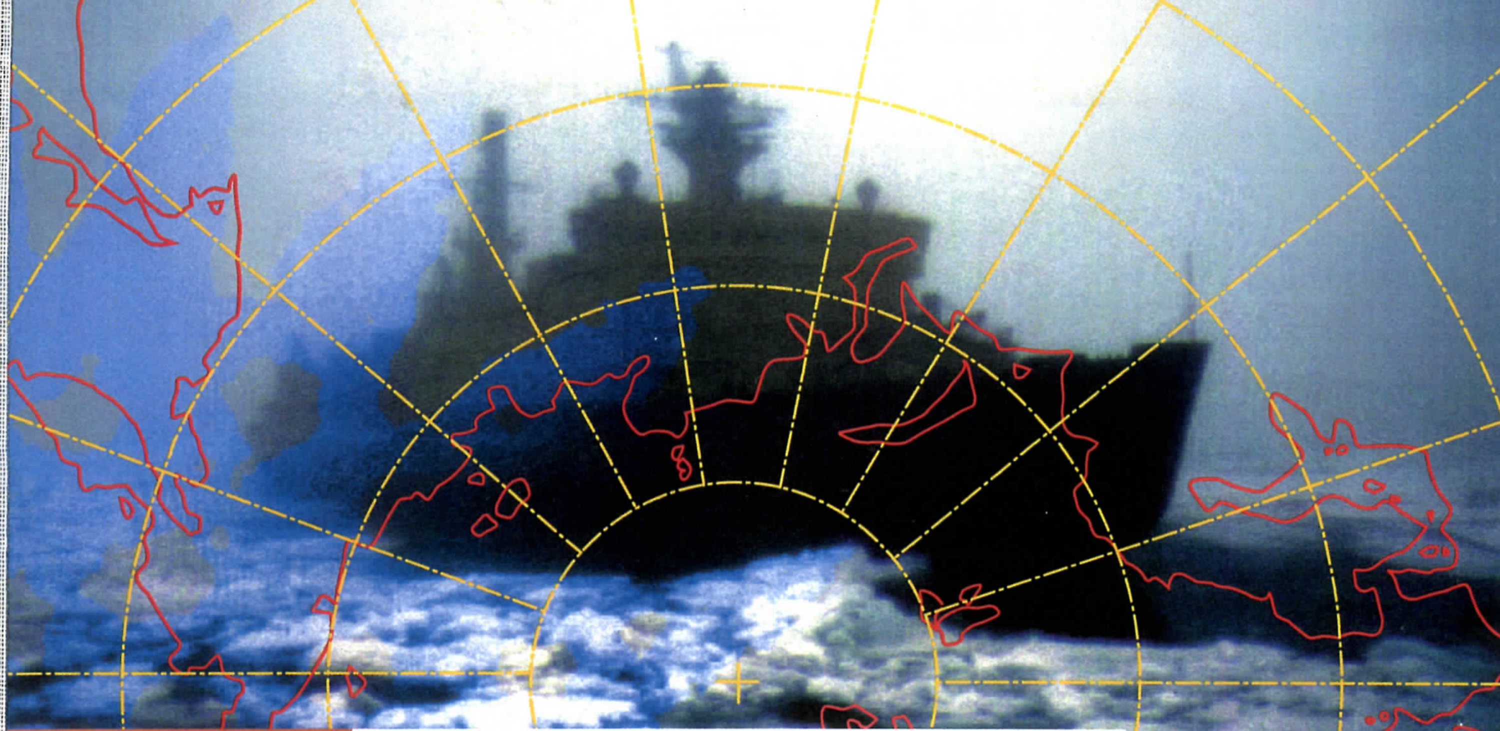

INSROP WORKING PAPER
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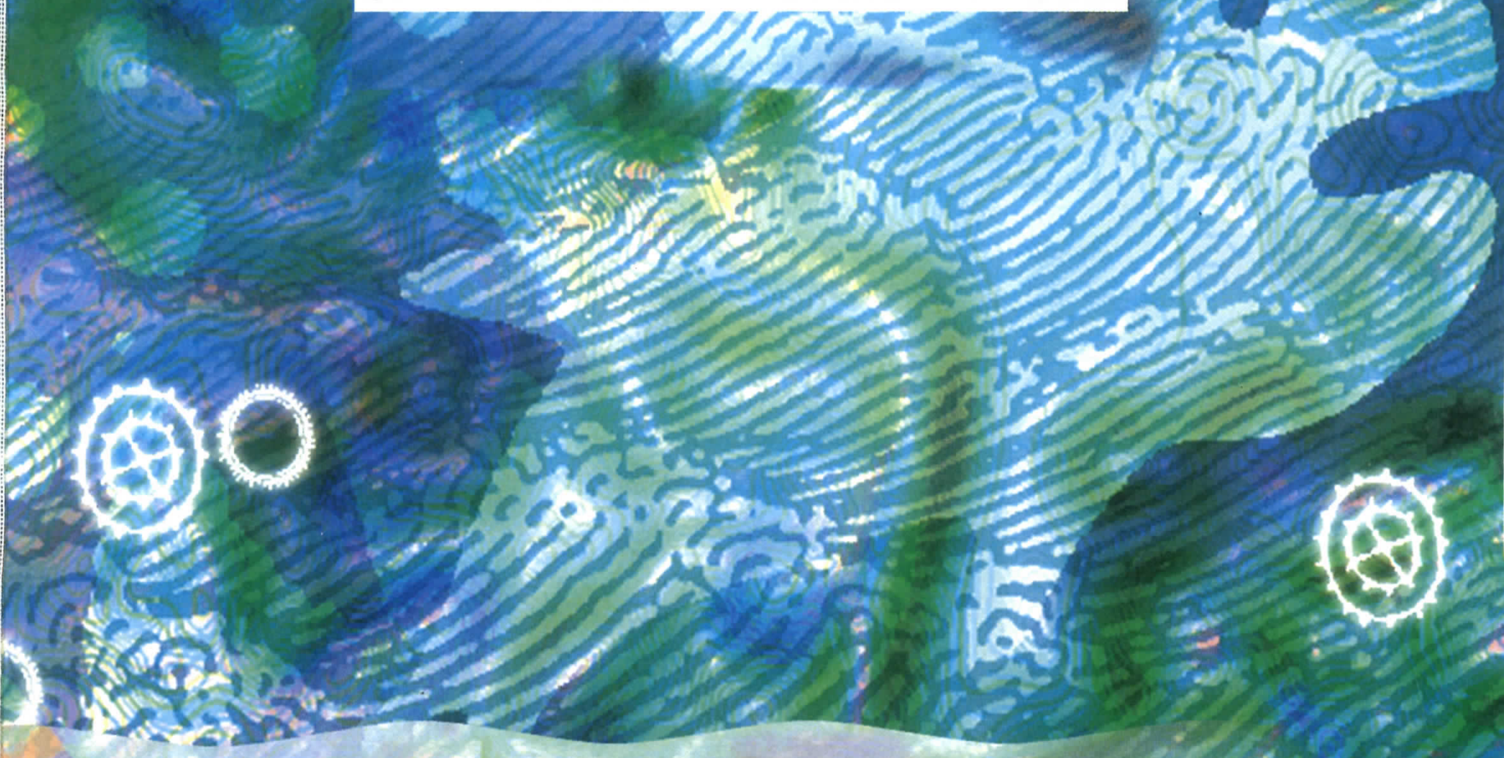
Practical Demonstration of Real-time RADARSAT SAR Data for Ice Navigation on the Northern Sea Route

By S. Sandven, V. Alexandrov, Ø. Dalen, M. Lundhaug, V. Melentyev, V. Smirnov, N. Babich and K. Kloster



INSROP International Northern Sea Route Programme

Central Marine Research & Design Institute, Russia

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International Northern Sea Route Programme (INSROP)

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Sub-Programme I: Natural Conditions and Ice Navigation

Project I.2.4: Practical Demonstration of Real-time RADARSAT SAR Data for Ice Navigation on the Northern Sea Route

Supervisor: Stein Sandven, NERSC

Title: **Practical Demonstration of Real-time RADARSAT SAR Data for Ice Navigation on the Northern Sea Route**

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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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EXECUTIVE SUMMARY

This project has for the first time demonstrated practical use of RADARSAT data for ice navigation in the Northern Sea Route. Since the launch of RADARSAT in November 1995 wide-scan SAR data have been available for sea ice studies and navigation support in the Canadian Arctic, Greenland Sea, Baltic Sea and other sea ice regions (Sandven *et al.*, 1998a, Gill *et al.*, 1997, Ramsay *et al.*, 1997). In the Northern Sea Route the first use of RADARSAT SAR for navigation support was demonstrated in August - September 1997 onboard the nuclear icebreaker 'Sovetsky Soyuz'. The SAR demonstration, organised by Nansen Centres in Bergen and St. Petersburg together with Murmansk Shipping Company, was carried out while the icebreaker sailed through the Vilkitsky Strait and into the western part of the Laptev Sea. During the expedition RADARSAT, ERS-2 and SSM/I data were obtained and analysed by the Nansen Center in Bergen. The data were transmitted onboard the icebreaker in digital form via INMARSAT and used for the navigation support. The SAR data were received from Tromsø Satellite Station (TSS) in Norway and the SSM/I data were obtained from Marshall Space Flight Centre in USA. Sea ice observations were obtained from the icebreaker and a helicopter for validation of the SAR sea ice signatures. The ice conditions were quite easy with no ice in the Vilkitsky Strait and thick first-year ice was only found in the western part of the Laptev Sea. This ice massif, denoted the Taimyr ice massif, blocked the route for cargo ships from Kara Sea to Khatanga and other destinations east of the Vilkitsky Strait.

The first RADARSAT SAR images from August 14, 15 and 31 were obtained before 'Sovetsky Soyuz' left Murmansk, and were used for detailed ice mapping as part of the planning of the expedition. The RADARSAT ScanSAR image of September 7 which was obtained 3-4 days before 'Sovetsky Soyuz' entered the ice area, was transmitted onboard the icebreaker. Because of the limitations imposed by INMARSAT communication system, the resolution of transmitted image was reduced to 500 by 500 m, which the original image had a resolution of 100 by 100 m. During this period sea ice conditions did not significantly change and the sea ice information from the SAR image was still useful in tactical navigation. Also SSM/I 85 GHz images and ice concentration maps were transmitted onboard the icebreaker and used for navigation in the Laptev Sea.

The image analysis showed that the main sea ice parameters, which are important for summer navigation, such as ice edge position, ice concentration and identification of large ice floes can be identified from RADARSAT SAR data. Sea ice bands in the open water can be also distinguished. Ice drift vectors and areas of convergence/divergence can be determined from successive images using an ice kinematics algorithm. The main problem with the SAR data is distinguishing between open water and new ice types (grease ice, nilas), because all the features have low backscatter during calm wind conditions. For this purpose RADARSAT images should be calibrated. The technique for RADARSAT data calibration is under development.

Sea ice charts from obtained RADARSAT ScanSAR images have been prepared by the Arctic and Antarctic Research Institute. The areas with different sea ice concentrations were delineated and concentration values were automatically calculated. Areas covered with grease ice, nilas and pancake ice, and ice bands in open water could only be identified with help of in-situ data.

The expedition in August-September 1997 has demonstrated that RADARSAT ScanSAR data can be effectively used for navigation support in areas of the Northern Sea Route where difficult ice conditions can occur during the summer. Image transmission is the main bottleneck in using SAR data for ship routing in near real-time. Because of limitations, imposed by INMARSAT communication system the resolution of images, received onboard icebreaker, is considerably less than that of original ones. In the central part of the Laptev Sea and in the Central part of the Arctic

Basin, satellite images cannot be received onboard the icebreakers because this is outside the range of INMARSAT. One important problem, which arises from this analysis is how to organise optimal use of remote sensing data for navigation support?

The experience from the first demonstration expedition for use of RADARSAT data was used to plan and implement a winter demonstration in the Kara Sea in April-May 1998. In this period two icebreaker expeditions were carried out were RADARSAT and ERS SAR data were used to map the whole ice area between the Barents Sea and the Yenisey Gulf in the Kara Sea. These demonstrations showed that satellite SAR data can play an essential role both in operative and tactical ice navigation, especially during the heavy ice conditions which prevailed in the winter of 1998. The winter demonstrations were parts of two EU-funded projects, ICE ROUTES (Alexandrov *et al.*, 1998) and ARCDEV (Pettersson, 1998).

SAR coverage of the whole Northern Sea Route with RADARSAT data is possible technically, but very expensive. It is therefore not realistic to use SAR data as exclusive data source for ice navigation. Another problem is the data transmission to icebreakers which is limited by the range of INMARSAT. An practical solution is to use a combination of SSM/I, ERS/RADARSAT, Okean, and Resurs/Meteor data. SSM/I data provide a global coverage and allows us to estimate ice edge position and ice concentration. Due to considerably small volumes these data could be easily transmitted onboard icebreaker and used for planning of operations. Areas with complicated ice conditions (ice massifs, ice isthmuses) can be analysed by SAR data. This scheme is more cost-effective and allows use of SAR data in the areas where it is most urgently needed.

For future operational ice monitoring in the NSR it is necessary to focus on the following problems:

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

1 INTRODUCTION

1.1 OVERVIEW OF CURRENT SEA ICE MONITORING IN THE NSR

Navigation in the Northern Sea Route (NSR) requires information about the ice conditions and its development. Due to the independence of light and clouds, satellite radar images are widely used for sea ice studies in the Arctic. Side-looking radar (SLR) images from the Russian 'Okean' satellite have been used for sea ice monitoring and studies since 1983 (Alexandrov *et al.*, 1992). In winter conditions, main sea ice parameters such as ice type, the boundary between first-year and multi-year ice, giant ice floes, fractures, and ice motion can be determined from these images. In the summer, these data are less useful, as wet and melting ice surfaces causes similar signatures from both open water and the different ice types. A more extensive description of satellite ice monitoring in the Northern Sea Route is given by Smirnov *et al.*, 1998 in the INSROP Working Paper No. 109 - 1998.

