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SURVEY OF ICEBERG SENSING BY SATELLITE IMAGERY

Annex I of Cost and Operational Effectiveness Analysis for Selected International Ice Patrol Mission Alternatives

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FINAL REPORT

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16. Abstract

This report is Interim Report Volume 9 for the Cost and Operational Effectiveness Analysis for Ice Patrol Mission Analysis Study. The International Ice Patrol has effectively used airborne surveillance, both visual and radar based, to detect, identify, and classify icebergs. With advancing satellite technology, there is the expectation that some satellite resources are or will become available that will provide a frequent, reliable look at the IIP area and be able to detect icebergs, thereby obviating the need for costly airborne surveillance. The survey of satellite platforms that would offer potential assistance in this report all led to the potential for RADARSAT as being the best candidate. The ICEC evaluation to date indicates that RADARSAT will not be useful except for detection of large icebergs. That capability has potential use for IIP for early detection of upstream icebergs. The IPAP image enhancement process developed by SAIC may yield better detection probabilities.

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METRIC CONVERSION FACTORS

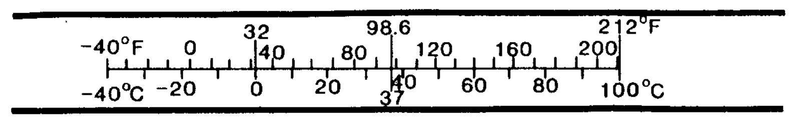
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (WEIGHT)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (EXACT)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly).

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (WEIGHT)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	0.125	cups	c
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (EXACT)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



SURVEY OF ICEBERG SENSING BY SATELLITE IMAGERY

ABSTRACT

The International Ice Patrol has effectively used airborne surveillance, both visual and radar based, to detect, identify, and classify icebergs. With advancing satellite technology, there is the expectation that some satellite resources are or will become available that will provide a frequent, reliable look at the IIP area and be able to detect icebergs, thereby obviating the need for costly airborne surveillance. The survey of satellite platforms that would offer potential assistance in this report all led to the potential for RADARSAT as being the best candidate. The ICEC evaluation to date indicates that RADARSAT will not be useful except for detection of large icebergs. That capability has potential use for IIP for early detection of upstream icebergs. The IPAP image enhancement process developed by SAIC may yield better detection probabilities.

INTRODUCTION

Objective.

The International Ice Patrol has effectively used airborne surveillance, both visual and radar based, to detect, identify, and classify icebergs. With advancing satellite technology, there is the expectation that some satellite resources are or will become available that will provide a frequent, reliable look at the IIP area and be able to detect icebergs, thereby obviating the need for costly airborne surveillance. The purpose of this report is to review existing and anticipated satellite sensors to determine whether there is a role for satellites in IIP operations.

Background.

In reviewing possible uses of satellite data, it is important to recall the basic performance requirements for such data collection. Clearly, accuracy and reliability of the data source and the resulting data is essential. Another important consideration is the timeliness of the data. With the existing models, IIP operates essentially on a two week data refresh rate. Of course, the use of the models impose an unknown amount of uncertainty. In an ideal world, one would be able to take a complete snapshot of the IIP area perhaps daily and that image would be the information distributed to the mariner. Forseeably, one could transmit the location of every known iceberg rather than the Limits of All Known Ice. The older the data, the more one has to avoid providing specific iceberg positions. If a satellite system were to be useful, IIP would probably require updated information at least weekly. The model uncertainty would probably justify that.

Moreover, the the capability existed, it would be prudent to obtain the more frequent information. Of course, acquisition and processing costs are another important factor to be considered. Finally, if satellite sensed data were to replace airborne surveillance data, the satellite would have to achieve probabilities of detection for all types of icebergs that are roughly equivalent to that generated by existing methods.

OPERATIONAL COMMERCIAL SATELLITES

Current Satellite Systems.

Commercial satellite systems are the possible candidates for use by the IIP. In responding to a request for a plan to manage the IIP, the National Ice Center noted that their access to National Technical Means Data would be available to the IIP and in 1995, had established a mechanism to provide any iceberg sighting data that would be available. Historically, there has been little data transferred.

Satellites use various technologies to acquire images. Many of these approaches are visual or infrared and require good visibility, a condition often absent on the Grand Banks in the IIP operating area. Generally speaking, only satellites that have a Synthetic Aperture Radar (SAR) sensor will be capable of providing the all weather capability that IIP needs.

The Office of Technology Assessment (1994) recently completed a study of commercial satellite remote sensing systems. OTA concluded that the United States has not yet made the commitment to ocean monitoring outside of meteorological applications. Other entities (e.g., the European Space Agency, Japan and Canada) are becoming the primary source of data for research and operations. Table 1, taken from that study, lists current operational commercial satellites.

Based on function, only ERS-1 would have potential application. ERS-1 is a C-band (VV polarization) SAR sensor. It has reasonable ground resolution of approximately 30 m, but it has a small swath width of 80 km. The satellite has had a number of different "mission phases," each with different orbital characteristics. In its "ice phases," ERS-1 has an orbital repeat period of 3 days but with substantially less than 100% coverage.

Table B-2 in Office of Technology Assessment (1994) lists 35 satellites that are planned through 2002. Of those, there are three that have the potential capability of assisting with icebergs: ERS-2, ENVISAT-1, and RADARSAT. Of these, only RADARSAT has the desirable orbital characteristics.

Table 1: Operational U.S. and Foreign Remote Sensing Platforms (OTA, 1994).

Platform	Country	Year	Function
Landsat 4	United States	1982	Land remote sensing
Landsat 5	United States	1984	Land remote sensing
NOAA-11	United States	1988	Meteorology (polar)
NOAA-12	United States	1991	Meteorology (polar)
GOES-7	United States	1987	Meteorology (GEO)
GOES-8	United States	1994	Meteorology (GEO)
UARS	United States	1991	Atmospheric chemistry
SPOT 1	France	1986	Land remote sensing
SPOT 2	France	1990	Land remote sensing
SPOT 3	France	1993	Land remote sensing
Meteosat 3	Europe	1988	Meteorology (GEO)
Meteosat 4	Europe	1989	Meteorology (GEO)
Meteosat 5	Europe	1991	Meteorology (GEO)
Meteosat 6	Europe	1993	Meteorology (GEO)
ERS-1	Europe	1991	SAR and ocean dynamics
TOPEX/Poseidon	United States/France	1992	Ocean dynamics
GMS-4	Japan	1989	Meteorology (GEO)
MOS-1b	Japan	1992	Land and ocean color
JERS-1	Japan	1992	SAR and land remote sensing
IRS 1a	India	1988	Land remote sensing
IRS 1b	India	1991	Land remote sensing
INSAT IIa	India	1992	Meteorology (GEO) and telecommunications
INSAT IIb	India	1993	Meteorology (GEO) and telecommunications
Meteor 2	Russia	1975 (series)	Meteorology (polar)
Meteor 3	Russia	1984 (series)	Meteorology (polar)
Okean-0	Russia	1986 (series)	Ocean
Resurs-O	Russia	1985 (series)	Land

Current Ice Detection Uses.

The Ice Centre Environment Canada (ICEC) has a major responsibility for forecasting the location of sea ice off the Canadian coast and has a significant capability for processing satellite imagery. ICEC currently uses ERS-1 and NOAA AVHRR images in its sea ice program. The AVHRR images are infrared and hence dependent on visibility.

The AVHRR swath width is 2700 KM with a resolution of 1.1 x 1.1 km. Clearly, even without clouds, AVHRR would not provide a reliable means of detecting icebergs. The ERS-1 has much better resolution, but its 3-day cycle is not sufficient for providing timely information for forecasting. The all weather capability of ERS-1 is a valuable supplement to visibility limited AVHRR images. To date, ICEC has not used either data sources for routinely identifying icebergs.

FUTURE COMMERCIAL SATELLITES

RADARSAT.

The most promising satellite for iceberg detection is RADARSAT, now scheduled for launch in mid-late 1995, that will be operated by the Canadian Space Agency. RADARSAT is intended to provide all weather coverage of the Canadian ice covered waters to facilitate ice forecasting for shipping. RADARSAT has eight imaging modes. ICEC intends to primarily use the ScanSAR(Wide) mode with a swath width of 500 km and resolution of 100m. The finest resolution of 12x9 m is provided by the Fine Res mode with a 45 km swath width. The RADARSAT program is described in Appendix I which includes a full description of the various modes.

