RADARSAT PROJECT REPORT 82-4
PLATFORM, SENSOR AND COMMUNICATIONS TRADE-OFF STUDY

PHILIP A. LAPP LIMITED

INTERIM REPORT
on Task 3 of the Ice and Oceans User Requirement Definition Study for RadarSat Program

Carried out for the
RadarSat Program Office
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Work Carried out by
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FOREWORD

The task of providing the RadarSat Project with a trade-off study on the best mix of remote sensing platforms and sensors is a very challenging one. PHILIP A. LAPP LIMITED has done a very credible effort in looking at the cost and the technologies involved even though the cost for the satellite products is very difficult to establish at this early stage. The proposal of having satellite and aircraft using both active and passive microwave sensors to acquire ice information under virtually all weather, day and night conditions, shows the impact these sensors have already made with the user community.

As the Scientific Authority, I would like to thank my colleagues from industry and government who have provided John Barry and Dave Lapp with numerous inputs to this study. In particular, I would like to acknowledge the continuing effort by members of the Ice Branch, Atmospheric Environment Service and the Coast Guard, Department of Transport, in providing advice, comments and in being good listeners throughout this effort.

Réne O. Ramseier
Scientific Authority
RadarSat Project

SUMMARY

This report describes the results of a study carried out for the RadarSat Project Office (RPO) in late 1981 and early 1982. The study objective was an engineering trade-off of platforms, sensors and communications options for ice reconnaissance in Canada. The study was one task (Task 3) of seven in a contract to examine Canadian ice and ocean user requirements both now and in the future. As a point of departure, the Canadian ice reconnaissance requirement was exemplified by combining the current ice reconnaissance activity of AES Ice Branch with the perceived requirement for year-round oil and gas shipping from the Arctic beginning in the latter half of the 1980's.

It is concluded that in terms of current Ice Branch operations, the year-round Arctic requirement will impose a 2½-to 3-fold increase in annual coverage of ice and ice-frequented waters. It is further concluded that effective reconnaissance will require high resolution imagery to be collected by an all-weather system capable of operating either by day or by night. Imaging radar is concluded to be the only suitable candidate sensor for this role.

Results of the study show also that a scanning microwave radiometer operating at 37GHz and 90GHz is the most suitable second sensor in an ice reconnaissance system because, in addition to being an all-weather,

day/night sensor, (except in the presence of intense rain and wet snow), passive microwave sensing complements rather than duplicates the measurements made by an imaging radar.

Either an aircraft or a satellite was assessed as an excellent platform for the recommended microwave sensor package, but each platform has unique advantages and disadvantages in a particular application. An aircraft is adaptable to changing circumstances, and cost of operation is entirely related to utilization. A satellite on the other hand is relatively inflexible, being in a fixed orbit with fixed coverage, and fixed cost, but the coverage is vast and continual, completely overshadowing what can be accomplished by an aircraft at practical costs. Combining the positive features of both platforms for ice reconnaissance is therefore highly desirable. The results of the study indicate that such a combination is technically practical and, based on RPO target prices for space platform data products, would be cost-effective. Heavy reliance on satellite coverage with supplementary support from aircraft platforms is envisaged for the end of the century, as satellites become more reliable, more complex (i.e. suiting many users), and more numerous.

Communications has been shown to be a critical and relatively costly (in the order of 10%) element in an ice reconnaissance system. Real-time transmission of radar imagery from reconnaissance aircraft to an Ice Information Centre is a unique requirement demanding a network of combined aircraft-downlink/satellite-uplink circuits for proper operation.

In a mixed aircraft/satellite system it is concluded that the lease of an entire channel in an ANIK satellite will provide cost-effectiveness with needed flexibility, particularly with respect to reducing costs of receive-only terminals for Ice Information Centre products. The technology to implement all of the communications requirements is readily available; implementation of the DOC M-SAT program would introduce a further degree of flexibility especially in thin-route service to and from mobile platforms.

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1. INTRODUCTION

1.1 Objective

The work reported here has been conducted under Task 3 of the "Ice and Ocean User Requirement Definition Study for RadarSat Program". The objective of Task 3 was to establish the relative importance of satellites and aircraft to collect ice reconnaissance information:

> "Conduct a tradeoff analysis of appropriate platform, sensor and communication system for a Canadian Ice information system. The analysis should consider:
>
> - best platform mix
> - best sensor mix
> - alternative communication system
>
> The analysis should also estimate the export potential for information, hardware and complete systems."

The study is a systematic effort to assess the combined benefits of ice reconnaissance from aircraft and satellites in a single system that serves the requirements of a wide cross-section of users. Such a system must collect and move ice information in many forms and formats quickly and accurately among a number of nodes in an ice information system. The nodes represent information sources, information processors and users.

1.2 Limitations

The work involved in cataloguing and analysing needs and in examining the most appropriate technology to meet these needs was conducted in an environment of rapidly-evolving perceptions, firstly, as to what the future requirement will, in fact, turn out to be, and secondly, as to what a future ice reconnaissance system is likely to be. Any future system is influenced by what future technology can, practically speaking, provide. A major element in the future requirement is year-round production and transportation of petroleum products from the Canadian Arctic to eastern Canadian ports and depots, but the dimensions of this requirement are only now beginning to emerge, as compromises among cost, performance, timing, risk, and other factors are sought.

1.3 Background

Task 1 of the project (Ref.1) sought to provide a statement of user requirements for ice and ocean* information at four time points - 1985, 1990, and 2000, plus the present. Task 2 (Ref.2) sought to reduce these requirements to a set of ice and ocean information products. Task 3 seeks to analyse and recommend the most appropriate system to provide the raw input for these products and then to review the communications alternatives for disseminating the information.

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* This report deals only with ice information.

The results of the user requirements study show that the prospects for important changes from the present (i.e. 1981) requirement, from the point of view of the criticality of ice information, will occur in the 1985-1990 period with the commencement of year-round production and shipping of petroleum resources from the Arctic in icebreaking tankers. Accordingly, the task of conceptualizing an optimum response to the ice information requirement can be seen as addressing two time-frames separated by the commencement of year-round tanker operations in the Arctic.*

Likewise the response to the requirement, that is, the system proposed for solving the problem, is divided into two time-frames separated by the introduction of satellites with imaging radars. Until such a satellite or satellites becomes a reality, the only sensor platform available is aircraft, supported by other remote-sensing satellites such as NOAA, NIMBUS, and LANDSAT. Though extremely powerful and useful, these other satellite do not meet the requirements.

The study emphasizes the major 1985-90 element, that of producing oil and gas in the Arctic and moving it to Southern markets. The requirements for global ice information at lower resolution over very large areas is discussed in qualitative terms only.

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* A need for steady increased scope of ice information for modelling research and research in general exists although its quantitative limits are very difficult to define since researchers in general use all available information, be it sparse or plentiful.

1.4 Form of the Report

This report is written in eight sections beginning with this Introduction. The next section outlines the methodology used. Following this, Section 3 is devoted to a re-statement of the requirements catalogued in Task 1 of the project (Ref. 1). This re-statement is made in terms of the practical technical options available to respond to the stated requirements. Emphasis on the practicality of the solutions forces the necessary compromises between essential and desirable but non-essential outputs of the ice reconnaissance system. This re-statement includes a detailed analysis of the seasonal and regional aspects of the requirements for ice reconnaissance to bring out its dynamic nature.

Section 4 covers sensor technology. From a brief review of some basic principles of remote sensing the discussion moves to the relative merits, limitations, and deficiencies of various ice- reconnaissance sensors in aircraft or satellites.

The section on sensor technology is followed by Section 5 in which the pros and cons of aircraft and satellites as platforms for ice reconnaissance sensors are examined. The impact of year-round Arctic petroleum production and shipping emerges in the discussion of aircraft platforms.

Section 6 covers the basics of communications system alternatives.

Section 7 covers financial aspects of the various system options.

The final section, Section 8, is devoted to a summary of the principal findings and the conclusions and recommendations on the optimum system for the present, 1985, 1990 and 2000.

2. METHODOLOGY

The study was conducted in the conventional way according to the task plan shown in Figure 2.1. Clear delineation of the various phases was neither practical nor desirable since the requirement to be met, as originally stated, was a combination of desirable and critical elements and had to be adjusted to conform to the realities of platform sensor and communications systems performance. In the end, a reasonable consensus representing a minimum level of ice information to a range of users was developed. Concepts for sensors, platforms and communications were developed concurrently.

Throughout, the study was viewed as a system (or systems) response to a requirement. This systems approach, although qualitative at times, has forced compromises in the interest of serving the basic perceived need. In particular, the aircraft versus satellite aspect was de-emphasized in favour of a system response based on aircraft, satellites or both.

To focus the study, a case study of ice reconnaissance requirements for Arctic Petroleum Transporation was examined in detail. Choice of this application stemmed from three considerations. Firstly, in terms of the time points in the study, the proposed activity of the Arctic Petroleum operators is the most clearly stated future operation that will require a significant change in the current pattern of ice reconnaissance. Secondly, the Arctic Petroleum shipping activity is one of the highest priority requirements; and, thirdly, the requirement is wide enough in its scope to serve as a base from which extrapolation to meet other activities is readily accomplished. This includes implications for route planning and route execution, plus meteorological and other geophysical and environmental factors.

Selection of a case study also drew out the seasonal and regional aspects of ice reconnaissance. Without a credible picture of the year-round dynamics of ice reconnaissance it would be impossible to assess the adequacy of platforms, in particular aircraft, to do the job.

Since this was essentially an engineering study, the technical capability of a system to respond effectively to the requirement was the key consideration in examining options. Logistics and the basic performance of the remote sensing technology are the foundations of the conclusions therefore. When the associated benefits, weaknesses and financial aspects are added, the optimum system can be identified.

It has already been noted that the conclusions of this study are based on an extrapolation from current reconnaissance practice into a case study situation which is, in truth, only a perceived requirement at this point in time. This feature was continually emphasized by many of the individuals interviewed. It is to be expected that the experience of the real event will reveal inconsistencies, shortcomings and excessive caution in our present forecast of the requirement.

Notwithstanding the differences that may emerge, however, most individuals believe that the general minimum level of ice reconnaissance as perceived is correct for short-term strategic planning and operations, even if the day-to-day dynamics and specific activities undergo significant change in the real environment. Within these limitations therefore, the conclusions are believed to be valid in the time-frames of interest, and implementation of the ice reconnaissance system suggested for the various time frames will be an effective solution to the requirement.

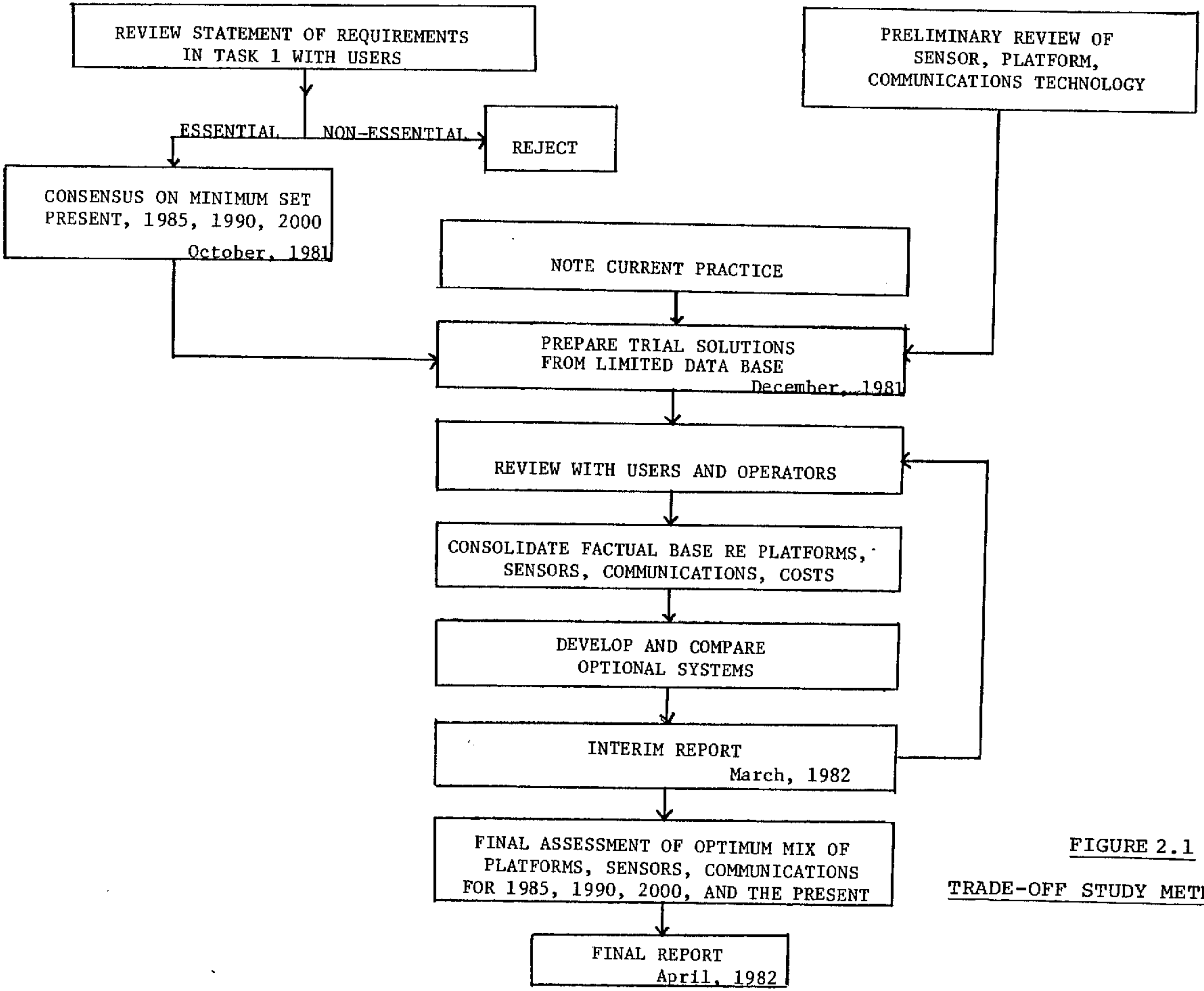

FIGURE 2.1

TRADE-OFF STUDY METHODOLOGY

3. RE-STATEMENT OF ICE RECONNAISSANCE REQUIREMENT

The questionnaire survey to users reported in Ref.1 produced a wide range of requirements in terms of time-of-delivery of information to users, repetition frequency, spatial resolution, discrimination among targets, coverage zones, and specific ice features. Taken at face value, the omnibus requirement could not be met by a single practical system, so the set of requirements was examined critically through a series of internal project reviews and meetings with AES Ice Branch and user personnel with a view to creating a narrower baseline requirement.

As a point of departure, the requirements for five features in terms of user needs - ice type, ice concentration, ice edge, ridges, and icebergs - were cross-correlated with the sea ice data in Markham's 1980 and 1981 Ice Atlases (Ref.3 and 4). This led to a seasonal/regional master requirement chart with explicit statements on repetition frequency. Next a quantitative statement of the areal coverage was required so quantitative systems responses could be considered. The shipping corridor being planned by the Arctic Pilot Project (APP), with a Westerly extension to the forecast oil production regions of the Beaufort Sea was selected. This corridor is shown in Figure 3.1. To this was added AES's current level of ice reconnaissance. Selection of this new requirement as a focus served manifold objectives:

- it illustrated the ice reconnaissance requirement after commencement of year-round Arctic production and shipping;

- it covered a wide range of ice features with typical repetition aspects;
- year-round transportation from the Arctic may be critically dependent, economically and technically, on having the right information at the right time;
- the requirement is reasonably well understood as far as the basic information base to be supplied is concerned, therefore the future 'load' on the ice reconnaissance system is likely real;
- a conceptual response to the technical feasibility of various solutions is urgently needed for sustained, year-round ice reconnaissance in the Arctic;
- the problem is general enough in scope to serve as a base from which to extrapolate feasibility and cost of other requirements.

On advice from Ice Branch, winter ice surveillance for the lower latitudes was assumed to be sensibly unchanged in future from the present. (In fact, modest reduction in aircraft coverage is forecast due to better use of weather satellite data.) The surveillance requirement was subsequently reviewed with Canada Coast Guard, AES Ice Branch, and petroleum operators. The final chart is reproduced in Table 3.1.* In terms of time-frames referred to earlier this chart illustrates the total ice reconnaissance requirement following commencement of year-round shipping from the Arctic.

Table 3.1 can be compared with the data in Figure 3.2. The shaded area of Figure 3.2 indicates roughly, by location and by month, the regional and seasonal activity of Ice Reconnaissance as now practiced by Ice Branch. In Figure 3.2 we have also noted the current

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* The 40 hrs/wk for Newfoundland and the Gulf - sections 10 and 11 in Table 3.1 - is unspecified as to coverage but daily coverage of large areas is not implied in the current Ice Branch outlook for the future.

annual level of ice reconnaissance by private operators in the Beaufort Sea. Combining both figures the total area surveyed annually as in the order of seventy five million square kilometres. It will be seen that summer activity is concentrated in the Arctic while winter activity is concentrated in the Newfoundland and Gulf of St. Lawrence regions. By and large ice reconnaissance follows and supports shipping and ice breaker activity patterns and is justified on these grounds, although important spin-offs for ice climatology and research purposes are also involved.

In the current AES ice reconnaissance operation the shift in activity from the Arctic to the East coast as the Arctic closes up for the winter months permits a very rational and effective deployment of two ice reconnaissance aircraft. The commencement of year-round shipping will introduce a new winter requirement which will cause the overall reconnaissance to increase significantly in winter. Discussions with experienced personnel at Ice Branch indicate that in the future scenarios the reconnaissance activity may well peak, not during mid-winter as might be supposed, but in May and June because of the need to widen reconnaissance activity in the North and still cover iceberg detection on the East Coast. In the current situation the iceberg reconnaissance increases on the East Coast as the ice reconnaissance requirement wanes, causing the current peak to occur approximately in August, with minimum demand in November and December. In future this minimum will disappear because of the intensity of activity in the Arctic during the onset of freeze-up.

Ice Branch conducts a mid-winter 'round-robin' survey of ice conditions in the Arctic once a year over a period of one to two weeks, usually in February.* Flights are also made up the Labrador Coast as far North as Cape Chidley once a month during the winter. Reconnaissance flights are made over the Great Lakes during freeze-up and break-up. The sum total of all of these is not large in terms of aircraft hours, so it has been omitted from the master chart as a relatively minor requirement.

The seasonal/regional/areal requirement of Table 3.1 can be converted into hours of aircraft on-site flying if some assumptions as to aircraft and sensor performance are made. For this analysis we postulate an aircraft speed of 250 knots or 460 km per hour and an effective, unbroken, sensor swath width of 100 km.** The results are given in Table 3.2. Note that no allowance is made in this table for ferry times or inefficiencies in the data collection process. These factors are dealt with in later sections.

To illustrate the dynamic nature of the requirement more clearly, the data in Table 3.2 was combined with monthly data supplied by Ice Branch for a current typical year to form the histogram shown in Figure 3.3.

In the light of the current AES flying level of 2200 hours per year total, including ferrying time and time lost due to inefficient surveillance, (weather, equipment failure, etc), the new requirement is in the order of three times the current level. To

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* This past winter (1981-1982) for the first time "round-robins" were conducted on a monthly basis.

** This is a compromise figure. Radar sensors with lower resolution could cover a 160km swath.

the extent that hours are convertible to area, the areal coverage will also increase threefold.

To summarize, reconnaissance of sea ice concentration, sea-ice types, ridging, sea/ice/water edge and icebergs will require the equivalent of three times the current general reconnaissance level to support the strategic requirements of year-round production and movement of petroleum resources from the Arctic in the mid-to-late 1980's. By combining this requirement with an assumed requirement for spatial resolution of 25 metres, the limit most frequently called for in the user survey, we are in a position to analyse the sensor/platform response.

For reasons of practicality, spatial resolution greater than 25 metres will be included in the discussion at times. To do otherwise would artifically restrict the true options. To illustrate the variation in resolution requirements, Hengeveld (Ref.5) suggests spatial resolution of 8m x 8m for certain ice reconnaissance situations; a satellite-borne microwave radiometer on the other hand can convey significant ice and ice/water information with very coarse resolution, in the order of 20 to 30 kilometers for current systems.

It is noted that other requirements may arise that cannot be met, even by this increased coverage. For example, a requirement to increase vastly the annual area covered would entail unreasonable increases in (aircraft) reconnaissance time. Such a requirement might be for synoptic coverage over regions of Canadian ice-frequented waters for initializing models for environmental forecasting. Quantitative statements on this type of requirement are not available at this time in terms of region, area, or frequency of measurement, but the areas could be very large. The eventual need is self-evident. As an indicator of this more global requirement, ice-frequented areas contiguous to the shipping corridor shown in Figure 3.1 have been identified in the figure and the size of the area noted. Clearly, frequent, detailed, reconnaissance of these areas, even at low resolution, would be a major addition to the requirement being baselined in this report.*

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*In a recent paper (Ref.6), Ramseier and Bunn confirm the usefulness of low resolution information by noting that the resolution of the NIMBUS-7 microwave radiometer is compatible with the grid size of current ice models.

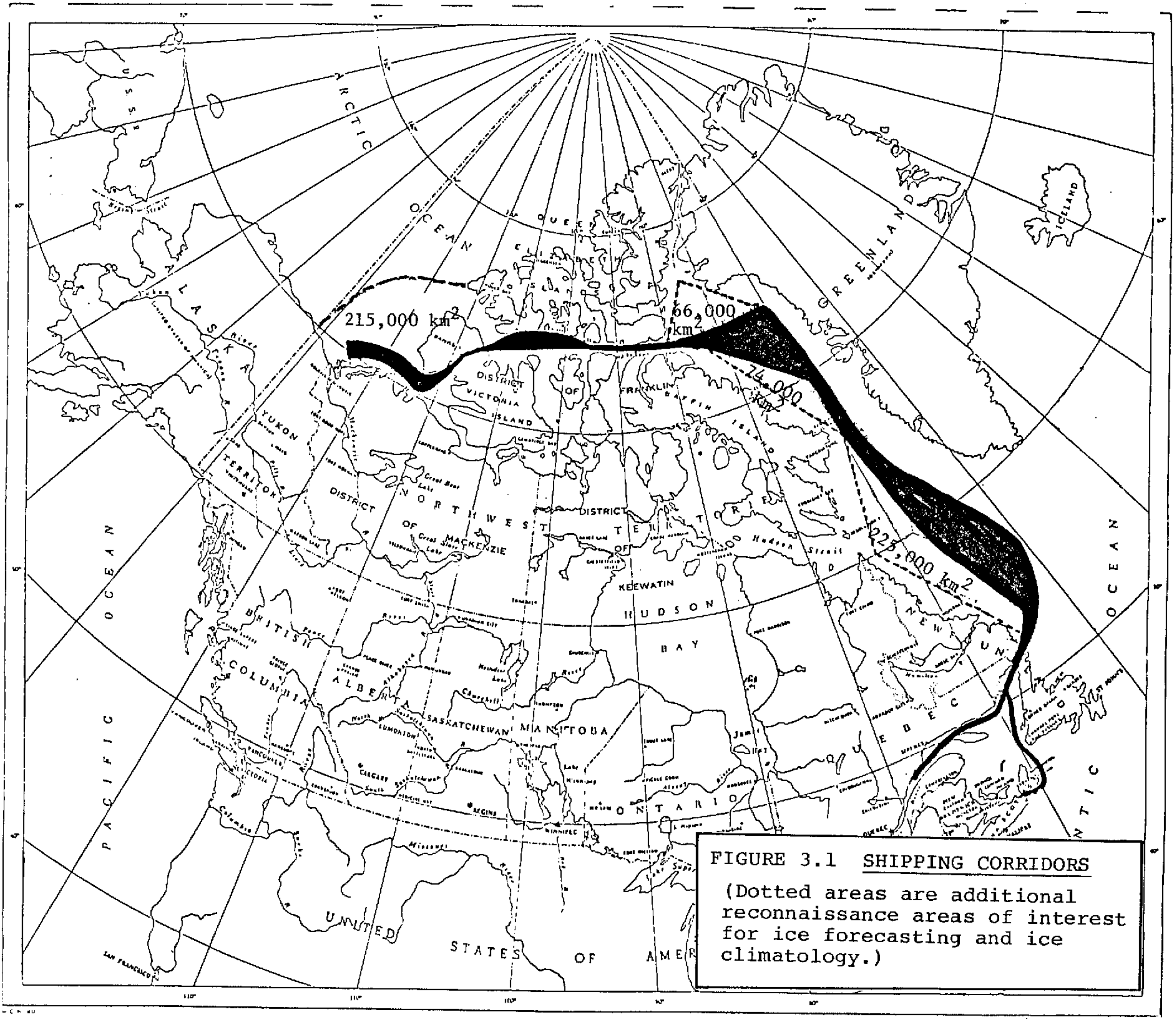


FIGURE 3.1 SHIPPING CORRIDORS

(Dotted areas are additional reconnaissance areas of interest for ice forecasting and ice climatology.)

