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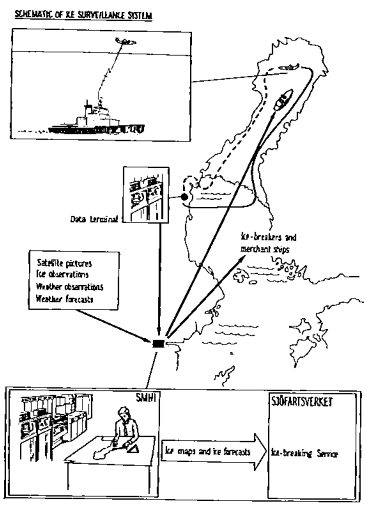

Summary report

by Åke Blomquist, Claës Pilo and
Thomas Thompson

Stockholm/Norrköping 1976

WINTER NAVIGATION RESEARCH BOARD
Swedish Administration of Shipping and Navigation, Finnish Board of Navigation
Research Report No 16:9

Cover picture:
The icebreaker TOR in the middle of the test area for SEA ICE-75.

SEA ICE 75
Summary report

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Table of Contents

Foreword

The Winter Navigation Research Board presents no. 16:9. This report summarizes the results from the remote sensing experiment SEA ICE-75, carried out in the Bay of Bothnia in March 1975. It is mainly based on the individual reports describing the execution of, and the results from the various sensor systems tests. These reports are also published in these series as nos. 16:1 to 16:7.

The project managing group that was responsible for the supervision of the project has had the difficult task of drawing the conclusion from the many individual reports and to prepare recommendations on future system developments. The Winter Navigation Research Board wish to convey its deep appreciation to the project managing group and to all other individuals and organizations that have so enthusiasticly contributed to the success of the experiment SEA ICE-75. The outcome of SEA ICE-75 will undoubtedly encourage the development of a modern, all weather, light independent sea ice mapping system.

Norrköping and Helsingfors, July 1976.

Lennart Johansson **Helge Jääsalo**

1. Introduction

The total volume of cargo passing the frontiers of Sweden amounted in 1974 to around 100 million tons/year. Of this volume 90 % was seaborne. Through the Swedish ports solely in the Bay of Bothnia passed 13 million tons/year and through the ports in the Sea of Bothnia 12 million tons/year. The corresponding volumes for the Finnish harbours in the Bay and Sea of Bothnia are 4 and 4 million tons/year respectively.

Huge industrial investments are planned in the northern parts of Sweden and Finland during the next ten years. Already by the end of the 1970's the overall volume passing through the Bay and Sea Bothnia is estimated to have increased considerably. Only the planned extension of the steelworks in Luleå would, if realized, increase the volume by 4—8 million tons/year.

It is evident that under these conditions it is of vital importance to keep the Swedish and Finnish ports open all the year around, particularly in the Bay and Sea of Bothnia. Closing the port of Luleå for instance would cause the industry in northern Sweden great losses.

A prerequisite for economical around-the-year shipping is the availability to the Ice-breaking Service and shipping of adequate ice information and ice forecasts. The ice information that is collected today by SMHI and made available to the Ice-breaking Service and shipping is principally based on visual observations from shore based observers, icebreakers equipped with helicopters, merchant ships and satellite pictures.

The methods used today give mainly qualitative information and are severely hampered by bad weather and darkness. During winter it is normal with long periods with poor visibility and extensive cloud cover. Moreover, in winter time darkness prevails during most of the day. Thus Luleå has daylight only between 09.30 and 14.00 in the middle of January. It is hence not unusual that reliable, current ice information is missing during long periods for large parts of the Baltic area.

In Fig 1 it is shown that both the Bay and Sea of Bothnia are covered by ice during normal ice winters. During severe ice winters, however, the entire Baltic area including Öresund as well as Kattegat and parts of Skagerrak are ice covered. In the last 20 years (1955—1975) not less than 6 winters have been classified as severe winters.

A surveillance system that independently of weather and darkness rapidly could provide quantitative, synoptic information on the current ice situation in the entire Baltic area should be of utmost value. Such a system would facilitate the preparation of reliable ice maps and ice forecasts by SMHI and thereby for the Ice-breaking Service to direct the traffic along the most economic routes. It should thus facilitate a further development of winter navigation in the Bay and Sea of Bothnia and contribute to keep the ports in this area open longer parts of the year.

A modern surveillance system for mapping of sea ice can only be based on remote sensing techniques.

In order to acquire own experience in Sweden and assess the capability of remote sensing techniques for surveillance and mapping of sea ice, a field experiment, SEA ICE 75, was organized in international cooperation in the Bay of Bothnia March 10—21, 1975. It is the first time such a comprehensive remote sensing experiment on sea ice has been performed in Europe. 5 aircraft, 3 helicopters, 1 ice-breaker and about 50 scientists and technicians took part in the experiment. Data were also received from 2 satellites. It should be stressed that almost none of the sensors used was optimized for remote sensing of sea ice. They were on the contrary developed for quite different purposes.

The experiment was performed within a general cooperation between Sweden and Finland on winter navigation research. The following organizations took active part in SEA ICE 75,

- ☐ Rijkwaterstaat Meetkundige Dienst (NL): SLAR installed in an aircraft,
- ☐ Helsinki University of Technology (SF): Microwave radiometer and IR radiometer installed in a helicopter,
- ☐ University of Helsinki (SF): Sonar for underwater ice profiling,
- ☐ Institute for Marine Research (SF): Field measurements,
- ☐ NASA (USA): Satellite Landsat-2,
- ☐ National Land Survey of Sweden (S): Multispectral camera package and measuring camera installed in an aircraft,
- ☐ National Defence Research Institute, FOA, in cooperation with the Air Force and Navy (S): FLAR and aircraft, ODAR and helicopter, IR scanner and aircraft. Represented in the project managing group,
- ☐ Swedish Air Force, 21st Air Command (S): High altitude camera installed in aircraft. Most of the aircraft used in the experiment plus one Vertol helicopter were based at F21, Luleå,
- ☐ Swedish Administration of Shipping and Navigation (S): Modern ice-breaker equipped with helicopter, hydrocopter etc,
- ☐ Swedish Meteorological and Hydrological Institute, SMHI (S): Extensive field measurements, Represented in the project managing groupe,
- ☐ Saab-Scania (S): Radar altimeter installed in a helicopter,
- ☐ Swedish Space Corporation (S): Coordination and management of the project.

The participating organizations bore their own expenses in connection with the experiment. The Swedish Board for Space Activities, however financed the participation of the Swedish Space Corporation and Saab-Scania, the production of the major part of the photographic material at the National Land Survey of Sweden, the evaluation of SLAR data at SMHI and some expenses at FOA.

SEA ICE 75 was coordinated and managed by a project managing group consisting of:

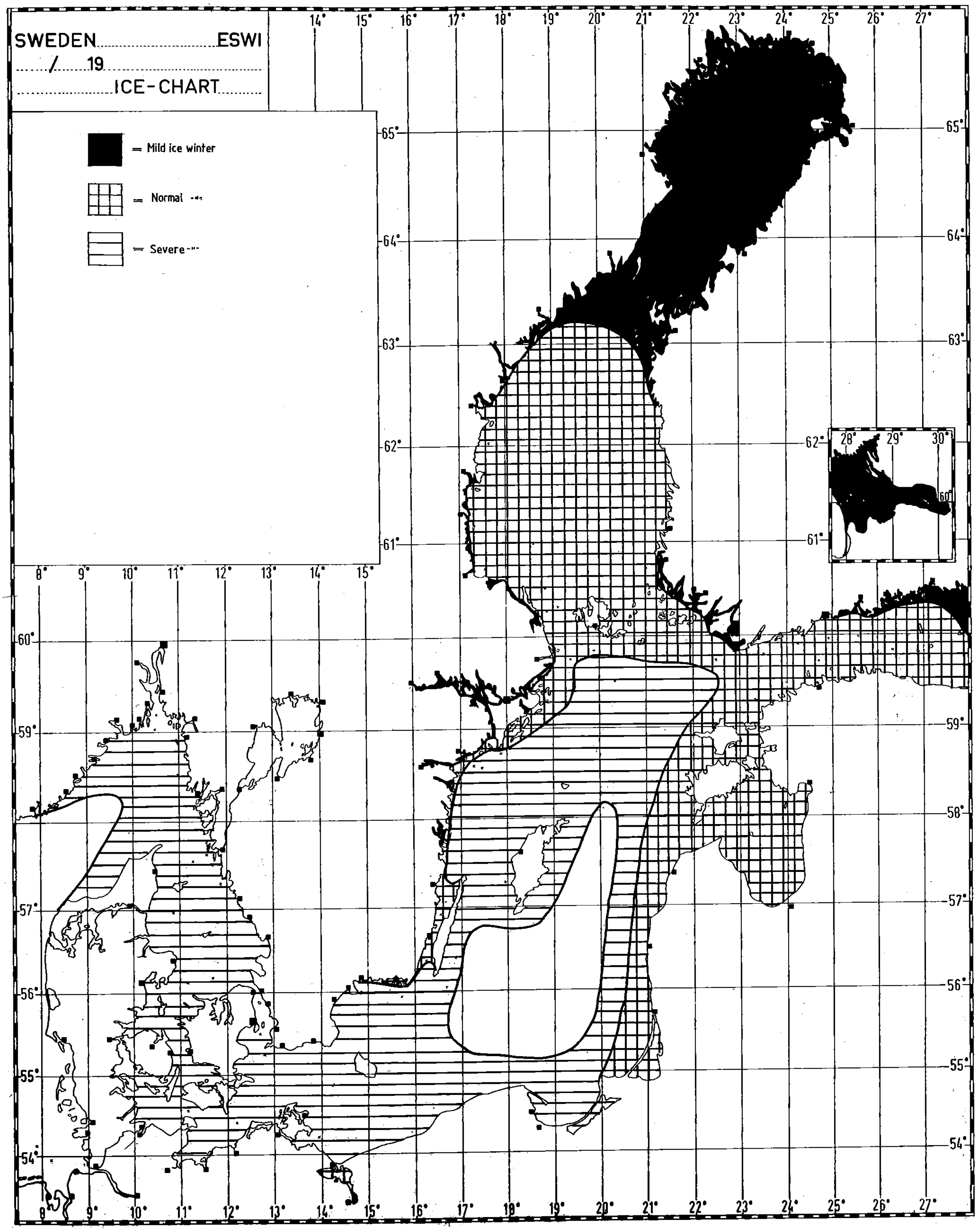
Project leader:	Claës Pilo, Swedish Space Corporation,
Scientific leader:	Thomas Thompson, SMHI,
Technical leader:	Åke Blomquist, FOA.

The head of the Ice-breaking Service of the Swedish Administration of Shipping and Navigation, Commander Agne Christenson, closely followed the project.

The project managing group was based on the ice-breaker TOR during the experiment and worked in close contact with the captain of the ice-breaker, Commander Yngve Nilsson.

