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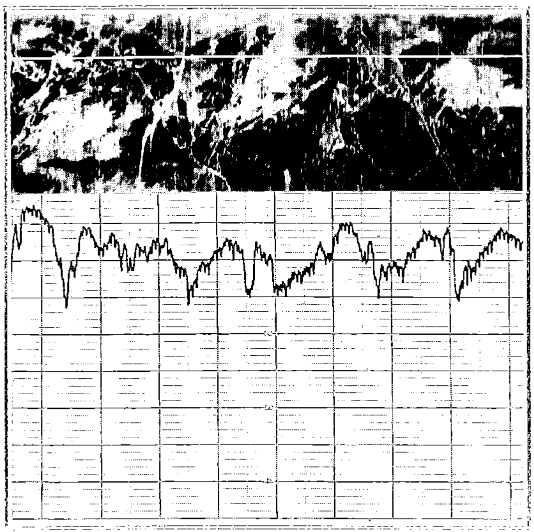

IR-scanner results

by Erik Fagerlund and
Gunnar Lundholm
Stockholm 1976

WINTER NAVIGATION RESEARCH BOARD
Swedish Administration of Shipping and Navigation, Finnish Board of Navigation
Research Report No 16:6

Cover picture:
The icebreaker TOR in the middle of the test area for SEA ICE —75 and an example of a thermal image with a radiation profile along the indicated line.

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SEA ICE 75
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Foreword

The Winter Navigation Research Board presents report No. 16:6. This report describes the test flights made with the infrared airborne linescanner TEKLA and summarizes the results. The instrument has been developed by the Swedish National Defence Institute and was flown in a DC-3 aircraft belonging to the Swedish Airforce.

The Winter Navigation Research Board hereby convey its sincere thanks to the authors of this report, to the National Defence Research Institute and the Airforce for their valuable contribution to the remote sensing experiment SEA ICE-75.

Norrköping and Helsinki, July 1976.

Lennart Johansson **Helge Jääsalo**

Abstract

During a field experiment over an ice covered area of the Gulf of Bothnia in March 1975, several different types of remote sensing equipments were tested. The purpose was to investigate the capabilities of different methods for ice reconnaissance, surveillance and forecasting. This report deals exclusively with infrared thermography performed with the airborne single line scanner TEKLA in the 8—14 μm region.

The thermal recordings were concentrated to a 5x5 km² test area, which was described in great detail by ground truth measurements and photography. During 14 runs at 300—2000 m flight altitude, the thermal radiation from the sea surface was recorded on photographic film and magnetic tape. The film recordings give a general survey of the apparent temperature variations within various parts of the mapped area. By processing the tape recorded information, a more detailed analysis of some interesting objects has been accomplished. The results have been compared with the available ground truth and aerial photographs.

In the thermal imagery the ice cover is reproduced in great detail. Contrary to the visual image, even new ice can readily be delineated from open water. The radiance variations are useful for a coarse mapping of relative ice thickness but unreliable for absolute thickness measurements. The isolating effect of snow results in a thermal difference between snow-covered ice and bare ice. Charactristic features, such as raftings, ridges and cracks, can be localized. Temperature profiles generated from the tape recordings may facilitate measurements of the relative radiance along interesting traces.

Infrared thermography is independent of illumination but is hampered by clouds and heavy fog. The area coverage for commercially available scanners is between 2 and 3.5 times the flight altitude. For ice surveillance an altitude of 2—5 km will be sufficient to resolve details of the order of 5—10 m with a high thermal resolution.

1. Introduction

Large parts of the Gulf of Bothnia are covered with sea ice during several months of the year. The ice is a great impediment to navigation, and there is a vital need for accurate information on the ice situation.

In order to investigate the possibilities of ice reconnaissance and forecasting by means of modern remote sensing techniques, a field experiment was carried out in the Gulf of Bothnia in March 1975 (Project "SEA ICE 75"). Several institutions, authorities and others from Sweden, Finland and the Netherlands took part in the experiment. The Swedish Space Corporation was responsible for the coordination of the programme.

Many different types of sensors were tested and evaluated in the experiment. This report deals exclusively with one of the sensors — an infrared line scanner — and the results that were obtained with this equipment. Separate reports on the other sensors and on the common conditions (test area, weather, ground truth, etc.) as well as a summary report on the whole project will also be published. Regarding the general background, purpose and organization of the experiment, we refer to the test programme (Blomquist et al., 1975) and the summary report.

