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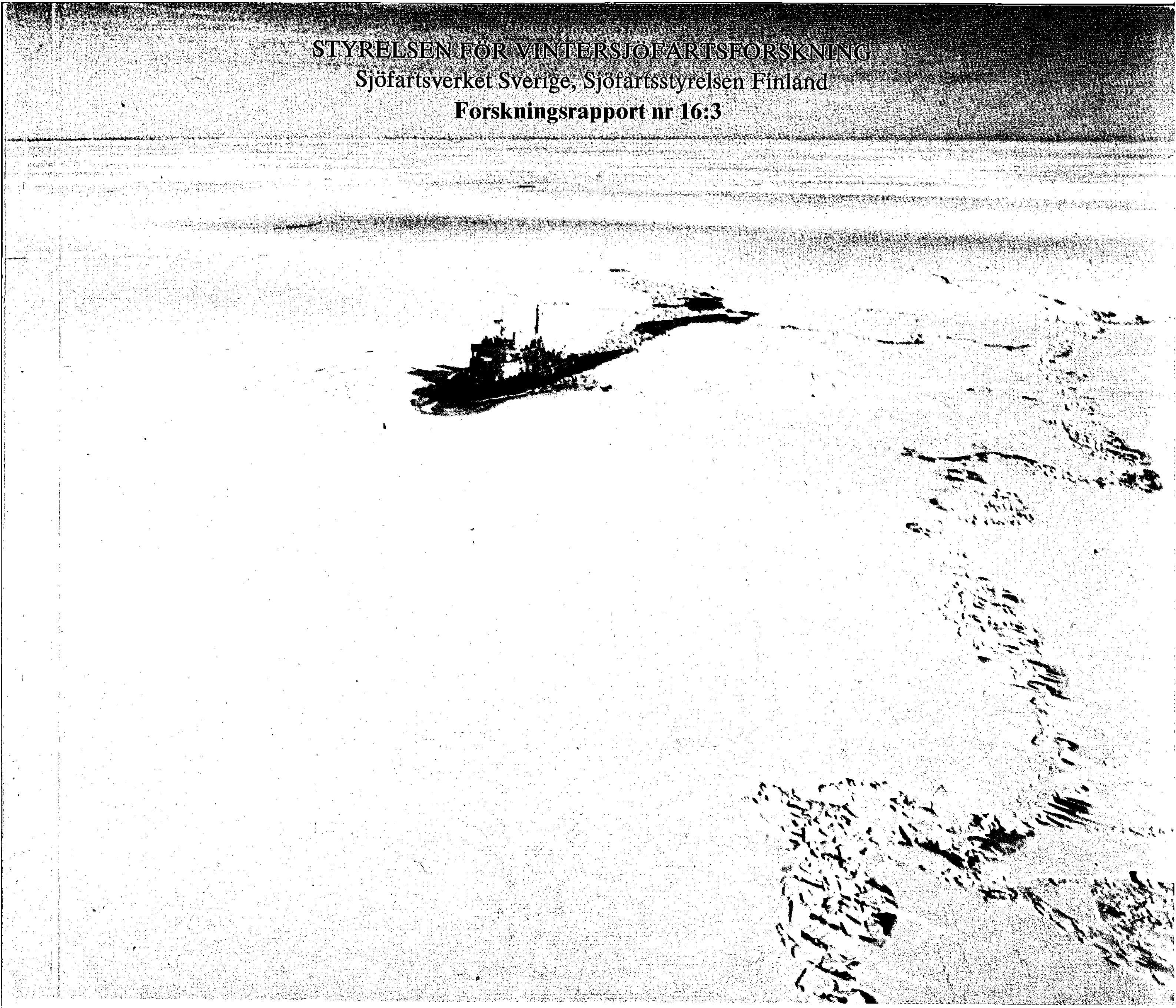

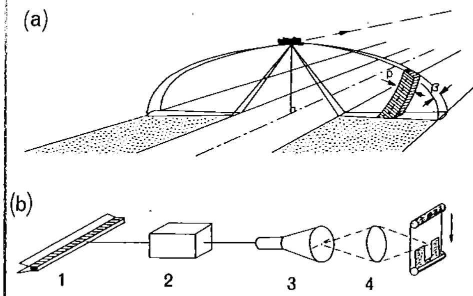

Ice detection by SLAR

by R.H.J. Morra and G.P. de Loor

WINTER NAVIGATION RESEARCH BOARD
Swedish Administration of Shipping and Navigation, Finnish Board of Navigation
Research Report No 16:3

(SLAR system:)
Cover picture:
The icebreaker TOR in the middle of the test area for SEA ICE —75 and the scan configuration of the side looking airborne radar.

SEA ICE -75
Ice detection by SLAR

by R.H.J. Morra and G.P. de Loor

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Foreword

The Winer Navigation Research Board presents report No. 16:3. The single most important and interesting sensor, tested during the remote sensing experiment SEA ICE-75, that was carried out in the Bay of Bothnia in March 1975, was a Side Looking Airborne Radar (SLAR). The participation of the SLAR was made possible due to the active interest of R.H.J. Morra from Rijkswaterstaat Meetkundige Dienst and G.P. de Loor from the Physics Laboratory of the National Defence Research Organization of the Netherlands. Under the leadership of G.L. Lamers from the National Aerospace Laboratory of Amsterdam a number of successful flights were undertaken over the test area as well as along the Bay of Bothnia.

This report gives an illustrative description of the principles of SLAR in general, and the Dutch SLAR in particular as well as an analysis of the results. A further analysis of the registrations is presented in report No. 16:4 of this series.

The Winter Navigation Research Board wish to convey its sincere thanks to the authors of this report as well as to the Rijkswaterstaat and other Dutch authorities, who made it possible to carry out this, for SEA ICE-75, so important SLAR programme. The mutual benefits that can be derived from international cooperation have hereby been further demonstrated.

Norrköping and Helsinki, July 1976.

Lennart Johansson **Helge Jääsalo**

1. Preface

For reasons of mutual interest **"Rijkswaterstaat"** (part of The Netherlands Ministry of Transport and "Waterstaat") assisted in the Swedish-Finnish project on sea ice, 1975. RWS participation in this project was with a real aperture X-band ($\lambda \approx 3$ cm) **Side Looking Airborne Rader.**

The SLAR unit was installed in a Beechcraft Queen Air 80 owned by the National Aerospace Laboratory (NLR) of Amsterdam. The NLR is under contract to support the RWS remote sensing investigations.

NLR aircraft carried out the SLAR survey flights in the Bothnian area during the field experiments in March 1975. In charge of this operation was **ir. G.L. Lamers,** staff member of NLR. The flight scheme is given in annex 1.

Further assistance to the RWS investigation were provided under contract by the Physics Laboratory of the National Defence Research Organisation TNO; this involved specialised technical support of the SLAR and radar physics, in particular the analyses and interpretation of images.

In charge was **dr. ir. G.P. de Loor,** who also participated in the Dutch portion of the sea ice experiment and who is the author of par. 3 and par. 4.

This report is of a practical nature and is not intended to be fundamentally scientific.

2. Summary

The theoretical background, types of SLAR systems with their specifications, properties and limitations are described in *par. 3.1 to 3.8.*

Based on properties, costs and operational requirements the real aperture X-band and/or Q-band SLAR should be given primary consideredation with a certain preference for combined use The r.a. X-band SLAR used during the sea ice experiments has certain specific limitations. These are discussed in *par. 3.9.*

In *par. 4* the SLAR images are interpreted; these were obtained during survey flights over the Bothnian Gulf. Actual interpretation is based on a comparison with aerial photographs, taken during the same period. Some typical reproductions of SLAR images are used to illustrate the text. Conclusions are also drawn up.

The project leaders defined a number of specified items to be separately discussed in individual reports. This discussion regarding SLAR is covered in *par. 5.*

This shows that while SLAR is an adequate primary sensor for an ice surveillance system due to its inherent capabilities, some natural limitations are present.

In *par. 6* some additional remarks are made. This shows basically that in practice there is no sensor which will adequately provide all the answers. Other sensors needed to back-up an operational system are referred to.

Some remarks are made regarding the carrier, which should be an aircraft. A special study on which type will have to be made.

3. Properties, Possibilities and Limitations of SLAR

3.1 Introduction

Radars major advantage over other observation systems is its independence of the weather. Although the absorbtion of radar waves by the atmosphere increases in the higher microwave frequencies (shorter wavelengths) it is still small when compared with the visible and thermal infrared part of the spectrum. Fig. 1 shows the microwave frequency band with related band designation as a function of atmospheric absorbtion in dB/km.

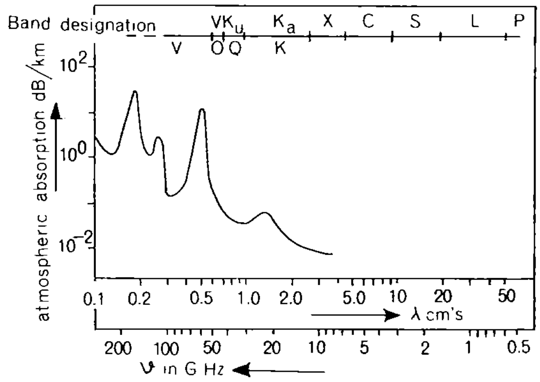


Figure 1. *The microwaves. Band designation and atmospheric absorption in dB/km.*

The ordinary radar with rotating aerial and image reproduction on a PPI screen (plan — position — indicator) has found wide application, also in aeronautics in particular for navigational purposes.

