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EXECUTIVE SUMMARY

The objective of this study is to review current ice charting and ship routing methods in the Northern Sea Route, as a background for development of new and advanced computer-based charting and routing techniques, which can utilise the large amount of ice information available from new wide-swath SAR images from satellites such as RADARSAT and ENVISAT.

The Northern Sea Route (NSR) is the sailing route along the northern coast of Russia between the Barents Sea and the Bering Strait. The distance from Murmansk to the Bering Strait is 3300 nautical miles, the longest sea ice navigation route in the world. The route is covered by sea ice most of the year, and some parts can have difficult ice conditions even during the summer. Year round navigation is only performed in the western part, from the Barents Sea to Dudinka on the Yenisei River. East of the Kara Sea the navigation season is limited to the summer period, typically from May to November.

Icebreakers and vessels designed for navigation in the NSR must meet specific requirements regarding ice-passability, ice speed limit, ice resistance, and manoeuvrability in different ice conditions. Ice class certification is given to a vessel according to these requirements. In order to operate year-round there has been a development to build larger and more powerful icebreakers. Today, MSC owns and operates several nuclear-powered icebreakers of the highest ice-class, such as Sovetsky Soyuz, built in 1989, with 75,000 horsepower (h.p.). The three most important icebreaker classes are:

- Class LL1: icebreakers with total engine power of 47,807 kW (65,000 h.p.) and more
- Class LL2: icebreakers with total engine power from 22,065 to 47,807 kW (30,000-65,000 h.p.)
- Class LL3: icebreakers with total engine power from 11,032 to 22,065 kW (15,000-30,000 h.p.)

The ice classes determine the geographical area, the ice conditions, and season for the icebreaker operations. In addition there are several classes of ice-going cargo vessels which are used for transportation, and which are escorted by icebreakers depending on the severity of the ice-conditions. Icebreakers, together with one or several cargo ships, often form a convoy where the icebreaker(s) normally are leading or towing the cargo ship(s).

Two Marine Operation Headquarters (MOH), one for the western (in Dikson) and one for the eastern part (in Pevek) of the NSR are responsible for planning and administration of all sea transport operations in the region. Special scientific-operative groups (SOG) at the MOHs provide the hydrometeorological support, including ice charting and forecasting, for the transport operations.

The international definitions of sea ice terms are standardised by the Sea Ice Working Group of the World Meteorological Organisation (WMO, 1970). This nomenclature is used world-wide by all institutions producing sea ice charts. Although the nomenclature is fairly standardised, the actual symbols used in ice charts differ slightly from region to region. An ice chart in the NSR is therefore different from an ice chart in for example the Baltic Sea. In Russia, the provision of specialised ice information has been developed for more than 50 years. A very extensive service using aircraft, satellite data, ship observations, and a network of hydrometeorological data from many stations in the Arctic have been developed.

Systematic observation and collection of hydrometeorological and sea ice conditions for the NSR started in the 1930’s using aircraft surveillance as the main observation method. The aircraft surveillance flights could only cover the main sailing routes. Therefore, it was not possible to observe the sea ice conditions over large parts of the Arctic Ocean. Major

technological improvements of the sea ice observation capabilities were gained in the 1960's, with the launch of satellites providing visual images of the whole Arctic region. In the 1980's also radar satellites were introduced, which provided sea ice observations independent of cloud and light conditions.

Use of special communication links for direct download and transmission of radar images to the icebreakers was developed for tactical and operative sea ice navigation reconnaissance. During the 1980's several Russian satellites such as Meteor and Okean, and the American NOAA satellite were used in the sea ice chart composition. NPO Planeta is the major Russian institution for receiving, processing and analysis of data from several Russian satellites. Visible range images from the Meteor and NOAA satellites are used to derive several sea ice parameters, including ice concentration, during cloud-free conditions and sufficient daylight. Images from the Okean Side Looking Radar (SLR) offer an opportunity for determination of several sea ice parameters also in the long and dark winter period. The Center of Ice and Hydrometeorological Information at Arctic and Antarctic Research Institute (AARI) is the main organisation responsible for regular production of ice charts, as well as ice forecasts, for the whole NSR.

In 1991 high-resolution satellite radar images from Synthetic Aperature Radar (SAR) sensors were introduced in sea ice recognition in the NSR. Russian SAR data have mainly been available from aircraft. Since the use of aircraft surveys declined during the 1990's, SAR data for ice monitoring have primarily been available from the ERS-1 and -2 satellites. The Nansen Environmental Remote Sensing Centers in Bergen and St. Petersburg have performed several pilot demonstration projects in the NSR. These projects have been carried out in co-operation with the European Space Agency and Murmansk Shipping Company, in order to demonstrate the capability of ERS SAR data for providing high-resolution sea ice information for ice navigation. The projects have supported ships with near real time SAR data. ERS SAR ice images contain information for determination of different sea ice parameters such as ice type classification, drift and motion, and other ice surface characteristics.

Despite the relatively small swath width of 100 km, the ERS SAR satellite is useful for ice mapping of limited areas such as straits, shores, river estuaries, and other difficult ice navigation areas. Operational experience shows that processed satellite images, with superimposed shorelines and geographical co-ordinates, are useful in many tactical ice navigation situations. As more satellite SAR systems become available, the volume of data for use in ice mapping is expected to grow significantly. Use of RADARSAT ScanSAR images, covering 500 km wide swaths, represents an enormous increase in data volume, which requires more automated processing chain for the ice chart production. The wealth of ice information available from SAR images can only be fully utilised with the help of adequate computer tools which the ice interpreters can use in the production of ice charts, and for transmission of data to the offshore users.

1 OBJECTIVE

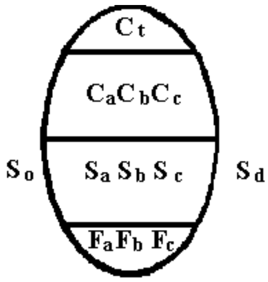
The objective of this study is to review current ice charting and ship routing methods in the Northern Sea Route, as a background for development of new and advanced computer-based charting and routing techniques, which can utilise the large amount of ice information available from new wide-swath SAR images from satellites such as RADARSAT and ENVISAT.

2 ICE CHARTING SYMBOLS AND NOMENCLATURE

2.1 INTRODUCTION TO SEA ICE NOMENCLATURE

The description of sea ice parameters has been standardised by the Sea Ice Working Group of WMO (WMO, 1970, 1985) which has defined a nomenclature used by all institutions producing ice maps today. A summary of the most important ice terms are listed in Appendix A. Although the nomenclature is fairly well standardised, the symbols used in ice charting differ somewhat between the Russian, Canadian and Baltic Sea ice charts. The main ice parameters, which are decried in the WMO egg code in Figure 1 are;

1) Ice concentration: C_t
2) Partial ice concentration of different ice types: C_a,C_b,C_c
3) Age or stage of development: S_a,S_b,S_c
4) Form (i.e. floe size): F_a,F_b,F_c, etc.



C_t	Total concentration of ice in area, reported in tenths.
$C_aC_bC_c$	Partial concentration in tenths of thickest (C_a), second thickest (C_b) and third thickest (C_c) ice types with C_a, C_b and C_c 1/10 or more. If only one thickness type is present equals C and the second level is left blank.
$S_aS_bS_c$	Stage of development (age) of ice concentration reported by C_a, C_b and C_c.
$F_aF_bF_c$	Predominant form of ice (floe size) corresponding to S_a, S_b and S_c, respectively.
S_aS_b	Development stage (age) of remaining ice types. S_o if reported is a trace of ice type thicker/older than S_a. S_d is a thinner ice type, reported when there are four or more ice thickness types.

$F_aF_bF_c$ Form of ice		Width	**$S_aS_bS_c$** Stage of development		Thickness
0	Pancake		1	New	< 10 cm
1	Brash		2	Nilas	< 10 cm
2	Ice Cakes	< 20 m	3	Young	10-30 cm
3	Small floe	20-100 m	4	Grey	10-15 cm
4	Medium floe	100-500 m	5	Grey-white	15-30 cm
5	Big floe	500-2000 m	6	First Year	> 30 cm
6	Vast floe	2-10 km	7	Thin First year/White	30-70 cm
7	Giant floe	> 10 km	1.	Medium First Year	70-120 cm
8	Fast ice		4.	Thick First Year	> 120 cm
9	Icebergs		7.	Old	
X	No Form		8.	Second Year	no
C	Ice in strips in which concentration is C		9.	Multi-year	Defined ranges
			Δ	Icebergs	

Figure 1. Description and explanation of the WMO egg code

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

5) Surface features (i.e. ridges), and
6) Motion

The WMO egg code provides numerical values for ice concentration, stage of development (thickness) and form of the ice (floe size) for more or less homogeneous areas of ice. For preparation of ice charts the egg code as well as different symbols are used to describe the ice conditions graphically on a map. Some ice services use the egg code, such as the US National Ice Center, the Canadian Ice Centre and the Danish Meteorological Institute's ice maps of Greenland waters. The Russian and Baltic ice maps use various other symbols, which will be described in the following sections. The main problem of the WMO ice code is that it does not describe all the ice characteristics that are relevant for ice navigation. In countries where ice navigation is of major concern, the WMO code is supplemented by a large number of other ice parameters. This is because it is difficult to define a few parameters that are sufficient to fully describe the navigability in sea ice.

2.2 THE BALTIC SEA ICE CODE

The countries surrounding the Baltic Sea do not use the normal WMO egg code in their ice maps, but a set of symbols that are consistent with the WMO standard nomenclature. The most important symbols are shown in Figure 2.