2. Instrumentation

Thermal mapping by means of an airborne infrared line scanning radiometer has turned out to be very useful in many applications to sea surveying. The infrared system used in this experiment was a single line scanner (TEKLA) developed by the Swedish National Defence Research Institute (FOA). It was mounted in a Swedish Air Force DC-3 aircraft.

The scanning principle and the scanner are shown in figure 1 and 2. The sensor scans through an angle of 90° across the line of flight at a rate of 100 scans per second. The ground coverage will then be about twice the flight altitude.

Figure 1. *Airborne line scanning.*

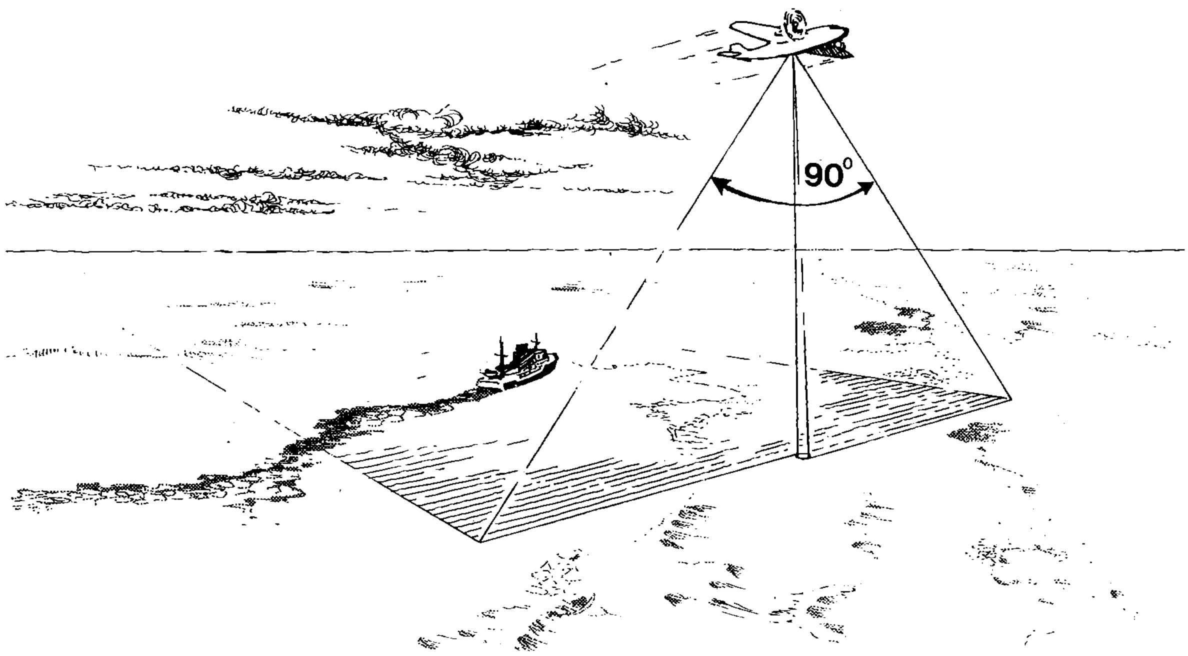
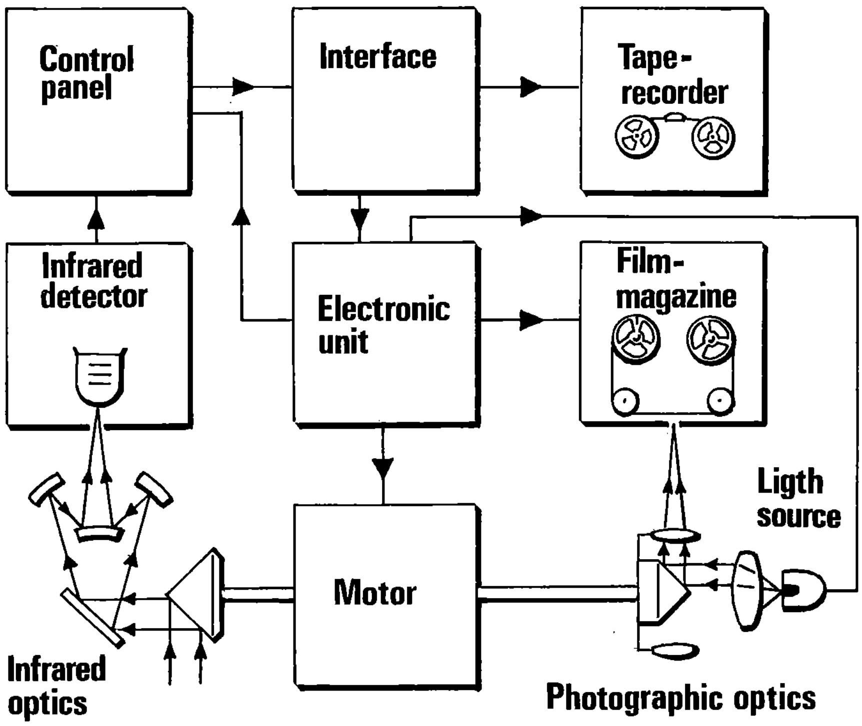


