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**THE REMOTE DETECTION OF DRAINED ICE AREAS AROUND BREATHING
HOLES AS AN ALTERNATE RINGED SEAL CENSUS TECHNIQUE**

by

✓ Susan A. Digby, B.Sc.

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A thesis submitted to the Faculty of Graduate
Studies and Research in partial fulfillment
of the requirements for the degree of
Master of Arts in Geography

Department of Geography
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Ottawa, Ontario

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AN ALTERNATE RINGED SEAL CENSUS TECHNIQUE"

submitted by Susan Ann Digby, B.Sc., B.Ed.
in partial fulfilment of the requirements for
the degree of Master of Arts.

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ABSTRACT

An alternate method of monitoring winter resident location and abundance of the ringed seal from aerial "haul-out" surveys is proposed. The alternate method consists of using remotely sensed data, aerial photography, airborne radar imagery or satellite imagery, to count breathing holes in undeformed fast first-year ice. The presence of holes are inferred from identification of areas of drier ice that form around the holes in water-covered fast first-year ice during the summer melt period. The reliability of using remotely sensed imagery for this application varies largely as a function of resolution. Surface observations and remotely sensed data used in this study were obtained in the vicinity of Prince Patrick Island, NWT.

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LIST OF ACRONYMS

AES	Atmospheric Environment Service
CCRS	Canada Centre for Remote Sensing
CV-580	Convair 580, CCRS aircraft
DAD	Data Acquisition Department (CCRS)
Electra	An aircraft operated by the Ice Branch of AES
MSS	Multispectral scanner
NOAA	National Oceanic and Atmospheric Administration (U.S.A.)
RC-10	A 23 cm format mapping camera
RPO	Radarsat Project Office (CCRS)
SAR	Synthetic aperture radar
SLAR	Side-looking airborne radar
TIR	Thermal infrared
VHRR	Very high resolution radiometer

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

This thesis examines the formation of drained ice areas around seal breathing holes, the use of remotely sensed data to detect the drained areas and the value of the information to studies of the ice-inhabiting ringed seal, Phoca hispida. Data consists of surface observations, airborne visible-light photography, radar imagery and satellite imagery for areas of first-year ice in Mould Bay (76°14' N, 119°21' W) and Crozier Channel, N.W.T. during the summer melt period, 1982 (figure 1.1).

The ringed seal, possibly the most ubiquitous Arctic mammal with a population thought to number in the millions (McLaren, 1958a; Smith, 1973b), has a circumpolar distribution. In spite of its abundance, rather little is known about the seal because its habitat impedes observations. Although no separate stocks have been defined, the species has been divided into six sub-species, largely on the basis of geographical distribution (figure 1.2) and small morphological differences. The seals are considered permanent residents in these areas as only limited migration is thought to occur (Burns and

Figure 1.1 Locations Referred to in Text

Figure 1.2 Location of *Phoca hispida* sub-species

Adapted from Blood (1978) and Stirling and Calvert (1975)

Harbo, 1972; Smith and Stirling, 1978). Subsequent reference to the ringed seal (Phoca hispida) in this study is to the subspecies P. h. hispida found in the Arctic Ocean and sea-ice of northern Eurasia, Greenland and North America. There has been some recent discussion as to the existence of a subspecies of P. hispida in the pack ice of Baffin Bay (Finley et al., 1983), although the sample size was small and differences between populations subtle.

The ringed seal forms the major trophic link between under-ice primary productivity and carnivores that live on the ice and adjoining land masses (Appendix A). The importance of the ringed seal in the very simple food chain provides the justification for habitat and population studies especially given mankind's growing intervention in recent years. As yet even natural population fluctuations are not understood and baseline information is in the process of being acquired (Stirling et al., 1982; Smith, 1975a).

A review of the ecology of the ringed seal in Chapter 1 reveals the reason for the commonly used census technique. This technique involves aerial surveys during the period of moult when seals are found in large numbers hauled out on the ice. A critical review of the census technique and of seal behaviour reveals a large number of complicating factors. These are such that estimates of winter resident seal population from 'haul-out' counts can be subject to inaccuracies of several orders of magnitude (McLaren Marex Inc., 1979).

Prior to this study, the use of remotely sensed data in studies of the ringed seal was restricted to experimental use of aerial photo-

graphy in two studies of seal breathing holes (Finley, 1978; McLaren Marex Inc., 1979), and use of LANDSAT data for delineating ice types (Finley, 1978).

Detailed surface observations and multifrequency remotely sensed data used for this study were obtained during a sea-ice experiment. Although not designed to obtain data on ringed seals, incidental observations revealed that breathing holes had a major effect on the ice which could be detected remotely at several wavelengths and from various altitudes.

The aim of the analysis of data from Mould Bay and Crozier Channel is two-fold; first, to examine the characteristics of the drained ice areas and their location relative to ice types, and, second, to determine the value of the differing types of remotely sensed data as sources of information on breathing holes either as implied from drained ice areas or as observed directly.

The final objective of the study is to evaluate the potential of monitoring drained ice areas by remote sensors in order to determine seal distribution and density.

CHAPTER 2

THE RINGED SEAL

2.1 GENERAL DESCRIPTION

The ringed seal (figure 2.1) derives its common name from its circular pelage markings. The scientific name is derived from the Greek phoca, meaning "seal" and the Latin hispida meaning "rough" or "bristly" which refers to its hair. The coloration of the seals varies but typically the markings found on the upper side are black or dark grey with a lighter grey background and the underside is commonly a more even grey. The seal averages about 135 cm long and has a girth, measured immediately behind the foreflippers, which averages 89 percent of the length (McLaren, 1958; Burns, 1970). Measurements of length and girth can be reliably used to estimate body weight (Usher and Church, 1969) which usually varies between 40 and 90 kg for adults.

2.1.1 Habitat and Ecology

The habitat and ecology of the ringed seal are of importance to this study as they determine the time and location of observations

Figure 2.1 The Ringed Seal (*Phoca hispida*)

Adapted from a photograph in Handbook of Marine Mammals, Vol. 2, Seals. ed. Sam H. Ridgway, Academic Press, 1981.

and seal counts. The ringed seal is one of two species of seal able to maintain a breathing hole year round in landfast ice. The adaption led to the suggestion by McLaren in his benchmark work of 1958, (1958a) that the extent of stable fast first-year ice for pupping is a limiting factor to seal populations. The bearded seal (Erignathus barbarus), the other seal found in fast ice is far less abundant than the ringed seal and is more commonly found in pack ice or in the vicinity of polynas where open water occurs year round (Burns, 1970; Stirling et al., 1982). The bearded seal is, however, primarily a benthic feeder with the result that it is usually found in shallow water 25 to 75 m deep, whereas the ringed seal appears to be unrestricted by depth.

Canada has a large amount of fast ice in the winter (figure 2.2) as the numerous islands of the Arctic archipelago prevent significant ice movement and development of areas of open water except in major channels close to pack ice (Markham, 1981) and in polynas (Smith and Rigby, 1981). Much of the fast ice melts or breaks up and moves away during the summer with the result that most winter fast ice is composed entirely of first-year ice or multiyear floes in a first-year matrix. A lesser quantity of fast ice is second-year and multiyear fast ice is relatively uncommon, usually associated with shallow waterdepths in the high Arctic.

Ringed seals are primarily found in first-year ice where they keep open breathing holes in ice as it forms in the fall (Smith and Hammill, 1981). In many cases breathing holes are found in areas

Figure 2.2 The Winter Extent of Fast Ice in the Arctic Archipelago

Adapted from material prepared for the Atmospheric Environment Service, 1981.

where open water persists until late in the year. The formation of ridges and hummocks by ice compression can also result in small areas of open water or areas of weakness which are often utilized by seals (Smith et al., 1978). Breathing holes are evenly distributed if the ice forms homogeneously (Finley, 1978). Once initiated, breathing holes, about 35 cm in diameter, are maintained throughout the winter in ice that may reach thicknesses in excess of 2 m (Bilello, 1977). Seals keep the holes open by abrading the relatively soft, new ice that forms on the sides and surface with the claws of their front flippers (Smith and Stirling, 1975). If first-year ice has not disappeared during the summer but has remained to form second-year ice, seals are thought to occupy the same holes. Similar hole densities have been noted in first-year ice and subsequent second-year ice (Finley, 1978). This seems reasonable as sea water in holes in second-year ice would freeze to form first-year ice so hole maintenance should be equivalent to that in a first-year ice cover. In addition, it has been suggested that seals exhibit site fidelity (Smith and Hammill, 1981).

Once breathing holes have been established it is thought that they are maintained and used by individual seals or groups of seals and may be territorially guarded (Stirling and McEwen, 1975; Smith and Hammill, 1981). By early winter the seals are able to rest on the ice surface within the snow cover in what are known as sub-nivean lairs. The sub-nivean lairs require a minimum snow depth of 20 cm (Smith and Stirling, 1975) and are not visible from the surface. The

roof of the lair, an icy layer covered with wind-packed snow, will support the weight of a person. The complete invisibility of the seals has resulted in little information about seals in winter. Biological information during the winter has been obtained from seals hunted by the Inuit or by scientists (McLaren, 1958b; Smith 1975b).

The only winter ecological studies have been undertaken by T.G. Smith of the Department of Fisheries and Oceans who, with the aid of a trained Labrador dog, has excavated large numbers of sub-nivean lairs in the winter and early spring. Results have shown that the lairs can be divided into five types: haul-out lairs, haul-out lairs used by rutting males, suckling lairs, escape lairs and birth lairs, all of which are recognized and distinguished in the Inuit language. The two major divisions are single haul-out lairs used by male or single seals and the complexes of more than one lair used by paturient females. The latter arrangement is thought to be a survival mechanism, whereby if a predator disturbs one lair, the pup can be transferred to another lair located nearby (Smith and Stirling, 1975).

As temperatures rise in the spring, a decrease in the snow depth and softening of the snow causes the roof to collapse, which leaves a hollow in the snow. By late May the young of the year, born in March or April, have usually been weaned and are able to fend for themselves. Unusually early springs can result in high pup mortalities from exposure and predation.

In June, while most of the winter landfast sea-ice is still

stable, the seals moult, at which time they spend a considerable portion of the day hauled out on the ice. Seals have been noted to spend up to 40 hours at a time on the ice although a more typical duration is eight hours (Smith and Hammill, 1980). It is thought that the haul-out behaviour is necessitated by the increase in temperature needed for mitosis of the skin (Feltz and Fay, 1977). This period, which lasts for about three weeks, is the one time of the year when seals are readily visible. For this reason, census-taking aerial surveys are commonly flown during this period.

After haul-out, seals become less easy to observe as they return to the water for July, August and September when ice extent is at a minimum. Considerable time is spent feeding to restore the blubber, depleted during haul-out, to a maximum thickness prior to the onset of winter. From this overview of the seal's habitat and ecology it can be seen that obtaining population estimates for winter resident seals is difficult.

2.2 POPULATION ESTIMATES

2.2.1 Introduction

Population estimates, first undertaken in the late 1950's, have been derived from summer boat surveys, catch statistics and aerial surveys (Mansfield et al., 1975). The latter census method has become increasingly common, as it is a cost-efficient method of

covering large and often remote areas. In the last decade, companies involved in hydrocarbon exploration and development have been funding surveys to determine the distribution and population of marine mammals in areas that may be affected by development and operational activities (Smith et al., 1979).

2.2.2 Aerial Census Techniques

The potential of aerial surveys for monitoring ringed seal distribution and population size was realized in the mid-1960's when McLaren (1966) flew surveys in the Cumberland Sound region during the haul-out period. In the early 1970's guidelines for aerial surveys were published (Smith, 1973a). The guidelines are followed in many surveys in an effort to provide comparative year-to-year data for various regions. Sampling procedures specified the time of sampling, transect design, flight parameters and the derivation of population estimates from the resultant count of seals.

Surveys as outlined by Smith (1973a) are designed to be conducted at the height of haul-out when a maximum number of seals are on the surface. The occurrence of the period, which varies from year to year and from one area to another, usually takes place in the two or three weeks before ice break-up. Sampling should be designed to include representative ice types, any areas subject to hunting, areas at various distances from the shore, and areas of known difference in seal abundance. Some repeat sampling is recommended to test

variation in seal density from day to day and within areas of similar ice types. Smith specified that overflights should be made with aircraft such as the Cessna 337 or Twin Otter at altitudes of 300 ft. (90 m) or 500 ft. (152 m) depending upon visibility. Constant speeds of between 200 and 250 km/hr. should be maintained in order to sight seals before they dive. Counts of seals are made within half mile swaths on either side of the plane, a distance defined by markings on the plane windows and wing struts established from a test run over a measured marked area on the ice. Observers, one in the passenger seat and one behind the pilot, record seal count totals every two minutes. In addition, Smith recommends that a record should be made of the extent and quantity of ice, leads, pressure ridges, snow cover as well as meteorological conditions such as cloud cover.

Smith derived seal populations by multiplying observed totals by a factor of two, based on localized surface observations that suggested that 50 percent of the seal population at any one time was under the ice.

Although investigators have generally followed the recommendations outlined by Smith, most have modified the methods in some way. According to a review of survey techniques by Davis, Finley and Richardson (1980), survey altitudes have varied from 30 m to 152 m, speeds from 170 km/h to 240 km/h and transect widths from 0.4 km to 1.6 km. Seating arrangements have varied and the correction used to account for seals under the ice vary from a multiplication factor of 1.2 to 2.0.

A degree of error is inherent in the observation process. White seal pups can be difficult to detect against the snow or ice and some seals may be obscured by the remnants of sub-nivean lairs if the surface is snow covered. Differences in the number of seals counted can be as much as 40 percent (Finley, 1976) because of differences in visual acuity, experience, concentration, position in aircraft or aircraft factors such as an error in marking wing struts, uneven speeds or aircraft yaw (Stirling et al., 1982). In addition, seals have been noted to dive as the aircraft approaches (Renewable Resources Consulting Services Ltd., 1977).

Regardless of the differences in the mechanics of survey techniques and observer differences which could theoretically be reduced, there are a number of biological factors which may prove to have a greater effect on observed or estimated populations. The ideal haul-out conditions, when up to 80 percent of the population are on the ice, are rare and probably hard to recognize (Smith and Hammill, 1981).

The proportion of seals hauled-out at a given time depends on a number of factors: solar radiation, time of day, temperature, wind speed, the presence of polar bears, and probably the presence of water on the ice surface. Studies show that simple bivariate relationships between hauled-out seals and environmental conditions may not exist; for example, seals show a positive relationship with solar radiation (Stirling et al., 1982) although, at higher temperatures a negative correlation has been observed to occur. (Finley, 1978; Burns and

Harbo, 1972). The negative response is thought to occur when thermal input exceeds the seal's tolerance (Finley, 1978). Ringed seal densities tend to decrease with wind speeds greater than 5 knots (9.3 km/h) (Stirling et al., 1982) however, Finley (1978) found that while increased wind speeds delayed the seal's emergence onto the ice, once the seal was hauled out, the duration of its stay on the ice was not significantly different from that recorded for calm days.

The extreme variability in haul-out population from one day to another was noted in a study by McLaren Marex Inc. (1979) when twenty fiords and bays in southeastern Baffin Island were resampled at intervals of five and seventeen days after the initial surveys. The report states that "The numbers obtained were variable and no pattern could be described. Differences between days approached tenfold" (McLaren, Marex Inc., 1979, 4-3).