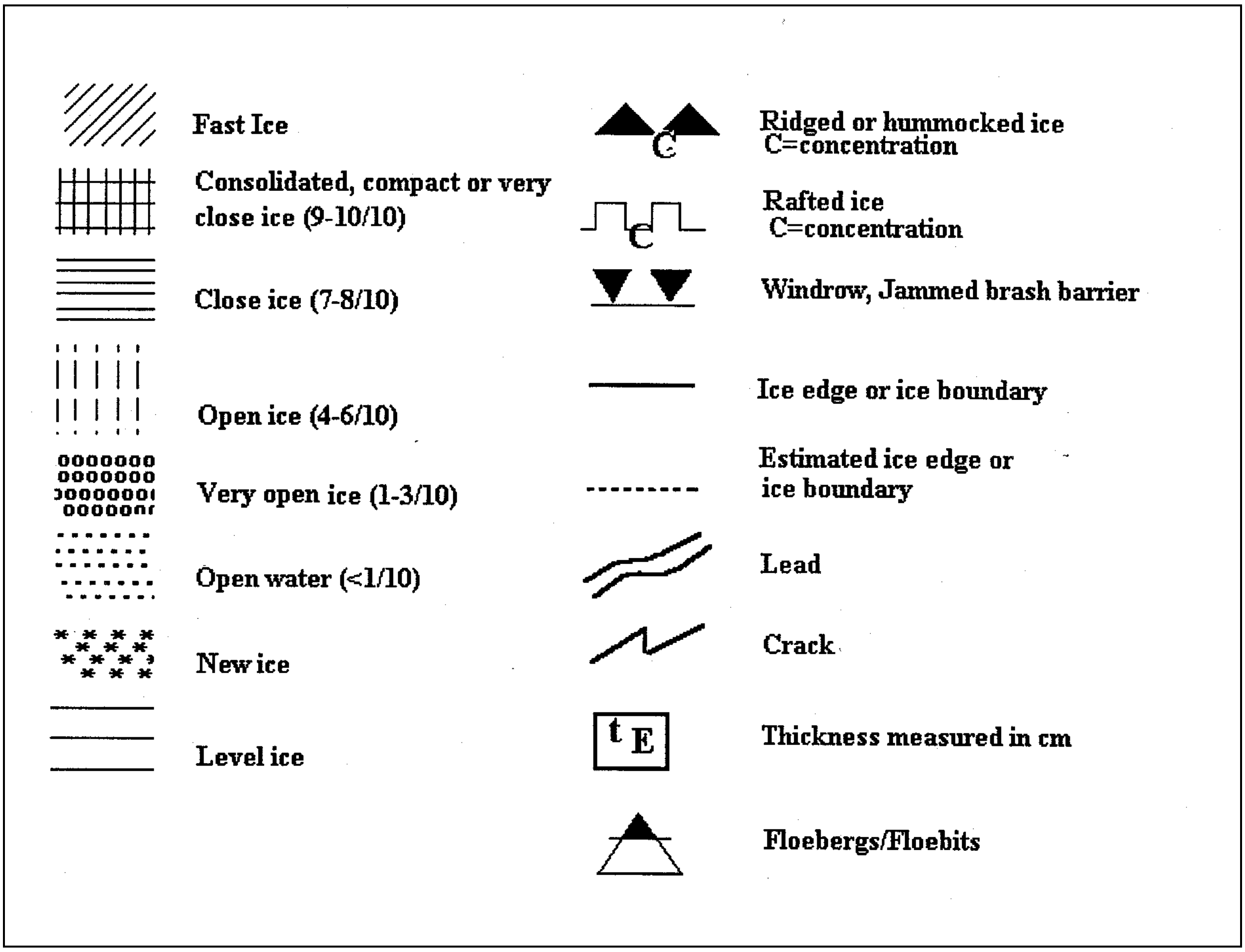


Figure 2. Description and explanation of the Baltic Sea ice symbols

In addition to the symbols used in ice maps there is the Baltic Sea Ice Code that is used for reporting and description of ice conditions in fairways, harbour areas, coastal sectors and sea routes. Sea or fairway districts are defined by letter AA, BB, CC etc. Districts shall follow each other consecutively along the coast starting from the north and following the direction out of the Baltic Sea. Each district consists of optional, up to 9 sections, which should preferably be numbered from the harbour and out. The Baltic Sea Ice Code is used in Denmark, Estonia, Germany, Finland, Latvia, Lithuania, The Netherlands, Norway, Poland, Russia and Sweden.

2.3 THE RUSSIAN SEA ICE CODE

Ice maps produced for the Russian Arctic contain a number of symbols that differ from the WMO symbols and the Baltic Code in several respects. The Russian ice symbols also include fracture width, compacting ice field, grounded ridges in fast ice, ridging degree, etc. The most important Russian ice codes are shown in Figure 3. These ice maps therefore allow more detailed description of local characteristics which are important for navigation. The Russian approach of "specialised ice information" is aimed at providing quantitative assessment of the difficulties (QAD) of ice navigation where the objectives are:

- to identify various ice cover characteristic affecting ship motion
- to describe the effect of ice conditions on ship motion
- to classify ice cover in terms of ice motion
- to obtain "en route" ice information from more regional ice information
- to collect relevant data.

The unique feature of QAD is the method of deriving "en route" ice conditions from regional ice conditions provided by ice charts. This is necessary because ice navigation seeks to find optimal routes of lower concentration, smaller floes and less ridging. Therefore the ice conditions experienced by a ship will be different from the regional ice information from the ice maps. Empirical relations estimate the effect of the ice cover on the ship motion. "Theoretical speeds" are used to calculate "operating speeds", where factors related to safety and other requirements are taken into account. The main ice parameters important for the interaction of ice with ships are shown in Table 1.

Ice conditions	Main ice-ship interaction	Ice resistance parameters
Fast ice, large floes	Breaking of continuous ice cover	Thickness, ridging, snow cover, degree of destruction
Medium sized floes	Breaking, pushing aside of floes	Concentration, ridging, degree of destruction, pressure
Small floes, channel ice	Pushing ice aside	Concentration, friction coefficient, channel width

Table 1. Ice resistance parameters in relation to ice conditions.

A similar approach has been suggested, describing a complex system of data flow for navigation support, that also includes forecasts. The idea is that real time access to all important ice parameters will not be sufficient for making the decisions because the areas of navigation are very large and the ice conditions can change rapidly. Therefore short term (up to 7 days) as well as long term forecast (up to 30 days) are needed for optimal ice routing.

Symbols	Ice parameters	
10 / 8 | 2	Pack ice concentration, total (tenths) Ice concentration, partial (tenths)	
	Development (age)	**Thickness**
	Greywhite ice (Gr W)	15 - 30 cm
	Thin firstyear ice (WTh)	30 - 70 cm
	Medium firstyear ice (WMd)	70 - 120 cm
	Thick firstyear ice (WTk)	> 120 cm
	Combination (WMd/WT k)	
	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
	Small ice cake/brash ice	< 2 m
	Ice age features	**Ice concentration**
	Combination (WMd/WTk,GrW)	9-10 [6|3-4]
	Combination (WMd/WTk,GrW)	10 [2-3|7-8]
	Combination (WTk, WMd, GrW)	8-10 [6-7|2|3]
	Combination (WMd/WTk)	4-6
	Combination (WMd, GrW)	3-4
	Combination (WMd/WTk, GrW)	1-3
	Combination (WMd/WTk)	< 1
	Ice free	0
	Forms of fast ice	**Thickness**
	Medium	70 - 120 cm
	Thick	> 120 cm
	Thick, brackish water ice	> 120 cm
	Grounded hummock	
	Miscellaneous features	
2	Melting stage (0-5)	
	Ridge	

Figure 3. The main symbols used in Russian sea ice maps from the Arctic.

2.4 THE CANADIAN SEA ICE CODE

The Canadian Ice Code also uses the WMO nomenclature but has some additional attributes especially relevant for ice navigation. These attributes are:

- Partial concentration of rafted ice
- Partial concentration of ridges and hummocks
- Snow coverage
- Snow depth
- Mean ridge height Extreme ridge height
- Direction of ice drift
- Speed of ice drift
- Trend in behaviour of ice
- Number of growlers and/or bergy bits
- Polynya characterisation

The most important additional Canadian ice symbols are shown in Figure 4.

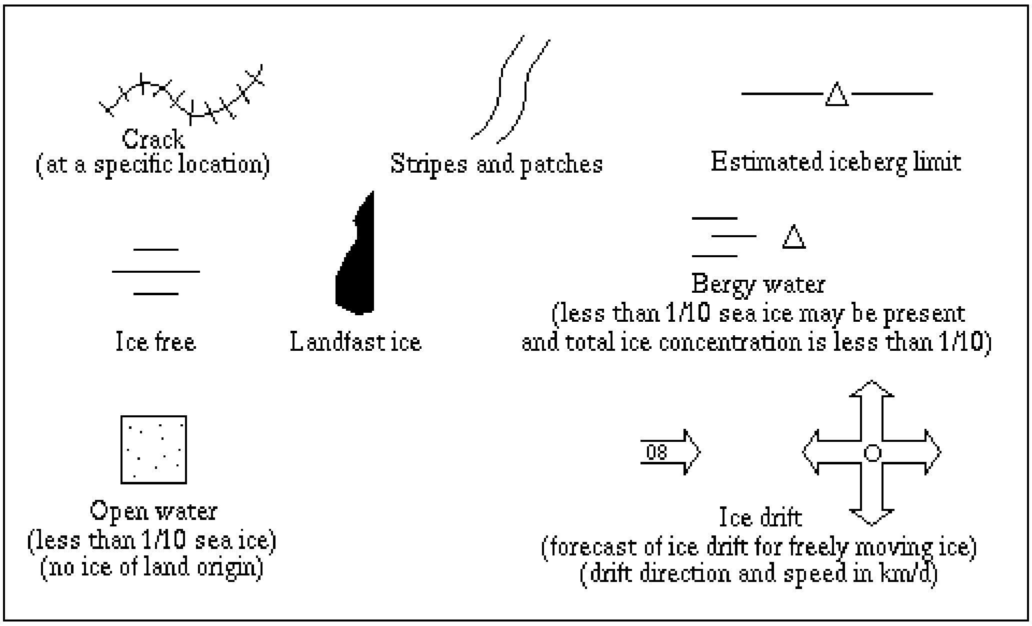


Figure 4. Some additional Canadian sea ice symbols

The Ice Regime Shipping Control System (IRS) in Canada uses the concept of “ice regime” in an attempt to characterise ice conditions in a way that is more directly relevant for ice navigation compared to the more simple Zone/Date system. In this system the Canadian Arctic is divided into 16 control zones with earliest/latest entry date for certain ship categories. An “ice regime” is defined as an area of relatively homogeneous ice conditions without predefined size or location. The ice cover within an “ice regime” may consist of several ice types, but their properties and relative coverage should not vary too much. The IRS stresses damage probability rather than speed and the measures of navigability. The basic idea is to calculate an “ice numerical” (IN), or an index of hazardousness, for each type of vessel as a sum of relative coverage of ice types weighted by their hazardousness to the vessel. The weights are called “ice multipliers”(IM) and the ice numerical is defined as

$$IN = (C1 \times IM1) + (C2 \times IM2) + \ldots\ldots$$

where Ci is concentration of icetype I and Imi is the corresponding ice multiplier.

The ice numerical must be non-negative for a vessel to be allowed to enter an ice regime. The ice multipliers may be increased if the ice is decaying (has thaw holes, for instance) or contains brash (floes < 2 m in diameter), or they may be decreased if the ice is ridged. Availability of icebreaker escort also modifies the multipliers (Lensu *et al*. 1996)

2.5 SHORTCOMINGS OF THE CONVENTIONAL SEA ICE CODES

According to Lensu *et al* (1996) the main shortcomings of the conventional ice codes from an ice navigation point-of-view are:

1. The classification of ice types is unnecessarily detailed for younger and thinner ice types that only exist for shorter periods in the freeze-up and early winter season. On the other hand, thicker, deformed and multiyear ice types are not characterised as detailed as is needed. The classification should be proportional to the decrease of ship speed and increase of damage probability.
2. There is no quantitative reference to deformed ice types like rafted ice, in spite of the fact that deformed ice can be predominant and several times thicker than level ice.
3. There is no quantitative reference to ice ridges, to their size and frequency of occurrence.
4. There is no reference to lead size, frequencies or orientations.
5. The relation of regional ice characteristics to what is experienced by an ice-going vessel is uncertain.
6. The codes cannot optimally use the information that is available from SAR images.
7. The terminology has no clear connection to geophysical ice models used in forecasting.

The main reason for these shortcomings is that the WMO code was defined in 1970, when

- no operative ice models existed
- no high resolution satellite data was available, and
- very little data on ice thickness, floe size and ridge distribution existed.

The code is clearly aimed to display visual and mainly qualitative observations, for example those made onboard a vessel. On the other hand, it is not feasible that a single ice code would satisfy all possible requirements. Therefore, a possible scenario for the future development of the ice codes could be three-folded:

1. a geophysical code with theoretically sound concepts which can be related to satellite imagery and ice modelling
2. a navigational code which can be related to ship speed and damage probability, and
3. an observational code as a further development of the WMO code.

3 THE MAIN CHARACTERISTICS OF THE NORTHERN SEA ROUTE

3.1 ORGANISATION OF ICE NAVIGATION

The Northern Sea Route (NSR) is a network of sailing routes in the Russian Arctic. Many of the routes include ice navigation in difficult conditions, and require icebreaker assistance. Some parts can have difficult ice conditions even in the summer. The state supervision of the NSR is performed the NSR Administration (NSRA) under the Russian Federation Ministry of Transport. The NSRA executes its functions both directly and through special navigation services of the Murmansk and Far-East Ship Companies through the Marine Operations Headquarters (MOH) of the western and eastern regions of the Arctic, respectively.