For mapping applications, however, this type of radar has its limitations. With the development of the side looking airborne radar or SLAR many of these limitations have been overcome.

Radar is an active system. It transmits a short pulse of electromagnetic energy and records the echoes received back in order of arrival and plots them as a line on an image tube e.g. in the form of small dots of light (vide fig. 2). After the reception of the preceeding echo — determined by the distance over which observation is carried out — a new pulse is emitted. This continues ad lib. Since an electromagnetic wave moves forward at the speed of light the turnaround time is short and a large number of pulses can be transmitted per second. Using this technique radar will measure distance to the reflecting object using as a base the time between the transmission of a pulse and the reception of the echo. This results in the formation of an image. In the SLAR system, two antenna's are used, one on each side of the airborne platform to concentrate the emitted energy. Fig. 2 shows the build-up of the system. A single line only is shown on the image tube.

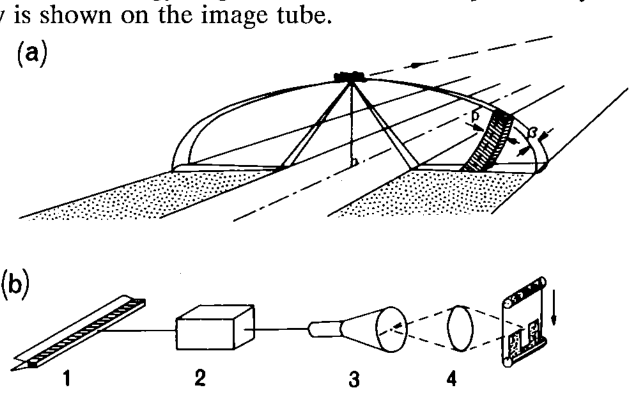


Figure 2. *Side looking radar. (a): Scan configuration; (b): Radar system: 1) antenna, 2) transmitter/receiver, 3) image display tube with one intensity modulated line; picture is built up to a continous image on moving film in camera system 4.*

By reproducing this line on a film which is set to move at a speed proportional to the speed of the aircraft, a continuous image will be obtained. Scale accuracy in the flight direction is determined by the amount of accuracy achieved in maintaining the correct relative proportion between the speed of the moving platform carrying the radar and the speed of the film.

Each radar unit operates at a single frequency (wavelength). This is a distinct contrast with most other remote sensing systems as e.g. scanning systems, where even in monochromatic operation, a wavelength band is always scanned. The most used frequencies for SLAR lie between 6 and 40 GHz ($\lambda = 5$ to $\lambda = 0{,}8$ cm). Table 1 shows the parameters of two representative systems. For a more complete survey refer to the EASAMS study for ESRO [EASAMS (1972)].

Table 1. *Average parameters of an X- and a K_a-band radar.*

	X-band	K_a-band
Operating Frequency (GHz)	9.5	35.0
Aerial Length (m)	4.6	4.0
Transmitter Peak Power (kW)	100	50
Pulse Repetition Frequency (sec^{-1})	2500	3800
Pulse Length (usec)	0.2	0.1
Resolution:		
across track (m)	30	20
along track (m/km)	8	2.7
Size (without aerials) (m^3)	0.35	0.4
Weight (without aerials) (kg)	155	156

3.2 Resolution

3.2.1 Real aperture SLAR

The parameters determining resolution are: aerial aperture in azimuth (along track) and pulse legnth in range (across track). See figs. 2 and 3. The aerial concentrates the electromagnetic energy emitted by the radar in a narrow beam with an opening in azimuth of β radians as shown in fig. 2.

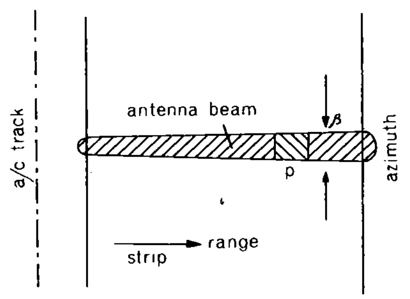


Figure 3. *Resolution in azimuth (along track) diminishes with range.*

Along track resolution is obtained from the well known formula for the antenna opening:

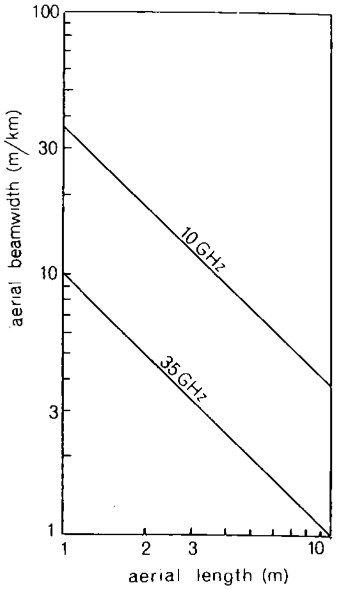
$$\beta = 1.2\ \lambda/D \text{ radians} \qquad (1)$$

where λ is the radar wavelength and D the antenna aperture, both in the same units. Absolute resolution along track therefore diminishes with range, see fig. 4.

Resolution in meters can never be better than the size of the aperture D. **Across track resolution** or the ability of the radar to discriminate two targets situated one behind the other in range, is determined by pulse length.

Since the radar pulse travels with the speed of light (300 m/μ sec) and the radar records the time taken for a pulse to travel to and from a target, each μ sec will represent 150 m on the screen. Current systems use pulse lengths between 0.05 and 0.3 μ sec which, dependent on the wavelength used and the maximum range required, will represent a resolution of between 8 and 50 m.

Figure 4. *Aerial beamwidth (resolution) vs. aerial length.*

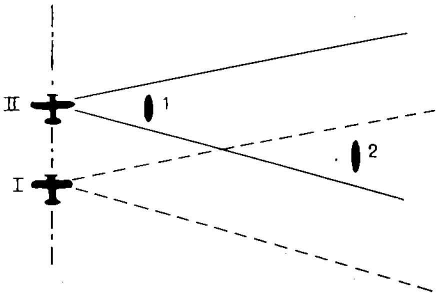


Because of the two effects described above, a **reflecting** object will be displayed longer than it really is while a non-reflecting object (as e.g. a lake) will be shown smaller because the reflecting surroundings are displayed larger than the actualle are. This is because the water of the lake will reflect the electromagnetic energy away from the radar like a mirror, so that no echo will be received back at the radar.

3.2.2 Synthetic aperture SLAR; improvement of the along-track resolution

Along-track resolution decreases with increasing range (see fig. 3 and 4). Since the size of the aerial is determined by the size of the aircraft this means that at a certain range along-track resolution will become less than that obtained across-track. Equation (1) gives resolution in azimuth. As fig. 5 shows, targets that are positioned farther away from the radar source are illuminated longer than targets located closer. While target 1 in fig. 5 will be scanned only when the aircraft is in position II, target 2 will, in fact, already have been illuminated when the aircraft was in position 1. This phenomenon can be advantageously utilized. With a coherent radar system all observations of target 2 will be integrated as the aircraft moves from position I to position II. The forward movement of the aircraft carrying the SLAR is utilized by treating the succesive aerial positions as if they were individual elements of a very long linear aerial array.

Figure 5. *Longer illumination of distant objects.*



The further away from the radar an object is, the longer it is illuminated and the longer will be the integrated aerial array. Because of this it is possible to make the along-track resolution **b** independent of range:

$$\mathbf{b} = 1.2\, D/2 \qquad (2)$$

Further details of the principles involved in the synthetic aperture SLAR system are contained in the literature [BROWN and PORCELLO (1969); HARGER (1969); EASAMS study (1972)]. It will be obvious that the procedure is a sophisticated one with the consequent higher demands in technique and price of the system [GOODYEAR (1970)]. For a good structural deployment of the long aerial array the positions of the individual elements of the array have to be known with an accuracy up to ¼ λ. For an X-band system this means an accuracy of 8 mm. This is obtained by employing an inertial platform as a reference and using aerial stabilisation. Because of the high information content the recording, made in the air, can be compared with an hologram. This hologram is later treated in an optical processor to become a readable image.

With the SAR principle it is not possible to improve the resolution at will. As already pointed out, absolute resolution in azimuth can never be improved beyond half the aerial aperture.

Another point is ambiguity: a single sweep of a target — and this is what high resolution in fact boils down to — may not be sufficient. For area targets as e.g. ice, soils, vegetation, the sea — all of which are Rayleigh scatterers — one single response of a target will not be sufficient. For such targets it will be necessary to integrate over sufficient resolution cells (independent samples) in order to obtain a reliable figure for the backscatter coefficient (accurate place along the dynamic range scale; grey tone) [MOORE, 1971].

This is the cause of the speckle in the images obtained from SAR. For large areas averaging gives at least an average grey tone. To get around this problem also for smaller areas resolution will have to be traded for accuracy. An average over 9 independet samples gives for a Rayleigh scatterer an accuracy in the radar backscatter coefficient of ± 1 dB (50 % confidence interval). Such a spread would be marginal already for many extended surface targets as e.g. land and vegetation. The following can be put forward as example:

3x3 m^2 is given as an obtainable resolution.[1])

Assuming now a shift of between a half and one resolution element as sufficient to obtain another independent sample of an extended target, the final resolution obtainable after integration lies at around 10x10 m^2.