Surveys are assumed to measure seal population within a geographically defined region, but it has been speculated that summer populations are not constant. It has been suggested that the peak of the haul-out period may not be a result of an increased proportion of seals on the ice; instead it may represent an influx of seals from outlying areas where landfast ice has broken up (Finley, 1978; Smith and Hammill, 1981). In addition, it is thought that once seals finish moulting they may return to the water to be replaced by others (Smith, 1981). Evidence of seal movement out of an area is provided by observations of unused seal holes (Smith et al., 1979).

Given these problems, some census takers have recently hesitated

to estimate population size from the aerial survey data and it has been stated that "there is no accurate way to deduce the total number of seals present from the number hauled out" (Stirling et al., 1982, 6).

2.2.3 Summer and Winter Seal Populations

The implied objective of aerial surveys is to provide an estimate of total population resident in an area (Smith and Hammill, 1981). From the foregoing discussion it is evident that aerial surveys are only able to provide measurements of seal density on the surface of the ice for a specific day in the summer. The summer hauled-out population may be composed of transient and/or resident seals with the result that the population on that day may, or may not, have any similarity to populations observed on other days. In addition, summer populations are thought to be composed of different individuals the winter resident population (Smith and Hammill, 1981).

2.3 SEAL BREATHING HOLES AND THEIR DETECTION

2.3.1 Introduction

The density of seal breathing holes might give a better idea of winter resident seal location, density and perhaps population than counts of hauled-out seals obtained from aerial surveys during the

summer (Finley, 1978; Smith and Hammill, 1981). To make use of seal holes for estimating population information, two types of information are necessary: the ratio of seals to holes and the number of breathing holes in the ice. Two studies included observations of the hole to seal ratio but sample sizes were too small to give conclusive results. Finley (1979) noted a hole to seal ratio of 1.12:1 for Freeman's Cove, southeast Bathurst Island, N.W.T. (figure 1.1). The result was obtained by observations during the early summer when the population was observed to be stable and for that reason assumed to be the winter resident population. Half of the observation area was second-year ice, but the density of seal holes did not significantly differ as a function of ice type. A study by Smith and Hammill (1981) of South Bay adjacent to Popham Bay on southeastern Baffin Island (figure 1.1) measured the hole to seal ratio of 4.8:1. That ratio was derived from the number of seals in the area, a total of ten, versus the number of seal holes. It appears unlikely that this represents the winter situation as only 20 of 48 holes had been used as hauling out positions. If the hole to seal ratio had been derived from the number of holes in use versus the number of seals, the ratio would have been 2:1, an estimate closer to that observed by Finley. There is no discussion by Finley as to the number of unused breathing holes.

From the two studies of seal occupancy of holes during the summer, it is evident that there is insufficient evidence at the present time to determine the summer hole to seal ratio. This ratio

may not be the same as the winter hole to winter resident seal ratio which is the measure needed to determine the winter resident population.

From the work on sub-nivean lairs by Smith and Stirling (1975) during the winter and spring, it appears that the hole to seal ratio may vary as a function of population structure as paturient females were found⁴ to maintain more than one hole. Establishing a winter resident hole to seal ratio is a task which requires further investigation based on extensive surface observations, work which is beyond the scope of this study.

The second type of information necessary to use seal holes as the basis for seal population estimates is a reliable count of seal holes. The detection of breathing holes can be difficult. Seal holes are not readily observable in the winter once there is snow cover. From the surface they are totally undetectable to the eye and the lairs can be walked or driven over without snow subsidence. The only method of detection in winter seems to be by using a trained dog that can locate the lair by smell. The method is labour intensive and the success rate is not known. Disturbance of the lair is known to prevent seals from returning to the hole (Smith and Hammill, 1981) with the result that the hole could subsequently freeze over and cease to exist. This labour intensive and possibly destructive method of locating seal holes is obviously not suitable for yearly population studies of large areas.

2.3.2 Remote Detection of Seal Breathing Holes

Detection of seal holes by some remote method would be ideal because of the large areas involved and difficulty of access but as yet only two studies which used aerial photography have been undertaken (Finley, 1978; McLaren Marex Inc., 1979). Seal holes in the winter cannot be remotely detected by visible light or radar imagery. Although microwave energy is capable of penetrating the snow, radar does not have sufficient spatial resolution to distinguish the seal holes, circular areas of open water in the order of 35 cm in diameter, from the surrounding ice. The only application of remotely sensed imagery, visible and microwave in the winter, is in the definition of ice types and features, habitats which might be associated with seals (Burns et al., 1976). To date, there has been almost no consideration or use of remotely sensed data for any of the Arctic marine mammals despite the large amount of work that has focused on part of their habitat, sea-ice (Appendix C).

The use of remotely sensed data to detect seal holes in the summer is possible. The holes are no longer covered with snow and the location of the hole can be inferred from considerable heights, as surface melt water drains down the hole, creating a distinctive drainage pattern and a circular area of drained ice (Finley, 1978; McLaren Marex Inc., 1979). The first study of breathing holes was made in 1977 by Finley in Freeman's Cove, Bathurst Island and in Aston Bay on northwest Somerset Island. It was found that the

drainage patterns become particularly well developed during late June and are evident on aerial photographs. Photographs were obtained as part of the Finley study with two cameras (6 x 6 cm format), one equipped with a 100 mm lens and the other with a 40 mm lens. The diameter of the drained ice around a seal hole was measured from photographs to be $160 \text{ m} \pm 30 \text{ m}$ ($N=20$). It was noted that although the drained ice areas were clearly observable, the actual breathing holes could not be identified on the high altitude imagery (2,200 m ASL). Low level photography, (900 m ASL) obtained with the 40 mm lens, of part of the same area allowed hole identification. It was noted that breathing holes close together resulted in drainage patterns which overlapped, complicating counts of seal holes.

The following year, 1978, McLaren Marex Inc., with J. Parson as the wildlife biologist concerned with seal counts, conducted a photographic survey of seal holes in conjunction with Dr. T.G. Smith with a view to investigating "... a possible new technique for ringed seal census..." (McLaren Marex, 1979, covering letter). The survey area was in southeastern Baffin Island, an area which is climatically different from the high Arctic areas of the Barrow Strait surveyed by Finley (Markham, 1981). Aerial photography for a number of fiords adjoining Frobisher Bay and Cumberland Sound was obtained at an altitude of 1220 m with an RC-8 survey camera with a six inch lens. Results, to be discussed in section 4.2.9 were not encouraging as only portions of 7 of 25 photographic surveys resulted in photography of conditions that enabled detection of seal holes from the drainage

patterns.

No studies have examined the potential value of remotely sensed data other than aerial photography, but as discussed in Appendix C, there are a number of wavelengths which may be of use in detecting drained ice areas or sea-ice types.

2.3.3 Questions Associated with the Remote Detection of Seal

Breathing Holes

From the two studies by Finley and McLaren Marex Inc., and from the habitat studies of T.G. Smith, it appears that under certain conditions seal holes develop drainage patterns which are highly visible on panchromatic aerial photographs. If remote sensing is to be used to locate seal holes from the drainage patterns that they create, a number of questions raised by the two surveys need to be addressed.

1. What proportion of holes are located in first-year ice?
2. Are seal holes randomly located?
3. What are ideal conditions for detection of drained ice areas around seal holes?
4. When do these conditions exist?
5. Where do these conditions develop?
6. Do the conditions develop reliably every year in the same area?
7. To what extent do drained areas serve as an indicator of seal holes?

8. Which wavelengths can be used to detect drained ice areas around seal holes?
9. What is the optimal remote sensor or sensor combination for detecting drained ice areas around seal holes?
10. Which remote sensing platforms in current use or planned to be in operation in the near future could be used to obtain information on seal holes that might supplement data acquired by current survey techniques?
11. What is the relationship between seal holes and seal population?

The data set from Mould Bay and Crozier Channel has provided a unique opportunity to examine several of the above issues including those concerning seal hole location, ideal conditions, time of year, accuracy of detection, use of a variety of wavelengths, optimal sensor parameters and possible platforms. Results of this study are not expected to be conclusive but will further serve to define the potential and limiting factors associated with this method of detecting seal holes. The other questions, those of geographic location, year to year repeatability of the occurrence of large drained ice areas around seal holes and the relationship between seal holes and population require long term data collection and on-ice studies. For these reasons those issues are outside the scope of this investigation.

CHAPTER 3

SURFACE OBSERVATIONS IN MOULD BAY AND CROZIER CHANNEL

3.1 INTRODUCTION

The surface observations in Mould Bay and Crozier Channel are the first to record and quantify daily changes in surface characteristics of undeformed fast first-year ice in North America on a daily basis from the onset of the melt period to the period of surface ablation and drainage. Changes in surface characteristics are probably representative of those that occur in sheltered inlets and channels of the western high Arctic where similar climatic conditions exist (see Appendix B.2).

This study makes use of the surface observations to investigate questions concerning the development of drained areas around seal breathing holes and their detection using remotely sensed data.

3.2 SURFACE OBSERVATIONS

The majority of surface observations were obtained at sites along a 7 km experiment line across Mould Bay which had been established in October 1981, during an earlier sea-ice experiment, shortly

after freeze-up when the ice was grey-white and lacked snow cover (Digby, 1982a). Eleven oil barrels were positioned on the line to mark sampling sites. In Crozier Channel additional observations were made on the northernmost edge of the first-year ice area which extended the entire 15 km width of the channel and south about 20 km to the ice edge (figure 3.1). Ice in this area was equally undeformed.

Initial surface observations concerning the existence of a seal population in Mould Bay were made in October 1981 when, prior to snowfall, breathing holes were incidentally observed in undeformed, grey-white sea-ice. In addition amphipods, a pelagic nektonic crustacean known to be a major component of the diet of ringed seals during the fall (Lowry et al., 1980) were often observed in sea water that was flushed on to the ice surface when ice cores were removed. On 7 June, 1982 at the start of the summer experiment, when air temperatures were consistently and substantially below 0°C, an initial snow depth survey revealed a sub-nivean lair located near a sampling site on the experiment line. The roof of the lair, an icy layer covered with wind-packed snow, yielded under the weight of a person to reveal a straight-sided breathing hole about 40 cm in diameter filled with granular ice floating in the sea water. The lair was noticed to have a strong odor, possibly the odor of a rutting male, known as "tiggak" by the Inuit (Smith and Stirling, 1975). Snow depths at the sampling sites were in the order of 60 cm as opposed to an average of about 25 cm, owing to drifting around the

Figure 3.1 Ice Types in Mould Bay and Crozier Channel, Summer 1982.
Interpreted from LANDSAT Imagery

oil drums used to mark the experiment line sites. Ice thickness at this time averaged 2.2 m in Mould Bay with some variations, in the order of 10-15 cm, thought to be largely attributable to the insulating effect of snow drifts. Husky dogs kept by the station, found a minimum of three seal holes and sub-nivean lairs on 14 June. By this time, the average snow depth, outside the influence of the oil drums, had decreased to 12 cm (Digby, 1982b) although the air temperature had not risen above 0°C.

When temperatures rose to above 0°C and remained above freezing for a considerable portion of the day, snow melt occurred very rapidly. Rapid snow-melt occurred on 18 June at which time it became apparent that five seal holes were preferentially located along the experiment line in the proximity of some sampling sites and that a similar density of seal holes did not exist elsewhere in the bay. At sampling locations, ice cores had been collected in October and 10 cm diameter holes had been made at alternate sites with an auger at weekly intervals throughout the winter in order to measure ice thickness. The revisit time at a specific site was two weeks, although the line along which the sites were located was traversed by a Bombardier every week. It is possible that the increased snow depth (Smith and Stirling, 1975), combined with a hole in the ice cover resulted in a more suitable habitat for sub-nivean lairs at the experiment sites, in spite of human activity.

By the third week in June the snow had melted in Mould Bay and Crozier Channel releasing water on to the surface of the ice. In

Crozier Channel an extensive water layer, approximately 4 cm deep, was noted on 29 June (figure 3.2).

Surface runoff was rapidly established following snow melt; drainage networks developed around fractures and seal holes, the two types of interruptions in an otherwise unbroken and undeformed ice cover. Fractures are of two sorts, those around the shore caused by tidal movement and those which commonly occur between land masses as very straight features from promontory to promontory due to thermal contraction in the summer (Jacobs et al., 1975). Drainage from the shore lead at Mould Bay appeared to be restricted by surrounding formations of raised ice, whereas the thermal fractures created distinct linear borders of drained ice as the drainage network extended back on either side (figure 3.3).

Seal breathing holes created circular areas of drained ice as the drainage network extended back from the hole (figures 3.4, 3.5). Initial flow into the holes was very rapid causing a vortex effect and enlargement of the holes to about 2 m in diameter. Core holes made daily by experimenters at sampling sites in June and early July did not develop into drainage features, but refroze, owing to low temperatures within the ice cover. Temperature measurements of ice cores could not be used to monitor the ice cover temperature because of rapid warming of the core when extracted. In two cases later in the season (mid-July), it is thought that core extraction did initiate a seal-type drainage feature.

The drained ice areas around fractures and seal holes were

Figure 3.2 - Water on First-Year Ice, Crozier Channel, 29 June, 1982

Figure 3.3 - Thermal Fracture Viewed from 150 m ASL, 14 July

Figure 3.4 Seal Breathing Hole Viewed from 2 m ASL

Figure 3.5 Seal Breathing Hole and Associated Drained Ice Viewed
from 150 ASL, 14 July

highly visible because the surrounding ice appeared predominantly blue with regularly oriented, slightly raised areas, originally generated by snow drifts, showing as white areas as surface water decreased. With lower levels of surface water, small topographic variations became very noticeable with ice 2 cm above the lowest areas becoming drained and, as a result, white. The high contrast pattern of circular drained areas against the predominantly non-drained areas existed for about three weeks in Mould Bay after which the contrast rapidly disappeared over a period of 2 days when a different drainage process caused the entire surface to become white. The exact mechanism of the second drainage process has yet to be determined (Untersteiner, 1968). It is proposed (Holt and Digby, submitted manuscript) that the first-year ice sheet suddenly becomes porous to water as a top layer of permeable desalinated ice extends and reaches a bottom layer of permeable desalinated ice. When this stage is reached, surface water is able to percolate through the ice cover to freeboard level rather than remaining in puddles on the surface unless subject to over-ice run-off. When the through-ice drainage stage was reached, seal hole locations were considerably less visible. Aerial detection was still enhanced, not by the white drained areas, but by the network of wet blue drainage channels below freeboard around each hole, which provided a contrast to the higher white ice surface.

Drained ice areas similar to those observed on Mould Bay were also noted on the first-year ice in Crozier Channel. The distinctive

circular patterns were not observed on or adjacent to old-ice floes.

From on-ice observations in Mould Bay a number of statements can be made concerning the situations in which drainage areas around seal breathing holes develop. It appears that in sheltered areas of the high Arctic, undeformed first-year ice can form to thicknesses of about 2 m. When air temperatures and insolation result in rapid snow melt and ice ablation, a layer of continuous or near continuous surface water can form on the cold ice. During this period, which in Mould Bay lasted for three weeks in the summer of 1982, seal breathing holes create large areas of drained ice which are highly visible against the blue wet ice, so that the location of these features can be determined from a considerable distance.