Figure 2. *Infrared line scanner system TEKLA.*



Two types of detectors sensitive to the 8—14 μm region (mercurydoped germanium and CMT) were used alternatively during the experiment. The spatial resolution was between 2 and 10 mrad (se table 1).

The output signal from the detector is recorded both on magnetic tape and — by means of a glow modulator — onto a photographic film. The information can be displayed as a thermal image, when the film has been developed, or in many other ways after signal processing of the magnetic recording (Lundholm, 1973).

The linear range of the photographic recordings is less than that of the magnetic tape. At the maximum thermal resolution, which is better than 0.1 K, the radiation range that is well covered by the photographic film will sometimes be insufficient. As a consequence of the non-linearity of the characteristic curve of the film, it is difficult to make accurate radiation measurements on the film. The magnetic tape recordings have a great radiation range with good linearity and offer good possibilities to analyze the information in detail.

3. Test Area and Flight Programme

The test area was situated in the northernmost part of the Gulf of Bothnia about 60 km south of Haparanda. Within an area of 15x15 km^2 a ground thruth work was performed at three different levels covering the whole 15x15 km^2 area, a 5x5 km^2 area and a 1x1 km^2 area, respectively. In the center of the test area close to the 1x1 km^2 area, the ice-breaker TOR was stationed (figure 3). TOR served as a base for the project managing group and the ground truth work.

Within the 5x5 km^2 area, which was the main area for the infrared line scanner, the ground truth measurements were made with high accuracy. Within the 1x1 km^2 area the measurements were still more detailed. Meteorological parameters were regularly observed from the ice-breaker.

During the test period (13—21 March, 1975) the area was mapped by different sensors according to individual availability and prospects. The thermal mapping was done during two missions on 19 March. Data were recorded on 12 runs in all over the test area, and two runs outside the test area (table 1). The flight programme was selected to cover the whole 5x5 km^2 area (lines A—F) and a special area south-west of the ice-breaker (lines Q and X).

Table 1. *Specification of thermal mapping missions.*

	Run No.	Hour	Detector type, size		Alti-tude	Indicated flight-line (see figure 3)
Mission I	1	1145-1200	Ge:Hg,	3x3 mm^2	2000 m	Bjuröklubb to test area
	2	1215-1217	"	"	500 "	C
	3	1217-1219	"	"	500 "	D
	4	1222-1224	"	"	300 "	Q
	5	1225-1227	"	"	300 "	X
	6	1229-1231	"	"	300 "	X
	7	1235-1237	"	0.8x0.8	500 "	C
	8	1244-1246	"	"	500 "	D
	9	1247-1249	"	"	500 "	E
	10	1251-1253	"	"	500 "	F
	11	1255-1257	"	"	500 "	B
Mission II	12	1540-1544	CMT,	0.5x0.5	2000 "	B
	13	1545-1549	"	"	2000 "	E
	14	1550-1610	"	"	2000 "	Test area to Skellefteå

Remarks: The real flight-lines deviated somewhat from the indicated ones. During runs Nos. 12 and 13 air turbulence disturbed the recordings. The recordings from runs Nos. 5, 7 and 8 are incomplete for various reasons.

An important part of the ground truth information is the imagery from the aerial photography that was performed with different types of cameras and different film-filter combinations. The photographs of interesting details that were taken by the ground truth people on the ice are also of great value in the interpretation of the thermal imagery from the infrared line-scanner. Unfortunately there are no photographs available from the day when the thermal mapping was done, so the imagery from the two days before the thermal mapping has been used as the best available ground truth material. In spite of great changes and movements of the ice field as a consequence of weather and sea currents during these days, there seems to have been a great area around the ice-breaker where the ice remained relatively intact. For that reason the air photos from 17 and 18 March could be used as a good reference regarding continuous areas of old ice without open water or thin ice.

Figure 3. *Aerial photograph of central part of the test area taken by the National Land Survey on 17 March, two days before the thermal mapping.*

A—F, Q and X are the indicated flight lines across the 5x5 km² area.