3.3 Image build-up; flight procedure

As pointed out earlier, radar records the distance to a reflecting object. This will introduce typical distortions in the reflected image when compared with a map of the terrain being surveyed, see fig. 6. The radar records the distances OA, OB, OC, etc. and not NA, NB, NC, etc. While it is possible to correct this in the system, it may be preferred to carry this out later on the ground together with the elimination of other errors; a correction technique may not function perfectly when done in the air; any information lost whilst the carrier in the air is irretrievable.

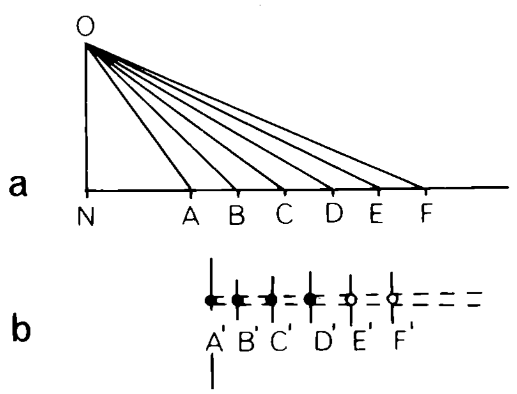


Figure 6. *Image distortion for SLAR. in range: a) actual situation, b) display. Since recording starts at A, the distances (OB—OA), (OC—OA), etc. are registered.*

It will be clear that the height of the radar above the reference plane must be accurately known. At low altitudes or over very large distances (high values of range (R) over height (H): R/H) corrections will be minute and a nearly orthographic image will be obtained.

Fig. 6 shows as well, that it is not particularly useful to scan straight down under the aircraft due to increasing distortion. In the SLAR system recordings are only made therefore for angles greater than 45° from the vertical. This means that an area with a width of roughly twice the height of the radar unit will not be recorded. This will require the drawing up of a special flight pattern to overcome this.

Fig. 7 indicates such a procedure. Although this suggests that it might be sufficient to allocate the following two flight lines alongside the two indicated it might well be more useful to shift only one stripwidth per flight line. Then a large part of the area will be flown over twice which, especially in mountaineous terrain, will give larger freedom in the choice of the flying height.

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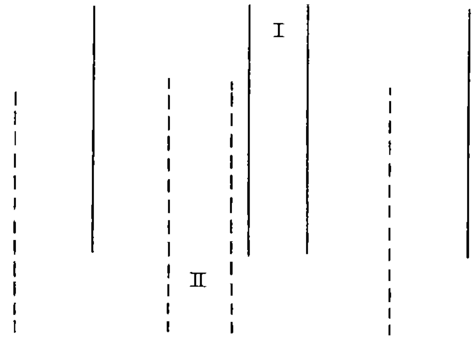
1) Representatives of ERIM at the Xth International Symposium on Remote Sensing of Environment, Ann Arbor, Oct. 6—9, 1975.

Figure 7. *Flight pattern for SLAR.*



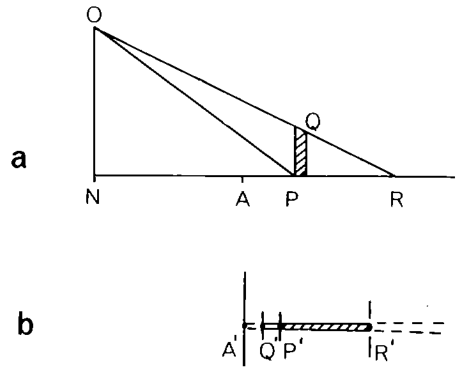
3.4 Parallax

In radar imagery two types of parallax are encountered: the echo parallax and the shadow parallax. See fig. 8.

3.4.1 Echo parallax

Since radar measures distance, the top of a high object will be recorded first before the bottom when the craft is flown at a certain height. As shown in fig. 8, OQ is less than OP, therefore Q will be recorded before P. This "inverted" echo will rapidly decrease in size as the distance between the radar and the target increases (higher values for R/H).

Figure 8. *Echo parallax: a) actual situation, b) recording. A beginning of record, P'Q' echo, P'R' radar shadow.*



This effect has been used. La PRADE (1963) made a theoretical study and considered several possibilities, choosing parallel flight lines in such a way that the image could eventually be evaluated in ordinary stereo comparators. It must be kept in mind, however, that this effect is usable only over a limited range and also that the minimum height difference observable is always larger than one resolution element of the radar system. In the application now under consideration it will therefore not be of any substantial help.

3.4.2 Shadow parallax

For a radar located at O (fig. 8) the target PQ screens the area between P and R from observation. PR, therefore, cannot be recorded (no signal) and shows up in the image as an area without echoes, thus as a black area or "shadow".

This radar shadow can eventually be used as well for height measurement providing that it is clearly outlined and located on the reference plane. Radar shadow increases with distance (higher values of R/H). Higher objects in the foreground can screen other objects located behind them (foreground screening).

Shadow can also be used to improve image contrast. Small differences in altitude can be enhanced in this way by flying low. This latter can eventually be useful when mapping ice.

3.5 Image correction

SLAR is a line-scan system, imaging a continuous strip of the earth's surface line by line. This means that for obtaining a geometrically correct depiction of the earth's surface a line by line correction of the image is necessary taking into account all aircraft movements as: tilt (pitch), tip (roll), swing (yaw), crab (drift), velocity and altitude changes. Fig. 9 shows the effect of yaw and drift errors. This will require the application in the aircraft of altitude and attitude sensors of which the signals are recorded simultaneously with the image signal.

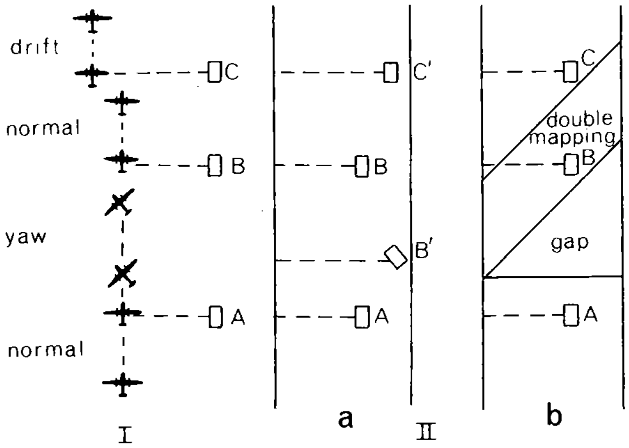


Figure 9. *Influence of yaw and drift on line-scan imagery. I. Flight configuration, II. Image, a) uncorrected, b) corrected.*

It can be shown [DE LOOR and ERADUS, 1973] that the resolutions given in Table I meet standard map accuracies for mapping at 1: 250.000 and 1: 500.000 (X-band) and 1: 100.000 (Q- or K_a-band). This will require however, improved accuracy in the determination of platform position, platform altitude and platform attitude (fig. 10).

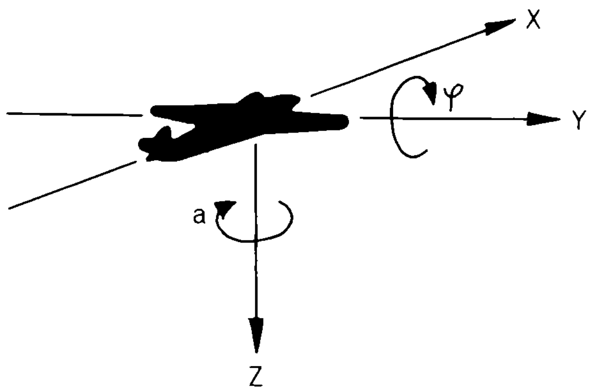


Figure 10. *Platform motions which require compensation during mapping.*

These are shown in Table II. This shows that positional accuracy up to a 50 m is required for mapping with an X-band system while 10 to 12 m will be needed for the Q- (K_a-) band system.

The "yaw" must be determined to better than 1 mrad while for "pitch" the degree of accuracy must lie between 5 and 20 mrad.

Table 2. *Allowable platform motions.*

SLAR -band	For Scale 1 :	Height H (km)	s_x(m)	s_y(m)	s_z(m)	s_α mrad	s_φ mrad
X	250.000	8.5	25	30	40	0.6	2.7
X	500.000	8.5	50	60	80	0.7	5.5
K_a	100.000	0.5	10	12	16	1.0	20
K_a	100.000	1	10	12	16	1.0	10
K_a	100.000	2	10	12	16	0.6	5

3.6 Further observations on radar-resolution vs mapping scale and working range

The parameters given in table I are typical for the real aperture systems involved: They have in fact different applications. As already seen in the foregoing paragraph, one system is good for small-scale mapping (1:250k; 1:500k), the other for larger scale mapping (1:100k); put differently, this means that while one system is ideal for long range (distance) work, the other can only be used for short range work. A combination of both these applications into one system is difficult. In this instance a synthetic aperture system would still require two channels, i.e. an separate channel for the longer ranges since these systems are usually laid out for mapping at shorter ranges (between 5 and 10 mm), however, with the advantage that this range can be arbitrarily laid further away from the flight path.