In the ScanSar(Wide) mode, RADARSAT will have a difficult time meeting the spatial sampling requirements and detect all types of icebergs. In the FinRes mode, it will be difficult to meet temporal sampling requirements and provide the coverage needed with a 45 km swath. The ICEC has concluded that the ScanSAR(Wide) mode will not be able to detect icebergs on a regular basis. It is possible that RADARSAT may provide early imaging of large icebergs upstream. To date, no one has explored the possibility of using a finer resolution mode.

Image Processing and Enhancement.

Recently, SAIC has developed a computer-based image analysis system named IPAP (ERS-1 Pilot Application Project for Polar Operations) that is designed to take ERS-1 SAR images and produce a range of data products to serve the needs of the polar community (Hodson and Parkington, 1994) [included in Appendix II.] One of the identified needs is detection and identification of icebergs requiring 5m resolution. SAIC has prepared an image analysis using ERS-1 data (with nominal pixel resolution of 100m) that yields a POD of 1 for large icebergs, 0.89 for medium icebergs, and 0.44 for small icebergs (Hodson and Parkington, 1994). The probabilities were computed by comparing the IPAP detections with IIP reports of iceberg positions. The numbers of icebergs considered is not included in the report. Moreover, the image presented includes many more detections than icebergs. Whether these are ships, false alarms, or undetected icebergs is an open question and part of the reasons for further evaluation. SAIC is participating in BERGSEARCH '95 to evaluate the IPAP system. The experiment is scheduled for April-May, 1995 when ERS-1 is favorably located with respect to the experimental area. IIP will provide ground truth through an ICERECDET sortie.

Application to RADARSAT.

If the experiment is successful and IPAP is able to generate reasonable images of iceberg locations using ERS-1 data, at least for large icebergs, there is a reasonable chance that such a system may be productive with RADARSAT images. A partnership agreement with Canada to process their RADARSAT images and provide the analysis results may provide a means to reduce surveillance requirements. If such a capability develops, it is important to identify the required frequency of the product. At present, the Coast Guard has indicated a need for weekly RADARSAT images. This approach would retain a strong reliance on the models. A more frequent update would put more emphasis on near real time information and reduce the dependence on the models.

Small Commercial Satellites.

Recently, the U.S. government authorized the commercial sale of high resolution satellite imaging services that had previously been restricted for national security reasons. International competition has drawn many U.S. firms into this market. A sampling of capability based on a telephone survey follows.

Spot Image Corporation. They have three commercial satellites in orbit now and plan to launch one more in a year and two more in three to four years. All of their satellites have optical coverage only. Their revisit rate is poor at the desired latitudes.

CTA Space Systems. CTA is building a satellite for NASA that will have imaging capability to 3 meters in the optical range. They may add IR sensors, but it will not be of much use for IIP.

Orbital Sciences Corporation. OSI plans to launch SEASTAR in May, 1995 as part of the NASA Mission to Planet Earth. Data is received in eight visual and near IR bands with 1.1 km resolution at nadir. OSI is part of a consortium that will launch EYEGLAS in 1997. EYEGLASS will have 1-3 meter resolution in panchromatic multispectral imagery. It will be in polar orbits with a two day or better revisit to the IIP area.

Based on this sample and discussions with the experts, there was general agreement that RADARSAT is the only vehicle that might have application for IIP in the near future.

SUMMARY AND CONCLUSIONS

The survey of satellite platforms that would offer potential assistance all led to the potential for RADARSAT as being the best candidate. The ICEC evaluation to date indicates that RADARSAT will not be useful except for detection of large icebergs. That capability has potential use for IIP for early detection of upstream icebergs. The IPAP image enhancement process developed by SAIC may yield better detection probabilities..

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Hodson, W. R. and K. C. Parkington, 1994, "IPAP: A System for Polar Operations Management Using ERS-1 SAR Data," unpublished paper, SAIC, Cambridge.

Office of Technology Assessment, 1994, *Civilian Satellite Remote Sensing: A Strategic Approach*, OTA, Washington, DC.

Appendix I. Background Information on the RADARSAT Programme

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BACKGROUND INFORMATION ON

THE RADARSAT PROGRAMME

Extracted from the RADARSAT
Benefit Analysis Study
for Ice Centre, Environment Canada,
12 November 1991,
Prepared by Noetix Research Inc.

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- SECTION TWO -

RADARSAT PROGRAMME

In this section, a description of the RADARSAT programme is provided and will serve as the baseline for the analysis of ICEC data requirements in Section Three. Information on the RADARSAT programme was extracted from the RADARSAT Mission Requirements Document (MRD), RSI/CSA/EMR MOU, International MOU, an overview paper by K. Raney, and meetings with RADARSAT project personnel. When facts from the sources conflicted, the specification outlined in the RADARSAT Mission Requirements Document was chosen. The MRD serves as the high level document for the development of RADARSAT and defines the baseline requirements adopted by the programme.

It should be noted that the MRD was provided to Noetix Research by the RADARSAT Project Office in a draft form and is awaiting approval by the CSA.

The programme description will begin with a general introduction into the mission objectives and will be followed by a discussion on the three RADARSAT subsystems :

1) spacecraft,
2) ground segment, and
3) mission operations and management.

2.1 The Mission

The purpose of RADARSAT is to provide global SAR data products to government, commercial, international and scientific users of remotely sensed data. Applications identified for its use are :

- environmental monitoring
- sea ice (ICEC)
- selected portions of the globe for crop forecasting
- global stereo coverage for geology
- obtain complete coverage of Antartica
- collect time and site specific data to support approved research and application demonstration studies sponsored individually or by IMOU partners.
- collect time and site specific data to support experiments by IMOU partners through an Experimental AO.
- collect and make available global data to any perons

It is anticipated that RADARSAT will be launched into a sun-synchronous orbit in the latter part of 1994 or early 1995 using a medium class expendable vehicle (McDonnell Douglas Delta II 7920-10) from Vandenburg AFB, U.S.A. [Raney, 1990]. Immediately after the launch, RADARSAT will enter a commissioning phase and is expected to span 3-4 months. After this period, it will become operational and is designed to operate for a minimum of 5 years.

RADARSAT will have an inclination of 98.549 degrees and orbit altitude of 797.9 km. These flight characteristics result in 14 7/24 orbits per 24 hour period, or a period of 101 minutes, with a repeat orbit of 24 days and a primary subcycle of 3 days (Table 2.1) [McNally,1991].

A unique aspect of RADARSAT is its dusk to dawn orbit. The ascending pass will cross the equator at 1800 local time, continue northward to a maximum of 81.4 degrees latitude, then track southward (descending pass) and cross the equator on the other side of the Earth at 0600 local time. It descent over the southern hemisphere takes the satellite over Antarctica and back to the equator where the cycle starts again. In the northern hemisphere, RADARSAT will have constant solar illuimination and therefore, the capability to image on both ascending and descending passes. No eclipse will be experienced over Canada and the ice areas of interest to ICEC.

In normal operation, the SAR is oriented to the north side of the orbital plane to provide complete coverage over the Arctic, including the pole [Raney,et. al., 1991]. However, an area centred on the south pole will not be imaged because the SAR will point in the opposite direction.

The launch is provided by NASA, free of charge, in exchange for data coverage of the entire continent of Antarctica. In order to map Antarctica, a special in-orbit 180° yaw maneouver will be required to reorient the satellite. The maneouver will take place twice during its mission - once during the winter and other in the summer. These maneouvers will occur during the periods of maximum and minimum sea ice formation. Each maneouver will not be less than two weeks in duration and will occur within the first two years of the mission. [McNally,1991]

TABLE 2.1 <u>ORBITAL SPECIFICATIONS:</u>

Altitude	797.9 km
Geometry	Sun-synchronous
Ascending node	1800 hrs
Descending node	0600 hrs
Inclination	98.6°
Period	100.7 minutes
Repeat cycle	24 days (343 orbits)
Orbits per day	14 7/24

2.2 Spacecraft

RADARSAT will weigh 3200 kg and carry a single sensor, C-band (5.3 GHz) SAR with HH transmit and receive (Table 2.2) [McNally,1991]. The sensor will operate in eight modes and have the capabiity to obtain data over a range of incidence angles from 20-50 degrees as shown in Table 2.2 and Figure 2.1.