4. Experimental Results

All photographic recordings of the thermal mapping have been cursorily studied. Some interesting and characteristic details have also been studied more in detail by means of specially enlarged copies and different kinds of signal processing and information presentation of the tape recordings. The material has been studied mainly in order to answer the following questions:

☐ the sensor's ability to differentiate
- — ice from water
- — water-covered ice from water
- — snow-covered ice from snow-free ice
- — thin ice from thick ice,

☐ the sensor's ability to measure
- — percentage ice/open water
- — ice roughness
- — ice thickness

Other questions of interest, such as mapping capacity, weather and light dependence, etc., can be answered on the basis of general performance data and experience.

The thermal imagery from 19 March has been compared with two sets of aerial photographs in the visual range taken by the National Land Survey of Sweden. One set was taken on 17 March on negative colour film with a Wild RC 8 23x23 cm camera. The altitude was 4600 m and the negative scale 1:30 000. One of the photos covering the main part of the 5x5 km^2 area is shown in (figure 3). The other set of photographs was taken on 18 March with a Hasselblad 6x6 cm four-camera package at an altitude of 1500 m. Type of film, filter and focal length were different in the four cameras. The negative scale was 1:15 000 or 1:30 000.

In the visual image it is easy to recognize areas covered with old ice. Variations in snow cover and roughness can readily be distinguished. By means of stereoscopic viewing of the aerial photographs, the topography can be studied to some degree. In the dark areas of the photographs, however, it is very difficult to establish the state of the surface. Both a surface of open water and a layer of new, thin ice look dark to the photographic camera, as well as to the human eye. If there is no texture on the water or the ice, these two kinds of surface may be impossible to discern in the visual image. Old or thick ice that occurs at the edges of leads, on the other hand, comes out distinctly in different shades of gray.

In the photographic (visual) image, the variations in density (graytone or colour-tone) depend on the reflectivity of the objects in the actual spectral band. The tones in a thermal image derive from the variations in the apparent surface temperature, which is a function of real surface temperature and surface emissivity of the objects. Under normal conditions the variation in surface temperature is dominating, and emissivity differences are of minor importance.

The variations of emissivity for ice, snow and water in the 8—14 μm range are small. The mean value is very high (0.97—0.99) for angles of incidence less than 45 degrees. The effect of emissivity differences may be neglected under normal conditions.

The surface temperature of the ice reflects an equilibrium between the heat conducted through the ice and the exchange of heat caused by incident solar radiation, from the surface and convection (between ice and air). During the period of ice formation and growth, the air temperature above the ice surface is normally below that of the underlying water. Then the heat transfer through the ice will vary with ice thickness, type of ice and amount of snow cover. Weather factors and surface roughness may have a great influence.

During the thermal mapping, the temperature difference between water (0°C) and air (0 to—2°C) was small. Six hours before the flights, the air temperature was —3°C. The wind speed was about 10 m/s.

In spite of the small temperature difference between water and air, there were great variations in the radiation from different parts of the test area. In the thermal imagery (figure 5 and others) one can easily distinguish at least three radiance levels corresponding to characteristic objects in the aerial photographs. The warmest parts correspond to areas of open water or thin ice, which are darkest in the photographs. The coldest parts correspond to snow-covered ice. Between these two levels is the old, bare ice. The tonal rendering of the apparent temperatures in the thermal image is roughly inverse in relation to the luminances in the visual image.