The imaging system involved is responsible for this. Good cathode ray tubes, (image tubes), can handle something like a little more than 1000 lines, extra good tubes somewhat more. For a 5" tube this means 10 to 15 lines/mm. This means that using one image tube per side anything from 1000 to 1500 lines per side can be handled. For a required range of say 60 km this means a resolution in range of 50 m (or 0.3 μ sec). 50 m is a reasonable resolution for a long range system.

High resolution systems use pulse lengths between 0.06 and 0.1 μ sec or a resolution of 10 m at most. The usable maximum range per side then becomes a 10 to 15 km.

Both systems therefore do have resolutions adequate for the mapping scales they can handle. Larger scales, requiring higher resolutions, will be more difficult to attain. A gain in resolution by a factor of two (to a mapping scale of 1:50.000) will result automatically in reduced range. Any improvement to this will be very costly and the question remains wether they will be of use since resolution and mapping scale are in fair agreement.

Resolution is clearly not the only criterion on which a radar system can be judged.

3.7 Background. The interpretation of radar images

The foregoing has dealt more with the metric capabilities of the SLAR system. The difference between it and other sensors goes deeper than this alone; it is these differences which play an important role in evaluating the usefulness of SLAR for any specific project.

Two properties in which radar differentiates from other remote sensing systems immediately strike the eye. First of all radar transmits electromagnetic waves at a single frequence instead of a frequency band. Even in monochromatic operation most other sensors work on a frequency band. Furthermore radar carries its own light source. In other words scanning is under better control than is the case with many other remote sensing systems which depend on light sources outside the system (as e.g. the sun in aerial photography).

Still another point of interest is the fact that radar uses centimetric wavelengths. As electromagnetic radiations, radar waves are similar in behaviour to light. The fact, however, that the wavelength is comparable with the dimensions of the radar system has some consequences. For example, aerials are nearly always in the order of 100 λ to 200 λ. In optics, the relationship between the diameter of a lens and the wavelength is greater than a factor 10^4. Diffraction and interference effects so play an important role in radar. Roughness or smoothness of a surface is another example; this is expressed in wavelengths. A surface is called smooth when height variations remain below ¼ λ. In radar technology, these effects are the same but play at a different scale.

For example, a surface (e.g. a ploughed field) would be rough to a radar system working with short radar waves (K_a- or X-band) but would be smooth to another system working at the long wavelength end of the microwaves (e.g. L- or P-band).

The above are just a few of the physical characteristics which have to be taken into account when describing the interaction of the radar waves with an object. It must always be borne in mind that a radar image is in fact a transformation. A radar image is a transformation from the microwave part of the electromagnetic spectrum, where the radar "sees", to the visible part where the human eye can "see". It must be clear from this that for such an image other criteria apply than are used in the visual part of the spectrum.

Radar targets are either point targets or distributed targets: Point targets are objects smaller than the illuminating beam whereas distributed targets are built up of several scatterers and can be larger than the illuminating aerial beam.

The ground returns obtained in the SEA ICE -75 experiments contain both. Ridges can be considered as a buildup of a series of point scatteres whereas the large ice areas and the sea are distributed targets. While the literature gives data on sea returns, such data ar not available for ice.[1)]

For this reason it is not possible to say which would be the best polarization to use (in SEA ICE '75 the polarization was HH) or to give figures for the contrasts: ice/water, ice/land.

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1) See e.g. the Procs of the URSI Specialist Meeting on "Microwave Scattering and Emission from the Earth", Berne, Sept. 23—26, 1974.

3.8 Available systems

EASAMS in a study for ESRO (EASAMS 1972) gave a complete survey of all SLAR systems. An investigation, made in 1972, on availability and prices resulted in Table III. The only available synthetic system is the Goddyear APQ-102. Military versions of this system are being flown in several configurations, with differing final resolutions.

The system indicated in Table III is the version also used for civilian applications (RADAM project). Its price is such that even a combination of two real aperture SLARs (a short-range system combined with a long-range system) is much cheaper than one SAR.

Together with the larger flexibility (direct availability of the image without the intermediate step of a hologram, combination of both long-range and short-range) such a combination will provide greater possibilities.

In Table III two short-range systems are listed, both operating in the Q- (or K_a-) band:

The Westinghouse APD-7 (US made) and the EMI P 391 (UK made).

Also listed are two long-range systems both operating in the X-band: The Motorola APS-94D (US made), (in two versions of which one operates in the C-band) and the EMI system, which is installed in the NLR aircraft and was used in the experiments for SEA ICE '75.

Experience in the Netherlands has been obtained with both EMI systems. However, on most occasions, the systems were not flown simultaneously. From the experience gained it can be stated that two such radar systems (a long-range and a short-range) do categorically form a good combination. Both systems were flown over land, over estuaries and over the sea. While each system has its typical preferred applications there was a sufficiency in overlap. While more work is needed in this particular sphere, it is beyond the meaning of this report to go here into more detail.

Table 3. *Available radar systems (Autumn 1972).*

Manufactures	Westingh.	Motorola		Goodyear	EMI	
	APD-7	APS-94D		APQ-102	P391	X-band
Wavel. (mm)	8.6	32	56	31	8.6	32
Type (aperture)	real	real	real	synth.	real	real
Resolution in azimuth (m)	$1.7R_{km}$	$7.7R_{km}$ $17.5R_{km}$	$15\ R_{km}$	15	$3.5R_{km}$	$16R_{km}$
in range (m)	8	30	30	15	15	30
Max.range (km)	21	100	100	37	28	63
Antenna pol.	HH	HH VV	HH VV	HH	HH	HH
Weight (kg)	225	235	307	232	195 2)	205 2)
Vol. (- ant., m^3)	0.25	0.306	0.306	0.28	0.44	0.44
Power, W	3170	1940	1940	2951	900	800
MTI	no	when required		no	yes	no
Price (in US $,1972)	650k	300k 3)		1.5m 1)	320k	190k

Notes: 1) with some spare parts and optical processor

2) with two aerials

3) without MTI

3.9 The SLAR system used in SEA ICE '75 and its limitations

Details of the X-band SLAR system used in the SEA ICE '75 experiments are given in summarized form in the last column of Table III. Table IV gives them in more detail.

The system is installed in the Beechcraft Queen Air laboratory aircraft of the National Aerospace Laboratory (Amsterdam).

A navigation system giving aircraft altitude, attitude and position is also carried in this aircraft; the output from this system is not yet incorporated in the software of the radar system.

Table 4. *The EMI X-band SLAR.*

Transmitting valve	Pulsed magnetron CV 6035.
Frequency	X-band, 9600.
Power output (nominal)	80 kW peak, or 25 kW in low level role.
Pulse duration (nominal)	0.2 sec.
PRF	1260 or 2520 Hz, depending on range.
Receiver	Superheterodyne with balanced X-tal mixers and using a(lin-) log i.f. amplifier (linear to about 5 - 10 dB above noise).
Local oscillator	Klystron (CV. 7494) with manual and automatic frequency control.
IF amplifier	log. law - 50 dB compression (lin-log).
IF	45 MHz.
IF bandwidth	6 MHz.
Aerial system	Slot radiators in 7'6" long aerial fitted with a horn; double. Available: single antenna ditto 15' long.
Polar diagram	$cosec^2$ (imperfect).
Beam width (elevation)	36^o at 6 dB, 23^o at 3 dB points.
Beam width (azimuth)	56' at 3 dB points.
VSWB	0.9
Display	Intensity modulated scan on a CRT photographed on 5" wide sensitized paper and rapidly processed. Film system (neg.) available.
CRT (indicator)	high resolution 2" Ø, flat faced, FM deflection and focussing.
Monitor display (control)	type of A-scan.
CRT (monitor control)	3" by 1" rectangular faced, with FM "X" deflection, electrostatic focussing and "Y" deflection.
Calibration markers	for test purposes only: ½, 1 and 4 n.m.
Display map scale	at low level 50K:1 and 100K: 1, corresponding to 3.15 and 6.3 km, both sides. At medium level 200K:1 and 500K:1 will be used corresponding to 25 and 63 km respectively (one side only).
Height measuring facility	5000 ft to 50.000 ft (not used).
Height measuring accuracy	within ± 150 ft (not used).
Power supplies	200 V ± 2%, 400 Hz 3-phase.
Power comsumption	approx. 800 VA.
Air pressure requirements for aerial and waveguide	17 lb. per sq. in. absolute
for transmitter/receiver and modulator	18.7 lb per sq. in. absolute.
Aerial switching	automatically after groups of 16 pulses, loosing 3 pulses each time when aerial changeover is actually occurring.

Weights and volumes of units:

Transmitter/receiver		18" x	18¾"	x 8"	64 lbs (29 kg)
Modulator		18" x	13"	x 8"	38 lbs (17.5 kg)
Rapid processor unit (incl. range indicator 27 lbs)		54" x	18"	x 7½"	105 lbs (47.5 kg)
Waveform generator		18" x	7½"	x 8"	15 lbs (6.8 kg)
Monitor, control		8½" x	9½"	x 10¼"	15 lbs (6.8 kg)
Power unit		18" x	5"	x 8"	23 lbs (10 kg)
Antenna		8' x	?	x ?	approx. 2 x 20 kg.
	resp.	15' x	?	x ?	approx. 1 x 30 kg.
Total weight (without antennas)					260 lbs (120 kg)

As already stated, the SLAR is a long-range system with a resolution associated with such a system; that is: 30 m in range (across-track) and 16 mrad ($16.R_{km}$) in azimuth (along-track) e.g. 80 m at R = 5 km.