The present final report summarizes results and conclusions from the reports so far produced within the project SEA ICE 75 (Ref 1—10). The reports are being published in the series of research reports issued by the Swedish-Finnish Board for Winter Navigation Research.

Figure 1. *Ice chart showing the maximum ice extension during a mild, normal and severe winter.*



2. Experimental Programme

A complete programme for the experiment was prepared in the autumn 1974 (Ref 1). The intention was initially to perform the experiment in the Sea of Bothnia. Because of the exceptionally mild winter 1975 with air temperatures 4 to 5°C above normal during the period January—March, the ice extension became considerably less than normal (Fig 2). The experiment consequently had to be organized in the northern part of the Bay of Bothnia. While the level ice in the Bay of Bothnia during normal ice winters is 50—70 cm thick it was only 20—40 cm during the experiment. The degree of deformation and the size of ice ridges was however comparable to normal ice winters.

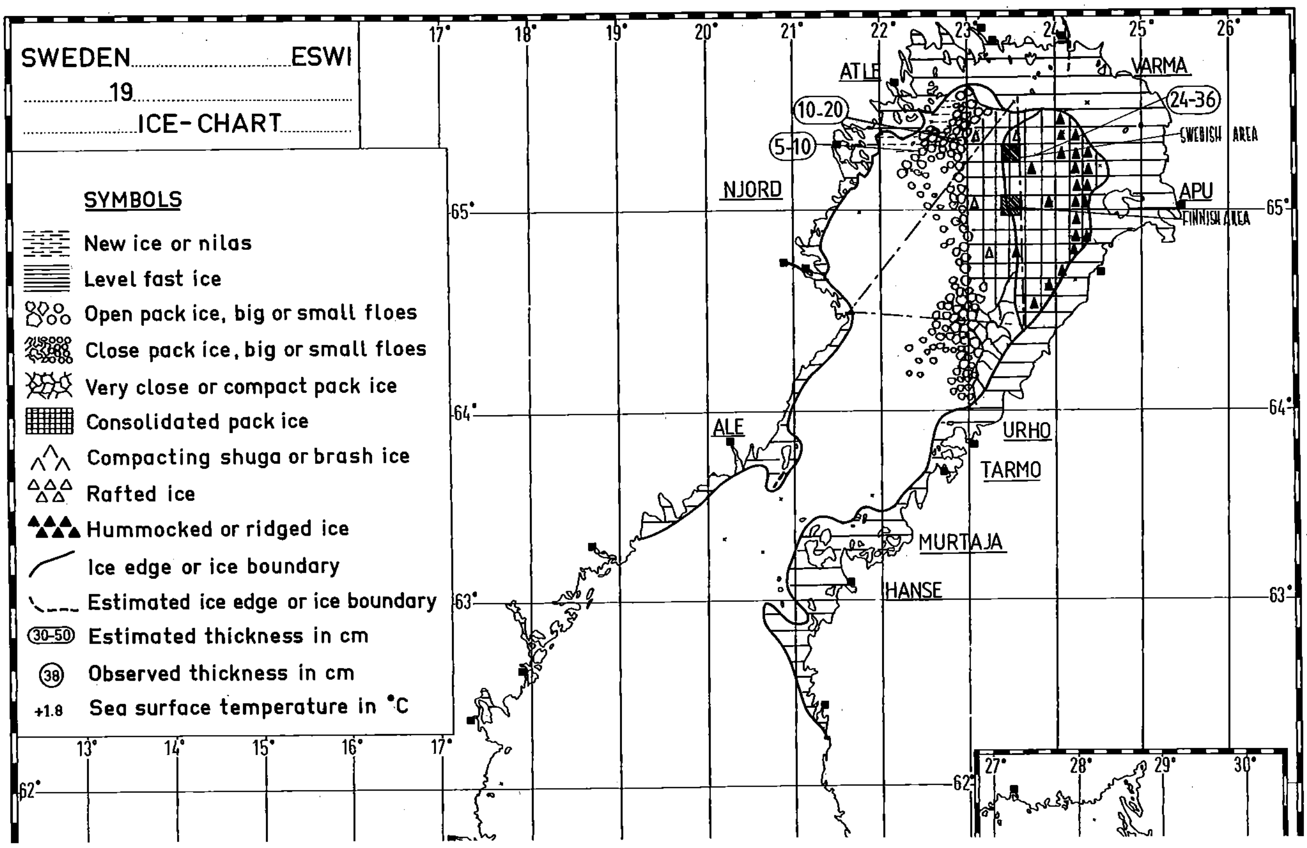
The weather during the experiment was unusually favorable with consistently very good visibility, and almost no clouds. The weather was at first dominated by a high pressure system with temperatures some degrees below 0°C. From March 15 passing low pressure systems resulted in a northerly gale followed by southerly and later westerly gale.

During the period of strong winds a considerable ice drift occured and the experimental areas drifted a total distance of 45 km (Ref 10).

Two ground truth areas — referred to below as GT-areas — were chosen. The Swedish GT-area was located 20 km SSE of Malören while the Finnish GT-area was placed further 20 km S of the Swedish GT-area and 40 km W of Hailuoto (Fig 2). SMHI was responsible for the field measurements within the Swedish area and the Finnish Institute for Marine Research for the corresponding measurements in the Finnish area.

Remote sensing registrations were made not only over the two GT-areas but also over great parts of the Bay of Bothnia following triangular tracks as shown in Fig 2. No field measurements were however undertaken in these areas, though satellite and some photographic material is available.

Figure 2. *Ice chart, from March 13, showing the Swedish and Finnish GT-areas and SLAR and FLAR tracks.*



The Swedish GT-area was divided into one test area 1×1 km, one 5×5 km and one 15×15 km, which were marked by flags, tarpaulines and radar reflectors (Fig 3). Within the test areas different types of field measurements were carried out. Helicopters, hydrocopters and snow scooters were used for the field activities. The most detailed measurements were made in the 1×1 km area. A detailed description of the ice parameters as well as the meteorological and oceanographic parameters that were measured is found in the ground truth report prepared at SMHI (Ref 2).

The ground truth report also describes the aerial photography that was undertaken, i. e. high altitude photography, photography by Wild measurement camera and multispectral photography by Hasselblad camera package. The photographic material has been assembled by the National Land Survey of Sweden into mosaics or photo maps. Mosaics are available for the 1×1 km area (Hasselblad), the 5×5 km area (Hasselblad) and the 15×15 km area (Wild). One example of a Wild photo is shown in Fig 4.

The ground truth material in the form of field measurements and air-photos has been compiled by SMHI, into ice maps over the 1×1 km area, the 5×5 km area and the 15×15 km area. SMHI has also prepared ice maps for the whole Bay of Bothnia (Fig 2) using mainly satellite registrations and routine observations.

A number of different sensors were tested during the experiment. Considering the difficult weather and darkness conditions that normally prevail in the Bay and Sea of Bothnia in winter time the experiment was focused on microwave instruments, which operate independently of weather and darkness. Most of the sensors tested have not earlier been used for sea ice measurements in Sweden. A list of the sensors and carriers tested during the experiment is found in Annex 1. A summary of registrations made during SEA ICE 75 is presented in Annex 2.

Figure 3. *Principle lay-out of the Swedish GT-area.*

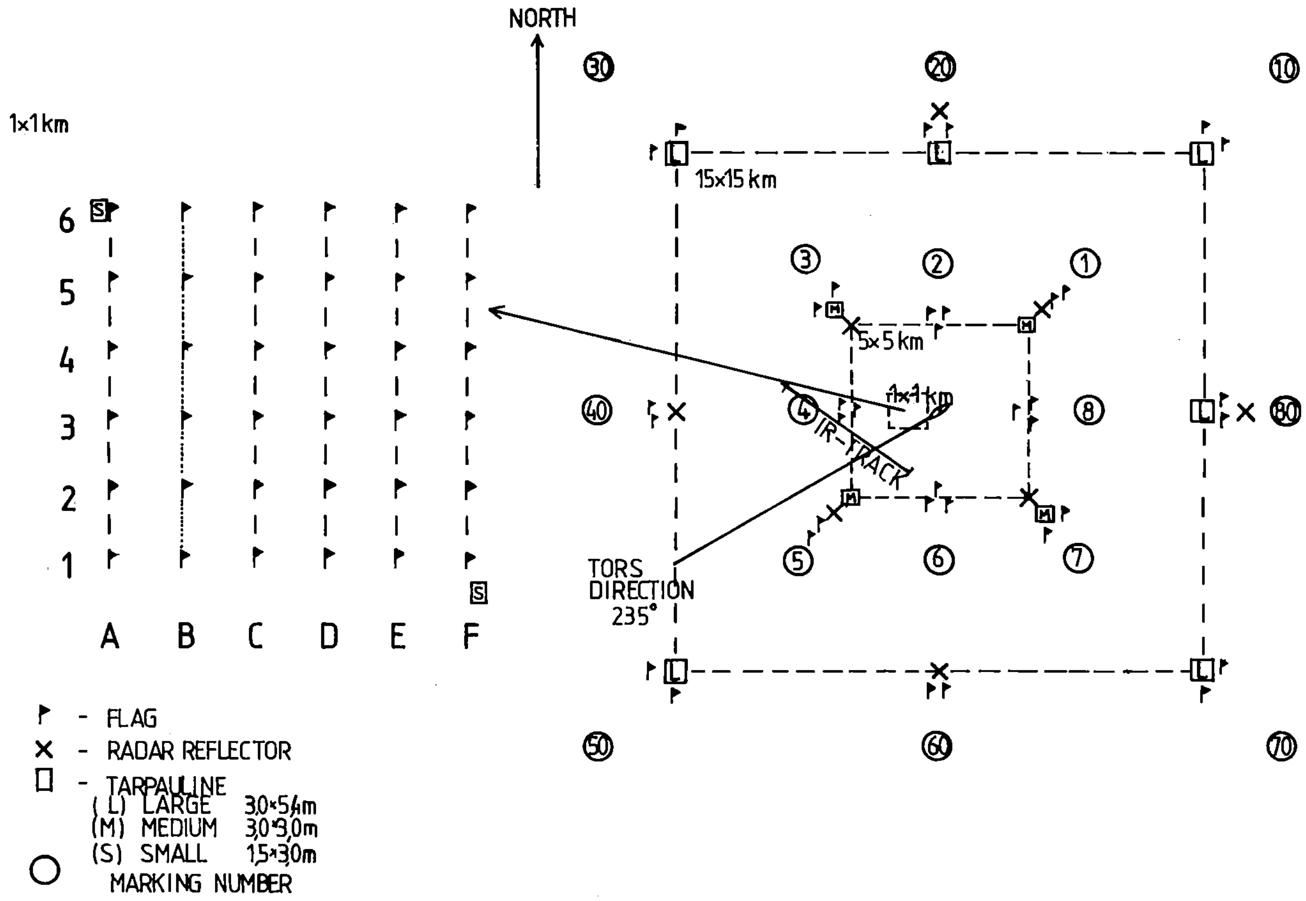
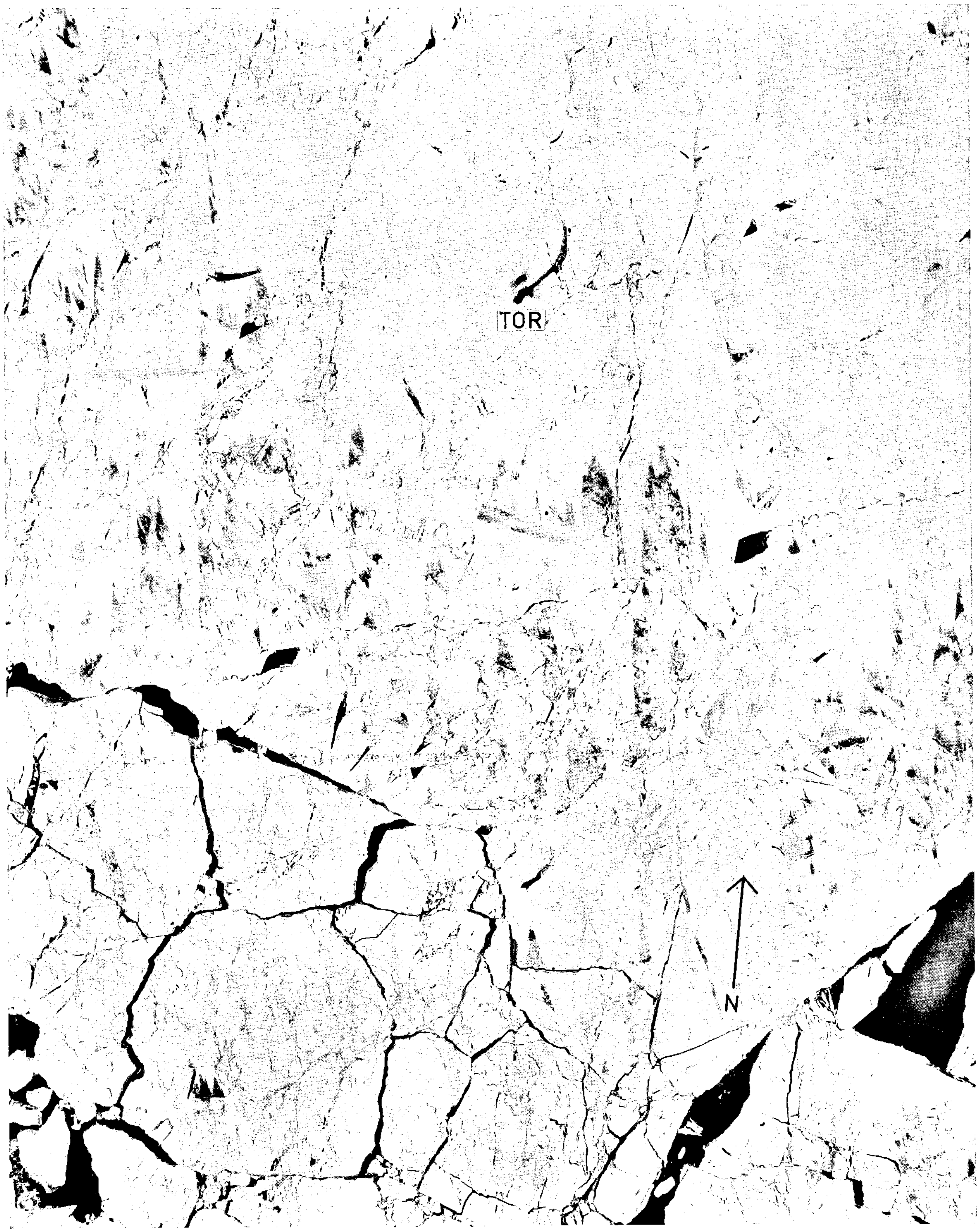