TABLE 3.1

SEASONAL ICE RECONNAISSANCE REQUIREMENT

SECTION	1 BEAUFORT	2 AMUND-SEN	3 PRINCE OF WALES STRAIT	4 VISCOUNT MELVILLE SOUND	5 BARROW STRAIT	6 LANCASTER SOUND	7 BAFFIN BAY (≥70°N)	8 DAVIS STRAIT (≥60°N)	9 LABRADOR SEA (≤60°N)	10 NFLD/ BELLE ISLE	11 GULF	12 HUDSON BAY/ FOXE BASIN	13 EUREKA/ NORWEGIAN BAY	14 RESEARCH
AREA (km^2)	33,000	23,000		20,000	6,000	6,000	137,500	175,000	70,000			ad hoc	ad hoc	ad hoc
/C HRS ON SITE (1)	0.72	0.7	0.5	1.2 (550km)	1.25		3 + .5 (6)	3.8 + .5 (6)	2 + .5 (6)			7½ hrs/ flt.	8 hrs./ flt.	8 hrs.
JANUARY	9/10 cover (4) 0-9/10 MY D	9/10-10/10 cover 0-2/10 MY D		10/10 cover 5/10-8/10 MY shorefast 3/wk	10/10 cover 1/10-6/10 MY shorefast 3/wk	9/10 cover trace MY bergs, 3/wk	9/10 cover bergs 2/10 MY D	0-9/10 cover trace MY bergs D	(8)		40 hrs. /wk (5)			
FEBRUARY										40 hrs/ wk (5)				Two 8 Hr. flts/ mo.
MARCH														
APRIL		10/10 cover 0-2/10 MY 3/week									clear			
MAY	9/10-10/10 (3) cover 0-9/10 MY D	9/10-10/10 cover trace MY D				9/10 cover 1/10 MY bergs D	9/10 cover 2/10 MY bergs, leads D	0-9/10 cover trace MY bergs D	bergs 20 hrs/wk	bergs 10 hrs per wk				Two 8 Hr. flts/ mo.
JUNE	0-10/10 cover (4) 0-9/10 MY D	5/10-10/10 cover 0-2/10 MY D (reduced area)				0-6/10 cover icebergs 1/10 MY D	5/10-9/10 cover 0-2/10 MY (1) bergs, D							
JULY	0-9/10 (4) cover 0-9/10 MY D			10/10 shorefast D	6/10-9/10 cover 0-3/10 MY D	trace FY trace MY icebergs D	0-9/10 cover 0-2/10 MY bergs D					9 flt/ mo.		
AUGUST	0-9/10 cover 0-9/10 MY (4) Edge Cleaner D	clear 0 MY ø		8/10-10/10 cover 2/10-5/10 MY D	0-5/10 cover 0-1/10 MY D		0-7/10 centre 0-2/10 MY bergs D	0-5/10 cover trace MY bergs D				12 flt/ mo.	2 flt/mo	
SEPTEMBER	reduced area			2/10-9/10 cover 2/10-5/10 MY D	0-5/10 cover Traces MY D reduced area		clear bergs D	clear bergs D					4 flt/mo	
OCTOBER	0-9/10 cover 0-9/10 MY (4) Edge Clean MY from shore D	0-5/10 cover 0-2/10 MY D		9/10-10/10 cover 5/10-8/10 MY D	7/10-9/10 cover D	5/10-9/10 cover trace MY Icebergs, D	0-5/10 cover bergs D	trace MY bergs D						Two 8 Hr. flts/ mo.
NOVEMBER	9/10 cover 0-9/10 MY (4) D	9/10-10/10 cover 0-2/10 MY D		10/10 cover 5/10-8/10 MY 3/wk	9/10 cover 1/10-6/10 MY D	9/10 cover trace MY icebergs D 3/wk	9/10 cover bergs 2/10 MY D	0-9/10 cover trace MY bergs D						
DECEMBER					10/10 fast 1/10-6/10 MY 3/wk					ø				

REMARKS

D = Daily

(1) where corridor width is less than 100 km aircraft time is derived from length of track.

(2) ice edge is well defined; daily reconnaissance needed re. ice edge.

(3) distinct pack edge to 9/10 MY; pack edge varies continuously.

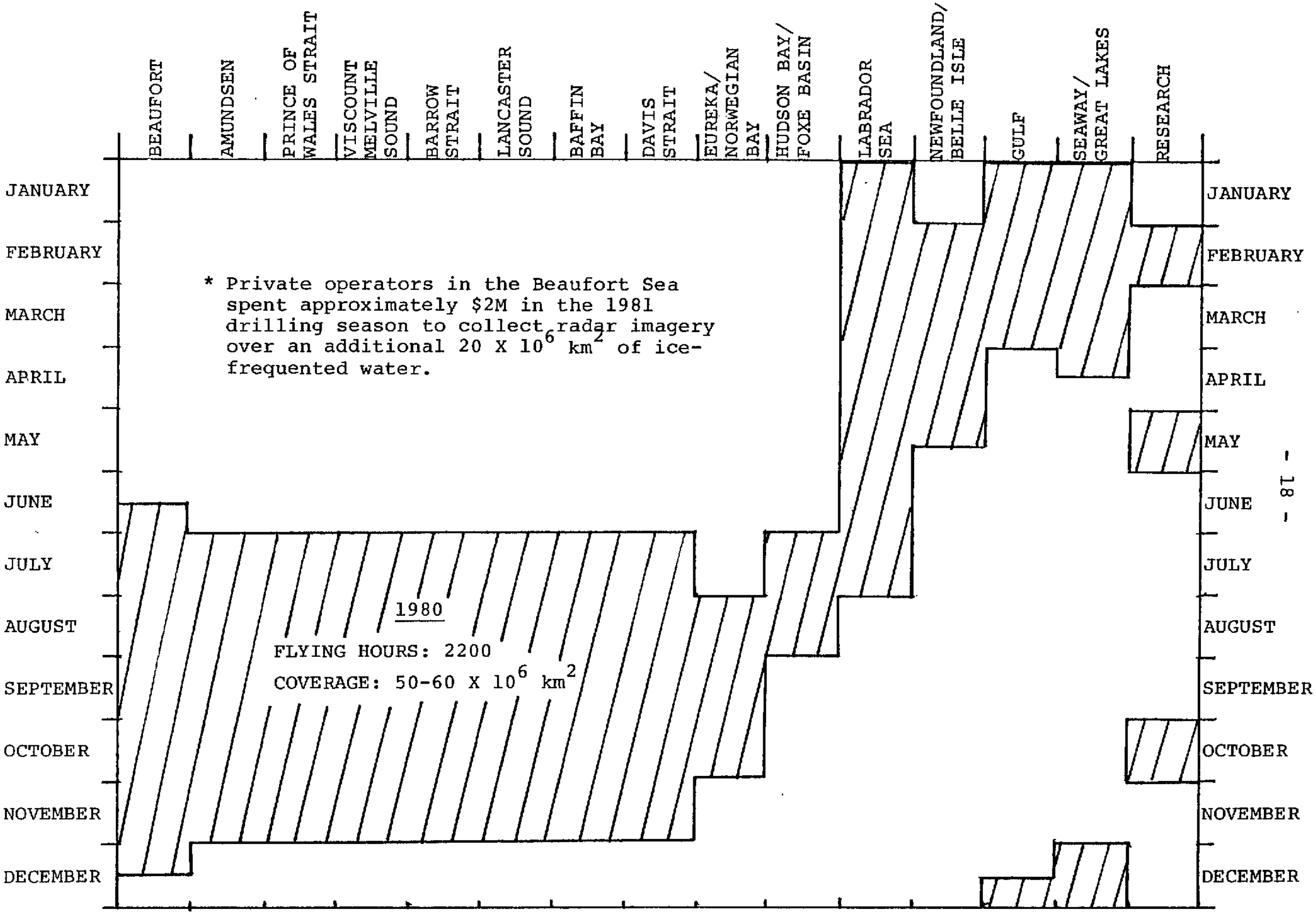
(4) ice island fragments year round.

(5) from W. Markham.

(6) additional hours are for end-of-lane turns in pattern flying.

(7) aircraft speed 250 knots (460 km/hr), 100 km swath.

(8) area of interest moves.



* Private operators in the Beaufort Sea spent approximately $2M in the 1981 drilling season to collect radar imagery over an additional 20 X 10^6 km^2 of ice-frequented water.

<u>1980</u>

FLYING HOURS: 2200

COVERAGE: 50-60 X 10^6 km^2

FIGURE 3.2: CURRENT AES REGIONAL/SEASONAL OPERATIONS (HATCHED AREAS)*

A MONTH	BEAUFORT	AMUNDSEN	PRINCE OF WALES STRAIT	VISCOUNT MELVILLE SOUND	BARROW STRAIT	LANCASTEP SOUND	BAFFIN BAY (≥70°N)	DAVIS STRAIT (≥60°N)	LABRADOR SEA (≤60°N)	NLFD/ BELLE ISL.	GULF	HUDSON BAY/FOXE BASIN	EUREKA/ NORWEGIAN BAY	RESEARCH	TOTAL HOURS PER WEEK	HOURS PER MONTH
HRS	0.72	0.7	0.5	1.2	0.65	0.65	3+0.5	3.8+0.5	2+0.5			7.5/flt	8/flt	8/flt		
	hrs/wk	hrs/wk	hrs/wk	hrs/wk	hrs/wk	hrs/wk	hrs/wk	hrs/wk	hrs/wk	hrs/wk	hrs/wk	hrs/mo	hrs/mo	hrs/mo		
JANUARY	5.0	4.9	3.5	3.6	2.0	2.0	24.5	30.1	0	0	40	0	0	0	115.6	512
FEBRUARY	5.0	4.9	3.5	3.6	2.0	2.0	24.5	30.1	0	40	40	0	0	16	---	638
MARCH	5.0	4.9	3.5	3.6	2.0	2.0	24.5	30.1	0	40	40	0	0	0	155.6	689
APRIL	5.0	2.1	1.5	3.6	2.0	2.0	24.5	30.1	0	40	0	0	0	0	110.8	475
MAY	5.0	4.9	3.5	3.6	2.0	4.6	24.5	30.1	20	40 10	0	0	0	16	---	559
JUNE	5.0	4.9	3.5	3.6	2.0	4.6	24.5	30.1	20	10	0	0	0	0	108.2	464
JULY	5.0	4.9	3.5	8.4	4.6	4.6	24.5	30.1	20	10	0	67.5	0	0	---	579
AUGUST	5.0	0	0	8.4	4.6	4.6	24.5	30.1	20	10	0	90	16	0	---	581
SEPTEMBER	5.0	0	0	8.4	4.6	4.6	24.5	30.1	20	10	0	0	32	0	---	491
OCTOBER	5.0	4.9	3.5	8.4	4.6	4.6	24.5	30.1	20	10	0	0	0	16	---	528
NOVEMBER	5.0	4.9	3.5	3.6	4.6	4.6	24.5	30.1	20	10	0	0	0	0	110.8	475
DECEMBER	5.0	4.9	3.5	3.6	2.0	2.0	24.5	30.1	20	0	0	0	0	0	95.6	423
															YEARLY GRAND TOTAL	6414

TABLE 3.2: AIRCRAFT TIME ON STATION BY MONTH WITH YEAR-ROUND ARCTIC SHIPPING

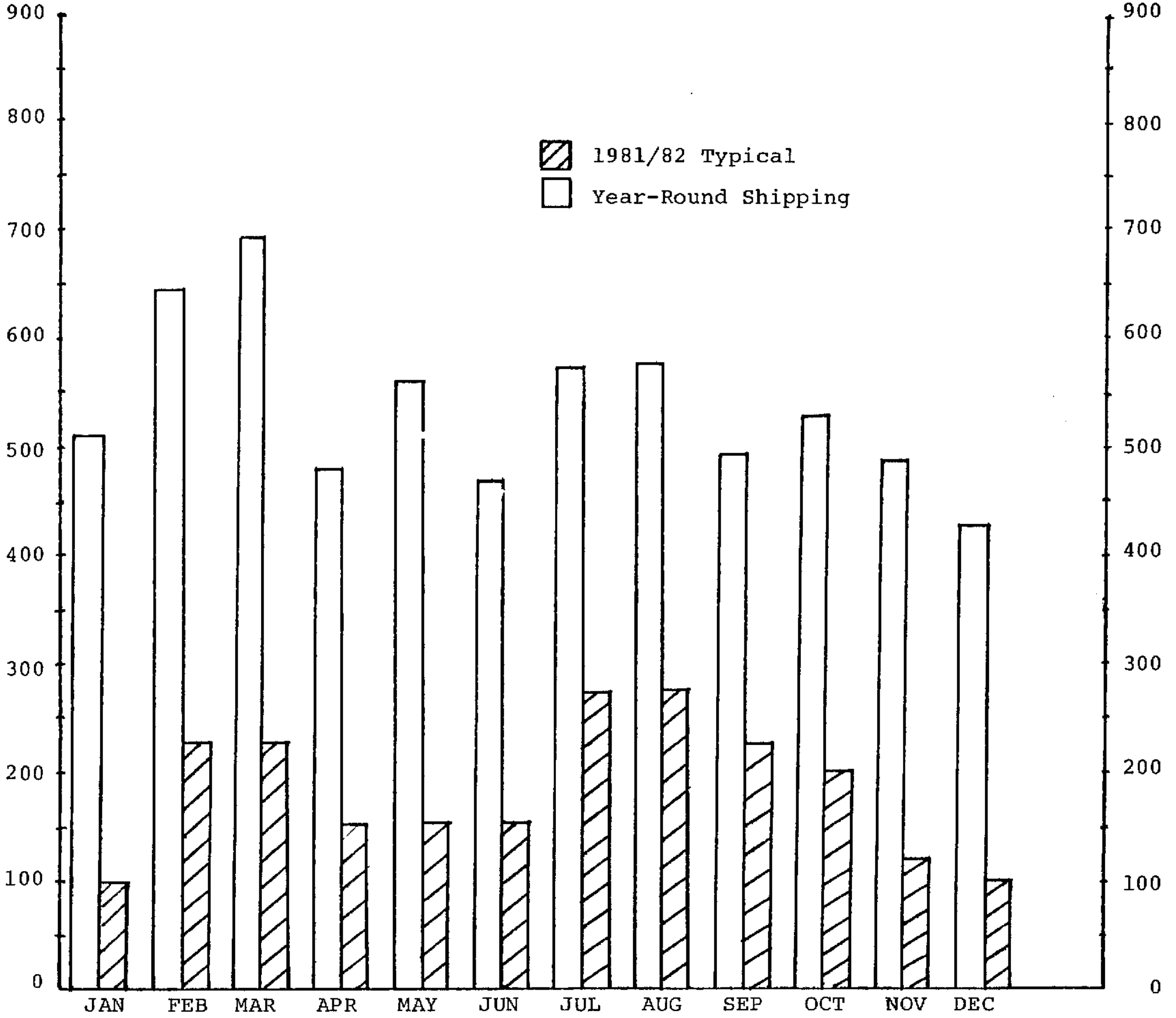


FIGURE 3.3: MONTHLY FLYING HOURS BEFORE AND AFTER COMMENCEMENT OF YEAR-ROUND ARCTIC SHIPPING

4. SENSORS

4.1 Introduction

All sensors used for ice reconnaissance are based on detection of electromagnetic (EM) radiation in some part of the spectrum, ranging from (microwave) frequencies of a few thousand megahertz (10^9), with wavelengths in the order of centimeters, to frequencies in the order of a thousand teraherz (10^{15}), with (optical) wavelengths in the order of tenths of a micrometer. Sensors for detecting other physical effects such as gravity fields, electrostatic fields, static magnetic fields and particle fluxes have not been proven to have wide application in ice reconnaissance and will not be discussed here.

The EM radiation being detected is emitted either naturally from the target or it has been reflected or scattered by the target, having originated in the sensor itself or from some other external source, for example sunlight.

Remote sensors are commonly divided into two generic classes - active and passive. Active sensors, as the name implies, illuminate the target with a self-contained source and receive the reflected or scattered radiation. Laser profilometers and radars are active sensors.

Passive sensors only detect radiation from targets. For the purposes of this study we must distinguish two sub-classes under the general heading of passive sensors - true passive sensors that detect radiation emitted by an object itself and pseudo-passive sensors that, while they only detect radiation, depend on a source external to the target to supply the illumination. The human eye, cameras, and optical instruments in general are pseudo-passive scanners; a microwave or a far infrared radiometer is a true passive sensor. A true passive sensor can measure the temperature of an object if the emissivity characteristics are known, and vica versa.

A target's capability to emit, reflect or scatter radiation depends on its dielectric properties, its shape, its roughness, and its temperature. These capabilities take on changing emphasis and changing values with changing wavelength. At optical frequencies, microscopic changes in roughness coupled with optical dielectric properties contribute to an object's brightness and colour and distinguish it against its background; at microwave frequencies optically rough surfaces are relatively smooth until the dimensions of the roughness features approach the dimensions of the microwaves themselves. Furthermore what is optically opaque can be transparent to microwaves due to changes in dielectric properties. For targets that are not truly smooth and transparent, reflection and scattering normally occur within a few wavelengths of the surface; hence the strong change in scattering properties when the dimensions of roughness and wavelength converge. Since it is not always possible to identify targets unambiguously even though they have been detected, it is desirable to have measurements based on more than one property at more than one wavelength to aid in the final interpretation of a signature. Fortunately, the basic properties of different targets are often revealed differently in different classes of sensors operating at different wavelengths. A priori knowledge of these independent variations can frequently produce unambiguous identification in cases where the intersection of measurements is unique. This is graphically illustrated in the work of Hawkins, et al (Ref.7). Taking the results of a particular set of trials in a particular region, a three-dimensional feature-space was constructed from the intersection of three measurements to discriminate ice types. Figure 4.1 has been reproduced from this report.

In the light of the foregoing, detection of the user features used to baseline our re-stated requirement for sea-ice reduces to an interpretation of target signatures arising from dielectric properties, shape, roughness, and apparent temperature at particular wavelengths. Stated in terms of targets, we look for detection and identification of five targets: first-year ice, multi-year ice, water, ridges, and icebergs. All other features associated with ice reconnaissance - for example, leads, ice edge,ice concentration, ice motion, accretion - can be, and are, derived from observation of these five targets.

The ideal sensor for ice reconnaissance would operate in all weather, in darkness or daylight, and would reveal ice features unambiguously and with high reliability. In addition, the ideal sensor would be an efficient data collector by virtue of its wide coverage coupled with high resolution features. No such sensor exists but combinations of sensors can be found that will provide an effective ice reconnaissance capability even though there are limits to their performance.

We will consider five sensors for ice reconnaissance:

1. Optical sensors: cameras and multi-spectral scanners,
2. Scanning infrared radiometers,
3. Scanning microwave radiometers, single frequency and multifrequency,
4. Imaging radar,
5. Laser profilometer.

We will discuss each of these sensors in turn, in terms of its ability to observe critical ice features from an aircraft or a satellite. We will also review the main features of a microwave scatterometer because of its importance as a research instrument for basic measurements of the microwave properties of ice.*

4.2 Optical Sensors

A camera is a pseudo-passive sensor. Long focal-length cameras can provide detection of a full range of ice features under proper lighting conditions. Resolution of image elements to fractions of a meter from an aircraft and a few metres from a satellite, with high contrast between targets, is readily achieved. Multi-spectral optical scanners for satellites of the Landsat-D or SPOT type provide resolution varying from 80 m to 15 m over swaths from 185 km to 60 km. Optical sensors are strictly surface detectors however and discrimination of targets under snow cover for example is impossible. They require external illumination on a

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*For an excellent review of microwave sensors and the characteristics of ice at microwave frequencies, the reader is referred to the proceedings of the Final Sursat Workshop, Atmospheric Environment Service, Toronto, June 23-27, 1981. René O. Ramseier, D.J. Lapp Editors, February, 1981.

target and operate in a portion of the spectrum where clouds, fog and snow will completely block the imagery. Notwithstanding their limitations, optical instruments are an excellent supplementary, or when conditions are right, primary, sensor. Cameras are usually carried on remote sensing aircraft as a relatively inexpensive and highly reliable sensor. Cameras have no application in remote-sensing satellites unless the film can be recovered. Multispectral scanners have seen extensive use on remote-sensing satellites and aircraft.

Positive Features, Aircraft and Satellite Platform

- very high resolution;
- fair discrimination of FY/MY ice targets;
- good discrimination of ice/water boundary;
- good discrimination of icebergs in water (aircraft only);
- fair discrimination of icebergs in ice; (aircraft only);
- excellent supplementary sensor on aircraft or satellite.

Negative Features, Aircraft and Satellite Platform

- daylight only;
- clear-weather or thin cloud only;
- surface detection only, target discrimination is blocked to varying degrees by snow cover.

4.3 Scanning Infrared Radiometers

Infrared passive scanning sensors are standard equipment on aircraft and weather satellites, with resolution in the order of 1 km on a satellite and a few metres on an aircraft.

Typical of a satellite radiometer is the Advanced Very High Resolution Radiometer (AVHHR) on NOAA 6 and 7 which achieves 1 km resolution, with a 1200 km scan swath, over 5 wavelength bands. Bands 4 and 5 are true passive thermal emission bands at 10.3-11.3 and 11.5-12.5 micrometers and are therefore capable of sensing in darkness. The other bands are near infrared and optical and are detected pseudo-passively. All bands are affected by cloud and snow and are therefore effective in clear weather only.

Infrared scanners have been highly developed for aircraft use for a range of remote-sensing applications such as pollution detection and water quality monitoring. At shorter wavelengths in the near infrared and visible spectrum though, cameras are frequently preferred because they are relatively inexpensive and have superior resolution. However, film data is not as readily useable in automatic analysis and has limited dynamic range so digital tape records from airborne scanning are preferred for specific applications.

True passive thermal infrared line scanners operating in the 8-14 micrometer range are available off-the-shelf for aircraft remote sensing and have seen extensive use for ice reconnaissance. Detection in this band takes advantage of the fact that thermal emission has a pronounced peak which shifts to shorter wavelengths with increasing temperature. Bodies at approximately 0°C show a peak in emission over the 7-14 micrometer wavelength octave. The peak is broad so that a reduction in temperature to, say, -40°C does not shift the peak noticeably although the overall emission drops.

A typical scanner - the Daedalus DB 1230 - has an instantaneous field of view (IFOV) of approximately 1/1000 of the aircraft altitude and a scanned field of view of ±39° from the vertical. Temperature discrimination is in the order of a few tenths of a degree Celcius or less depending on IFOV and, to some extent, on the overall scene brightness.

Thermal scanners have proven to be effective in discriminating ice, water and ice types during freeze-up because of the strong temperature differences occuring during transient conditions. These temperature differences, when coupled with variations in target emissivity permit reliable detection of ice types when the new ice is thin - 1/4 to 1/3 meter - and free of puddles and snow. Thermal infrared scanners are ineffective in cloud, fog, rain and snow and are therefore classed as day/night, clear-weather sensors.

Thermal scanners have been particularly effective for ice reconnaissance in combination with Side Looking Airborne Radar (SLAR). A SLAR provides wide coverage - to 200 km - but only for angles greater than 45° from the aircraft nadir line; the thermal scanner complements the radar image by filling the remaining radar 'hole' under the aircraft.

There is no basic reason why a thermal scanner could not operate to angles greater than ± 45° to achieve overlap with the radar imagery. As mentioned earlier, sensing the same target at different wavelengths with a mixture of passive and active techniques is beneficial in resolving ambiguities.

A spin-off benefit of overlap is the opportunity to use one sensor to calibrate another when both sensors detect an object with known scattering and emissive properties.

Positive Features, Satellite Platform:

- acceptable resolution for certain features such as ice edge, wide leads, and tracking of large floes;
- excellent swath width gives multiple coverage daily in the North and daily coverage North of 40° North Latitude;
- cross-correlation of multiple spectra permits rough classification of targets where targets are not snow-covered;
- far infrared thermal bands have day/night capability.

Positive Features, Aircraft Platform:

- adequate resolution for all ice features of interest;
- complements SLAR coverage;
- very reliable;
- thermal-bands have day/night capability.

Negative Features, Satellite Platform:

- clear-weather operation only;
- insufficient resolution for all except large targets;
- near-infrared unusable in darkness.

Negative Features, Aircraft Platform:

- clear-weather operation only;
- 8-14 micrometer detector requires cryogenic cooling;
- near-infrared unusable in darkness;
- narrow swath, approximately twice aircraft altitude. Limited use in isolation.

4.4 Scanning Microwave Radiometers

Scanning microwave radiometers are now emerging as a mature technology for aircraft and satellites. The Scanning Multichannel Microwave Radiometer (SMMR) carried on the experimental NIMBUS-7 and SEASAT-A satellites, the aircraft-mounted 90 GHz scanning radiometer being flown by the United States Naval Research Laboratories (NRL), and the Special Sensor Microwave/Imager (SSM/I) to be flown in 1984 on the U.S. Block 5D-2 Defence Meteorological Satellite Program (DMSP) represent technology with acceptable reliability for operational missions. It has been established that passive microwave sensors operating at 13.3, 19.35, 37, 88, and 90 GHz can distinguish FY and MY ice and the 88-90 GHz instrument can distinguish certain stages of new ice formation when deployed from an aircraft platform.