As used the system is not entirely representative of the possibilities of such a long-range system for the following reasons:

1. The aerial (in a pod) is hard mounted to the aircraft. Since no electro-

nic corrections for aircraft motions are incorporated in the system all movements of the aircraft (see fig. 9) are reproduced in the image.

2. The system was originally intended as a navigation system for the UK TSR-2 aircraft. It was therefore equipped with a rapid processor unit (RPU) to give the navigator an immediate view of his surroundings for updating his navigation equipment. The imagery is thus produced on a film with a paper base. Although the manufacturer claims that the film can handle a sufficient range of density steps to cover a dynamic range of 20dB, this form of image presentation is not optimal.

   On the other hand it has the clear advantage of offering the operator in the air an immediate assessment of what he is doing.

   Developments are underway
   a. to change over to a film with a standard transparant base,
   b. to record the image on magnetic tape in order to preserve the full dynamic range present in the original signal.

3. The system is one of a prototype series made during the development of the TSR-2 aircraft. When the development of this aircraft was stopped the further development of the radar system was also cancelled. For this reason, the system still has two major drawbacks:
   a. The aerial system is not $cosec^2$.
   b. The time constants used in the MF- and video circuitry are not optimal (too long).

   These drawbacks result in the far out signals becoming weaker when a strong echo is met at short range (loss of signal at the longer rangers). For this reasons the 1:100k scale (range 2x6 km) was primarily used and the 1:200k scale (range 24 km) to a limited extent since these effects play only a minor role at these ranges.

   These drawbacks are now being considered and worked on and will hopefully be eliminated in due course.

   It should be emphasized here that the drawbacks of this particular radar should be taken into account in the evaluation of the possibilities of using the SLAR system over ice.

4. Analysis of SLAR Imagery in Comparison With the Aerial Photography

4.1 Discussions

Mosaics and high-altitude photography obtained from the flights indicated in Table V were evaluated and compared.

Table 5. *Imagery used in the analysis.*

Date March '75	Flight No	Mosaics 5 x 5 km	15 x 15 km	High-alt. photog.
12	950			
13	951	x		x
14	952		x	
17			x	x
18	953	x		
19	954			

The immediate surroundings of TOR were compared with the 5x5 km mosaics. In particular the flights 951 and 953 were used for this purpose. Many lines can be seen in the radar image. This seems to indicate that small altitude differences (ridges, leads: edge ice/water) show-up clearly in the radar image in comparison with the stereopairs obtained with the Hasselblad camera. The altitude differences involved are small, much smaller in fact than the height of the helicopter and TOR. This observation was met again during ice thickness measurements and in measurements with the radar altimeter.

Narrow ship-tracks in ice are probably scanned from one side only (see fig. 11).

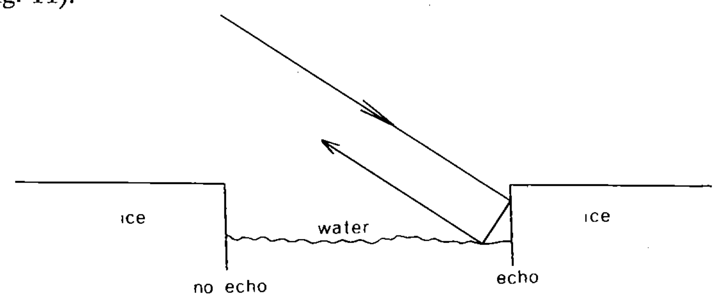


Figure 11. *Echo from the far side of a channel caused by corner effect.*

Because of this effect it is diffecult to differentiate between ridges and narrow channels.

Efforts were made to plot ridges and channels from the mosaics and to compare the image so obtained with the lines found in the radar images (see fig. 12).

There seems to be a reasonable amount of agreement between the two types of images; this becomes more evident by taking into account that:

a. not much time was available for the analyses,
b. the "whiteness" of the aerial photography makes it easy to miss small altidude variations in the ice,
c. the large number of lines and dots on the SLAR images means that it is quite possible to miss echoes in plotting simply by misjudging their significance.

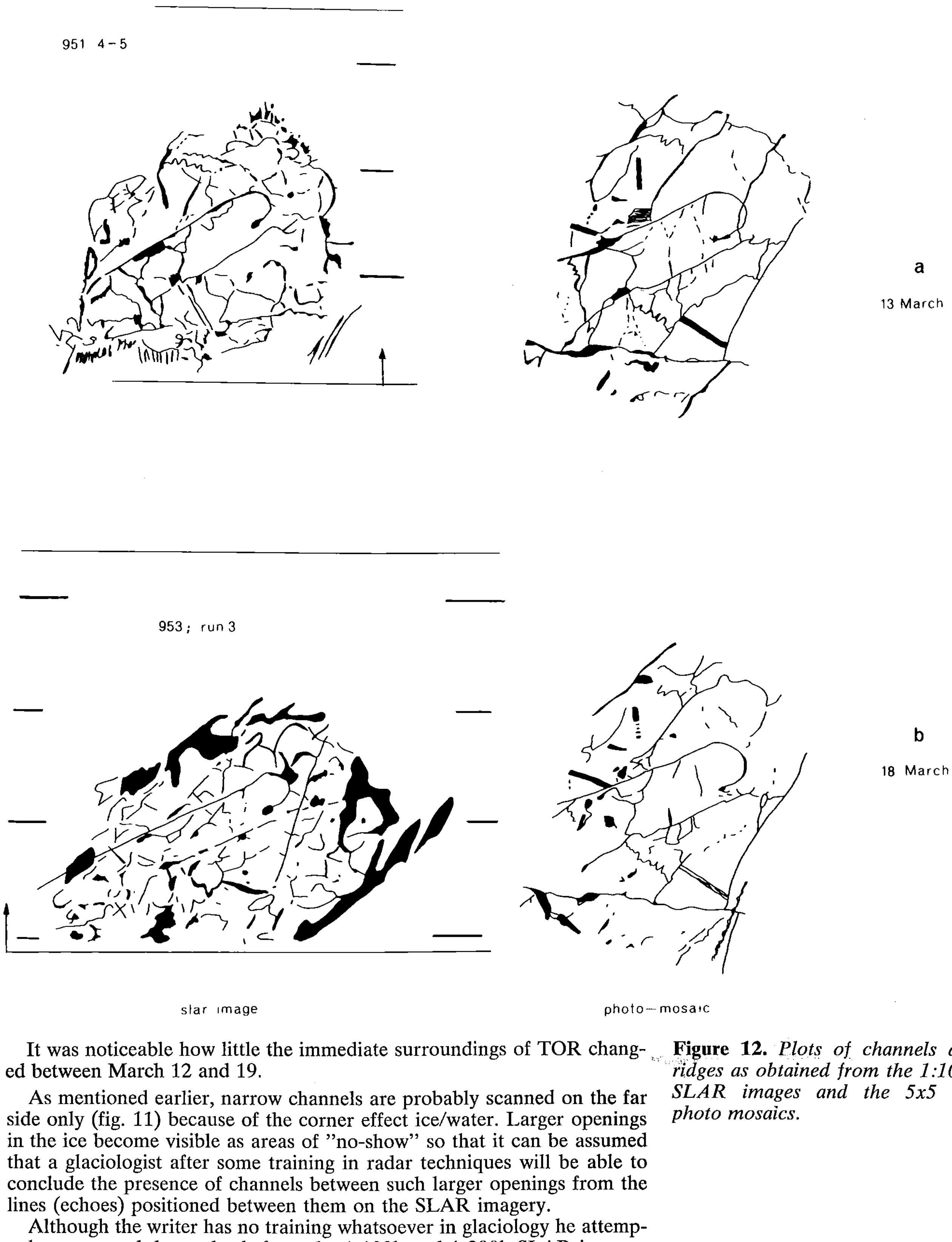


Figure 12. *Plots of channels and ridges as obtained from the 1:100k SLAR images and the 5x5 km photo mosaics.*

It was noticeable how little the immediate surroundings of TOR changed between March 12 and 19.

As mentioned earlier, narrow channels are probably scanned on the far side only (fig. 11) because of the corner effect ice/water. Larger openings in the ice become visible as areas of "no-show" so that it can be assumed that a glaciologist after some training in radar techniques will be able to conclude the presence of channels between such larger openings from the lines (echoes) positioned between them on the SLAR imagery.

Although the writer has no training whatsoever in glaciology he attempted to map such larger leads from the 1:100k and 1:200k SLAR imagery taken from the immediate surroundings of TOR (up to a 20 km). For this purpose flights 950—952 were combined together and used with the flight 953. Maps were made from these flights (fig. 13A and B). Flight 954 of March 19 showed that the whole ice pack near TOR had merged together again sometime between March 18 and 19.

These two SLAR maps can be compared with the 15x15 km mosaics made on March 14 and 17 respectively and the high-altitude photography taken on March 13 and 17 respectively. The conclusion has to be that the maps obtained with the SLAR are in fact far from complete. Only the wider openings in the ice are immediately recognizable.

