

The Role of Imaging Radar in the Development of the Canadian Arctic: Background and Applications

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ABSTRACT. Imaging radars have been in use in the Canadian Arctic for over 20 years. Initially the use was sporadic, as the relatively new, declassified technology in the form of real aperture side-looking airborne radars (SLAR) was flown and the results studied. This situation existed until the late 1970s, when the use of two types of imaging radars became more widespread. The Atmospheric Environment Service (AES) introduced the Motorola APS-94 SLAR for use on regular reconnaissance flights, while the Canada Centre for Remote Sensing (CCRS) introduced the CV-580 X-L Synthetic Aperture Radar (SAR) for periodic missions in the Arctic for research in support of ice studies and shipping.

As demand for ice information increased in support of offshore drilling in the Beaufort Sea and navigation in the Eastern Arctic and along the east coast, more systems were brought on line. AES added two more SLARs to their reconnaissance efforts in the early '80s, while Intera developed a digital SLAR and two digital SAR systems, STAR-1 and STAR-2. As part of a multi-year program to support AES's ice reconnaissance mandate in the Arctic and east coast areas, Intera has developed a dual-sided SAR in a jet aircraft for high-resolution, large-area coverage. Imaging radar, with its all-weather, day/night and cloud-penetrating capability, has proved to be the almost ideal sensor for many arctic applications. In support of offshore drilling in Alaska and Canada, large areas were flown to obtain up-to-date information for use in navigation and forecasting ice conditions. Real-time SAR and SLAR data can be downlinked to ships navigating in ice-infested waters to aid officers in determining the safest, most efficient and economical routing through the ice. Research into ice properties and signatures has improved our knowledge and understanding of the ice, which covers a large part of Canada's territorial waters for much of the year.

Key words: synthetic aperture radar (SAR), side-looking airborne radar (SLAR), Arctic, offshore drilling, modelling, navigation, development

RÉSUMÉ. Les radars imageurs sont utilisés dans l'Arctique canadien depuis plus de 20 ans. Au début, leur utilisation était sporadique, vu qu'il fallait faire voler cette technologie déclassée et relativement nouvelle qui avait la forme de radars aéroportés à antenne réelle à vision latérale (SLAR), puis étudier les résultats. Cette situation prévalut jusqu'à la fin des années 70, période à laquelle l'utilisation de deux types de radars imageurs devint plus courante. Le Service de l'environnement atmosphérique (SEA) introduisit le SLAR Motorola APS-94 pour utilisation lors de vols de reconnaissance ordinaires, tandis que le Centre canadien de télédétection (CCT) introduisait le radar à antenne synthétique (RAAS) CV-580 X-L à utiliser lors de missions de recherche périodiques dans l'Arctique visant à soutenir l'étude des glaces et la navigation.

Comme la demande d'information sur les glaces augmentait avec l'extension des forages au large dans la mer de Beaufort ainsi que la navigation dans l'Arctique oriental et le long de la côte est, on mit sur pied un plus grand nombre de systèmes. Au début des années 80, le SEA ajouta deux radars à vision latérale SLAR sur ses vols de reconnaissance, tandis qu'Intera mettait au point un SLAR numérique et deux radars à antenne synthétique (RAAS) numériques, STAR-1 et STAR-2. Dans le cadre d'un programme s'étalant sur plusieurs années et visant à soutenir le mandat de reconnaissance du SEA dans les régions de l'Arctique et de la côte est, Intera mit au point un RAAS bilatéral à installer sur un avion à réaction permettant de couvrir de vastes superficies, avec une haute résolution. Capable de fonctionner en toute saison, de jour comme de nuit, et de pénétrer les nuages, ce radar imageur s'est révélé être le détecteur quasi idéal pour bien des applications dans l'Arctique. Pour soutenir le forage en mer en Alaska et au Canada, de vastes étendues ont été survolées dans le but d'obtenir de l'information récente pour aider à la navigation et à la prévision des conditions des glaces. Les données en temps réel obtenues avec les RAAS et les SLAR peuvent être envoyées aux navires naviguant dans des eaux encombrées d'icebergs, dans le but d'aider les officiers à se frayer le chemin le plus sécuritaire, efficace et économique à travers les glaces. La recherche sur les propriétés et les signatures des glaces a permis d'accroître notre connaissance et notre compréhension des glaces qui recouvrent une grande partie des eaux territoriales canadiennes, et ce, pendant la plupart de l'année.