The NRL 90 GHz airborne scanning radiometer has opened up the higher frequency microwave spectrum to operational remote sensing. According to interview reports from senior NRL staff, the technology is mature and with good engineering instruments such as the NRL model can be made robust and reliable. The higher frequency permits a narrower Instantaneous Field of View (IFOV) with a reasonably-sized antenna so that the radiometer may properly be classed as an imaging sensor. The frequency is low enough to be essentially unaffected by atmospheric condition except rain. Cloud, fog, or dry snow do not degrade the imagery unacceptably hence it is well suited to Arctic operation and operation on the East Coast in fog. There is some optimism regarding the detection of icebergs in a 90 GHz imaging instrument but not enough data is available in the literature to positively confirm this. Because the radiometer scans $\pm 45^{\circ}$ it's swath is an excellent complement to that of a SLAR, in addition to having all-weather (except rain) and day/night capability. Figure 4.2 shows an example of 90 GHz passive microwave data. It was taken by a U.S. Navy P3 aircraft during the AES RadarSat Experiment at Mould Bay on October 7, 1981.* The data is not calibrated or geometrically corrected but the high contrast in the ice cover structure is very evident. The imagery of Figure 4.2 can be compared to the SLAR image of the same region in Figure 4.6. The rectangle in Figure 4.6 shows the approximate location of the radiometer image. The two data sets show some correlation even though the SLAR image was taken four days later on October 11, 1981.

The yellow portion on the left-hand of Figure 4.2 represents land, the remainder of the features are ice in various stages of maturity.

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*We are grateful to Dr. J. Hollinger of NRL for the use of this data.

The identifiable floe size in the passive microwave imagery is of the order of 30 to 40 m in diameter.

Analysis of satellite SMMR-type data is still appearing in the research literature but the general trend of results indicates successful discrimination of water, multi-year, and first-year sea ice due to strong variability in emissivity. (There are minor temperature differences among these targets but the effective radiometric temperature as measured is dominated by variations in emissivity.)

SSM/I is a four-frequency (19GHz, 22GHz, 37GHz, and 85GHz) sensor. Due to operational constraints, only the vertical (V) and horizontal (H) polarizations of the 37GHz signals will be used for ice reconnaissance. Algorithms on V & H signals are to be used for sea ice concentration; algorithms on V only are to be used for sea ice age.

The algorithms for computer analysis of SSM/I signals are expected to yield (Ref.8) the following quantitative results:

Feature	Resolution	Range	Accuracy
Ice Age	50 km	0-36 months	12 months
% ice cover	25 km	0-100%	10%
Ice edge	25 km	N/A	N/A

SSM/1-measured features will be checked routinely against ground truth year-around to generate verification statistics.

The SSM/I will not detect ice concentration accurately during the summer melt because of water puddles which can cover large percentages of the field of view.

The SMMR and the SSM/I type instruments cover very wide swaths in the order of 1200 to 1400 km. Because of this wide swath width, instruments of this type are well suited for providing information of ice concentration, ice type distribution, and ice extent as an imput to initialize and update ice dynamics models, or for simply providing a view of current ice conditions as shown in Figure 4.2. The data can serve as a base for climate studies which require hemispheric and total coverage, and for ice climatology.

Positive Features, Satellite Platform

- Wide-swath synoptic coverage ideal for ice climatology and climate studies;
- Virtual daily coverage with many re-visits daily at Northern latitudes;
- Unique emissivity/temperature-dependent measurement due to its true passive nature;
- multi-wavelength operation is readily achievable and has been demonstrated in operational conditions;
- Data is calibrated and quantitative;
- More reliable than an active sensor.

Positive Features, Aircraft Platforms

- Unique emissivity/temperature measurement;
- Multiple wavelength operation is feasible;
- Resolution is adequate for imaging many ice features, being comparable to SLAR performance;
- More reliable than an active sensor;
- Does not require cooled detector as do infrared thermal scanners.
- Complements SLAR or SAR coverage in the radar 'hole'.
- Measurements are calibrated and quantitative.

Negative Features, Satellite Platform

- Resolution not sufficient for many ice targets of interest operationally.

Negative Features, Aircraft Platform

- Relatively narrow swath width (±50°) and cannot be increased indefinitely because of antenna sidelobe problems;
- Unlike radar where ultimate resolution can be arbitrarily reduced with increased complexity in signal processing, resolution in a passive scanner is limited by intrinsic target brightness, and receiver noise figure.

4.5 Imaging Radar

The two types of imaging radar being considered in this study are real-aperture Side-Looking Airborne Radar or SLAR and Synthetic Aperture side-looking Radar or SAR. Both radars function with a narrow vertical beam illuminating the terrain for several tens of kilometres to one (or both) sides of a moving platform with the forward motion of the platform being used to build up an image scan by scan. Both types of radar produce an image in real time or near real-time but the manner in which it is produced is vastly different in each case. Figure 4.3 has been reproduced from a brochure describing an Ericsson SLAR and illustrates the basic geometry in a side- looking radar system.

The real-aperture side-looking radar system depends on a very narrow beam to resolve targets as they enter and leave the beam from scan to scan and the image is built up. A typical antenna beamwidth in a SLAR is a few tenths of a degree (in the APS-94E it is 0.45°), the antenna being several metres long in the direction of the platform motion. In a real-aperture system resolution along track, or azimuthal resolution as it is commonly called varies with range or distance from the platform because of beam geometry. Taking for example a 1/2° beam, a point target at 1 km range would enter and remain in the beam for 8 3/4 meters of forward motion, a point target at 2 km range would remain in the beam for 17 1/2 metres and so on. Since the image is built up in a time sequence, distant objects take on an elongated or cigar-shaped appearance in the direction of the platform motion, a phenomenon that can be readily observed in SLAR Imagery. The across-track or range resolution on a SLAR is essentially constant at all ranges because it is established by the length of the radar transmitter pulse. The APS-94E has a 0.2 microsecond transmitter pulse and will just distinguish two targets separated by 30 meters in range.

Combining range and azimuthal performance, a typical SLAR, operating at 100 km range setting, with a 1/2° antenna beam, and a 0.2 microsecond pulse, images a point target at 100 km range as an object 875 meters long and 30 meters wide. Clearly such imagery requires skilled interpretation to identify and classify targets correctly.

A Synthetic Aperture radar forms an image from the consecutive scans by an entirely different process. Instead of a very narrow antenna beam, a SAR utilizes a relatively wide beam, in the order say of a few degrees. The image is built up as before from successive scans and, as in a SLAR, range resolution is defined by short transmitter pulses. (The transmitted pulse is actually long but it is modulated in such a way that on reception it can be processed into an effective narrow pulse.) To obtain high azimuth resolution however, use is made of the doppler history of targets, as they move across the beam, to compute their position in the beam, and hence compose a scene, retroactively. This computation involves a complex series of very high speed calculations varying from a few million to 1 billion per second depending on platform velocity, spatial resolution, and scene size.

The effect of the complex computation is to synthesize a very long antenna and hence achieve in effect a very narrow beamwidth, much narrower than would be practical in a SLAR. It is characteristic of SAR that the azimuth resolution does not vary with range. In other words resolution is 'square' over an entire SAR scene. A SAR depends for its functioning on a stable, coherent, transmitter source, a fact that leads to the well-known 'speckle' phenomenon in SAR imagery. Incoherent averaging of the same scene detail calculated from different sectors (looks) of the beam will reduce the speckle effect. Averaging over ten looks of the same scene produces an image with close-to optical quality. Averaging over three to six calculations produces a useable image.

The photographs reproduced in Figures 4.4 through 4.6 illustrate the performance achieved with three different imaging radars.* Figure 4.4 was obtained from the experimental SAR in the Canada Centre for Remote Sensing CV-580 aircraft. The scene was taken in the Beaufort Sea in 1981 from an altitude of 2 km. The image was processed in real time on board the aircraft and downlinked from the aircraft on a digital VHF circuits to a local receiving station. The resolution of the received image is in the order of several metres, there are at least 16 grey levels in the image.

The straight tracks visible in the ice scene are from supply ships and a drill ship. The curved tracks are from an icebreaker that was keeping the area navigable. Tracks of this kind are detectable for long periods after the ship has passed. The speckle due to the coherent process is quite evident in this image.

The images in Figure 4.5(a) and (b) were processed by MDA of Vancouver B.C. from SEASAT-A data. The scenes include Russel Point on Banks Island and illustrate the ability of an imaging radar to detect the formation of leads in an ice pack. The lead from Russel Point in Figure 4.5(b) was created sometime between July 11, 1979 and July 28, 1979. It is about 100 metres wide. The

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*The image in Figure 4.4 was provided through the courtesy of Dome Petroleum Limited and Intera Environmental Consultants Limited. Figure 4.5 was provided by MDA. Figure 4.6 was supplied by Dr. R.O. Ramesier of AES Ice Branch.

image in Figure 4.6 was taken by an airborne Motorola APS-94E SLAR over Mould Bay in October 1981. At the time the radar was operating in a dual-look mode with range settings at 25 km maximum but the image from only one side of the aircraft has been reproduced. A faint range marker at 20 km can be seen in the imagery. The white lines are 2-minute along-track markers. The azimuthal resolution at 25 km range is about 200 metres. Oil drums layed out on a line on the ice in Mould Bay on the left are just visible. Note (a) the apparent clarity of the image due to good range resolution at all ranges and (b) the natural tone of the image due to the incoherent property of the system.

The applicability of imaging radars to ice reconnaissance has been well established in the past decade to the point where it is generally accepted as the preferred prime sensor in an all-weather day/night system. Although it lacks the one property that an imaging microwave radiometer has, that is the ability to discriminate between ice types in a scene, the imaging radar represents the best compromise for swath width, resolution and target discrimination in a single sensor.

4.6 Choice of Imaging Radar

The choice between a real-aperture radar (SLAR) and a synthetic aperture radar (SAR) is still being debated, although the debate centres less on the ability of either system to be effective in a particular ice reconnaissance situation than on what level of performance is actually sufficient for a particular user situation.

The state of the technology of imaging radars is also a factor in the current debate. A SLAR can be procured off-the-shelf with a range capability of 100 km to one side. In a dual-look configuration therefore the SLAR can cover a 200 km swath - at the expense of progressively poorer azimuth resolution with increasing range. A SAR on the other hand is not available off-the-shelf in a wide-swath configuration. Current performance is in the range of 25 km swaths, one-side-only operation. A wide-swath dual-look (100 km) SAR was built for the military in the late 1960's but a civilian version was never made available. Modern signal-processing hardware and software are fully capable of supporting a real-time SAR processor for wide-swath, dual-mode operation and MDA of Vancouver is making plans to develop an airborne SAR with a 75 km range dual-look capability and 11x16 meter azimuth and range resolution respectively.

Military applications have focussed on maximum range, relatively narrow-swath systems, having very high resolution, in the order of fractions of a meter, and very wide dynamic range to permit detection, classification, and identification of a wide range of military targets. SAR technology is therefore mature but the configurations appropriate to ice reconnaissance have not been developed. The extrapolation is not demanding technically but the development must still be made before key factors like reliability and dynamic range are proven. The emergence of demanding resolution requirements that exceed the capability of a real aperature system may provide the stimulus needed to develop a generation of airborne ice reconnaissance SARs.

Two remaining factors must be noted to put imaging radars in perspective: wavelength of operation and angle of incidence. Both of these factors are under intensive study in Canada and elsewhere at the present time, in particular with reference to discrimination of first-year (FY) and multi-year (MY) sea ice, and discrimination of icebergs and ridges in sea ice and in water. Wavelength of operation is a key element in discriminating ice types partly because of the variations in dielectric properties (on a macro scale) and partly because of variations in surface topography roughness. Radar scattering coefficients tend to change rapidly when topographical features of a target approach the dimensions of the radar wavelength. This phenomenon is used to advantage in classification of ice types. Recent work at the Canada Centre for Remote Sensing (CCRS) indicates a positive progression in the discrimination between FY and MY signatures as the wavelength is varied from L-band through C-band to X-band.

The angle of incidence of the radar beam to the target is also a significant contributing factor in discriminating FY and MY ice types, with low incidence (25^{o}-50^{o}) angles being preferred to the high incidence (grazing) angles where specular reflection dominates.

Reliable iceberg and ridge detection in the other hand dictate higher incidence or near-grazing angles 70^{o}-85^{o}. This geometry accentuates the gross topographic features of iceberg and ridge targets for the obvious reason that they stand out against a flatter background best when they are viewed obliquely. The dielectric properties of these targets are also a factor in detection so that detection improves with increasing frequency and large incidence angles*. Results of recent work can be found in Gray (Ref.9 and 10), Pearson et al, (Ref.11), and Hengeveld (Ref.5). From the foregoing it will be obvious that an aircraft platform will give the best performance for icebergs and ridges because the radar can be operated at very large (to 85°) incidence angles while a satellite platform is preferred for discriminating ice types because the radar operates steeper incidence angles, typically 25° to 45°.

Optimum angles notwithstanding it must be emphasized that reliable detection of icebergs in the sea or in sea-ice has not been successfully demonstrated from aircraft or satellite radars.

A unique feature of the satellite-borne system is the relatively small spread in incidence angle across the swath when compared to an airborne system. Near-uniformity of the incidence angle parameter makes interpretation simpler and more reliable because one variable in the data set is at least partially eliminated. Variability in one parameter such as incidence angle is useful to an interpreter when it is applied to the same targets. When comparing different targets however, the ideal situation occurs when only the features of the targets change, everything else being constant. Indeed, automatic (machine) processing of imagery is very susceptible to ambiguous answers when scene changes can be attributed to changes in more than one parameter.

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*The statements made here are generally true but the research field is very active. Improved measurements and analysis are appearing regularly for specific ice and ice/water configurations.

A general conclusion regarding an optimum imaging radar must include a reference to a large number of factors regarding the radar itself and the specific application: reliability, technical maturity, swath width (including single or dual-mode operation), wavelength (and wavelength agility should it become available), and angle of incidence (including the spread of angle of incidence across the path). All contribute to image clarity. Successful development of a new SAR by MDA will clarify some of the factors.

From the point of view of the maturity of the technology and the current pace of improvements in software technology, we forsee the SAR as the pre-emptive system by the late 1980's. The incentive to develop the wide-swath, medium-resolution technology needed for ice reconnaissance could assure the development of the technology in Canada.

An impression of the relative merits of different imaging radar systems as perceived by a cross-section of users can be gained from comments received:

> "Imaging radar is superior with steeper angles because the signal return is more sensitive to target reflectivity than target topography. The angle and the resolution favour SAR at short ranges and narrow swaths."

> "SLAR imagery is more useful than its limitations on azimuth resolution would lend you to believe because range resolution is uniformly good. The apparent sharpness in the image contributes confidence to the interpretation."

"Imagery, however derived, should be presented on a scale and in a format that gives the appearance of sharpness at least. Imagery that has a blurred appearance is distracting and difficult for the user."

"High resolution, comparable to what is available in the CCRS SARs, is very desirable for ice reconnaissance over a 50 km radius from a drilling site."

"Ships masters will in all probability demand un-degraded imagery of the ice fields ahead of them, in particular the region they expect to penetrate in the next few hours."

"Dual 100 km SLAR settings provide useful ice reconnaissance data to approximately 80 km on each side of the aircraft. The 100 km range setting is very convenient because it matches the 1:1,000,000 maps operators use."

"Iceberg and ridge detection improve as the radar beam approaches grazing incidence. This geometry favours the major topographic features in a scene."

"SAR technology is well established in military technology for particular applications. Given the current state of progress in microelectronics, in particular reliable Very Large Scale Integration (VLSI), the prospects for the near future is one of (virtually) unlimited computational capability, with signal processing essentially limited only by the efficiency of the software algorithms."

"At 50 km range an airborne SLAR such as the APS-94 is useful for distinguishing ice from water and ridges from pack ice but not much more. Identification of ice types requires steeper viewing angles and better resolution."

"The lower wavelength and steep angles of the SeaSat SAR reduce its effectiveness when compared to airborne SLAR for distinguishing MY and FY sea ice during the summer melt."

"For Beaufort Sea exploration and development work it is likely that an airborne resolution SAR will be required from October to January to provide early warning of modest-sized MY floes approaching. This aircraft platform will likely be maintained in the Beaufort every season regardless of satellite coverage particularly if the SAR can be operated in a high resolution mode at 100 km swaths."

"It is debatable whether the master of a drilling platform will ever place his confidence completely on remotely-sensed data, even if it is taken at high resolution. Some masters may well prefer an accurate on-site observation of features that have been previously identified in low-resolution systems as potential hazards. In those circumstances a high-resolution SAR may be replaced by on-site observation from a support vessel."

"SAR is expensive to operate because of the narrower swath widths. SLAR can be used to delineate regions requiring high-resolution survey. Some ships masters will opt for ground-truth in lieu of SAR coverage because exact measurements of thickness and ridge lengths can be made. A combined SLAR/SAR system would combine features of both radars."

Positive Features, Satellite Platform (SAR Only)

- Medium swath width for synoptic coverage;
- High resolution;
- All-weather, day/night operation;
- Steep viewing angle is best for discriminating ice types.

Positive Features, Airborne Platform (SLAR and SAR)

- Medium swath coverage sufficient for synoptic coverage in low resolution modes;
- High resolution permits discrimination of most sea-ice targets;
- All-weather, day/night operation;
- FY/MY discrimination is possible when the correct SAR/SLAR mode is used;
- Mature technology, expecially for the SLAR;
- Imagery amenable to computer-assisted analysis;
- High incidence angles available for ridge/iceberg detection.

Negative Features, Satellite Platform

- Daily coverage by single satellite limited to North of 68° latitude. Southern Canada average at least once every three days;
- Data is uncalibrated and qualitative.

Negative Features, Airborne (SAR or SLAR)

- Discrimination of ice types is hampered by lack of steep viewing angles;
- large variation in incidence angles with range confuse identification of different targets because scattering properties change with angle;
- Aircraft motion can cause problems in forming an image in a SAR or a SLAR;
- Radar produces uncalibrated, qualitative image;
- The radar 'hole' under the aircraft becomes significant at the higher altitudes preferred for stable flight.
- Aircraft can be "grounded" due to weather.

4.7 Laser Profilometer

A laser profilometer is an active downward looking sensor. It features a very narrow beam, typically 0.005 degrees so that its footprint at 10 km altitude is 1 metre. In operation, a laser profilometer, as the name implies, gives a detailed record of the ground topography in a narrow strip along the aircraft track to an accuracy of a few cms. In future it is expected that scanning instruments will be developed for imaging over a swath. In this regard we note that a system has already been developed for mapping the seabed from aircraft. Clearly a system with sufficient power to overcome the losses associated with penetrating sea-water to depths of 20-30 meters could form the basis of a system required to detect only the ice surface.

Advantages, Aircraft Platform (Only)

- Only available along-track, ridge-counting, sensor;
- Very high precision for macro and micro (e.g. roughness) measurements;
- Mature technology;
- Capable of being developed for scanning modes to provide swath-type coverage.

Disadvantages, Aircraft Platforms (Only)

- Currently no swath capability, areal coverage is very poor;
- Clear-weather operation. Clouds, fog, and heavy snow will obliterate the target return.

4.8 Microwave Scatterometer

A microwave scatterometer is an active sensor. In its basic configuration it resembles a microwave radar but it differs from a radar in that the transmitter and receiver are calibrated for power and sensitivity respectively, by virtue of which the absolute scattering coefficients of targets can be measured. The antenna beam of a microwave scatterometer is usually configured in a fan shape with the wide dimension oriented in the direction of motion of the platform. When used in this mode variations in doppler frequency shift at various angles in the beam can be used to separate targets in different sectors and angles of the beams. Thus, scattering coefficients can be measured over a wide range of angles. Aircraft-mounted scatterometers have been used extensively to measure absolute scattering coefficients of ice types. The range of frequencies over which measurements have been made is steadily increasing. As an operational sensor, the microwave scatterometer finds wider application in the measurement of wind velocities over the ocean. A unique relationship between scattering coefficient versus viewing angle and wind velocity has been identified for capilliary ocean waves. It has been shown that wind velocities can be derived directly from measurements of the variation of scattering coefficient with incidence angles for capillary ocean waves. This technique was used successfully with data collected by the scatterometer on SeaSat. Because the scattering coefficient of the waves must be measured absolutely, information on any unusual signal attennation in the transmit/receive path between the sensor and the waves must be known and allowed for in the subsequent calculations. This would be particularly true for example in the situation where scatterometer measurements were being made in the presence of heavy rainfall.

4.9 Optimum Sensor Packages

Table 4.1 lists the important features of the five ice reconnaissance sensors chosen for the study. In the beginning of this section the features of an ideal ice reconnaissance sensor were noted, also noted was the importance of simultaneous observation of a target with different sensors, in absence of an ideal sensor. In the light of these earlier statements of principle, and the information in Table 4.1, the best technical compromise for a sensor package for ice reconnaissance from an aircraft and a satellite can be derived. It is emphasized that this sensor package is aimed solely at operational ice reconnaissance. Sensors for oceans and land are dealt with elsewhere.

1. Optimum Sensor Package For an Aircraft

(i) Main Sensor System:

Prime:	Imaging radar, preferably SAR when wide-swath options become available.
Secondary:	Imaging microwave radiometer at 37 and 90 GHz with scan increased to allow at least 5° of overlap with the imaging radar.

(An infrared line-scanner would be a marginal choice for a secondary sensor but is ruled out because it is not operable in fog, rain, snow storms, or through cloud.)

(ii) Supplementary Sensors in the Aircraft Package:

(Not in order of preference)

1. Laser Profilometer,
2. Camera,
3. Scanning infra-red radiometer.

2. Optimum Sensor Package For a Satellite

(i) Main Sensor System:

Priminary:	Imaging radar (SAR).
Secondary:	Scanning microwave radiometer operating at 37 and 90 GHz, in both polarizations.

(ii) Supplementary Sensors in a Satellite

(for ice only - oceans and land dealt with in other studies

(not in order of preference)

1. Scanning infrared radiometer,
2. Additional frequencies in the microwave radiometer,
3. Optical sensor.

The main system chosen for each of the platforms has all-weather, day/night capability, although the 90 GHz radiometer on the aircraft cannot operate through rain, and each system is comprised of two sensors that are sensitive to two different physical characteristics of ice - microwave scattering power and microwave emissivity effects.

Aside from the coverage capability of each platform, the optimal aircraft and satellite sensor packages have distinct qualitative advantages and limitations when compared one with the other:

(1) Both packages are acceptable for detecting water and ice and in discriminating multi-year ice from first year ice. In the case of the satellite-based microwave radiometer, wide swath is achieved at the expense of resolution. The satellite SAR has a slight advantage over the airborne SAR in discriminating among targets in that the variation of incidence angle across a scene taken with a space SAR is notably less than the variation in an aircraft-derived scene.

(ii) The airborne radar will exhibit superior performance in detecting ridge and icebergs at the extremities of the coverage because of near-grazing angles at the edge of the beam. Reliable detection of icebergs, even from an airborne imaging radar, cannot be assured however.

In summary, both the aircraft and the satellite meet a basic requirement to detect and identify water, first year ice and multi-year ice in a broad range of occurences; the aircraft package will have superior performance in detecting ridges and will have the best chances for detecting icebergs; the satellite package will have superior uniformity in radar-imaged scenes and vastly superior coverage from a microwave radiometer.