Another problem can occur with other areas of "no-show" as very flat and smooth icefloes, although these are sometimes recognizable by their

Figure 13a. *Map of larger openings in the ice as of March 13, as obtained from the 1:100k SLAR images of flights 950 to 952.*

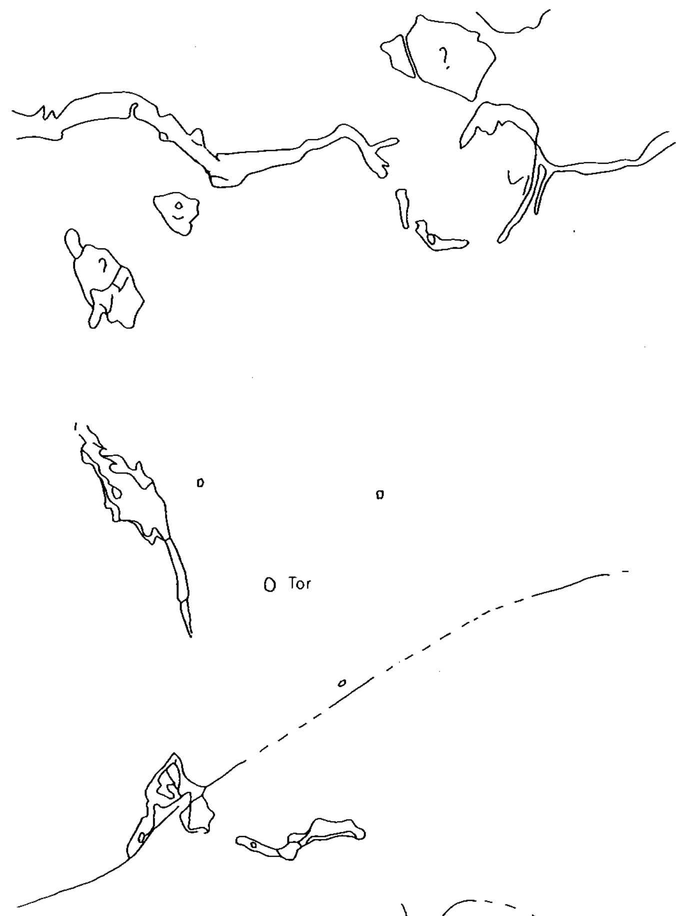
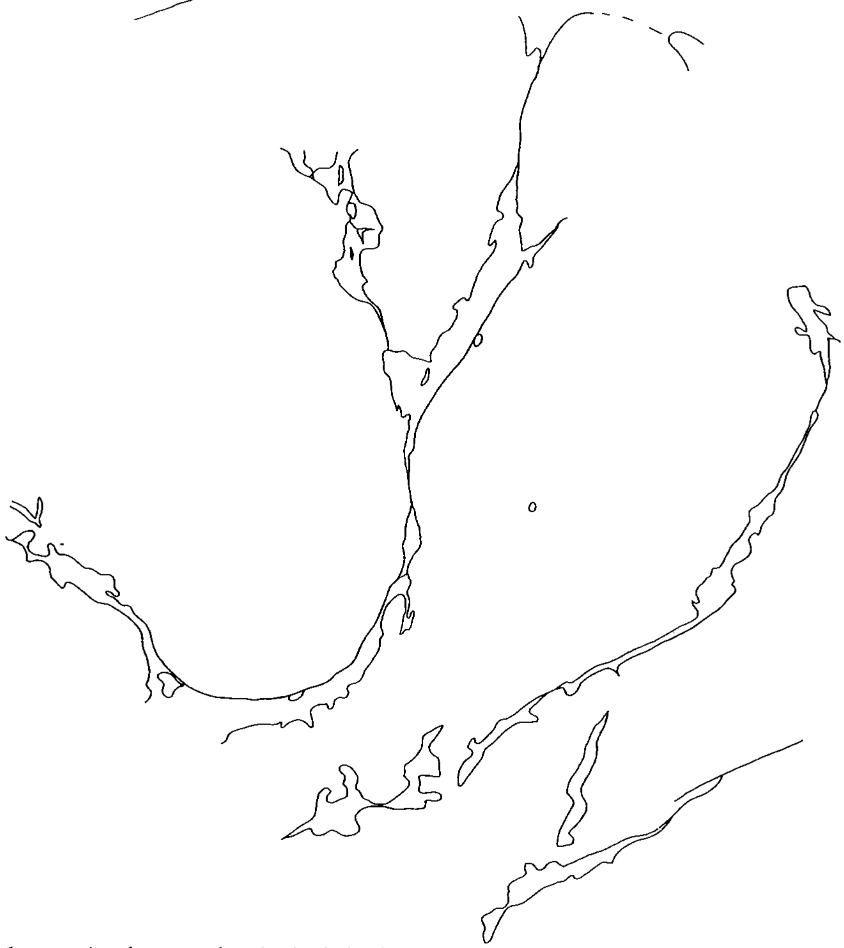


Figure 13b. *Map of larger openings in the ice as of March 18, as obtained from the 1:100k and 1:200k SLAR images of flight 953.*



shape. Again a trained glaciologist may do better following some radar training.

It is difficult to indicate at what width a channel will be seen as an area of "no-show". Resolution of the system used was 30 m in range and 16 mrad in azimuth, which means 64 m at mid-range (1:100k scale). The channel openings have to be in any case greater than this figure. Up till

64 m in width a channel will show-up as a line of echoes (corner effect of the further edge). Its actual presence will then have to be deduced by taking the surroundings into consideration. It should be remembered that the particular system used is in fact a long-range system, with a resolution for mapping at the scale of 1:250k and 1:500k. It was used at the shorter ranges because of the particular limitations this system has (see par. 3.9). A short-range system with a resolution of 10 to 15 m and working at a scale of 1:100k would certainly give better results.

Another limitation of this particular radar system is its presentation (RPU). A better representation of the full dynamic range of the target signal will certainly make visible more detail in an ice field. Registration on tape and later density slicing may provide the tool to investigate this better.

Looking to all imagery the impression is gained that the average radar cross-section of ice will lie in between that of sea and land clutter.

4.2 Conclusions

All abrupt altitude differences — even very small ones — in an ice pack will be recorded by a SLAR. These can be: ridges, but also the far edge of a lead. This gives to the SLAR image its streaky characteristic.

Resolution of this particular radar system is such that leads up to a 50 m wide will not be seen as an area of "no-show" but as a continuous line (echo from the far edge). Their presence must then be inferred from the surroundings. A high resolution (up to 10 m) short-range system will certainly do better in this respect.

Larger openings can be mapped as areas of "no-show".

Borders of ice fields can be mapped directly. Slush is visible in the sea clutter and in the larger channels.

By a better use of the dynamic range of the echoes, more detail can probably be made visible.

Taking into account the limitations of the particular system used for these experiments it seeems justifiable to conclude that a similar long-range radar — but with a better resolution in dynamic range and used at the proper scales — can have a great potential for surveying large ice masses.

This usefullness will be greatly enhanced when such a system is supplemented with a high resolution (spatial as well as in dynamic range) short-range system.

5. Discussion on Specified Items

It was decided that the report of each participating group should in particular discuss a number of specified items. The discussions on those items regarding SLAR is based on the results of the experiment in the Bothnian Gulf, however, the effect of the specific limitations of the SLAR equipment used (see par. 3.9) has been taken into account. This means that the remarks will apply to any commercially available system of the same type (”long range” real aperture X-band SLAR).

As outlined prominently in paragraph 3:

- ☐ SLAR transmits its signal cross track of the aircraft at angles $\geq 45°$ from the vertical.
- ☐ it receives the returning signals in the same direction, also at angles $\geq 45°$ from the vertical.
- ☐ the reflection of the radar signal from the earth's surface can only be directed back towards the radar aerial providing there are irregularities, even very small, at the surface. This means that a very smooth surface will not reflect back to the aerial but away from the aerial (mirror effect).
- ☐ basically the SLAR will provide information on surface structures and geometrical shapes of objects. The intensity of the returning signal will show differences in the nature of the targets.

5.1 Ability of SLAR to differentiate

Water

Due to the presence of capillary and larger waves at windforces ≥ 1 Beaufort on the watersuface the radar image will show sea clutter or, under certain conditions, even distinct patterns which features are easy to recognize.

At windforces between 0 and 1 Beaufort only will there be no sea clutter on the image (mirror effect).

Ice

A large and very smooth icedeck will not show on the radar image, neither when it is bare nor corvered in snow, or covered with a thin layer of water on which the wind cannot generate waves (mirror effect).

The boundary between such an ice area and open water will be seen on the image because of differences in height. However, this will accur very seldom. Due the effect of currents and wind, a large icedeck will be more or less cracked. Cracks, small and larger ridges, irregularities, leads, smaller open waterareas, floe structures are normal features.

The radar image of such an area is typical for ice. Single floes and slush in water will also show-up on the radar image (see figures 14a—14e).

Based on theoretical considerations as well as on the results obtained during the experiment in the Bothnian Gulf and on experience gained elsewhere in the world, the following conclusions can be readed on the viability of SLAR observations, assuming that personnel familiar with ice conditions and radar images is available.