The MOHs are responsible for planning and implementation of all sea ice operations. The regulations of the ship traffic in the NSR are formulated in the “Rules of navigation on the NSR routes”. It is an overall objective of these rules to provide the safety of navigation, and to minimise the pollution of the marine environment. At present, the different ship routes in the NSR are classified into the coastal, high-sea, high-latitude and near-pole routes (Figure 5). On the coastal and high-sea routes, several legs are defined according to major directions of fleet operation: the Barents Sea - port Dixon; port Dixon - Cape Chelyuskin; Cape Chelyuskin - port Tixi; port Tixi - River Kolyma; River Kolyma - port Pevek; port Pevek - Cape Schmidt; Cape Schmidt - Bering Strait. The coastal and high-sea routes lie in the coastal regions and practically cover the whole area of the Eurasian Arctic seas. Also the estuaries of the Siberian rivers belong to this definition: the Ob Bay - to Cape Kamenny; Yenisey River - to port Igarka; Kolyma River - to port Zeleny Mys. The hydrometeorological and bathymetric conditions in the coastal and high-sea routes have been studied since the beginning of the 1920’s. With the introduction of powerful atomic icebreakers, such as Lenin and Arktika, trial voyages on the high-latitude routes began in 1971. The atomic icebreaker Sibir was the first icebreaker to steer a transport ship on these routes from Cape Desire to Bering Strait in May-June 1978. The experience from these tests showed that it was very difficult to use the high-latitude routes on a regular basis. From a time saving viewpoint the best results would be a combination of high-latitude, high-sea and coastal routes making use of the zones with most easy ice conditions.

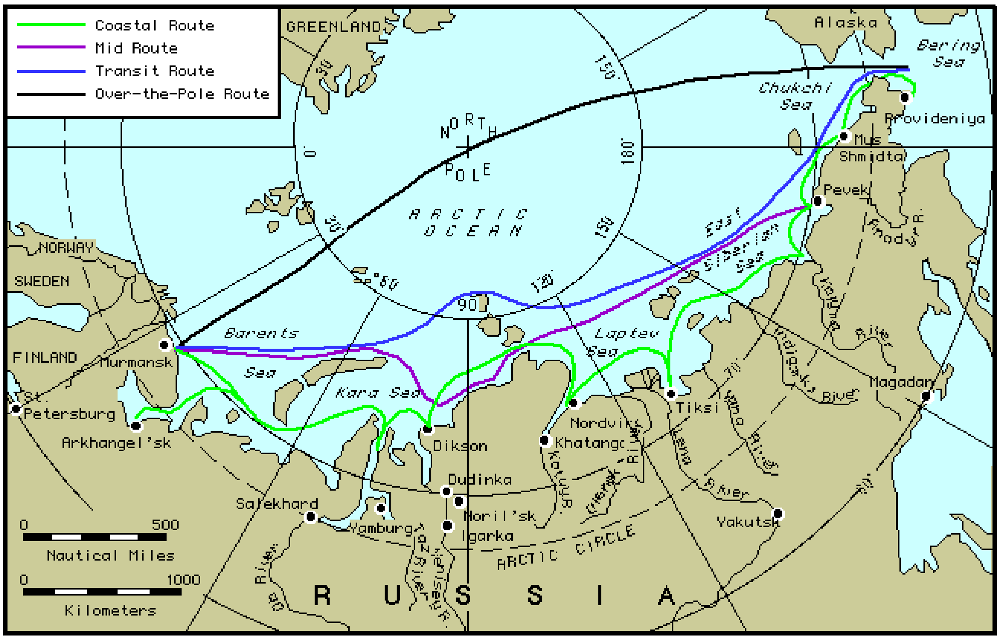


Figure 5. Map of the Northern Sea Route with the main sailing routes

The basic stages of transport management in the NSR are characterised, first of all, by the duration of the navigation period, and availability of an icebreaker and transport fleet. The most important winter navigation route is from the Barents Sea to the port of Dudinka on Yenisey. This route is kept open for transport of nickel from Norilsk, one of the major mining towns in Siberia. The year-round navigation requires powerful diesel-electric icebreakers of the type Captain Sorokin (capacity 22000 h.p, and 8.5m draught), and atomic icebreakers such as Taimyr and Vaigach (capacity 48000 h.p, and down to 9m draught), specially designed for operation in the fast ice of the river Yenisey. Year-round navigation routes in the Kara and Laptev Seas (east of the meridian Dixon Island - New Siberian Islands) require participation from icebreakers of the Arktika type, with more than 65000 h.p. Even these icebreakers can only operate in easy ice conditions in this region. If the ice conditions are heavier than average, navigation on the coastal and high-sea routes is only feasible from May to February. In the eastern region of the Arctic, the participation of atomic icebreakers of the type Arktika has made it possible to extend the

navigation period on the coastal and high-sea routes from mid-May to mid-November. The technical capabilities of these icebreakers are not sufficient to extend the navigation period in these regions, which means that year-round navigation cannot be guaranteed.
The selection of new voyage routes, in particular, the high-latitude or near-pole routes cannot radically extend the Arctic navigation beyond the current situation. A solution for this problem totally depends on further improvements of the technical capabilities of the fleets, as well as improvements of the ice reconnaissance.

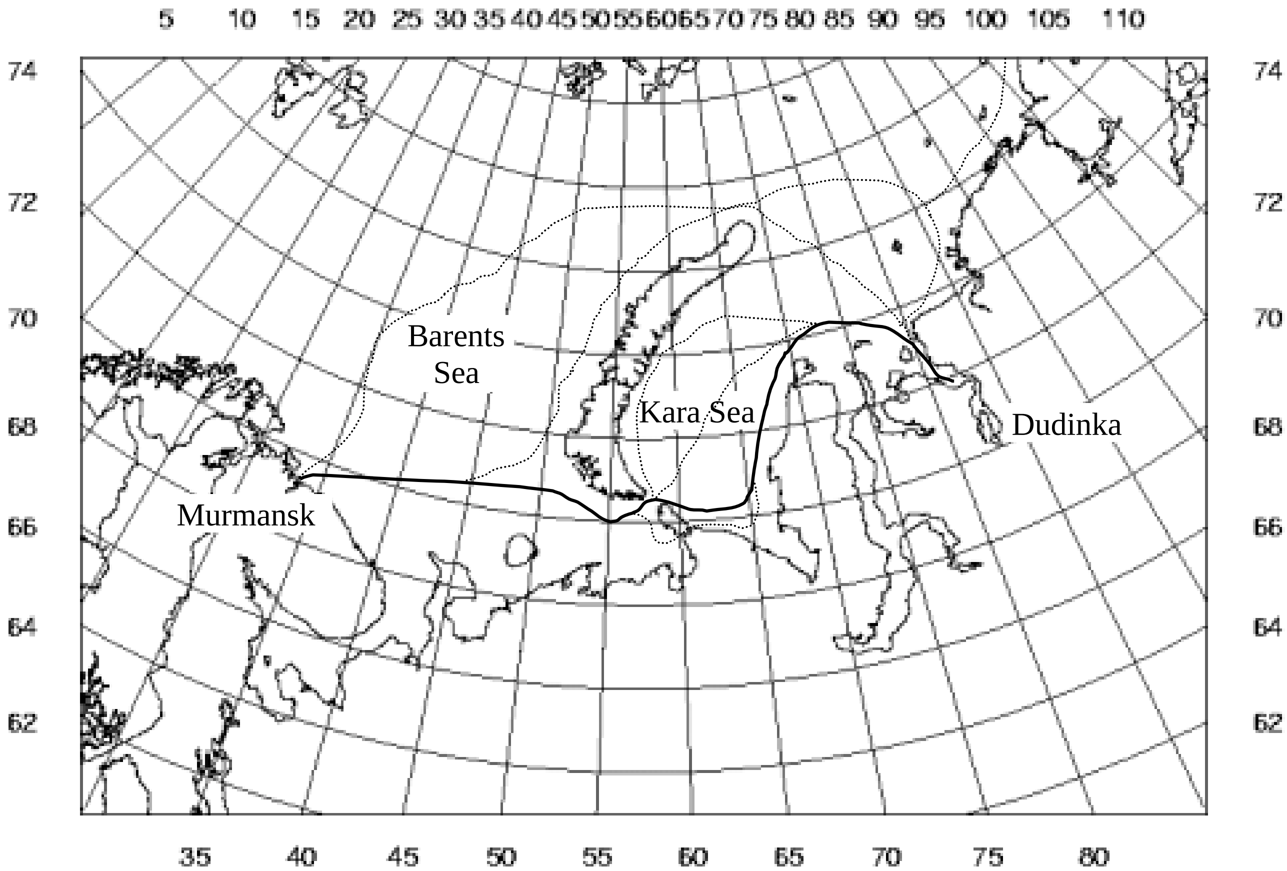


Figure 6. Map of the western part of the Northern Sea Route. The bold line is the main sailing route, whereas the dashed lines are alternative routes depending on ice conditions.

3.2 BRIEF HISTORY OF ICE RECONNAISSANCE IN THE NSR

Hydrometeorological and sea ice observation in the Northern Sea Route, which is ice-covered most of the year, is very important for Russia because of the ship traffic that requires icebreaker support. The system of hydrometeorological navigation support was formed in 1932, after establishment of the Northern Sea Route administration. A Polar Aviation group was established for navigational air reconnaissance and the net of Polar stations was widened. In 1938 a considerable part of the Arctic seas was covered with visual air recognisance. Only the western part of the Northern Sea Route is used for year-round ice navigation (Figure 6). The whole Northern Sea Route, from Murmansk to Bering Strait, is used mainly in the summer navigation season from July to November.
Several major technological improvements of the ice observation capability were achieved in the 1960s when airborne and satellite remote sensing were developed. In 1968 the Side-Looking Airborne Radar (SLAR) Toros was made especially for ice surveys. The swath-width of about 60 km, the independence of light and clouds, and the possibility to compose ice charts onboard the aircraft, made it possible to use SLAR regularly for ice reconnaissance and for ice research.

Use of special communication link for transmission of radar imagery to icebreakers was very useful for the purposes of tactical and operative ice reconnaissance. Images from meteorological satellites have been used for ice charting since 1967, when the experimental system Meteor, consisting of Kosmos-144 and Kosmos-156 satellites, were launched. This system consisted of 2 or 3 meteorological satellites, regional centers for receiving, processing and transmission of satellite information and service for control of the onboard satellite systems. In 1967-1969 a net of autonomous centers for reception of satellite information in the Arctic was established by the Arctic and Antarctic Research Institute (AARI) in St. Petersburg. From this time data from meteorological satellites was used in the composition of ice maps for navigation support in the Arctic.

Since the 1980s data from the Meteor, Okean and NOAA satellites were used in ice chart composition [Alexandrov *et al.*, 1992]. The first satellite of the Russian Okean series was launched in September 1983. The instruments onboard the satellite consisted of a side-looking radar (wavelength 3.15cm, 2km resolution, and a swath-width of 450km), a scanning microwave radiometer (wavelength 0.8cm, 25km resolution, and a swath-width of 600km), and a four channel visual band scanning radiometer. From 1983, the Okean satellites provided regular sea ice data for ice chart composition both in the Arctic and Antarctic.
High-resolution radar images from Synthetic Aperture Radar (SAR) were not used in ice chart composition until the 1990s. Spaceborne SAR instruments, operating at a wavelength of 9.6cm with 20m resolution, were installed onboard the Russian satellites Kosmos-1870 and Almaz. Their images were used primarily in ice research and not in regular ice monitoring. The SAR data were used however, in emergency situations, for example, to map sea ice conditions in the area where the research vessel M.Somov was beset in ice in the Antarctic [Alexandrov *et al.*, 1993].