CHAPTER 4

REMOTE SENSING DATA FOR MOULD BAY AND CROZIER CHANNEL

4.1 INTRODUCTION

Remotely sensed data for Mould Bay and Crozier Channel, obtained during the melt season of 1982, includes large and small scale airborne visible light photography, spaceborne visible and near infrared imagery and airborne active microwave imagery.

The analysis of remotely sensed data as part of this study concentrates on determining the location of breathing holes, their relation to sea-ice types, the size of drained ice areas around seal holes, visibility of drained ice areas on imagery from various sensors, the optimal parameters of sensors for observing seal holes and the problem of positive identification of drained ice areas around seal breathing holes.

The wavelengths and sensors used to obtain Mould Bay/Crozier Channel data set include those which possibly have the greatest potential for detecting drained ice areas around seal breathing holes and those which have sufficient resolution to provide positive identification of the actual hole and its location relative to ice types (Appendix C).

Remotely sensed data was acquired from two aircraft overflights summarized in table 4.1 and figure 4.1.

The first aircraft overflight, on 3 July involved the Atmospheric Environment Service (AES) Electra, an aircraft which is used operationally for ice reconnaissance. Large scale visible light photography and X-band SLAR imagery of Mould Bay and Crozier Channel was acquired. The flight lines were arranged to obtain a SLAR mosaic (figures 4.1, D.2). On 7 July, the Canada Centre for Remote Sensing (CCRS) Convair 580, an aircraft which provides a platform for a number of experimental microwave sensors, obtained remotely sensed data including photography and X-band SAR imagery of Crozier Channel.

In addition, two separate helicopter flights were dedicated to provide photographic records. The first was undertaken to document specific features observed on SLAR imagery and the second to record the experiment line across Mould Bay. Additional photography of the area was acquired on an opportunity basis from a helicopter while travelling to and from experiment sites.

The Landsat satellite provided multispectral scanner (MSS) imagery for the Mould Bay/Crozier Channel region on 29 June during the period of maximum surface flooding and on 15 July, late in the period of drainage contrasts. Cloud coverage on these days was minimal so the ice condition is clearly recorded.

Sensors, flight parameters and more detailed maps of image swath coverage are provided in Appendix D because these factors impose constraints on the analysis.

TABLE 4.1 Imagery Obtained from Overflights During the Period of Melt

<u>Parameters</u>	<u>AES Electra</u>	<u>CCRS Convair</u>	
		<u>Northbound</u>	<u>Southbound</u>
Date	3 July	7 July	7 July
Flight Pattern	Multiple Passes	1 pass	1 pass
Mapping Camera	Vinten	RC-10	RC-10
Scale of Photography	Medium	Small	Large
Auxillary Photography	-	35 mm, oblique	-
Microwave Sensor	X-band SLAR	X/L-band SAR	-

Figure 4.1 Areas Imaged by Airborne Sensors During the Melt Period

4.2. VISIBLE LIGHT PHOTOGRAPHY

4.2.1 Introduction

Visible light photography from the Mould Bay and Crozier Channel area (figure 4.2) was examined for three reasons: to provide a map of seal breathing holes located in the large expanses of undeformed first-year ice with which to compare SLAR and SAR imagery, to examine the drainage patterns around the breathing holes and to examine the location of the breathing holes with respect to sea-ice types. It is recognized that sea-ice types can be identified from panchromatic photography with the result that they are used as verification for information from other sensors (Gray et al., 1982). The level of information that can be extracted from photographs is partly a function of scale. The analysis of each scale will be discussed before combining the data from all photographs to provide a map of seal breathing holes in undeformed first-year ice. The location of the holes are determined by observation of the actual hole in large scale vertical photographs, or by implication from the areas of drained ice seen on small scale or oblique photographs.

It is considered reasonable, for the following reasons, to assume that all holes in the ice surface were breathing holes. By the end of the period of photography, 14 July, the first-year ice was still about a meter and a half thick, very firm and was supporting a considerable amount of water indicating that the ice cover had yet to

Figure 4.2 Airborne Photographic Coverage, 3, 7 July 1982

become isothermal. Topographic development was minimal and there was no indication of any thaw hole development. For these reasons and with an absence of any ice movement, it is safe to assume that all holes observed on the photographs are seal breathing holes which had been maintained throughout the winter.

4.2.2 Large Scale Photography

Hand-held 35 mm photographs taken from a helicopter at an altitude of 150 m (500 ft.) are of considerable value, because they have a larger scale than the low level RC-10 photographs, the largest scale photography obtained by the fixed-wing overflights. As a result, the helicopter based photographs from 14 July provide a valuable link between features that had been monitored on the ice and smaller scale aerial photographs.

The 35 mm photographs in figures 4.3 and 3.5 provide excellent documentation of the effect of a seal breathing hole on the surface water that exists on flat, first-year landfast ice and of the resulting spectral contrast. A high oblique photograph (figure 4.3) shows the high visibility of white drained areas around seal breathing holes in a view over the eastern half of Mould Bay. The bay can be seen to be ice-covered with the exception of a small open area near the shore about 3 km distant, where Station Creek enters the bay. The location of the experiment line is shown by the superimposed line. Saturated or water-covered ice appears blue

• COLOURED PICTURES
Images en couleur

//////experiment line

Figure 4.3 Drained Ice Areas Around Breathing Holes in Mould Bay

whereas slightly higher dry ice, appears white. Ice thickness on 14 July averaged 1.47 m across the bay.

A low oblique photograph (figure 3.5) taken during the same flight shows a closer view of the drained ice area around a seal breathing area hole. The actual hole, enlarged by the passage of meltwater, can be clearly seen. Some idea of scale is provided by the oil drum, located left of the hole. The drainage channels are visible as a blue network within the area of white drained ice. Drainage becomes less well developed with distance from the hole, and there is a fairly sudden transition to the predominantly wet, blue ice. This hole was one of those found by the dogs prior to snowmelt.

4.2.3 Low Level RC-10 Photographs

On RC-10 photographs at 1:3,000 (table 4.2), seal breathing holes can be seen as black "dots", 0.5 to 1 mm in diameter surrounded by a drainage pattern (figure 4.4). The majority (>90%) of the photographs were obtained for the area of old-ice in a first-year matrix in Crozier Channel with the result that they can be used for an analysis of breathing hole location relative to ice type.

An examination of the photographs reveals that a variety of ice types can be distinguished. Old-ice, ice that has survived at least one summer, is distinct from first-year as the old-ice has a better developed topography so water collects in specific areas known as meltponds rather than being spread over large areas as is the case

TABLE 4.2 Nadir Viewing Camera and Photograph Characteristics for the
Electra and Convair Overflights

Parameter	AES Electra	CCRS Convair 580	
Date	3 July	7 July	
Camera	Vinten	Wild-Heerbrugg RC-10	
Film Size	70 mm x 70 mm	23 cm x 23 cm	
Focal length	7.6 cm	15 cm	
Filter	none	420 AV 2.0	
Altitude	1524 m	6096 m northbound	457 m southbound
Swath Width	1.4 km	9.04 km	0.68 km
Photo Scale	1:20,000	1:40,000	1:3,000
	1 cm rep 200 m	1 cm rep 400 m	1 cm rep 30 m

Overlay for figure 4.4

Overlay for figure 4.5

Figure 4.5 An RC-10 Photograph of Breathing Holes Adjacent to
Old-Ice (.75 x negative size)

Overlay for figure 4-6

Overlay for figure 4.5

Figure 4.5 An RC-10 Photograph of Breathing Holes Adjacent to Old-Ice (.75 x negative size)

Overlay for figure 4-6

Figure 4.6 An RC-10 Photograph of a Breathing Hole in Old-Ice
(.75 x negative size)

TABLE 4.3 Table Used For Low Level RC-10 Analysis

Frame No	% Old-ice	Breathing Holes	Distance Between Hole Pairs	Associated Ice Feature	Ice Type	Distance to Old Ice	Size of Drainage Network (mm)	
							Length	Width
39	30	1		Edge	f/y	0	180	40
40	30	1		Edge	f/y	0	170	100
41	40	0						
42	20	1			f/y	8 cm	140	70
43	40	0						
44	40	0						
45	70	1		Edge	f/y	0	260	10
46	30	2	7 cm		old		off frame	
				Edge	f/y	0	off frame	
47	50	3	8.5 cm	Edge	f/y	0	140	10
			9.0 cm	Edge	f/y	0	100	10
				Edge	f/y	0	off frame	

TABLE 4.4 Summary of Observations from Low Level RC-10 Photography

Number of photographs examined	106
Area covered by photographs	$57.7 \times .68 = 39.2 \text{ sq. km.}$
Area of undeformed, homogeneous first-year ice coverage	8.1 sq. km. (20% of coverage)
Area of old-ice floes in a first-year ice matrix	31.1 sq. km. (80% of coverage)
Total number of breathing holes	69
Average Breathing hole size	1 m
Percentage of holes in first-year ice	81-88%*
Percentage of holes in old-ice	12-19%*
Percentage of holes in first-year ice located at edge of old-ice floe	86%
Average length of drainage network	410. m
Average width of drainage network	164.5 m

* Range due to uncertainty in ice type analysis.

Figure 4.7 Breathing Hole Density as a Function of Ice Type Concentration

the drainage patterns spread out around the edge of the floe and are relatively difficult to distinguish as they create an extension to the spectrally bright old-ice rather than the distinct isolated bright drained circular areas. The tendency of drainage patterns to follow features such as old-ice floes or shear lines is reflected by the elongated nature of most drained ice areas (table 4.4, figure 4.8).

The examination of breathing hole location as a function of ice type is important to this study because it reveals that seal breathing holes are not randomly located but are preferentially located in first-year ice adjacent to old-ice (figure 4.7). As a result, calculations of seal breathing hole densities for unbroken areas of first-year ice or areas with few old-ice floes cannot be considered representative of densities for adjacent areas containing many old-ice floes. It was also observed that to identify breathing holes adjacent to old-ice floes, the actual hole has to be detected because drained first-year ice is not spectrally distinct from the old-ice.

4.2.4 Vinten Photography

The Vinten photographic coverage (figure 4.2), is also largely of old ice floes in a first-year matrix. The analysis concentrated on the first-year ice area with a view to obtaining information on the location of breathing holes in areas of first-year ice relative

Figure 4.8 Drained Ice Extents Measured from Vinten Photographs

to deformation features and measurements of the extent of the drained ice areas. On the Vinten photographs (table 4.2) at a scale of 1:20,000 it is less easy to determine the location of seal breathing holes adjacent to old ice as in many cases the actual hole is not visible. Owing to the difficulty of determining whether drainage patterns in areas near old-ice were generated by an active breathing hole, or were relict drainage patterns from previous years, no study was made of seal holes in old-ice.

From an analysis of 60 breathing holes in first-year ice (table 4.5) using a format similar to that shown in table 4.3, several site preferences became apparent. Seal breathing holes in areas of 100 percent first-year ice were often (63%) associated with areas of weakness such as ridges, rafting and old shear zones. This tendency was reflected by the greater average length than width of the drained ice areas (figure 4.8). The holes were more often found in undisturbed ice if there were no areas of weakness nearby. Seal holes often seemed to occur in pairs, but there also seemed to be a minimum distance between groups of pairs (figure 4.9). This pattern is not apparent from calculation of the distance between holes (figure 4.10) although the sample size is too small to produce conclusive results.

The average size of the drainage networks was measured to be 200 m by 125 m, which corresponds to a distance of 10 - 6.5 mm on 1:20,000 photography. The large size and the considerable spectral contrast results in easy visibility of the drained ice areas. It was noted that in Muskox Bay, drainage appeared more advanced than in

TABLE 4.5 Analysis of Breathing Holes Unassociated With Old-Ice
from Vinten and High Level RC-10 Photography

	<u>Vinten; 3 July</u>	<u>RC-10; 7 July</u>
Sample size	60	13
Mean length of drained ice area	200 m	310 m
Mean width of drained ice area	125 m	260 m
Standard deviation of sample population length	105 m	22 m
Standard deviation of sample population width	63 m	47 m

Figure 4.9 Vinten Photography Showing Pairs of Breathing Holes

Figure 4.10 Distance Between Breathing Holes Measured from Vinten Photographs

other areas of Crozier Channel and Mould Bay, with a greater development of topographic relief. In Muskox Bay (figure 3.1), the drained areas around breathing holes were poorly developed because rafting had occurred during freeze-up.

The importance of the Vinten analysis to this study is two-fold. Firstly, panchromatic photography at scales of 1:20,000 can be used to locate breathing holes in first-year ice as inferred from the drainage pattern although the actual hole is often hard to distinguish. The inference is not possible in areas where breathing holes are adjacent to old-ice floes. Secondly, seal breathing holes appear not to be randomly located in first-year ice so surveys to determine breathing hole density in an area should not be based on results from a sub-area. Sampling procedures are discussed in Chapter 5.

4.2.5 High Level RC-10 Photographs

Photographs from the RC-10 with a scale of 1:40,000 cover a 9.04 km swath up the entire length of the Crozier Channel including the southern area of first-year ice, an area not covered by the Vinten or the low level RC-10 (figure 4.2). At this scale, individual breathing holes are visible only with magnification (x2-5) although the drainage network can be distinguished with the naked eye. Drained ice areas around holes at the edge of old-ice floes are in most cases impossible to separate from the old-ice floes. The drained areas around breathing holes in large areas of undeformed

first-year ice are easily visible (figure 4.11).

Measurements obtained from photographs of the 13 breathing holes in first-year ice areas, table 4.5, show the size of the drained ice areas to be 310 m by 260 m. The larger size when compared to measurements from the earlier photography of 3 July suggests an increase in drainage, but the sample size on 7 July is small. The location and spacing of the breathing holes indicated the same tendencies as observed from the Vinten analysis.

Monitoring the larger area of first-year ice substantiates the previous observations of low seal breathing hole densities in 100 percent first-year ice. The density of seal breathing holes is 0.5/sq. km as compared with a maximum of 6.4/sq. km observed from the Vinten photography in ice composed of 50 percent old ice. In addition, high level RC-10 photography clearly demonstrates the high visibility of drained ice areas on undeformed first-year ice and the potential of 1:40,000 photography for inferring the location and density of seal holes.

4.2.6 Oblique 35 mm Photographs

Oblique 35 mm photographs taken from a high altitude (6096 m/20,000 ft) were obtained to provide visible light documentation of the area imaged by the SAR system (figures 4.1, D.3). The photographs cover a swath of about 15 km on the ice at depression angles of approximately 10°-60°. No breathing holes or drainage networks

Overlay for figure 4.11

old-ice floes in a first-year matrix

old-ice floes in a first-year matrix.

location of figure 3.2

ice holes

ice formation

July 7, 1982

TABLE 4.6 Information as a Function of Photographic Scale

	Low level RC 10	Vinten	High level RC 10	35 mm
Scale	1:3,000	1:20,000	1:40,000	variable 1:40,000+
Breathing hole visible	Yes	Yes	sometimes	No
Drainage network visible	Yes	Yes	sometimes	No
Drainage ice areas visible	Yes	Yes	Yes	Yes
Size of 200 m drained area	6.6 cm	1 cm	0.5 cm	--
Drainage areas distinguishable from adjacent old-ice floes	Yes	sometimes	No	No

Figure 4.12 Map of Breathing Holes in First-Year Ice Interpreted from Photography

directional heading and ground speed of the aircraft. The October 1981, and July 1982 SLAR mosaics of the area were used to help position the holes relative to features such as fractures and multiyear ice floes but the SLAR imagery is not totally geometrically accurate owing to the motion correlator and slant range characteristics (Appendix D.1, D.2). RC-10 imagery and 35 mm photography of the Crozier Channel were positioned relative to the fractures as imaged by LANDSAT of 29 June. LANDSAT imagery at high latitudes is also subject to some geometrical distortion. The 35 mm oblique photography of Mould Bay was positioned from the location of the intersecting fractures observed from the summer SLAR mosaic and the LANDSAT image.