Figure 4. *Photo taken with the Wild mapping camera from altitude 4600 m on March 17.*



3. Sensors

3.1 General

The microwave sensors are almost independent of meteorological conditions and are not influenced by darkness. Heavy rain and snowfall (especially wet snow) may, however, obscure parts of the mapped area but they hardly effect the mapping range of the sensors. The effects of rain and snow, especially at short ranges, can be reduced by differentiating the video signal of the radar sensors. This technique is a standard feature on most radars used for navigational purposes. It does not prevent ice echoes from being mapped.

Infrared sensors are also independent of darkness but very sensitive to weather conditions, such as fog, clouds and precipitation.

Due to the excellent weather conditions during SEA ICE 75, no experience was gained on the weather dependence of the sensors. Furthermore no tests were carried out in darkness. The weather and darkness dependence of the various types of sensors is, however, well known from earlier use and from other types of experiments.

One of the main features of a sensor intented for ice mapping is its mapping capacity. The highest mapping capacities are obtained by radar sensors, such as SLAR, FLAR and ODAR. The particular radars used in SEA ICE 75, had, however, rather low mapping capacities varying between 3 000 (SLAR with good resolution) and 20 000 km²/h (FLAR and ODAR with less good resolution). But as stated before, the tested sensors were not designed for ice mapping. With improved radar systems optimized for ice surveillance considerably higher mapping capacities can be obtained, such as 20 000—30 000 km²/h with still an acceptable resolution. These figures should be compared with the approximate areas of the Bay and Sea of Bothnia which are 35 000 km² and 55 000 km² respectively.

It should be pointed out that in the future (after 1990) satellites will be used as platforms for radar sensors. Approximately, the same resolution can for instance be obtained by a synthetic aperture SLAR from satellite as by a real aperture SLAR from aircraft.

3.2 SLAR

The real aperture SLAR (Side Looking Airborne Radar) used in SEA ICE 75 is descibed in Ref 3 and the results are analysed and discussed in Ref 3 and 4. Although the instrument was not designed for ice mapping and the instrument setting was not optimized, the radar images showed a wide range of details of the ice and a good correspondence between the radar image and the actual ice features as they appear on the photomosaics. The features were mapped consistently from image to image. Fig 5 shows a typical SLAR image from SEA ICE 75.

Fig 6 shows a photomosaic of the 5×5 km area from March 18. Overlay A shows 8 ice categories based on available ground truth information and on analysis of their appearance on the photomosaic. The 8 categories (see Table 1) were formulated keeping in mind the needs for operational ice information and the objectives of the experiment. From the SLAR

Table 1. Ice categories

Category 1	Open water
Category 2	New ice (<5 cm thick)
Category 3	Level ice (>5 cm thick)
Category 4	Rafted ice
Category 5	Ice <50 % covered by light to moderate ridges
Category 6	Ice >50 % covered by light to moderate ridges
Category 7	Ice <50 % covered by heavy ridges*)
Category 8	Ice >50 % covered by heavy ridges*)

*) heavy ridges = ridges heigher than 1.5 m above the level ice

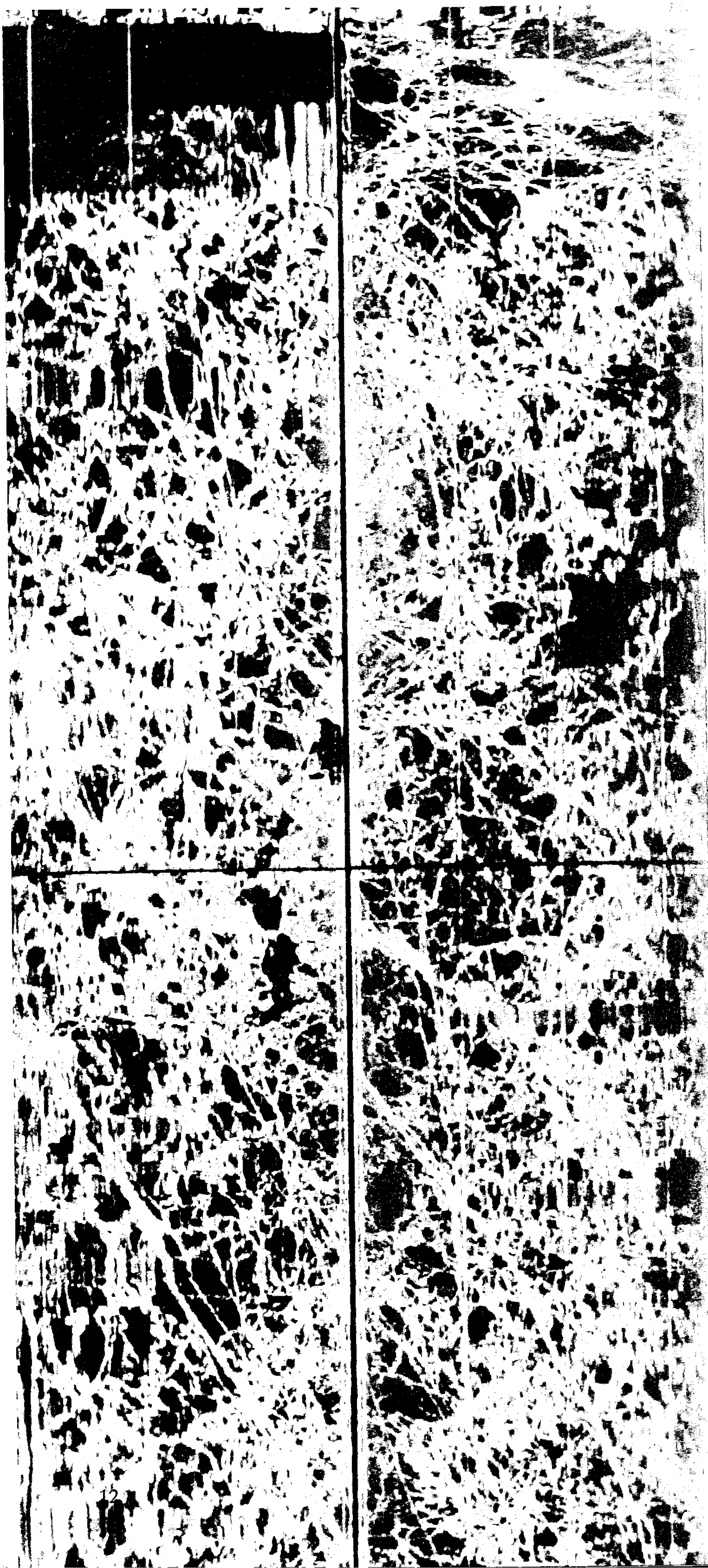


Figure 5. *SLAR image in the neighbourhood of TOR.*

Figure 6. *Photomosaic of the 5×5 km area (Hasselblad pictures) from March 18.*
Overlay A — Ice categories.
Overlay B — SLAR categories.