In July 1991 the ERS-1 satellite was launched, providing high-resolution SAR images with 100 km swath width coverage up to 84° latitude. In August the first ERS SAR derived sea ice maps were sent by telefax to the French polar vessel L'Astrolabe during her voyage in the NSR from Norway to Japan [Johannessen *et al*., 1992]. 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. Since autumn 1993, such demonstration campaigns were carried out several times by the Nansen Centres in Bergen and St. Petersburg, in co-operation with Murmansk Shipping Company. These campaigns showed the importance of high-resolution SAR images for navigation support in the Northern Sea Route [Johannessen et al., 1994, 1995]. As a result of these successful demonstrations, a joint project between European Space Agency and Russian Space Agency was started in 1995 to establish a satellite radar monitoring system for the western Arctic ice cover using Okean SLR and ERS-1 SAR images [Johannessen et al., 1997].

The first demonstration of RADARSAT SAR images for ice navigation support in the NSR was performed in the ICE ROUTES project.

4 STRUCTURE OF HYDROMETEOROLOGICAL SUPPORT IN THE NSR

4.1 INTRODUCTION

The hydrometeorological support to sea operations in the NSR is provided by the special scientific-operative groups (SOG) at the MOHs of the Western and Eastern regions of the Arctic. The SOGs collect data of the ice and weather conditions in the Arctic seas, produce maps of the ice cover, and work out the forecasts of weather and ice conditions. The forecasts are divided into short-range diurnal prediction and long-range forecasts for periods of 3-10 days, and 3-6 months. The hydrometeorological information processed by the SOGs is delivered to the MOHs, which plan and make decisions concerning the icebreaker fleet operations and work out navigation recommendations. The ice- and weather-maps, the forecasts of weather and ice conditions 1 to 7 days in advance, and the navigation recommendations of the MOH are transmitted to the ships and icebreakers via communication channels.

The sources of data on the ice and weather conditions in the Arctic are the following:

- data from satellites (Meteor, NOAA, Okean, etc.);
- data from aircraft and helicopter surveys, visual and instrumental (side-looking radar Nit);
- data of observations at the island and coastal polar stations;
- data of simultaneous observations from ships and icebreakers
- data from scientific expeditions in the Arctic seas.

All these data are delivered to the SOGs and used by the MOHs to organise safe and efficient navigation. The structure of the hydrometeorological service is shown in Figure 7.

For planning of sea operations, the MOHs and the NSRA use both statistical data on the average mean ice conditions, as well as general and partial laws of the ice regime. This information is also used in the preliminary stage of transport-technological planning of cargo transport, and in transport management of new cargo traffic.

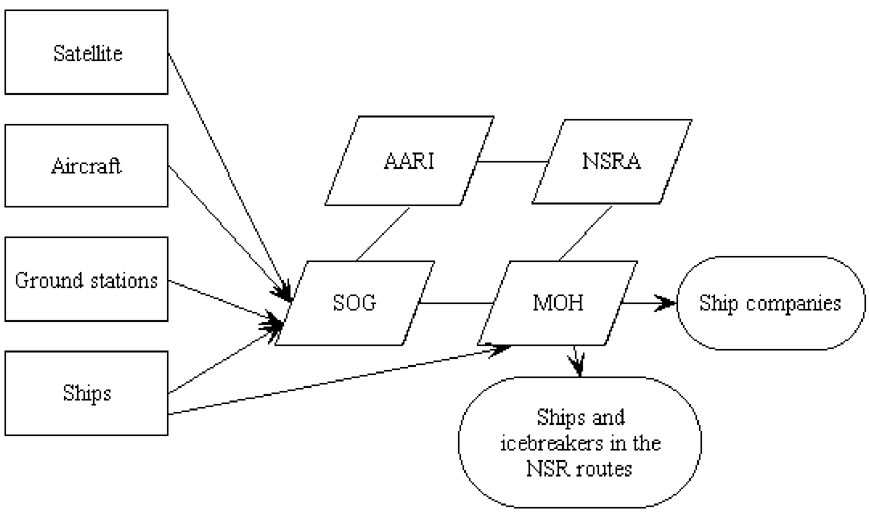


Figure 7. Structure of hydrometeorological survey in the Northern Sea Route.

4.2 SPECIAL OPERATION GROUPS (SOG) IN DIXON AND PEVEK

AARI and the MOHs in Dikson and Pevek issue regular ice charts for navigation support in the NSR. The SOG in Dikson, organised under the Federal Hydrometeorological Service of Russia and the MOH of MSC, produces synoptic and predicted ice information for the western part of the NSR (between 55° and 120°E). A department of AARI in Dikson, and the Amderma Hydrometeorological Administration provide the hydrometeorological support, using data from several sources within the Federal Hydrometeorological Service of Russia. Ice charts for the western part of the NSR cover the Barents Sea, the White Sea, the Pechora Sea, the Kara Sea, as well as the western part of the Laptev Sea. The ice charts are based on data from satellite images, polar stations, and ships, and are issued 3 times per week (Monday, Wednesday and Saturday). An ice chart prepared by the SOG in Dikson is shown in
Figure 8. The SOG in Dikson also produces short-term forecasts, 1-3 days in advance. Navigation support in the eastern Arctic is carried out by the SOG in Pevek, which only operates in periods with summer navigation conditions. The SOG in Pevek is organised under the Federal Hydrometeorological Service of Russia and the MOH of the Far East Shipping Company, and has similar function as the SOG in Dikson.

Special ice forecasts of quantified difficulties for ice navigation were widely issued during 1986-1992, but are more rare now. Special forecasts of spring and autumn ice-hydrological conditions in the Yenisey estuary are issued respectively on April 15 and September 29. Also provided by the SOG in Dikson are forecasts of sea level variations for important navigation parts in the Yenisei river. Satellite images from NOAA, Meteor and Okean satellites are the main data source for estimates of the sea ice distribution. In 1995, a total of 143 ice charts were produced from satellite data. Also numerical ice forecasts and hindcasts are composed for the NSR.

4.3 ARCTIC AND ANTARCTIC RESEARCH INSTITUTE

AARI has a long and extensive experience in sea ice mapping and forecasting using different information sources. An Automatic Ice Information System for the Arctic (AIISA) is under development. The system will unify and integrate the data collection, the processing steps, the analysis, the information transmission and dissemination, and forecast and hindcast products. AIISA is a complex and spatially distributed information system. The Center of Ice and Hydrometeorological Information (CIHI) of AARI started to use AIISA in 1989 [Bushuev *et al*, 1995]. The CIHI issues ice charts for the entire Arctic by combining partial ice charts made from single satellite images, and composite weekly ice charts. All available ice data, such as satellite images, drifting buoy data, data from ships and icebreakers, polar stations and composite ice charts by the SOGs at Dikson and Pevek are used to produce these charts. Images from the NOAA, Meteor and Okean satellites are used for the partial ice charts. A receiving station for NOAA AVHRR images has been available since 1995. Satellite images from the Main Center for Receiving and Processing Satellite Information (Moscow) and Regional Centers in Novosibirsk and Khabarovsk are transferred to AARI through different communication channels. From autumn 1995 to the summer 1996 ERS SAR images, transmitted from NERSC-Norway, were used in the ice chart production, as a part of the ICEWATCH project [Johannessen *et al*, 1997]. For planning and support of navigation, ice forecasts for different time periods are issued. These forecasts include parameters such as the beginning of a stable freeze-up or melting, the ice thickness, the destruction of fast ice zones, ice drift, ice compactness, and ice concentration.

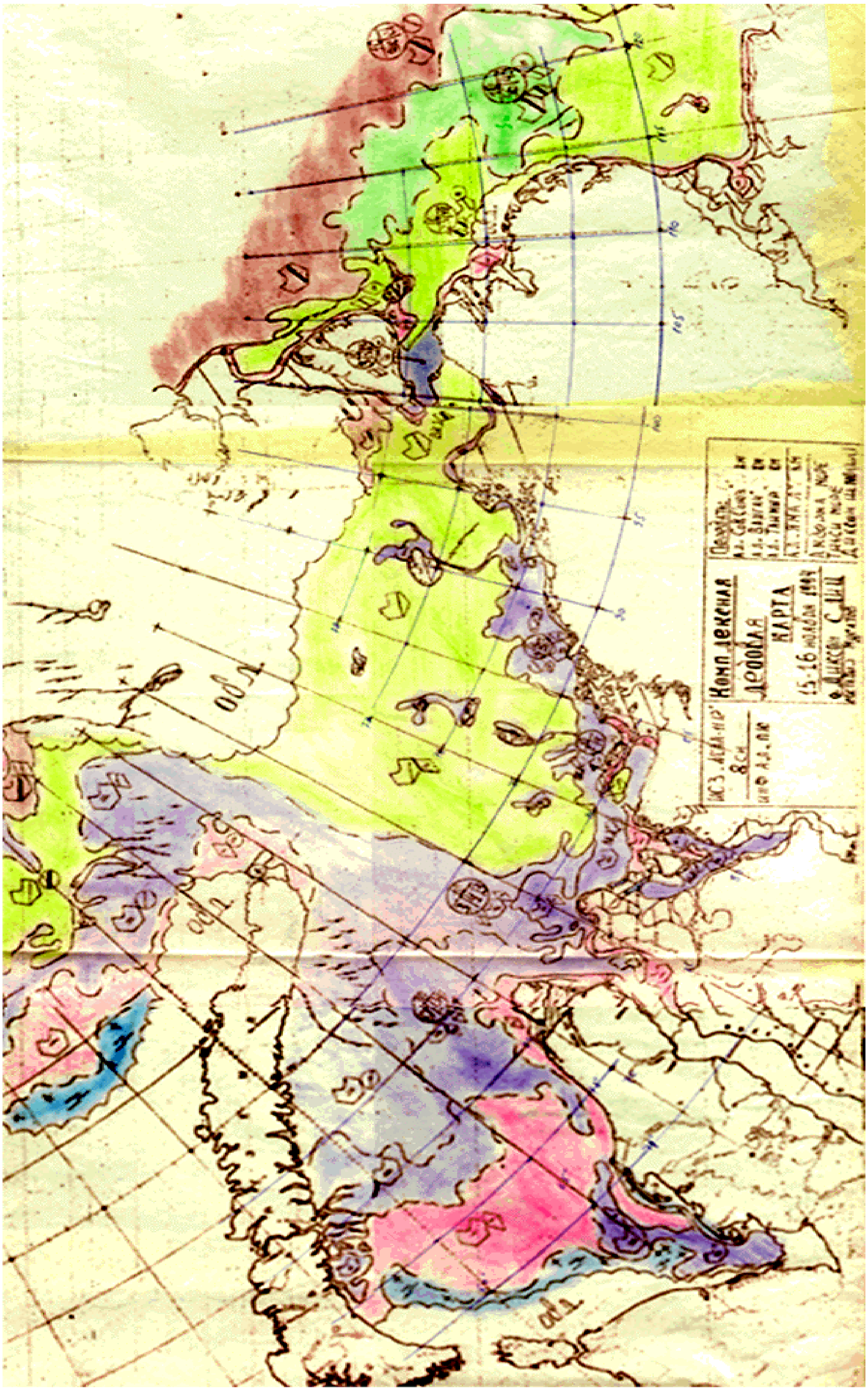


Figure 8. Example of an operative ice map from November 16, 1994, covering the western part of the NSR.. The ice symbols shown in Figure 3 are used to identify the ice types and other ice characteristics. Image courtesy of SOG-Dikson

4.4 NPO PLANETA

NPO Planeta is the major Russian institution for receiving, processing, archiving, and analysing of data from Russian satellites. For sea ice studies, the most important data are from the Side Looking Radar (SLR) and passive microwave (RM-0.8) sensors onboard the Okean satellite. The major processing steps for the Okean data are:

- radiometric correction
- geometric correction
- integration (i.e. mosaic) of successive and/or adjacent images
- cluster analysis by unsupervised classification
- supervised classification for generating ice distribution maps

Figure 9 shows a mosaic of Okean SLR images obtained during a six days interval. These products are made by NPO Planeta only for scientific purposes, and are not used for operational navigation support or in routine ice chart productions.