Seal breathing holes have been located as accurately as possible on the map relative to adjacent ice features. Spatial accuracy will be reduced with distance from locating features. Positional inaccuracy may be as great as 2 km due to inaccuracies in the motion correlator (Appendix D.2). The total number of hole locations in the first-year ice should be accurate as drained areas are easily detectable at all scales used.

4.2.9 Discussion

Analysis of photography of Mould Bay and Crozier Channel showed that all breathing holes created large areas of drained ice and so high level photography could provide an accurate count of breathing

holes in the area. These results are contrary to those obtained in the study by McLaren Marex Inc. (1979) that was discussed in Chapter 2. The 1:8,000 scale photographs, obtained for the southwest coast of Baffin Island from 12 June to 28 June, 1978 could not be used to obtain a count of breathing holes except in a few areas. A lack of surface observations prevented people involved in the study from discovering why clearly defined drained areas did not develop around seal breathing holes.

An examination of the McLaren Marex Inc. photographs as part of this study reveals two factors which seem to have hindered the development of the high contrast drainage features that were witnessed in Mould Bay and Crozier Channel. The first is a well developed surface topography which appears to have restricted drainage and which provides a difficult background for detection. This is possibly a function of greater snow accumulation and more drifting than in the Mould Bay area. Average annual precipitation on the southeast coast of Baffin island is between 10 and 15 cm in comparison with the 3.5 cm average of Mould Bay. The second observation from the McLaren Marex photographs is that in many areas the through-ice drainage appears to have started, there is little surface standing water and the surface is white in areas not obviously connected to drainage networks. The through-ice drainage which was noted in late July in Mould Bay, may occur earlier at lower latitudes where ice is thinner and warms up more rapidly. Most breathing holes in the McLaren Marex study were identified from their drainage networks, which appeared

dark against the white ice but the area of contrast with the surrounding ice was much smaller and less spectrally distinct than in cases where drained ice was surrounded by wet ice.

Photography obtained for the study in Freeman's Cove (Finley, 1976) showed drainage features better developed than those for Baffin Island but not as well developed as those in Mould Bay and Crozier Channel. Drained ice areas were $160 \text{ m} \pm 30 \text{ m}$ in diameter at Freeman's Cove, considerably smaller than the 250 m diameters measured in Crozier Channel. As with fiords on southeastern Baffin Island, a more developed topography seems to be apparent in photographs of Freeman's Cove, but the drained ice areas are clearly defined in low level (900 m ASL) photographs.

From these two studies and the observations in Mould Bay and Crozier Channel, it appears that large areas of drained ice around breathing holes develop under conditions where there is minimal snow cover on a flat sea-ice surface. It also appears that it may be necessary to have a thick (2 m) and hence cold, ice cover in order to maintain standing surface water for several weeks. The standing surface water is necessary for two functions: to facilitate large drainage networks that develop over a period of weeks and to provide a contrasting dark background for the white drained ice.

P

4.3 SIDE-LOOKING AIRBORNE RADAR

On 3 July, a number of passes were made by the AES Electra over Mould Bay and Crozier Channel to obtain SLAR imagery (figures 4.1, D.2) which could be used to construct a mosaic. The general principles of a SLAR, the specifications of the individual sensor which impose certain constraints on image analysis, the flight lines and image quality of the data set are discussed in Appendix D.1, D.2.

4.3.1 Identification of Drainage Patterns

Seal breathing holes in areas of first-year ice were first observed to create distinct returns on radar imagery during a reconnaissance flight on 6 July 1982. The helicopter flight was made two and a half days after the SLAR imagery had been obtained to identify selected features on a section of the SLAR imagery that was air-dropped to personnel at Mould Bay. During the flight, selected features on the SLAR were identified and photographed from a height of about 61 m (200 ft.). Bright spots of high return with diffuse edges in areas of little or no return corresponded to areas of drained ice around seal breathing holes surrounded by wet, first-year undeformed ice (figure 4.13). The bright returns, measuring about 1-1.5 m in diameter in the central portion of the image swath, corresponded to areas of equivalent size, approximately 200 m in diameter on the ice. Similar diffuse markings in first-year ice

Overlay for figure 4.13a

a. SLAR

b. 35 mm oblique photograph of
a drained ice area around a
breathing hole

c. 35 mm photograph of an
old-ice floe

Figure 4.13 SLAR Imagery and Photography of Drained Ice Areas

Overlay for figure 4.13a

65

a. SLAR

b. 35 mm oblique photograph of
a drained ice area around a
breathing hole

c. 35 mm photograph of an
old-ice floe

Figure 4:13 SLAR Imagery and Photography of Drained Ice Areas

areas, differing slightly by having very bright centers, were found to be isolated multiyear floes estimated to be over 100 m in diameter (figure 4.13c). Drained ice on either side of fractures also created a bright return confirming that microwave response is sensitive to drained ice areas. Drained ice along fractures forms a linear pattern so the features created by fractures are geometrically distinct from the drained areas around seal holes.

4.3.2 Analysis of SLAR

For this thesis, SLAR image analysis of drained ice around breathing holes, based on information from the verification flight described in section 4.3.1, was approached in three stages. Firstly, the variable appearance of drained ice areas from imagery of one pass to another was examined because it had been observed that for a given area, response to ice features varied from pass to pass. Secondly a composite map of seal breathing holes was made using all of the information from all passes. The map was compared with that created from the photographs (figure 4.12) to determine the effectiveness of SLAR for detecting drained ice areas around breathing holes over a large area. This was not entirely successful for reasons to be discussed, and so a third stage was undertaken. This involved making a map of seal breathing holes with information obtained only from those sections of the passes that contained optimal information as defined in the first stage of analysis.

4.3.3 Image Comparison

When the fourteen SLAR passes were examined, many areas were found to be imaged more than once. It was found that if imagery from one pass was used to determine the location of seal breathing holes the resulting map of breathing holes could vary substantially from that made from another pass. Possible causes of the variable information are the decreasing resolution across track, the worsening of the video and bias adjustments (Appendix D.2) and surface water changes during the flight period.

From a graph of resolution vs distance from aircraft (figure 4.14) and the graphs of the sizes of the drained area around breathing holes at that time (figure 4.8) some interesting observations can be made. At a distance of 15 km from the aircraft, i.e. 13.5 km from the near edge of the 25 km swath, the azimuth resolution is 120 m. Consequently between 30 percent and 60 percent of the drained areas will be below resolvable size, depending upon the orientation of elliptical drained areas with respect to the aircraft. In addition drained ice areas within 50 m of each other will appear as one large drained ice area so breathing holes close to each other cannot be individually resolved beyond a certain range (figure 4.15). Another result of the decreasing resolution is that at far range, targets tend to "smear", or elongate in the flight direction, making identification between old-ice floes and drained areas around seal breathing holes very difficult.

Figure 4.14 Azimuth Resolution of the SLAR System

Calculated from specifications in "An Introduction to Radar Surveillance Set AN/APS-94 D (1970)." Motorola Military and Aerospace Electronics Inc.

Drained ice extents shown by the circles are
100m in diameter.

Figure 4.15 Merging of Drained Ice Areas Around Adjacent Breathing
Holes

The second factor, that of video and bias adjustments, is more difficult to quantify. The initial pass over Mould Bay was made shortly after the video and bias controls had been set to obtain optimal imagery across the entire swath (figure 4.16a). At these settings, microwave return for the nearest three kilometers of swath is in many cases very high, saturating the film and causing loss of feature definition. Across the remainder of the swath, feature definition, as judged by the appearance of old-ice floes, land and fractures, is good. At the start of the mosaic flights over Mould Bay and Crozier Channel, two hours after passes over the west coast, the area of near-range saturation had lessened in extent and intensity. This resulted in a better definition of features in the near-range with less than a kilometer obscured.

Unfortunately the optimal situation at near range was at the expense of the far swath definition. The passes over Mould Bay and Crozier Channel which took nearly three hours to fly show a decreasing return across the swath. By the final passes, the swaths show very little microwave return in the far range and definition of floes and drained areas is hindered. It appears that drained ice areas are not detectable beyond about 7 km from the near edge of the imagery from the last three or four passes (figure 4.16b).

The third factor that appears to affect the visibility of drained areas around seal breathing holes is surface water. Imagery for the first pass over Muskox Bay permits clear identification of drained areas around seal breathing holes. On imagery from passes

Time
1659 GMT

Time
2144 GMT

Figure 4.16 SLAR Imagery Showing Effect of Untouched Video and Bias Adjustments

two hours later the first-year ice gives a much higher return and the previously identified drained areas are not readily definable. It is thought that significant drainage may have taken place during the two hour period.

4.3.4 Mapping Breathing Holes from All SLAR Imagery

The SLAR imagery was used to make a map of breathing holes. From imagery of each pass an overlay was made on which the diffuse bright dots in areas of dark first-year ice were marked. In addition major ice features were marked to provide registration for the drained ice areas, a necessary step given the scale variations of the imagery. When the overlays were compared, it was noted that for a given pass the marked breathing hole locations did not always correspond to breathing holes noted from other passes. To obtain maximum information, two composite overlays were made, the first combining all the information from overlays from the right antenna (figure 4.17) and the second amalgamating the observed drained areas from the left antenna (figure 4.18). The composite overlay for the right antenna had considerably more seal hole locations marked on it than the map made from observations of imagery from the left antenna. Fifty-five seal hole locations were recorded in Mould Bay from imagery obtained with the left antenna, compared to 77 on imagery from the right antenna. The lesser information is to be expected given the antenna interference from the aircraft on the left hand

Figure 4.17 Drained Ice Areas Mapped from Right Antenna SLAR Imagery

Figure 4.18 Drained Ice Areas Mapped from Left Antenna SLAR Imagery

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swath (Appendix D.1).

4.3.5 Comparison of SLAR and Visible Light Breathing Hole Maps

An initial comparison of the composite SLAR map of drained ice areas around seal breathing holes (figures 4.17, 4.18) and the map of breathing holes derived from photography (figure 4.12) demonstrates that SLAR response is sensitive to the drained ice areas around seal holes in undeformed or slightly rafted first-year ice. Examination of the two maps reveal similar patterns, but as with the SLAR maps for imagery from left and right antennas, precise matching of seal breathing holes with areas of high radar response is not possible. Both SLAR composite maps, but particularly the one from the right-hand swath show many more seal hole locations than the composite map derived from visible light imagery whereas an examination of material presented in figure 4.13 and 4.20a shows an exact correspondence between drained areas on radar imagery circled with a dashed line and photography. It is suspected that considerable hole duplication occurred in the mapping process owing to the SLAR positioning problem, a function of the motion compensator.

4.3.6 SLAR Mosaic and Visible Light Comparison

Owing to the ambiguous results of the comparison between the map of breathing holes made from the SLAR passes with that made from the

photography, a second comparison was made. A new map (figure 4.19a) was made from the SLAR imagery obtained from the right antenna using the optimal portions of the swaths. The optimal portion was considered to commence at a range of about 2.5 km depending on the saturation at near range and end at a maximum distance of 15 km where range resolution is 120 m. The latter distance was reduced for passes acquired later in the series to account for reduced energy return, a function of the video and bias controls. The new mosaic of breathing holes inferred from the single SLAR passes can be compared to the underlying map derived from the RC-10 and 35 mm photography (figure 4.19b). Information from Vinten photography was not included in the underlying map owing to the difficulty of accurate positioning, a result of the small area coverage and aircraft motion. A comparison of the two maps shows a better correlation between breathing holes interpreted from visible light imagery and those interpreted from all SLAR imagery.

4.3.7 Discussion

Figure 4.13 shows a section of SLAR imagery and figure 4.20a shows corresponding visible light photography obtained four days later. It can be seen that there is an unmistakable correspondence in size and location between the spectrally bright areas with diffuse edges on the SLAR and the drained ice areas around breathing holes on the photograph.

Figure 4.19b Map of Breathing Holes from Selected Photography

Figure 4.19b Map of Breathing Holes from Selected Photography

Figure 4.19a Map of Breathing Holes from Selected SLAR Imagery

It had been anticipated that the comparison of the maps of drained areas from SLAR imagery with that derived from visible light would result in a quantifiable statement expressing the accuracy of the SLAR image analysis for locating breathing holes in first-year ice over a large area. Unfortunately, this is not possible given the SLAR system variability, limited photographic coverage of first-year ice and the limitations on spatial accuracy of the SLAR imagery, Vinten photography and 35 mm slides.

Although the effectiveness of SLAR imagery for detecting seal breathing holes cannot be defined exactly, it is possible to define optimal conditions for the detection of drained ice areas from SLAR imagery. Optimal surface conditions appear to be wet non-rafterd homogeneous first-year ice which gives a uniform area of low return. The drained ice areas need to be well developed, preferably as large as 200 m and extend almost equally in all directions so they are detectable up to 25 km from the aircraft. Adjacent breathing holes need to be separated by a least 75 m so that drainage networks do not connect to make a drained ice area which would indicate one hole rather than two (figure 4.15). Optimal radar parameters appear to be a 25 km swath rather than a 50 or 100 km swath as the large scale on the film product is necessary in order to detect the areas. The optimal distance from the aircraft for detection of drained ice areas using SLAR imagery appears to be between 4.5 km and 13 km. It is apparent that the video and bias adjustments need to be altered at appropriate intervals. (See Appendix D.2.)

Given optimal surface conditions and optimal radar operation, it appears that SLAR imagery could be used to detect drained ice areas from about 4-15 km on either side of the aircraft. This gives an interpretable swath coverage of 11 km separated by 11 km in the center, an area that could be imaged by a second pass. Positional accuracy in the flight direction of any given breathing hole appears to be limited to ± 2.5 km, a distance which is reduced near locating features such as land. From the results of this study the SLAR is judged worthy of further investigation as discussed in section 5.5.

4.4 SYNTHETIC APERTURE RADAR

On 7 July, X- and L-band synthetic aperture radar imagery (like and cross polarized) with a swath width of 10 km was obtained for the Crozier Channel by the CCRS Convair 580 (Appendix D.3, D.4). An initial examination of the SAR imagery (optical film) and corresponding 35 mm photography (figure 4.20) several weeks after the experiment revealed circular areas of bright response in areas of low response corresponding to drained areas on wet undeformed first-year ice. It was also noticed that the return from the first-year ice varied as a function of wavelength, polarization, incidence angle and ice surface characteristics. In cases where the first-year ice gave a bright return for reasons to be discussed, the drained ice areas were not visible.

The general principles of a SAR and the specifications of the

individual sensor which determine the potential of the imagery for detecting drained ice areas are discussed in Appendix D.3.