Figure 4. *Coverage of the film recordings in figure 5.*

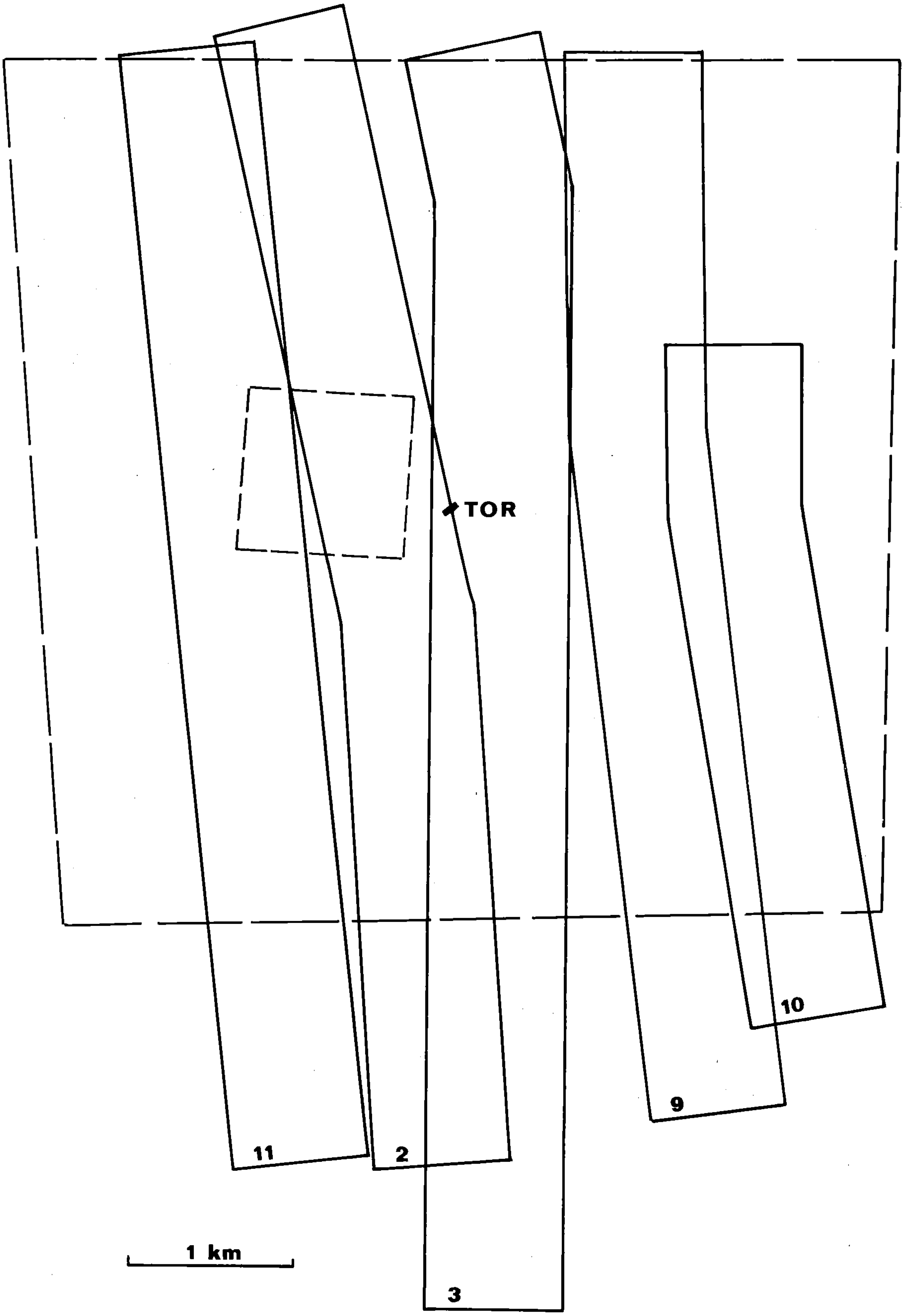


Figure 5. *Film recordings from five runs at 500 m flight altitude. The coverage of the strips is indicated in figure 4.*

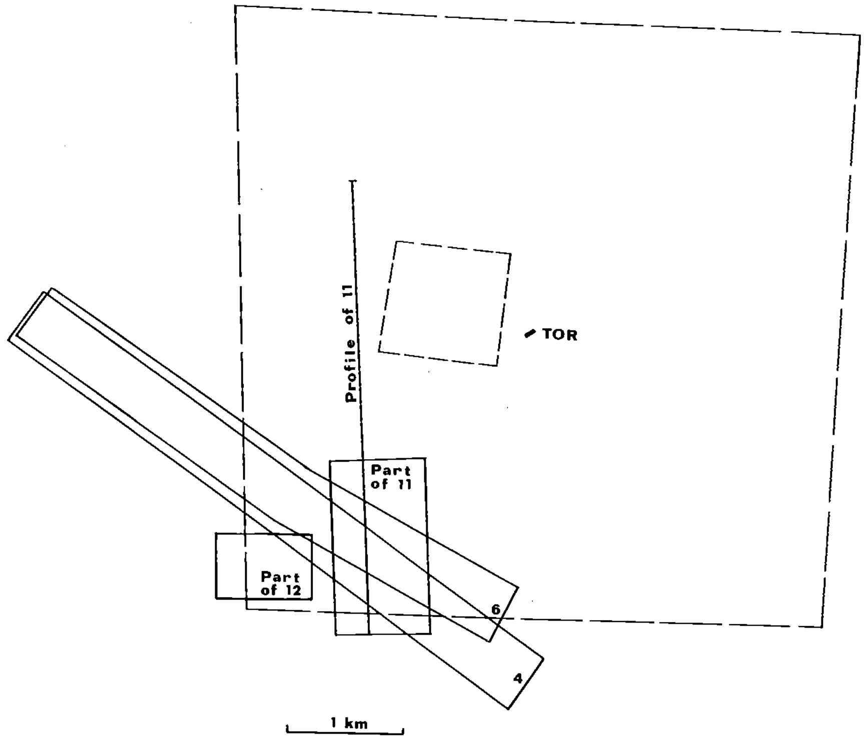


Figure 6. *The coverage of the film recordings from run No 4 (see figure 7) and run No 6. The location of the special parts of runs Nos 11 and 12 shown in figures 8—11 is also indicated.*