1.2 PREVIOUS ERS SAR DEMONSTRATIONS

Studies of SAR signatures of sea ice in the NSR started in August 1991, just after launching of the ERS-1 satellite. SAR images were directly transmitted to the research vessel 'L'Astrolabe' when it passed the NSR in summer, and used for navigation support (Johannessen and Sandven, 1992). A series of demonstration experiments using ERS SAR data for ice navigation support in the Arctic have been carried out since then (Johannessen *et al.*, 1994). These experiments were organised jointly by the Nansen Centres in Bergen and St. Petersburg, together with the European Space Agency (ESA) and Murmansk Shipping Company (MSC). The main objective has been to investigate the possibilities of SAR for sea ice monitoring in the NSR. Using the INMARSAT communication system, digital ERS SAR images have been successfully transmitted in near real-time to both icebreakers and the Western Arctic Marine Operation Headquarters (MOH). The SAR data have been widely used for selection of optimal ship routes in the ice. Thematic decoding features of the main sea ice parameters have been revealed by comparison with quasi-synchronous sub-satellite sea ice observations, obtained onboard the icebreakers. The narrow swath-width of 100 km considerably limits the use of ERS SAR for global and strategic sea ice monitoring, and the data should mainly be used along shores, and in straits and river estuaries, etc. Combined use of ERS SAR with wide-swath Okean SLR images to support ice navigation in the NSR, the offshore industries, and in environmental studies, was investigated in frame of the ICEWATCH Project, funded by ESA and the Russian Space Agency (Johannessen *et al.*, 1997).

2 PREPARATION OF FIELD DEMONSTRATION AND SAR DATA ACQUISITION

2.1 THE RADARSAT SYSTEM

RADARSAT data for the western part of the Northern Sea Route are downlinked and processed at Tromsø Satellite Station, Norway and in Gatineau, by the Canadian Space Agency.

The Canadian RADARSAT is the first SAR satellite with the potential to provide comprehensive monitoring of sea ice conditions globally. RADARSAT has a horizontally polarised C-band SAR operating at 5.3 GHz. The instrument is designed to operate in several imaging modes: standard, Wide beam (1/2), Fine resolution, ScanSAR (N/W), extended (H/L), as shown in Table 1 and Fig. 1.

Table 1 *RADARSAT imaging modes.*

Mode	Resolution m (Range by azimuth)	Looks	Width (km)	Incidence angle (degrees)
Standard	25 by 28	4	100	20 - 49
Wide -1	48-30 by 28	4	165	20 - 31
Wide -2	32-25 by 28	4	150	31 - 39
Fine resolution	11-9 by 9	1	45	37 - 48
ScanSAR narrow	50 by 50	2 - 4	305	20 - 40
ScanSAR wide	100 by 100	4 - 8	510	20 - 49
Extended H	22-19 by 28	4	75	50 - 60
Extended L	63-28 by 28	4	170	10 - 23

The main advantage of RADARSAT is the 500 km wide ScanSAR mode which will supply sufficient coverage, both spatial and temporal, for operation ice monitoring. The ScanSAR mode can provide imagery every day for the entire polar region north of 79° N. With HH-polarisation, it is expected that the discrimination between ice and water will be better than with the VV-polarisation of ERS. In addition, RADARSAT has the fine resolution modes, which can provider higher resolution images (pixel size of 10 m) in specific areas where more details are needed. This will be very useful in the detection of deformed ice, icebergs and other smaller scale features.

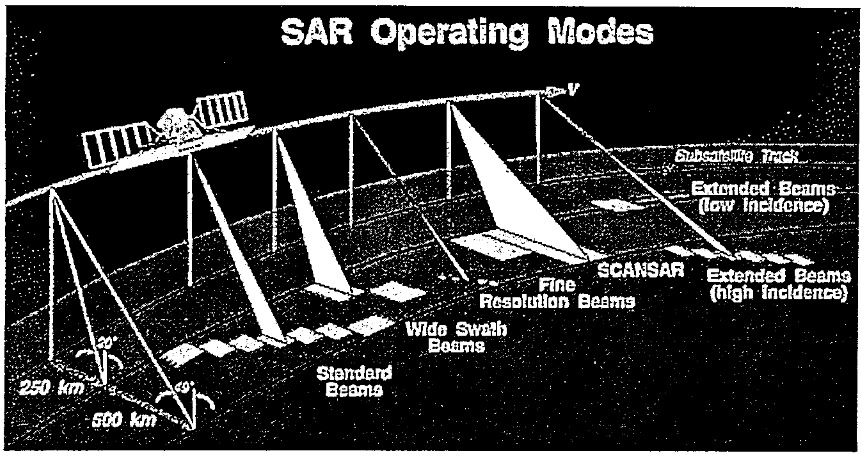

Figure 1 *SAR operating modes.*

Since the launch of the Canadian RADARSAT satellite in November 1995, wide-scan SAR data have been available for sea ice studies and navigation support in the Canadian Arctic, the Greenland Sea, the Baltic Sea, and other important sea ice regions (Ramsay *et al.*, 1997, Gill *et al.*, 1997). The first demonstration experiment of using near real-time RADARSAT ScanSAR data for ice navigation support in the NSR was carried out onboard the nuclear icebreaker 'Sovetsky Soyuz' in August-September 1997, supported by INSROP I.2.4 and the EU-funded IMSI project (Sandven *et al.*, 1998a). Analysis and results of this pilot experiment is outlined here.

In co-operation with Murmansk Shipping Company's Icebreaker Fleet the first demonstration of RADARSAT ice monitoring was planned in the Vilkitsky Strait and the western part of the Laptev Sea in connection with the 'Sovetsky Soyuz' expedition to this region in August 1997. A scientist from the Nansen Center in St. Petersburg participated in the voyage which started from Murmansk on September 6. A system of PC and modem was linked to the INMARSAT station onboard the icebreaker. Transmission of SAR image files to the icebreaker, prepared at the Nansen Center in Bergen was tested while the vessel was still in harbour.

The ordering of RADARSAT SAR data was previously scheduled to start in the middle of August and to be completed in the first week of September. This was in accordance with the sailing plan of 'Sovetsky Soyuz'. Unfortunately, there was about 3 weeks delay in the departure time, and at the same time it was not possible to change the RADARSAT acquisition schedule. Therefore most of the SAR images were obtained too early compared to the ship's schedule. The SAR images were, however useful for detailed ice mapping as part of the planning of the expedition. Only the image obtained on September 7 was transmitted to the ship just before the ship went into the ice area. The time delay was 3-4 days, but the ice conditions changes very little, which made it possible to use the SAR image as support for navigation and to obtain *in situ* validation data.

2.2 DATA COLLECTION

During the expedition, RADARSAT, ERS-2 and SSM/I data were obtained and analysed by the Nansen Center in Bergen, Table 2. Using the INMARSAT communication system, the data were transmitted onboard the icebreaker in digital form. The SAR data was received from Tromsø Satellite Station (TSS) in Norway and from Canadian Space Agency, while the SSM/I data were downloaded from the Marshall Space Flight Centre in USA. Visual ice observations for validation of the SAR sea ice signatures were obtained from the icebreaker and the helicopter used for the expedition. An example of SSM/I ice concentration map is shown in Fig. 2.

Table 2 *Data used during the expedition with 'Sovetsky Soyuz'.*

Date	*Satellite*	*Location*
14-AUG-1997	RADARSAT	Vilkitsky Strait
15-AUG-1997	RADARSAT	Vilkitsky Strait
31-AUG-1997	RADARSAT	Vilkitsky Strait
04-SEP-1997	RADARSAT	East Siberian Islands
04-SEP-1997	RADARSAT	Vilkitsky Strait
06-SEP-1997	RADARSAT	East Siberian Sea
07-SEP-1997	RADARSAT	Vilkitsky Strait
11-AUG-1997	ERS-2	Laptev Sea
14-AUG-1997	ERS-2	Laptev Sea
27-AUG-1997	ERS-2	Laptev Sea
14-AUG-1997	SSM/I	Kara and Laptev Seas
15-AUG-1997	SSM/I	Kara and Laptev Seas
31-AUG-1997	SSM/I	Laptev Sea
04-SEP-1997	SSM/I	East Siberian Sea
07-SEP-1997	SSM/I	Laptev Sea

In the summer 1997 complicated sea ice conditions occurred only in the western part of the Laptev Sea, were the Taimyr ice massif developed and blocked the route from the western Arctic to Khatanga. The Taimyr ice massif is clearly seen in the SSM/I ice concentration map, (Fig. 2). The Vilkitsky Strait, which can have very difficult ice conditions even in summer, had very little ice during the expedition.

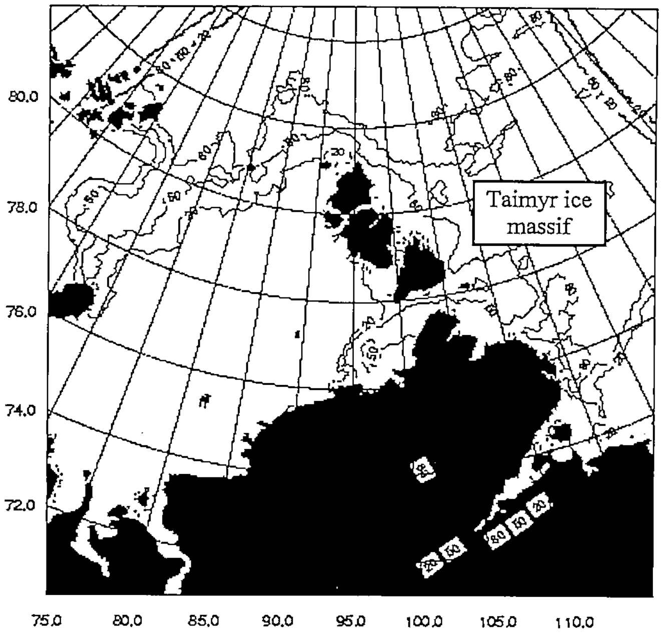

Figure 2 *SSM/I ice concentration map of 14 August 1997. The Taimyr ice massif is marked. The isolines in the upper corners mark the border of the data coverage from the SSM/I swath.*

3 Analysis of sea ice conditions by SAR images

3.1 SAR data coverage

The SAR scenes from the Vilkitsky Strait and the western part of the Laptev Sea were obtained from Tromsø Satellite Station (TSS) in near real-time, (Fig. 3). This area is as far east as the TSS can cover. With RADARSAT ScanSAR it is possible to reach 120° E at 77° N on ascending orbits. The images covering the New Siberian Islands and parts of the East Siberian Sea were obtained off-line from Canadian Space Agency.

During August-September 1997, 5 RADARSAT ScanSAR scenes, each covering 500 by 500 km, and 3 ERS SAR stripes with a swath-width of 100 km were acquired for the Vilkitsky Strait and western part of the Laptev Sea. Geo-located and contrast enhanced images, superimposed grid and coastline contours, were digitally transmitted onboard the icebreaker 'Sovetsky Soyuz', and to the MOH of the Murmansk Shipping Company (MSC), and used for navigation support and planning of icebreaker operations. This was the first time RADARSAT ScanSAR data were obtained and used in near real-time for navigation support in the NSR. Unfortunately, at this stage, no sensor calibration was provided, and the initial contrast of the images was poor due to experimental SAR processing at TSS. Nevertheless, the pilot demonstration expedition showed that RADARSAT ScanSAR images can provide a significant contribution to the ice navigation support, especially due to the combination of a wide coverage and high resolution.

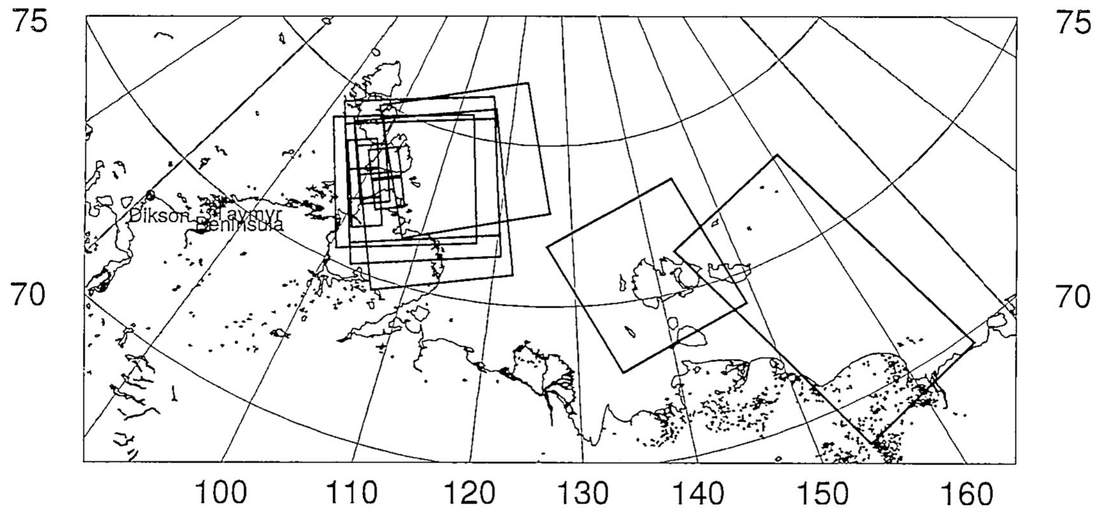

Figure 3 *ERS and RADARSAT SAR coverage in August-September 1997. The large rectangles show the coverage of ScanSAR wide mode image which are 500 km wide. The small boxes show the coverage of 100 by 100 km ERS-2 SAR scenes.*

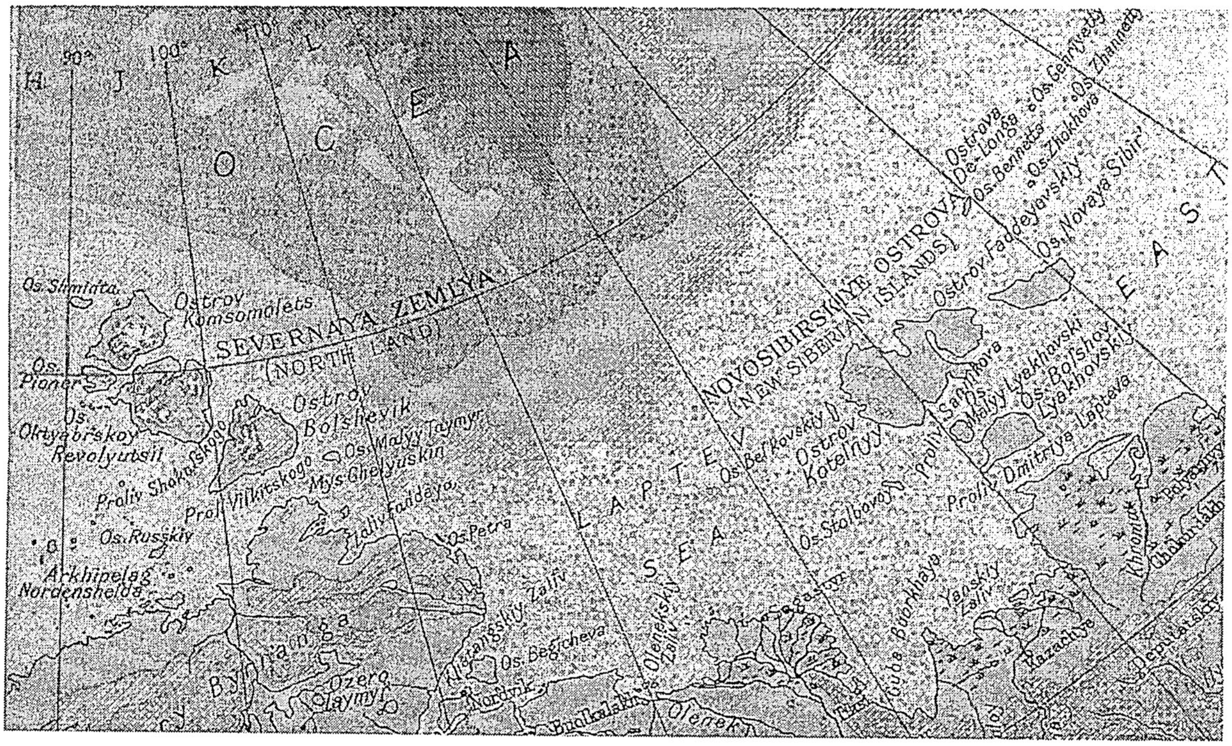

Figure 4 *Map of the study area in the Laptev Sea, The Times Atlas of the World, 1986.*

3.2 The Vilkitsky Strait and the western Laptev Sea

The development of the sea ice conditions in the western Laptev Sea and Vilkitsky Strait can be described from subsequent RADARSAT images, obtained on August 14, 15 and 31, and September 4 and 7 and the SSM/I data from the same period.