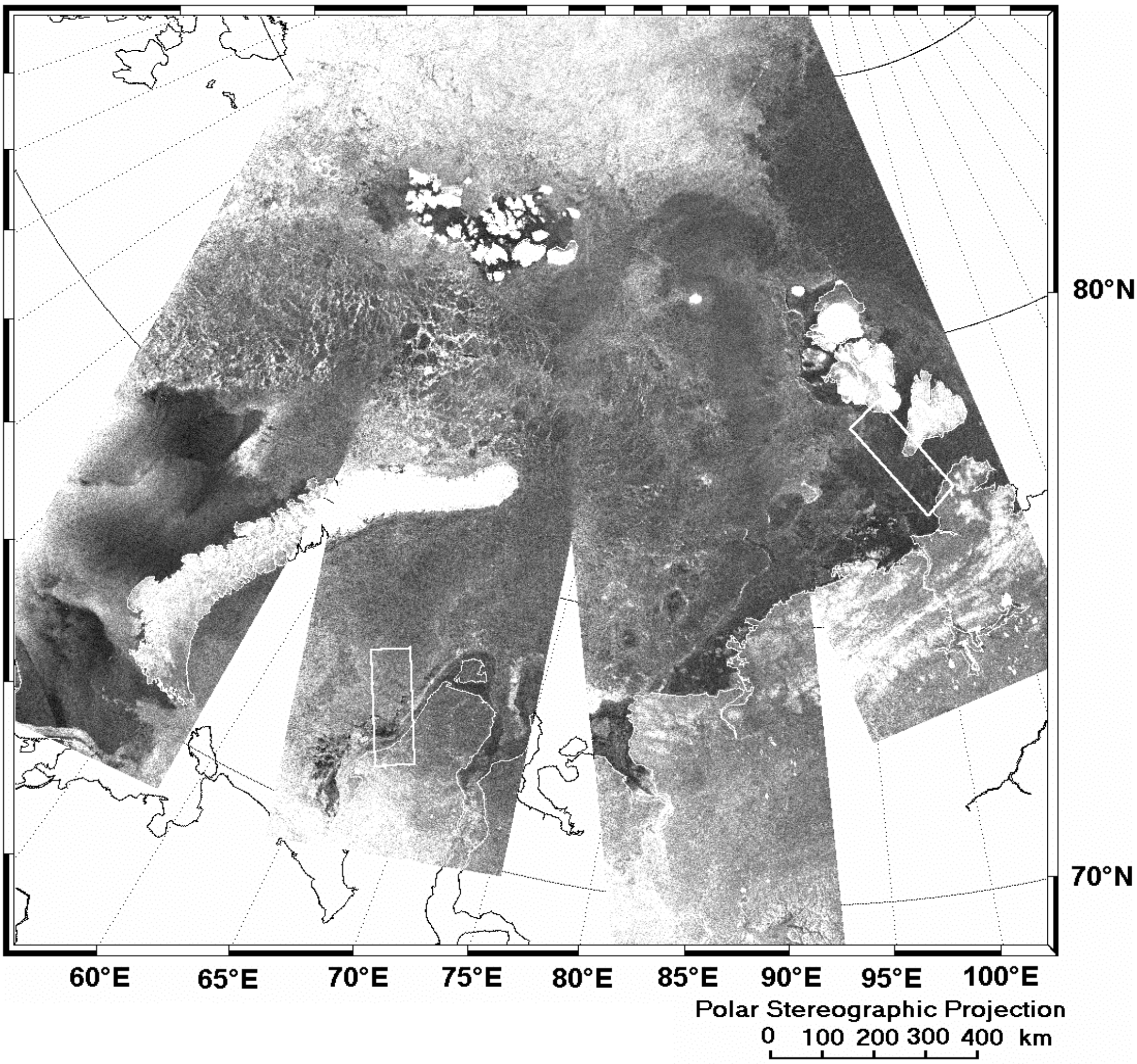


Figure 9. Okean SLR mosaic of the Barents and Kara Sea, composed of four stripes each of 450 km width, obtained 16-21 May 1996. The two white rectangles indicate ERS SAR scenes obtained in the same period. Courtesy of NPO Planeta.

4.5 NANSEN INTERNATIONAL ENVIRONMENTAL AND REMOTE SENSING CENTER

Since 1994, the two Nansen Centers in Bergen and in St. Petersburg have, together with MSC, carried out several pilot demonstration projects in the NSR. These projects have documented the capability of ERS SAR for providing high-resolution sea ice information for navigation support [Johannessen, *et al*. 1997]. As a part of these demonstrations, ERS SAR images and detailed ice charts have been transmitted to the icebreakers and the MOH for retrieval of sea ice information. Ground truth observations made by NIERSC scientists during the experiments have been used to interpret detailed features in the ERS SAR images. Despite the narrow coverage of only 100km, ERS SAR images can be useful for ice mapping of limited areas such as straits, river estuaries, etc. A major bottleneck in the processing chain is the transmission of the ERS SAR images to users onboard the icebreakers. Although the image quality is significantly reduced in the transfer process, A4 sized greyscale satellite images can be transmitted by telefax, using the INMARSAT tele-communication system. Digital transmission of satellite images and ice charts to both ships and shore locations have also been successfully tested [Johannessen, *et al*. 1997]. During the winter campaigns a number of images were obtained at relevant time and places, and could be used directly in tactical ice navigation. Also SAR scenes obtained in areas surrounding the initial ice route were useful information for the MOH, because they contributed to the overall analysis of the ice conditions in the region.

5 THREE TYPES OF SEA ICE NAVIGATION INFORMATION

Hydrometeorological information including sea ice data, is considered to be an important and integrated part of the navigation safety and environmental protection. For planning, organising and managing safe sea operations in the Arctic, all types of ice information are useful. The most important part of the ice navigation information is accurate and timely mapping of the sea ice conditions. Ice navigation reconnaissance can be divided into three main categories:

- strategic (survey) ice reconnaissance (global)
- operational ice reconnaissance (regional)
- tactical ice reconnaissance (local)

Coverage	Strategic (global)	Operative (regional)	Tactical (local)
Spatial resolution	10 km	1 km	100m
Repeat period	10 days to 30 days	2 - 3 days	3 - 6 hours
Need for archived data	yes	yes	no
Need for real time data	no	yes, within 1 day	yes, within 2-3 hours
Need for forecast	yes, long-term (month, season)	yes, up to 7 days	yes, short-term up to 24 hours
Users	general planning (NSRA, MOH)	during specific operations (MOH, captains)	onboard ships (captains)
Role of satellite data	essential	important , also aircraft survey	aircraft most important, SAR data is coming

Table 2. Key characteristics of the ice navigation reconnaissance categories.

Strategic ice charts are composed for the whole Russian sector of the Arctic Ocean, and are necessary for planning of fleet operations. Tactical sea ice information is necessary for selecting optimal and safe ship routes in the ice. Ice reconnaissance using the onboard helicopter is currently the main provider of tactical sea ice information. Tactical sea ice information is also obtained during air reconnaissance flights, and the sea ice maps are produced onboard the aircraft. During the flight, expert analysis of the sea ice conditions can be done, and recommendations for the ship route can be prepared as an ice chart.

5.1 STRATEGIC (GLOBAL) ICE RECONNAISSANCE

The strategic (global) ice reconnaissance covers all water basins in the NSR, from the Barents Sea to the Bering Strait, as well as the near-polar regions. The strategic ice maps are usually made with azimuth or conical projection, with scales from 1:5,000,000 to 1:20,000,000. They are issued once every 10 day during the main navigation period, while in winter seasons they may be issued only once pr month. These maps normally outline the ice edge, the boundaries of the fast ice zones and ice massifs, the recurring of flaw polynyas, and fields of different ice types, age (thickness) and concentration. Space-borne sensors with low resolution (5-10 km) and wide coverage are the basic data source for the strategic ice reconnaissance. The NSRA and MOHs use the strategic ice maps for planning of fleet operations.

5.2 OPERATIVE ICE RECONNAISSANCE

The operative ice reconnaissance is carried out in the active navigation period. The ice reconnaissance covers areas of the NSR where ship and offshore operations are carried out. The operative ice maps are produced with Mercator or conical projection, with scales from 1:2,000,000·to 1:7,000,000. They are issued once every 2-3 days during the operation period. The maps include the following information: the ice edge position, the fast ice zones (including areas of different thickness), hummocking and deformation, flaw polynyas and clearings, areas of different thickness and concentration, orientation and extent of leads and fractures in the more compact ice, both individual and systems of cracks, the amount of prevailing ice forms at locations, separate larger ice floes from smaller, local areas with increased hummocking, hummock ridges, grounded hummocks and icebergs, zones with various orientation and compression, snow cover characteristics and destruction, and man-made canals in the ice. The main information sources are images from satellites with medium resolution (100-1000m), data from visual and instrumental air-borne reconnaissance, and observations from polar stations, ships and expeditions. The operative ice maps are used by the MOH to:

- choose the initial navigation routes, and allocate the icebreaker support
- determine places for departure, destination and formation of convoys
- determine the size of the convoys, and estimate motion schedules for the operation
- work out navigation recommendations for the icebreakers and ships throughout the voyage
- locate shelter places (safe “parking” of ships) in case of dangerous ice conditions
- locate places for cargo delivery operations (harbours, shores, temporally harbours in the fast ice, or ship-to-ship passing)
- ensure the safety of floating and stationary derricks and oil terminals.

In order to make operational decisions, additional information such as weather and ice forecasts for the next 1-10 days, and the ice distribution, drifting and compression are needed. Operative ice maps and ice forecasts are transmitted to all icebreakers and ships within the area covered. With this information the navigators onboard can correct the ship route, and plan and take measures to ensure a safe navigation.

5.3 TACTICAL ICE RECONNAISSANCE

The tactical ice reconnaissance is carried out in real time during actual sea operations, such as ship or convoy steering, icebreaking maneuver, and cargo loading operations away from the ports (ship-shore, ship-ship). The main goal of the tactical ice reconnaissance is to choose an optimal, safe and efficient route for ice navigation. The main data sources for the tactical ice reconnaissance are:

- visual ice observations using a helicopter carried by the icebreakers
- high-resolution radar satellite images

Tactical ice reconnaissance is usually carried out during navigation through fast ice, ice massifs and ice fields. The reconnaissance distance may vary from a few km to 100km. Navigators and ice pilots onboard the icebreakers and ships are the major users of the tactical ice reconnaissance. To be valid, the observations should not be more than a few hours old. Tactical ice reconnaissance maps are prepared in a scale comparable with sea navigation maps, from 1:100,000 to 1:1,000,000, where the former is most frequently used. The helicopter reconnaissance is mapped graphically, and these maps reflect ice characteristics especially important for a given sea operation. Geo-rectified images from the airborne side-looking radar Nit' and high-resolution radar satellites (with resolution from 10-100m), superimposed geographical grid and shore lines, are adequate for solving most of the tactical ice navigation. Direct transmission of images from the aircraft to icebreakers and ships can be done. In 1978 and 1979 experimental studies on direct transmission of airborne SLR images to icebreakers confirmed its practical importance for navigation support. Receiving of images from the NOAA, Meteor and Okean satellites onboard, and onshore transmission of ERS SAR images to the icebreakers, have also been very useful for the navigation support. The information content in the satellite images is often too complex to be fully utilised in a generalised ice chart, and hence the information value of the images can increases significantly with onboard expert analysis and interpretation.