Figure 7. *Film recording from run No 4 at 300 m flight altitude. The scale along the flight line is about 1/3 of the scale across. The position of the area is indicated in figure 6.*

Within the warm parts, there are minor variations which can be amplified by special printing of the photographic recordings or by processing and presentation of the tape recorded information in a convenient way (figure 8—10). The radiance profiles across the thermal images in figure 10 clearly indicate two separate levels within the warm areas. These two levels are related to open water and thin, new ice, respectively, which has been confirmed by observations during the thermal mapping missions (figures 9 and 10).

Many of the small areas, which come out dark in the photographs and accordingly are open water or thin ice, have a light gray tone in the thermal image. These were most probably ice covered at the time of the thermal mapping but they could quite well have frozen after the time of the photography.

As there has been no ground truth available concerning areas of water on the ice, this object has not been studied. Under normal circumstances it may be assumed that also in that case the water is warmer than the surrounding ice. Then there should be a contrast similar to that between open water and ice. The temperatures of the water above and below the ice may of course be different owing to the isolating effect of the ice.

If the ice is bare (not covered with snow or water) the heat flux from the underlying water is mainly a function of ice thickness. Under such conditions a coarse classification of relative ice thickness could be done. In the thermal imagery there are at least two quite different radiation levels which can be correlated to new and old ice. Radiation profiles obtained from the tape recordings indicate that a much more detailed division into thicknesses is possible (figure 11).

The inverse relation between the luminance levels in the photographic imagery and the radiance levels in the thermal imagery seems to be valid in uniform areas where the surface is level and smooth. In rough areas the relations between photographic and thermal imagery are more irregular. Roughness of the ice caused by ridging or rafting is associated with thickness variations and re-distribution of ice layers. At ridges where the surface is very irregular and formed by broken ice, the thermal conditions may be very different from those at level ice. The radiation from a ridge is a more complex function of the thermal parameters.

A few ridges, about two metres high, 650—750 m between nort-west and north of TOR have been studied in the imagery. In spite of the great thickness they come out lighter (warmer) than the surrounding snow-covered, level ice. Probably the age of the ridge, the air temperature and the sun conditions have a great influence on the integrated radiation from the ridge. In the photographic image the luminance of the ridges varies in an irregular way probably depending on the distribution of snow and ice surfaces and the frequent occurrence of shadows in the broken structure.

The characteristic square-wave type pattern of finger rafting which is seen in the photographic image as dark parallel lines (e.g. 1500 m west-north-west of TOR) comes out as a light-toned, warmer temperature feature in the thermal image (figure 5).

The results of the field experiment agree in the main with similar experiment in other countries (Hengeveld (1973), Schertler et al (1973), Poulin (1975), Tooma et al (1975)). Some of those experiments have been carried out in the Arctic, where also multi-year ice occurs. Various periods of ice formation and growth, as well as the melt season have been studied. In spring and summer, when the ice begins to melt, the surface conditions change considerably. The identification of ice types and special features, as well as the general interpretation of the thermal image will then probably be different from that in autumn and winter.

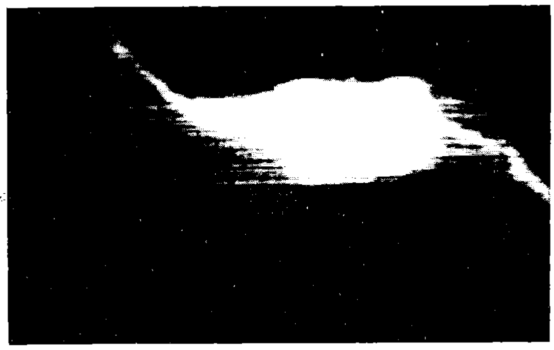


Figure 8. *Photographic presentation of a part of the tape recording during run No 12 at 2000 m flight altitude. Position indicated in figure 6. Signal level and contrast ratio have been choosen to show the difference between open water (white) and thin ice (gray) in the lake.*