The SAR will be capable of performing 6 data takes per orbit with a minimum on-time of 1 minute and a maximum of 15 minutes with a goal of 20 minutes on a single orbit.

The spacecraft is being procured from Ball Aerospace (U.S) while SPAR Aerospace (Can) has the prime responsibility for the radar system under a contract with the Canadian Space Agency. [Raney,et. al., 1991] Subcontractors will include CAL Corporation and COMDEV

Limited.

Two recorders will be on-board the spacecraft. Each recorder will be able to store a minumum of 10 minutes of SAR data with a design goal of 15 minutes. The recorders will playback the data when the satellite is within the direct line-of-site of a ground receiving station at a minumum rate of 85 Mb per second with a goal of 105 mb/sec. The image quality will comparable to the real-time downlink data. Recording and playback are possible without operational restrictions [McNally,1991].

TABLE 2.2 SPACECRAFT SPECIFICATIONS

Spacecraft mass	2750 kg
Antenna size	15 m by 1.5 m
Solar array	3.4 kW

IMAGING/SAR SPECIFICATIONS

Frequency	5.3 GHz
Wavelength	5.6 cm
Polarization	HH
Accessibility Swath	500 Km
Swath Incidence Angles	20 - 50
Extended Incidence Angles	10-20, 50-60
Minimum detectable signal	-18 dBm2
RF bandwidth	11.6, 17.3 or 30.0 MHz
Sampling rate	12.9, 18.5 or 32.2 MHz
Transmit pulse length	42.0
Pulse repetition frequency	1270 - 1390 Hz
Transmitter peak power	5 Kw
Transmitter average power	300 W (nominal)
Maximum on time	28 min per orbit

TABLE 2.3 **IMAGING MODES:**

Mode	Resolution[1]	Looks[2]	Swath Width (km)	Incidence angle[3] o	Pixel size (m)	bits/ pixel
Standard	25 x 28	4	100	20-49	12.5x12.5	8-16
Wide (1)	48-30 x 28	4	165	20-31	12.5x12.5	8-16
Wide (2)	32-25 x 28	4	150	31-39	12.5x12.5	8-16
Fine Res	11-9 x 9	1	45	37-48	12.5x12.5	8-16
ScanSAR (N)	50 x 50	2-4	305	20-40	25x25	16
ScanSAR (W)	100 x 100	4-8	510	20-49	50x50	16
Extended (H)	22-19 x 28	4	75	50-60	n/a	n/a
Extended (L)	63-28 x 28	4	170	10-23	n/a	n/a

[1] Nominal; ground range resolution varies with range.
[2] Nominal; range and processor dependent.
[3] Incidence angle depends on sub-mode.

(after Raney et al & McNally)

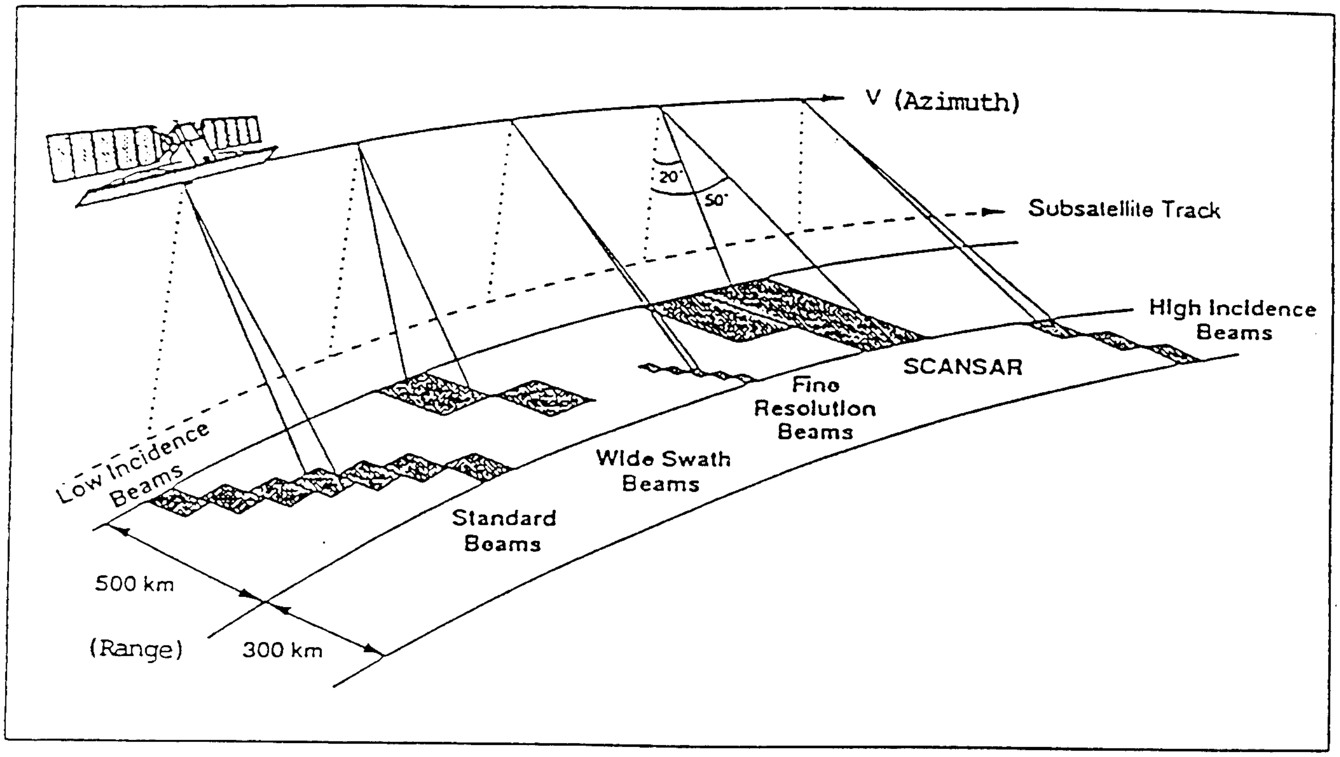

Figure 2.1 RADARSAT modes of operation.

2.3 Ground Segment

The ground segment has the responsiblity for the management of RADARSAT mission, including the : control and operation of the spacecraft, communication with the spacecraft, reception of data, transfer of raw data to the processing facilities, reception and handling of user requests, processing and archiving of data, maintenance and cataloguing of data and calibration of the data.

The central element to the ground segment is the Mission Control Centre (MCS) which includes the : Mission Management Office (MMO), Mission Control Facility (MCF), and the Telemetry, Tracking & Control Facility (TTCF).

The MMO will be responsible for all executive and administrative matters to ensure the mission objectives and requirements are met. RISC (RADARSAT Information Scheduling and Cataloguing) is the front end of the MMO and interacts with other elements of the ground segment. Its prime responsiblities will be to prepare an acquisition plan from data requests submitted to CODD from government, RSI and foreign users. This plan is then incorporated into the satellite operations schedule by the MCF. A daily schedule is uplinked by the TTCS to the spacecraft and downlink imagery received at the Data Reception Facilities (DRF).

At least two Canadian archives will exist and may reside with RSI, EMR, AES, and/or Provinces.

Ground Receiving Stations

In Canada, the SAR Data Reception Facility (DRF) will consist of the existing receiving stations located in Gatineau, Quebec and Prince Albert, Saskatchewan. Their primary function will be to follow the schedule produced by the MCF.

At the time of writing, the station at Prince Albert, Saskatchewan will only record data received at the station. **Consideration is being given to :**

a) a dedicated satellite microwave link between Prince Albert and the processor, and

b) **a separate quick look processor with a direct link to ICEC.**

Option (b) is possible because the cost of the processor is less expensive. However, no budget exists for the implementation of either option within the CSA or CCRS.

SAR data will be also be received at Fairbanks, Alaska as stipulated in the IMOU. A description of the facility is given in the next section.