B

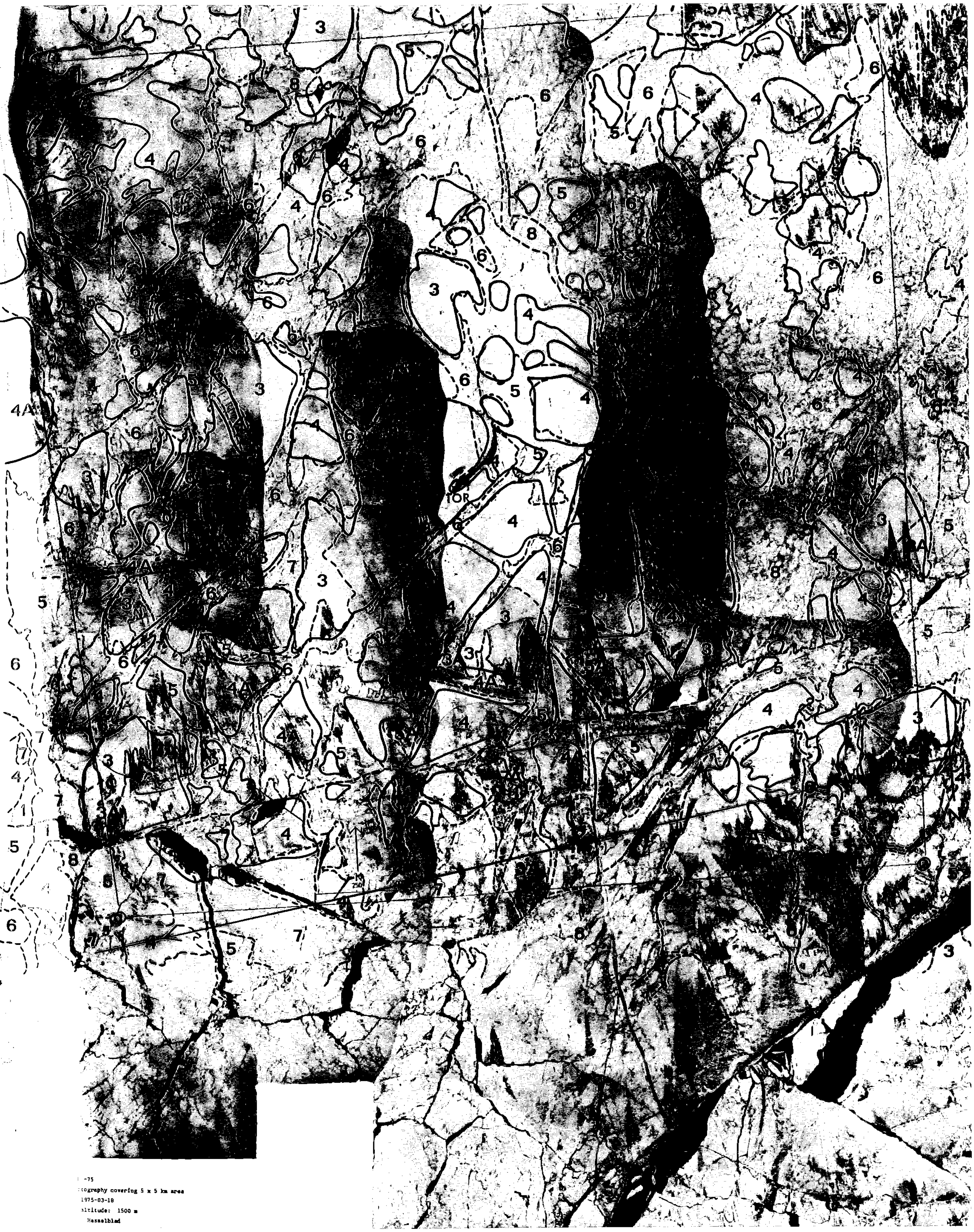


Figure 6. *Photomosaic of the 5×5 km area (Hasselblad pictures) from March 18.*
Overlay A — Ice categories.
Overlay B — SLAR categories.

A

Figure 6. *Photomosaic of the 5×5 km area (Hasselblad pictures) from March 18.*
Overlay A — Ice categories.
Overlay B — SLAR categories.

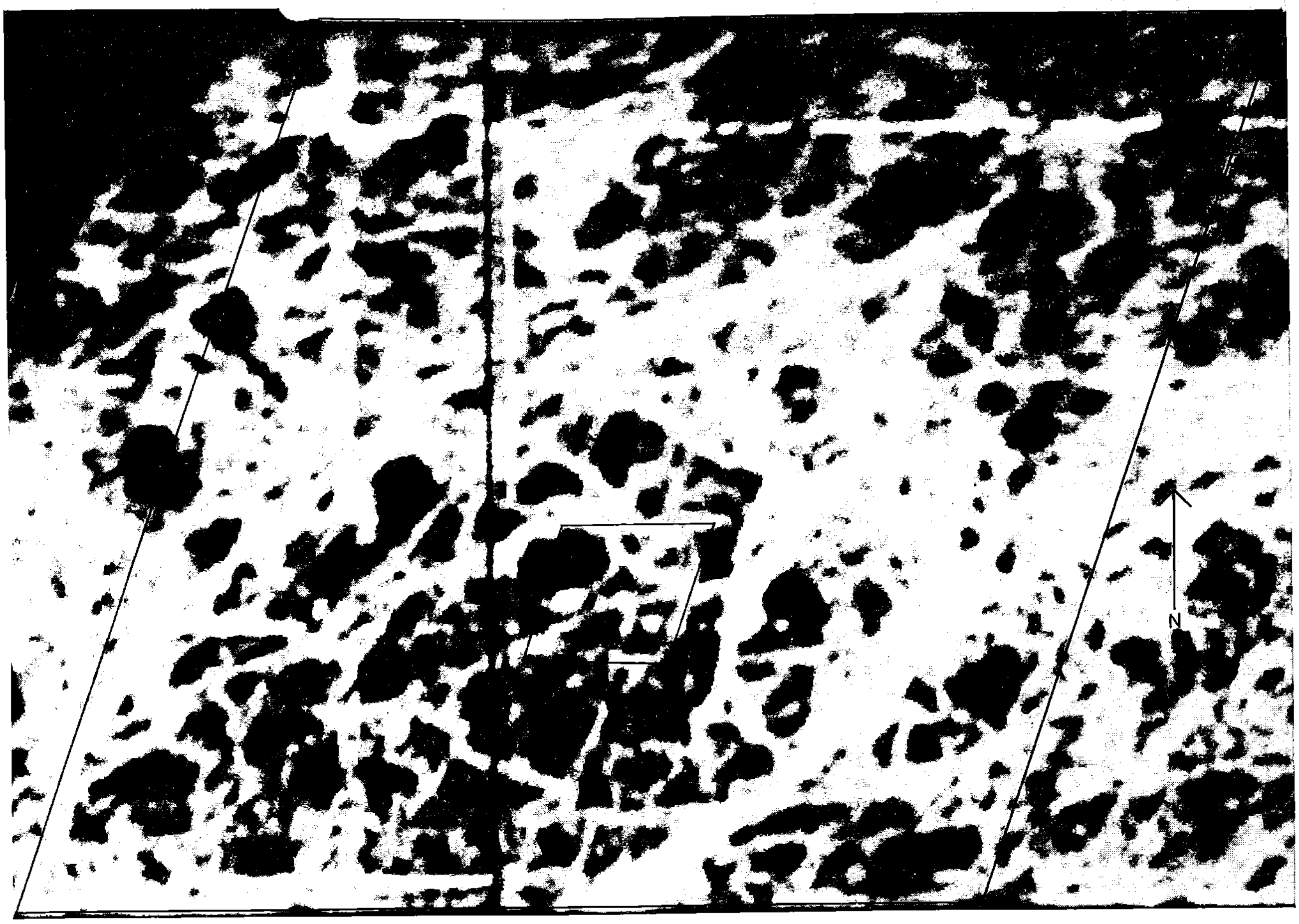


Figure 7. *SLAR image of the 5×5 km area from March 18.*

image from the same day (Fig 7), it becomes clear that it is not possible to distinguish all these categories. The SLAR images from the experiment gave only a very limited range of graytones and essentially exhibited black and white. In order to compare the SLAR images with the ice categories two very simple SLAR categories were defined, the first one showing black tones and the other one white. These categories are shown on overlay B to Fig 6. A comparison reveals that the first 4 ice categories, which are, open water, new ice, level ice and rafted ice fall within the SLAR category giving black tones. The remaining 4 ice categories, which include various stages of deformed ice fall within the second SLAR category giving essentially white tones. Further examination of the second SLAR category reveals ridges, leads with broken ice, ice/water edges, fractures, broken leads and areas with very rough ice. It is possible to distinguish individual ridges, leads and fractures. Also floes of level ice down to the size of 100 meters are detectable. It is not possible to distinguish open water from level ice from graytone alone except in areas with "sea clutter".

It is, however, possible to locate and discriminate open water areas on the basis of location, shape, size and sharpness of edges. There seem to be no detrimental effect of snow cover. The lack of graytone on the SLAR images from this experiment is attributed to improper gainsetting and choice of imaging angles. Other SLAR experiments have demonstrated a better graytone capability wherefore a final operational system would certainly provide better quality information.

Despite the not so good quality of the radar images presented here the utility of SLAR can still be appraised for navigational and forecast model purposes. Shipping routes can for example be selected through areas appearing black on the images, thus avoiding ridged and deformed areas, which are difficult to navigate through. For large scale mapping and ice forecast models the coverage and concentration as well as the roughness of the ice can be sufficiently well mapped by SLAR.

The results from the present SLAR studies (Ref 3 and 4) are consistent and in agreement with SLAR measurements made by USA and Canada in the Arctic, on the Great Lakes and on the St Lawrence river. In judging the utility of SLAR the all-weather, the day and night operational capability, the utility to provide repeated and timely coverage and the high mapping capacity should be kept in mind.

The results obtained during SEA ICE 75 together with the above considerations, indicate that SLAR has enough proven and demonstrated capabilities to be the primary sensor in a future sea ice surveillance and mapping system.

3.3 FLAR, ODAR and ship's radar

The FLAR (Forward Looking Airborne Radar) was tested at flight levels up to 1 800 m without observing any definite differences in mapping quality (Ref 5). Horizontal and vertical polarization was also tested but no significant differences could be established. An example of a FLAR registration is shown in Fig 8, recorded over the archipelago east of Luleå on March 11. East of a line Småskären—Brändöskär is a narrow lead. Shallow waters west of the lead are covered by high ice ridges visible as a bright line with high reflectivity outside and between Småskären and Brändöskär. Further westwards the ice between the islands is level and snow covered with low reflectivity, i. e. black on the picture. The lead is not covered by new ice as can be seen from the sea clutter present on the PPI.