Figure 9. *Ditto for run No 11 at 500 m flight altitude. See figure 10 for details.*

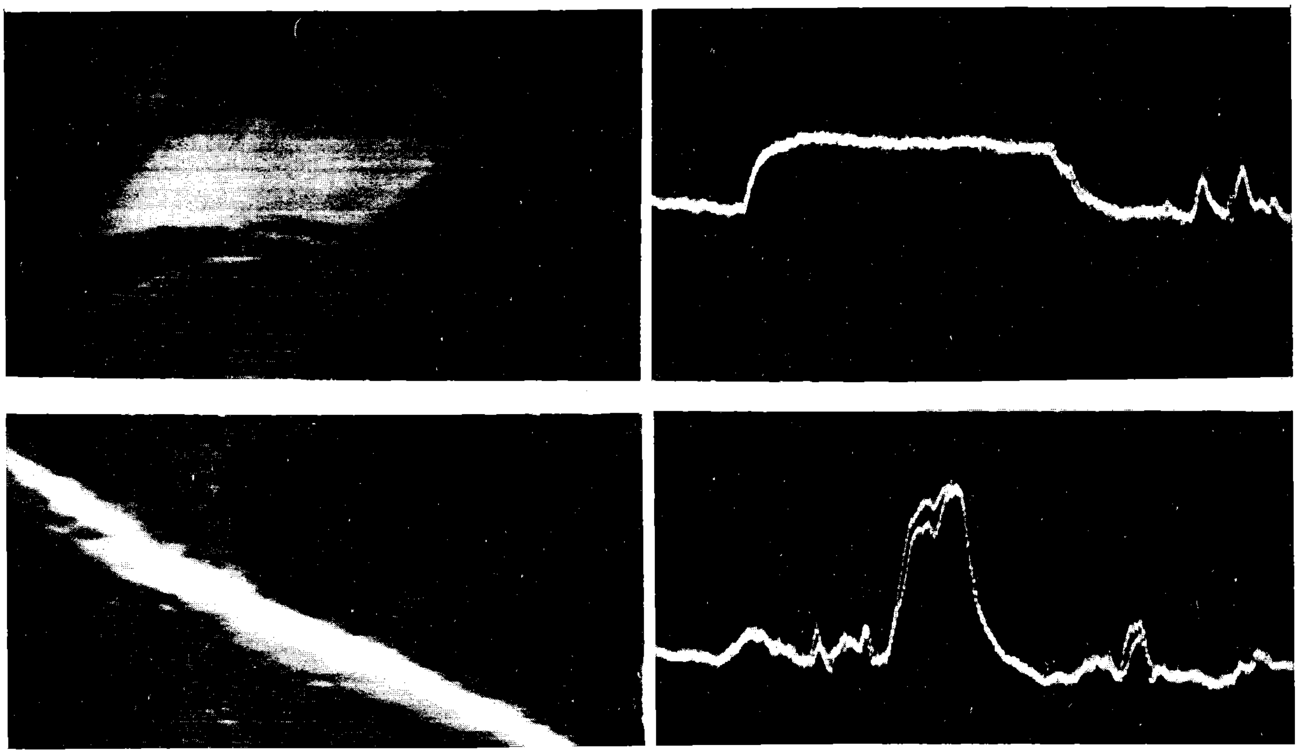


Figure 10. *Enlargements of details of figure 9. Top left a lake with thin ice, bottom left an open lead. The curves (right) are radiation profiles across the two areas.*