It is expected that other foreign stations will receive RADARSAT data under the RMOU. Negotiations with foreign countries are ongoing and will not impact ICEC directly. However, regions outside of a station mask must be stored on the tape recorder.

Processing Facilities

In Canada, the MRD specifies that the SAR Data Processing Facility (DPF) will produce and dissimenate required SAR data products from data collected at Gatineau, Prince Albert, and perhaps from Fairbanks. The location of the facility is not identified, but will likely be located at the Gatineau receiving station since the ERS-1 processor is there.

Initially, the SAR processor will be designed to operate at 1/10 real-time (i.e. it will take ten minutes to process 1 minute of data collected by RADARSAT) with the option to upgrade to 1/4 real-time in the future.

There is a wide range of products available to users and are summarised in Table 2.4. Values in the column titled turnaround time were derived from the RADARSAT survey. It is interesting to note that ice (meaning ICEC) has the most stringent throughput requirement by a factor of 6.

Products targeted for ICEC, but not limited to, are the :

1. Georeferenced coarse resolution (100 meter resolution) for the standard, wide swath and high incidence modes.

2. ScanSAR georeferenced narrow (50 meter resolution)

3. ScanSAR georefenced wide (100 meter resolution).

NOTE: georeferenced refers to product whose earth locations are determined from orbit prediction data and are oriented in the geometry of the swath (along track and cross-track dimensions of the orbit, ground tracks marked by lat/long ticks).

The precision of the products are as follows [McNally,1991] :

- absolute location accuracy: <1500 m (without ground control pts), 750 m goal.
- within scene geometric accuracy for a 100 Km by 100 Km scene: <40 Km (relative, excluding terrain effects).
- radiometric accuracy within scene for a 100 Km by 100 Km scene: (<1 dB).
- radiometric accuracy scene to scene : during one orbit <1.5 dB (orbit to orbit variation); over 3 days <2 dB (variation over sub-cycle); over the satellite lifetime (<3 dB).

The radiometric accuracies stated above will require calibration of the SAR. This will be accomplished by an internal calibration of the SAR on spacecraft and external calibration devices on the ground [McNally,1991]. Internal references will provide relative calibration, but a quantitative comparison of RADARSAT imagery with other data will require cross-calibration using the external calibration sites to verify the antenna gain, beam shapes and steering. [Raney,et. al., 1991] **It is unlikely, however, that ICEC will be able to receive calibrated SAR data within specified the 4 hour turnaround time [Denyer, pers. comm, 1991].**

In addition to the Canadian stations, the Alaska SAR Facility (ASF) located in Fairbanks, Alaska and operated by the United States is capable of capturing RADARSAT data over the Arctic region. At present, ERS-1 data is processed on-site in the SAR Processing System (SPS) and stored in the Archive and Operations System (AOS). Special geophysical products can be genereated (i.e. ice motion and ice classification) in the Geophysical Processor System (GPS). However, this configuration is not meant to be real-time. In order to meet the timely requirements of the Joint Ice Centre (JIC) located in Suitland, Maryland, 30% of the 10 minutes of real-time imagery collected will be processed through a quick-look processor then held on disk for transmission to the JIC using the NOAA SARCOM satellite link. The MOU between the JIC and NASA states that the imagery will be made available at the SARCOM port within 6 hours of acquisition.

Quicklook ERS-1 imagery transmitted to the JIC will have a pixel spacing of 100 meters with a 240 meter resolution by performing an 8x8 block average of the full resolution data. The imagery will not be geocoded.

A link is also being established between the JIC and ICEC for the purpose of transferring imagery and products between the facilities. It is very possible that the network between the ASF, JIC, and ICEC could be used for RADARSAT.

Table 2.4. Data products from the Canadian Data Processing Facility (from McNally, 1991).

Product	Code	Spatial Resolution (m)	Pixel Size (m)	No. of Looks	Bits per pixel	Turnaround time
For standard, wide, fine resolution, and high incidence angle modes						
SAR Georefenced Full Res.	SGF	Table 2.3	12.5x12.5	Table 2.3	16	1-2 days (agr)
SAR System Geocoded	SSG	Table 2.3	12.5x12.5	Table 2.3	8	1-2 weeks (agr)
SAR Precision Geocoded	SPG	Table 2.3	12.5x12.5	Table 2.3	8	2-3 weeks
For standard, wide swath, and high incidence angle modes						
SAR Georeferenced Coarse Resolution	SGC	100x100	50x50	64	16	4 hrs (ice) 1-2 days (agr)
For ScanSAR modes						
ScanSAR (N)arrow modes	SCN	50x50	25x25	4	16	4 hrs (ice) 1-2 days (agr) 2-3 weeks (agr)
ScanSAR (W)ide modes	SCW	100x100	50x50	7	16	4 hrs (ice) 1-2 days (agr) 2-3 weeks (geol)

2.4 Data Ordering

The Canadian Order and Dispatch Desk (CODD) will be responsible for handling user requests. CODD will provide an on-line access to browse the catalogued acquisition plans, programs information and ordering. CODD will have two order desks : one for RSI (RODD) and the other for Canadian Government users (GODD).

Request for data from CODD are transferred to the MCS for filling. Then, the MCS schedules the spacecraft and ground receiving stations.

Data aquisition priority will be based on rules provided by MMO through the RISC. The SAR on time will be shared among NASA/NOAA, CSA, and RSI and incorporated into the acquisition plan. The scenario for scheduling is outlined in the MRD [McNally,1991] and is stated in full here because of its importance to ICEC:

A Systems and Operations plan covers 48 days and is prepared 24 days in advance and updated every day by the MMO. The plan will form the basis of the generation of the Spacecraft and Ground Segment Activity Schedule formulated one week in advance and released daily. These schedules are rationalised against the latest ground segment and spacecraft status to generate daily spacecraft command and reception schedules formulated 48 hours in advance. The implementation of the data acuisition will be frozen 48 hours in advance, except for environmental or system emergencies. However, the system will be repsonsive to the incorporation of new user requests until the weekly schedule is frozen (i.e. 7 days in advance).

2.5 Discussion

The dawn to dusk orbit of RADARSAT will expose the the solar arrays to constant sunlight and therefore, enable the SAR sensor to be turned-on over the Canadian ice areas at all times of the day or night. However, imaging can be inhibited by the design constraints of the spacecraft and the throughput requirements of ICEC are subject to a communications network linking the ground segment facilities.

The SAR on-board the spacecraft has a maximum on-time per orbit of 15-20 minutes and can turn-on/off, 6 times per orbit. Moreover, imaging is inhibited if the batteries are discharged or the power consumption reaches a threshold value. Areas outside of the station direct line-of-site must be stored on tape recorders and replayed when the satellite reenters the station mask. The recorders will store a maximum of 10-15 minutes of data.

The ability to receive SAR data in a timely manner at ICEC will rely on the simultaneous imaging and downlink of data to a ground receiving station and the communications network to transmit the raw data to the processor and products to ICEC. This network will also determine the geographic regions that can be monitored. Under certain circumstances, the recorder may be used in a supporting role to provide timely coverage over areas outside of the station mask.

All of these factors will determine the utility of the RADARSAT for ICEC.

Appendix II. IPAP: A System for Polar Operations Management Using ERS-1 SAR Data

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IPAP: A SYSTEM FOR POLAR OPERATIONS MANAGEMENT USING ERS-1 SAR DATA

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Abstract

Almost all polar operations are influenced to some extent or another by the prevailing sea ice environment. Navigation in polar waters is one obvious example of when this influence is extremely strong. The effectiveness of many polar operations is substantially increased by a knowledge of sea ice conditions in the area of interest.

There are various sources of sea ice information derived from satellite data. Until recently, all of these used sensors operating in visible or near infra-red wavebands. Such sensors cannot penetrate cloud cover and the data they produce thus has no value in the cloudy conditions which occur frequently at high latitudes. This is a serious obstacle to the popularisation of satellite-derived data products in the operator community - it is simply not possible for a ship's master to rely on a source of information that may or may not be available at any given moment. Synthetic aperture radar (SAR), on the other hand, is able to penetrate cloud and sea ice information derived from this source offers all-weather capability. This paper describes the development and application of a tool for polar operations management which uses SAR data from the ERS-1 satellite.