FEATURE-SPACE FOR THE CLASSIFICATION OF SEA ICE
CCRS/SURSAT ACTIVE - PASSIVE EXPERIMENT 1979-1980

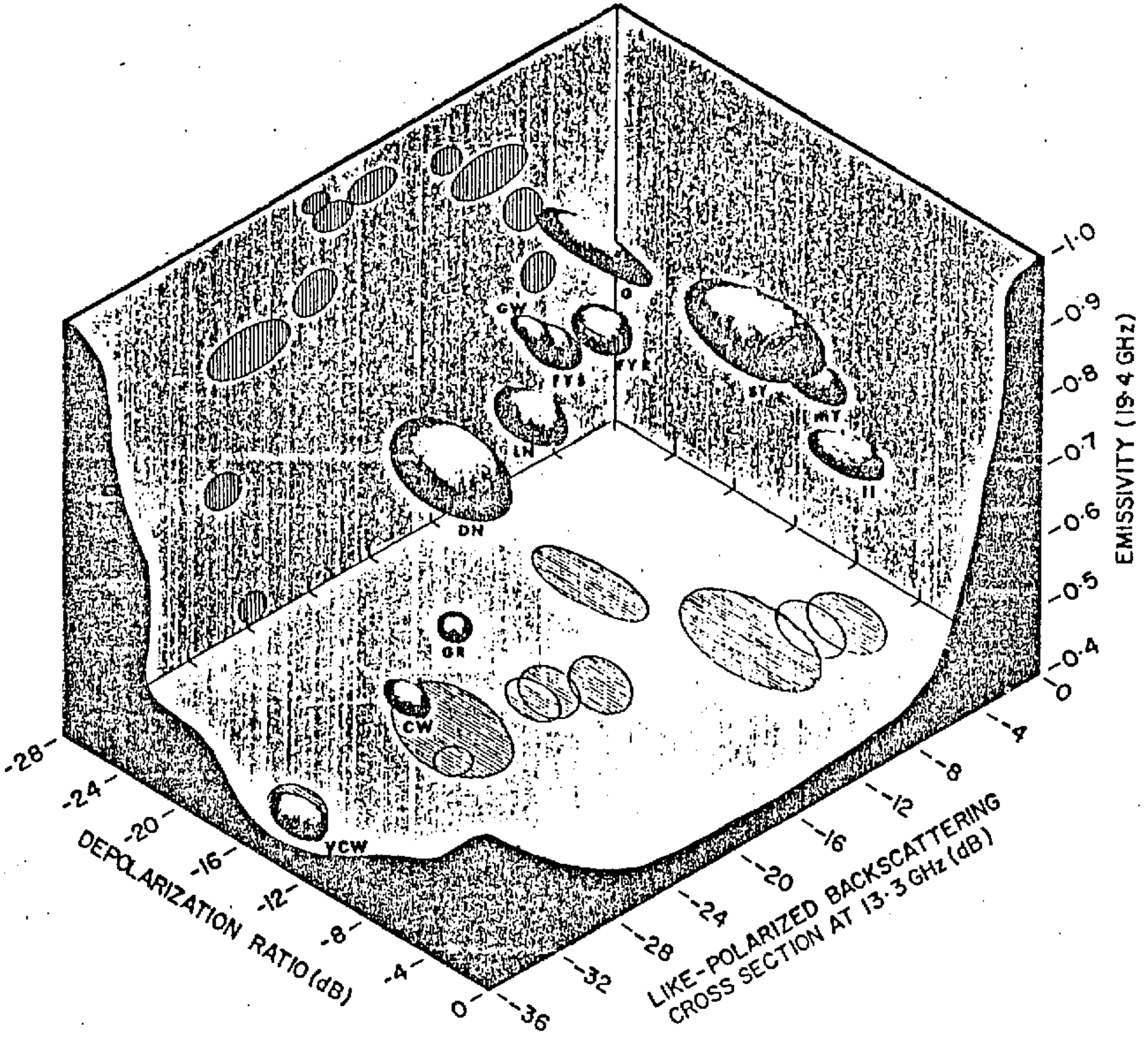
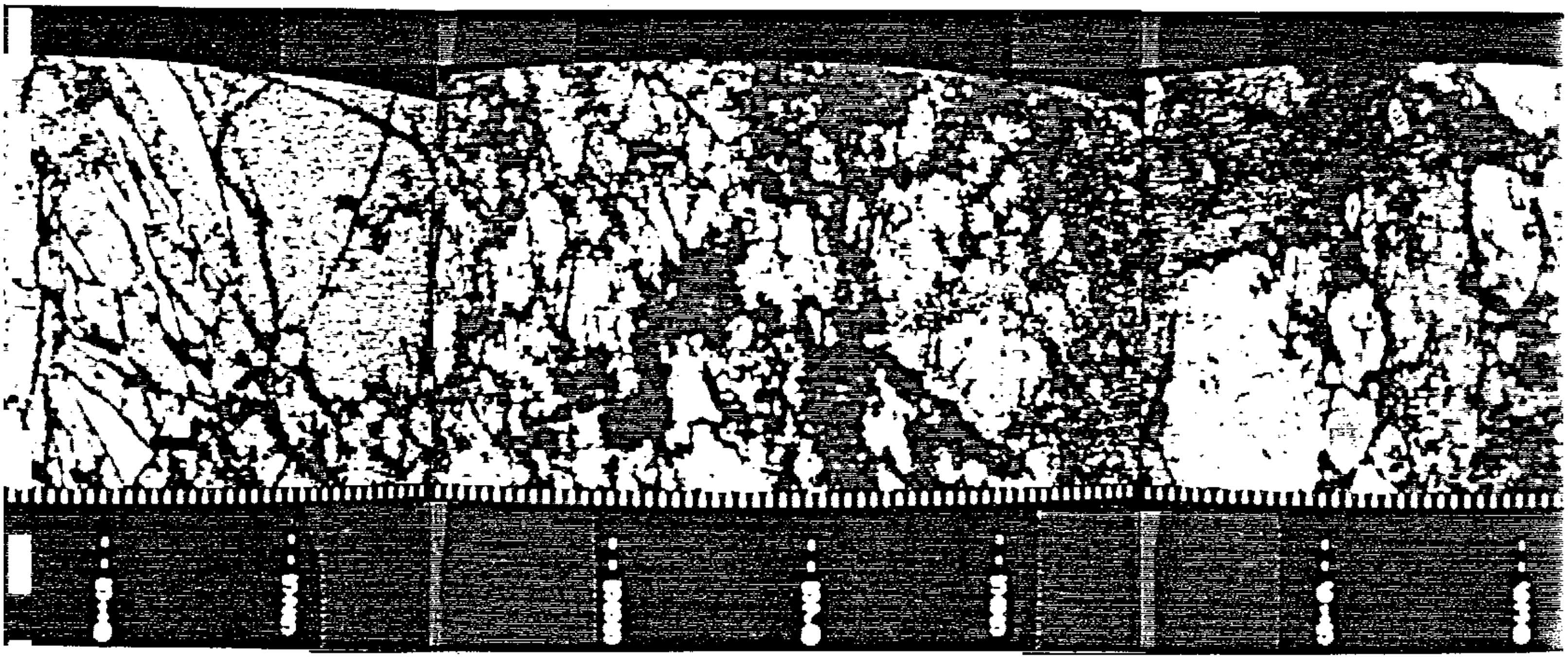


Figure 4.1 Illustration of the feature-space for the classification of sea ice, using like-polarized backscattering coefficient, σ^o_{hh}, depolarization ratio, $\sigma^o_{hv}/\sigma^o_{hh}$ and microwave emissivity, ϵ, at a common incidence angle of 45°.



Scanning Radiometer Image, October 7, 1981

(courtesy NRL)

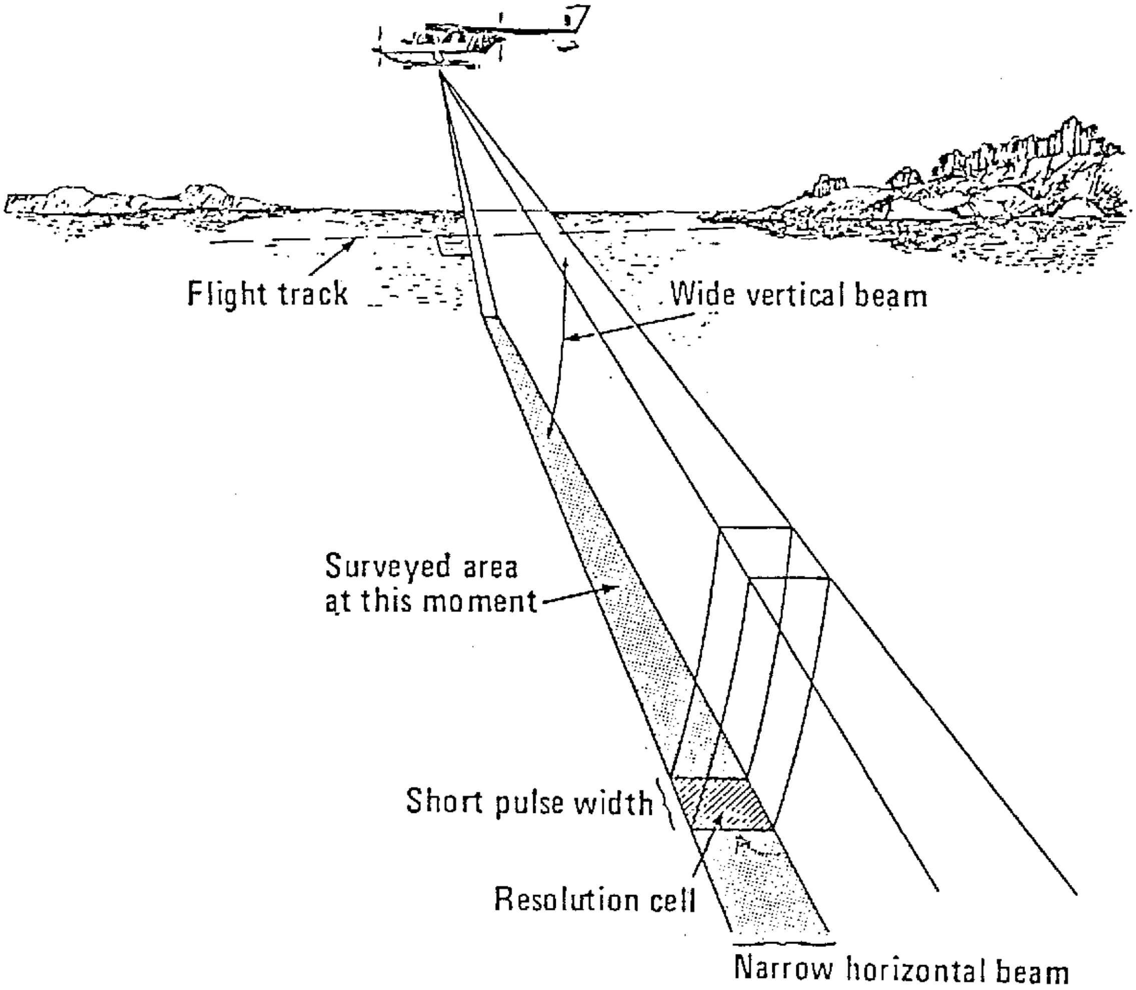


FIGURE 4.3: Side-Looking Radar Beam Geometry

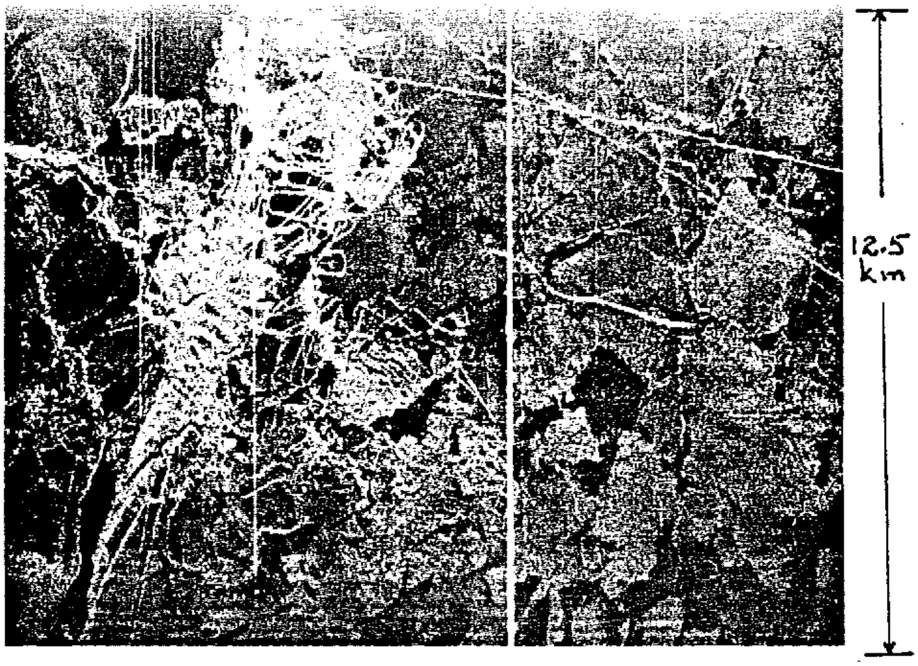
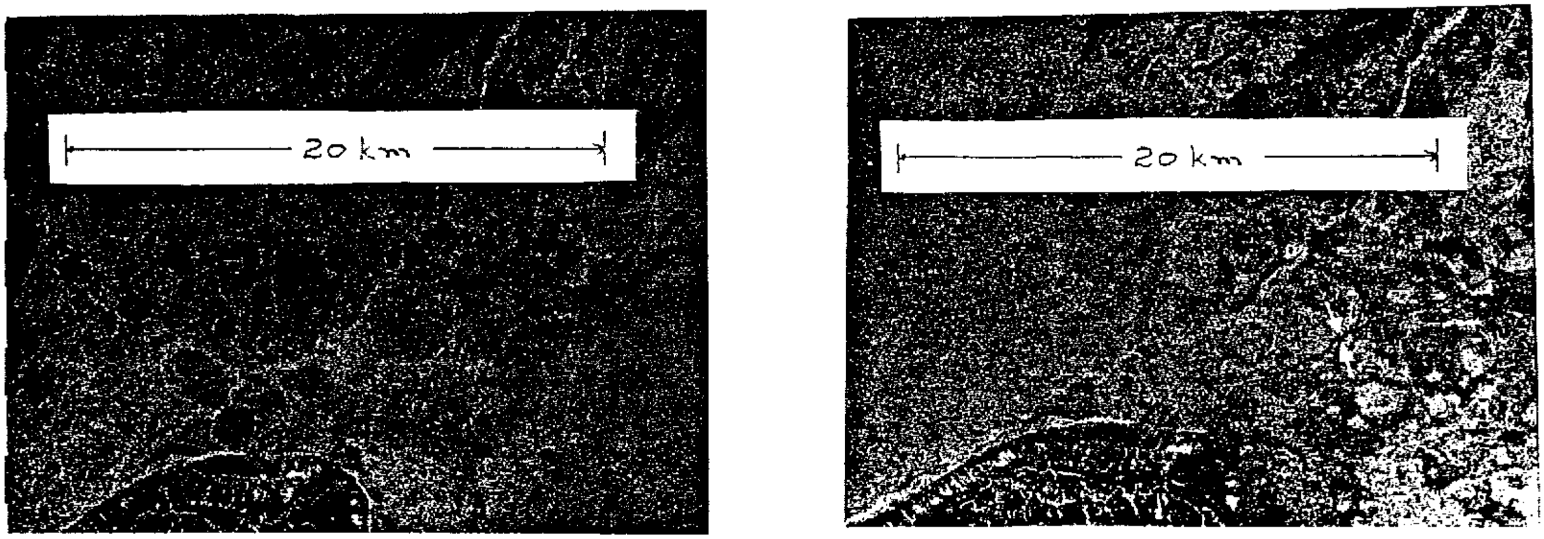


FIGURE 4.4: CCRS X-BAND AIRBORNE SAR
Beaufort Sea, October 23, 1981

(Photo Courtesy Dome Petroleum and
Intera Environmental Consultants Ltd.)



(a) July 11, 1979

(b) July 28, 1979

FIGURE 4.5: SEASAT SAR, Russel Point, N.W.T.
(Photos Courtesy MacDonald, Dettwiler & Associates Ltd.)

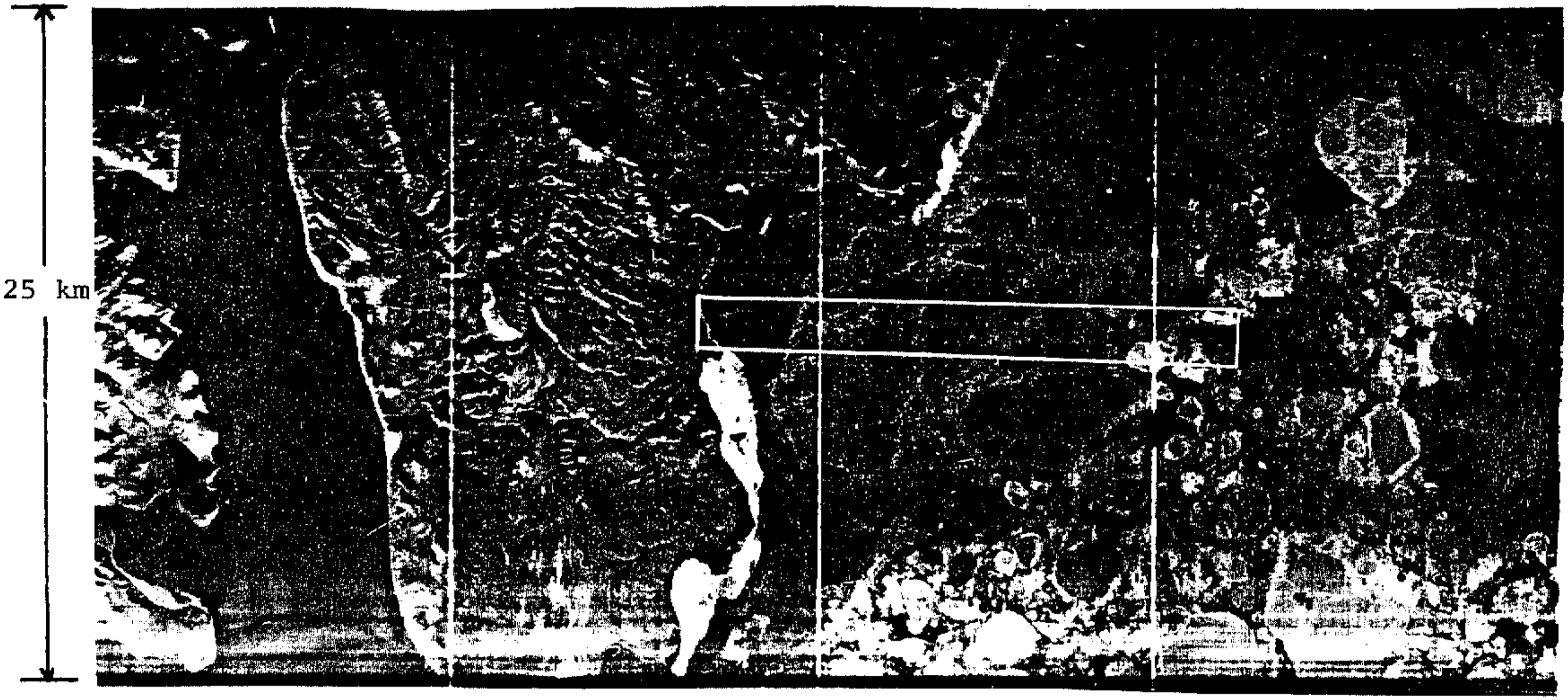


FIGURE 4.6: Airborne SLAR (MOTOROLA APS-94E)
Mould Bay, N.W.T., October 11, 1981

(Photo Courtesy AES Ice Research)

TABLE 4.1: CHARACTERISTICS OF ICE RECONNAISSANCE SENSORS

SENSOR	ACTIVE/ PASSIVE	PLAT- FORM*	COVERAGE	OPERATING CONDITIONS	RESOLUTION AND PERFORMANCE
Camera	Pseudo-passive	A	80° FOV	.clear weather .daylight	. Very high spatial resolution . High target discrimination by colour and dynamic range . Surface features only
Optical Scanner, Visible and near IR	Pseudo-passive	S & A	Typically ±45°	.clear weather .daylight	. 50 - 100 m spatial resolution . Good target discrimination with multiple wavelengths
Optical Scanner, Far IR	True passive	S & A	Typically 45°	.clear weather .day or night	. 1 km spatial resolution, satellite . IFOV 1-2 mrad., aircraft . Good target discrimination due to emissivity and temperature differences
Scanning Microwave Radiometer	True passive	S & A	Typically ±50°	.all weather .day/ night	. 20-30 km, satellite . 50-100 m aircraft . High target-type discrimination with multiple wavelengths
Side-look Radar	Active	S & A	200 km (sat) 100 km (A/C)	.all weather .day/ night	. 25 m, satellite . 5 m, aircraft SAR . Aircraft SLAR: 8 m in range, 8-800 m in azimuth (varies with range) . High target discrimination
Laser Profilometer	Active	A	Fixed at 0.005°	.clear weather or thin cloud .day/ night	. Uniquely high vertical resolution to a few cms . No (presently) scan capability

* S=Satellite, A=Aircraft

5. PLATFORMS

5.1 Present-to-1985

It has already been noted that the choice of sensor platforms for extensive ice reconnaissance is limited to aircraft until the late 1980's when a Canadian RadarSat becomes a valid option. There are no near-term prospects for changes in this schedule unless some compelling requirement arises to advance it. Foreign satellites being planned could provide some interim capability. The European Space Agency, ESA, plans to launch a satellite with an imaging radar (SAR) in 1988. This satellite, to be designated ERS, will provide limited SAR coverage over regions of Canada's ice-frequented waters on an interim basis from 1988 onwards but the orbital parameters and the relatively narrow swath of the SAR (80 km) will not provide a high percentage of repetitive coverage except at very high latitudes. Japan is planning but has not yet approved a satellite carrying a SAR. Nominal features of the Japanese SAR are L-band wavelength, 100 km swath, 25 metre resolution, and four-look processing capability. For the first time-frame in our study therefore, that is from the present to 1985, the backbone of the ice reconnaissance will be aircraft. As evidence of this fact, AES and CCG are currently negotiating a new 5-year contract for two aircraft and a case has been made for a third aircraft for iceberg reconnaissance along the Eastern seaboard. Final selection of the contractors and the aircraft types depends on a number of factors but the aircraft chosen will probably have a range in the order of 2700 kms minimum and will be capable of carrying a full range of sensors. The annual loading on this system will continue at 2200 hours per year total with some reduction possible due to increased use of NOAA and other (for example LANDSAT) satellite data. Some increase in the use of the aircraft for synoptic coverage to aid in, for example, development of ice forecasting models, is likely to occur as NOAA and Landsat data is used increasingly to support routine ice reconnaissance. The current outlook is that this platform system will meet the now-to-1985 requirement.

Following introduction of year-round Arctic shipping in the 1986-87 time frame, and before the introduction of 'ERS' or RadarSat, the aircraft platform system will have to be increased to support daily winter reconnaissance in parts of the Beaufort Sea, Baffin Bay, Davis Strait and Labrador Sea, depending upon where the ice-breaking tankers are. A precise statement of this requirement is not possible at this time but it seems reasonable to suppose that the early coverage requirement will be limited and will move with the ships, and thus will be more on a local than a regional basis. Use of ERS imagery when it becomes available would permit (very) occasional synoptic review of ice conditions over the regions of interest and could possibly be effective in optimising the deployment of the aircraft. The ERS imagery would not be an acceptable replacement for aircraft because of its limited temporal and spatial coverage.

5.2 1990, All Aircraft System

5.2.1 Number of Aircraft

By 1990, the ice reconnaissance requirement will have increased to the scale depicted in Table 3.1. This would still be a minimum requirement, for, while it meets the strategic requirement in the shipping corridor and would be adequate as synoptic coverage for modelling and ice forecasting in areas like the Parry Channel and the Gulf, it would represent a bare minimum requirement in regions such as the Beaufort Sea, Baffin bay, Davis Strait and the Labrador Sea. In these regions large un-reconnoitered areas lie outside the shipping corridor. Much more extensive coverage, albeit at lower resolution, would be required for reliable quantitative forecasting because the dynamics of the enviroment in these regions are so vast in their dimensions.

An all-aircraft reconnaissance system would imply deployment of aircraft in the Arctic during the winter. Typical routes for aircraft based at Inuvik, Resolute and Frobisher are illustrated in Figure 5.1. Nominal route lengths are included. Flying these routes with a 100 km swath would cover the shipping corridor north of 60°. Coverage south of 60° would be the same as at present. Lengthy discussions have been held with commercial, military and government operators of aircraft on the complement of aircraft platforms necessary to support a sustained year-round reconnaissance requirement of this magnitude.

Reference was also made to a detailed study of Canada Coast Guard ice reconnaissance requirements by a mid-1970's task force (Ref. 12) and a Batelle Institute study (Ref. 13).

The problem can be approached qualitatively (and intuitively) or quantitatively. A qualitative analysis of the coverage and the regions indicates a requirement for four operating platforms at the peak of activity: two in the Gulf/Newfoundland area and two in the Arctic - one in the East Arctic and one in the West Arctic. Tasking of the two Arctic aircraft is particularly demanding in that daily flights are required over long periods. Based on DND experience, the average availability of a sophisticated airborne system like a long-range ice reconnaissance aircraft varies from a minimum of 60% to a maximum of 80%. The 80% figure has been obtained by DND at the expense of an unusually high level of preventive maintenance and service in a benign climate. On the basis of these figures, the Arctic winter complement of two aircraft would have to be increased to three to assure availability of ice reconnaissance service on a daily basis. Discussion with AES and CCG personnel support this conclusion. The winter complement of two Gulf/Newfoundland aircraft is not normally tasked to fly every day so one might be considered as back-up to the other in the event of malfunction. The existence of a spare Northern platform would also reduce the problems associated with a protracted breakdown of one of the East Coast units. In summary, 5 aircraft are seen as needed to meet the 1990 requirement.

A quantitative analysis of the requirement illustrated in Tables 3.1 and 3.2 can also be carried out using a simple formula:

$$n = \frac{N \quad 2nFD;}{H} \qquad n = \frac{N}{H-2FD}$$

where n is the number of aircraft required,
N is the number of hours of on-target flying,
F is the one-way ferry time to the target from base in hours,
D is the number of days a year each aircraft flies,
H is the number of hours a year an aircraft flies.

Based again on a large number of discussions with operators and users, values for the constants in the formula were assigned as follows:

N = 6414 hours (from Table 3.2)
F = 1 hours
D = 250 days
H = 2000 hours

from which:

$$n = \frac{6414}{2000 - 500} = 4.3 \text{ aircraft}$$

This simple formula takes no account of the peaks and valleys in the yearly operation, so n must be adjusted to take account of this fact. This is done by correcting the number of aircraft required in accordance with the deviation of the highest and lowest month from the monthly average.

From Table 3.2 the monthly average is 6414/12 = 534 hours.
The monthly maximum and minimum according to Figure 3.3 is 700 and 450 hours respectively.
Increasing and decreasing the aircraft proportionately leads to a requirement

for $4.3 \times \frac{700}{534} = \underline{5.6}$ aircraft for a typical month of March,

and $4.3 \times \frac{450}{534} = \underline{3.6}$ aircraft in December.

The quantitative analysis serves to confirm the qualitative result. At this point in time, however the qualitative analysis is the more believable because it takes into account, at least intuitively, the realities of distance and operating conditions.