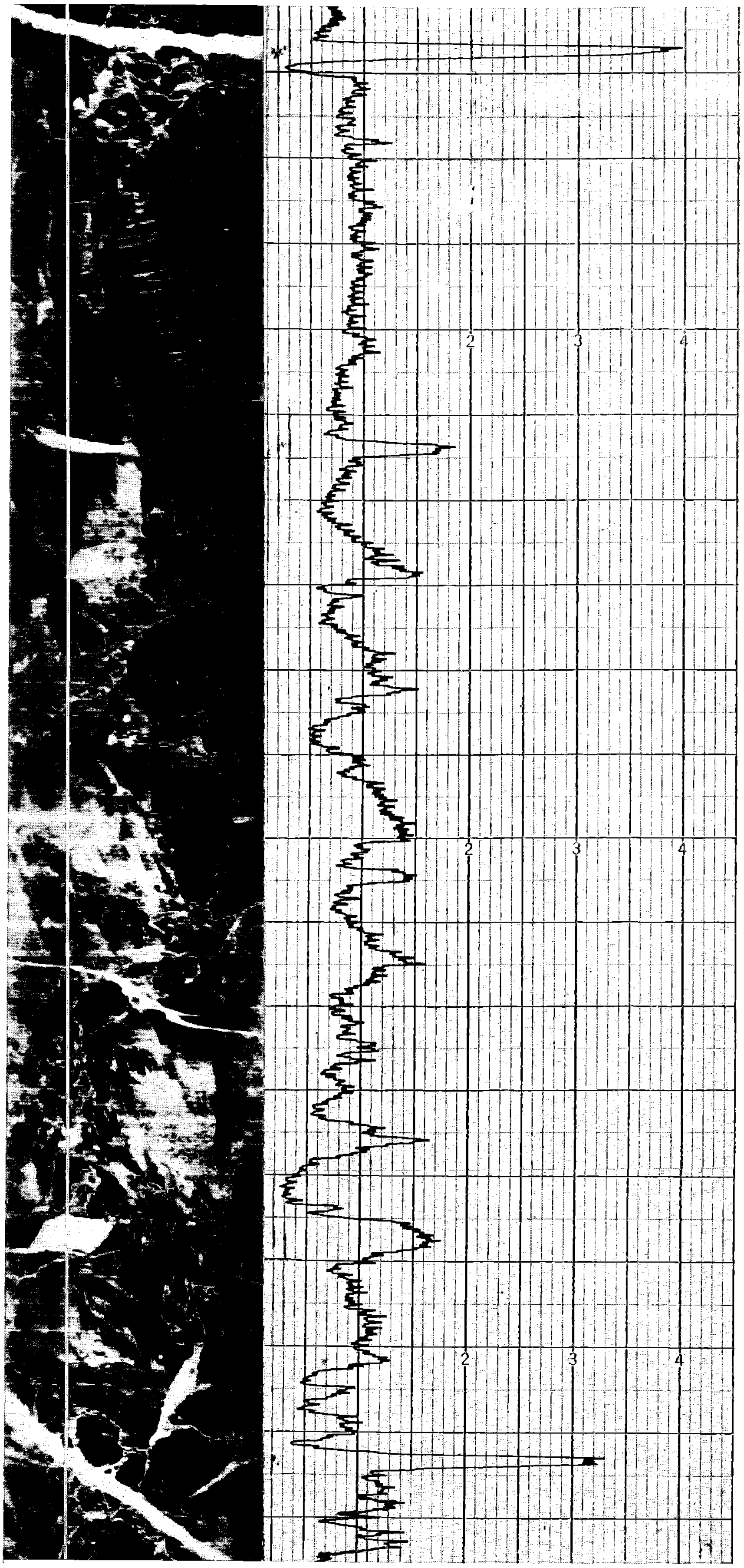


Figure 11. *Radiation profile (right) along run No 11. The position of the profile is indicated with a white line in the thermal image (left) and in figure 6.*

Figure 12.

Figure 13. *These film recordings are from different parts of run No 14 (outside test area) at 2000 m flight altitude.*
Figure 12 is an ordinary thermal image showing the variation of radiation.
In figure 13 the signal has been differentiated before recording which emphasizes the thermal gradients.

5. Conclusions

The field experiment has shown that thermal infrared sensing can be used to differentiate ice from water and new ice from old, thicker ice. The thermal imagery has a much better capability than visual imagery in differentiating new ice and open water. The possibilities to make quantitative thickness measurements of the ice are limited. If the surface of the ice is bare and reference measurements are available, it should very likely be possible to get a rough information about the thickness distribution.

Special features, such as rafting patterns, ridges and cracks, are correlated to thermal variations and can be detected and identified in the thermal image. Tape recordings are very useful for studying the objects in detail.

Whenever weather and light conditions permit, it is of great value if aerial photographs could be taken simultaneously with the thermal recordings. The thermal sensing technique itself is, however, independent of illumination and can be used day or night. The weather dependence is less than for the visual and photographic techniques, but clouds or heavy fog cannot be penetrated.

The mapping capacity of a thermal scanning system depends on the scanning angle and the flying altitude and speed. The scanning angle for most types of existing scanners varies between 90 and 120°. It means that the coverage across the line of flights is between 2 and 3.5 times the flight altitude. For ice surveillance an altitude of 2—5 km will be sufficient to resolve geometrical details of the order of 5—10 m with a good thermal resolution.

If a real-time presentation of the thermal information is desired in the aircraft for immediate in-flight interpretation and analysis, it will be easy to add such a facility to the system (Hengeveld, 1973). The signal from the scanner is also available for immediate and continuous radio transmission directly to a ship or other station where the information is needed.

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