The IPAP system has been developed jointly between GEC-Marconi Research Centre, SAIC Science & Engineering Limited and the Scott Polar Research Institute under funding from the BNSC. Conceived from the outset as an **operational** tool, a key feature of the IPAP development process has been the close and continuous involvement of a group of operators with interests in the polar regions. It is the requirements of the operators that have shaped the range of data products available from IPAP (which include ice concentration maps, ice edge location/motion diagrams and ice berg location maps) and the format of their presentation. These products cover a range from very high level, interpreted, charts (which requiring little or no specialist knowledge on the part of the operator) through to detailed products which support the work of the operator's own in-the-field ice expertise.

The paper outlines the process of IPAP system development and its implementation on a SUN workstation in the AVS visual programming environment. The range of system data products is discussed in detail and example applications of these products to operations requiring both tactical (short term) and strategic (long term) decision-making are described. A full description is given of an demonstration in which the fundamental requirement was to transmit accurate data to a field operator in as close to "real time" as possible. The overall emphasis of the paper is placed on the operational value of IPAP products.

Key Words

ERS-1, ice, image processing, operational, SAR

1. Introduction

The effects of sea ice on operations in polar waters can be profound. Consider, for instance, the shipping of some natural resource mined at a high latitude location to its marketplace in more temperate regions. The route taken by the vessels used must reflect the prevailing sea ice conditions. However, those conditions can be subject to significant uncertainty and it is necessary to be conservative in route selection so that possible problems are avoided. Unfortunately, conservative choices also tend to imply financial penalties as a result of longer transit times. These penalties can, and have, made the difference between a polar operation being viable or not.

Commercial pressures have therefore driven the development of sea ice monitoring and forecasting services around the globe. The requirement for these services is closely analogous to the requirement for weather monitoring and forecasting. Huge geographical areas must be covered frequently and the vast quantities of information involved must be rapidly summarised into an assimilable form. Satellite-borne sensors are now the pre-eminent tools for weather monitoring and the same is rapidly becoming true for sea ice monitoring and forecasting. No other means can provide the sheer geographical coverage available from sensors in earth orbit.

Sea ice information can be derived from a range of satellite sources. Until fairly recently, the available range of sensors was primarily concerned with visible and infra-red wavelengths. These can have limited value for sea ice work. They cannot penetrate cloud cover (all too frequent at high latitudes) and optical sensors clearly have little value at night. The lack of a reliable data source has been a serious obstacle to the popularisation of satellite products amongst polar operators.

Over the last few years, a number of commercial satellites equipped with synthetic aperture radar (SAR) capability have been launched. SAR instruments are not affected by cloud or whether it is day or night. This paper is concerned with the development and application of a tool for polar operations management based on SAR data derived from the ERS-1 satellite.

The ERS-1 Pilot Application Project for Polar Operations (usually abbreviated to IPAP) has been in progress for the last three years. The project has been conducted by a team consisting of GEC-Marconi Research Centre (UK), SAIC Science & Engineering Limited (UK), the Scott Polar Research Institute (UK), Matra-Marconi Space (France/UK), BP (UK), Canarctic Shipping Co. Ltd. (Canada) and Nunaoil AS (Denmark). It is approved by ESA and NASA and has been funded by the British National Space Centre with project management from the UK Defence Research Agency. The goal of IPAP was relatively simple: implement a computer-based image analysis system to take ERS-1 SAR images and produce a range of data products to serve the needs of the polar operator community.

It is commonly the case that remote sensing applications are driven by technology and not by end-user requirements. However, IPAP was - from its conception - intended as a tool for operators. A key feature of IPAP development has been the close and continuous involvement of a group of operators with interests in polar regions. IPAP has been shaped by the requirements of these operators.

2. Operator Requirements

The first steps in IPAP system development comprised a detailed assessment of the sea ice monitoring/forecasting requirements of a representative group of commercial operators in the polar regions. The operators involved in the IPAP project have a mixture of interests relating to hydrocarbon prospecting and/or exploitation and shipping in Arctic regions.

It was immediately apparent that the operator requirements covered a broad range. At one end of the scale, some operators have little or no experience in dealing with satellite data and have no interest in developing such a capability. Their basic requirement is for high-level, highly interpreted, sea ice information. At the opposite end of the same scale, some operators have an existing and formidable in-house resource of ice expertise. Such operators are generally more interested in receiving low-level data for their own interpretation.

The diverse range of operator interests is reflected in table 1 which summarises the detailed technical requirements of the operators. Different operators had different requirements in some categories and the table presents the most exacting operator requirement in each case.

The ERS-1 satellite is able to supply SAR images with a ground resolution of 30m with each image covering an area of 100km by 100km. The coverage requirements in table 1 therefore cannot be met by the use of a single ERS-1 SAR image. However, the spatial sampling requirement is readily satisfied except for the "ideal" need to resolve icebergs as small as 5m in diameter. The temporal sampling requirement is not easily satisfied by ERS-1. The satellite has had a number of mission "phases", each with different orbital characteristics. In its "ice phases" ERS-1 had an orbital repeat period of 3 days but with substantially less than 100% coverage of the Earth's surface.

Another aspect of operator requirements not brought out by table 1 is the delivery timescale of sea ice information. All operators had needs for strategic information for planning purposes with required lead times ranging from a few days to a few weeks. Almost all of the operators questioned also had or could foresee a requirements for tactical information which had to be transmitted into the field within a few hours of the image data being acquired by satellite.

At IPAP inception, ERS-1 was the best available vehicle for a SAR-based sea ice monitoring system. It was also clear from early in the IPAP project that ERS-1 will not allow all of the operator requirements to be fully satisfied. This was not, however, inconsistent with the initial objective of providing a fully-functional "proof of concept" demonstration of a satellite SAR sea ice monitoring system. It was recognised from before the system design stage that the further objectives of providing operational systems and services would probably require a vehicle other than ERS-1. For instance, ERS-1 performance will soon be surpassed by newer satellites such as the Canadian RADARSAT, which will give daily SAR coverage at latitudes greater than 70°N at a similar resolution to ERS-1. RADARSAT will also deliver images over a 500km swath. An implicit operator requirement for IPAP was that it should be able to take advantage of the best available SAR data as and when available.

Requirement Category	Coverage (km)	Spatial Sampling (m)	Temporal Sampling	Attribute	Required Accuracy
Iceberg detection	240×240	5 (ideal, otherwise as small as possible)	12 hours	Position	±500m
				Bearing	±10°
				Drift speed	±0.1kt
Ice edge	150×300	100	12 hours (ideal)	Position	±500m
				Bearing	±45°
				Speed of movement	±0.25kt
				Banding width/position	±100m
				Eddy centroid location	±500m
				Eddy centroid drift rate	±0.25k
				Eddy circulation	Clockwise/anti-clockwise
				Eddy diameter	±100m

Table 1(a): Operator requirements summary (1)

Requirement Category	Coverage (km)	Spatial Sampling (m)	Temporal Sampling	Attribute	Required Accuracy
Ice concentration/type	150×300	100	12 hours	First year ice concentration	Nearest 2/10
				Multi-year ice concentration	Nearest 2/10
				Location of highly ridged areas, rubble fields and shear zones	±250m
				Floe size distribution	
Enhanced imagery	100×150	As high as possible	Unprocessed image, geolocated and enhanced for ice features		

Table 1(b): Operator requirements summary (2)

3. The IPAP System

IPAP system design was founded entirely on the operator requirements described in Section 2. The intention was to allow the project to be driven by "requirement pull" and not by "technology push".

The requirements were used to define the following range of IPAP data products which the system was to generate:

- Enhanced SAR image
- Ice type charts
- Ice concentration (multi-year and total) charts
- Ice edge location and motion charts
- Ice berg location and motion charts
- Ice floe motion charts

Each of these data products was specified to be delivered in the following format:

- Areal coverage of 100km by 100km
- Nominal pixel size of 100m
- Display in a range of map projections
- Suitable for transmission by fax or e-mail
- Latitude-longitude grid overlay
- Option to overlay data product on "raw" image
- Header giving time, date, corner co-ordinates, etc.