The SSM/I ice concentration maps, shown as greyscale images in Fig. 5, provide an overview of the distribution of ice and open water in the study area. The predominant features are the open water (dark areas) in the Northern Kara Sea (Fig. 5a), the Laptev Sea and areas in the East Siberian Sea (Fig. 5d). Ice areas are marked by bright signatures. From 15 to 31 August the Taimyr ice massif and the ice in the Vilkitsky Strait is reduced, but a branch of the Taimyr ice massif is attached to the coast during the period, acting as a barrier for ships sailing from Vilkitsky Strait to the Laptev Sea.

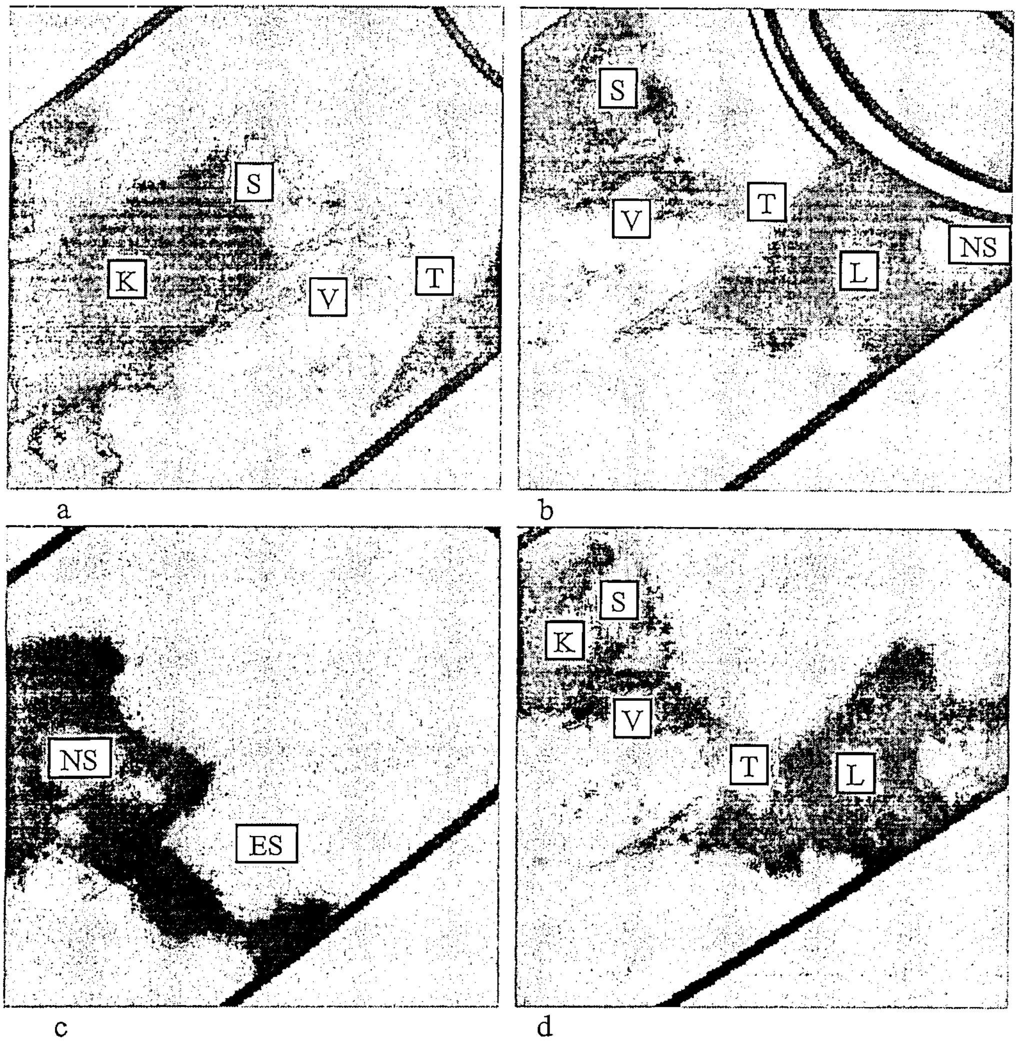

Figure 5 *SSM/I from ice concentration displayed in greyscale, were dark areas are open water and bright areas are 90-100 % ice concentration. Also land is marked as bright areas. The scenes are a) 15 August, Kara Sea, b) 31 August, Laptev Sea, c) 4 September, East Siberian Sea and d) 7 September, Laptev Sea. K = Kara Sea; S = Severnaya Zemlya; V = Vilkitsky Strait; T = southern branch of the Taimyr ice massif; L = Laptev Sea; NS = New Siberian Islands; ES = East Siberian Sea.*

3.2.1 THE PERIOD 14-17 AUGUST

The RADARSAT image from August 14 shows that the eastern part of the Kara Sea is mainly ice free with some scattered ice near the mainland and Severnaya Zemlya archipelago, (Fig. 6). Some fast ice can be identified in Shokalskogo Strait at 79° N, 100° E. The Taimyr ice massif in the Laptev Sea is clearly seen in the SAR images (Fig. 6 and 7) and the SSM/I shows that the ice massif reaches the coast of Taimyr Peninsula. Further east there is open water, ice concentration map (Fig. 2). Due to westerly winds the ice edge near the western entrance to the Shokalskogo Strait is compacted, ice drifts from the Kara to the Laptev Sea and mainly open water with single ice floes are shown to the east of Severnaya Zemlya. Ice concentration in Taimyr ice massif varies from 5/10 to 9/10. RADARSAT discriminates quite well large individual ice floes in this massif. Due to the eastward current in the Vilkitsky Strait the Taimyr ice massif is intruded by a wedge of predominantly open water.

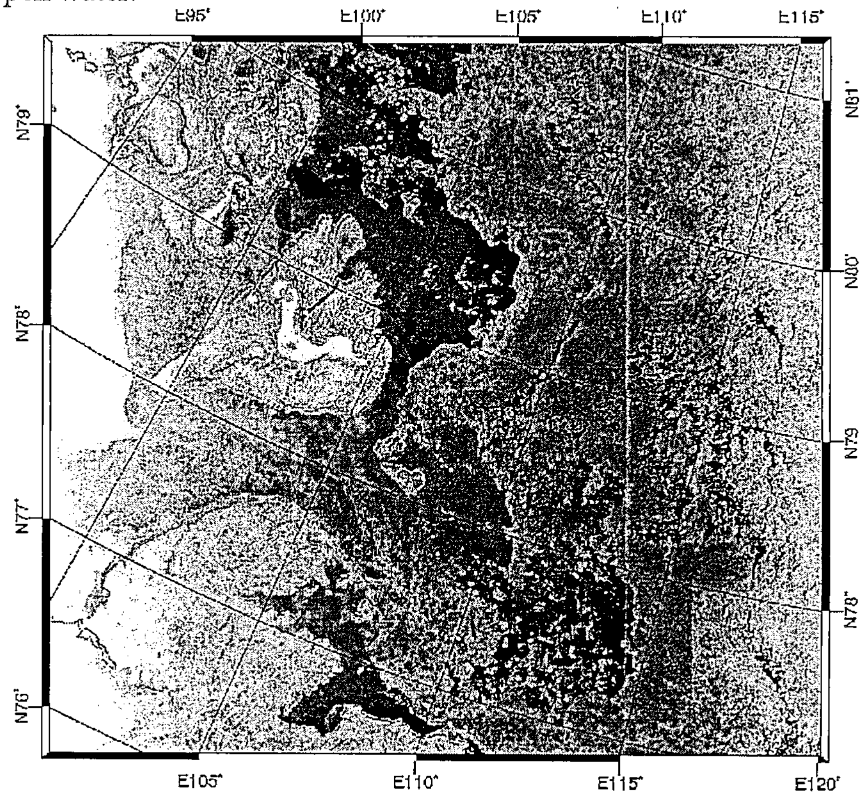

Figure 6 *RADARSAT ScanSAR 14 August 1997. Image Data © Canadian Space Agency 1997.*

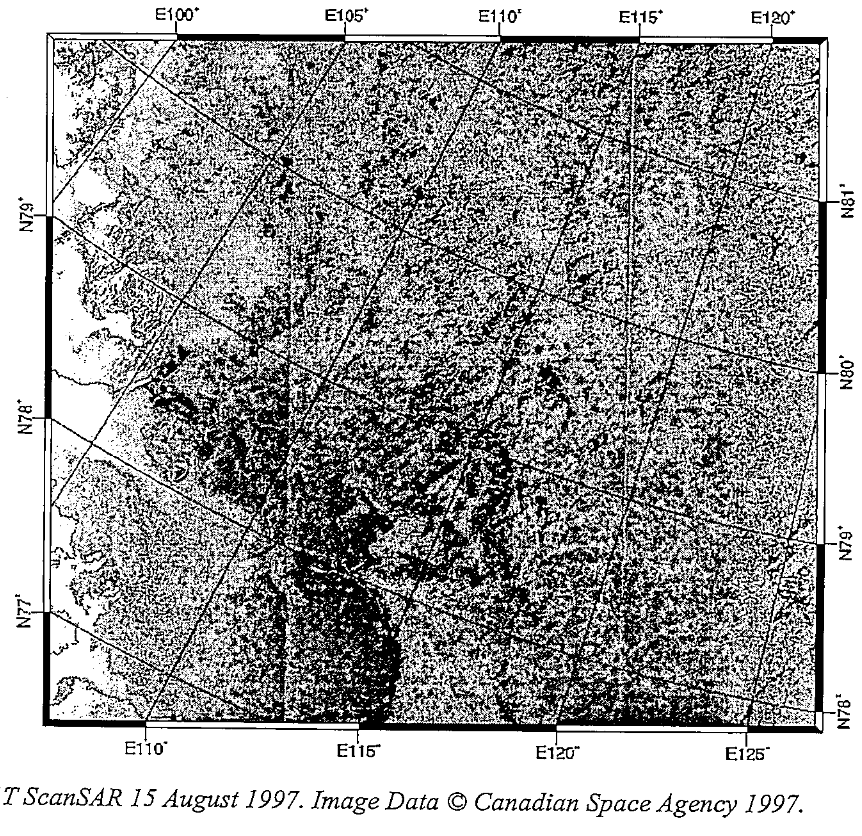

Figure 7 *RADARSAT ScanSAR 15 August 1997. Image Data © Canadian Space Agency 1997.*

The RADARSAT image from August 15 shows that due to one-day difference with a previous image sea ice conditions did not change very much, (Fig. 7). Backscatter from open water increased due to stronger wind and wind-roughened water is clearly identified in the northern part of the Vilkitsky Strait and to the east of Severnaya Zemlya. Sea ice with small ice floes in the southern part of the Strait is clearly distinguished from the open water in the northern part.

From successive geo-rectified images covering the same area, it is possible to measure the displacement of distinct ice floes found in the images. Given the pixel dimension and the time interval between the images, the physical distance and flow velocity can be calculated. The time-interval should not be more than a few days, in order to preserve the shape and backscatter signal from the ice floes.

The ERS-2 SAR images from the 14 and 17 August are shown in Fig. 8. The comparison between ERS and RADARSAT the 14 August cannot be done quantitatively, because the RADARSAT images are not calibrated while the ERS images are calibrated to about ± 1.5 dB. The backscatter values of the RADARSAT images are not normalised in range direction, so it is only possible to extract features and patterns from the RADARSAT images.

The most pronounced feature in the ERS images is the dark areas in the Vilkitsky Strait and north of Cape Neupokoeva (78° N 99°30′ E). These areas are most likely covered with grease ice or nilas which are clearly distinguishable from the open water areas. The same features can also be observed in the RADARSAT images, but the resolution of the RADARSAT images used in this analysis is coarser (400 m) than for the ERS images (100 m). On both images wind roughened water in the Kara Sea is characterised with high backscatter and clearly distinguished from sea ice, but the contrast between open water and sea ice appears to be better for ERS SAR. For sea ice with concentration less than 8-9/10, ERS SAR identifies single ice floes considerably better than RADARSAT, but this can be explained by the difference in resolution.

Because it was no clear ice features in the SAR images in the Vilkitsky Strait it was not possible to estimate the ice motion in this strait. However, the motion of the Taimyr ice massif could be estimated because the RADARSAT images on the 14 and 15 August showed a number of features which could be recognised in both images. The results showed that the mean ice velocity was 18.9 cm/s over 23.5 hours in a south easterly direction, (Fig. 9).

During August 14 strong winds from west and north-west with speed 12 m/s and higher made the ice edge in the Kara Sea compact. It also led to destruction of the ice breccia on the Taimyr ice massif in the Laptev Sea. During the day, prevailing westerly winds in the Kara Sea removed ice in the Mathissen Strait and fractured the fast ice in the northern part of the Vilkitsky Strait. An intensive ice drift to the east was also observed. Supposed fracturing of the fast ice in the southern part of the Vilkitsky Strait and drift of the ice into the Laptev Sea took place before this date. The winter fast ice from this area had drifted in south-easterly direction. Big floes of thick and medium ice (including thin ice) with concentration between 7-8/10 to 9-10/10 was mainly centred here. From the RADARSAT image it was possible to distinguish vast floes (from 2 to 10 km) and medium floes. In the southern part of the Vilkitsky Strait the ice is more broken up, small and medium floes are predominant. The same type of ice influenced by the westerly winds are located to the north-west of Neupokoev Cape, where the southern boundary of the fast ice in the Shokalsky Strait is evident, according to the ERS-2 SAR data. The northern boundary of the fast ice in the strait lies along the latitude 79° 10' N.