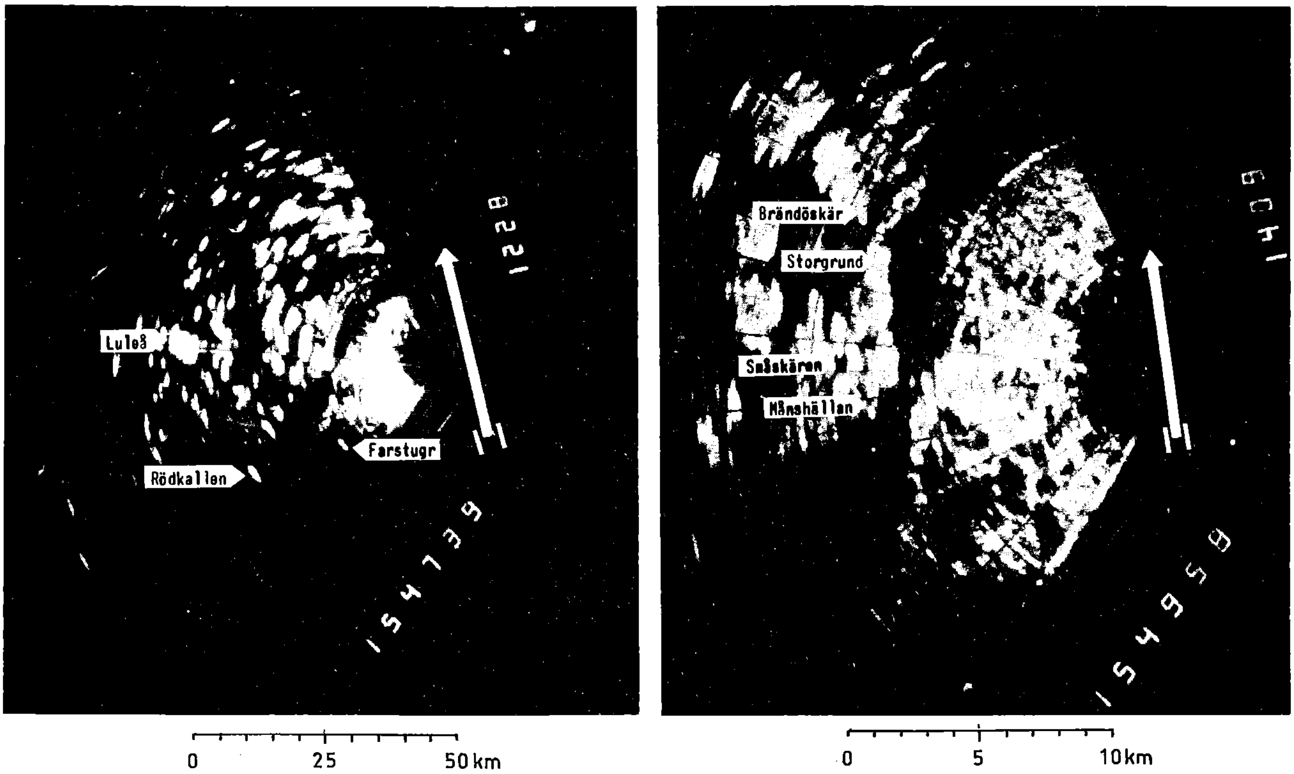


Figure 8. *Example of FLAR image from March 11.*

The major differences between FLAR and SLAR concern the type of presentation, the resolution and the time of integration. One advantage of the FLAR is the real time presentation and the possibility of mapping at different scales, which makes it possible for an operator to have an overall view of the ice situation and then select and map in greater detail areas of special interest. The same features can be achieved by a SLAR, though it is more complicated and thus more expensive. The main advantage of the SLAR is its considerably higher resolution which makes the SLAR more suited for detailed mapping. Another advantage is that the SLAR in contrast to FLAR gives an image which is comparable to an ordinary map.

The ODAR (Omni Directional Airborne Radar) was also tested at different altitudes (Ref 5). At low altitudes a relatively detailed PPI-image was obtained, on which several ice characteristics should be recognized. With increasing altitude the large scale structure of the ice appeared. At an altitude of 1 500 m, the ODAR could overview the total Bay of Bothnia and give a rough indication of the ice extension. In Fig. 9, which is a combination of two PPI-images taken at an altitude of 600 m, heavily ridged areas are seen east of Malören. A lead south of this area and a system of leads west and southwest of Karlö are also clearly visible as well as the open water in the western part of the Bay of Bothnia.

The ship's radar had a much better resolution than the FLAR and ODAR. It gave a detailed map of some of the ice parameters close to the

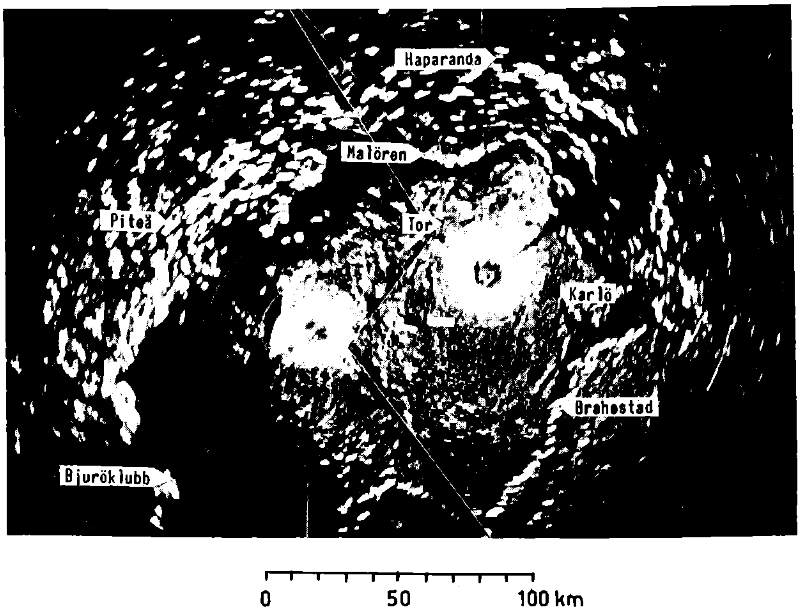


Figure 9. *Example of ODAR image from March 20.*

Figure 10. *Example of ship's radar image March 17.*

0 = TOR with snowfree ice area, 1 = the track of TOR, 2 = level ice, 3 = ridges h 40 cm, 4 = ridges h 100—160 cm, 5 = old frozen track from ship.

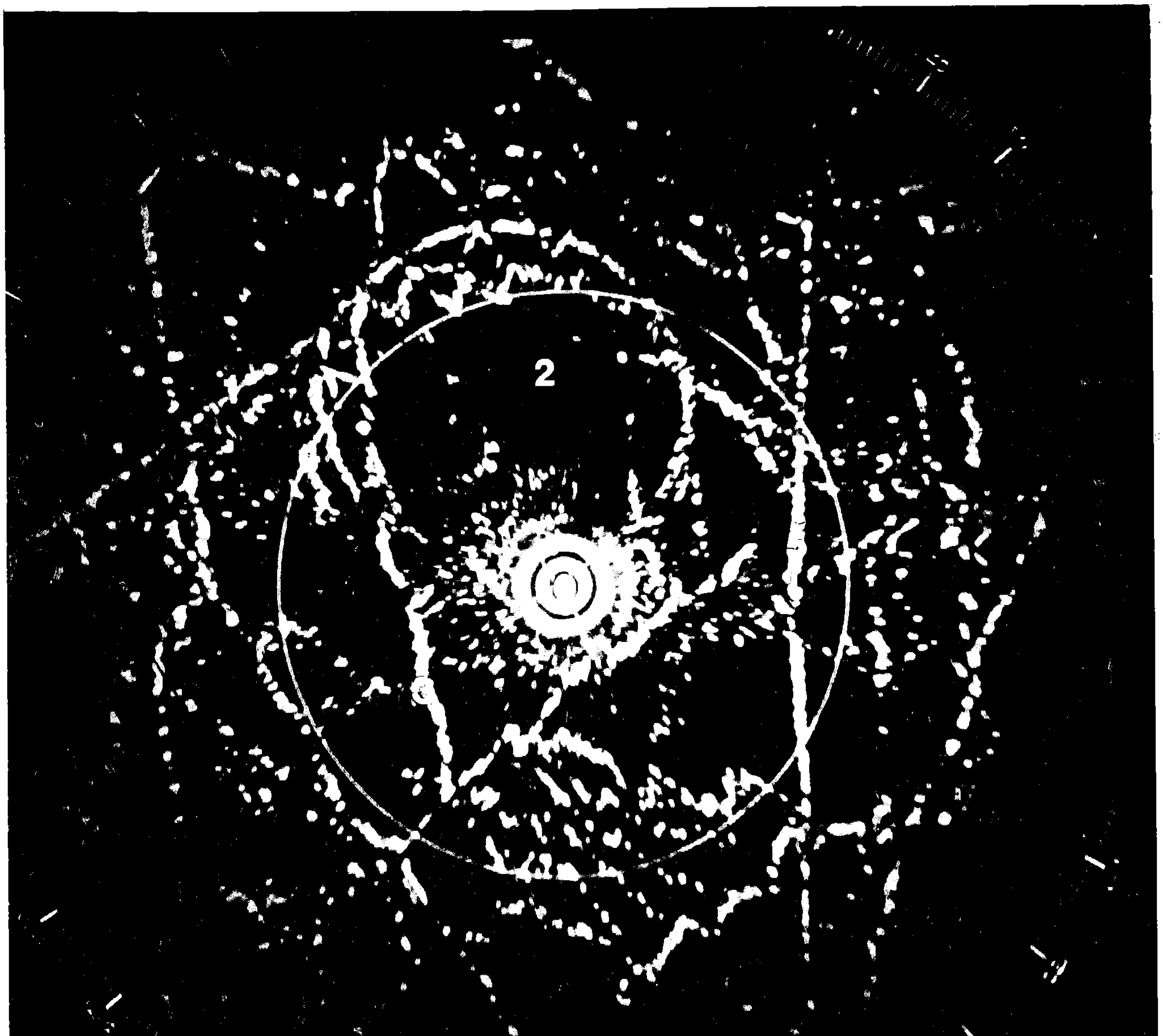
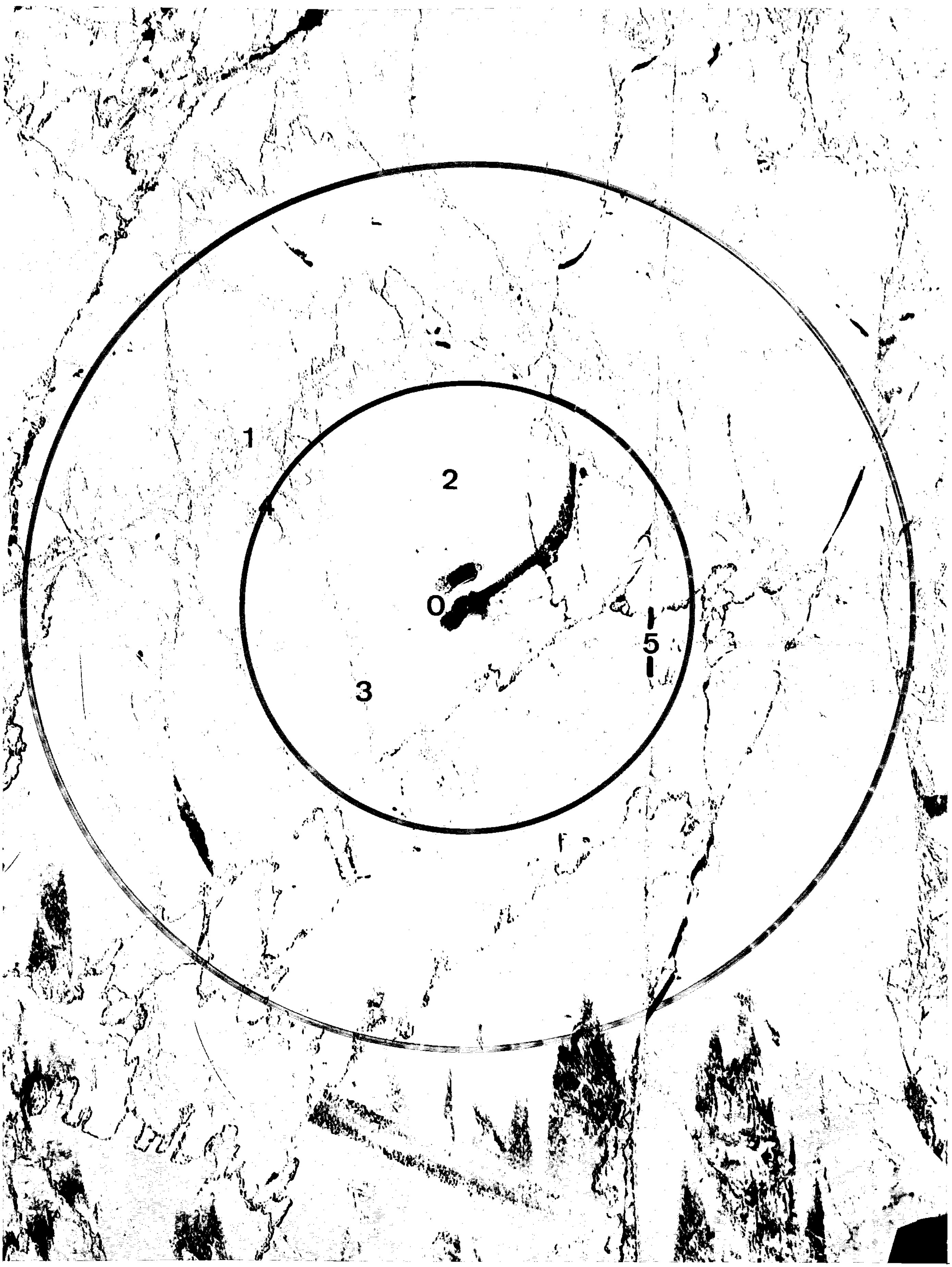