This product specification derives in part from the requirements, but also in part from what ERS-1 can deliver. The 100m pixel resolution (ERS-1 has a maximum nominal resolution of 12.5m) was selected to minimise computing time during image processing.

An outline of the IPAP system design is shown in figure 1. There are two main processing streams: one for the iceberg products and one for all other products based on the segmentation and classification of the ERS-1 SAR image into different ice types, open water and land. The enhanced SAR image product derives from segmentation. All other in this processing stream derive readily from the classification module.

Having made this system breakdown into modules, considerable R&D efforts were needed to identify, test and implement suitable signal processing means to satisfy the needs of each module. It is beyond the scope of this paper to go into detail on each of the algorithms used in each module, but a summary of the methods used is given in table 2.

Module/Product	Algorithm Method
Segmentation	Edge-based.
Classification	Supervised calibrated backscatter and texture. Four algorithms implemented: neural network, maximum likelihood, minimum distance & nearest neighbour.
Ice concentration	Moving filter on classified image
Ice edge	Poly-line delineating ice/no ice for a specified minimum length scale
Iceberg	Point target detector - seeks to find co-located bright points and dark radar shadows
Ice floe motion	Area correlation between an image pair Region boundary matching

The single most important algorithm worked on during IPAP development has been the classification algorithm. Not only do many of the other products derive directly from the results of this algorithm, but it is a technically difficult problem. The reason for this is that there can be significant overlap in the ranges of radar backscatter from different ice types and from open water. Different ice types can appear to be exactly the same shade of grey in a SAR image. Using the grey-scale value of each image pixel in isolation is therefore an unreliable classification means. The IPAP system therefore also makes use of measures of the texture of each image segment in its classification scheme. These include inertia, entropy, uniformity, dissimilarity and inverse difference moment. The classification scheme is also described as *supervised* which means that it requires training data before it can be applied.

The IPAP system design has been implemented under UNIX on a SUN workstation. The development environment used for IPAP is known as Application Visualisation System (AVS) and it is available "off-the-shelf". AVS is a visual programming environment which allowed IPAP development to concentrate on ice science and not computer science. The individual algorithms specified above were implemented in C and run under AVS.

Figure 2 shows an example ERS-1 SAR image - the raw material that the IPAP system has to work with. Figure 3 shows an example of the enhanced image product derived from an ERS-1 SAR scene. Figure 4 is an example product (in this case, total ice concentration) derived from the classification processing stream. Its format is indicative of other IPAP products.

4. <u>Validation & Demonstration</u>

IPAP system design and implementation concluded in spring 1994. The system has since undergone a phase of product assessment, validation and demonstration.

The first IPAP product to receive serious validation testing was the iceberg detection product. Based in Groton, Connecticut, the mission of the International Ice Patrol (IIP) is to provide shipping with information on the icebergs driven by the Labrador current past the east of Newfoundland and into the shipping lanes. (This is, of course, exactly the area where The Titanic struck a berg with such tragic consequences in 1912 and led directly to the formation of the IIP.) The IIP flies frequent ice berg reconnaissance missions with airborne SLAR and FLAR in this region and collects and collates other iceberg sightings from shipping, commercial aircraft and chartered ice reconnaissance missions by other airborne SAR operators. This information is maintained in a database and used to generate the IIP's products for shipping.

The first validation of the IPAP iceberg product was attempted using the database. ERS-1 SAR images were used to generate the iceberg location product for regions covered by the IIP and then compared with known iceberg locations from the IIP database.

Figure 5 shows an Arc/INFO plot of the positions of known icebergs in one region of the Grand Banks off north east Newfoundland for 31st May 1994, based on the IIP database. Figure 6 shows the equivalent IPAP data product for the same area and time with iceberg detections marked. The IPAP product appears to show almost all of the IIP berg detections, plus many other targets besides. It is unknown whether these are bergs undetected by the IIP, fishing boats (or other shipping) or simply false alarms. Simulations have suggested that the false alarm rate for this particular image should be 9%. The prevailing sea state is an important parameter for iceberg detection since it has a very strong influence on the radar backscatter produced by the ocean surface. A calm sea looks dark on a SAR image, but as the windspeed increases, the sea surface appears brighter and brighter until it can obscure the bright point target of a berg. In this latter case, it is possible to detect bergs via their radar "shadow": see figure 7.

Analysis to date on IPAP iceberg data products (which have a nominal pixel resolution of 100m) has yielded the following results in detection of known icebergs:

Iceberg size (m)	Probability of Detection (%)
15-60	44
60-120	89
120+	100

Whilst these results are extremely encouraging, it must be emphasised that they are preliminary at the time of writing (November 1994). The validation activity is still in progress for the iceberg product for a range of geographical locations.

A very similar validation exercise is in progress for other IPAP products, although results are not yet ready for publication.

At the same time as technical validation, IPAP products are being supplied to a range of polar operators for strategic assessment. The purpose of this exercise is to ensure that the products are in a format which is readily accessible to, and useable by, those operators.

One of the most serious obstacles to the use of satellite-derived information as a means of supporting polar operations is the speed with which information can be supplied into the field. In a tactical situation, where a ship's master must decide on his course around or through the ice, there can be little value in supplying data that is days out of date. The

RAIDS (RApid Information Dissemination System) facility, which has been established by Matra-Marconi Space (MMS) at West Freugh, Scotland, has enabled the IPAP system to overcome this problem to some extent. RAIDS is able to offer extremely rapid turnaround on ERS-1 data covering a region from the Barents in the east to Greenland in the west and the Arctic Ocean to the north.

In summer 1994, Nunaoil AS mounted a summer voyage to the waters off eastern Greenland. The aim of the voyage was seismic exploration for oil and gas reserves via the deployment of a long (many hundreds of metres) seismic streamer towed behind the ship to listen to the response induced by the firing of air guns. Such seismic streamers are extremely expensive items of equipment and operating in ice-prone waters takes great care. IPAP was used to supply the Nunaoil vessel with ice information during the summer 1994 voyage. IPAP products were derived from ERS-1 data supplied through the MMS RAIDS facility. Data products were faxed to the vessel (via Inmarsat) within two hours of image acquisition by ERS-1. This is an extremely rapid rate of data supply by the standards of satellite data products.

5. Conclusions

The IPAP system is a powerful tool for providing sea ice information derived from satellite SAR to support polar operations. It has been developed using ERS-1 SAR, but is fully compatible with the enhanced capabilities of RADARSAT and ENVISAT.

The system is operational and generating data products. Many of those data products have been validated against ground truth information. IPAP data products have been despatched to field operators within two hours of image acquisition by ERS-1.