5.2.2 Deployment of Aircraft

Examination of Table 3.1 reveals that for several months of the year daily reconnaissance is not required in the region lying between the Beaufort Sea and Baffin Bay, the region that divides the two regions where intensive reconnaissance is required. Unfortunately the areal requirement is heavily biased towards the Eastern region comprising Baffin Bay and the Davis Strait. In fact, in terms of area, the routes drawn in Figure 5.1 suggest a requirement for two aircraft in the East, -

one at Resolute and one at Frobisher - and only a fraction of an aircraft in the West except on days when sorties through the Northwest passage are required. The distance between the two major regions is large enough to make routine back-and-forth movement of aircraft very uneconomical however, so a compromise on the full daily coverage of the Baffin Bay/Davis Strait region, is suggested. The logistics might be as follows:

The 'spare' Arctic aircraft is based at Frobisher. The operating East-Arctic aircraft flies Frobisher to Resolute and Resolute to Frobisher on alternate days to provide approximately 50% areal coverage of the shipping corridor each day. The West aircraft is stationed at Inuvik and supports the daily reconnaissance in Beaufort Sea and the thrice weekly reconnaissance through the narrower regions. The spare is available for increased areal coverage in the Baffin Bay/Davis Strait sector. If it has to be deployed to the West because of a breakdown, the remaining East unit can support the limited reconnaissance and, under urgent circumstances could increase the daily eastern coverage for a limited time without unduly increasing its own risk of failure.

5.2.3 Weather Factors

Weather is a significant factor to be considered in deploying aircraft for sustained high-reliability service. It has been pointed out that the most urgent requirement for ice reconnaissance could arise under weather conditions that would simultaneously prevent take-off and landing. A detailed analysis of the scope of this problem and its solutions is beyond the scope of this study but a number of enquiries were made and enough information was obtained to put bounds on the problem. The following points summarize what was learned:

1) AES figures for the two Electra aircraft collected over 1978, -79, -80, and -81 are tabulated in Table 5.1.* Note that these figures do not include winter operations in the Arctic because AES has not had a requirement for protracted reconnaissance in the Arctic after freeze-up. Choosing the data for the SLAR-equipped aircraft the fraction of missions aborted due to weather averaged over four years varies from zero in December to a high of 13 in October.

2) Queries were made at Bradley Air Service but scheduled airline experience was not deemed to be praticularly relevant. Cancellation of scheduled flights frequently depends on the number of scheduled stops that are closed in rather than on the aircraft's ability to take off perform a mission and land.

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* We are grateful to W.E. Markham for the compilation of these figures.

3) In the context of ice reconnaissance missions one operator when pressed for an opinion guessed that on the average one day per month per aircraft might be lost due to weather.

This opinion was given on the assumption that suitable alternates are available for landing after the mission is completed, since an aircraft can normally take off under more extreme conditions than it can land.

The matter of alternative landing sites complicates the choice of aircraft for ice reconnaissance. Heavy long-range aircraft can fly longer distances to alternate sites but because they cannot land on short runways they are limited in the choice of alternates especially in the Arctic. Medium-range aircraft on the other hand can land on shorter runways but they lack the capability to seek an alternate at a long distance after a mission is completed. A shorter-range aircraft would be preferable for the Western Arctic because of the more local nature of the area of interest. One the other hand a mixed fleet adds a new dimension to training and maintenance costs.

5.2.4 Aircraft Range Requirements

The routes shown in Figure 5.1 call for flights of 2200km to 3600nm duration in the Arctic. Below are some basic data on four aircraft that have been suggested for ice reconnaissance.

Type	Price	Range with Reserves	Fuel	Payload Capabilty
Lockhead Electra	$8-10M	3600km	2250 kg	excellent
Lockhead C-130 Hercules	$14M	5500km	2250 kg	excellent
DeHavilland DASH-7	$8M	2500km	700 kg	adequate
BAC 748	-	2800km	700 kg	adequate

The Electra, P3 and C-130 are characterized by excellent payload capability , a very long operating range, high fuel consumption (2250 kg per hour). They require relatively long runways. The DASH-7 and the BAC 748 are characterized by low fuel consumption (700 kg per hour), short landing strips, just-adequate payload capability and limited range (in terms of the ice reconnaissance requirements). A final choice of platform could only be made in the light of an explicit requirement.

5.2.5 Hangars

In discussion with a number of operators of aircraft, it was generally assumed that aircraft operating in the Arctic on a sustained basis would require heated hangers for maintenance and protection from the elements. New hangars at Inuvik, Resolute and Frobisher would cost approximately $1-2M to construct and between $100,000 and $250,000 per annum to maintain and operate. (Exact figures are not available because there are no large hangars being maintained year-round in the Arctic.)

5.3 1990, Satellite Platform

5.3.1 Areal Coverage

For a discussion of satellite platforms, the current RadarSat baseline concept is taken as an example. This baseline has two significant elements.

(i) swath coverage
(ii) orbital tracks

The current RadarSat baseline calls for an imaging radar (SAR) as a prime sensor. The SAR has a nominal 200 km swath which is steerable on ground command to four overlapping positions relative to the sub-satellite point. All positions lie within an angle ranging from 20° to 45° from the nadir. The total available ground swath is approximately 500 km. In this 500 km swath one of the four 200 km swaths can be covered at a particular instant. A large number of graphical representations of these swaths have been developed for particular orbits by Canadian Astronautics Ltd. Three are reproduced in Figures 5.2, 5.3, and 5.4. The shipping route has been added to Figure 5.4. Figure 5.2 illustrates the extreme inner and outer limits of the swath namely 20° and 45°. In Figure 5.3 and 5.4 the shaded, areas represent areas not covered after the number of days noted. These figures are for a one-satellite system, a two-satellite system would provide superior daily coverage at Southern Canadian latitudes. However, a realistic mission profile calls for delayed launch of a second satellite so single - satellite coverage is the most likely situation of the most of the mission and will be used for this study.

The one-day coverage in the 3-day subcycle is inadequate for daily reconnaissance South of 68° latitude. However, as noted in the footnote on page 11, AES has not adopted a strict daily coverage requirement in this region so the satellite system is not ruled out by reason of coverage. Above 68° there are some small unsurveyed regions at 71° latitude which would appear in the Beaufort Sea periodically. The dimensions of these regions are approximately 60 km on a side.

A RadarSat carrying a scanning microwave radiometer with swath width of 1400 km would esentially cover all of Canada every day. Hence, an all-satellite system would be sufficient if the combination of complete daily coverage to 30 km spatial resolution coupled with a minimum every-third-day coverage to 25 m spatial resolution from a satellite-borne SAR were an acceptable response to the Eastern seaboard requirement.

5.3.2 Satellite Reliability

Satellite platforms by virtue of their high altitude are completely isolated from the weather factors that must be accommodated in routine aircraft operations. By reason of this same isolation the reliability of a satellite operating system differs fundamentaly from that of an aircraft system in at least two failure modes:

(i) Platform failure: An ice reconnaissance system of the type being considered in this report might be supported at any one time by a number of aircraft or by a single satellite. Failure of an aircraft represents a temporary loss of service in a position of the system - the loss could be very serious under many circumstance - but the remainder of the system would continue to function. On the other hand, loss of a satellite platform in a satellite-dependent system means a virtual shut-down of the whole system until corrective procedures (often protracted) can be implemented or a spare satellite brought into service.

(ii) Sensor failure: Failure of an aircraft sensor can usually be coped with by replacement from strategically located spare stores. Failure of a satellite sensor is frequently final and no replacement or repair is practical unless and until the Space Shuttle system becomes available for in-space service of satellite modules at a future date.

This fundemental difference of failure modes makes a simple comparison of the numerical reliability of a satellite or an aircraft system meaningless. Estimates of reliability can be produced for both systems but knowledge of the statistical failure modes can only be used to advantage in the context of an explicit operational requirement. Even then, fundamental differences in the failure modes of the two systems requires a judgement call on whether one failure mode is more acceptable than another in the light of the benefits being provided up to the time of failure.

5.4 1990, Mixed Aircraft/Satellite Platforms

A mixed system of aircraft and satellites, given the satellite coverage discussed in the previous section would assume satellite coverage North of 68° and aircraft coverage South of 68°. By regions, the satellite would support the year-round reconnaissance requirement in the Arctic, the aircraft would support the daily high-resolution requirement in winter in the Gulf/NFLD region much as is done now. The aircraft loading would be reduced significantly from the current level since approximately 50% of the Gulf/NFLD region is covered by the satellite each day. However, if daily high-resolution was mandatory, a minimum of two aircraft would be required to assure a minimum capability to have at least one. The only alternative would be to have prior arrangement for other commercial support on a priority basis in case of failure.

5.5 Review of 1990 Platform Options

From the foregoing it is clear that an all-aircraft system can meet the minimum requirement for daily coverage in the shipping corridor. Risks due to weather cannot be avoided but they can be minimized with careful stationing of aircraft and arranging for alternate landing sites. The reserve capacity in a fleet of five aircraft could be used for more extensive reconnaissance if the cost of additional flying hours warrants. The problem of delivering raw imagery from an aircraft to an Ice Information Centre (IIC) without delay is a serious one but, as will be shown in the next section, solutions, though somewhat clumsy, do exist.

A mixed aircraft/satellite solution makes use of the unique features of both platforms. The satellite is used to cover the Arctic in winter (and summer), an operation that is very costly when performed by aircraft on a sustained basis. The aircraft are used to cover the Gulf/NFLD region in winter, thus following the current pattern of AES operations, albeit at reduced frequency.

There is no all-satellite solution to a rigid requirement for daily coverage to 25 metre resoluton at lower latitudes but an all-satellite solution does exist for a compromise requirement:

(a) A wide-scan microwave radiometer provides daily synoptic coverage in the Gulf/NFLD region, and;

(b) High resolution SAR coverage of 40 to 50% of the area is obtained daily.

If the current positive outlook for progress in reliable ice forecast models continues for the next three to five years the all-satellite solution, though not optimum, looks acceptable for 1990. It is assumed that special aircraft reconnaissance on an ad hoc basis would be arranged by contract with the private sector. Such an arrangement would be necessary, for example, for iceberg reconnaissance and verification of doubtful ridge features in satellite imagery. For 2000, the solution to ice reconnaissance requirements is not expected to have changes as far as collection of raw data is concerned. Heavier reliance on satellite reconnaissance but with aircraft support, is expected.

5.6 Summary

Selection of aircraft or satellite platforms with their respective sensor packages for particular ice reconnaissance applications will involve trade-offs in four areas: cost, coverage, flexibility, reliability. For ad hoc coverage of limited areas, the flexibility of an aircraft system is attractive but at the expense of some risk due to weather, high standby costs (in the Arctic), and a near-linear rise in cost with increasing coverage. For routine wide-area coverage the satellite system will be attractive; the system will be reliable although performance will be achieved at the expense of flexibility.

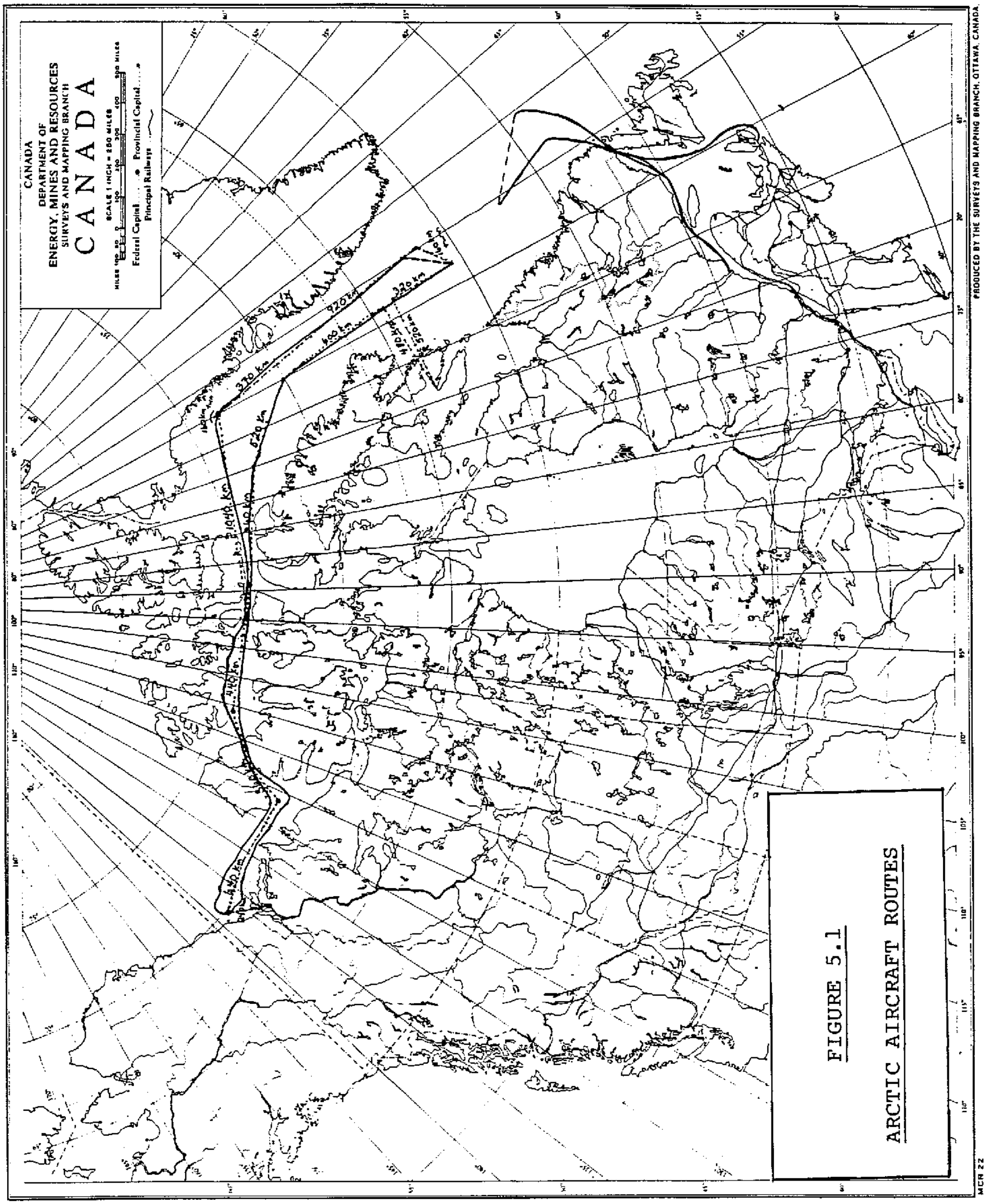


FIGURE 5.1

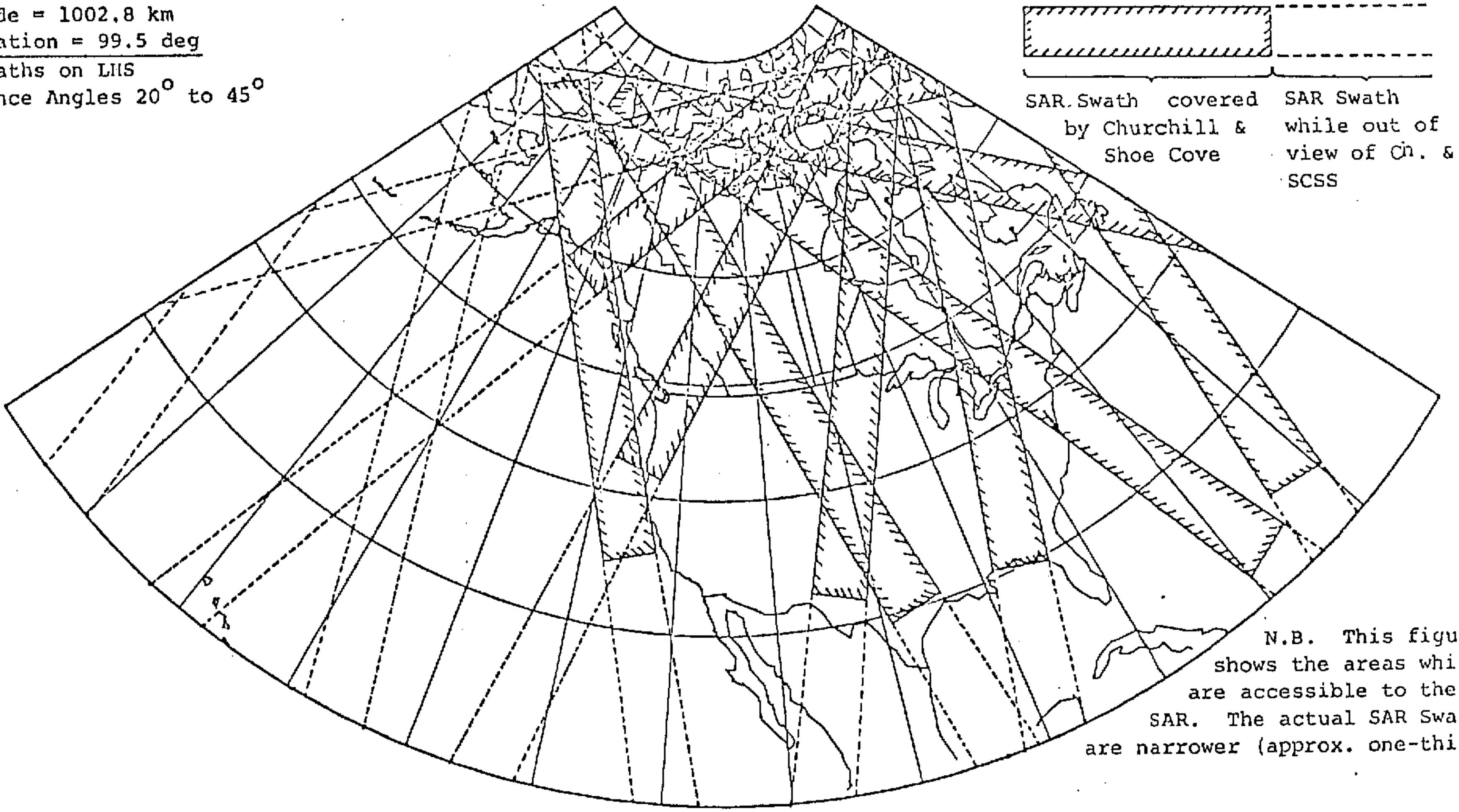
ARCTIC AIRCRAFT ROUTES

TABLE 5.1

ARCTIC FLYING CANCELLATIONS, JULY - DECEMBER INCLUSIVE

	NAY			NDZ (SLAR)		
	WEATHER	AIRCRAFT U/S	# ACCOMPLISHED	WEATHER	AIRCRAFT U/S	# ACCOMPLISHED
1978	6	4	65	14	7	104
1979	11	3	71	3	15	105
1980	7	4	55	4	4	110
1981	24	6	46	10	21	103
TOTAL	48	17	237	31	47	422
JULY (4 YRS)	4	3	70	3	7	87
AUGUST	17	4	69	4	2	93
SEPTEMBER	16	10	56	7	5	93
OCTOBER	11	0	40	12	21	63
NOVEMBER	0	0	2	5	9	76
DECEMBER	0	0	0	0	3	10
TOTAL (4YRS)	48	17	237	31	47	422

Orbit
Altitude = 1002.8 km
Inclination = 99.5 deg
SAR Swaths on LHS
Incidence Angles 20° to 45°



N.B. This figure shows the areas which are accessible to the SAR. The actual SAR Swaths are narrower (approx. one-third).

FIGURE 5.2 BASIC SAR ACCESSIBILITY PATTERN - 1 DAY

NORTH AMERICAN COVERAGE

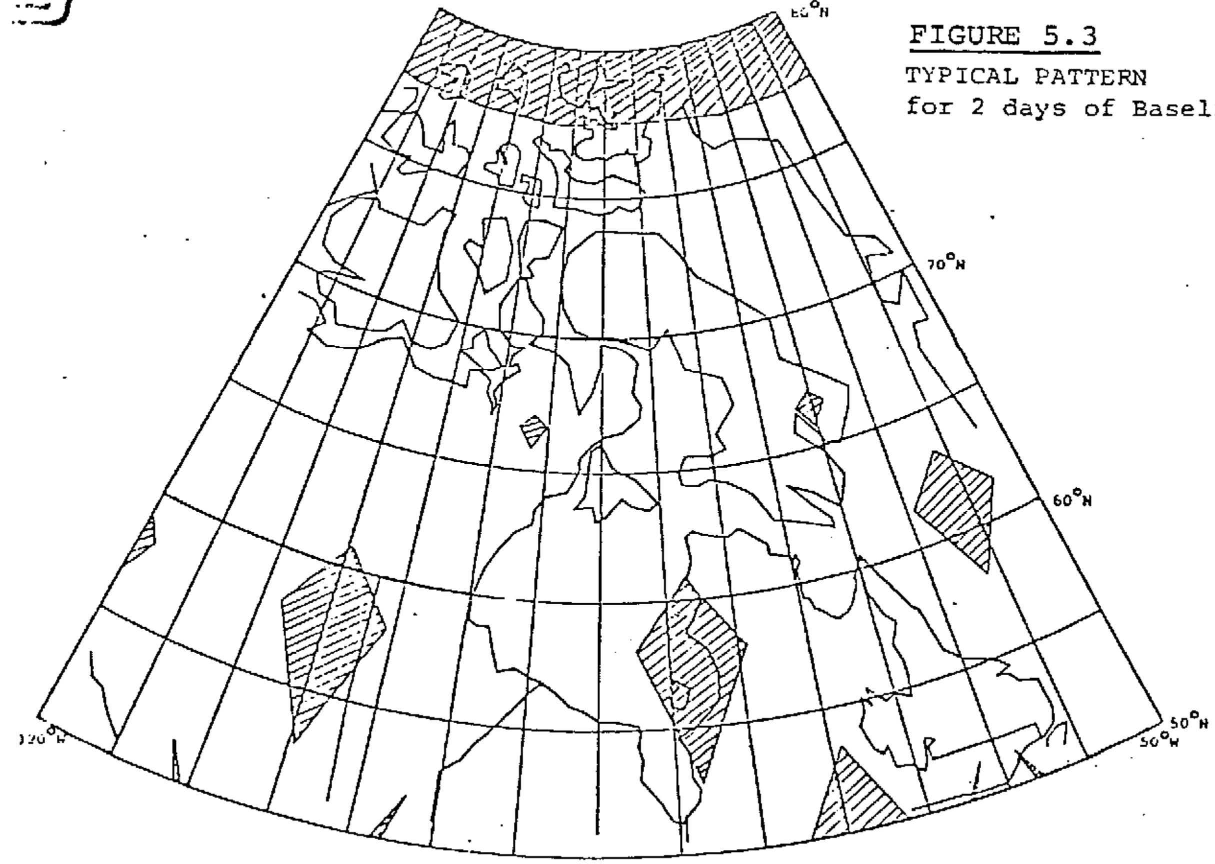


FIGURE 5.3

TYPICAL PATTERN
for 2 days of Baseline Orbit

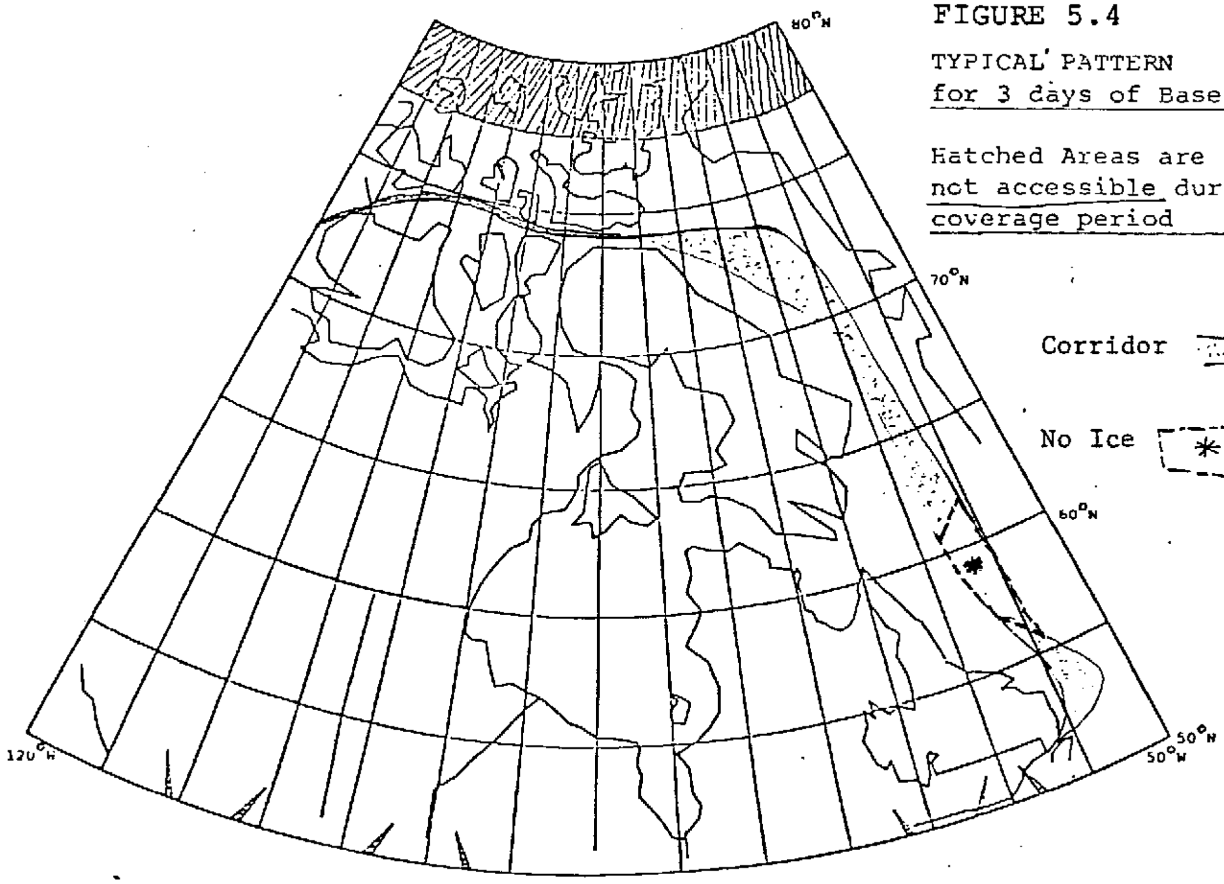


FIGURE 5.4

TYPICAL PATTERN
for 3 days of Baseline Orbit

Hatched Areas are those not accessible during the coverage period

COVERAGE ACCESSIBILITY PATTERN BASELINE ORBIT

6. COMMUNICATIONS

6.1 Overview

To users, the movement of data and messages in an ice information system ranks equally in importance with the original collection of the data. During the course of this study, great emphasis has been laid by current and would-be users of ice information on the need to obtain information that is still relevant in the time-scale of the dynamics of ice changes. Indeed, one of the principal challenges of an ice information system will be to turn raw data around quickly enough to meet the commitments to a range to clients.