The orientation of the fractures inside the Taimyr ice massif seen in the RADARSAT image, as well as the state of the ice edge and the configuration of the open water areas north of Maly Taimyr Island, support the conclusion that the north-western component of the near surface wind dominates in this part of the Laptev Sea.

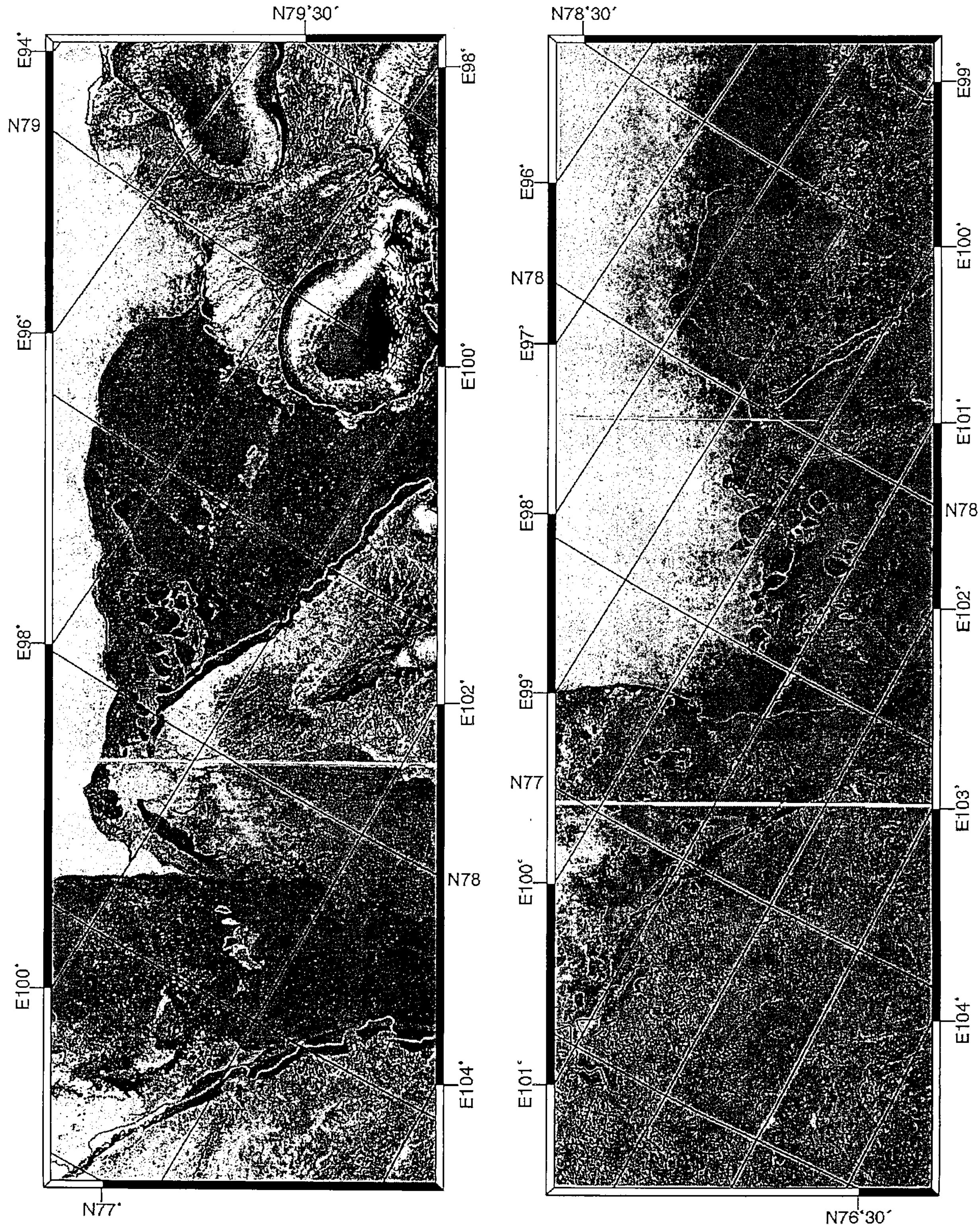

Figure 8 *ERS-2 SAR 14 and 17 August 1997. Image Data © European Space Agency 1997.*

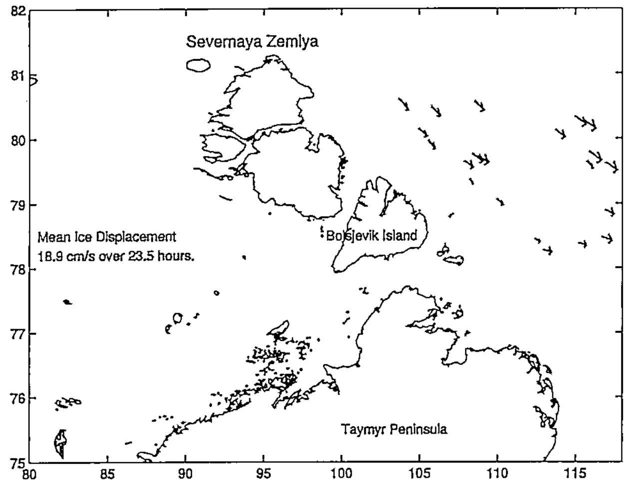

Figure 9 *Sea ice displacement 14 to 15 August 1997.*

3.2.2 THE PERIOD 27-31 AUGUST

Two weeks later, by the end of August open water areas had considerably increased within the RADARSAT image from the 31 August, (Fig. 10). Ice in the Shokalskogo Strait and Vilkitsky Strait was fractured and only a few ice bands could be identified. The open water area east of Severnaya Zemlya and Vilkitsky Strait had increased considerably, and also the openings in Taimyr ice massif were enlarged. Large areas of compact ice were observed in the southern part of the Laptev Sea, near the coast of Taimyr. Fast ice and much of the grease ice and nilas north of Cape Neupokoeva had disappeared. Only single ice floes and ice bands are evident in the eastern part of the Kara Sea, in the Vilkitsky and Shokalskogo Straits and to the east of Severnaya Zemlya. Backscatter from open water in the eastern part of the Kara Sea varies considerably, due to variability of the wind field. The Taimyr ice massif had shifted to the east and partially melted, areas with low ice concentration are evident from RADARSAT image.

The ERS-2 SAR image from August 27 shows a more detailed picture of the Vilkitsky Strait where scattered ice floes and areas of grease ice and nilas can be identified, (Fig. 11). The SSM/I map shows that the Taimyr ice massif had been reduced over the two weeks period from 15 to 31 August, and that large parts of the Laptev Sea was ice free, (Fig. 5).

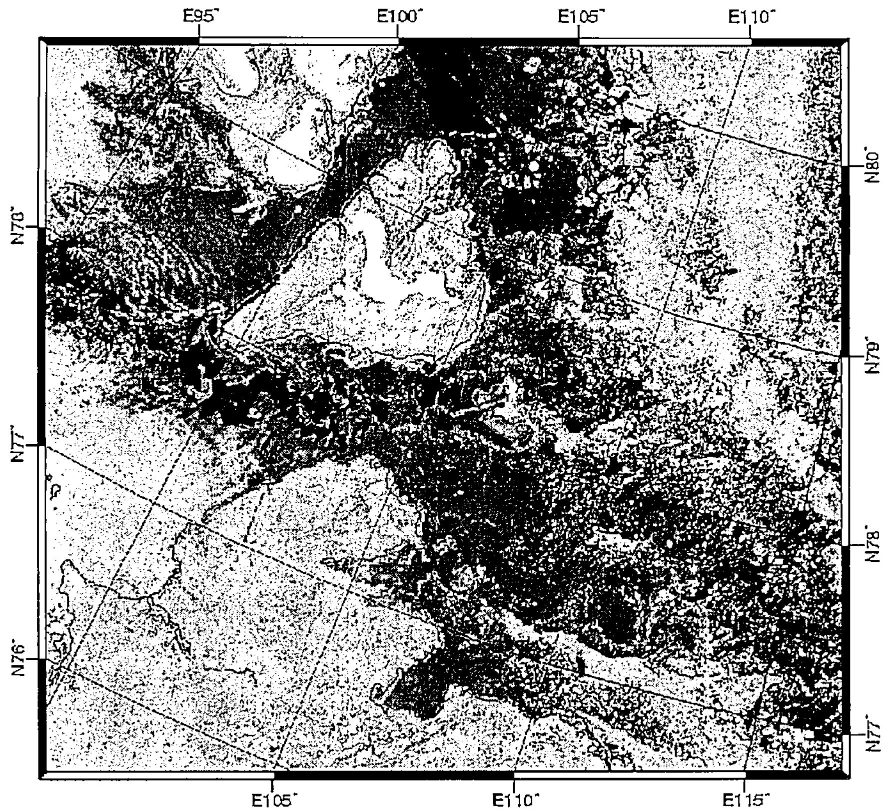

Figure 10 *RADARSAT ScanSAR 31 August 1997. Image Data © Canadian Space Agency 1997.*

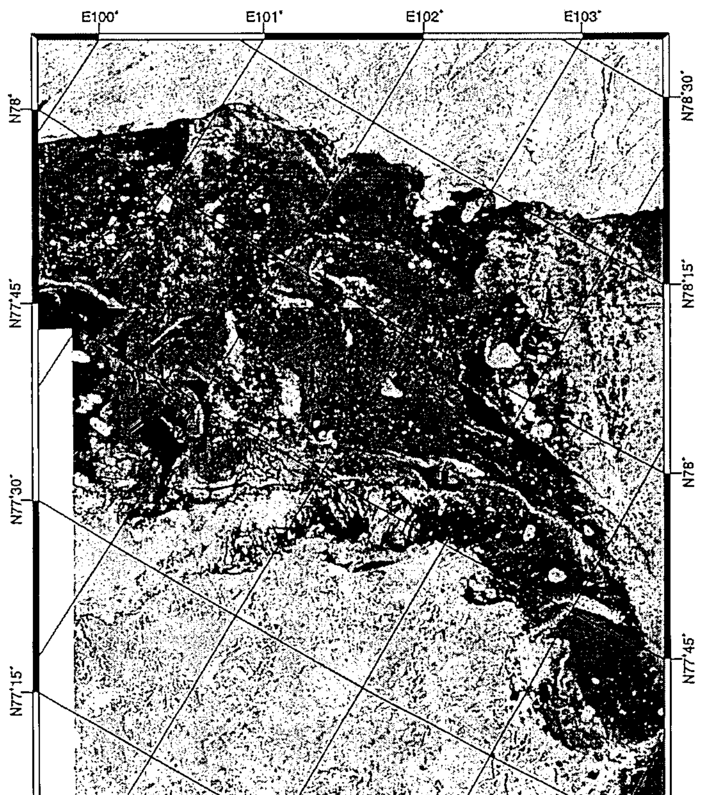

Figure 11 *ERS-2 SAR 27 August 1997. Image Data © European Space Agency 1997.*

3.2.3 THE PERIOD 4-7 SEPTEMBER

The image from 4 September, (Fig. 12), compared with August 31 shows that the Taimyr ice massif shifted in the south-western direction and open water areas in the central Laptev Sea, east of Severnaya Zemlya, has decreased. Open water area south-east of Vilkitsky Strait were considerably enlarged. Areas with low ice concentration in the central part of the massif were conserved. The radar signature of first-year sea ice in Taimyr ice massif varies probably due to different degree of ice melting. It is clearly evident from this image, that the Taimyr ice massif was divided into northern and southern parts due to ice and water outflow of ice water/masses from the Kara Sea through the Vilkitsky Strait. Only a narrow ice stripe centred at 77° N and 120° E connects the two parts of the ice massif. This would also be observed in the SSM/I data for September 4 and 7, (Fig. 5). Very compact sea ice was evident in the southern part of the Laptev Sea. Comparatively narrow ice isthmuses in the Taimyr ice massif (76°30N/120°E to 77°N/120°E) could be seen in the RADARSAT ScanSAR image for September 4, and was used for ship routing.

The ice kinematics estimates, (Fig. 14), show that the motion of the ice massif is 15.3 cm/s over 3 days. Areas to the east of Vilkitsky Strait not covered by the ice massif are shown with lower signal due to beginning of freeze-up were grease ice and nilas are typical new ice types which are formed. Multiple ice bands and single ice floes are identified in the area centred at (77° N; 115° E). A more detailed description is presented in the validation discussion.