Figure 11. *Airphoto (Wild) corresponding to ship radar image (Scale 1:10 000).*

ship, i. e. within a radius of 3 km (Ref 5). Heavy ridges could be detected up to a distance of 5 km from the ship. An example of a ship's radar image is given in Fig 10. A comparison with the corresponding high altitude photo in Fig 11 shows that several ice characteristics can easily be recognized in both pictures.



3.4 Radar altimeter

A helicopter born radar altimeter operating at 5 GHz was tested (Ref 6). The most useful results were obtained over the 1×1 km area and over an area with high ice ridges. Due to the wide antenna beam of the equipment, a very low altitude had to be used (4—10 m). The output signals were recorded on tape. The signal processing of the recorded data was carried out in laboratory after the experiment.

Tests showed that the radar altimeter could differentiate between ice and open water. However, thin layers of water on the ice gave the same signal as open water. Tests over rough and smooth water surfaces, and over level and rough ice showed that the signal is highly influenced by the height of the surface roughness. An example of a radar altimeter registration is given in Fig 12.

The usefulness of the radar altimeter for ice ridge detection was clearly demonstrated at flights over areas with high ice ridges. Very abrupt increases of the signal were obtained at every ridge passage. Moreover, the tests indicated that the radar altimeter might be used for estimation of the height of ice ridges.

No clear information was obtained during the experiment, however, whether the radar altimeter could be used for ice thickness measurements.

It should be stressed that the radar altimeter used at this experiment was of standard type and not specifically adapted to the operational requirements of sea ice monitoring. A future ice sensor should probably be rather different. It should for instance include a real-time facility and a larger antenna permitting operation from altitudes of at least 30 m.

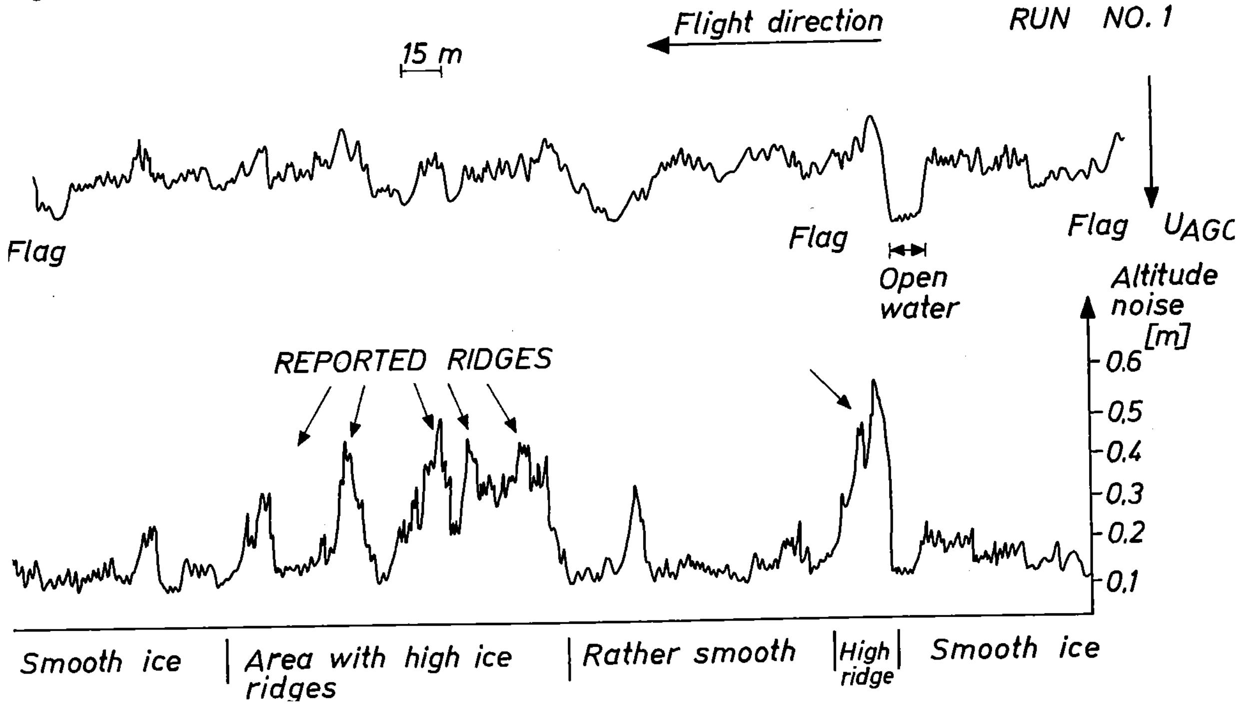


Figure 12. *Radar altimeter registration.*

3.5 Microwave radiometer

A microwave radiometer with two frequencies 0.6 GHz and 4.7 GHz was tested (Ref 7). The possibility of using microwaves for measuring ice thickness depends on the frequency used, the ice temperature and the salinity of the ice.

The results show that the low frequency radiometer is a possible means for determining ice thickness provided the salinity of the ice is very low. The high frequency radiometer on the other hand has a much better resolution but it requires surface temperatures below —10°C if ice thicker than about 40 cm is to be measured. This is due to the great attenuation of radio waves in ice at high frequencies.

Recent measurements (I Udin, private communication, 1976) have indicated that the salinity of the ice in the Bay and Sea of Bothnia, at least occasionally, can be much higher than earlier expected. This leads to the conclusion that it might be even more difficult to measure ice thickness in these waters.

Because of the differences in resolution the 0.6 GHz radiometer reproduced large ice ridges as areas of very thick ice, whereas the 4.7 GHz radiometers indicated only the centres of the ridges.

3.6 IR-scanner

The use of infrared thermography was tested by means of an airborne infrared line scanner. The thermal radiation from the ice surface was recorded in the 8—14 μm region simultaneosly on photographic film and magnetic tape. The measurements were concentrated to the 5×5 km test area. An example of an IR-scanner image is shown in Fig 13. It has been possible to compare most of the results with available ground truth data and aerial photographs. A more detailed analysis of some interesting objects has been accomplished by processing the information recorded on tape (Ref 8).

Thermal infrared sensing can be used to distinguish ice from open water and new thin ice from old thick ice. There is also a significant thermal difference between snow-covered ice and bare ice, at least when the snow is dry. As no verified area with water on the ice was present, this case was not studied.

Thin new ice and open water are both in the warmest parts of the thermal imagery, but it has been shown that these types can be distinguished, at least under the conditions of SEA ICE 75.

The difference in radiance temperature between snowcovered and non-snowcovered ice might reduce the possibility of mapping ice deformation, though some characteristic ice features were localized.

It is not possible to make absolute measurements of ice thickness by the IR-scanner, but the variations in radiance may give a rough indication of relative ice thickness.

The area coverage of the IR-scanner depends on the scanning angle. At an altitude of 5000 m, a maximum coverage of 17.5 km is obtained with a resolution of better than 10 m.

Infrared thermography is independent of light conditions but very sensitive to fog, clouds and any type of precipitation, which often confines the maximum useable flight altitudes and thus reduces the mapping capacity.

3.7 Satellite information

Different types of satellite information were available:

- ☐ the weather satellite NOAA-4 with a scanning radiometer (SR) and a very high resolution radiometer (VHRR) and
- ☐ the earth resources satellite LANDSAT-2 providing information from four spectral channels (MSS) in the visual part of the electromagnetic spectrum.

SR data can be received in Sweden. The resolution is however bad and variable. SR images give only a very rough view of the ice extension in the Baltic area.

VHRR data require a more advanced receiving station, which is not available in Sweden. The resolution is 0.9 km, or about 5 or 8 times better than for the SR. It is possible to distinguish some ice parameters using VHRR pictures.