4.4.1 Analysis

The SAR imagery was examined for three types of information as a result of the initial observations. First, the location of the circular bright returns on the L-band SAR imagery of first-year ice were compared to the simultaneously acquired visible light photography to verify that the bright returns are caused by drained ice areas around breathing holes. L-band was chosen as it appeared to provide the best contrast between wet and dry ice. The second stage of analysis was a comparison between the information content of imagery acquired at the two frequencies and polarizations. From these portions of the study a statement can be made about the potential of SAR imagery for detecting seal holes by inference from the surrounding drained ice areas and the optimal parameters of the SAR system for monitoring breathing holes. The third stage involved using a section of digital SAR containing drained ice areas around breathing holes to perform a computer manipulation which simulated satellite imagery.

4.4.2 A Comparison of Visible Light Photography with L-Band SAR

The areas of high backscatter in first-year ice areas on the L-band SAR imagery measuring about 2 mm on imagery with a scale of

approximately 1:125,000, correspond with areas of drained ice observed on visible light photography. There are no bright areas on the SAR imagery that are not accounted for on the photography and all drained ice areas on the photography create a response on the SAR imagery (figures 4.20, 4.21). The initial comparison was made by examining the high level RC-10 photography and the L-band optical imagery using ice boundaries for registration. Owing to the small amount of overlap (2.5 km) there were only 6 seal holes and associated drainage patterns that were covered by both systems. Nevertheless, the overlap is valuable because on the nadir-looking RC-10 photographs the drainage networks and actual breathing holes in the ice can be seen with magnification, so there is no doubt as to the origin of the drained ice areas. The greatest spatial photographic coverage of the ice imaged by the SAR is provided by the 35 mm slides (figures 4.20, 4.21, D.3) on which the correspondence of a large number of drained areas can be seen. Correspondence was noted for all areas of drained white ice, a total of 47.

The isolated areas of white ice on the photography and high backscatter on the SAR imagery are thought, for several reasons, to be drained ice areas created by seal breathing holes rather than old-ice floes. The L-band SAR imagery shows a diffuse bright area, lacking the bright surround commonly created by old ice floe edges and LANDSAT imagery from 29 June does not show any multiyear ice in those areas. In addition the diffuse edged drained areas appear very similar to those photographed at similar angles in Mould Bay (figure

Overlay for figure 4.20

a. 35 mm photograph

b. L-band (HH) SAR imagery

c. X-band (HH) SAR imagery

Figure 4.20 X- and L-Band SAR and Aerial Photography of Crozier Channel North. For location see figures 3.1, D.3

Overlay for figure 4.21

a. 35mm photograph

b. L-band (HH) SAR imagery

film motion error

c. X-band (HH) SAR imagery

Figure 4.21 X- and L-band SAR and Aerial Photography of Crozier
Channel South. For location see figures 3.1, D.3

4.3) where the drainage patterns are known, from on-ice observations, to be the result of seal breathing holes.

From the comparison of L-band SAR with visible light photography it appears that a SAR with 3 m resolution provides imagery that allows reliable detection of drained ice areas around breathing holes.

4.4.3 Frequency and Polarization Comparisons

Imagery of two areas of undeformed 100 percent first-year ice was examined and a considerable difference in response was found between the frequencies and polarizations (Appendix D.3). For this reason imagery at both frequencies and polarizations was examined. The northernmost area was located at the junction of Crozier Channel and Fitzwilliam Strait where surface conditions as seen from the visible light photography were wetter than in the southern first-year ice area in Crozier Channel between the open water and the conglomeration of old-ice floes (figures 4.21, 4.22).

Imagery obtained at XHH (X-band, horizontal transmit, horizontal return), the wavelength and frequency at which the AES SLAR operates, was examined. It was found that first-year ice in the north gave a fairly low return which was reduced with decreasing depression angle across the swath. Within the first-year ice, irregular areas of very bright return corresponding to the drained ice areas were easily distinguished (figure 4.20). Using a computer program developed by

J. Currie (University of Western Ontario) and D. Hudson (Waterloo University), under the direction of R. Hawkins of the Data Acquisition Division, Canada Centre for Remote Sensing (DAD/CCRS), the ground extent of the drained ice areas was measured. From input including the swath width, position of the drained area within the swath, size of drained area on the optical film, aircraft altitude and system parameters including incidence angles and range delay, 12 drained ice areas were calculated to have an average diameter of 270 m. This measurement is very close to the 290 m average diameter of 69 drained ice extents in the northern part of Crozier Channel measured from the low level RC-10. The similarity suggests that X-band microwaves are sensitive to approximately the same drained ice extent as visible light.

In the southern part of Crozier Channel (figure 4.21) where the first-year ice can be seen from the 35 mm photography to be drier, the overall backscatter is considerably higher with the result that the drained ice areas around breathing holes are barely distinguishable. Other areas of drained ice, found on either side of fractures, are also obscured.

Old-ice in the first-year matrix can be easily defined by XHH but the precise location of the floe edges is made difficult by the borders of drained ice. No information can be obtained concerning drained ice areas around seal breathing holes located adjacent to the old-ice floes in spite of the 3 m resolution.

On the XHV (X-band, horizontal transmit, vertical receive)

imagery, the overall level of microwave energy returned to the antenna is low compared to that recorded by the XHH imagery. This response is partly to be expected as most of the energy returns with the same orientation as emitted and a smaller proportion experiences a change in polarization at the ice surface. Although the overall return is low, the contrast between old ice and first-year ice appears slightly greater than at XHH. With a reduction in the level of return the drained ice areas in first-year ice are increasingly harder to detect. In the north (figure 4.20) drained ice areas are not visible at distances beyond 9 km from nadir which corresponds to an incidence angle of 55° . In the southern section, the circular areas of drained ice are not visible (figure 4.21).

L-band imagery, used in the comparison with visible light photography to determine the origin of the drained ice areas (figures 4.20, 4.21) appears quite different from X-band imagery. The difference is to be expected given the longer wavelength of 23 cm. compared to 3 cm for X-band. At LHH (L-band, horizontal transmit, horizontal receive), the drained ice areas in the first-year areas are much more visible than on the X-band imagery. In the north the first-year ice gives a very low response especially at far range. Drained ice areas can be distinguished as very bright areas across the entire swath. In the southern area, the overall response from the non-rafterd, first-year ice is higher than in the north, but it is still sufficiently low for the drained areas to be distinguishable across the entire swath. It was noticed that all drained areas, although very bright,

appeared relatively small in spatial extent. To check this observation, the surface extent of the drained ice areas measured on the XHH imagery using the CCRS computer program were measured on the LHH imagery. From the comparison, it appears that at L-band the area of high response is actually smaller than, at X-band, coming from an average area of 175 m compared with 270 m. This suggests that the L-band energy is sensitive to the greater topographic relief made by drainage channels located in the central two-thirds of the drained ice areas rather than the small scale (<3 cm) roughness of the drier ice.

LHH imagery also proved to be effective for delineating the old-ice floes which, for the most part, have a similar backscatter return to the first-year ice but are surrounded by a very bright margin, a response to the floe edge. Discrimination is such that the first-year ice between the floes is easier to recognize, and within that area some drained ice areas can be distinguished. Owing to the sporadic nature of the bright linear return around the old-ice floes and the non-uniform areas of drained ice that develop adjacent to old-ice floes, it is not possible to accurately monitor drained ice areas on first-year ice between old-ice floes.

LHV (L-band, horizontal transmit, vertical receive) imagery does not appear very different from L-band like-polarized imagery: first-year ice in both the northern and southern areas appears dark with bright drainage features and old-ice floes are distinguished by their bright surround. When examined more closely, subtle differences can

be seen, the overall level of return from the first-year ice is lower, especially at near range, with the result that drainage features in the near range are better defined. In the far range there seems to be a considerable fall-off in energy return and drainage features in the furthest 2-3 kilometers are not visible. Some multiyear floes appear to have a higher return in the cross-polarized imagery, although the extent and magnitude of the bright linear surrounds seem to be similar to that observed on LHH imagery.

4.4.4 Satellite Imagery Simulation

A section of digital X-band imagery of the northern section of Crozier channel was processed on a Dipix image analysis system at the RADARSAT Project Office (RPO) of CCRS to simulate satellite obtained resolution. The resolution was reduced to 21 m, and noise and "looks" were simulated using a program developed by T. Hirose of RPO. It was found that seal breathing holes could be inferred from the satellite image as shown in figure 4.22.

4.4.5 Discussion

From the analysis of SAR imagery it is apparent that L-band SAR with a 3 meter resolution provides an accurate method of monitoring drained ice around seal breathing holes. At L-band there is a good discrimination between wet and dry ice, and old-ice floes are well

Overlay for figure 4.22

Figure 4.22 Simulated Satellite SAR Image Derived from Airborne SAR
Image

Figure 4.22 Simulated Satellite SAR Image Derived from Airborne SAR
Image

defined. The best contrast between wet and dry first-year ice is achieved at depression angles between 30° and 80° . LHV would be marginally preferable over LHH provided that enough energy could be emitted to ensure adequate levels of backscatter.

The study of X-band SAR indicated that this wavelength is not as useful as L-band, as there are more limitations on surface conditions and instrument parameters if the drained ice areas on wet first-year ice are to be detected. It does appear that X-band imagery can be used for reliable detection of drained ice areas if the surrounding ice is very wet (probably in excess of 60 percent water coverage as judged from RC-10 photographs) and if the imagery is acquired at depression angles of less than 50° . SLAR imagery discussed in section 4.3 has these characteristics as it was obtained at shallow depression angles during the period of high (>80%) water coverage. This suggests that the inability to find a good correspondence between breathing hole location mapped from the SLAR and the visible light is a function of the spatial accuracy and small scale of the SLAR image film rather than an inability of microwave imagery to detect drained areas.

From the satellite image simulation it appears that drained ice areas can be detected from space with a SAR system. A cursory examination of SEASAT SAR imagery for landfast first-year ice in Amundsen Gulf (July 1978) reveals areas of high response that are similar to the drained ice areas observed on the simulated imagery.

4.5. LANDSAT IMAGERY

Visible and near-infrared imagery from the LANDSAT multispectral scanner (MSS), obtained on 15 July during the summer melt-period exhibited small bright "dots" on dark areas of undeformed ice. The "dots" are visible on all bands of the MSS from the visible at 0.5-0.6 μm , to the near-infrared at 0.8-1.1 μm . The "dots", not apparent in earlier imagery obtained on 29 June during the period of maximum surface water coverage were found by comparison with photography to be the drained ice areas around seal breathing holes. Pertinent characteristics of LANDSAT MSS imagery and observations of image quality are examined in Appendix D.5 to demonstrate that it is reasonable to expect to be able to detect areas of drained ice created by seal breathing holes from 900 km above the earth given a system with an 80 m resolution and a cloud-free situation.

4.5.1. Analysis

Three approaches were taken in the MSS image analysis, first a comparison was made between the bright "dots" on the 15 July image with the RC-10 and 35 mm photography of drained ice areas around seal breathing holes. The second comparison was made between the four bands of 15 July LANDSAT imagery and finally, a comparison was made between Band 6 imagery from 29 June and 15 July.

4.5.2 Comparison of July LANDSAT Imagery with Aerial Photography

From figure 4.20a, 35 mm photograph showing drained ice areas in the north section of Crozier Channel and figure 4.23a, a section of the LANDSAT image of 15 July it can be seen that the drained ice areas are clearly visible on MSS images. Although small, less than 0.2 mm on the 1:1,000,000 LANDSAT image, the drained ice extents are spectrally quite distinct from the wet ice that reflects almost no energy. Drained ice areas around seal holes appear as bright "dots" on the LANDSAT image and drained areas on either side of the fractures appear as a bright linear feature. In places where the drained ice areas are close together, within about 100 m, they appear as one large, irregular, bright feature. Seal holes located along irregularities in the ice such as rafting or an old shear zone can be obscured by the linear drainage pattern. The differences in drainage patterns between the LANDSAT imagery and aerial photographs might be a function of the increased drainage that had occurred in the week between 7 July when the photographs were obtained and the 15 July when the LANDSAT imagery was acquired. The difference in resolution between the two image types might also account for the difference in apparent drainage patterns.

Small (≈ 200 m) old-ice floes in a large extent of first-year ice identified on the high level RC-10 photographs, and two old-ice floes in Muskox Bay give bright signatures which are indistinguishable from drained areas of first-year ice on the LANDSAT MSS images (figure

Figure 4.23b LANDSAT IMAGE, 29 June, Band 6

Figure 4.23a LANDSAT Image, 15 July, Band 6

fractures

diffuse whitened
with speckles

Location of Figure
3.2

rafting

Figure 4.23a LANDSAT Image, 15 July, Band 6

Figure 4.23b LANDSAT IMAGE, 29 June, Band 6

4.23b). Drained ice areas adjacent to old-ice floes cannot be detected.

The southern area of first-year ice in Crozier Channel appears spectrally different from the area north of the conglomeration of old-ice floes. In the south, the first-year ice is considerably brighter and the brightness increases towards the open sea. First-year ice in Mould Bay is still dark, but ice in Walker Inlet to the south has become white.

Drained areas around seal breathing holes are still distinct in the area immediately south of the old-ice floes in Crozier Channel but with the increasing spectral response of the ice further to the south, drained ice areas become obscured. The process of diffuse whitening is probably the same phenomenon that was observed in Mould Bay on 17 July (see section 3.2). Associated with the diffuse white areas is a brighter speckling, which on the basis of comparison with high level RC-10 photography, appears not to be associated with seal breathing holes, but which could be the development of thaw holes. The speckling is distinct from bright "dots" created by seal breathing holes as the former does not appear until the first-year ice drains and turns from dark to light on the imagery. In addition, the bright speckles are not as bright or large in appearance as areas drained by breathing holes.

4.5.3 Band Comparison

LANDSAT MSS bands 4, 5, 6, and 7 were examined to determine which frequency interval provided maximum contrast between wet first-year ice and the drained ice areas. Drained ice areas were visible in all bands, but band 6 and 7 in the near-infrared appeared to be optimal. The black and white prints used for the analysis had been produced by CCRS personnel at Prince Albert, specifically to maximize the dry/wet ice contrast.

Imagery from band 4 appeared to provide the least contrast between wet and dry ice, although all drained ice areas seen in imagery from bands 6 and 7 can be detected. To produce reasonable contrast in the photographic print of the image at band 4, detail in the land and old-ice floes was entirely lost. Imagery from band 5 was considerably better for detecting wet/dry contrasts as the first year ice appeared quite dark in the north and drained ice areas were bright. Imagery from bands 6 and 7 in the near-infrared appeared very similar. In the near-infrared, wet first-year ice gives little or no return and drained ice areas are very bright, creating optimal conditions for detecting breathing holes. Land and multiyear floes are well defined although as mentioned earlier, small isolated old-year floes, less than about 80 m, cannot be distinguished from areas of drained first-year ice.

4.5.4 Multitemporal Comparison

LANDSAT imagery was obtained on the previous overpass of 29 June (figure 4.23b) during the height of the melt water coverage (figure 4.2). The image provides an interesting contrast with the image of 15 July and analysis demonstrates a possible means of distinguishing isolated old-ice floes from drained first-year ice. Old-ice floes on the 29 June image are clearly distinct, giving a bright return, and the first year-ice is predominantly dark. Rafted first-year ice is clearly visible as bright, fine, crinkled lines in the south of Crozier Channel and as diffuse bright areas in the first-year ice section in the north of Crozier Channel. The location of some fractures can be seen. No small bright "dots", the response to drained ice around breathing holes, can be seen because the drained areas have not yet developed to the necessary spatial extent or spectral brightness.