Figure 12 *RADARSAT ScanSAR 4 September 1997. Image Data © Canadian Space Agency 1997.*

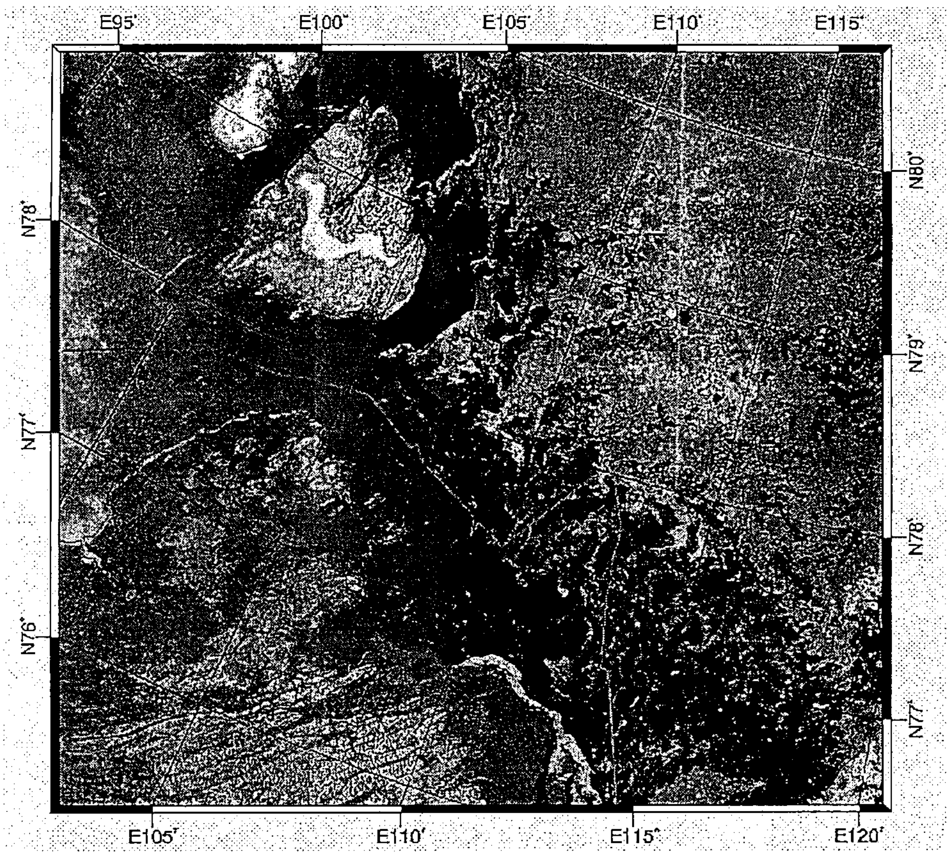

Figure 13 *RADARSAT ScanSAR 7 September 1997. Green line is sailing route of 'Sovetsky Soyuz'. Image Data © Canadian Space Agency 1997.*

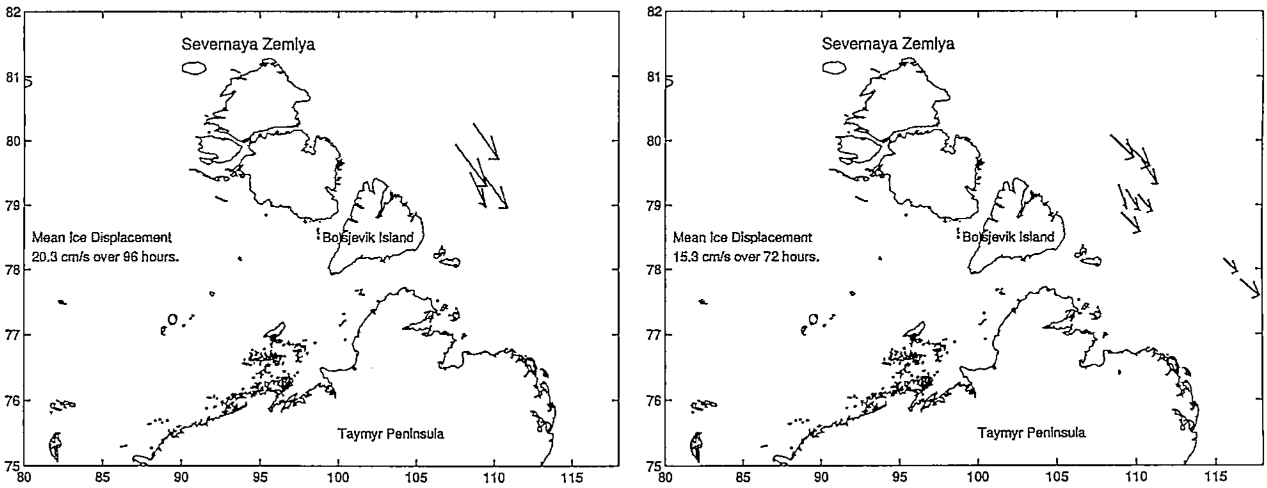

Figure 14 *Sea ice displacement 31 August to 4 September and 4 to 7 September 1997.*

Specialists at Arctic and Antarctic Research Institute (AARI) have composed ice charts based on the acquired RADARSAT ScanSAR scenes of September 4 and 7, (Fig. 15 and 16). Areas with different ice concentrations are delineated, and the concentration values are both manually and automatically calculated. The ice drift for the period September 4-7 is determined from successive images, and is also shown on the map. Areas covered by grease ice, nilas and pancake ice, and ice bands in the open water, could not delineated without *in situ* information.

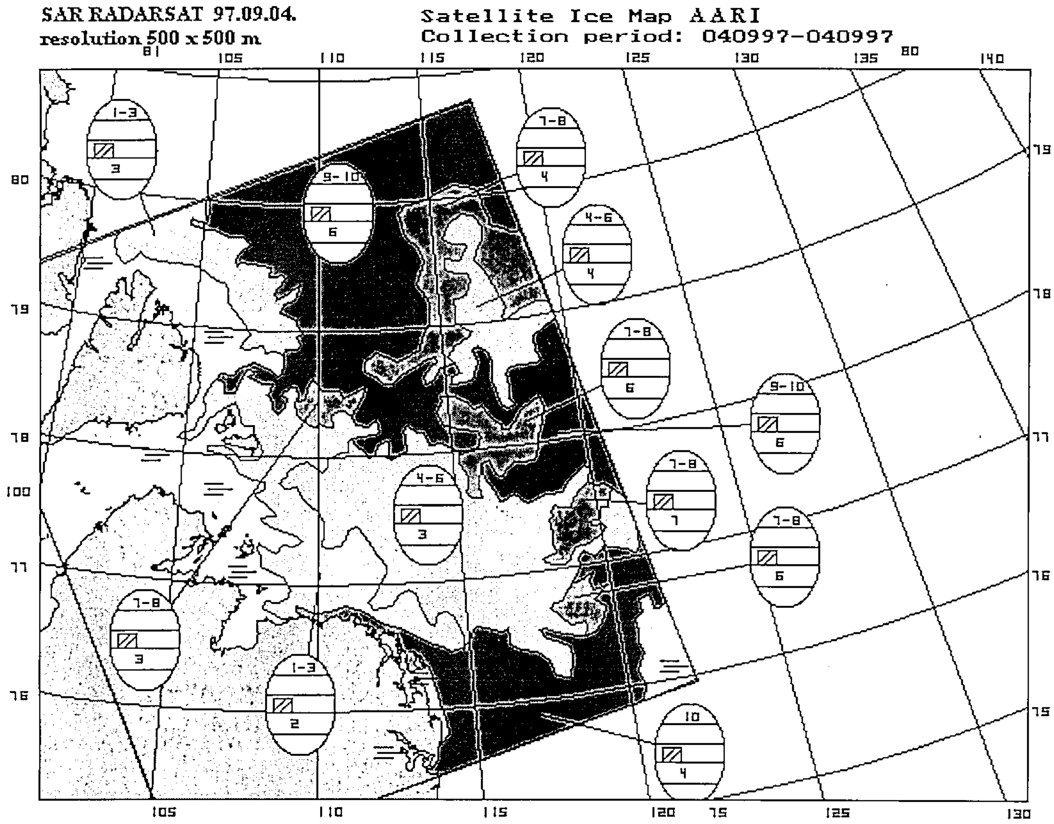

Figure 15 *Sea ice map from RADARSAT data of 4 September 1997. Image Analysis © AARI 1997.*

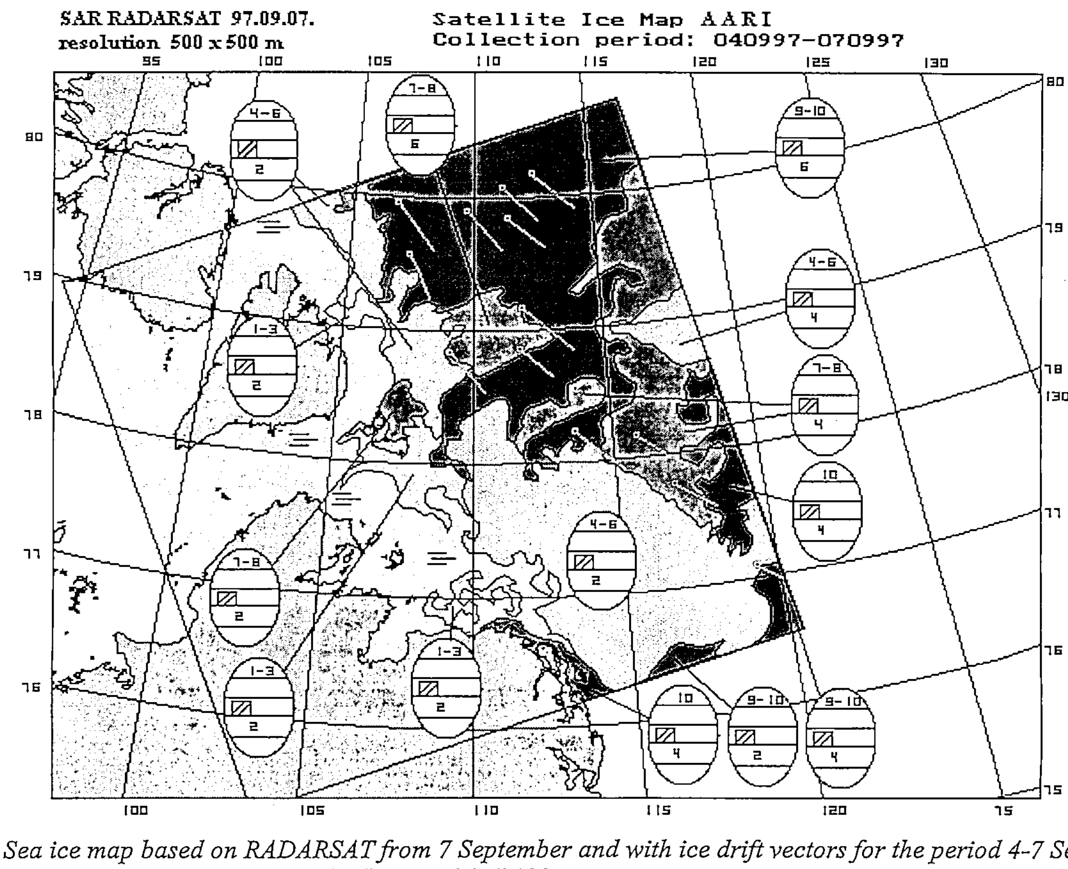

Figure 16 *Sea ice map based on RADARSAT from 7 September and with ice drift vectors for the period 4-7 September, showing south-easterly ice drift. Image Analysis © AARI 1997.*

3.3 NEW SIBERIAN ISLAND AND THE EAST SIBERIAN SEA

Two RADARSAT images, one consisting of two ScanSAR scenes, were obtained in the area of the New Siberian Islands, including the eastern part of the Laptev Sea and a part of the East Siberian Sea on 4 and 6 September. These images were obtained from the Canadian Space Agency which used onboard recording and downlink of RADARSAT data at Gatineau receiving station in Canada, (Fig. 17 and 18). Alternatively, Alaska SAR Facility could have received SAR data from this region. AARI has analysed these images and produced an ice chart with interpretation of ice types and ice concentration, (Fig. 19).

As it is evident from RADARSAT images, the eastern part of the Laptev Sea and an area north of the New Siberian Islands are ice-free, (Fig. 17). Also a 100-200 km wide zone along the coast eastwards to 165° E is ice free, (Fig. 18). Sea ice in the New Siberian Straits did not melt during the summer and it is easily identified to the south of the islands. This ice is heavily deformed. The position of a diffused ice edge to the north of the islands is also readily identified from the RADARSAT image. Some individual ice floes are observable in the ice massif. The ice concentration varies from approximately 4-5/10 to 9-10/10. Ice edge goes mainly from north to the south and in the 155 meridian situated less than 100 km from the mainland. Open water areas with single ice bands are evident near the ice edge here. Radar signatures of first-year ice vary, probably due to different stage of ice melting. Single ice floes and fractures are clearly identified in the ice massif.

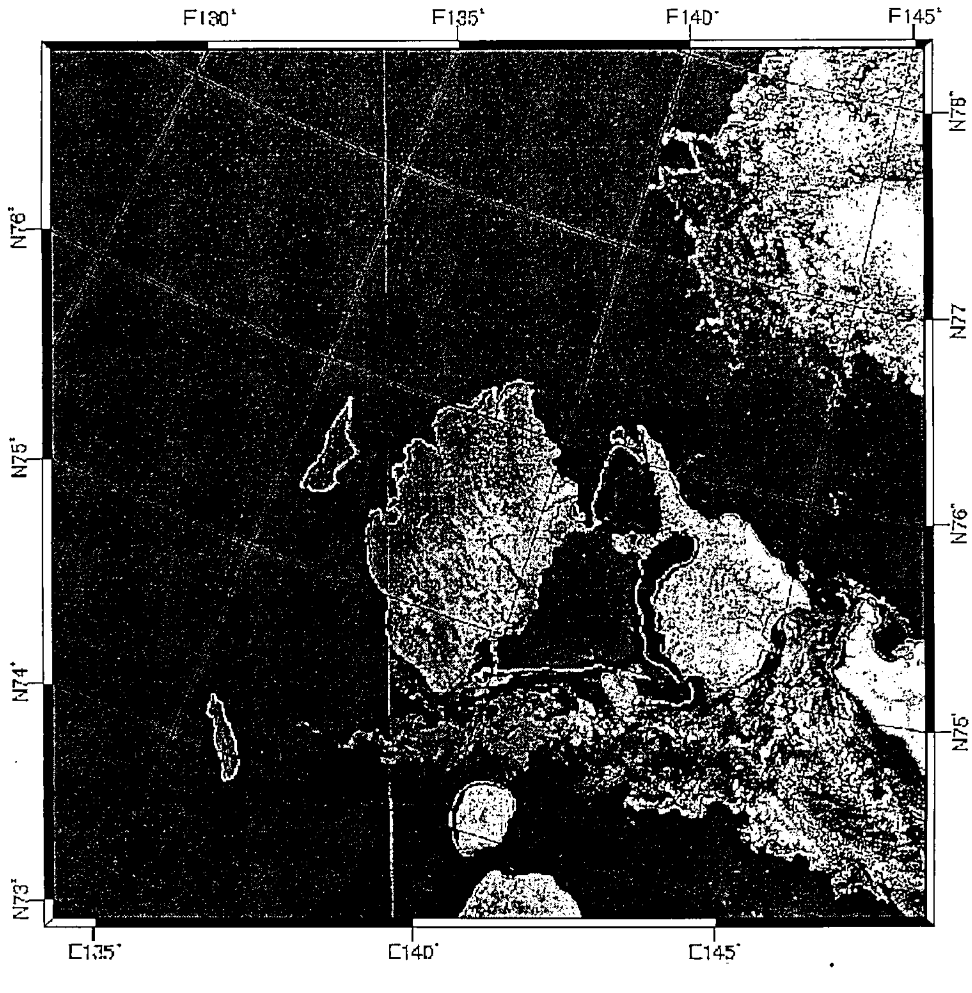

Figure 17 *RADARSAT ScanSAR 4 September 1997. Image Data © Canadian Space Agency 1997.*