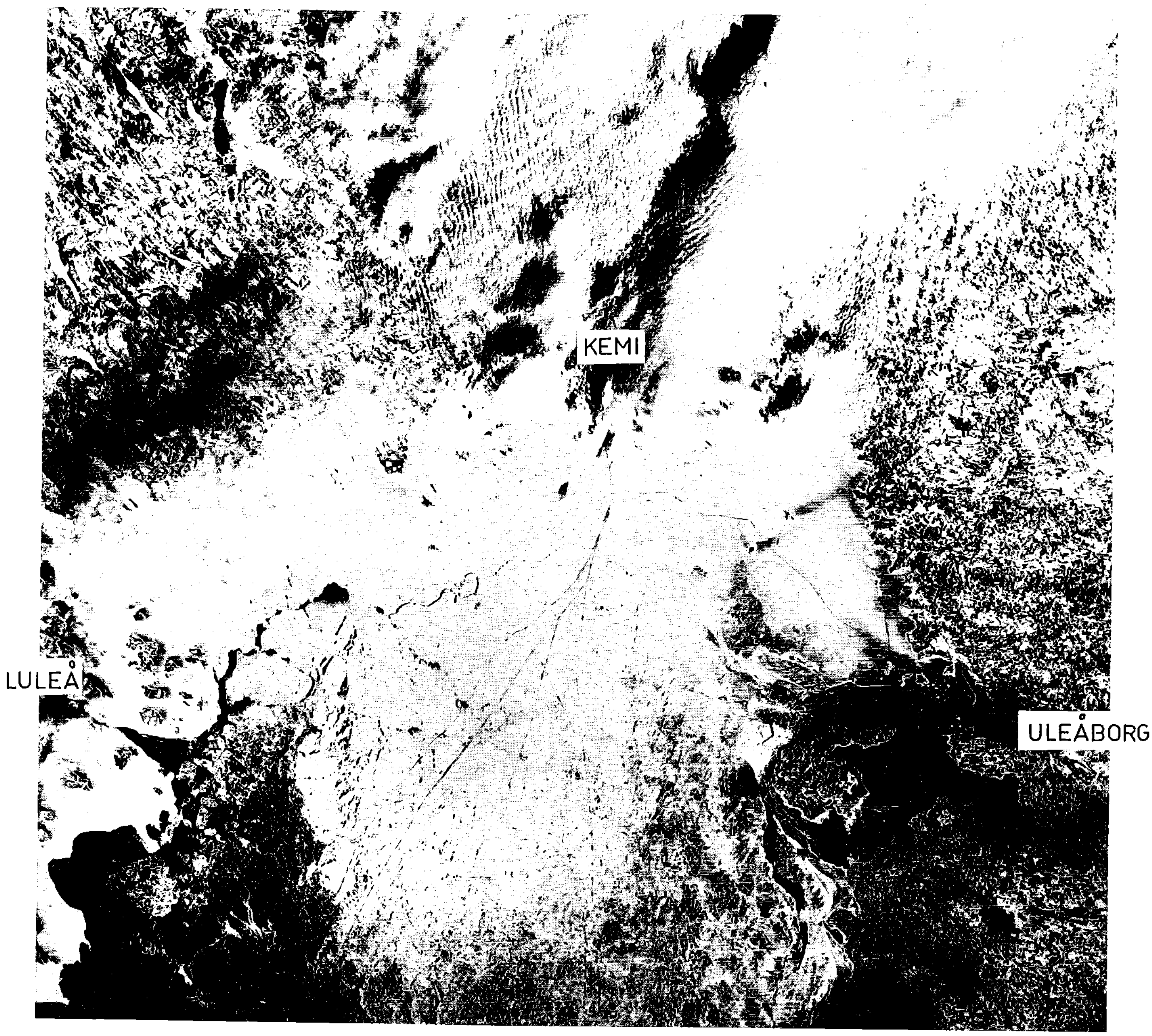
The information from LANDSAT-2 is of very good quality. The resolution is about 80 m which makes it possible to identify different ice parameters, such as large ice floes and leads. The areal coverage is good enabling large-scale mapping for e.g. ice forecasting (Fig 14).

There are however, severe restrictions in the availability of the LANDSAT information. It is obtainable only 2—3 times every 18th day and only on request from NASA. The information is recorded on magnetic tape on board the satellite and tapped when passing a receiving station.

One further drawback of the satellites NOAA-4 and LANDSAT-2 is the weather dependence and, as concerns the visual part, also the light dependence.

Figure 13. *IR image from March 19.*

Figure 14. *LANDSAT image from the near IR spectral band, March 15.*



4. Studied Ice Parameters

4.1 Ice concentration

Information on ice concentration is important for navigation and as an input parameter to ice forecast models.

The ice concentration within the test areas was close to 100 per cent during most of the period except for the western part of the 15×15 km area where fractures and leads opened during the last 4 days of the experimental period.

The radar registrations did not permit differentiation of level ice from open water on the basis of intensity or grey tone alone. Larger areas with open water are, however, easily identified when the wind creates waves giving "sea clutter". In fractures and narrow leads sea clutter rarely occur and they will therefore appear as level ice. Fractures and leads may however be identified on the basis of size, location and shape but it is not possible to decide whether they contain open water or are covered with thin new ice. The radar registrations clearly distinguish between deformed ice and level ice/open water. It is therefore possible to map the concentration of deformed ice but not the concentration of the total ice cover.

The IR-scanner showed clear distinction between thick ice (bare or snowcovered) and thin new ice/open water. With appropriate processing also thin new ice can be differentiated from open water. The ice concentration can therefore be obtained from IR-scanner registrations with a high degree of accuracy.

The radar altimeter registrations showd a clear distinction between ice and open water. But as the instrument is nonscanning, information is only obtained along the flight track and the ice concentration is therefore not easily obtained.

The passive microwave radiometer should theoretically have the same advantages and disadvantages as the radar altimeter, but the report from the experiment gives no direct example of the capability of the instrument to differentiate between ice and open water.

The satellite information is of 3 different categories,

- The SR images from NOAA-4 with a resolution of 7.5 km do not permit any detailed ice concentration evaluations.
- The VHRR images (NOAA-4) can give some information on the ice concentration in areas with larger fractures and leads, but it is not possible to differentiate between bare level ice and open water.
- The MSS data (Lantsat-2) give the best information on ice concentration. By multispectral technique, it may in some cases also be possible to distinguish new ice from open water. A major disadvantage with the Landsat is that it only gives information every 18th day. A further disadvantage with all the present satellite systems is the sensitivity to fog and cloud cover.

4.2 Ice roughness

The ice roughness, which is an important ice parameter both for immediate navigation purposes and as input to ice forecast models, is roughly divided into two categories.

- Rafting where the ice has a limited vertical extent (2—4 times the thickness of the level ice) but often a wide horizontal distribution and
- Ridges which have a distinct vertical extension, 0.5—3 m above the sea surface, but mostly a limited, linear extension in the horizontal. Information on the vertical dimensions as well as the areal coverage (concentration) is required in an ice mapping system.

The radar sensors all gave a reasonable good information as to the areal coverage of the ridges but less information on the rafting. The best system seemed to be the SLAR where also certain rafted areas appeared.

None of the radar systems gave any reliable information on the vertical dimensions of the deformed ice. It was also difficult to distinguish between ridges and broken ice in leads and fractures. This could only be done by careful analysis of the images based on history, shape and relative location.

The IR-scanner gave some indications as to the areal distribution of deformed ice. The radiance temperature of the ridges differed from the surrounding level ice. This differences will depend on the weather and the temperature history. It is therefore difficult, from this experiment, to assign an unambiguous signature code for ice ridges on IR-scanner images.

The radar altimeter gave a clear indication of its capability to map ice roughness and from the registrations it seems possible to obtain information on the vertical dimensions as well as the areal coverage of the deformed ice along the flight path.

The passive microwave radiometer also gave certain indications of its capabilities for ice roughness mapping. Further tests are however required before firm conclusions can be drawn.

The satellite images give no conclusive information about the ice roughness, but it is likely that some information may be derived through processing of digital MSS data from LANDSAT.

4.3 State of ice surface

The state of the ice surface is of interest both for navigation and for ice forecasting.

The radar sensors gave no or very little information on state of the ice surface. **The IR-scanner** could distinguish snow covered ice from bare ice. Water on the ice would appear as open water. **The radar altimeter** and **the passive microwave radiometer** gave no information on the state of the ice surface. **The satellite images** gave some coarse information on snow cover.

4.4 Ice thickness

The ice thickness is an important parameter in the ice model, where it is used together with the roughness parameter to calculate the ice mass. Also for navigation it is useful to know whether the ice is thin or thick, although it is not basically the thickness of the level ice that is decisive for the navigability, but the degree and extension of deformation (i.e. the ice roughness).

The radar systems have not proved any capability to measure ice thickness. The **IR-scanner** may give rough information on the relative thickness of the bare level ice.

The passive microwave radiometer. The tests indicated that the thickness of level ice could be determined up to a thickness of about 40 cm. Thicker ice could not be measured by this specific radiometer. Neither could the thickness of ice ridges be determined. In view of the relatively large influence of salinity and temperature it seems to be principally difficult to obtain any accurate values of ice thickness.

The satellite data gave no information on ice thickness.

4.5 Ice dynamics

Information on the ice dynamics is of importance for the navigation in ice, since it defines areas with ice pressure which are difficult or even dangerous to penetrate as well as areas in which fractures and leads are forming and consequently are easy to penetrate. Remote sensing measurements can only give information on the past or close to present situation while it is the present and future situation that is of interest for navigation. This information can only be obtained from forecast models using the present ice parameters and weather forecasts as input.

The radar system, the IR-scanner and some of the satellite data may give rough indications on the ice dynamics provided that fixed geographical locations as well as easily identifiable points on the ice are present in successive registrations of the same area.

5. Discussion and Conclusions

None of the tested sensors alone gave satisfactory mapping of all the ice parameters required. The FLAR and ODAR gave a general view of the ice fields, identifying major ice/water boundaries as well as major areas of deformed ice. The SLAR gave much more details about the deformed ice fields and also identified more leads and fractures. Though it was not possible by any of the radars to distinguish open water from level ice directly from the graytones in the images, it appeared that open water areas could be located indirectly in SLAR pictures on the basis of location, shape, size and sharpness of edges. All the radar systems had a good areal coverage.

The IR-scanner differentiated between ice and open water and gave a rough indication about the relative thickness. Deformed ice was detectable but not in an unambiguous way.

The radar altimeter and the passive microwave radiometer also distinguished level ice from open water and, in particular, the radar altimeter gave good information about the ice surface roughness. Both the vertical dimension and the horizontal extent was clearly mapped but only along the line of the flight path. The microwave radiometer also gave information about the relative ice thickness.

The experiment clearly demonstrated that a future ice mapping system will have to include a combination of sensors if all the required ice parameters are to be mapped. The choice of sensors and carriers will depend on the actual requirements and the general layout of the total ice mapping and ice surveillance system. The two major requirements are:

1. To provide the ice-breaker units with real-time information on the ice situation within say 20—50 km ahead of the ice-breaker. This is required in order to find the immediate safest and most economic route through the ice.
2. To provide an overall picture of the ice situation in the whole Baltic area. This is required for the preparation of reliable ice maps and ice forecasts, which are needed by the Ice-breaking Service when planning the operations of ships and ice-breakers for the next days.

The observation system (sensors and carriers) is only one link in the total ice mapping and ice surveillance system. The total system will include besides the observation system, transmission of remotely sensed data to a processing centre and to ice-breakers, data processing, presentation (including production of ice maps and ice forecasts) and transmission of ice maps and ice forecasts to the Ice-breaking Service, ice-breakers and shipping. A general view of the flow of information in a future ice service system is outlined in Fig 15.