6 TECHNIQUES OF ICE CHART COMPOSITION

6.1 PREPARATION OF PARTIAL SEA ICE CHARTS AT AARI

Satellite images are the main information source for ice chart composition. The ice chart composition process includes image re-processing, geo-rectification, interpretation, and ice chart generation. Procedures for ice charts composition from multi-band sensor satellites are also developed. AARI has automated the process of geo-rectification using both orbital and ground control points, while the interpretation is still done manually. A software system is developed for operative processing of satellite images and ice chart composition, using data from the Meteor, Okean and NOAA satellites. The following procedures are carried out:

1) geo-rectification using orbital data
2) geo-rectification using ground control points, with an accuracy of 2-5 km
3) image brightness adjustment
4) simultaneous visualisation of two or more images in adjacent windows
5) visualisation of image, superimposed shore-lines and geographical
6) interactive composition of sea ice chart, with delineation and notification of homogenous areas, and delineation and marking of linear and single ice objects
7) ice thickness classification of IR images, and prepare ice thickness chart
8) automatic preparation of a vector-based ice chart, assigned symbols according to the WMO Sea Ice Nomenclature, to produce a file in the 'Contour'-format
9) interactive determination of ice drift vectors from successive images of the same area

An example of a partial ice chart, composed from Okean SLR and ERS images is presented in Figure 10. Ice chart in the 'Contour' format can be transmitted to the users by telephone or radio-link channels. Due to cloud cover or limitations in the swath width, ice charts composed from a single image generally cover only a small part of the study area.

Since all necessary sea ice parameters cannot be retrieved from a single sensor, it is necessary to use information from sensors with different spectral bands and spatial resolution. The MOH and the Ice Center at AARI have access to all available sea ice information, and can therefore produce composite ice charts.

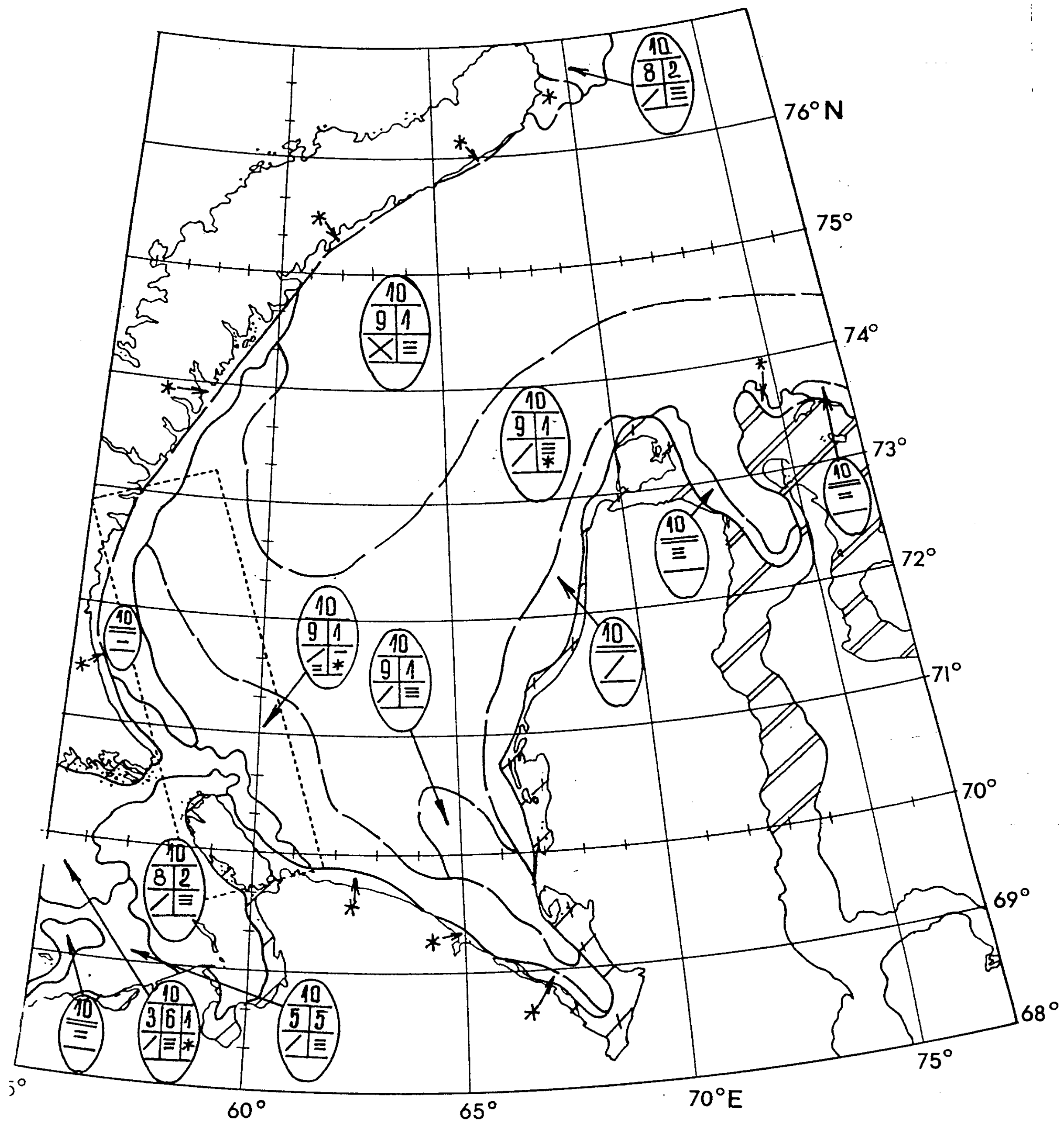


Figure 10. Partial ice chart of the western Kara Sea prepared from Okean SLR and ERS SAR data (dotted area) 25-31 January 1996. Map courtesy of AARI.

6.2 PREPARATION OF COMPOSITE ICE CHARTS

The information input to operative composite ice charts, consists of regional ice charts composed from radar, visible and IR satellite images, airborne SLAR and visual ice reconnaissance, as well as data from ships, polar stations, drifting buoys and automatic ice stations. Composite ice charts are composed using the Universal Topographic Projector (UTP-2). The ice charts are transmitted to the users by telephone or radio-link communication channels. Methods for preparation of composite ice charts using GIS such as ARCINFO is currently under development at AARI.

6.3 PREPARATION OF ANNOTATED IMAGES

After detailed analysis and interpretation by ice experts onshore, hardcopies of ERS SAR images, superimposed geographical grid, coastlines, and annotations indicating the main sea ice parameters have been faxed to the icebreakers. Digital ERS SAR images, compressed to 50 KB using JPEG-format, have successfully been transmitted to the icebreakers using a modem and the INMARSAT communication system. INMARSAT can be used at latitudes as high as 75°-78°N, depending on the ship's longitudinal position and the visibility towards the southern horizon. Using this method, SAR images can be received onboard the icebreakers in near real time, i.e. within 2-3 hours after acquisition. The time delay includes reception and initial processing of the SAR image at Tromsø Satellite Station, file transfer to NERSC-Bergen, antenna gain correction, geo-rectification, analysis and interpretation at NERSC, and transmission to the users at sea. The SAR images have also been transmitted to SOG-Dikson, and used in the composition of ice charts later transferred to ships in the NSR. An example of an annotated ERS SAR image of the Yenisei river estuary is presented in Figure 11.

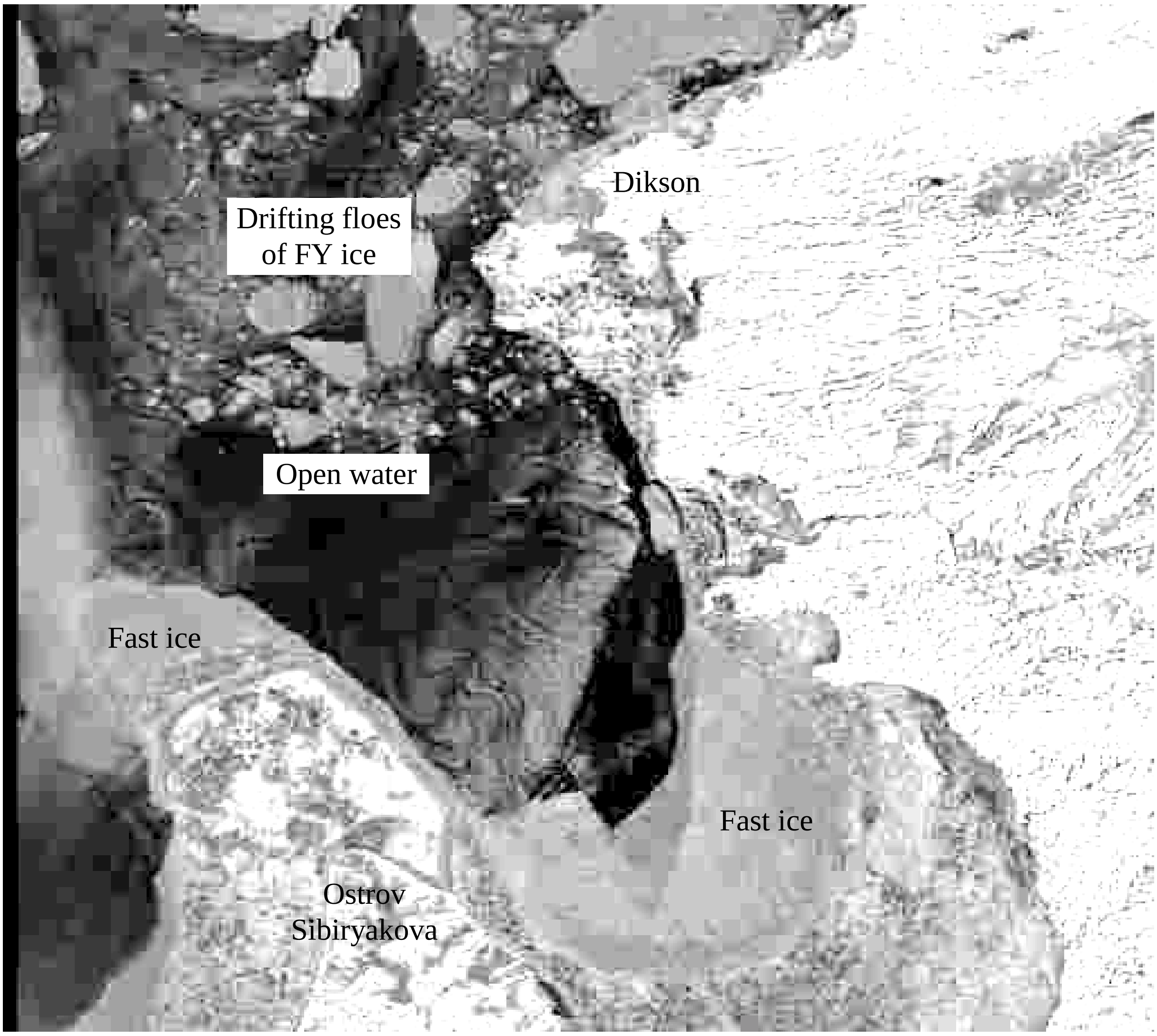


Figure 11. Annotated ERS SAR image from the Yenisei Gulf, obtained June 28 1996. ©ESA 1996. The image quality is degraded due image compression necessarily for transferring the image to the ship with INMARSAT. The main ice features needed for navigation support are maintained.

6.4 INTERPRETATION OF SEA ICE SATELLITE IMAGES

Several sea ice parameters can be retrieved by image analysis, such as ice concentration, ice type classification (multi-year, first-year, young, and fast ice), and surface characteristics and roughness (level ice, rough ice), and from successive images; ice drift and ice motion, and the fast ice boundary. These interpretations are based on many years of validation experience, using data such as airborne SLR and visual reconnaissance surveys, aerial photographs, ground-truth observations of ice topography, thickness and composition, and knowledge about the general ice situation in the area. The satellite sensors only observe the upper layer of the ice surface, while the critical factor for the ice navigation is associated with the thickness of the ice cover. The interpreter must know the connection between typical ice situations, including thickness estimates, and the corresponding SAR signal.