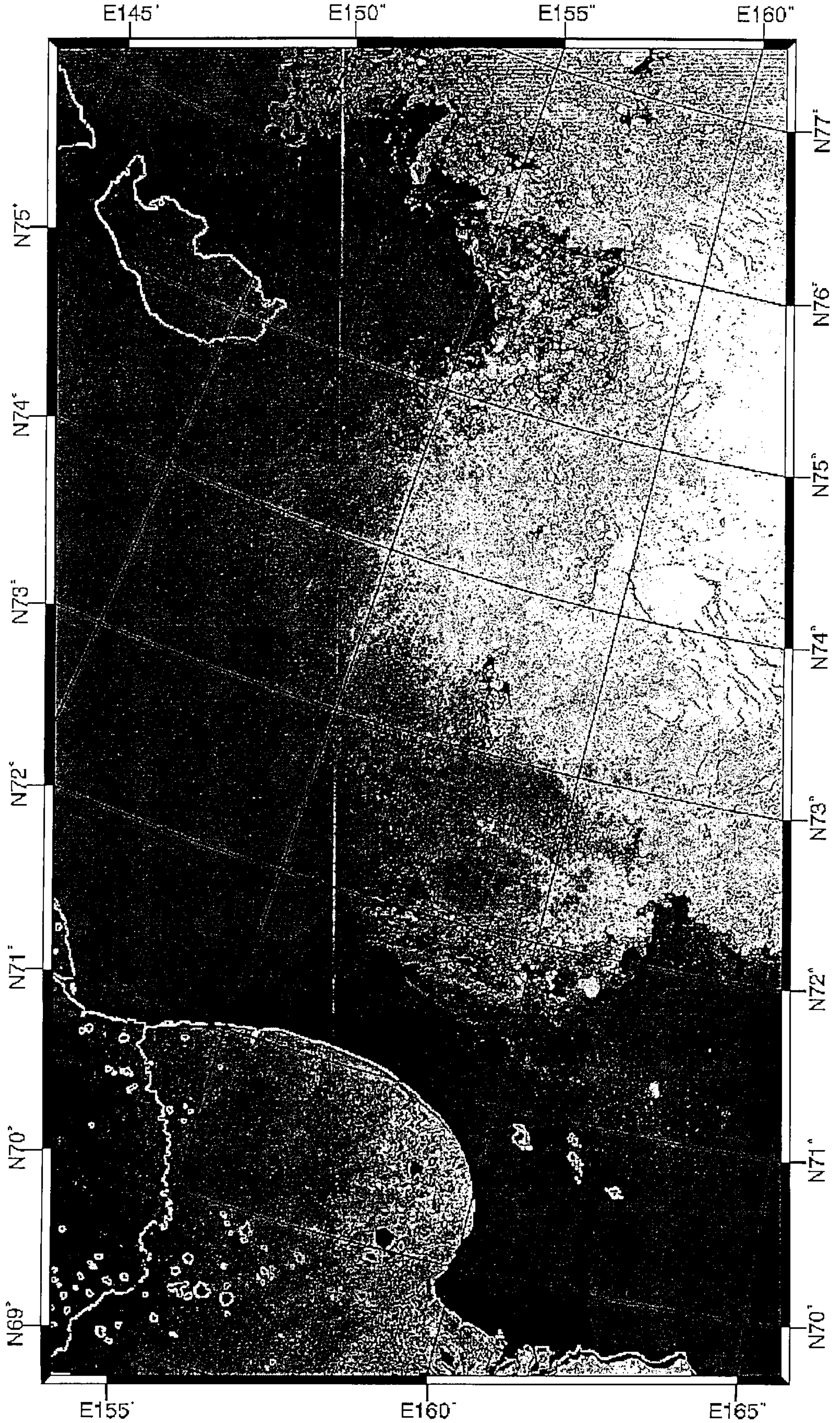

Figure 18 *RADARSAT ScanSAR 6 September 1997. Image Data © Canadian Space Agency 1997*

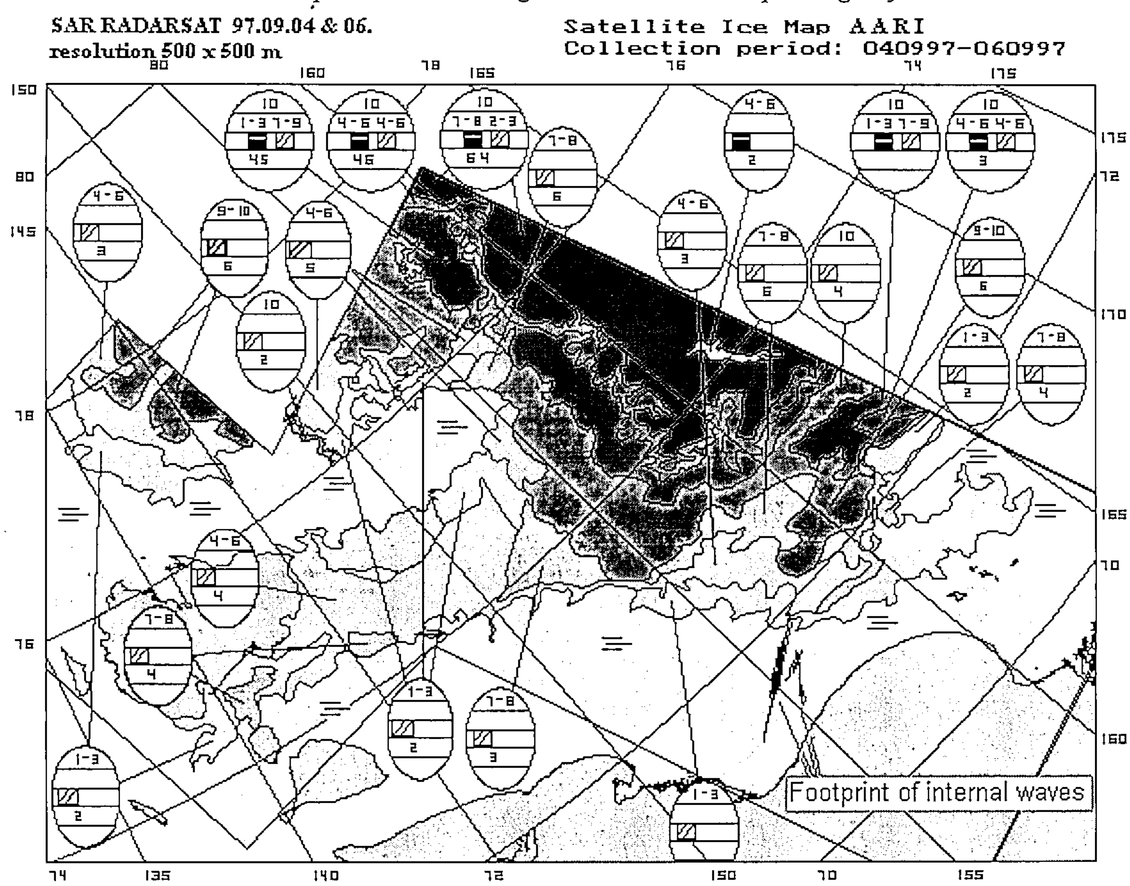

Figure 19 *Sea ice map from RADARSAT SAR scenes from 4 and 6 September 1997. Image Analysis © AARI 1997.*

4 DETAILED ANALYSIS AND VALIDATION OF SAR IMAGES

Due to limited coverage by INMARSAT north of 72° N, only small data files (below 200 kB) were feasible for transmission. Therefore, the image resolution was first reduced to 500 by 500 m, and then the file size was further reduced using JPEG-compression.

Sub-satellite sea ice observations were carried out continuously while the icebreaker operated in the ice, and consisted of visual estimates of sea ice parameters from the bridge, visual helicopter ice reconnaissance, and photographs of different sea ice conditions. All observations were geo-located, and compared with the corresponding areas in the image. Sea ice observations were collected onboard the icebreaker every four hour, and included in an *in situ* database. Subsequent analysis of the validation data allowed determination of the RADARSAT SAR summer signatures of the different ice conditions found in the Laptev Sea.

These hydrometeorological observations included meteorological (air pressure, wind velocity and direction, sea and air temperature) and sea ice observations. In order to validate the RADARSAT ScanSAR images obtained before the icebreaker expedition, routine ship observations within the areas covered by SAR were analysed. On August 14 and 15 when the two first RADARSAT images were acquired no validation data were available. However, for the images of August 31 and September 4 and 7, in situ data were obtained within 3-4 days of the time of the SAR acquisition.

Throughout the expedition the temperature of the upper sea layer was stable at about -2°C. The air temperature varied from about -3°C at night to +1°C in daytime. The wind speed did not exceed 9 m/s. Validation observations in more than 50 positions were collected. Joint analysis of the SAR image and the *in situ* ice observations allowed us to delineate five distinct areas with different sea ice conditions along the ship track. Although there were a few days between SAR acquisition and the ship observations, several features remained the same, and could be recognised in the image. In situations where the comparisons were uncertain, it is at this stage difficult to say whether this is due to the time spacing or properties of the radar.

The validation activities were concentrated to the image of 7 September because *in situ* observations were available 3-4 days later. Observations from the icebreakers 'Sovetsky Soyuz' and 'Yamal' during the 10th and 11th of September 1997 are used to discuss some aspects of the RADARSAT's ability to measure sea ice features. From the ScanSAR scene three sub-images were extracted which covered areas where the icebreakers had sailed, (Fig. 20). With 8 looks, the ScanSAR wide beam mode has a resolution ranging from 85 to 150 m, and covers an area of 500 by 500 km. The image was resampled to yield a pixel size of 100 by 100 m. While relative backscatter values are known (0.37 dB/bit), absolute calibration is presently unknown. We have performed an *ad hoc* calibration to preserve a constant reflection from similar features in the range direction.

The first sub-image no. 1 covers approximately 100 by 100 km of an area with predominately open water just east of the Vilkitsky Strait, (Fig. 21). Several bands of ice are visible in the open water as bright line features against dark background. Ship observations were made along the straight white line in the lower part of the image, reporting ice concentrations between 50 % and 100 %. The ice mainly consisted of a mixture of grease ice and pancake ice (pancake size up to 1 m), with occasionally patches of FY in-between (with a rough, snow covered surface). The floe size ranged from 20 up till 100 m. Patches of ice cakes and smaller ice floes drifting around in the open water were observed continuously. Presumably the brightest areas are pancake ice and rough first-year ice, while the darker areas are open water mixed with grease ice. Due to low winds open water can have as low backscatter as grease ice. Small, very bright spots occasionally appearing within the open water, may be larger icebergs, as was observed several times from the ship. Going northwards from the ice edge, the ice concentration increases, introducing massive FY ice.

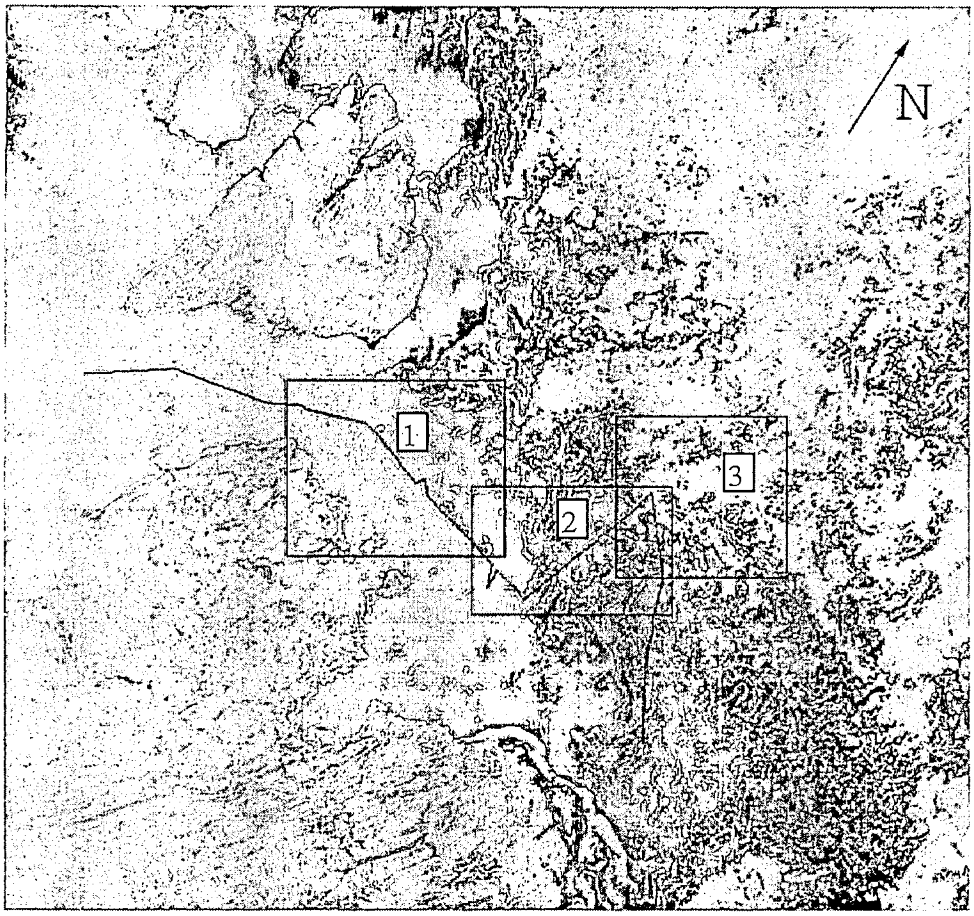

Figure 20 *RADARSAT ScanSAR wide beam image of 7 September 1997, 16.33 local time from Vilkitsky Strait. The ship track of 'Sovetsky Soyuz' is shown as the dark line. The rectangles mark the sub-images which are analysed in this chapter. Image Data © Canadian Space Agency 1997.*

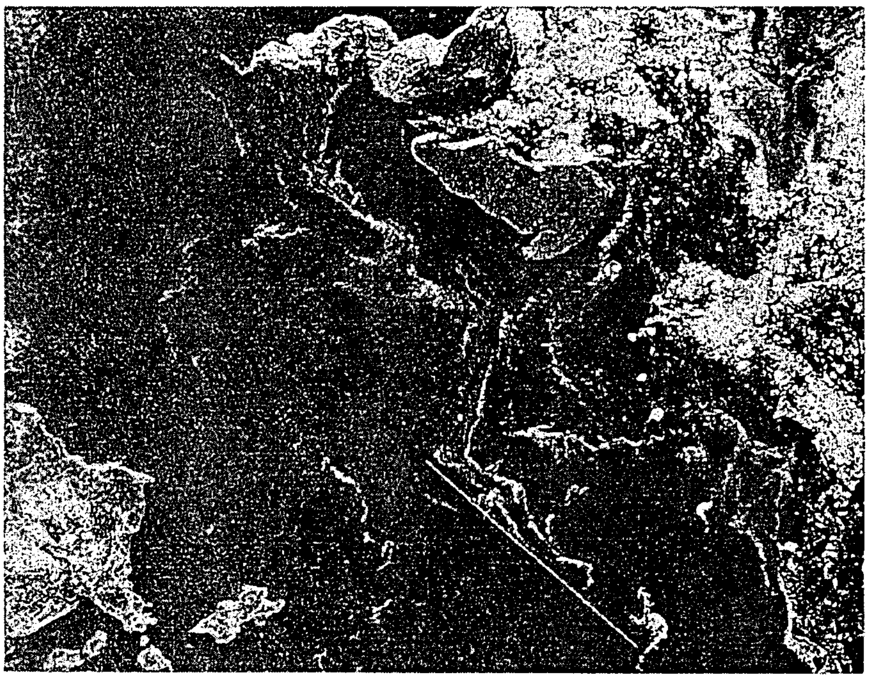

Figure 21 *Sub-image no. 1 of the RADARSAT ScanSAR wide beam image of 7 September 1997 covers approximately 100 by 100 km of the eastern opening of the Vilkitsky Strait.*

Figure 22 *Sub-image no. 2 of the RADARSAT ScanSAR wide beam image of 7 September 1997 covers approximately 110 by 60 km.*

Sub-image no. 2 covers approximately 110 by 60 km of an area where the icebreaker went into the Taimyr ice massif, (Fig. 22). The left part of the sub-image covers mainly open water with a few bands of ice. The ice concentration increases towards the right. An iceberg which was about 100 m in horizontal scale was observed in box a), where water depth was about 70 m. The very bright spot within the box shows the iceberg. A ship moved from the upper left corner of box b), towards the lower right corner, grease ice was first observed, then two larger stripes of FY ice were observed, with ice box concentration between 30-50 %. The FY ice was surrounded with grease ice. Then an area of mainly open water and with some grease ice was observed. The lower part of box b) was dominated by small pancake ice. In box c) dark nilas, including some patches of pancake and FY ice was dominating, with ice concentration between 50 and 80 %. The image brightness of dark nilas is higher than the dark signature of grease ice/calm water and lower than FY ice.