From a comparison of the two images (figures 4.23a, b), one taken shortly after snow melt, and the other well into the drainage period, it is possible to separate the bright dots caused by old-ice floes from the bright dots caused by drained ice areas. This may not be of great importance because from the study of seal hole habitat (section 4.2.3) it is known that the seals preferentially make breathing holes in the first-year ice around the edge of old-ice floes. If seals are known to be in the area, based on the presence of seal breathing holes in areas of undeformed first-year ice, it is

reasonable to assume that breathing holes will be found around the edges of old-ice floes. As a result, to count an old-ice floe as a drained ice area caused by a breathing hole is probably not erroneous, provided there are seals in the area.

4.5.5 Discussion

It appears that the LANDSAT MSS is capable of providing imagery that can be used for monitoring seal breathing holes in large areas of first-year undeformed ice to a level of accuracy dependent upon the spacing and location of the holes. In this data set, accuracy, as judged by a comparison with 35 mm and RC-10 photography seems to be 97 percent, but the sample of 43 drained areas is perhaps too small to have much reliance placed on it. In the Crozier Channel there appeared to be a 2-3 week period that commenced about 4 days after snow melt when suitable conditions existed for monitoring drainage patterns from LANDSAT. The major problem with using LANDSAT imagery for monitoring breathing holes and that which prevents operational use, is the infrequent coverage owing to orbit characteristics, limited northern "on-time" and cloud coverage. For this purpose it is not feasible to use LANDSAT MSS data on an operational basis to count breathing holes.

4.6 A SUMMARY OF REMOTE SENSOR CAPABILITIES

From surface observations and analysis of aerial photography, airborne microwave imagery and LANDSAT imagery for Crozier Channel and Mould Bay in June and July, 1982, it is apparent that remotely sensed data can be used to infer the existence of seal breathing holes during a short period in the melt cycle.

A summary of the potential of the remotely sensed data for detecting breathing holes is presented in table 4.7. From the table it can be seen that drainage patterns around breathing holes can be detected on small scale airborne or satellite, visible or microwave imagery provided the drained ice is surrounded by wet ice. Owing to the size of the drained ice areas, between 200 and 300 m on average (table 4.5), small-scale imagery can be used to detect breathing holes in areas of first-year ice with little loss of information. Large scale photography appears to be the only means of detecting breathing holes in and adjacent to old-ice and areas of ridging, where the areas drained by breathing holes are not spectrally distinct from surrounding ice types. At the current time it is not possible to quantify the accuracy of remotely sensed radar imagery for detecting breathing holes.

It should be noted that these findings are restricted to Mould Bay and Crozier Channel during June and July 1982. It is thought, from cursory examination of aerial photographs, LANDSAT MSS imagery and SEASAT SAR imagery, for other areas of the central and western

TABLE 4.7. A Comparison of Image Types Examined

	Low Altitude RC-10	Winten	High Altitude RC-10	35 mm	LANDSAT MSS	X-Band SLAR	X-Band SAR	L-Band SAR
Spectrum	visible	visible	visible	visible	visible and near-infrared	microwave 9.1-9.4 GHz	microwave 9.35 GHz	microwave 1.2 GHz
Altitude acquired	457 m	1524 m	6096 m	6096 m	900 km	1524 m	6096 m	6096 m
Swath width	0.68 km	1.4 km	9.04 km	≈20 km	185 km	25+25 km	10 km	10 km
Data type	photograph	photograph	photograph	photograph image	photograph image	optical image	optical/ digital image	optical/ digital image
Scale	1:3,000	1:20,000	1:40,000	non-uniform	1:1,000,000	1:250,000	≈1:56,000	≈1:56,000
Ground resolution/ footprint size.	0.06 m	0.5 m	0.8 m	variable	80 m	30 m at best	3 m	3 m
Breathing holes visible	yes	yes under magnification (x2-4)	partially under magni- fication (x2-4)	no	no	no	no	no
Size of 200 m drained area	6.6 cm	1 cm	0.5 cm	variable	0.2 mm	0.8 mm	1.6 mm	1.6 mm
Optimal viewing geometry	nadir	nadir	nadir	-	nadir	50-80°	50-80°	30-80°
Wet/dry ice contrast	good	good	good	good	excellent	good	weak	good
Geometrical distortion	minimal	minimal	minimal	angle dependent	minimal	variable	distorted at near edge	distorted at near edge
Ability to differentiate between old-ice and drained first-year ice	yes	partial	partial	no	no	partial	partial	yes

high Arctic, that similar surface conditions may exist throughout this area. Further study is needed to verify the preliminary findings.

At the simplest level, the inference of breathing holes could be used to detect the existence of winter resident seals in an area, given suitable ice and climatic conditions. A count of seal breathing holes could also be used as a relative measure of winter resident seal abundance in year to year studies or from place to place.

CHAPTER 5

SUMMARY AND DISCUSSION

5.1 SUMMARY

From surface observations of undeformed fast first-year ice in Crozier Channel and Mould Bay obtained during the late spring and early summer 1982, it appears that breathing holes can create large areas of drier white ice on areas of otherwise wet, dark ice during a three-week period following snow-melt. Analysis of multifrequency airborne data obtained during this period demonstrates that visible light photography at scales to 1:40,000 can be used to detect the drained ice areas when they are surrounded by expanses of wet ice. Radar imagery can also be used to detect the drained ice areas although spatial accuracy of the systems varies. Drained ice areas were observable on LANDSAT MSS, particularly in the near-infrared bands.

Measuring winter resident seal abundance by the remote detection of drained ice areas around breathing holes should be viewed as a complementary method to the currently employed haul-out survey. Detection of breathing holes is only possible for large areas by means of remotely sensed data. As with the haul-out method, a number

of limitations exist in using remotely sensed data to detect breathing holes, but these do not negate the benefits of this method to provide additional and otherwise unavailable information.

5.2 LIMITATIONS OF USING REMOTELY SENSED IMAGERY TO LOCATE BREATHING HOLES

The successful use of any method depends on the realization of its limitations so that they can either be avoided, or taken into consideration. Unless these points are considered, the information derived can be misleading, which can be worse than a total lack of information.

5.2.1 Limitations Created By Surface Conditions

To infer breathing holes from drainage patterns observed on small scale aerial photography, radar imagery or LANDSAT MSS imagery, certain surface contrasts must exist. Drainage patterns must develop as white areas against dark wet ice. The contrast can only develop in a specific ice type, areas of undeformed first-year ice, where there are few ridges or old-ice floes. The ice needs to be located in a climatic zone where ice develops to a considerable thickness, possibly in order of 2 m and where snowfall is low and evenly distributed so hummocks do not form. Summer temperatures during the period immediately following snowmelt need to stay consistently above 0°C, to ensure surface-water generation at a rate that exceeds vertical

drainage through brine channels. Many of these conditions may exist in sheltered bays and inlets of the high Arctic, and in any given location may occur on a fairly regular basis from year to year.

The likelihood of these surface conditions occurring in a particular area can be judged from maps of climatic zones and ice type locations in conjunction with LANDSAT MSS and SLAR imagery from past years. For instance, from an examination of these materials for Barrow Strait, it is apparent that ice in any given year will probably be highly deformed, ice in M'Clure Strait will be predominantly old-ice, and ice in inlets of Baffin Island will have heavy snow cover. As a result there is a low probability of using drained ice areas to monitor seal abundance in any of these areas.

In other areas such as Bracebridge Inlet, Bathurst Inlet or Liddon Gulf, Melville Island, conditions are more likely to be favourable for detecting drained ice areas around breathing holes because ice is usually undeformed first-year, snowfall is less than 30 cm and winter temperatures are severe.

5.2.2 Limitations of Inferring Seal Breathing Holes from White Areas

There are four sources of inaccuracy inherent in inferring breathing holes from areas that appear white against the dark, wet ice. The first is that old-ice floes within the same size range as drained ice areas (150-300 m diameter) can be mistaken for the drier ice around breathing holes when examining radar or visible light

imagery. This error can be avoided by locating old-ice floes on imagery obtained prior to the melt season. The solution is not necessarily appropriate because, as observed from large scale RC-10 photography, if seals are occupying the sea under an area of first-year ice containing old-ice floes, a prime location for breathing holes is adjacent to old floes. Given this habitat preference, it might be appropriate to count isolated old-ice floes as an indicator of breathing holes, just as drained ice areas are indicators of breathing holes, provided that the floes are not grounded and that seals are known to be in the area.

The second problem is that if two seal breathing holes are located close to each other, the drainage patterns merge and depending upon the hole spacing could be interpreted as being caused by one rather than two holes. From figure 4.15, it can be seen that given a drained ice area of 200 m in diameter, it would be difficult to infer the existence of two breathing holes if separated by less than 50 m. Breathing holes close together are thought to be made by a female expecting young and the mean distance between holes thought to form a complex, has been measured to be about 25 m (Smith and Stirling, 1975). This spacing is considerably below the minimum distance needed for the development of separate drainage patterns. Counting the two breathing holes in this case as one is not a problem, because the hole count will reflect the adult population rather than the adult plus newborn. Newborn pups have a high mortality due to exposure in early springs and predation by foxes and

bears (Smith, 1976; 1980), so to count holes that are made for them as those of an adult could result in overestimates. Further studies on territoriality and breathing hole distribution are needed to determine the probability of a miscount due to overlap of drained ice areas.

A third problem can arise if seal breathing holes are located along a linear feature, such as a remnant lead, that restricts lateral development of drainage patterns. Initially during the drainage period, the drainage patterns would be distinct and elliptical, but with time they could enlarge primarily in one direction to form a bright linear feature, indistinguishable from drained ice areas around a fracture. To minimize the underestimation of breathing holes, imagery should be obtained as early as possible during the period of drainage feature development. The optimum timing would partially be a function of the sensor resolution.

The fourth limitation also concerns timing. The drained ice areas need to be imaged before the development of thaw holes which can also create somewhat similar areas of drained ice (section 4.5.2). In thick ice, in areas not subject to underwater erosion from tides and currents, thaw holes probably are only able to develop at a time when the ice becomes isothermal. At this time, the surface standing water can be expected to decrease, resulting in an increase in the overall level of visible light and microwave return. To avoid mistaking thaw holes for breathing holes, it appears from the Crozier Channel/Mould Bay data set, that imagery should be

obtained within two weeks of snowmelt. Any drained ice areas in extents of drier first-year ice should be compared with those of a nearby wet area to ensure that the drained ice areas are not created by thaw holes. Drained ice areas around breathing holes should be larger than those around thaw holes.

It can be seen that the four limitations to using remotely sensed data for detecting breathing holes need not have a major impact on the accuracy of interpretation, providing imagery is obtained as soon as drained ice features reach a sufficiently large size to be resolved by the particular sensor.

5.2.3 Limitations of Estimating Seal Breathing Hole Densities from Results Obtained from One Ice Type

The extrapolation of breathing hole densities for an area based on results from a sub area of first-year ice is considered to be the most serious limitation to the proposed method of measuring seal abundance from a count of inferred breathing holes. Areas of drained first-year ice caused by breathing holes located near old ice floes are not spectrally distinct from the old-ice and cannot be detected on aerial photographs at scales smaller than 1:3,000. As a result, breathing hole location cannot be inferred from drainage patterns in these areas on small scale photography or on radar imagery, even with a 3 m resolution. As discussed in 4.2.3 isolated old-ice floes in first-year ice could be counted as indicators of breathing holes, but

in an area where there is a large number of old-ice floes, the situation becomes more complex as the entire area will appear bright on visible light or radar imagery. Unless the actual holes in the ice can be resolved, breathing holes in, or adjacent, to old-ice cannot be implied.

From an analysis of large scale (1:3,000) photography (section 4.2.3) it was found that breathing hole densities averaged $4.12/\text{km}^2$

in areas of first-year ice with 30-70 percent old-ice, compared to 0.8 breathing holes/ km^2 in 100 percent first-year ice. As a result, the use of drained ice areas around breathing holes as a reliable estimate of seal abundance would appear to be restricted to locations with little or no old-ice.

A method to reduce the inaccuracy of applying results from the first-year ice to areas with old-ice might be to multiply the number of inferred breathing holes counted in areas of adjacent first-year ice by some factor, to be determined by further analysis of hole distribution. A correction factor may not be universally applicable as breathing holes in first-year ice were found not to be randomly distributed but to be located along previous lines of weakness. The ratio of the distribution of seals in areas with old-ice to that of areas of 100 percent first-year may therefore depend upon the number of leads that existed during freeze-up and the amount of low level rafting in the first-year ice.

5.2.4 Limitations of Species Identification

Drained ice areas around breathing holes made by bearded seals cannot be differentiated ~~from~~ those of the ringed seal. One can assume from the habitat and observations of general abundance, that the majority of seal breathing holes especially in deep waters will belong to ringed seals. Ratios of ringed seals to bearded seals have been recorded as 84:1 (Heard and Donaldson, 1981) which if representative would result in a small error factor if breathing holes made by bearded seals are attributed to ringed seals.

5.2.5 Breathing Hole to Seal Ratio

Counts of breathing holes will give a measure of seal abundance rather than absolute population. Although a universal ratio between holes and the number of seals has yet to be established, it will probably be a more stable ratio than that which has been used between seals hauled-out at any one time and the total population that existed in that area 3 months previously. If counts of breathing holes are undertaken prior to establishment of the seal to hole ratio, they constitute a measure of abundance which is of value for comparative temporal or spatial analysis. At some future point in time when the seal to hole ratio is established, the measure of seal abundance could be converted to an estimate of population.

5.3 HAUL-OUT SURVEYS vs MONITORING OF INFERRED BREATHING HOLES

Although there are a number of limitations to using drained ice areas as an indicator of winter resident seal abundance, as discussed in 5.2, the method is worth seriously considering in the absence of a better technique. Currently employed seal survey methods employed during haul-out have limitations, reviewed in section 2.2.2, which result in an error factor in population estimates of 10 orders of magnitude (McLaren Marex Inc., 1979). In addition estimates from haul-out counts are based on the assumption that the summer population is the same as the winter population.

The review of the current knowledge of seal habitat, section 2.1.2, reveals that there is, at present, no easy, obvious method of monitoring seal abundance particularly during the major portion of the year when they live under the ice and snow cover. Yet, given the trophic importance of the ringed seal (Appendix A) it is necessary to monitor seal abundance, so that population fluctuations can be understood and human disturbance minimized.

CHAPTER 6

RECOMMENDATIONS FOR FURTHER STUDY.

It is recommended that a number of ecological and remote sensing studies be undertaken to clarify the ability of remote sensors to detect breathing holes and the relationship of breathing holes to the seal population. These studies are listed in table 6.1.

The recommendations in table 6.1, section C are described in greater detail in the form of a suggested study program in sections 6.1, 6.2. The remote sensing program forms a sequel to findings in this thesis.

6.1 SENSORS TO BE INVESTIGATED IN A REMOTE SENSING PROGRAM

There are two radar systems operational in Canada that were not deployed in the 1982 experiment but which are worthy of consideration table 6.1, section C.1). In addition, two satellites will be launched within the next five years, and may provide imagery applicable to seal studies.