6.4.1 VISIBLE IMAGES FROM THE METEOR SATELLITE

Visible range images from the Meteor satellite are used to determine sea ice parameters in cloud-free areas during the summer season. Techniques for interpretation of these images are developed [Bushuev, *et al*. 1978]. Individual ice floes with a diameter more 1-2 km can be detected, while ice floes with a diameter more than 2 km can be seen as very bright spots. If the floe size exceeds 5 km, it is possible to determine the contour. In areas with 90-100% ice concentration large ice floes are seen as very bright spots compared to smaller surrounding floes. Ice channels, leads and fractures wider than 0.5 km can also be identified in Meteor images. If their width is about 1 km, they are shown as a broken chain of grey tone elementary squares, and the brightness does not depend on the width. Longer fractures with a width of 1.5-2 km are seen in their full length, with a grey tone very similar to open water.

Fractures wider than 5 km are characterised by a very dark signal, and both their shape and size can be determined. The ice concentration is fairly easy to determine from visible range satellite images. In the winter season, compact ice and fast ice are seen with maximum brightness. Areas of fractured ice with 90-100% ice concentration are characterised by weak spots, due to the different brightness from large ice floes and spaces in-between the floes. In the summer season the brightness of such areas decreases, and at a certain stage in the melting process the floes have a weaker signal than broken ice.

In winter conditions the total brightness of areas with 70-80% ice concentration is less than from compact ice. Such areas are shown as connected bright spots on a dark background. Areas with smaller floes are shown as interleaved spots with different grey-values. The brightness from such areas decreases during the melting process. During the winter and spring, areas with 40-60% ice concentration are characterised by a patchy texture, with single bright spots situated far away from each other. After a strong melting the tone becomes dark grey, and almost inseparable from open waters. Evenly distributed areas of broken ice with 10-30 % ice concentration can only be identified outside the melting season. Areas with similar ice concentration gradients are delineated quite reliably, and the concentration in these areas is estimated accurately, provided cloudless conditions.

Previous studies show that it is possible to discriminate young ice areas in visible range images. The sea ice albedo increases from 0.15 - 0.17 to 0.35 - 0.40 when the ice thickness approaches 40 cm. Ice 40 cm thick is usually covered by snow, which increase the albedo to 0.75 - 0.85. Therefore, ice older than grey-white generally has similar brightness signatures. As a rule, sea ice thinner than 10 cm cannot be identified in satellite images, as the albedo is close to the albedo of open water. In some cases, rafted nilas is shown in the 0.5-0.7μm spectral range, but cannot be separated from grey and grey-white ice. Fractures in the ice cover can be a complementary feature of young ice areas. Young ice is mainly characterised by a low brightness signal, and parallel chains of small and short fractures. In some cases, large areas of dirty ice can be identified in visible range images.

6.4.2 Infrared images from the NOAA and Meteor satellites.

Infrared (IR) images are most reliable for sea ice analysis in the winter season when the air temperatures are below –10 to 15°C. Patterns of fractures and single fractures wider than 0.5 km can be identified. Also the ice edge position and areas of young and thin first-year ice can be detected. Research have shown that it is possible to determine ice thickness up to 100 cm from IR images [Bogorodskii and Paramonov, 1995].

6.4.3 Okean Side-Looking-Radar images

The Okean Side Looking Radar (SLR) operates independently of light and clouds, and several sea ice parameters can be estimated from the images, which have a resolution of about 1 km. The ice edge position, boundary between fast and drifting ice, three stages of ice development, total and partial ice concentration, size of larger ice floes, and shape and distribution of wide channels and fractures in the ice cover can be identified in SLR images [Bushuev, *et al*. 1985]. From sequential images, the general ice drift and areas with probable ice compactness can be determined by estimating displacement vectors of distinct features recognised in the images. The Okean SLR can separate new/young, first-year and multi-year ice, as in Figure 9.

In periods of intensive melting the radar signatures can change considerably due to surface temperature fluctuations near 0°C. Identification of fractures in the ice cover is possible if there is good contrast to the surrounding ice. In first-year ice, fractures covered by grey ice can be reliably identified, due to a significantly higher backscatter signal, while fractures covered by new ice and nilas, cannot be identified. In multi-year ice, fractures covered by grey ice cannot be identified because of similar backscatter coefficients.

Unfrozen leads and fractures covered by nilas and thin first-year ice can be distinguished quite reliably. Giant ice floes are evident in the mulit-year ice massifs. Such floes can be tracked for a long time, and used for sea ice dynamics studies from subsequent images.

In the summer season the ice concentration is the most important parameter, but very difficult to determine from SLR images, because the backscatter value at this time is near the noise level. It is also problematic to distinguish ice from open water in this period. The brightness signal of open waters depends on the wind speed and direction. This dependency considerably limits the possibility to determine the ice edge position, unless there is a very calm wind situation.

6.4.4 RM-0.8 passive microwave images.

Microwave emission from sea ice is different from open water, which makes passive microwave data suitable for ice mapping. The ice edge position is usually well detected in passive microwave images, but is limited by coarse resolution. RM-08 operates at a wavelength of 0.8 cm, and has a spatial resolution of 15 km. In winter conditions, the strong contrast between first-year and multi-year ice is used to determine the multiyear ice boundary. During the summer this discrimination is impossible, due to melting and wet surfaces. Large polynyas, even with a thin ice cover can be determined. In many cases it is an advantage to use RM-08 jointly with SLR images in order to increase the accuracy and spatial resolution of ice charts composed from these data sources.

6.4.5 ERS SAR IMAGES

It is well documented that ERS SAR images are capable to identify several different ice parameters. Experience from interpretation of satellite and airborne SLR images, and knowledge of the general ice condition in the Pechora and Kara seas, is useful for interpretation of ice features in ERS SAR images. Scientists from NERSC and NIERSC have received digital SAR images onboard icebreakers, and performed ice observations of specific features seen in the SAR images. However, the most important method for decoding of ice features in SAR images is to collect *in situ* ice data from field investigations. The following ice parameters can be determined from ERS SAR images [Johannessen, *et al*. 1997]:

Identification of open water

Normally, the SAR backscatter signatures of open water are different from most ice types. However, the SAR signal strongly depends on surface roughness, i.e. the wind speed. Calm water is characterised by a very dark signal, while the backscatter value increases with increasing wind speed. In some cases, it is difficult to separate open water from ice in the ice edge region, especially in the summer season.

Fast ice forms

The fast ice boundary can be distinguished from drifting ice in most cases. Areas with ridged ice in fast ice zone can be detected.

Ice type determination

The following sea ice types can be determined in ERS SAR images:

- grease ice (dark signature)
- nilas (somewhat brighter)
- pancake ice (very bright)
- young ice (grey and grey/white) (bright)
- level first-year ice (medium to dark)
- ridged first-year ice (medium to bright)
- multi-year ice (medium)

Detection of the ice types is done using image brightness, texture, and seasonal information on the ice condition. In ice regimes with mixed ice types the partial concentration of each ice type can be determined.

Ice concentration, ice forms and ice edge position

The ice concentration in an area is based on the ice type classification. Individual giant or big floes can be identified and delineated if the concentration is less than 90-95%. Under favourable wind conditions the ice edge position can be determined due to a sharp brightness change.

Channels and fractures in compact sea ice

Fractures in the ice cover can be identified even if their width is smaller than the 20-30 meter spatial resolution of the radar. Also man-made channels is evident as thin bright lines in level fast ice, and sometimes in compact drifting ice.

Ice deformation

Heavily and moderately deformed ice can be identified in SAR images as bright features, due to high backscatter from ridges. Areas with different degrees of deformation , from level ice to heavily deformed ice can be classified.

6.4.6 AIRBORNE SIDE LOOKING RADAR (SLR) IMAGES

Airborne SLR images were widely used for navigation support in the Arctic before 1991. From these images, the following sea ice parameters can be determined [Bushuev, *et al*. 1983]:

- the ice edge position, with an accuracy of ± 2 – 3 km
- the ice concentration, with an accuracy of ± 10%
- the main stages of sea ice development (nilas, young, first-year and multi-year ice), with an accuracy of ± 10%
- boundaries of areas with similar ice concentration, with an accuracy of ± 2 – 3 km
- areas covered by floes with similar shape and size, for floes from 100-500m in diameter
- size, shape and position of fast ice, and polynyas, fractures and leads wider than 50 m
- ice drift vectors, with an accuracy of ± 1 – 2 km

Not all sea ice parameters necessary for ice mapping can be quantitatively retrieved from airborne SLR images. Ice hummocks can be assessed only qualitatively. Smooth ridges on the multi-year are not detectable. Reliable relations between radar signatures and stages of melting are not established. Some cracks and leads will look similar to ridges. It is not possible to measure the snow cover, determine the thickness of first-year ice 70–200 cm thick, and to identify polluted ice.

6.5 FEASIBILITY OF AUTOMATED ICE CLASSIFICATION OF SATELLITE IMAGES

Sea ice mapping from satellite image is still done by manual interpretation methods. Automatic procedures for determination of sea ice parameters from satellite images is under development, and so far the following algorithms have been developed:

- derive ice thickness from infrared satellite images, using a physical model. Thickness' up to 1m can be determined.
- linear and non-linear algorithms determining sea ice concentration from visible satellite images
- determination of partial multi-year ice concentration from Okean satellite radar images
- delineation and description of fractures in regular grid points
- automatic ice type classification from simultaneous radar and passive microwave OKEAN images
- semi-automatic ice type classification from ERS SAR images
- ice drift estimation from subsequent ERS SAR images

6.6 SUMMARY OF THE RUSSIAN SEA ICE CHARTING ROUTINES

In this review the different organisations providing hydrometeorological navigation support and sea ice charts in Russia have been described. The main information sources for the ice mapping production are remote sensing satellite images, airborne ice reconnaissance surveys, and field observations. Methods for satellite ice image analysis are described. The concepts of partial and composite ice maps are illustrated, describing various stages in the preparation procedures. Much of the ice charting routines are done manually, but some automated procedures are also used. Automatic ice interpretation procedures are an ongoing research topic.

As the volume of satellite data used in ice mapping increases, the issue of automated processing becomes essential. The wealth of information available from for example SAR images can only be fully utilised with efficient software tools. Ice map producers must be able to receive and analyse all types of ice data, including satellite data, in a streamlined fashion in order to operate efficiently. This means that also the transmission and distribution of data to users both onshore and on ships must be streamlined.

In the last years, as the use of aircraft reconnaissance flights has decreased due to financial constraints, the importance of satellites providing sea ice information have has increased. With high-resolution SAR images it will be possible to obtain ice information with a quality similar to what was previously only possible with airborne sensors. The commercial prices of western satellite SAR data are currently far too high for the Russian ice services. Only commercial users such oil and shipping companies are expected to afford to use SAR data in the NSR in the near future. Unless there is considerable new funding available, it is not realistic that the Russian ice service can use SAR data on a regular basis.

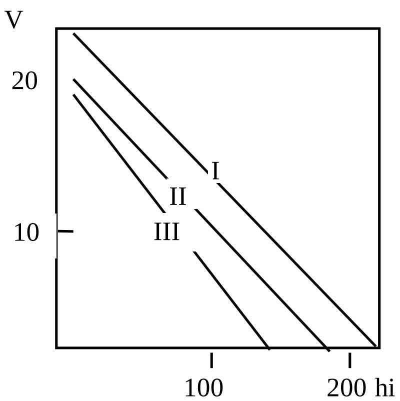
7 ANALYSIS OF THE ARCTIC SHIP ROUTING OPERATIONS

7.1 ICEBREAKER AND SHIP CLASSIFICATION

The icebreakers and ships designed for ice navigation in the NSR routes must meet specific requirements, determined by the following characteristics: the ice-passability, the ice speed-limit, ice resistance, and manoeuvrability in various ice conditions.