- ☐ Ice can be differentiated from open water.
- ☐ Water-covered ice and water can be differentiated in most cases.
- ☐ Snow-covered ice can only be differentiated from snow-free ice providing the surface irregularities are different.
- ☐ Information on the thickness of ice cannot be obtained by SLAR. Some indication of thickness can be inferred from differences in surface structures of younger, thinner ice and of older, thicker ice.
- ☐ The overall percentage ice/open water can be estimated with an accuracy sufficient for practical purposes.
- ☐ The presence and concentration of ice roughness can be established.

It is not possible to measure the height of ridges and heavy deformations or to differentiate between smaller ridges and heavy deformations.

- ☐ Using a series of SLAR flights it is possible to establish the movement of ice for a large ice area as a whole provided a position finding system is included in the system.
Movement within an ice area can be established because the larger structures last longer and provided their identification is simple.

5.2 Operative aspects of the SLAR

The **resolution** of the SLAR system is discussed in paragraph 3.

The **mapping capability** depends on the speed of the aircraft and the magnitude of SLAR coverage. This coverage will be defined by the choice of the image scale.

Based on the aircraft used during this experiment and the SLAR equipment used the maximum mapping capability of this typical system is as follows:

Scale 1: 50.000,	250 km/h x 6 km =	1.500 km²/h
Scale 1: 100.000,	250 km/h x 12 km =	3.000 km²/h
Scale 1: 200.000	250 km/h x 24 km =	6.000 km²/h
Scale 1: 500.000,	250 km/h x 60 km =	15.000 km²/h

The effective capability is somewhat lower on account of time loss for turning the aircraft to a new course and overlaps defined by the flight pattern (see fig. 7). The scales of 1: 200.000 and 1: 500.000 were only suitable for obtaining very general and basic information; both were only used occasionally.

An optimal SLAR system will achieve higher figures than mentioned depending on system, aircraft and flight procedure.

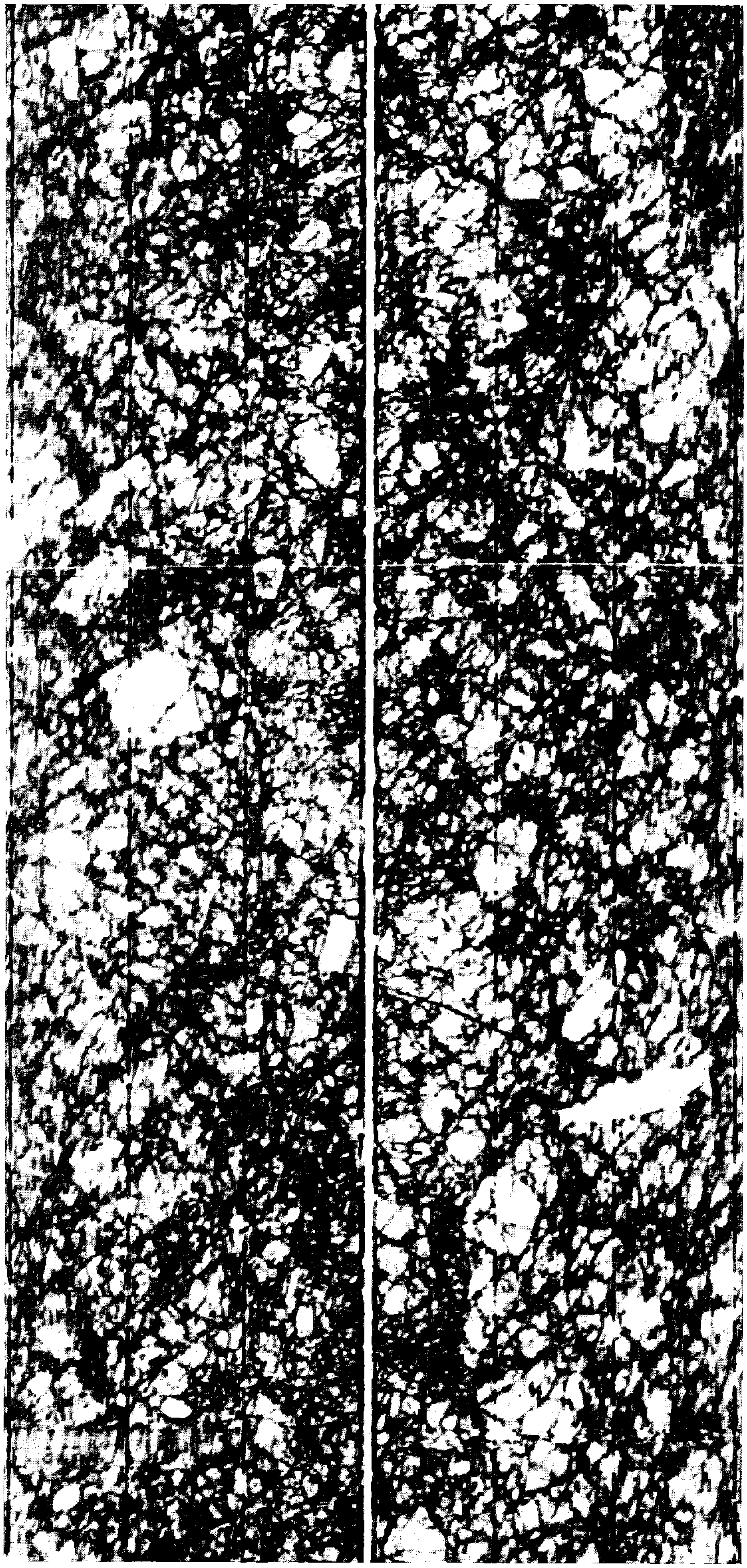
In respect of **weather dependence,** it is clear that SLAR results will not be directly influenced by clouds, fog, haze or wind. Indirectly air turbulence can distort the image due to unstable behaviour of the aircraft. Heavy showers of rain, hail or snow can impair the image. Q-band radar is more sensitive in this respect than is X-band radar.

The SLAR results are not at all influenced by light conditions, in other words the SLAR system is operational during 24 hours a day.

Figure 14a. *Negative SLAR image (scale 1:100.000) of ice and open water.*

Figure 14b. *Negative SLAR image (scale 1:100.000) of open water with slush.*

Figure 14c. *Negative SLAR image (scale 1:100.000) of cracked ice area.*



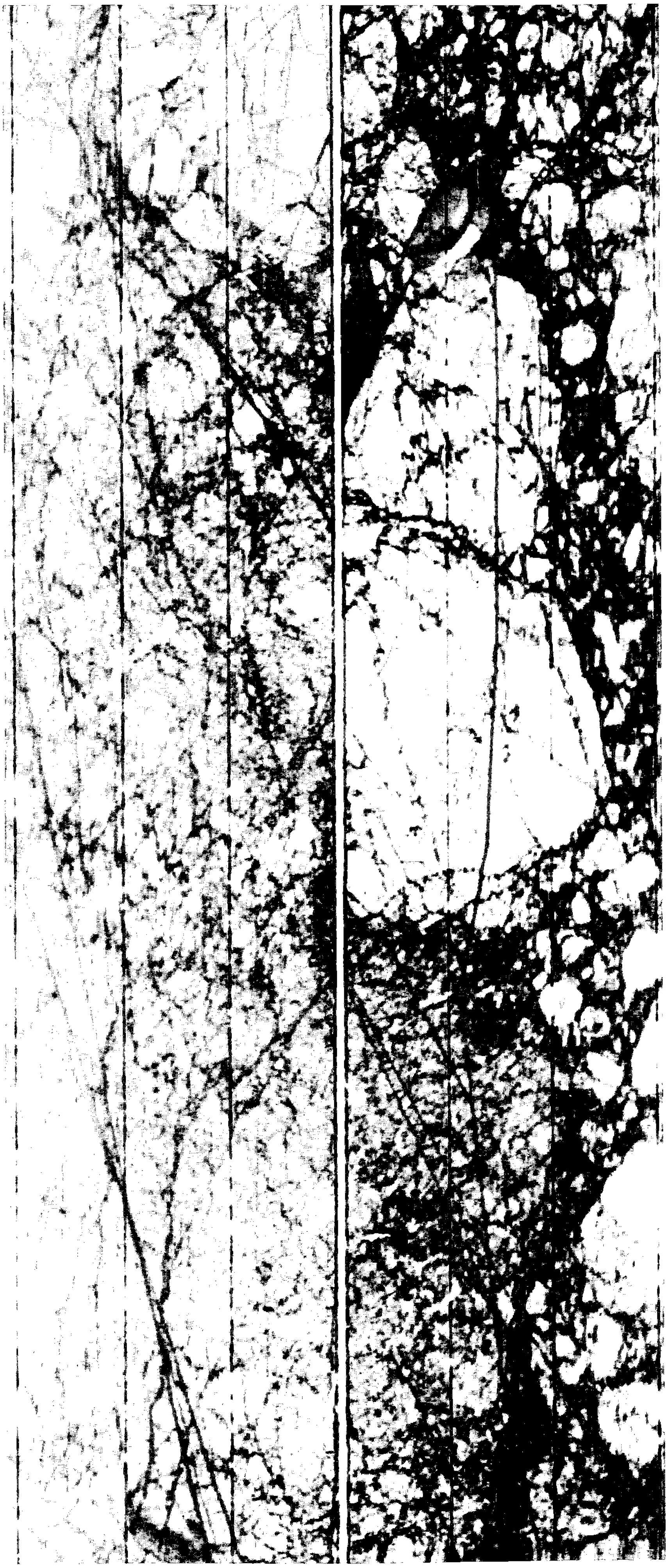


Figure 14d. *Negative SLAR image (scale 1:100.000) of cracked ice area with larger structures and ship tracks.*