One of the radar systems, a SLAR owned by a private company, MARS, is essentially the same system as that operated by the AES, although a wet silver processing procedure is used which produces

TABLE 6.1 Recommended Study Programs

<u>Type of Study</u>	<u>Aim</u>
A. Habitat study	1) establish a universal hole to seal ratio 2) establish a ratio between breathing holes in first-year ice and the number among adjacent old-ice floes.
B. Historical data analysis LANDSAT/SLAR/AES ice maps	1) Determine location of recurring areas of first-year ice. 2) Determine areas of recurrent surface water flooding and drainage development.
C. Remote Sensing programs	1) Test additional sensors. 2) Monitor an area chosen on basis of study B over a period of 5 years.

imagery with a greater dynamic range than that produced by dry silver development used by AES. The MARS system is currently used to obtain ice imagery for oil companies and because the company is in competition with other remote sensing companies the equipment is maintained and operated to obtain the best possible results. Consequently, imagery obtained by the Mars, Inc. system is superior to that obtained by the AES system.

In fall 1983, Intera had a SAR installed which is now operational. The system designed by the Environmental Research Institute of Michigan and built by MacDonald, Dettwiler and Associates, is the first of a new generation of SAR's and the first to be used for commercial, operational data collection. The image quality of the system appears to be excellent. The system can image a swath 25 or 50 km wide with minimal geometrical distortion. At 25 km, the resolution in range and azimuth is 6 m and with a 50 km swath, the resolution is 6 x 20 m which is still ample for detecting drained ice areas around breathing holes.

France will be launching a satellite, SPOT, in 1986. The satellite will have a multispectral scanner operating in the visible and near-infrared with a 20 m resolution which is capable of operating in a panchromatic mode with a 10 m resolution. Imagery from both modes will be worth investigating although usefulness of the imagery is restricted by the 26 day revisit interval and cloud coverage.

ERS-1 is another satellite that will be launched in the near future (1989) that may provide imagery of value for monitoring

drained ice areas around breathing holes. It will carry a C-band SAR with a resolution of 25 m which, as noted in section 5.4.4, is anticipated to have the potential of monitoring drained ice areas (Paci and deLeffe, 1982).

6.2 EXPERIMENT DESIGN FOR REPEAT MONITORING OF AN AREA

A remote sensing experiment series designed to obtain data for one site over a minimum period of five years forms a major part of the recommendations in table 6.1, C2. It is suggested that the study should be initiated as soon as possible, but that it should not replace traditional methods of seal surveys.

A study area, known to have undeformed first-year ice and experience surface water flooding on a yearly basis, should be chosen from an examination of ice charts, SLAR data and LANDSAT imagery. A second and third area might also be chosen as alternate sites. In the late fall of the year preceding the experiment, imagery for the area should be examined to determine if ice conditions are suitable for the experiment. LANDSAT data obtained after freeze-up but before heavy snowfall, or AES SLAR imagery obtained during the fall or winter routine reconnaissance flights should be used for analysis. If ice conditions are not suitable, an alternate site should be chosen. In the event that imagery does not exist a visual reconnaissance flight should be made.

Two weeks before anticipated snowmelt, as judged by weather

records and by past melt season occurrence, a ground observer should be located in the chosen area at a site which commands a view of the ice. The observer should also have transportation to allow sampling of the snow cover and ice thickness in several locations within the study area. Daily measurements of snow depth and examination of snow structure will allow prediction of snowmelt several days prior to the event. It is recommended that the observer have meteorological instruments so that snowmelt models can be constructed at a later date using input from basic parameters such as solar radiation and temperature. In addition, an annotated photographic record of surface conditions taken at 8 hour intervals from fixed locations should be made, to provide documentation of the surface flooding and drainage events. Ice thickness should also be monitored on a 5 day repeat basis.

Overflights to monitor the drained ice areas should be scheduled between one and two weeks after snow melt. At the current time, using information obtained from the Crozier Channel and Mould Bay data set (table 4.7) it is recommended that the basic sensor be an RC-8 with a colour corrected lens, or an RC-10. The instrument should be flown at an altitude to obtain panchromatic photography at a scale of 1:40,000, set to obtain a 20 percent forward overlap in a flight pattern that will obtain 20 percent side overlap. The resulting photography would form a mosaic which would result in 100 percent count accuracy of drained ice targets for a large area.

During the first experiment, if surface conditions develop as

anticipated, the Mars SLAR should be deployed to determine its potential. SLAR imagery should be obtained in conjunction with the RC-8. The RC-8 will provide photography of a 9 km strip under the aircraft and the SLAR should image an area from 4 km - 29 km on either side of the aircraft. The Intera SAR should also be deployed to obtain imagery at both a 25 km swath and a 50 km swath. Locations and counts of drained ice areas analyzed from imagery produced by all systems should be compared with results from the photographic mosaic.

Remotely sensed radar imagery or photography obtained the following years should be acquired by the system that proved to be reliable and economic. If any doubt exists, the photographic mosaic program should be maintained. The program, if run for five years would provide interesting comparative data on seal abundance, a better understanding of the potential of this method, melt cycle information, and might, if combined with seal observations, provide population estimates.

6.3 CONCLUDING REMARKS

The data set from Crozier Channel and Mould Bay has led to the proposed alternate method of measuring seal abundance by inferring the existence of breathing holes from the drained ice areas that the seals create. A variety of remotely sensed imagery can be used for this purpose. In addition, the study has contributed to the understanding of the development of drained ice areas and breathing hole

location with respect to ice type. Although using a count of breathing holes derived from remotely sensed imagery has a number of limitations, it is worthy of further investigation given the current lack of a reliable census method. The breathing hole survey method should be used to obtain supplemental information at relatively low cost/unit area and is not intended at the present time to replace the traditional "haul-out" surveys.

APPENDIX A

THE ROLE OF THE SEAL IN THE ARCTIC ENVIRONMENT

The ringed seal feeds on a wide variety of food which varies with the time of year and geographical location (Lowry et al., 1980). Its diet is composed of two major food types: primary carnivores, fish, for the most part cod, and primary consumers, pelagic nectonic crustaceans (figure A.1). The crustaceans are mostly amphipods and mysids which are small animals 12-35 mm long which feed on under-ice algae and phytoplankton. It is thought by some (Lowry et al., 1980) that the seal population may be limited by food availability.

Arctic fox (Smith, 1976), the polar bear (Smith, 1980; Furnell and Ooolooyuk, 1979) and man (Sabo and Jacobs, 1980; Wenzel, 1981) are predators of the ringed seal. The Arctic fox prey on newborn seal pups. In a three year survey of sub-nivean lairs in Prince Albert Sound, an average pup predation of 26.1 percent was found (Smith, 1976:1613). This is a major factor in maintaining the fox population as a newborn pup is estimated to provide a fox with food for between 30.2 and 45.2 "fox-days" (Smith, 1976:1615). Most predation by polar bears occurs in pack ice where the majority of the catch are sub-adults (Stirling, 1974). Bears also excavate sub-nivean lairs, but successful kills seem to be relatively low, in the

Figure A.1 Trophic Relations Involving the Ringed Seal

order of 15 percent (Smith, 1980). In Radstock Bay, southwest Devon Island, it was observed that one seal was killed per five bear days, a number which, if representative of large areas, could account for a very large number of seals.

Man could be considered as a natural predator in that he has existed as a relatively stable and integral part of the food chain until recently. Excavations of Thule winter houses occupied from AD 1100 to the present century demonstrate the long-term importance of the ringed seal in the diet (Sabo and Jacobs, 1980). In the last century man has overstepped the bounds of a natural predator by increasing in numbers and employing sophisticated methods to travel and hunt the ringed seal and by killing for purposes other than to acquire food. In 1963 when seal prices were at a maximum value of \$20.00 per pelt (Wenzel, 1978), hunting for skins resulted in greater numbers of seals being taken (Smith, 1975b). In Cumberland Sound, Baffin Island, the kill rate has been judged to have been in excess of the birthrate (Smith, 1975b). It has been suggested that it is a situation which only continues because seals from the unhunted surrounding areas move into the heavily hunted Cumberland Sound. Since that time, the value of adult ringed seal pelts decreased to around \$1.00 in 1977 in response to public outcry concerning the annual kill of harp seal pups in the Gulf of St. Lawrence and Labrador Sea (Wenzel, 1978). This has resulted in a severely reduced cash flow, income which is necessary for the upkeep of snowmobiles on which their hunting now depends. It has been suggested by Wenzel that an

inability to maintain snowmobiles will reduce hunting, forcing an increased dependence on prepared "southern" foods. The dependence on southern foods may not take place as it appears that seal meat is vital to the Inuit because it has a high caloric value and is rich in vitamin C, two dietary necessities which prepared foods available in the north generally lack (Geraci and Smith, 1979).

The activity associated with oil and mineral exploration is of environmental concern. Very little appears to have been done to assess the impact of development with the exception of a series of studies to investigate the behavioral, physiological and pathological effects of crude oil (Englehart et al., 1977; Smith and Geraci, 1975) and a summer aerial survey in an area of seismic exploration (Burns and Harbo, 1972). The latter study suggested that the intensive disturbance associated with exploratory activities in the shallow waters of the Arctic Ocean off the coast of Alaska during the spring pupping season did not result in an appreciable displacement of the summer haul-out population.

Owing to the importance of the ringed seal in the Arctic ecosystem and to the simplicity of the inter-relationships, it is of importance to predators, both man and other animals, that seal populations not be unduly disturbed. A reduction of the seal population by human intervention could have a drastic effect especially if it coincided with a naturally caused reduction in the seal population. More information is needed to understand and possibly circumvent such a situation.

APPENDIX B

PHYSICAL CHARACTERISTICS OF THE EXPERIMENT SITE

B.1 GEOGRAPHY AND SEA ICE

Prince Patrick Island is one of the westernmost islands of the Arctic archipelago and is the most western of the Queen Elizabeth Islands. The Island, about 250 km in length (NE-SW) is dissected by three major inlets on the southeastern side, one of which is Mould Bay. These reduce the width of the island to less than 50 km in some places. A manned weather station known as Mould Bay is located on the east side of the inlet (figure B.1).

On the southeastern side of the island in the Mould Bay region elevations reaching 700 ft. Mould Bay has a fairly small watershed with the result that there is a relatively low fresh water input to the bay. The bay has steep sides, the angle of which in many places appearing to be the angle of repose of the frost shattered rock. Less steep areas are found where streams form alluvial fans. The bay, better described as an inlet averages 200 m in depth and is 7 km wide in the vicinity of weather station. Salinity values have been recorded at 32 parts/thousand and a distinct current has been observed. Water depths in the adjoining Crozier Channel exceed 1750 m. From

Figure B.1 Prince Patrick Island

these observations it is safe to assume that sea ice formed in Mould Bay and the Crozier Channel is true sea ice representative of that found in other areas. If the Arctic archipelago is examined (figure 1.1), it can be seen that water bodies with configurations like Mould Bay and the Crozier Channel are common throughout the area. As a result it can be reasonably suggested that ice in the study area that forms is similar to that which forms in other sheltered areas in the same climatic zone.

Much of the northwest coast of Prince Patrick Island has a border of multiyear landfast ice which is extensively grounded in areas such as Hardinge Bay. No seals or breathing holes were noted in this area, so data from this area was not included in the study.

B.2 CLIMATE AND ICE

The major control on the climate in the Mould Bay area is the latitude which results in an absence of incoming shortwave radiation from late October to early March and relatively low levels of solar radiation during the remainder of the year owing to low sun angles. As a result the average temperature for July and August, the only months when the averages exceed 0°C, are 6°C and 3°C. From an examination of maps of mean daily temperatures it appears that Mould Bay is representative of much of the western and central Arctic. Unlike Eureka which is an "oasis" where local climatic controls result in a mesoclimate that is similar to more southerly areas,

Mould Bay would seem, from the ecology of the area, to be fairly representative of a considerable area.

The widespread homogeneity in temperature values is of interest because it has been found that the growth and ablation of sea ice can be estimated from temperature histories. (Bilello, 1961, 1977). Bilello (1961) found that a distinct relationship exists between ice during the period of growth and the accumulated degree days of frost as calculated from a base of -1.8°C with greater accuracy possible if corrections are made for snow depth. In a later study, (Bilello, 1977) was able to establish a relationship between accumulated thawing degree days (ATDD) calculated from a base of 0°C and sea ice ablation. Although maximum ice thickness at a given station varies from year to year, the pattern of subsequent ice decay appears to be similar with an average of 10 cm of ice ablation per 10 ATDD. This work would tend to suggest that similarities of ice thickness and melt stages exist in locations with similar summer and winter temperatures.

With yearly temperature fluctuations, ice growth and ablation rates vary. Although differences are not great, as shown by records from 1958 to 1964 when ice thickness varied by a maximum of 45 cm, the ice which forms to an average thickness of 200 cm in Mould Bay (Bilello, 1977) appears to break up and move out of the bay approximately every other year (Lindsay, 1979). A similar pattern exists for ice in Crozier Channel.

APPENDIX C

REMOTE SENSORS AND THEIR POTENTIAL TO STUDIES OF THE RINGED SEAL

C.1 INTRODUCTION

A brief survey of the capability of remote sensors is presented in this appendix. Comments have been made about the use of the sensors for wildlife applications and the potential of a given sensor to seal studies.

C.2 ARCTIC MARINE MAMMAL REMOTE SENSING

To date, there has been almost no consideration or use of remotely sensed data as a source of information for any of the Arctic marine mammals despite the large amount of work that has focused on part of their habitat, sea-ice. The isolated studies that do exist largely use aerial photography (Heyland, 1974). Remotely sensed information concerning the ringed seal or its sea-ice habitat would be a considerable asset because remote sensors are capable of obtaining synoptic information at relatively low cost per unit of area. The Arctic, a vast inaccessible area that is sparsely populated and often inhospitable to observers, is one of the areas of the world

where remotely sensed data may be the only practical way of collecting data for extensive areas. The other major advantage of remotely sensed imagery is the option of using wavelengths other than visible which do not rely on the sun's illumination and which can penetrate snow (Carsey, 1982). Much of the recent work on sea-ice has concentrated on exploring the potential of various wavelengths with a view to defining more clearly the sea-ice/water boundary and sea-ice types (Onstott and Gogini, 1982).

In order to examine the possible use of remotely sensed imagery as a source of information on the ringed seal and its habitat, it is important to understand the capabilities of the sensors. The most useful way of examining the potential value of remotely sensed imagery to studies of the ringed seal or its habitat is to consider the attributes of the major components of the spectrum; visible light, ultra-violet light, infrared, thermal IR and the microwave band (figure C.1).

C.3 VISIBLE AND NEAR-INFRARED PHOTOGRAPHY

Visible light photography has a number of advantages; in cloud-free, daylight situations, photographs with a sufficiently large scale can be used to count seals (Lavigne and Oritsland, 1974), to determine ice edges and to provide some ice type information. In the melt season, when there is a large amount of surface water and no snow, the major ice types, multiyear and first-year, are readily

Figure C.1 The Portion of the Electromagnetic Spectrum Used in Remote Sensing

Adapted from Lillesand/Kiefer (1979), and Ulaby, Moore and Fung (1981).

discriminated as are deformation features. Perhaps the greatest advantage of photography is that it produces a familiar product because it records the same spectral bands to which human eyes are sensitive. As such, it is readily interpretable particularly by a person who has experience with related surface conditions.