Numerous discussions with users indicated clearly that they were prepared to compromise; although no one said how far the quality of the ice information product could be comprised in the interest of receiving it on a timely basis. These discussions confirmed that the time during which certain types of ice information remained current was in the order of several hours. Correlation of this time with the frequency with which raw data should be collected was inferred in some instances and stated in others, but the over-riding concern was to get products to the users while the information in the products still had a reasonable correspondence with the actual state of affairs. Repetition rates while important, were a secondary consideration.

The foregoing serves to emphasize the critical role the communications infrastructure will play in an effective ice information system. The remainder of this section is devoted to identifying the variety of messages in an ice information system and suitable methods for expediting them to users.

6.2 Types and Source of Traffic

The types of messages and products that must be moved through and out of the system have been analysed in Task 2 of the study (Ref.2). A diagram taken from the Task 2 report illustrating this movement is reproduced here as Figure 6.1.

It is convenient at this point to summarize the requirements along the lines of the message being carried with a view to understanding the complexity of the communications subsystem. For the purposes of discussion we use the same terminology as is used in the Task 2 report, that is, in addition to the collector platforms, there are three types of nodes in the system:

- main processors (MPs);
- intermediate processors;(IPs)
- user processors (UPs).

The location and number of those processors will be determined at a future time in accordance with the known or perceived traffic pattern. However, the basic characteristics of the communications subsystem that moves different messages and products among the nodes is less dependent on the number of nodes than it is on the nature of the traffic, so the communications alternative can be examined before the full scale of the operation is known.

Main processors (MP's) collect, analyse, reformat and distribute information on a national scale. The three MP's that are on-line for ice information are the Ice Information Centre (IIC) which will emerge from the current Ice Forecasting Central Office in Ottawa, the

RadarSat earth station where the SAR processor is located and the AES Satellite Data Laboratory. The RadarSat earth station may eventually be located at Churchill but for this analysis the location is not a first-order effect, nor is the number of earth stations.

Intermediate Processors (IP's) collect, analyse, reformat and distribute information on a regional or user-oriented basis. IPs may therefore exist as AES regional offices or industry centres (for example petroleum operators and commercial environmental consultants). UPs are at the eventual user or local distribution service terminal.

The traffic in the ice information system as it is envisaged can be classified as one of three classes of message:

CLASS I:	ice imagery at full resolution and full dynamic range;
CLASS II:	ice imagery at reduced resolution, or dynamic range, or both;
CLASS III:	line drawings such as charts and maps.

This division is made according to the information content in each of the messages. From this the demands on the communications subsystem can be extracted.

Sources of Class I messages are RadarSat and an airborne SAR.* In the satellite case the message is passed from the RadarSat ground station to the IIC along with the appropriate geographical referencing data. After annotation and co-registration with geometrical coordinates it is passed as a re-formatted image to IPs and perhaps to a select group of UPs such as icebreaking tankers or drilling platforms.

In the aircraft case IIC will receive raw imagery in near real-time from aircraft equipped with imaging radars. These messages will include sufficient geographical reference data to allow co-registration of the imagery with earth coordinates in the same manner as will be done with RadarSat imagery, although the precision of the aircraft imagery may be reduced somewhat when data is taken under difficult flying conditions. In the event of an all-aircraft ice reconnaissance system this traffic will be very heavy, replacing as it must the minimum synoptic coverage that would otherwise be obtained by RadarSat.

To control communications costs it may be necessary to compomise the original quality of airborne SAR imaging in the interest of moving it quickly to IIC. The communications requirement is awkward and is discussed in more detail later.

Class II messages may be passed eventually from either of the two MP's to any other node in the system but will definitely be sent from IIC and IPs to a number of UPs.

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* IIC may be a source of Class I traffic to some sophisticated UPs but this is not clear at present. Some operators (UPs) may require full-resolution image of large areas in digital format to perform image enhancement and "zoom and roam" analysis.

Class III messages will be sent from IIC to all IPs and UPs in the form of maps and charts conveying the information in the products in Figure 6.1. The flow of traffic between the various nodes is summarized in Figure 6.2.

A representative description of the composition of the three classes of traffic would be as follows:

CLASS I: Digital; 8-level pixel code image plus geo-reference; maximum pixel-rate $5x10^5$ pixels per second;* maximum bit-rate $4x10^6$ bits/sec; channel loading in the order of 2½ hours per day out of the RadarSat earth station with an equal amount (possibly) out of the IIC to IP's and UP's.

CLASS II: Analogue or 4-bit-per pixel digital code; maximum bandwidth or data rate set by the particular inter-node link, typically several kHz or several tens of bits/sec; channel loading is indefinite but overall level of product output from MPs and IPs will be high.

CLASS III: Line drawings, analogue or digital transmission with bandwidth requirements equal or less than voice circuits.

There is room for trade-off between bandwidth and the time allowed to complete transmission in some instances but the requirement for fastest-possible reduction of the raw data to products and outputting of products to users will in many instances dictate a trade-off biased towards speed of transmission. This applies particularly to the turn-around of radar imagery from

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*This is the forecast pixel rate from the RadarSat SAR processor. The processor will operate at one quarter the output of the RadarSat SAR.

platform to user, traffic which happens also to be the most demanding of bandwidth. The technical communications options available to AES for moving this ice information traffic exists or can be made to exist on the domestic common carrier networks. Important developments in Time Division Multiple Access (TDMA) and sophisticated coding systems are emerging, in particular with reference to satellite links. These improvements will make more efficient use of the capacity of communications links.

6.3 Service via ANIK D Satellite

It has been suggested that a RadarSat Mission operation would acquire dedicated service of an Anik 4/6 GHz channel to support the bulk of the communications traffic load. Since one such channel will support a bit rate in excess of 60 M bits/sec it would readily provide simultaneous movement of Class I traffic in and out of the IIC. Addition of narrow band single channel per carrier (SCPC) voice circuits in the same channel would provide significant and probably sufficient capacity for the Class III and perhaps the Class II traffic, depending on the number of different Class II images to be sent. Introduction of TDMA as an option might make better use of the remaining channel capacity; allow more flexibility for configuration (software versus hardware) changes, and would permit a wide range of modern digital transmission techniques to be exercised. An Anik-based backbone system of this kind has other positive features. Most of the traffic in

Figure 6.2 is downwards, with the number of nodes increasing towards the UP level. The ice information products therefore are being outputted in a sort of broadcast mode. A satellite-based system is ideally suited to this configuration because it provides for the addition of IPs and UPs at the incremental cost of the receiving station only, without regard to distance. With a number of IPs and UPs being visualized in the Arctic the benefits of the satellite system become very attractive. From the point of view of reliability also, experience has shown that satellite communications channels can equal or outperform terrestrial systems in terms of reliability and freedom from interference.

Access to an entire satellite tranponder has a significant additional benefit. The levels and spacing of the various signals can be optimised to meet the unique AES requirements. This flexibility could alter the cost and complexity of small receiving terminals drastically.

6.4 Use of Partial Satellite Transponder Circuits

In the event that an entire transponder was not available, use would still be made of conventional satellite circuits, for example, to link IIC with IPs and UPs. It has been pointed out in Reference 2 that a decision on the class of imagery required on ships and drill-sites cannot be taken before a full study of costs and requirements is done. If we assume that a ship or drill-site will require imagery but with reduced resolution and dynamic range consistent with an analogue product, service by conventional circuits through ANIK or the M-SAT system being proposed by DOC becomes practical. High fidelity facsimile-type equipment exists in which an analogue SLAR or a SAR image can be divided into 512 x 512 pixels and transmitted over channels of the order of a kilohertz bandwidth. A 200 km X 200 km RadarSat scene or a 100 km X 100 km aircraft scene, with resolution degraded to 100 meters (comparable to the azimuth resolution of an airborne SLAR at 12 km range), in analogue format can be transmitted through such a channel in less than 10 minutes. With modified earth terminals and slow enough data rates, reception on a drill-ship might be economically attractive. Conventional ANIK C-band voice circuits to a moving ship may not be economical because of the problem of stabilizing a relatively large antenna.

Thin-route TDMA channels through M-SAT are being examined at DOC for South-to-North traffic. A 25 kilobit/sec. rate has been suggested. Transmission time for the images described above, with 4-level digital coding (16 grey levels) would be about 50 minutes if the TDMA system was being shared equally with other messages. Fifty minutes is a relatively long time in terms of the stated requirement to have the image product available within two to six hours of data collection so some pre-empting of other traffic might be scheduled. Whatever the nature of the circuits, the M-SAT service is ideally suited to thin-route service to the Arctic.

It is be noted that the service envisaged for M-Sat is in the 800-900 MHz UHF band. The final beam configuration for M-Sat is yet to be decided but a multiple beam system appears certain. A possible four-beam configuration is illustrated in Figure 6.3. This figure is taken from a SPAR report prepared for DOC (Ref.14).

6.5 HF Circuits

A third option for transmitting Class III traffic is slow-speed modems on HF circuits. HF circuits are already in use by AES and MOT for disseminating ice charts on the East and West coast and in the Arctic but the transmission time is lengthy and the quality varies. Research work at the DOC laboratories and at MDA has resulted in an improved modem for increasing the quality of transmission over HF circuits at low (300 bit/sec) rates. This equipment would support the transmission of Class III products in all but the most extreme HF circuit interference conditions. Use of image-coding and other techniques to remove redundancy could increase the speed of transmission of class III traffic dramatically.

6.6 Aircraft-to-IIC Circuit

The most difficult communications link in Figure 6.2 is the link for transmitting radar imagery from AES aircraft to the IIC.* Current practice in AES operations, for the aircraft equipped with an imaging radar, is to perform an immediate interpretation of the radar imagery as it is produced on board the aircraft, blend this interpretation with visual observation and data from other on-hand sensors into a master chart, and transmit the chart on a facsimile HF circuit at a scheduled time from the aircraft. When the aircraft lands, the chart is re-transmitted over a commercial circuit to Ice Forecasting Central. The hard copy of the imagery and the laser profilometer record are sent via Airvelope to Ottawa for analysis and retention.

AES is in the process of acquiring a VHF downlink for telemetering the airborne SLAR imagery to receivers of opportunity. This imagery has reduced range resolution (in the order of 50 meters if the radar is configured for dual 50 km swaths), and normal azimuth resolution. For an aircraft height of 6 km the line-of-sight radio range will be approximately 200 km. The data rate in the VHF channel is 256 kilobits/sec. CCRS and a private operator currently operate similar downlinks.

Other real-time circuits for telemetering airborne radar imagery have been investigated in the past few years, notably by NASA and the U.S. Coast Guard. In 1979 NASA developed a 6 kilobit real-time UHF uplink for transmitting SLAR imagery of reduced resolution

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* In this discusssion we address the imaging radar communications problem exclusively because the other sensors on an aircraft cover narrower swaths, comparable to the radar 'hole' under the aircraft. Typically this swath is 20 km (at 9 kilometres altitude) or 20% of the radar swath. Equal spatial resolution implies 5 times reduction in bandwidth.

(125x125m) in real time from an aircraft via the GOES satellite to NASA's Lewis Research Center in Cleveland. No records of the as-received imagery were preserved but the quality of the imagery is reported by users to have been excellent for the intended purpose of routing ships through ice in the Great Lakes. The NASA system was also used to support the Arctic Sealift to Prudhoe Bay in 1976. Full descriptions of these systems are found in references 15, 16, 17, and 18.

In the ice information system being envisioned for the future, it is assumed that high-resolution radar imagery will be available to the IIC for sophisticated image analysis . Imagery with reduced resolution such as has been discussed in the preceding paragraphs, while useful to certain users in certain circumstances, will not have enough spatial resolution to support a full range of analyses at IIC. To meet the stated requirement of 25m spatial resolution and a fast turn-around of the imagery through IIC an airborne platform must have a real-time or near real-time communications link to IIC. In terms of data rates for a single reconnaissance aircraft the requirement can be calculated directly:

$$\text{(Bit-rate)} = \text{(Swath)} \times \text{(Velocity)} \times \text{(Digitization Level)}/\text{(Pixel area)}$$

For an aircraft travelling at 250 knots (125m/sec), imaging a 100 km swath with a SAR that processes to 25 m resolution (625m^2 pixel area), with 16 grey levels in each pixel (4-level code), the data rate is 80,000 bits per second. This data rate would consume the equivalent bandwidth of 24 standard telephone channels. While the cost of such a circuit on a dedicated basis is significant, the matter of implementing it is a more basic consideration. The combination of a relatively small platform moving at high speed, close to the earth surface, limits the option for a high-speed data link to line-of-sight. In this study two options were reviewed:

(i) VHF downlink to sites equipped with ANIK uplinks to IIC;
(ii) Direct transmission through M-SAT to IIC.

Option (i) is technically feasible, it requires a multiplicity of ANIK uplinking sites (and channels) to support ice reconnaissance in the Arctic because of the line-of-site limitation on the VHF (or UHF) downlink. To be specific an aircraft operating between 6 km and 10 km has a miximum range of 200 to 350 km.

The magnitude of the VHF/ANIK uplinking requirement is illustrated in Figure 6.4. Circles of 320 km radius have been drawn around sites along the most probable shipping route to permit, as far as possible, complete coverage of the aircraft track during reconnaissance. Full circles indicate existing ANIK stations, dotted circles indicate sites where service will be needed but none exists. Though costly to operate, such a network of coastal stations would permit real-time transmission of the radar imagery from the aircraft to IIC. From Figure 6.4 it will be seen that the imagery of the North-East portion of the tanker route in Baffin Bay cannot be telemetered (reliably) in real-time because of excessive range to an uplink site. In this case, the imagery would have to be recorded on board the aircraft and downlinked in parallel with the imagery being collected at the same time. The maximum delay in receiving this particular section would be in the order of one hour depending upon how the reconnaissance pattern was flown. Note that at the peak of the flying season there would be as many as four aircraft operating daily, 2 in the North and 2 in the East, with flights in the order of six to eight hours duration. The daily loading on the system would amount to 25 to 30 equivalent hours per day.

A spin-off benefit of such a system, if implemented, is that it would serve as a ready-made basis for the transmission of data in the reverse direction from IIC to IPs and UPs.

The second option for R/T transmission of airborne radar imagery to IIC is the M-Sat system. Preliminary engineering calculations by M-SAT project staff at CRC indicate that an aircraft-to-M-Sat satellite link would support data rates of one to two megabits. Transmission of the radar imagery therefore would be technically feasible, and preferable to the VHF/ANIK-D solution because it avoids the intermediate VHF hop. Access to such wide bandwidth in a thin-route system might be difficult to accommodate operationally. Because of the multiple-beam configuration of M-Sat, there would have to be beam-to-beam handovers as the aircraft moved from East to West or West to East.

Present planning for M-Sat is to launch in 1987-88 and operate in a pre-operational mode until the mid-1990's. Therefore, should the M-Sat Mission proceed into Phase C and D on the present time table, it would support the ice reconnaissance communications requirement within one or two years of the start of year-round shipping.

With a limited number of tankers operating year-round in 1985-87, and before M-Sat, a compromise solution in the form of direct VHF transmission of imagery to a limited number of ships may be practical because the entire shipping route need not be surveyed. Thus an ice reconnaissance aircraft would fly more restricted patterns with on-board recording and transmit on VHF in a high-data-rate mode to the ship requiring the information. IIC would receive the imagery after the aircraft lands via slower-speed circuits. This mode of operation, though not consistent with centralized collection, processing, analysis and distribution of ice information might be acceptable on an interim basis.

6.7 Image Analysis and Coding

An aspect of image transmission that was not examined in detail for this study was the subject of bandwidth reduction arising from sophisticated image analysis techniques. In an earlier study for AES (Ref.19) Computing Devices Company (CDC) investigated the loss of visual information in an image due to variations in grey scale, in spatial resolution, and in bit-error rates. Coding at 4-bit level was shown to be adequate for visual interpretation. The 4-bit coding (16 grey levels) used earlier in this section to analyse communications requirements for aircraft radar imagery was selected on the basis of the CDC report. The visual aspect of this selection is emphasized. For computer-assisted analysis of imagery, up to 8-level coding is useful for extracting and delineating subtle features in a scene. In this study CDC also examined more esoteric bandwidth reduction techniques such as differential coding of image scenes and run-length coding of line drawings and charts. It was estimated that 2:1 bandwidth reduction due to differential coding was possible and up to 5:1 bandwidth reduction was possible with run-length coding of ice charts. There is an extensive literature on the subject of image coding but an investigation of its effectiveness would require hands-on experimentation. It was remarked during one interview that "2:1 bandwidth reduction due to coding is not cost-effective given the cost of the coding and decoding subsystem".

The communications alternatives for an ice information system for 1985 and 1990 are summarized in Table 6.1.

6.8 ANIK C

Use of ANIK-C statellite channels has been excluded in the present analysis because of the probable bias of the satellite beams towards southern latitudes and correspondingly poorer coverage at latitudes of interest to operators in the Beaufort Sea, the Parry Channel, and Baffin Bay. This is unfortunate for service via this satellite, with the advantage of higher frequency operation (14/12 GHz versus 6/4 GHz) and higher power satellite emissions would materially reduce the cost and complexity of earth terminals in the North, especially on ships. DOC is presently experimenting with reception of wideband analogue (television) and 2-way telephone terminals for semi-submersible platforms. Preliminary trials indicate that such systems for Television Received Only (TVRO) and 2-way telephony will be practical and effective for reliable communications. A typical installation is visualized as requiring a 1.8 m (6 foot) antenna reflector on a stabilized platform. At the ANIK C downlink frequency of 12 GHz a 1.8m antenna has a 3-db beamwidth of approximately 0.8° and would require 3-axis stabilization in the order of $1/2^{\circ}$ to maintain a link to the satellite. Reduction in bandwidth requirements would permit a proportional reduction on antenna aperture size and a corresponding relaxation of the pointing accuracy requirement.

DOC experiments to the present have included a TVRO terminal on a DOME Petroleum drill-ship and a modified telephone terminal on a PetroCanada drill ship. In both cases performance was sufficiently good to warrant further study and development. In the case of the telephony terminal the circuit was used while the ship was underway, the antenna being mounted on a simple stabilized platform.

6.9 Direct Telemetry of RadarSat Imagery

The possibility of direct telemetry of imagery from a RadarSat has been suggested as a means of meeting the first-order requirement of operators able to use un-interpreted imagery at reduced resolution. Inclusion of this feature in a RadarSat mission would require development of a simple real-time processor on board the satellite and dedicated telemetry down-link. As an example a processor yielding resolution of 100 meters was used as a baseline (it compares with the 120x120m resolution used successfully by USCG). With a 200 km swath and 7 km/sec forward velocity the pixel rate is:

$(7x200x10^{6})/100x100 = 140x10^{3}$ pixels/sec.

An order-of-magnitude calculation (see for example Ref. 20) of the main parameters of a 400 MHz analogue FM link indicate that it is at least technically feasible:

VHF carrier frequency	400	MHZ
Satellite transmit Power	10	watts
Satellite antenna gain	6	db
Video baseband	140	KHz
FM deviation ratio	1	
FM improvement	5	db
Receiver antenna gain	19	db
Receiver noise figure	5	db
Receiver bandwidth	280	KHz
Path attenuation (1200 km)	147	db
Atmospheric attenuation	3	db
Receiver noise power threshold	-144.3	dbw
Received carrier level	-114	dbw
Pre-detection C/N ratio	30	bd
Post-detection S/N ratio with 5 db FM improvement	38	db

The Canadian ISIS satellites were operated successfully with 93 kHz FM subcarriers on 400 MHz using 19 db (or less) receive antennas. On the strength of the ISIS performance and the order-of-magnitude link calculation, a direct downlink of RadarSat imagery is an option that warrants further study if a practical on-board processor could be developed. Aspects that need to be examined are the utility of low-resolution, un-interpreted imagery to users, and the cost, weight, power and reliability of a simple on-board processor on RadarSat.

From the point of view of reception of such a signal on a ship, an antenna with 19 db gain at 400 MHz is a practical objective. There have been a number of new developments in ship-borne VHF and UHF antenna. For example, a design exists for a shipboard antenna system that coherently adds signals from a number of monopole antennas mounted at several locations around a ship's exterior. The average gain of this system is 12 db.

Finally, it has been suggested that RadarSat might carry a communications transponder for linking IIC to UP's. Such a scheme was proposed for the ICEX Mission. Though outside the scope of this study, the suggestion has the merit of permitting a communications system uniquely tailored to the requirement.

6.10 Relocation of RadarSat SAR Processor

In an interview with CRC staff it was noted that an ANIK-C 14/12 GHz transponder channel could carry the raw RadarSat data from the earth station to a SAR processor located at IIC. A configuration of this type would have the advantage of allowing complete, instantaneous reaction at IIC to the imagery (and other data) being obtained and would reduce the production of unwanted imagery. Relocation of a complicated hardware/sortware system from an isolated region of the country to an area with ready access to spares etc., might improve the down-time statistics on the processor. Location of highly-skilled personnel in a more challenging technical environment would be a secondary benefit. Given the option of configurating the primary data system this way, the suggestion warrants a second look at the advantages and disadvantages.

6.11 Summary and Conclusions

The communications alternatives discussed in this section are summarized in Table 6.1. The node numbers correspond to the number in Figure 6.2.

Two difficult links to establish will be the real-time link from the ice reconnaissance aircraft to IIC and the link from IIC to free-floating platforms. In the first case the problem is outputting data from the aircraft, in the second case the problem is to control the cost and complexity of the receiving terminal given the bandwidth and speed of transmission of the messages. The aircraft to IIC link is likely to be expensive to establish and operate unless services can be provided through M-SAT or some acceptable operational work-around can be found to alleviate the real-time requirement. Non-conventional use of satellite channels may well solve the IIC to platform requirement.

All of the other message circuits can be implemented with conventional common carrier offerings. However, a non-conventional approach to the use of satellite transponder capacity would enhance the flexibility and cost-effectiveness of all of the communications links. In detailed engineering design, the opportunity to design the basic system to match the need, instead of force-fitting the need into conventional technology, should be stressed.