Ice speed limit

The ice speed-limit is the ability of a ship to overcome the ice pressure at a certain speed, whose value is governed by the prescribed ice cover characteristics, the dimensions and the shape of the hull, the propulsive properties, and the engine capacity [Bogorodskii *et al*, 1985]. The ice speed-limit is estimated both by calculation techniques and testing results from field trials in the ice. As can be seen in Figure 12, there is a linear dependency between an icebreaker’s non-stop maximum motion speed and the thickness of compact level fast ice.



Dependence of icebreaker speed (V-knots) and ice thickness (hi-cm) for power on the shafts

I - N= 60 000 hp
II - N= 40 000 hp
III - N= 20 000 hp
[v] = knots
[h] = cm

Figure 12. Ship speed as function of ice thickness for three icebreaker types.

Ice resistance

The resistance to ice is the ability of the ship hull to avoid damage from ice loads in ice navigation and during ice compression. The ship’s resistance to ice is determined by her dimensions, the shape of the hull, the material and design of the hull, and the ship speed, together with the thickness and the physics-technical characteristics of the ice cover. While the ice speed-limit determines the maximum possible (achievable) full-capacity speed of the ship, the ship's ice resistance implies a certain limitation of the speed, imposed by the strength of the hull structures. In Arctic navigation, the ships have to move as safe as possible at a certain speed, which eventually serves as a criterion for the ship's ice-passability.

Ice-passability

The parameters of the ships' ice-passability are determined both for unescorted and icebreaker-escorted Arctic voyage convoys. The ultimate ice thickness an icebreaker can overcome with a non-stop motion at a minimum steady speed, usually within one knot, is taken as a criterion for the icebreakers' ice-passability. If the icebreaker moves in ice with a lower speed, it can get nipped and has to move with thrusts. The icebreakers' ice-passability in summer and in winter is different. For example, in summer conditions the ice-passability of an icebreaker with a capacity of 75,000 h.p. is about 2.8 - 3.0 m, while in winter conditions it is lowered to 1.8 - 2.0 m. The ice-passability of a nuclear icebreaker with a capacity of 75,000 h.p., which is the most powerful icebreakers operating in the NSR, is sufficient for summertime near-pole voyages. For winter navigation in these routes, the ice-passability of such icebreakers is not sufficient for safe operations.

Ice maneuverability

The last important ice operation requirement for the ship (icebreaker) is her maneuverability, which means her ability to turn, stop, and change direction (forward, backward) in the ice. For an icebreaker, the maneuverability determines its ability to turn in the ice, to perform forward and backward forcing of ice, and to cut the ice around ships and port constructions. For transport ships the maneuvering properties are the ability to turn in the meandering canal when following an icebreaker, and to run and stop in order to preserve a safe steering distance in convoy voyages. In the case of unescorted ice voyages, the transport ship should be able to make efficient turns, in order to change the direction to avoid a collision with heavy ice floes, and to actively maneuver in heavy ice jams.

According to a classification register, the icebreakers and the ships are assigned to an ice class (a category of the ice strengthening of the hull). For an icebreaker to operate in the NSR, the requirements of the Register is determined by the power supply, with reference to the following tentative conditions:

Class LL1

Assigned to icebreakers with a total engine power of 47,807 kW (65,000 h.p.) and more, capable of moving in compact ice more than 2m thick, and performing all kinds of icebreaker operations in the coastal and high-latitude routes throughout the year, and in the near-pole routes during the summer.

Class LL2

Assigned to icebreakers with a total engine power from 22,065 to 47,807 kW (from 30,000-65,000 h.p.), capable of moving in compact ice up to 2m thick, and performing all kinds of icebreaker operations in the coastal, high-sea and high-latitude routes during the summer, and in the coastal and high-sea routes during the winter.

Class LL3

Assigned to icebreakers with a total engine power from 11,032 to 22,065 kW (from 15,000-30,000 h.p.), capable of moving in compact ice up to 1.5 m thick, and performing all kinds of icebreaker operations in non-Arctic ice covered seas (e.g. the Baltic, White, and Okhotsk Seas). In the Arctic seas, these icebreakers can operate throughout the year in shallow coastal waters and in river estuaries such as Ob and Yenisey. In the high-sea and high-latitude routes the LL3 icebreakers can only operate together with higher-class icebreakers.

Transport ships operating in the Arctic are classified into the following classes, according to the category of the ice strengthening of the hull:

ULA
Assigned to ships capable of unescorted ice voyages in the coastal and high-sea routes and other ice covered regions of the world during summer conditions. Escorted by icebreakers they can operate in the Arctic and other ice covered areas of the world throughout the year, in accordance with the technical capabilities of the escorting icebreakers

UL
Assigned to ships capable of unescorted Arctic voyages in the coastal and high-sea routes during easy ice conditions in the summer-fall period. Escorted by icebreakers they can operate throughout the year in the Arctic and other ice covered regions of the world, except for the Antarctic and high latitudes of the Arctic, in accordance with the technical capabilities of the escorting icebreakers

L1
Assigned to ships capable of unescorted Arctic voyages only in open waters and open pack ice situations (with concentration about 40-60%) during the summer. Escorted by icebreakers, they can operate in the coastal and high-sea routes during the summer-fall period. In non-Arctic ice covered seas these ships can operate unescorted throughout the year only in easy ice conditions, and any ice conditions if escorted by an icebreaker

L2
Assigned to ships capable of operations in easy summer ice conditions only if escorted by an icebreaker. In the non-Arctic ice covered seas, these ships may operate unescorted in ice conditions with less than 40% concentration. For all other ice conditions year-round operation is only possible with the help of an escorting icebreaker.

The ships of lower categories of the ice strengthening of the hull (L3 and others) are as a rule not allowed to sail in the Arctic seas.

7.2 TACTICS OF THE ARCTIC ICE NAVIGATION

The current definition of the notion "Tactics of the Arctic ice navigation" includes a number of methods for choosing an optimal sailing route, methods of ship manoeuvring, ice conditions that issue maximum safety, and efficient work of the fleet in the ice navigation. An optimal route during the Arctic navigation is the motion of the icebreaker, ship or convoy, under any navigational and hydrometeorological conditions, which enables to fulfil a safe voyage in the shortest terms and with minimum fuel consumption. The captain of the icebreaker or ship chooses an optimal route in the process of convoy escorting or autonomous voyages.

An efficient choice of route depends first of all on the details of the ice navigation reconnaissance data. Experience from using various sources and methods of obtaining ice reconnaissance data, when the convoys are steered by LL1 and LL2 icebreakers during the summer-fall navigation period has shown that:

- using maps from operative ice reconnaissance to choose the route without additional data from tactical reconnaissance, permits a 3-5% increase of the average voyage speed
- using data from tactical ice reconnaissance (visual observations from helicopters carried by the icebreakers, SLR Nit images, and SAR images) permits a 150-200% increase of the average voyage speed

Using SLR Nit plane tables to select the navigation route in ice 1.7 - 2.5 m thick, increased the operational voyage speed by 180-220%. Estimates for use of space-derived high-resolution SAR images (resolution up to 100m) predict a 150-200% increase of the operational voyage speed. The graphic generalization of high-resolution SAR images through ice maps causes substantial losses of the initial resolution and ice information embodied in the reconnaissance data. Therefor it is very useful for icebreaker captains and pilots onboard the icebreakers to receive SAR data on digital form in near real time.

The icebreaker escorting of ships is carried out by two basic methods: leading and towing.

- Escorting by leading means that either one or several ships in a convoy follow behind an icebreaker (simple convoy), or a group of ships lead by several icebreakers (complex convoy). The steered ships move independently.
- Escorting by towing means that the ships move in a lead after the icebreaker, and usually one ship is lead by one icebreaker. The towing is used for very difficult ice conditions, when the ships cannot move independently.

The ice conditions, or more specifically the characteristics of the lead made by the icebreaker, govern the choice of ship escort. Most important is the geometric characteristics of the lead (width, meandering, size of broken ice in the lead collapse) and the morphological characteristics (coverage of small ice floes, increase or decrease of the amount of ice in the lead due to ice convergence or divergence, respectively).

To improve the characteristics of the lead in difficult areas, the icebreaker has to make non-stop manoeuvres to choose most easy areas and directions for ice breaking. The icebreaker can make relatively linear leads if the ice thickness is within 60 - 70% of the icebreaker's passability. An increase of the meanders of the ice lead may increase the length of the actual route significantly, up to 20% and more, as well as impede on the steering of the large-tonnage ships, whose length is either similar to or greater than the average length of an icebreaker.

Analysis of the characteristics of icebreaker-made leads (width, filling with broken ice, meandering, etc.) are based on the quantitative composition of the convoy, the choice of escorting methods, safe distances between the ships in the convoy, and the convoy motion speed. Currently, powerful icebreakers with a strong hull and high manoeuvring properties are capable of forcing the ice (making a lead) in a variety of ice cover characteristics. Year-around Arctic navigation operations with icebreaker support, has made it possible to work out certain new tactical methods of ice forcing. These methods can be used to overcome the ice resistance with a minimum of time and energy consumption, and still meet the requirements of safe navigation. Present guidelines and manuals of Arctic ice navigation specify the practical information needed for all seasons to ensure regular operations in the NSR.

8 CONCLUDING REMARKS

In this study existing methods of ice charting and routing in the NSR have been reviewed. It is shown that at present time, satellite data is the main information source for the ice navigation support in the Arctic seas. Global and regional ice charts are based low- and medium resolution satellite images. This ice chart generation process is partially automated, but image interpretation is still carried out manually. During the last 5 years high-resolution SAR images have occasionally been transmitted onboard icebreakers belonging to Murmansk Shipping Company and used for detailed planning of the tactical ice navigation. Selection of the optimum sailing route in the ice is a complex task, and depends both on the sea ice conditions (current and future) and on characteristics of the icebreakers and ships in the convoy. At present time this problem is handed manually, using expertise knowledge. The ICE ROUTES project has demonstrated that ice maps based on satellite data are useful for solving strategic and operative ice navigation tasks. Detailed analysis of satellite ice images in the generation of local and regional ice maps have demonstrated their usefulness for providing information about the ice condition. Visual ice reconnaissance from helicopter and near-real time high-resolution SAR images, transmitted onboard the icebreaker, have proven to be the most useful information sources for solving tactical navigation problems.

Automatic processing of remote sensing ice data becomes more and more important, due to the increased amount and better resolution of satellite data available in coming years. Robust and validated automatic procedures will improve the quality of ice charts derived from satellite images, reduce the time gap from information acquisition to ice chart issuing, and the subjectivity of visual interpretation.

In many cases the interpretation of RADARSAT ScanSAR images is quite difficult, and limits the usefulness of these data as an information source for tactical ice navigation, which will be described in detail in Part 2. High-quality automated interpretation of these images will be very useful onboard the icebreakers for selecting the optimal route in the ice. It is necessary to take into account sensor-specific SAR image parameters, such as brightness, texture and structure. Classification results can be improved by using auxiliary ice and hydrometeorological information. For automated survey and operative ice chart compositions to meet the ice navigation requirements, it is necessary to prepare image mosaics and develop techniques to generalise the results of the image processing. Together with the ship characteristics, ice and hydrometeorological conditions should be taken into account when selecting optimal convoy routes in the ice. This problem must be solved for automatic classification of satellite images to work properly together with ship routing simulation software.

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