Sub-image no. 3 is from an area of more first-year ice, covering about 85 by 65 km, (Fig. 23). Ship observations from three locations show different ice conditions. Box a) which typically had ice concentration up to 80 %, consisted mainly of nilas (60-70 %). In the lower right corner some FY ice with floe size of 2-20 and thickness of 80-100 cm was observed. In box b) the ice concentration reached almost 100 %, and is dominated by FY ice. There are only some small patches of nilas and open water in this area. The floe size has increased to 50-200 m, and the thickness to 100-150 cm. The ice surface is fully covered by snow. This is characteristic ice concentrations for the compact Taimyr ice massif observed as bright areas in several of the RADARSAT images in this area. In box c), nilas was the dominating ice feature, though the ice concentration was lower than in box a), between 30-60 %. Here, the brightness signature of the nilas appears slightly darker than in box a), which may be due to the lower ice concentration.

A lot of photos were taken for validation purposes, two are shown in Fig. 24. The photo from 10 September is located within sub-image no. 1, and shows a mixture of grease ice and pancake ice. The photo from 11 September is located within sub-image no. 2. And shows dark nilas, including some patches of FY ice.

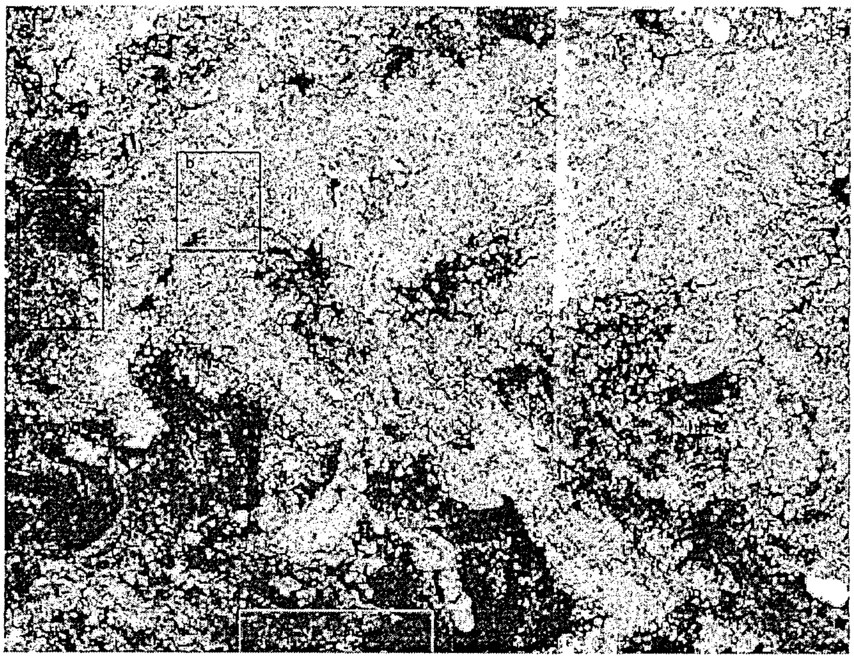

Figure 23 *Sub-image no. 3 of the RADARSAT ScanSAR wide beam image of 7 September 1997 covers approximately 85 by 65 km.*

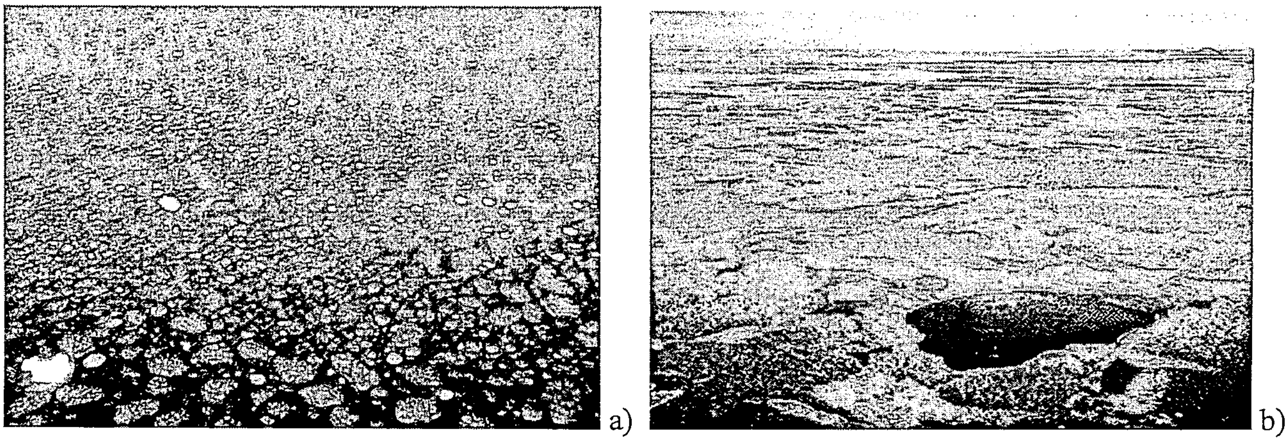

Figure 24 *Photos from a) 10 September 1997 10.35 local time, 77° 55' 43" N, 104° 20' 2" E and b) 11 September 1997 06.20 local time, 77° 37' 8" N, 111° 1' 2" E.*

4.1 SEPARATION OF ICE AND WATER IN RADARSAT

An important ice parameter is the border between open water and different types of ice. By simple image thresholding, it is possible to separate the FY ice from the surrounding water and areas of grease ice and nilas. Another method which have been tested to enhance the ice edge is power-to-mean ratio, PMR. This ratio is based on the local standard deviation, σ, and the local mean, μ, of the graylevel values. The difference between the original image and the calculated PMR-image was found to give an enhancement of the ice edge, (Fig. 25). First-year ice appear to be well separated from open water. The main problem is that grease ice and nilas appear to be difficult to separate from open water. Optimal filtering before use of the different techniques shown here, would probably give better results..

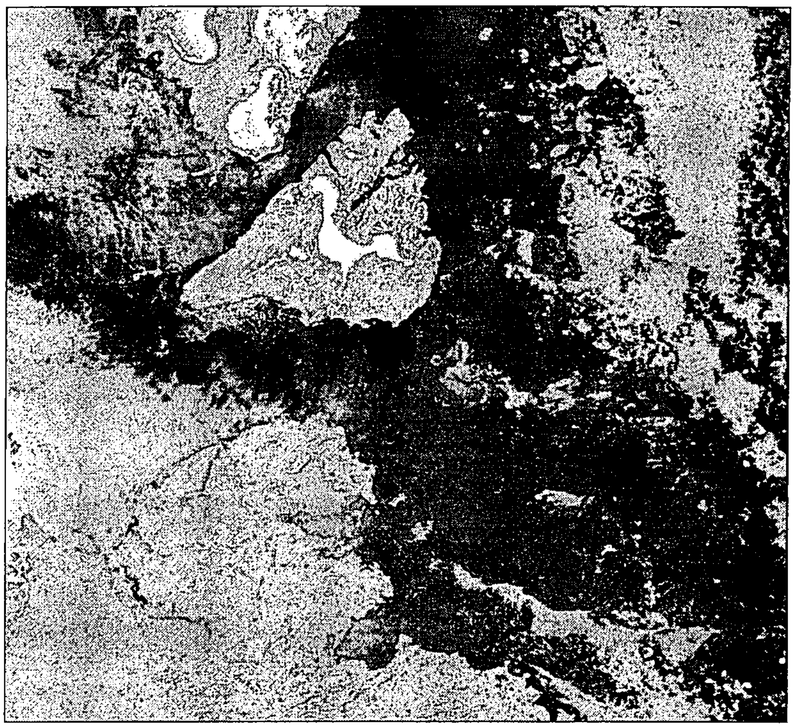

Figure 25 *Difference between original image (31 August) and PMR values gives a better discrimination between first-year ice and open water/thin ice.*

4.2 COMPARISON OF ICE CONCENTRATION ESTIMATES BY RADARSAT AND SSM/I

A comparison of concentration estimates by SSM/I and RADARSAT from the same day was performed for September 7. Ice concentration contours derived from SSM/I data were superimposed on the RADARSAT image, and is shown with a polar stereographic projection, (Fig. 26). The isolines for 20 %, 50 %, and 80 % ice concentration are shown for the SSM/I data. The areas with lower than 20 % concentration correspond to the dark areas in the SAR image with predominantly open water, grease ice and scattered bands of first-year ice. The areas between 20 % and 50 % correspond to a mixture of open water, nilas and first-year ice, while the areas above 50 % agree well with the bright areas in the SAR image where first-year ice dominates.

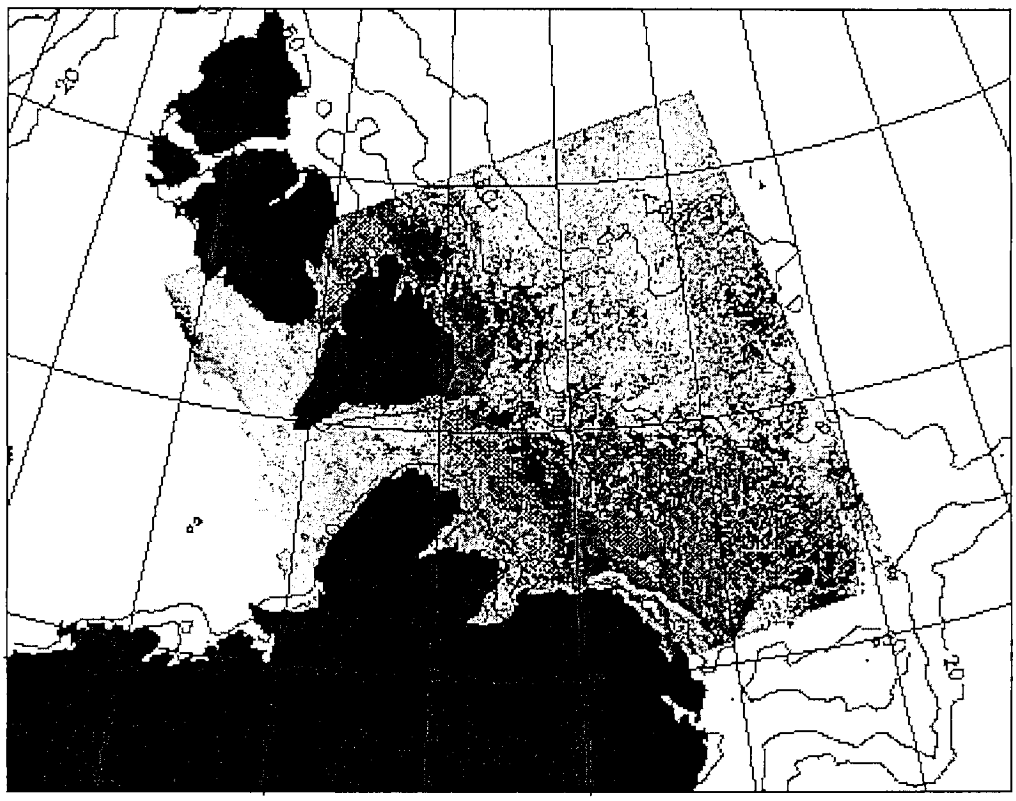

Figure 26 *SSM/I ice concentration isolines and RADARSAT ScanSAR image from the 7 September 1997. Image Data © Canadian Space Agency 1997.*

4.3 WINTER NAVIGATION IN OB ESTUARY

During the winter expedition to Ob estuary in April-May 1998 SAR data from RADARSAT and ERS-2 were also used in ice navigation. In this expedition several icebreakers were involved in escorting the Finnish tanker 'Uikku' sailing to the Tambey area as part of the ARCDEV project (Pettersson, 1998). The ice conditions in the Ob estuary are not well known, even by ice specialists. Therefore, use of SAR data was important as part of planning, to find the optimal sailing route through the fast ice which dominates in the estuary (Fig. 27). The ERS SAR image of 6 May was obtained when the ships were located in Tambey (in the lower part of the image). It shows the ship track trough level fast ice (dark signatures), and that the route was chosen to avoid the hummocked ice areas which appear brighter in the SAR image. Also RADARSAT images were used to map the ice in the estuary. Without SAR data it could have been more difficult for the icebreakers to find the most efficient sailing route.