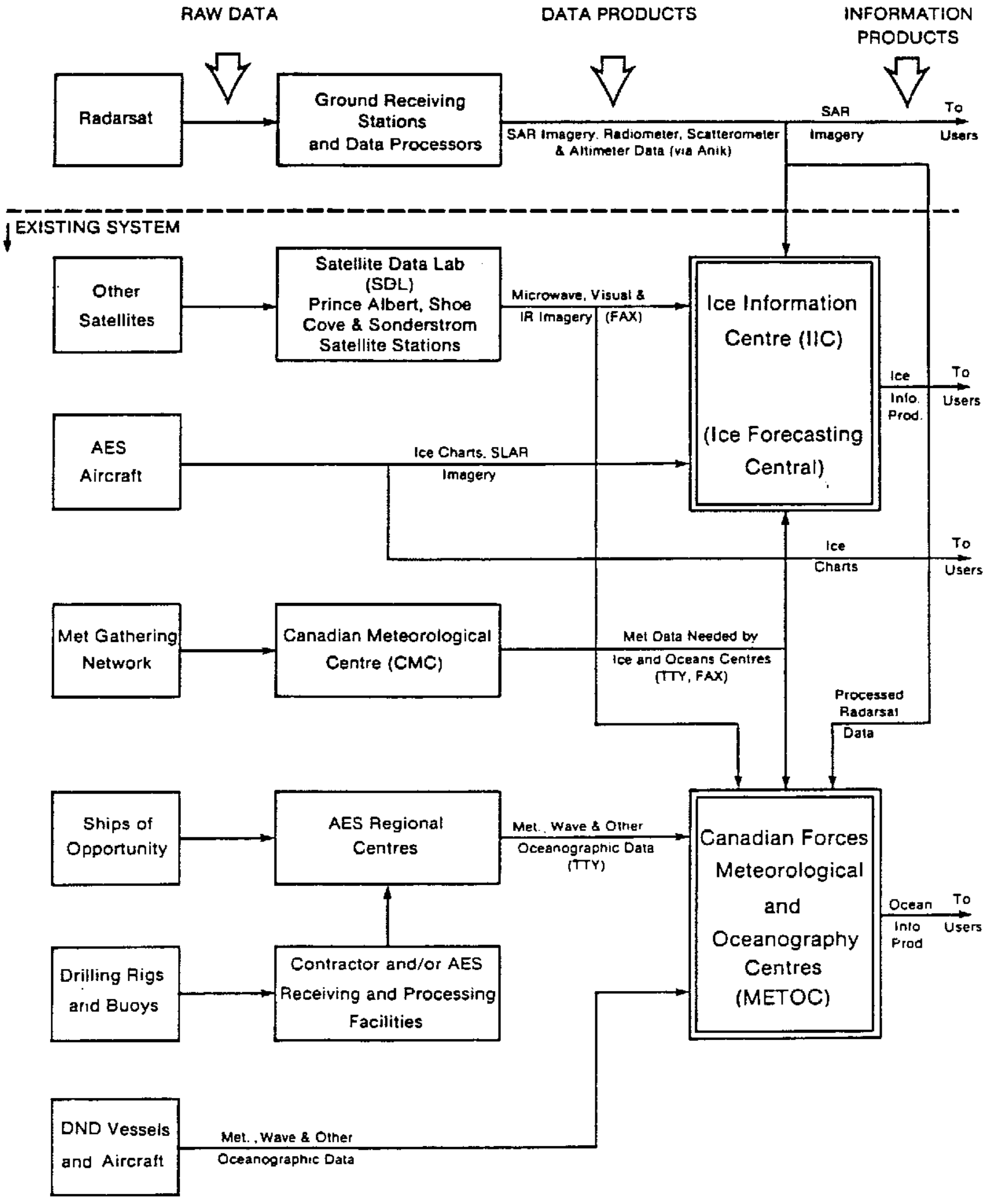


Fig. 6.1 Ice and Oceans Information System

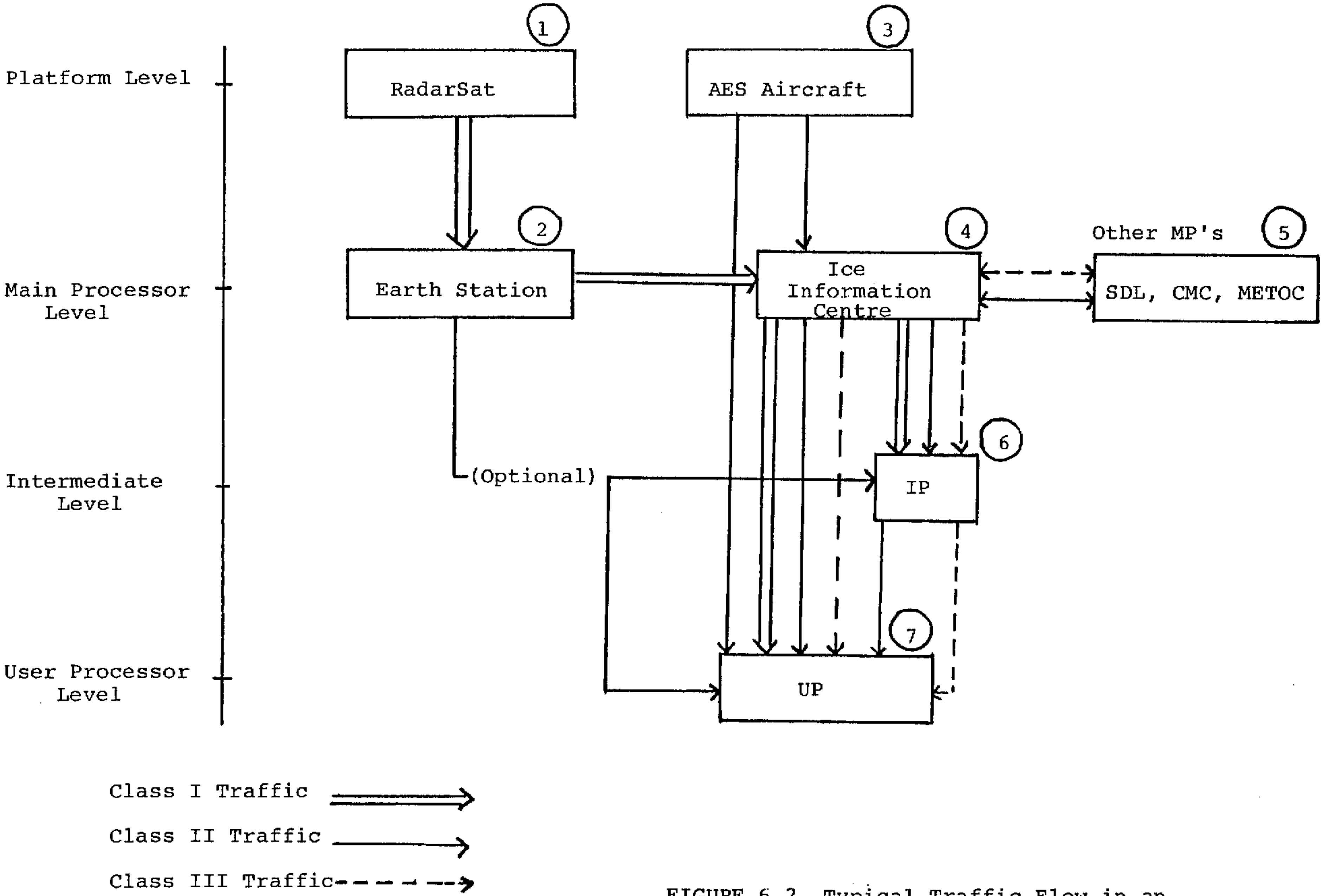
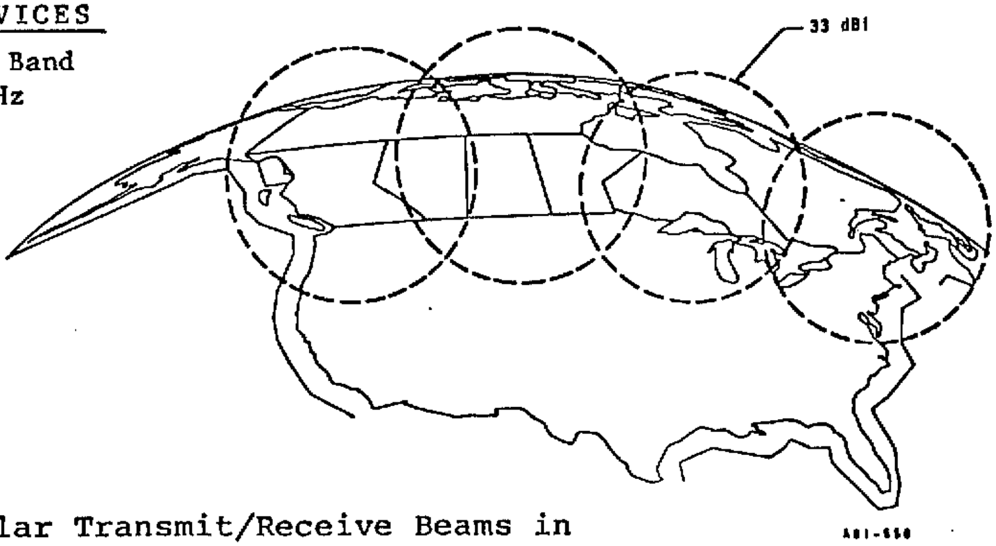


FIGURE 6.2 Typical Traffic Flow in an Ice Information System

D - Commercial Communication Services

MOBILE SERVICES

In Upper UHF Band
821-870 MHz



Four Circular Transmit/Receive Beams in Upper UHF Band give All-Canada Coverage for Commercial Mobile Services.

FIGURE 6.3 TYPICAL M-SAT MULTIPLE-BEAM COVERAGE PATTERN

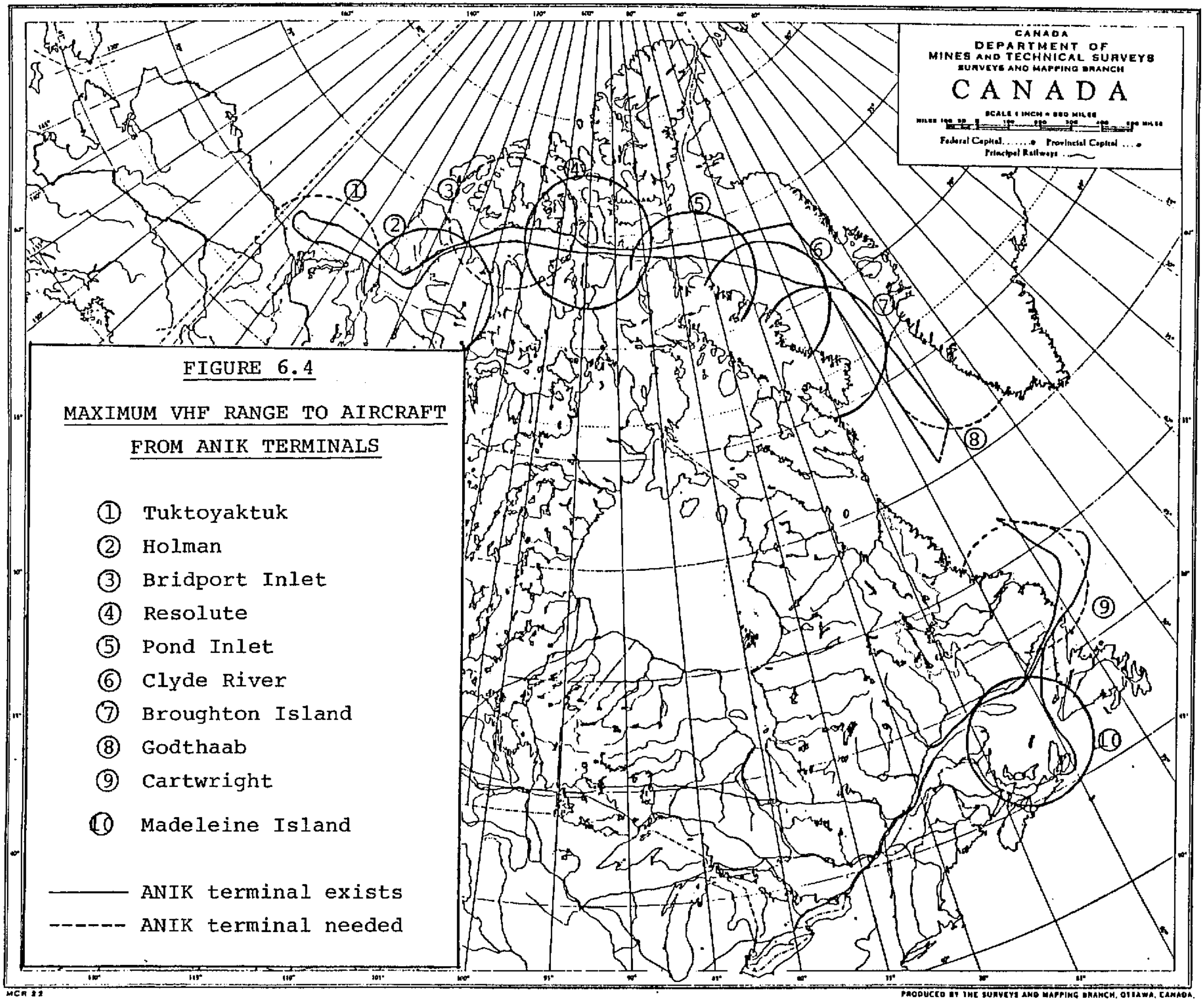


FIGURE 6.4

MAXIMUM VHF RANGE TO AIRCRAFT FROM ANIK TERMINALS

① Tuktoyaktuk
② Holman
③ Bridport Inlet
④ Resolute
⑤ Pond Inlet
⑥ Clyde River
⑦ Broughton Island
⑧ Godthaab
⑨ Cartwright
⑩ Madeleine Island

——— ANIK terminal exists
------ ANIK terminal needed

TABLE 6.1: COMMUNICATION ALTERNATIVES IN AN ICE INFORMATION SYSTEM

LINK (From Fig. 6.2)	MESSAGE	DATA RATE	VOLUME	ROUTE	REMARKS
② → ④	RadarSat SAR Imagery	4 Megabits/sec	2½ hrs per day	ANIK	Assume 35 minutes total access to satellite and 4X reduction in information flow
② → ④	Other RadarSat Sensors	10^5 bits/sec	35 mins/day	ANIK	
③ → ⑦	Airborne radar imagery plus other sensors	80 kilobits/sec	15-30 hrs/day (more than one aircraft)	VHF Radio	
③ → ④	Airborne radar imagery plus other sensors	100 kilobits/sec	15-30 hrs/day (more than one aircraft)	VHF Radio & ANIK or M-Sat	M-Sat preferred because of simplicity
④ → ⑥ ④ → ⑦	Un-degraded imagery	4 megabits/sec	T.B.D.	ANIK	Data rate could be reduced drastically if volume is low and up to 1 hr. transmission time acceptable
② → ⑦ ⑥ → ⑦ ④ → ⑥ ④ → ⑦ ② → ⑥	Analogue imagery	100 kilobits/sec	T.B.D.	ANIK --or-- M-Sat TDMA	Data rate could be reduced significantly if volume is low and some delay in receipt is acceptable
④ → ⑦ ④ → ⑥ ⑥ → ⑦	Charts	Voice channel or less	T.B.D.	ANIK --or-- M-Sat or HF	
④ → ⑤ ⑤ → ④	Charts, analogue imagery	Voice channels or less	ad hoc	land-line	Extension of present operations

7. FINANCIAL CONSIDERATIONS

Two of the major cost factors in an ice information system are the cost of collecting the data, (platform plus sensors), and the cost of transmitting the data through and out of the system, (communications). In this section these factors will be examined in the light of options available. First, the basic cost of the platforms is derived. The cost of an aircraft or a satellite platform only takes on meaning in the context of what the platform can do; so, the cost of each of the platforms is derived in terms of the coverage it permits, the basic purpose of a platform being to carry a sensor to where it is needed. Next the basic costs of sensors and communications are derived. Finally, the basic costs of these three elements are combined into the various options for an ice reconnaissance system. It will be understood that the accuracy of some of these calculations is no better than an order of magnitude at this time.

7.1 Satellite Platforms, Cost and Coverage

Order-of-magnitude cost for a single-satellite, 5-year RadarSat mission is $360 million. For a two-satellite 8-year mission this cost would rise to $570M. The figures are detailed below and cover the cost of developing and launching satellites and operating a receiving station for the length of the mission. Since the 2-satellite mission is seen as providing double coverage for only a limited period of overlap, the revenue from the sale of images is calculated in the basis of one satellite.

(i)	Develop 2 satellites*, #1 @ $225M, #2 @ $130M	$355M
(ii)	2 launches*, @ $50M	100M
(iii)	8 year's operation at $12.5 per year	100M
(iv)	Ground Segment Development	35M
	Total Mission Cost, 8 years of operation	$590M
	Total Annual Cost	$ 74M

The output of this system is images and data from other sensors, "f.o.b." the receiving station.

The cost per unit area covered can be derived readily. A SAR imaging a 200 km swath in a satellite travelling at 7 km per second would image:

$$7 \times 200 \times 3600 \times 24 \times 365 = 44 \times 10^{9} \text{ km}^{2} \text{ per year}$$

if there were no limitations on power. The power budget in the RadarSat baseline will allow about 20 minutes per orbit or approximately 15% of the time for SAR operation. So annual RadarSat coverage is:

$$15\% \times 44 \times 10^{9} = 6.6 \times 10^{9} \text{ km}^{2} \text{ per year}$$

The cost per unit area covered is the total annual cost divided by the annual coverage:

$$\frac{74 \times 10^{6}}{6.6 \times 10^{9}} = \$0.0112 \text{ per km}^{2}.$$

Since only a small fraction of this imagery is likely to be paid for by users, the unit price to the user will be correspondingly higher if users are to pay for the full Mission cost. To put it into perspective, assume that

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* Foreign participation would reduce these capital and launch costs significantly.

Arctic to the East Coast. If all the day and night coverage of this route was supplied year-round, it would amount to approximately 35 minutes of satellite data per day. This is 17% of the 200 minutes available to the SAR daily. The cost to the user then increases by 1/0.17 to \$0.066 per km^2. Of course during the summer months and for some areas in winter, this complete coverage is not required, so the price would be correspondingly higher if there were no other users. Such is not likely to be the case however. The radar imagery gathered in the 200 minutes daily could service a range of other land and ocean users; geological mapping; equatorial forest monitoring; coastal zone monitoring for fishing fleets; oil pollution and ocean wave patterns. Furthermore, since RadarSat is likely to carry sensors other than imaging radar, the data from these sensors must be assumed to be valuable to users.

Taking into account other sensors and sales of imagery and data taken in other countries, the correct multiplier to use, before any experience has been gained, is very tentative. For this study RPO initially suggested a price of \$0.025 per km^2. On the basis of a number of discussions with RPO and users since that time, a target price of \$0.10/km^2 appears more realistic. This figure is used exclusively in the remainder of the cost calculations.

The inverse relationship between cost-to-user and the amount sold has been plotted in Figure 7.1. The current and forecast future demand for ice imagery is marked on the graph for interest. Note that the corresponding price takes no account of other RadarSat revenue from data sold.

7.2 Aircraft Platform, Cost and Coverage

Unlike the satellite case, where the cost of imagery varies inversely with the amount used because the actual collecting process is fixed as to quantity, the cost of collecting imagery from an aircraft varies more or less linearly with the amount collected. The aircraft platform portion of the unit cost can be derived as follows:

Platform rental	$4,000 per hour
Average ferrying time	10%
Unuseable radar imagery*	5
Aircraft velocity	460 km/hr (250 knots)
Image swath**	100 km

Unit cost is $4,000/(460 x 100 x 0.9 x 0.95) = $0.10 per km^2.

As an independent test of the cost of acquiring radar imagery from an airborne platform the unit cost was calculated on the basis of aircraft cost per mile flown and compared to the cost based on an hourly rate. The prices are budgetary and were provided through the courtesy of a northern operator:

(i) The cost per mile flown for an C-130 Hercules or an Electra, based at Resolute for a month at a time, with eleven (total) air and ground crew and a minimum of 200 hours flying per month, excluding hangarage, is $15 and $13 per mile respectively for the two aircraft. With a radar imaging a 60 mile (100 km) total swath the cost of the imagery from the Electra platform is:

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* 95% is based on APS-94 performance over target. AES report 95% effectiveness of the APS-94 radar when the aircraft is 'on-site'.

** This is a conservative figure for budget pruposes. 150 km swaths at high resolution may be possible in the late 1980's.

$13/60 $0.22 per sq. mile
or $0.083 per km^2.

Cost of the sensors is not included.

(ii) At an Electra platform cost of $4,000 per hour, flying at 250 knots, the area covered is:

250x1.15x60 sq. miles per hour
so the cost is

$$\frac{4000}{250\times 1.15\times 60} = \$0.23 \text{ per sq. mile}$$

or $0.089 per km^2.

The difference in the two answers is only 7%.

The cost of sensors in each case would be the same.

7.3 Sensors

7.3.1 Aircraft Sensors

AES budgetary cost of a new SLAR is $3M. An airborne SAR with a dual 50 km swath capability is estimated to cost $4M (price range is $3-5M). An imaging radiometer is estimated to cost $500,000. The cost will vary according to the particular features required. If ancillary sensors such as cameras and profilometers on the aircraft are added, a sensor package cost of $5M is reasonable. The annual rental of this package could be in the order of 40% of the capital cost or $2M per year. For an aircraft flying 2,000 hours per year the hourly cost is $1,000/hour.

7.3.2 Satellite Sensors

No attempt will be made to assign unit costs to the sensors on a satellite. The order-of-magnitude calculation of satellite costs in Section 7.1 includes the cost of the sensors.

7.4 Communications

Whether or not RadarSat arranges for a dedicated ANIK channel, the raw imagery will be sent to IIC via satellite. An annual bulk cost of $1M for the transmission of ice imagery from RadarSat earth stations to IIC is postulated.

The high data-rate (80 kilobit) links from the Arctic to Ottawa that carry aircraft radar would be expensive if the circuits are dedicated. Bell Canada, with TCTS and TeleSat, examined the cost factors for these links. The information is presently undergoing an interval tariff review. As an interim figure for this study, a cost of $60,000 per circuit per month was assumed by the authors. The estimated accuracy is 50%. Multiplexing these circuits through a dedicated ANIK channel would probably produce significant cost savings.

The VHF downlink from aircraft are estimated to cost $25,000 per aircraft per year. This includes the cost of receive terminals.

7.5 Other Costs

Two other cost factors are included for completeness, although they are not directly related to RadarSat or Aircraft costs. They are the cost of acquiring and transmitting imagery and data from other satellites. These costs are itemized as follows:

Source	Annual Cost	Communications
LANDSAT	150,000	N/C
SPOT	150,000	N/C
ERS	300,000	N/C
DMSP or NIMBUS	N/C	100,000
NOAA	N/C	N/C

7.6 Systems Costs

Based on the foregoing cost elements, order-of-magnitude costs to collect and distribute data in an ice information system have been calculated. The calculations were carried out for four scenarios:

(i) Present-to-1985; primarily aircraft;
(ii) 1990, primarily aircraft;
(ii) 1990, mixed RadarSat and aircraft;
(iv) 1990, primarily RadarSat.

The present-to-1985 estimate assumes progressive development of the present system. Features likely to be added are a wide-swath (to 50 km each side) airborne SAR, routine use of satellite microwave radiometer data and acquisition of an early development model or a prototype of 90 GHz scanning radiometer. One additional aircraft for iceberg patrol is noted but not not included in the cost estimate. Also noted is the fact that, with improvements in the reliability of and confidence in the data from the sensor package, low-altitude flying for visual reconnaissance will slowly yield in favour of higher altitide missions for smoother all-weather radar sensing and longer VHF downlink range. Trial transmission of aircraft data to IIC in near-real time is also envisaged in this time frame as a learning experience for later years.

The three options for 1990 were separated into a system based primarily on aircraft reconnaissance with additional data from foreign satellites, a system based on shared RadarSat/aircraft coverage with, again, data from foreign satellites, and finally a system based primarily on RadarSat coverage with data from foreign satellites used on a routine basis and aircraft used on an ad hoc, short-term basis. The third 1990 option imposes a restriction on users in the fact that daily coverage of the East coast south of 68° North is available at low resolution (20-30 km) from an imaging microwave radiometer, with approximately 50% of the area covered by the high-resolution RadarSat SAR each day.

In all of the options, the areal requirement is based on the findings in Section 3 "RE-STATEMENT OF ICE RECONNAISSANCE REQUIREMENT". The large additional areal coverage available from a satellite, though unquestionably of value, has not been factored into the cost equations.

The detailed calculations, assumptions, features, and PRO and CON statements for each of the four scenarios are given in Appendix I. The cost data is summarized in Table 7.1.

7.7 Qualitative Description of a System for 2000

The system envisaged for the year 2000 is seen as evolving from the 1990 system.

From the point of view of the analysis technology likely to be available at the time, significant improvements in ice and environment modelling systems are forseen, to the point where froecasts are available to users. These models will require more extensive but less frequent data inputs, a requirement that is well-matched to a satellite's capability. Aircraft systems will continue to be prohibitively expensive to operate over vast areas of ice and ocean. Satellite SAR technology may not improve significantly from the point of view of swath width or resolution, except that use of shorter wavelengths may become practical. The reliability of space SARs will improve significantly.

Airborne SARs can be expected to be a mature technology with 200 km swaths plus a range of options for real-time processing. Airborne systems will continue to see extensive use in short-term ad hoc applications.

Domestic communications service, principally by satellite, should be available along the Beaufort Sea, the North West Passage and down the East Coast of Canada to the standard now common in Southern Canada. In particular thin-route telephone service to mobile users will be well developed on MSAT-type satellites. Notwithstanding the availability of a wide-range of communications services however, these services will continue to be a significant expense item in the operation of an effective ice reconnaissance system.

The most difficult aspect of a 2000 ice information system to visualize is the user information demand in a context of extensive year-round shipping. Data needs are more widespread but the very existence of a large fleet of operating vessels is itself a source of reliable local data. IIC will certainly make use of this data, although organizing its timely collection and analysis will be a major task.

It seems reasonable to predict less (or more selective) use of conventional IIC products as experience builds, so a decline in system use and a corresponding rise in unit cost will occur. Offsetting this trend will be a requirement for wider areal coverage for ice-forecasting models.

7.8 Observations and Conclusions for 1985 and 1990 System

Table 7.1 includes a column for each system showing the fraction of the total cost each element of the system absorbs.

The first seven rows of Table 7.1 relate to the cost of collecting the ice data. Rows eight to twelve relate to the cost of moving the data among the critical points in the ice information system. In all of the options the cost of collecting the information is 80-90% of the total annual cost, with communications accounting for the balance. This confirms an earlier observaton that adequate communications will always be a significant cost factor regardless of the nature of the data collection system.

The total annual costs of the three 1990 options for acquiring essentially the same annual areal coverage differ by about 14%. The assumed cost of the RadarSat imagery is the reason sensor for this spread. Since it represents 77% of the total annual cost of the 1990 option 3, changes to this assumed cost will affect the total annual cost of this option significantly.

The 1990 Option 3 scenario provides the highest imagery return per dollar spent of all the 1990 options but at the expense of the loss of flexibility that goes with not having dedicated aircraft will reserve flying hours.

No attempt has been made in this study to assign fractional benefits to aircraft or satellites services because of weather, unserviceability or unreliability and none of these factors is implied in Table 7.1. Deviations of this kind are only useful in the context of a particular requirement where the urgency or otherwise of successful data collection has meaning.