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Ice System Overview

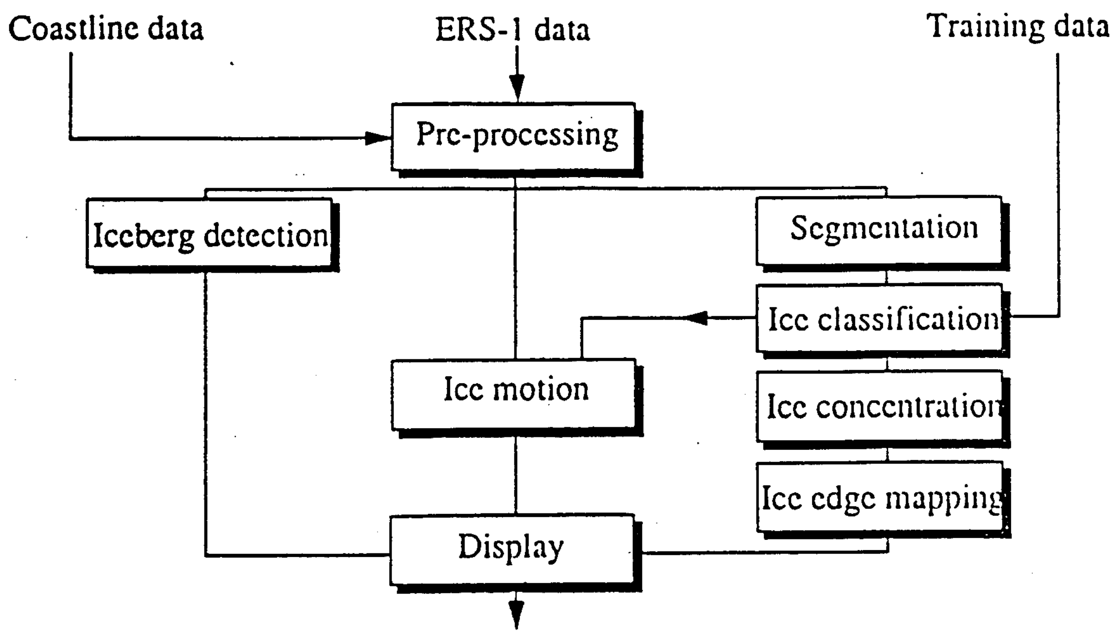
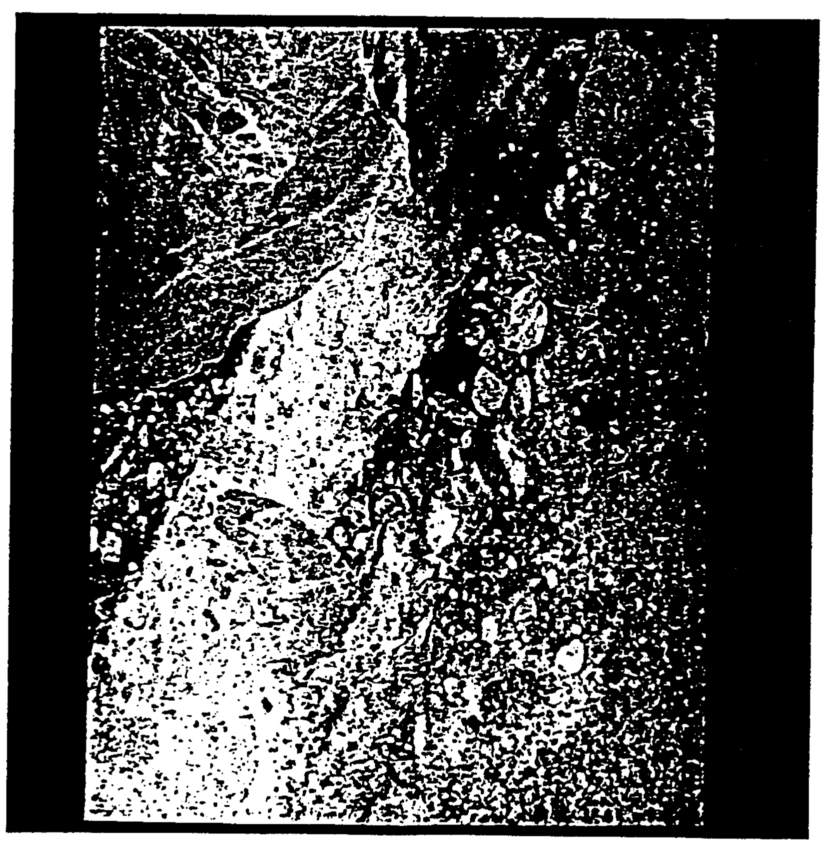


Figure 1: IPAP system schematic



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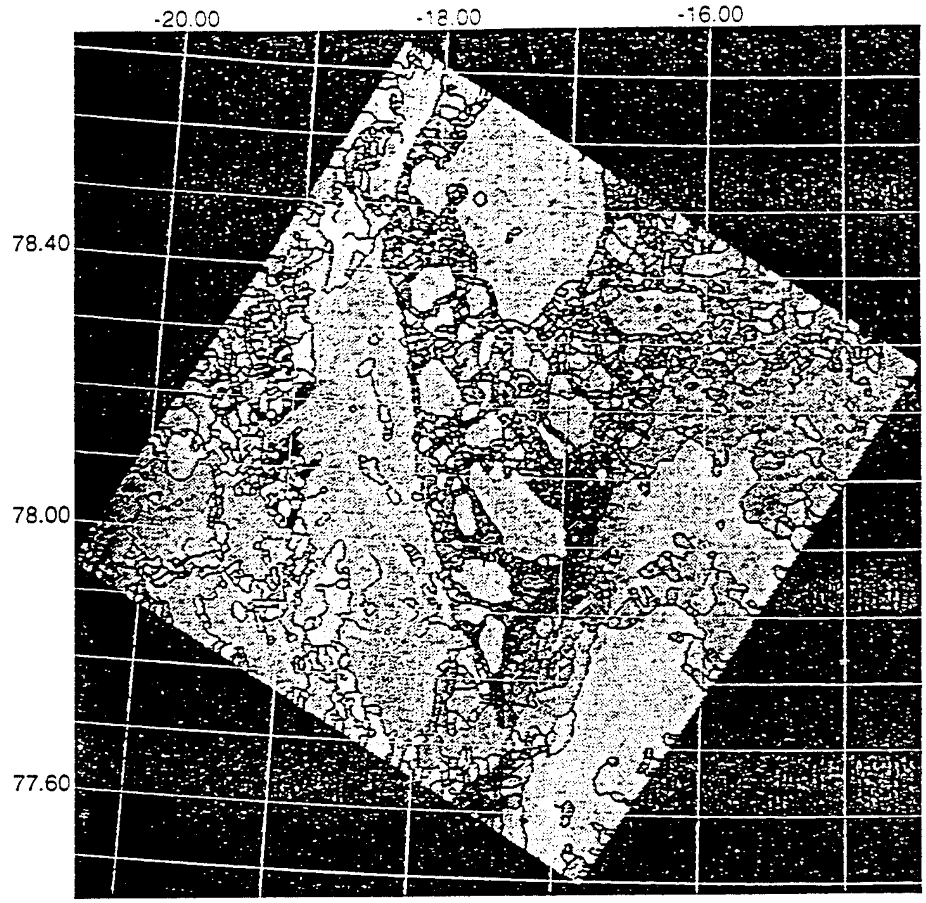
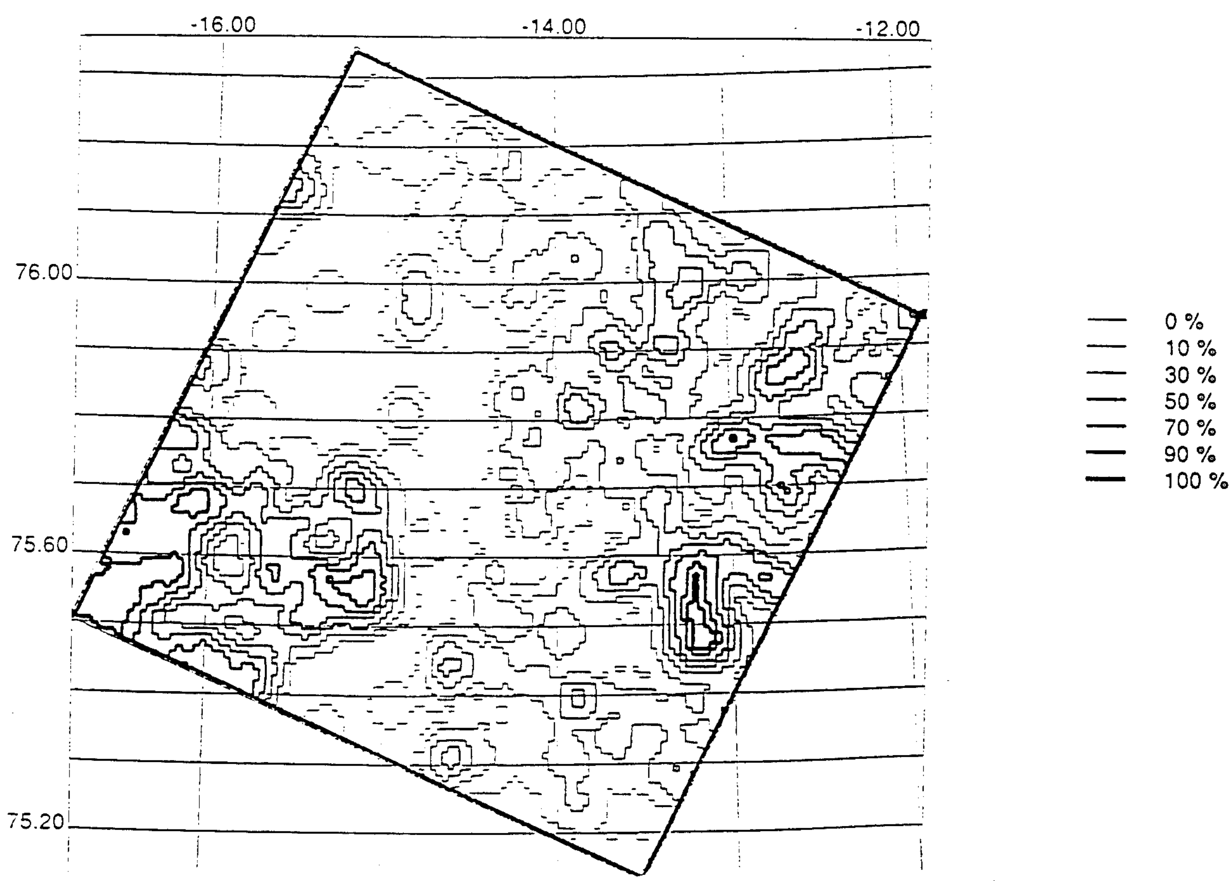