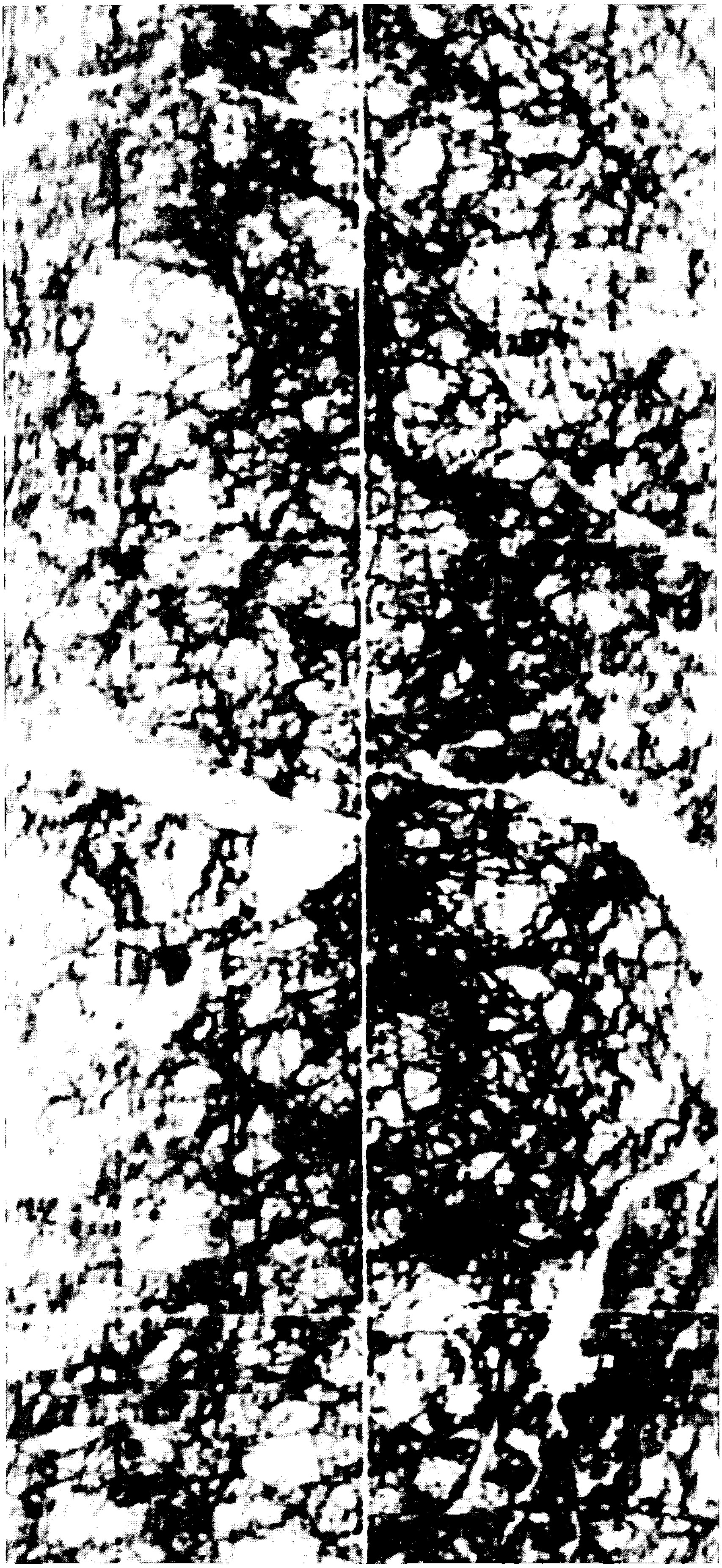


Figure 14e. *Negative SLAR image (scale 1:100.000) of cracked ice area with enclosed water areas.*

6. Some Remarks on Sensors and Carriers

Sensors

For remote sensing purposes there are a number of effective sensors available both in the microwave part of the spectrum as in the so-called optical part (including the thermal infrared) of the electromagnetic spectrum. Naturally each sensor type will have its own inherent limitations.

As a result, one or more additional sensors will be needed in most applications.

The value of any operational system depends on the level to which it can meet the requirements. In this particular case, the system under consideration has to meet a number of operational requirements under rather unfavourable conditions.

It is not reasonable to expect that one sensor will be able to provide all answers required.

Beacuse of the unfavourable conditions to be overcome, microwave techniques will obviously be the primary choice.

The most capable sensor for an operational system such as that under discussion, is the SLAR. Because of the demand for almost real-time presentation and because of the costs involved, the most advisable type would seem to be real aperture SLAR.

There are 2 SLAR systems available: X-band (longed range) and Q-band (shorter range). In combined use they are very capable.

When considering one SLAR system only (X-band) it may be worthwile to choose a better resolution as well in azimuth as in range, than available in the system used during these experiments.

The APS-94D is delivered standard with a 15 ft antenna (resolution 7.7 R_{km}) with horizontal polarization. Experience gained recently in the Netherlands learned that hor. polarization fits many applications.

It would be a very worthwile proposition if the pulselength could eventually be improved to 0.1 μ sec (15 m).

Before making a choice, an exercise with a high resolution Q-band system (e.g. the P 391) might be worthwile.

The X-band SLAR system has already shown its capabilities as a sensor in oil and in navigation and surveillance systems.

For measurements of ice thickness and height of heavy ridges at least one other sensor should come under consideration. However, it is beyond the scope of this report to discuss additional sensors.

The authors suggest that further information could be obtained by reference to the activities of the U.S. Coast Guard in respect of an oil and ice surveillance system.

Carrier

An aircraft is the obvious carrier. A helicopter is not suitable on account of excessive vibration and on price. As far as the SLAR system is concerned, the aircraft must be suitable for installation of the aerial system. The length of the antenna system is about 2.5 or 4.5 m (see par. 3). In practice installation can be done either in a pod, at the side of, or at the tail of the aircraft. The total weight of a r.a. X-band SLAR system is between 160 and 200 kgs.

For flights over the sea the aircraft is required to have more than one engine.

The selection of the aircraft is based on a number of considerations, e.g. payload, types of missions, price, operating costs, ground based facilities, spares and so on.

A trade-off study for the aircraft selection, based on well defined requirements and on available alternatives will be necessary.

Related subjects as navigation equipment, recording facilities and so on should be included in this study.

References

BROWN, W.M., PORCELLO, L.J.: An Introduction to Synthetic-Aperture Radar. IEEE Spectrum *6*, pp. 523—561, (1971).

DE LOOR, G.P. and ERADUS, W.J.: Remote Sensing Equipment for Rijkswaterstaat, Part II: Backgrounds. Report Physics Laboratory TNO, PHL 1973—34, (1973).

EASAMS: Side-Looking Radar Systems and their Potential Application to Earth Resource Surveys. 7 volumes; report prepared for ESRO under ESTEC Contract 1537/71/EL; August 1972.

GOODYEAR AEROSPACE CORP.: Earth Resources Radar for a Remote Sensing System. Goodyear Aerospace Corp. Report GAP—4947, Rev. A; 28 Oct. 1970.

HARGER, R.O.: Synthetic Aperture Radar Systems: Theory and Design. New York: Academic Press 1969.

La PRADE, G.L.: An Analytical and Experimental Study of Stereo for Radar. Photogramm. Eng. *92*, pp. 294—300, (1963).

MOORE, R.K.: Imaging Radars for Geoscience Use. IEEE trans. on Geoscience Electronics *GE-9*, pp. 155—164, (1971).

NATIONAAL LUCHT- EN RUIMTEVAARTLABORATORIUM — NATIONAL AEROSPACE LABORATORY NLR	Microwave sensors SLAR[1]	

DATE	TIME	SCALE	ALTITUDE	COVERED AREA
12-3-1975	14.45 - 16.00 h	1:100.000 Band Width 2 x 6,3 km	300 m	Swedish 15 x 15 km area Preliminary tests
13-3-1975	13.00 - 14.30 h	1:100.000 1:200.000	300 m	Swedish 15 x 15 km area 1 run on track 270° S of TOR
14-3-1975	11.00 - 13.00 h	1:100.000	400 m	1 run over TOR → Malören → Bjuröklubb → east southeast to Finnish coast → north to Malören → Luleå
18-3-1975	11.00 - 12.00 h	1:100.000	150/300 m	Swedish 15 x 15 km area
"	12.00 - 13.30 h	1:200.000 Band Width 1 x 25 km	6000 m	65.30N, 23.00E → Gasören → east to 64.40N, 23.10E → north to 65.30N, 23.10E covering Finnish and Swedish 15 x 15 km areas → Luleå
19-3-1975	13.15 - 15.30 h	1:100.000	150/300 m	Swedish and Finnish 15 x 15 km areas

1) For further details see Form of SLAR Programme Flight Data.

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