As the final choice of sensors and carriers in an operational ice surveillance system will depend on the configuration of the total system it is of utmost importance that an overall system definition study is initiated as a matter of urgency. SEA ICE 75 has provided the first necessary information as to which sensors might be included in the system. In parallel with such a system definition study further tests should be carried out, especially measurements of radar signatures of different types of ice at varying frequencies, polarization and imaging angles. Recommendations on such measurements are given in Ref 4. Tests should also be made with IR-scanner, radar altimeter and scanning microwave radiometer.

For the short range operations of ice-breakers, the ship's radar is an obvious component. In addition the helicopters stationed on board the ice-breakers could profitably be equipped with suitable remote sensors. The choice of the sensors will depend on the capability of the long range system to provide detailed real-time information to the ice-breakers.

The long range system will basically require an all-weather sensor, or

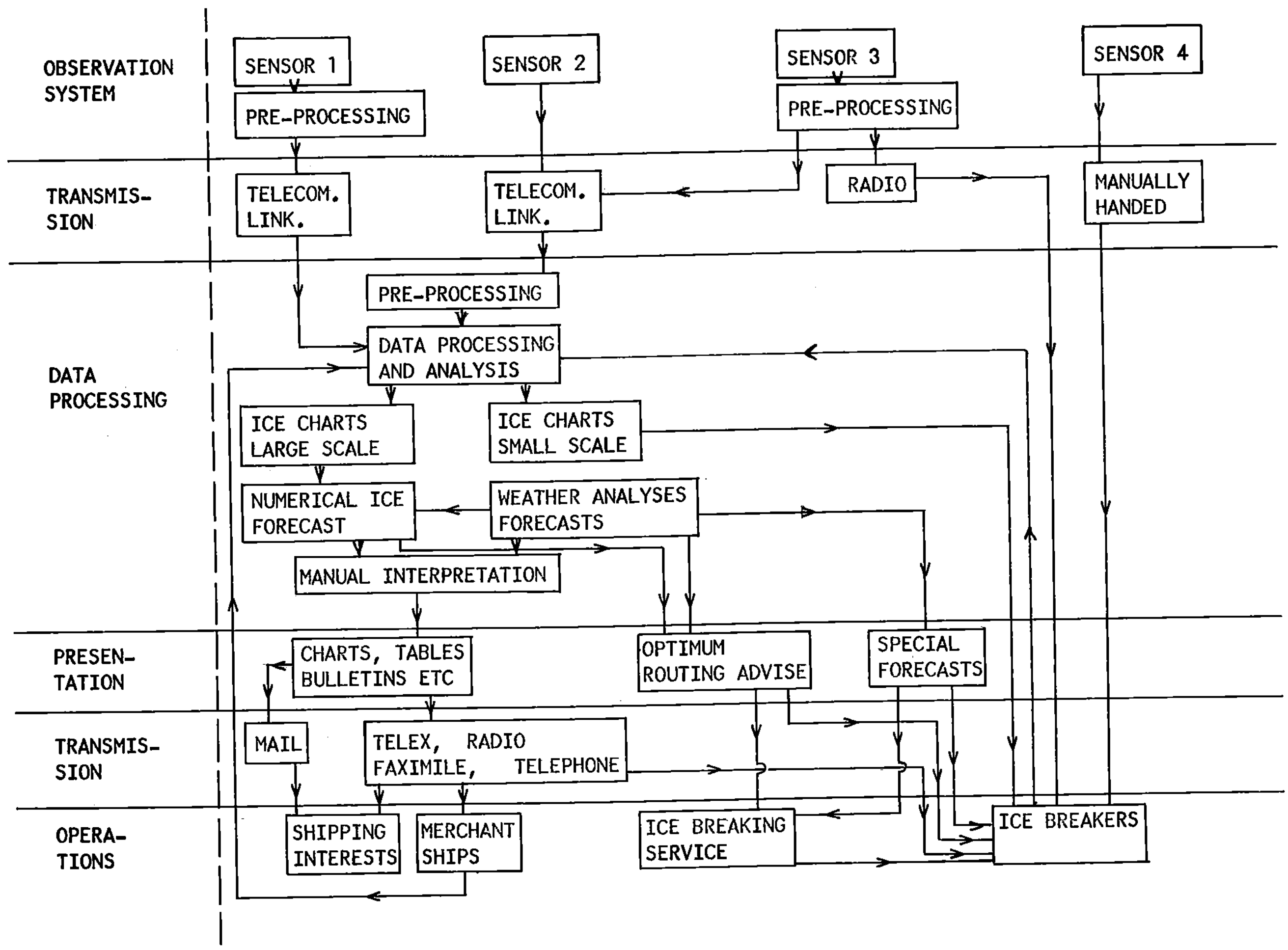


Figure 15. *General flow of information in a modern ice service system.*

combination of sensors, capable of mapping, with good spatial resolution, major parts of the Baltic area within a period of some hours.

The results from SEA ICE 75 indicate that SLAR could profitably be the main sensor in such a system. The SLAR might be supplemented by other sensors such as an IR-scanner.

American and Canadian experience also strongly support that SLAR should be the main sensor in a future long-distance ice reconnaissance system (Ref 11—13). In a recent report on the Canadian airborne ice reconnaissance programme (Ref 14) it is thus stated that:

"an all weather collection capability is of significant strategic, as well as economic, importance to shipping and would greatly reduce the amount of unproductive reconnaissance, estimated as high as 30 %, currently flown over cloud covered ice. Considerable effort in investigating the sensor market for a solution to this problem has, therefore, been undertaken. Side Looking Airborne Radar (SLAR) equipped with real time capability appears to provide the only realistic answer. These systems, having wide area coverage, high resolution and unique imaging characteristics, are effective under almost all weather and visibility conditions".

In another Canadian report (Ref 15) the following evaluation of the economic benefits of including a SLAR into a total ice service system has been made:

"The use of an airborne microwave imaging sensor (eg SLAR) would yield an estimated average saving of about 6 hours for each ship moving through the Gulf of St Lawrence in winter." "It is estimated that there will be 3000 ship movements recorded in the Gulf of St Lawrence in the 1973—74 winter season. The average ship charter rate is estimated to be $ 8000 per day." "At an average ship charter rate of $ 8000 per ship-day, a 6 hour average saving of time per movement attributed to SLAR would have an average annual gross benefit of $ 6 million."

6. Recommendations

- ☐ The exact parameters of an operational ice surveillance system cannot be determined merely from the results of SEA ICE 75. A thorough overall system definition study is needed before an operational ice surveillance system can be finally decided upon. It is therefore strongly recommended that an overall system definition study is undertaken without unnecessary delay in order that required technical studies and developments can be started as soon as possible.
- ☐ The results from SEA ICE 75 as well as analyses and tests carried out in USA and Canada clearly indicate that SLAR should be the main sensor in a Swedish ice surveillance system. It is therefore recommended that a technical study is undertaken immediately to establish if a real aperture SLAR for ice mapping purposes can be purchased from abroad or must be developed in Sweden. If development in Sweden turns out to be the only realistic alternative it is strongly recommended that the development is started as soon as possible and carried out in parallel with the above recommended system definition study.
- ☐ SEA ICE 75 was carried out under one set of environmental conditions and with available standard instruments. All desired tests and intercomparisons could therefore not be carried out. The project itself gave rise to questions requiring further tests. It is consequently recommended that further field experiments are carried out during the forthcoming seasons in parallel with the above recommended system definition study.

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List of sensors and carriers, SEA ICE 75

Sensor	Carrier	Altitude	Type of registration	Frequency	Responsible for experiment	Responsible for evaluation
Optical and IR sensors						
SR[1]	NOAA-4	1 400 km	Tape	0,5-0,7 µm	-	SMHI
"	"	"	"	10,5-12,5 µm	-	"
VHRR[2]	"	"	"	0,6-0,7 µm	-	"
"	"	"	"	10,5-12,5 µm	-	"
MSS[3]	Landsat-2	900 km	"	0,5-1,1 µm	NASA	"
High altitude camera	Draken	9-12 km	Film	0,4-0,7 µm	F21	"
Measuring camera	Aero Commander	4 600 km	"	0,4-0,7 µm	Land Survey	"
Multispectral camera	"	1 500 m	"	0,35-0,8 µm	"	"
IR-scanner	DC-3	300-2 000 m	Tape and film	8-14 µm	FOA	FOA
IR-radiometer	Jet Ranger	20-100 m	Tape	8-14 µm	Radio Laboratory Helsinki	Radio Laboratory Helsinki
Microwave sensors						
SLAR[4]	Queen Air	150-6 000 m	Film	X-band (9,6GHz)	Rijkswaterstaat	Rijkswaterstaat
FLAR[5]	Pembroke	150-1 800 m	PPI	X-band (9 GHz)	FOA	FOA
ODAR[6]	Vertol	30-1 700 m	"	X-band (9 GHz)	"	"
Ship's radar	Ice-breaker TOR	20 m	"	X-band (9,4GHz) S-band (3,0GHz)	Ice-breaker TOR	Ice-breaker TOR
Radar altimeter	Lama	2-30 m	Tape	C-band (5 GHz)	Saab-Scania	Saab-Scania
Microwave radiometer	Jet Ranger	20-100 m	"	C-band (5 GHz) L-band (0,6GHz)	Radio Laboratory Helsinki	Radio Laboratory Helsinki
Under water sensors						
Sonar	-	-		-	University of Helsinki	University of Helsinki
Under water camera	-	-	Film	-	Ice-breaker TOR	Ice Breaker TOR

1) SR = Scanning Radiometer
2) VHRR = Very High Resolution Radiometer
3) MSS = Multi Spectral Scanner
4) SLAR = Side Looking Airborne Radar
5) FLAR = Forward Looking Airborne Radar
6) ODAR = Omni Directional Airborne Radar

Summary of registrations. SEA ICE 75.

	10/3	11/3	12/3 Day 0	13/3 Day 1	14/3 Day 2	15/3	16/3	17/3	18/3 Day 3	19/3 Day 4	20/3	21/3
SR (NOAA 4)	X	X	X	X	X	X	X	X	X	X	X	X
VHRR (NOAA 4)	X	X	X	X	X	X	X	X	X	X	X	X
MSS (Landsat 2)					X	X	X					
High altitude camera	X		X					X				
Wild camera					X			X				
MS-camera				X					X			
IR-Scanner										X		
IR-radiometer										X	X	
SLAR			(X)	X	X				X	X		
FLAR		(X)	(X)	X	X			(X)	X	X		X
ODAR									X	X	X	
Ship's radar		X	X			X	X	X		X		
Radar altimeter		(X)			X	X	X					
Microwave radiometer								(X)	X	X	X	
Under water camera	X			X	X		X	X	X		X	
Under water TV	X					X					X	
Sonar							X	X	X			
Meteorological parameters	X	X	X	X	X	X	X	X	X	X	X	X
Oceanographic parameters	X	X	X	X	X	X	X	X	X	X	X	X
Ice parameters	X	X	X	X	X	X	X	X	X	X	X	

(X) indicates preliminary tests
X indicates successful registrations

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