Figure 3: Example enhanced image product



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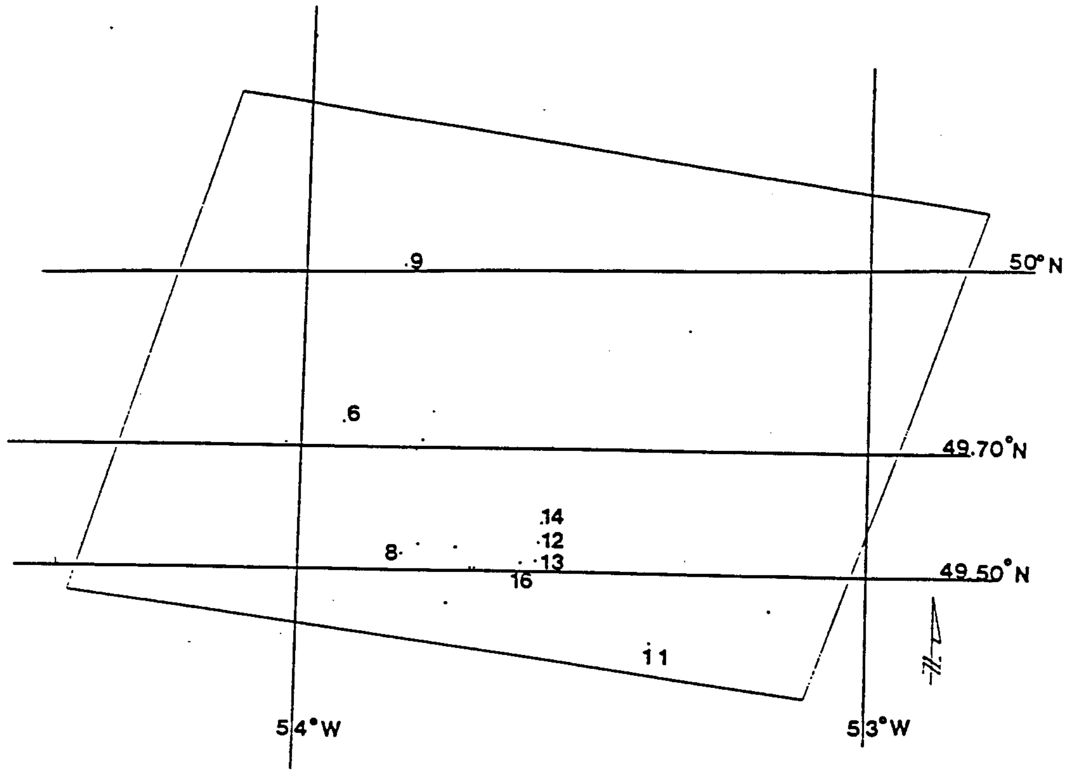
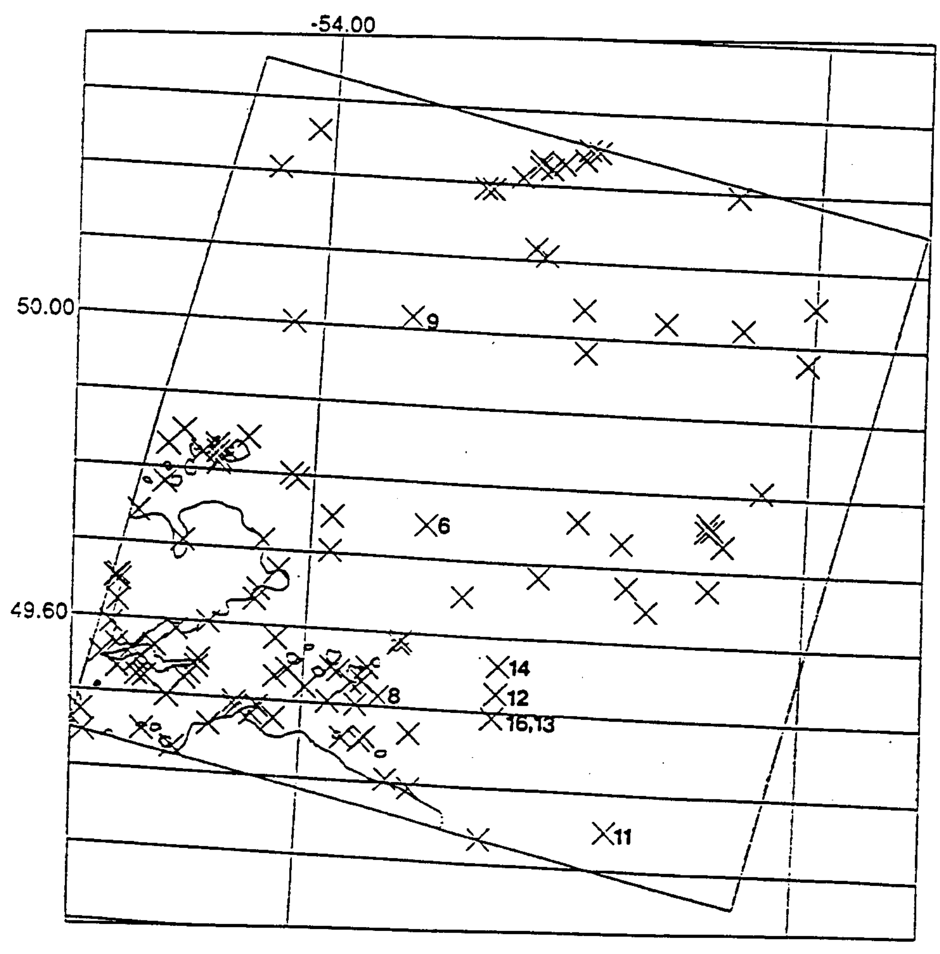


Figure 5: GIS plot of known iceberg positions off Newfoundland, 31st May 1993



Calm ≤5 m/s	Intermediate	Strong ≥12 m/s
Strong 'point target'	Weak signature	Strong 'shadow'

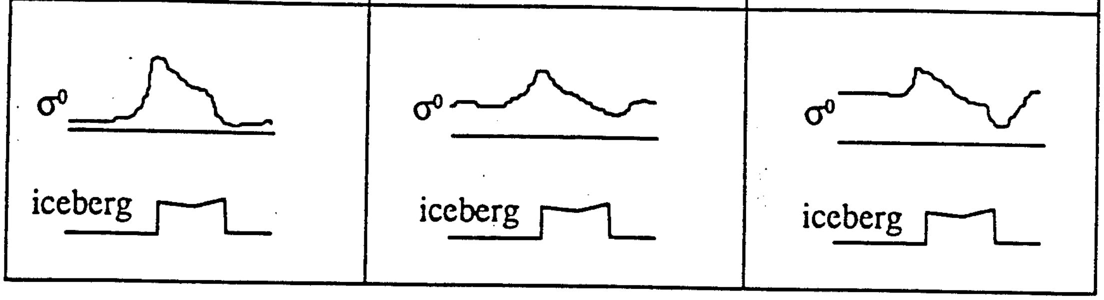


Figure 7: Iceberg SAR "signatures" as a function of prevailing wind speed: note the strong shadow at higher wind speeds