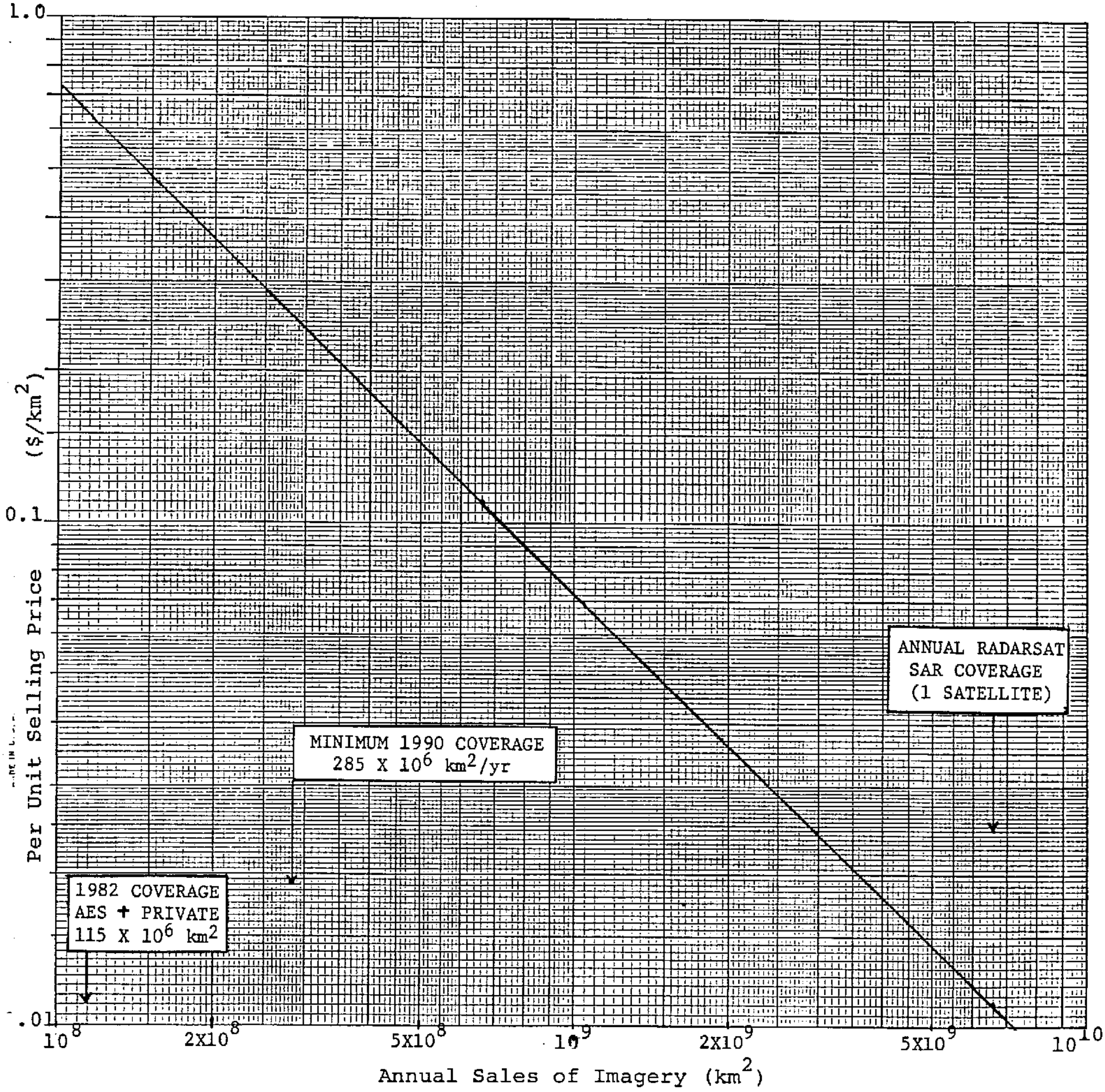

FIGURE 7.1: VARIATION OF SELLING PRICE WITH AMOUNT OF RADARSAT SAR IMAGERY SOLD, FULL COST RECOVERY

TABLE 7.1: ORDER OF MAGNITUDE COST ANALYSIS OF SATELLITE AND AIRCRAFT OPERATIONS

	OPTION / ITEM	PRESENT TO 1985			1990, OPTION 1 ALL AIRCRAFT			1990, OPTION 2 MIXED AIRCRAFT/SATELLITE			1990, OPTION 3[2] MOSTLY SATELLITE		
		ANNUAL UNITS	ANNUAL COST ($000)	% OF TOTAL COST	ANNUAL UNITS	ANNUAL COST ($000)	% OF TOTAL COST	ANNUAL UNITS	ANNUAL COST ($000)	% OF TOTAL COST	ANNUAL UNITS	ANNUAL COST ($000)	% OF TOTAL COST
1	A/C HOURS ON SITE	2 X 1080 @ $4000	8,640	60%	6500 @ $4000	26,000	61%	1800 @ $4400[1]	7,920	22%	749 @ $4400[1]	3,296	9%
2	AIRCRAFT AEREAL COVERAGE (km^2)	95 X 10^6	---	---	285 X 10^6	---	---	79 X 10^6	---	---	33 X 10^6	---	---
3	A/C SENSOR HOURS	2 X 1200 @ $1000	2,400	17%	7000 @ $1000	7,000	16%	2000 @ $1100[1]	2,200	6%	832 @$1100	915	3%
4	A/C HOURS FERRY	2 X 120 @ $4000	960	6%	500 @ $4000	2,000	5%	200 @ $4,400[1]	880	2%	83 @ $4400[1]	365	1%
5	RADARSAT IMAGERY COVERAGE (km^2)	---	---	---	---	---	---	206 X 10^6 $0.10	20,600	57%	285 X 10^6	28,500	77%
6	OTHER RADARSAT DATA								100	0.3%		N/C	
7	NON-RADARSAT DATA COST	LANDSAT NOAA NIMBUS	150 N/C N/C	1%	DMSP ERS SPOT	N/C 300 150	1.0%	---	450	2%	PHSD ERS SPOT	N/C 300 150	1%
8	VHF DOWNLINKS	2 @ $25000	50	0.3%	5 @ $25000	125	0.3%	1 X $25,000	25	0.1%	1 X $25,000	25	0.1%
9	A/C TO IIC LINKS	3 X 12 @ $60,000 per month	2,160	15%	10 X 12 @ $60,000 per month	7,200	17%	2 X 12 @ $60,000 per month	1,440	4%		---	
10	IIC-IP/UP LINKS	Included in Row 9	---	---	Included in Row 9	---	---	2 X 12 @ $60,000 per month	1,440	4%	3 X 12 @ $60,000 per month	2,160	6%
11	GND. STN. TO IIC COMMS.								1.000	3%		1,000	3%
12	NON-RADARSAT COMMS. COST	LANDSAT NOAA NIMBUS	N/C N/C 100	0.7%	DMSD ERS SPOT	100 N/C N/C	0.2%	---	100	0.3%	DMSP ERS SPOT	100 N/C N/C	0.3%
13	TOTAL ANNUAL COST ($000)	---	14,510	100%	---	42,875	100%	---	36;115	100%	---	36,811	100%
14	COST PER UNIT AREA ($/$km^2$)	---	$0.15/$km^2$	---	---	$0.15/$km^2$	---	---	(2) $0.13/$km^2$	---	---	$0.12/$km^2$	---

1. Hourly rate increases with reduced total aircraft usage.
2. 1990 option 3 covers the greatest area at the lowest cost.

8. SUMMARY AND CONCULSIONS

In the foregoing sections we have reviewed the technical merits of sensors, platforms and communications alternatives for an ice information system, we have analysed the financial implications of some optional combinations. The analysis is based on the assumption that a baseline requirement of daily coverage of ice-frequented waters to 25 metre spatial resolution over a strategically important area will be valid, on average, even if significant variations occur in both areal coverage, spatial resolution and repetition frequency. Current AES experience show that such variations due to major changes from one year to the next in ice conditions do occur but the average requirement is reasonably predictable. To this must be added the learning experience for the first few years of year-round Arctic Shipping.

Over the next decade real improvements in the credibility of ice and ocean models and environmental forecasting techniques will change the nature of the data required to run these models. It should not be supposed however that a successful ice or ocean model will require less routine data - the converse may be true. However, the frequency/area/resolution equation may alter drastically in the direction of more area, low resolution in general with specificly limited high resolution data, and less frequency.

Recalling that the optimum sensor package provides measurement on a target of more than one physical parameter, that combined sensors can feature high inherent discrimination among targets, and targets and background; that all-weather, day-night operations is mandatory; that areal coverage and swath widths bear directly on cost and speed-of-collection;that steady improvements are being made and will continue to be made in sensor reliability, sensitivity, resolution, and area coverage, it is concluded that an active microwave sensor in combination with a true passive microwave sensor is the best sensor mix for detecting and delineating MY, FY, water, ridges and, insofar as is feasible, icebergs. An imaging radar and a scanning microwave radiometer are two sensors that provide the best complementary combination of spatial resolution and swath. Multifrequency performance is not practical in a radar but is recommended in the radiometer. Dual polarization capability is desirable in both. The airborne radiometer would include operation at 90 GHz, the satellite radiometer would include a 37 GHz channel.

When compared one with the other, a scanning microwave radiometer and imaging radar have reversed coverage capability on an aircraft and a satellite. On an aircraft a radiometer scanning $\pm 50^{\circ}$ to the side of the nadir line covers a swath somewhat larger than twice the aircraft altitude, while an imaging radar has sufficient power to cover a swath up to 200 km but leaves a radar 'hole' approximately $\pm 45^{\circ}$ about the nadir. In the 5° region of overlap the two sensors complement each other as is desired. Increased scan from the radiometer (beyond 50°) would be possible but at the expense of progressively stronger interference from side-lobes on the antenna. On a satellite, a radiometer scanning ±50° can cover swaths ranging from 1100 to 1500 km depending on the satellite altitude, whereas an imaging radar is restricted by practical considerations of power and signal-handling requirements to swaths in the order of 200 km. The radiometer therefore overlaps the radar swath completely. In essence, the radar provides high-resolution data from an active sensor along a 20% strip of the scanning microwave radiometer swath.

Possible secondary sensors for a satellite include pseudo-passive high-resolution visual and infrared scanners, passive thermal scanners for the far infrared bands, a microwave altimeter and a scatterometer. Were it not for its limitations to clear weather operation, an infrared thermal scanner would be an acceptable second sensor by virtue of its superior resolution when compared to a microwave radiometer (1 km versus 20 km). Possible secondary sensors for an aircraft are a camera (assumed to be included unless there are compelling reasons for deleting it), a laser profilometer, and a passive infrared scanner which complements the 90 GHz microwave scanner in clear weather. The order of preference would be dictated by the particular range of application being considered. In an airborne platform of the size being considered for year-round reconnaissance, a redundant sensor complement may be cost-effective because it can be adopted to a variety of missions.

To the extent that the financial data presented here holds true in the future, the choice of platforms for ice reconnaissance for well defined, limited areal coverage can be weighted in the direction of the preferred technology and the user requirements. Cost differences, though significant, are not as compelling as might be imagined intuitively whereas intangibles such as aircraft logistics or the inflexibility of satellite coverage may affect the effectiveness of an ice reconnaissance operation in unforeseen, and prolonged, manners. For wide-area coverage, cost comparisons weigh heavily in favour of a satellite system because its coverage; the cost of moving the data to users though significant is still in the nature of an incremental cost increase.

On the basis of what has been learned in this study with respect to sensors, platforms, user requirements, communications, and price, a mixed satellite/aircraft system offers the best performance for a number of specific ice-reconnaissance requirements, coupled with the greatest potential for acquiring data over vast areas. Moreover, it offers the greatest flexibility which is a virtue, recognizing the learning that will occur during the early phases of full, year-round tanker operation. Both the all-aircraft solution and the all-satellite solution have unique limitations that are well-mitigated when combined in a mixed system. By the turn of the century, assuming continued growth in reliability, complexity and numbers of satellites, primary dependence on satellites with supplementary input from aircraft is the most probable outlook. Such a system would still be 'mixed' in the strictest sense but satellite data would have emerged as the backbone of the ice information system.

* * *

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APPENDIX I

SYSTEM OPTIONS

- Present-to-1985
- 1990, OPTION 1
- 1990, OPTION 2
- 1990, OPTION 3

PRESENT - TO - 1985 SYSTEM: PLATFORMS AND COVERAGE

LIMITED OPTIONS

Platforms

- 2 aircraft for ice reconnaissance;
- One additional aircraft possible for iceberg patrol;
- LANDSAT;
- U.S. Weather Satellites - NOAA, DMSP (may be possible after 1984 launch);
- Gradually move to high-altitude (6 km flying altitude).

Coverage*

Assuming 2400 hrs of flying annually, 90% on site and 95% successful coverage for every hour flown on location, areal coverage is 94,000,000 km^2 per year.

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* Assumes 100 km swath and 460 km/hr (250 knots) velocity.

PRESENT - TO 1985 SYSTEM DEVELOPMENT: SENSORS

Satellite	Aircraft
• AVHRR* • MSS* • Thematic Mapper • SMMR** • SSM/I (DMSP)**	• SLAR • 90 GHz scanning radiometer • Prototype SAR (2X50 km swath) • Laser Profilometer • Scatterometer (for research) • PRT-5 Fixed-beam IR radiometer (PRT-5) • Camera • Infrared line scanner (backup to microwave scanner) • Limited visual
*Daylight, clear-weather coverage of ice features, high and medium resolution. **Day/night, all-weather, low resolution sensors.	All-weather coverage of all five features: water, FY ice, MY ice, ridges, icebergs.

PRESENT - TO - 1985 SYSTEMS DEVELOPMENT: COMMUNICATIONS

Imagery

- VHF downlinks aircraft to offshore, to private and gov't Ops centres and small number (3) of ANIK up-linking sites, 2 Arctic, 1 Maritime;
- Trial R/T transmission of raw imagery in real time from 3 VHF receiving sites to IIC via ANIK;
- Trial annotated imagery, IIC to AES intermediate processors and Ops centres via Common carrier in digital and analogue format.

Charts

- Hard copy broadcast on HF FAX;
- Hard copy via common carrier FAX to Ops centres and offshore;
- Computer-generated charts via common carrier FAX to small computer terminal printers.

PRESENT - TO - 1985 SYSTEM: ANNUAL COSTS

AIRCRAFT

Platform: 2 X 1200* X $4000	$9,600,000
Sensors: 2 X 1200 X $1000	$2,400,000

Satellites

Quick look LANDSAT imagery	$ 150,000**
NOAA/NIMBUS imagery	N/C

Communications

NIMBUS, DMSP (estimated)	$ 100,000
Aircraft VHF	$ 100,000
Common carrier imagery East and North to South and South to North and East 3 X 60,000 X 12	$2,160,000
Hard copy and Computer-generated charts via common carrier	N/C, GTA
Total per annum cost	$14,510,000

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* From AES TB submission, April, 1981 1200 hrs per aircraft annually.

** Includes U.S. royalty charge from mid-1982.

FEATURES OF FINAL 1985 SYSTEM

PRO

- Meets minimum (current) requirement for coverage,
- Provides improved products;
  - more reliable radar, high resolution with wide scan;
  - scanning radiometer;
- all-weather, day/night operation of primary sensors;
- improved turn-around of radar imagery through IIC to clients;
- improved global inputs for ice dynamic models (SMMR and SSM/I);
- Fast, reliable automated analysis of microwave radiometer data may be possible.

CON

- Significant increase in areal coverage not possible without more aircraft.

Summary: Satisfactory for the particular set of tasks envisaged. Limited in capability to provide additional coverage. Technology: satisfactory; scope of operations: acceptable. Cost per unit area = $0.15 per sq. km.

1990 SYSTEM: PLATFORMS AND COVERAGE

OPTION I

Platforms

5 aircraft
NOAA weather satellites
ERS-1
SPOT
DMSP
Japananese resource satellite with a SAR.

Coverage

6500 hrs. flying on station required. Add 500 hrs. (approximately 10%) for ferrying time for total required flying time of 7000 hrs.

Nominal areal coverage at 95% success is 284,000,000 km^2.

200 additional hours available July - December when aircraft are lightly tasked.

1990 SYSTEM: SENSORS

OPTION 1

Aircraft	Satellite
. SAR, 2 X 50 km swath; . 90 GHz scanning microwave radiometer; . Laser Profilometer; . Microwave scatterometer; . Fixed-beam IR radiometer (PRT-S); . Camera; . Infrared line scanner; . Limited visual.	. SAR (80 km swath); . Altimeter; . SSM/I; . AVHRR; . Push Broom Visible/IR Scanner.
All ice features covered.	. Daylight, clear-weather coverage of ice features. . SSM/I give all-weather day/night low resolution coverage. . SAR gives limited-area coverage of all ice features.

1990 SYSTEM: COMMUNICATIONS

OPTION 1

Imagery

- VHF in each A/C to offshore, ANIK uplink sites*, and coastal Ops centres;
- ANIK North and East to South link 10 circuits;
- Annotated and analog imagery from IIC to AES IPs and UPs, common carrier.

Charts

- Common Carrier FAX IIC to IPs and UPs;
- HF/FAX broadcast to users;

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* Might be replaced by direct aircraft to IIC circuit via M-SAT.

1990 SYSTEM: ANNUAL COSTS

OPTION 1

Aircraft subsystem

7000 X 4000 for aircraft	$28,000,000
7000 X 1000 for sensors	$ 7,000,000
VHF 5 X 25,000	$ 125,000

Satellite imagery

SPOT	$ 150,000
ERS (estimated)	$ 300,000
DMSP	N/C
NOAA	N/C

Communications

DMSP (estimated)	$ 100,000
Raw imagery, North and East to IIC, 10 X 60,000 X 12*	$ 7,200,000
Annotated imagery, IIC to North and East, same links*	$ N/C
Total annual cost	$42,375,000

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* M-Sat might replace VHF/ANIK links at lower cost and less complexity.

1990 SYSTEM: OPTION 1 FEATURES

PRO

- Meets minimum requirement for all-weather (Note 1) day/night system;
- Limited complementary global coverage from ERS-SAR and DMSP-SSM/I;
- SSM/I input to ice models;
- reserve capability in aircraft.

CON

- Possible offshore purchase of 3 large aircraft;
- Dependence on foreign satellites for radar imagery;
- Extensive R/T transmission of aircraft radar and radiometer imagery is complex and hence prone to system outages;
- Possible major price increases for foreign data products.

Summary

Technologically sufficient for the minimum requirement with some reserve. Cost per unit area = $0.15 per km^2.

Note 1: Assumes aircraft logistics are such that an aircraft can, even under severe environmental conditions, be deployed for ice reconnaissance in a specific problem area.

1990 SYSTEM: PLATFORMS AND COVERAGE

OPTION 2

Platforms

- 2 Aircraft
- Canadian RadarSat
- ERS
- SPOT
- NOAA
- LANDSAT
- DMSP

Coverage

- Assume 1982-85 level of 2400 hrs. flying reduced to 2,000 hours because of RadarSat coverage.

- Assume same areal coverage as in 1990 option 1, i.e. 284,000,000 sq. km, of which 79,000,000 km^2 is by aircraft and 205,000,000 km^2 is by satellite.

1990 SYSTEM: SENSORS

OPTION 2

AIRCRAFT

- SAR;
- Scanning microwave radiometer;
- Laser Profilometer;
- Microwave scatterometer;
- Fixed-beam IR radiometer (PRT-S);
- Camera;
- Infrared line scanner;
- Limited visual.

SATELLITE

- SAR (Canadian)
- Microwave Radiometer (Canadian);
- Scatterometer (Canadian) for oceans;
- AVHRR;
- SPOT;
- SAR (ERS);
- SSM/I (DMSP).

1990 SYSTEM: COMMUNICATIONS

OPTION 2

IMAGERY

- Aircraft VHF downlink to offshore, ANIK uplink sites in Maritimes*, and OPS centres;
- Raw imagery from RadarSat earth station to IIC via common carrier (ANIK);
- ANIK East to South links - 2 circuits**;
- Annoted digital and analogue imagery from IIC to AES IPs and UPs common carrier.

ICE CHARTS

- Common Carrier FAX IIC to IPs and UPs;
- HF/FAX broadcast to users;

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* Assume satellite covers Arctic, aircraft covers East Coast south of 68°.

** Could be replaced by M-SAT circuits.

1990 SYSTEM: COSTS

OPTION 2

Aircraft c/w sensors	
2000 X $4400* aircraft	$ 8,800,000
2000 X $1100 sensors	$ 2,200,000
VHF 1 X 25,000	$ 25,000
RadarSat imagery	
206,000,000 km^2 X $0.10	$20,600,000
Microwave Radiometer data (estimated)	$ 100,000
SSM/I data	N/C
ERS/SAR	$ 300,000
SPOT	$ 150,000
Communications	
SSM/I (estimated)	$ 100,000
East to South raw imagery** 2 X 60,000 X 12	$ 1,440,000
South to East annotated imagery, same circuits	$ N/C
South to North, annotated** imagery, 2 X 60,000 X 12	$ 1,440,000
RadarSat earth station to IIC imagery, estimated	$ 1,000,000
FAX charts	$ N/C
Total annual cost	$36,155,000

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* Price per hour goes up as contracted hours go down.

** M-Sat circuits would be more reliable and less expensive.

1990 SYSTEM OPTION 2 FEATURES

PRO

- Good coverage of ice features.
- Highly flexible, aircraft is undercommitted.
- Satellite has huge coverage reserves for ice and oceans reconnaissance, at modest incremental cost.
- Wide-area data from satellite under Canadian control brings fringe benefits.
- Satellite SAR imagery superior to aircraft for detecting water and ice types because of steeper viewing angle;
- Satellite coverage of land areas permits cost-sharing;
- Low-resolution, direct, telemetry of RadarSat imagery to ships etc. is unique and exportable if it can be implemented.
- Avoid cost of (possible) new foreign aircraft.

CON

- Satellite coverage of ridges and icebergs less reliable than aircraft coverage;
- C-Band satellite imagery inferior to X-Band aircraft imagery;
- Cant't develop slowly - RadarSat is a large quantum decision.

PRICE

Imagery cost is \$0.13 per km^2.

Summary: System meets requirements with large reserve coverage capability.

1990 SYSTEM, PLATFORMS AND COVERAGE
OPTION 3

- Ad Hoc Aircraft Support
- Canadian RadarSat
- ERS
- SPOT
- NOAA
- DMSP

Coverage

- Two 8-hour flights per week, 52 weeks per year for a total of 832 hours. Aircraft support is short-term contract from industry.

- Emergency support from CCRS and private sector.

- Assume Satellite covers 251,000,000 km^2 annually. Aircraft covers a 33,000,000 km^2, assuming 90% on-site time and 95% on-site success.

1990 SYSTEM: SENSORS

OPTION 3

Aircraft (Note 1)

- SAR, 2 X 50 km swath;
- 90 GHz scanning microwave radiometer;
- Laser Profilometer;
- Microwave scatterometer;
- Fixed-beam IR radiometer (PRT-S);
- Camera;
- Infrared line scanner;
- Limited visual.

Satellite

- SAR (Canadian)
- Microwave Radiometer (Canadian);
- Scatterometer (Canadian) for oceans;
- AVHRR;
- SPOT;
- SAR (ERS);
- SSM/I (DMSP).

Note 1: A full complement of sensors might not be available on aircraft under short-term lease.

1990 SYSTEM: COMMUNICATIONS

OPTION 3

Imagery

- VHF A/C aircraft downlink to offshore sites and Ops Centres, No R/T to IIC.
- Raw imagery RadarSat earth station to IIC, Common carrier (ANIK);
- Annotated analog and digital imagery via Common carrier (ANIK) IIC to AES IPs and UPs.

Ice Charts

HF FAX broadcast mode,
Common Carrier FAX IIC to IPs and UPs.

1990 SYSTEM: ANNUAL COSTS

OPTION 3

Aircraft C/W sensors

832 X $5000 aircraft	$ 4,160,000
832 X $1000 sensors	$ 832,000
1 VHF	$ 25,000

Satellite data

• RadarSat imagery 251,000,000 X $0.10	$25,100,000
• Radarsat Radiometer data included with radar imagery	
• SSI/M data	N/C
• ERS/SAR imagery	$ 300,000
• SPOT imagery	$ 150,000

Communications

SSI/M to IIC	$ 100,000
RadarSat earth terminal to IIC	$ 1,000,000
IIC to IPs and UPs, North and East 3 X 60,000 X 12	$ 2,160,000
TOTAL	$33,827,000

1990 SYSTEM OPTION 3 FEATURES

PRO

- Good coverage with large reserves.
- High quality, consistent, RadarSat data sets are more useable.
- Greatly increased coverage is obtained at modest incremental increase in cost as satellite utilization increases.
- Cost-sharing with other users of RadarSat data.

CON

- Incomplete daily coverage to high resolution south of 68°.
- Satellite radar less reliable than aircraft for detecting ridges and icebergs.
- C-band satellite imagery inferior aircraft to X-band imagery.
- Dependency on short-term contracts for ad hoc aircraft support.
- Private non-dedicated, aircraft support may lack complete complement of sensors (e.g. scanning radiometer).
- Can't develop slowly-RadarSat is large quantum decision.

PRICE

- Price per unit area is \$0.12 per km^2.

Summary: Meets compromise (resolution) requirement south of 68°.