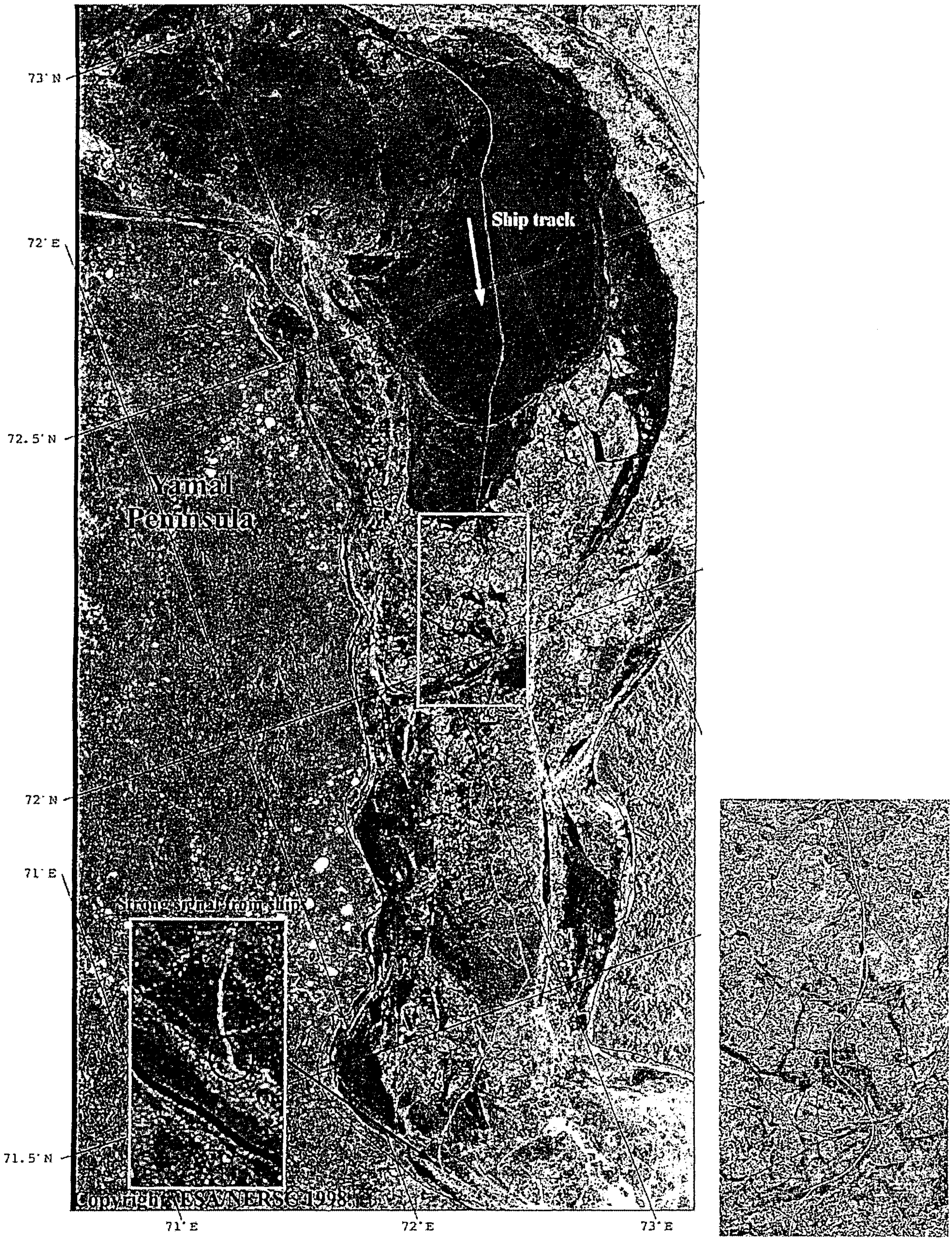

Figure 27 *ERS SAR image of 6 May 1998 showing the sailing route of the ARCDEV expedition in the Ob estuary. SAR images were also obtained before the expedition started for planning of the sailing route. The sub-image is a blow up of a difficult sailing area and shows how the ship avoided hummocked ice areas. Image Data © ESA/NERSC 1998.*

4.4 First assessment of RADARSAT ScanSAR data in ice navigation

The main improvement of RADARSAT data in ice monitoring is first of all that high resolution SAR images are available over much larger areas, and with more frequently observation interval, than was possible with other satellite systems such as ERS-1/2. In areas such as the Ob estuary, ERS SAR data are equally important as RADARSAT data, because the size of the area is limited. The quick delivery time of RADARSAT and ERS SAR data from Tromsø Satellite Station is another advantage which makes near real-time ice monitoring possible. Transmission of SAR images to icebreakers within 2-3 hours is a main advantage for tactical and operative ice reconnaissance. SAR images can be used as an important supplement to helicopter ice reconnaissance for icebreaker convoys.

Preliminary analysis of the data from the 'Sovetsky Soyuz' expedition shows that the main sea ice parameters important for summer navigation, such as the ice edge position, ice concentration, and floe sizes can be identified in RADARSAT ScanSAR images. Single ice bands in the open water can be also distinguished which are not problematic for ice breakers. For other ships with lower ice classes such ice bands can be dangerous. Ice drift vectors and ice dynamics can be determined from successive SAR images obtained with 1-3 days interval. The main ice classification problem is to separate between open water and new ice types (grease ice, nilas) because these features are shown as similar dark features in the SAR images. Improved classification of ice types requires that RADARSAT images should first of all be calibrated. If texture analysis and contextual information is utilised it is expected that SAR ice classification will improve the information value of the images.

The experience from the first demonstration expedition for use of RADARSAT data was used to plan and implement a winter demonstration in the Kara Sea in April-May 1998. In this period two icebreaker expeditions were carried out were RADARSAT and ERS SAR data were used to map the whole ice area between the Barents Sea and the Ob estuary in the Kara Sea. These demonstrations showed that satellite SAR data can play an essential role both in operative and tactical ice navigation, especially during the heavy ice conditions which prevailed in the winter of 1998. The winter demonstrations were parts of two EU-funded projects, ICE ROUTES (Alexandrov *et al.*, 1998) and ARCDEV (Pettersson, 1998).

5 Use of SAR data in sea ice operational monitoring

5.1 Users of sea ice information

In order to design a system for polar ice monitoring it is essential to know the requirements from the main user categories, both from established users and new or potential users (Table 3). The users can be divided into three main groups: 1. operational users which need ice information in near real-time; 2: consulting services which mainly need archived data and statistical information on ice conditions, and 3: scientific users who need data in research and development projects. 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.

Table 3 *Users of sea ice information in the Northern Sea Route.*

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

5.2 OPERATIONAL SCHEME FOR USE OF SAR

In an operational service there is a number of requirements which need to be satisfied before the SAR monitoring technology can become an operational tool, such as: selection of SAR coverage in strategic areas, real-time access to SAR data, data ordering procedure, interpretation of SAR images, quantitative ice parameters from SAR, linking ERS data to the Russian ice monitoring services, transmission of ice maps and images to ships and other end users.

It is suggested to implement an operational radar ice monitoring system which will be included in the general Russian ice monitoring service. It will use Okean SLR data for large scale surveying and SAR data for detailed observations in specific key area, which are identified as difficult for the navigation It is recommended to obtain weekly coverage of SLR for the whole Northern Sea Route, and RADARSAT/ERS SAR stripes covering high priority areas as shown in Table 4:

Table 4 *Priority areas for SAR coverage.*

Area	Season of priority	Main users
White Sea	December - June	Ship traffic
Pechora Sea	December - June	Oil and gas exploration
Kara Gate and Jugor Strait	March - July	ship traffic
Yamal coast, Bely Island, Ob estuary	March - August	Ship traffic, oil and gas industry,
Yenisey estuary	March - July	Ship traffic
Vilkitsky and Mathiessen Str.	June - October	Ship traffic
Laptev Sea and New Siberian Islands	June - October	Ship traffic
Long Strait	July - October	Ship traffic

RADARSAT ScanSAR scenes, with 500 km swath width, will technically be the best data source in an operational system, supplemented by ERS SAR data in smaller regions (estuaries and straits). Weekly coverage of RADARSAT/ERS data of the sailing routes supplementing Okean SLR data, would be an optimal solution. The main limitation is the cost of the data, and it is unclear if and how much funding can be available for such data. A more realistic scenario for use of RADARSAT/ERS SAR data is during specific expeditions where the ice conditions are difficult. In such cases the costs of using SAR data can be justified. The SAR coverage of large sea ice areas represent an enormous amount of ice information, and it is a great challenge to extract the most important information needed for ice navigation in near real-time ice service. From 2000, also ENVISAT ASAR will provide wide-swath data which will be useful for operational monitoring. ASAR represents an improvement in spaceborne SAR technology because it can provide dual polarisation SAR imagery which will be better for discrimination of open water from sea ice. Real-time SAR monitoring requires a new receiving station in Russia in order to have full SAR coverage of the whole NSR. ESA is planning to establish this station in near future.

A fully operational system will provide SAR data from several satellites and as well as Okean SLR and other Russian satellite data which will be distributed to users in near real time. Also off-line data and data products should be made available for offshore industry and environmental agencies as well as other users who need SAR ice information.

6 CONCLUSION AND FUTURE PERSPECTIVES

SAR derived ice information has proven to be essential in ice monitoring of the NSR to support sea transportation. Near real-time use of SAR data onboard Russian icebreakers can improve the ice navigability considerably if the data are obtained over the critical areas at the right time. The main limitation of SAR data is the high cost relative to the area where information is needed. Therefore it is realistic that only selected parts of the NSR can be covered. A synergetic use of ERS SAR, RADARSAT SAR, ENVISAT ASAR and Okean SLR data is considered to be the optimal scheme for real time ice monitoring. The combination of these data will provide radar coverage of all sea ice areas every day. The SLR data will be used for regional mapping every week, whereas SAR data will be used mainly in the most critical areas where high resolution ice information is needed.

This study has demonstrated that RADARSAT ScanSAR data can be effectively used for navigation support in the Northern Sea Route for summer as well as winter conditions. Digital image transmission to ships is an important part of this service, but there are technical limitations in the NSR for this transmission. The northern Kara Sea and the Laptev Sea are outside the INMARSAT range, and near real time satellite images cannot be received onboard icebreakers in this area.

Both ERS and RADARSAT SAR images make it possible to estimate the spatial distribution of different sea ice types, and also with the help of successive images it is possible to study the ice formation history and changes caused by different weather conditions through seasons. To get highly reliable products from satellite images for sea ice navigation it is essential to use all information available, like synergetic data from different satellites, weather data and historic information about the specific region and its hydrometeorological processes.

For future operational ice monitoring in the NSR it is necessary to focus on the following problems:
- Facilitate access of SAR data for Russian users. Today both organisational, financial and technical barriers make use of SAR data difficult for Russian users.
- Improve the utilisation of Russian satellite data, which require improved data communication and financing.
- A new SAR receiving station is needed in Siberia which can cover the whole Northern Sea Route.
- Involvement from key end users (shipping companies, oil companies) to support a cost-efficient ice service for the Northern Sea Route.

- Strengthen the hydrometeorological data acquisition and distribution necessary to provide ice analysis and forecasts.
- Support new Russian satellites which can contribute to ice monitoring.

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Practical Demonstration of Real-time RADARSAT SAR Data for Ice Navigation on the Northern Sea Route

Dear Ms. Berteig,

This message is to inform you that I have just finished reading the text of the report on Project I.2.4 Practical demonstration .....RADARSAT SAR....Northern Sea Route by Sandven et al. As only part of the illustrations were included in your transmission and as I was unable to print the illustrations because of a Postscript error of some sort, I cannot state that I have examined everything. However the figures I was able to examine were quite informative. I found the text to be well written and to the point. Based on my experience with SAR images of sea ice, I am completely in agreement with the conclusions as stated in the report. I believe the paper to be both informative and very useful. It clearly is a report of which INSROP can be proud.

I might add that although I have never had the pleasure of meeting Stein Sandven, when his name appears on a paper I have always found that the work is of a very high standard.

Sincerely yours,

W. F. Weeks

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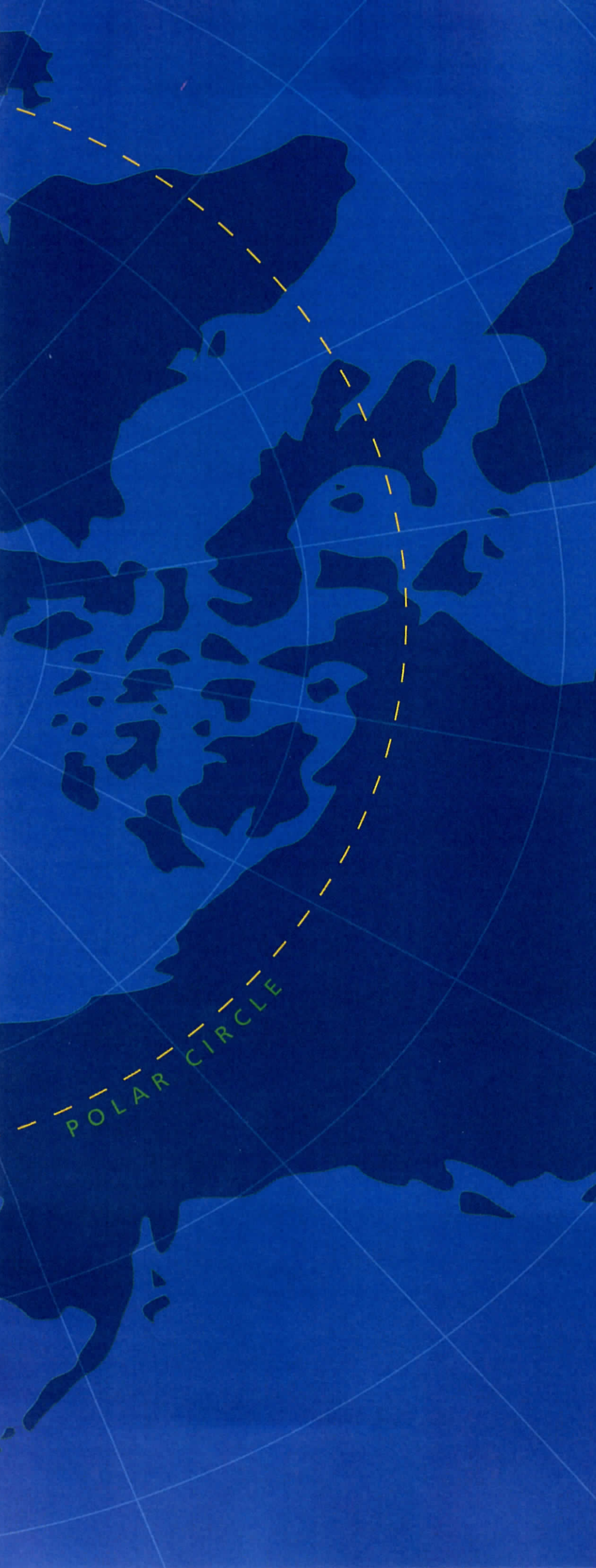

The three main cooperating institutions of INSROP

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 Nippon 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.