Visible light photography has been used in conjunction with visual observations by the Atmospheric Environment Service to delineate the sea-ice/water boundary and sea-ice types since the early seventies. It was not until 1982 that the Department of Fisheries and Oceans used this technique and installed a 90 mm nadir viewing camera in an aircraft for use during seal survey flights to obtain a record of sea-ice types and ice concentration. Photography has been used in test cases to count harp seals (Lavigne and Oritsland, 1974) but it has not been used to count ringed seals or used on an operational basis perhaps because of the high cost and limited swath coverage when compared to visual observations. Visible light photography has been used in two studies to provide documentation of seal holes and drainage patterns during the melt season (McLaren Marex Inc., 1979; Finley, 1978).

Visible light imagery obtainable on a repetitive basis from satellites has been very useful for sea-ice mapping and monitoring ice dynamics (Dey, 1980; Barry et al., 1979; Sobczak, 1977). The relatively low resolution, 80 m for LANDSAT MSS (multispectral scanner) and 1 km for NOAA-VHRR (very high resolution radiometer) imposes limits on the detail that can be acquired (Dey et al., 1979).

Current civilian satellites are not capable of detecting individual seals.

Both LANDSAT and the NOAA satellite series also obtain imagery in the near infrared, at wavelengths slightly longer than visible (figure C.1). This wavelength (0.8 - 1.1 μm) has much the same characteristics as visible light although it is more sensitive to, and hence emphasizes, the water/dry ice contrasts in the melt season.

Satellite imagery both in the visible and near-infrared bands has been used to a limited extent by biologists and geographers to identify features which are known to form habitats for marine mammals (Smith and Rigby, 1981) and in particular ringed seals (Finley, 1978). A study by Burns, Shapiro and Fay (1976), includes a discussion of the winter distribution of pinnipeds as a function of widespread sea-ice conditions. The sea-ice information derived from NOAA and LANDSAT imagery was used as a basis for planning aerial seal surveys. Prior to this thesis, the possibility of detecting drained ice areas around seal holes on LANDSAT imagery had not been discussed in the literature.

The usefulness of visible and near infrared photography and imagery is limited to the summer months and early fall as the Arctic is in darkness throughout the winter and snow can obscure differences between ice types and surface features. In addition, substantial cloud or fog cover often prevent summer photography. Photography or imagery, with partial cloud coverage can be difficult to interpret as snow or drained ice provides little contrast against cloud or fog,

and snow drift patterns can be confused with sporadic cloud edges.

C.4 ULTRA-VIOLET

Ultra-violet (UV) energy emitted by the sun is at wavelengths a little shorter than those visible to us. Use of the ultra-violet band is not common because ultra-violet energy is absorbed by the atmosphere and glass lenses. Little or no data exist concerning the use of ultra-violet for sea-ice studies.

Ultra violet energy has, however, been found to be very useful to counting harp seals in whelping herds on pack ice (Lavigne, 1976), where a quartz lens was used to overcome problems of UV absorption in the lens. Newborn "white-coats" which were almost totally undetectable against the snow at visible wavelengths were found to be readily discernible with ultra-violet photography because their fur absorbs ultra-violet energy. The absorption of ultra-violet energy results in photography at an optimum scale of 1:2,900 showing "black" seal pups and adults against a white background. Although the results were very successful, ultra-violet is not currently employed. The advantage of using ultra-violet over visible light would be less marked in the case of ringed seals as they are counted later in the season when most pups are no longer white. In addition, ice in the Arctic archipelago is less deformed than that of the Labrador pack so that there are fewer ambiguities created by shadows. The use of ultra-violet airborne photography is, however, an area that is worthy

of further study.

Atmospheric absorption and resolution constraints preclude the use of the ultra-violet band for similar studies from a space platform.

C.5 THERMAL INFRARED

The thermal infrared (TIR) band with wavelengths longer than those in the visible and near-infrared, (figure C.1) has an advantage over visible light in that TIR is emitted energy and is not dependent on the sun's illumination. As a result, imagery can be acquired throughout the winter in the Arctic. A major disadvantage to TIR is that clouds obscure the ground.

TIR imagery from the NOAA satellites has been found useful for sea-ice studies. Features with relatively high temperatures - leads, polynas and open water with thin ice appear in grey to black tones whereas pack ice and multiyear ice which are cooler are imaged as light grey. (Dey, 1981). Accurate ice type discrimination appears to be limited and with a ground resolution of 0.8 km at nadir, information derived from the NOAA TIR band is most useful for monitoring major sea ice dynamics (Dey, 1981).

C.6 MICROWAVE IMAGERY

Since the Second World War there has been increasing interest and technological development in the microwave band for sea ice studies and other applications. Microwave energy has much smaller amplitudes and longer wavelengths than visible light and as a result is affected by physical properties that may not be readily apparent. Microwave sensors can either be active in which case microwaves are either emitted by the sensor and backscattered by earth's surface, or passive in which the sensor records microwaves emitted naturally at low levels. Microwaves are not dependent on the sun's illumination and they can, to varying degrees dependent on wavelength, penetrate cloud and atmospheric moisture (Ulaby et al., 1981). As a result, microwave imagery can be obtained year round, day or night and in all weather conditions. Snow is largely transparent to microwaves with the result that the microwave response measured by the sensor is a function of the underlying sea ice. There are no known biological studies that have used any form of microwave imagery.

C.7 PASSIVE MICROWAVE

Passive microwave sensors, radiometers, measure the intensity of naturally emitted microwaves and the recorded energy is known as the radiometric temperature or temperature brightness, T_b . A given radiometer is designed to be sensitive to a specific wavelength (Ketchum

and Lohanick, 1980). Because of the low level of naturally emitted radiation, the sensors have to obtain energy from a large area: that is, they have a large "footprint" and as a result, low resolution. Radiometers such as the 19 GHz ESMR (Electrically Scanning Microwave Radiometer) on Nimbus 5 typically have resolutions of 25 km at best.

Given the poor resolution, it is apparent that space-borne radiometers are probably not capable of providing any information concerning ringed seals as individuals or their fast-ice habitat. Meaningful passive microwave imagery cannot be obtained close to shore because the large "footprint" combines response from coastal areas with that from the land to give ambiguous results. As yet, to the knowledge of the author, no imagery from the recently developed airborne high resolution radiometers (Hollinger et al., 1976) has been obtained for undeformed landfast ice during the melt phase.

C.8 ACTIVE MICROWAVE

Active microwave imaging sensors otherwise known as radars have little in common with passive microwave sensors except that they operate in the microwave region. In many cases, changes in the sea-ice surface are detectable with both active and passive instruments, but the responses have been noted to display an inverse relationship (Grey, 1981). Imaging radar systems emit microwave pulses which are scattered, to varying degrees, at the surface or by sub-surface inhomogeneties so that a portion of the energy returns to the

receiver. The amount of energy backscattered is a function of many factors: surface roughness, angle of incidence and the dielectric constant of the sea-ice which in turn depends upon the salinity, moisture, temperature, bubble content and orientation (Weeks and Ackley, 1982; Kovaks and Morey, 1978). Owing to the greater strength of the backscattered signal measured by active radars as compared to the emitted energy measured by a passive radiometer, the resolution of an active system, either a real aperture side-looking airborne radar (SLAR) or a synthetic aperture radar (SAR), is potentially much higher.

X-band SLAR imagery has been used for interpretation of ice types for some time (Dunbar, 1979) and in Canada the Atmospheric Environment Service Ice Branch and a private company F.G. Bercha and Associates Ltd., are using an X-band SLAR on a routine basis for ice reconnaissance. The choice of X-band was fortunate as the 3 cm wavelength appears to provide optimum backscatter differences between major ice types (Ketchum and Tooma, 1973). In spite of familiarity on the part of ice observers with X-band radar images and their use in distinguishing many ice types, ambiguous situations such as that between calm open water and undeformed first-year ice do exist (Grey, 1981). For this reason, visual observations are also made whenever possible.

The synthetic aperture radar (SAR) which can also be side looking has the same general characteristics as a SLAR with the exception of the resolution. The SAR has an increased resolution

that is relatively constant across the swath whereas the resolution of SLAR imagery deteriorates with slant range distance from the sensor. A recently developed commercial SAR has a resolution of 6 m across a 25 km swath. It is feasible to obtain high resolution imagery (25 m) from space as was demonstrated by the SEASAT SAR that was launched in 1978 (Fu and Holt, 1982). Although it ceased to operate after three months, the data obtained emphasized the potential benefits of spaceborne SAR for synoptic day/night, all weather, repeat coverage.

Space-borne and airborne radar imagery has yet to be used in studies of marine biology. Although it is unlikely to have the capability of monitoring individuals it does have a very strong potential use in the definition of ice types and open water areas which form habitats for many marine animals (Arsenault, 1980; Hall and Rothrock, 1981). In the case of ringed seal studies, it is highly possible that operationally acquired SLAR imagery would be useful in determining habitats associated with high or low densities of seals and establishing aerial survey flight lines to maximize sampling of representative ice types. A satellite-borne SAR would be similarly useful and would provide greater geographical coverage.

C.9 DISCUSSION

From this review of remote sensors it can be seen that no sensor combines the resolution to detect individual seals with the ability

to obtain a synoptic overview. Large scale visible, near infrared and ultra-violet can be used to detect individuals in a restricted area. Small scale, airborne, visible light photography, satellite visible light and IR imagery, airborne and satellite microwave imagery provide small scale synoptic information which can be used to provide information on the sea ice habitat but not on individuals. If the monitoring of drained ice areas around seal holes is possible with the second group of low resolution sensors, information on the individual could possibly be inferred from imagery on a synoptic scale. This would be a considerable advantage given the large geographical range of the ringed seal.

APPENDIX D

SENSORS, IMAGE CHARACTERISTICS AND QUALITY

D.1 SLAR CHARACTERISTICS

As its name suggests, the side looking radar obtains imagery of the area on either side of an aircraft. The SLAR in the AES Electra is a modified AN/APS-94E developed by Motorola initially for the military. It is one of two such sensors in Canada. The radar operates at X-band, a wavelength of about 3 cm. Microwaves are transmitted and received at a horizontal polarization. Swath width of the imagery can be set at 25, 50 or 100 km. Over Mould Bay and Crozier Channel, imagery was acquired on both sides of the aircraft at shallow angles from 45° at the near edge to grazing angles at the far edge (figure D.1). The imagery is seen in "real-time" with a delay of a few minutes. The radar return is recorded on a strip of film 25 cm wide, with each swath being 10 cm across, regardless of ground extent.

Resolution of the system is not constant across the imagery. The image is in slant range, although very little distortion is observable. In slant range, range resolution is constant at 30 m,

SLAR Acquisition Geometry - 25 km Swaths

SAR Acquisition Geometry - 10 km Swath

Figure D.1 SLAR and SAR Image Acquisition Geometry

however, if the imagery is converted to ground range, i.e. so it is geographically correct the range resolution degrades at near range.

The azimuth resolution, the resolution in the flight direction is far more variable; determined by beamwidth, it decreases from 25 m at the near range to over 200 m at the far range (figure 4.14). The relationship is expressed by the following equation:

$$\text{azimuth resolution} = \text{distance from aircraft ground} \times \text{beam width}$$

Although the SLAR imagery is obtained in the slant range, the distortion is so minimal that a 25 km swath can be overlaid on 1:250,000 map with no noticable inaccuracies except in the near range.

Theoretically, imagery from the right hand and left hand swaths should be of the same quality, however, the left hand swath of the AES imagery is of poorer quality. The difference is caused by the antenna which runs lengthwise underneath the aircraft, offset to the left hand side with the result that the left swath experiences interference.

D.2 SLAR IMAGE QUALITY

The SLAR imagery for Mould Bay and Crozier Channel, obtained for a number of passes (figure D.2) in a three-hour period during the afternoon of 3 July, is of good quality. There is very little motion-caused banding. The video and bias controls, which regulate the

Figure D.2 Passes Made by the AES Electra, 3 July

exposure and the map contrast respectively, were adjusted for optimal results at the start of the passes in the morning and not altered during the day-long flight. As a result the recorded response was rather weak by the end of the seven-hour imaging period. The only other problem concerns the motion correlator which is a device which matches film speed with aircraft ground speed. It appears that the system is not accurate, as in most passes, distances between features in the flight direction on the imagery are larger or smaller than the corresponding distance on the 1:250,000 map. The film was misplaced by a maximum distance corresponding to five km.

D.3 SAR CHARACTERISTICS

Synthetic aperture radars are considerably more mechanically complex than SLAR systems, a complexity which is created by the process that is responsible for increased spatial resolution. The SAR in the Convair, one of three systems in North America, was originally developed by ERIM (Environmental Research Institute of Michigan) and has since been substantially modified by personnel at the Data Acquisition Division (DAD) of CCRS. The CCRS SAR is used to obtain data for experimental purposes and is frequently modified.

The radar is side-looking to either the right or the left. It is capable of operating at X- and L-band or at X- and C-band. The system has 4 receive channels so the chosen frequencies are received at both horizontal and vertical polarizations. Ice type discrimina-

tion is aided by cross-polarization but the overall level of return is much weaker. Resolution in both range and azimuth is 3 m. Resolution in azimuth remains constant across the swath owing to the process of synthesizing a longer antenna by detecting Doppler frequency shifts. Resolution in range is constant in slant range, according to the same principals that govern SLAR resolution. The imagery is more obviously slant range than the SAR as severe compression is readily detectable close to nadir and it is not possible to register the imagery to a map with any degree of accuracy. Measurements of distance and incidence angles for given objects can be computed accurately using a program developed under the direction of R. Hawkins (CCRS) or estimated using a series of monographs developed by C.E. Livingstone (1983).

D.4 SAR IMAGERY, 7 JULY

SAR imagery was obtained at X- and L-band on a single pass over the Crozier Channel from open water in the south to Prince Patrick Island in the north. SAR imagery obtained on 7 July is at XHH, (X-band, horizontal transmit, horizontal receive); XHV (X-band, horizontal transmit, vertical receive); LHH, (L-band horizontal transmit, horizontal receive); and LHV, (L-band, horizontal transmit, vertical receive). Simultaneous high level RC-10 photography covers the 2.5 km closest to the aircraft where geometrical distortion is greatest and the 35 mm oblique photography covers the remainder of

the swath (figure D.3).

The SAR imagery is of good quality with the exception of two 0.5 km wide bands of data loss on both X-band data channels and a rather weak return at XHV which may be a function of instrumentation and not of surface conditions (L. Gray (CCRS), personal communication).

D.5 LANDSAT 3 CHARACTERISTICS

LANDSAT 3, the third in a series of earth resource satellites, was operational in an orbit at a nominal altitude of 900 km from the spring of 1982 to December 1983. It carried a multifrequency scanner which operated in four narrow adjacent frequency ranges, or bands, from visible to near-infrared. Two bands were in the visible light range, from 0.5 to 0.6 μm and from 0.6 to 0.7 μm and two bands are in the reflected infrared from 0.7 to 0.8 μm and 0.8 to 1.1 μm . The bands were designated consecutive numbers from 4 to 7. The resolution of the system was 80 m, but objects smaller than 80 m can be distinguished if they are spectrally very different from the surrounding material. The MSS on LANDSAT 3 covered a 185 km swath which was processed into sections or scenes measuring 185 x 185 km. Coverage of a given area can be obtained every 18 days given cloud-free conditions. Coverage in the Arctic is more frequent with increasing latitude, as the shape of the earth causes swath overlap in the East-West direction. The MSS carried in all of the LANDSAT satellites is not always turned on over the high Arctic so coverage is not

Figure D.3 SAR and Simultaneous Visible Light Coverage

as frequent as might be expected. Requests can be made through CCRS for specific coverage.

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