Mots clés: radar à antenne synthétique (RAAS), radar aéroporté à vision latérale (SLAR), Arctique, forage en mer, modèle, navigation, innovation

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INTRODUCTION

Over the past several decades imaging radars, both real aperture side-looking airborne radar (SLAR) and synthetic aperture radar (SAR), with their almost all-weather and day/night reconnaissance capabilities, have played an important role in the development of the Canadian Arctic. The short navigation season, often hazardous ice conditions and low levels of visibility have, in the past, hampered navigation, exploration, development and resupply efforts. The use of imaging radar data in support of these activities has enabled shipping companies to extend their period of operation, aided oil and gas exploration and allowed the shipping of ore from the northernmost mines in Canada. The level of support, experience and understanding presently available has, as with other remote sensing technologies, been developed over years of experiments and operations.

Imaging radar, with its proven ice-imaging capabilities, is also useful for non-ice imaging purposes, such as geology

and land use. Several studies have used X-band imagery to study the geology of Cornwallis Island and the Houghton Meteor Crater, Devon Island. Information needs regarding Canada's large arctic landmass and the surrounding ice-covered waterways suggest that the ongoing use of imaging radar in the Arctic is assured for a number of years to come. In future years, airborne imaging radars will be part of the information chain that includes the Canadian Radarsat C-band radar satellite.

SLAR IN THE CANADIAN ARCTIC

SLAR was the first imaging radar used in the Canadian Arctic in the late 1960s and early 1970s. Initial investigations using different wavelengths were conducted by American investigators and included support of the transit of the tanker *Manhattan*, as well as other studies (Anderson, 1966; Johnson and Farmer, 1971). The first Canadian experience was in Nares Strait, in the Eastern Arctic, where a Motorola APS-94D

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SLAR obtained from the U.S. military was used (Dunbar, 1975). A series of three flights in January, March and August 1973 was flown by the Canadian Forces Maritime Proving and Evaluation Unit using an Argus aircraft. The results of these flights, along with tests performed by the Atmospheric Environment Services (AES) Ice Branch using the same radar system, showed the usefulness of imaging radar for the identification of sea ice.

A Motorola APS-94D SLAR image of the Ward Hunt Ice Shelf, northern Ellesmere Island, is shown in Figure 1. The ice shelf of glacial origin (bottom of image) is very distinct in tone and texture from the rest of the sea ice in the image. This is a negative image, so that shadows (B) and younger ice (C) are light tones, while old ice (D) is darker in tone. Ridges are dark-toned, linear features, such as E.

Until 1977 AES had been conducting regular ice reconnaissance missions in the Arctic, on the east coast and in the Great Lakes area using visual reconnaissance supported by cameras. In 1977 AES obtained the APS-94D system from the Canadian military on permanent loan for use in an Electra aircraft on regular ice patrol reconnaissance missions. After some equipment modifications, relating mainly to the radar display, and installation in the aircraft the first mission was flown on 11 February 1978 off of Canada's east coast. The first arctic flight occurred on 19 February in the Frobisher Bay (Iqaluit) area. Regular operation flights, supplemented by research flights, were flown using the APS-94D in the Electra aircraft CF-NDZ until 1988, when, after over 1900 radar missions, the aircraft and radar were taken out of service. The appendix contains information on data availability and formats.

The radar imagery proved to be such a useful source of information that a second SLAR system was acquired on loan from the U.S. Coast Guard and installed on the AES patrol aircraft CF-NAY, another Lockheed Electra, in the fall of 1984. The first flight of this system occurred on 20 November 1984, again to Frobisher Bay. The Motorola SLAR on CF-NAY was retired in 1988 after over 400 flights.

Both Electras were equipped with observation bubbles on the top and sides of the aircraft fuselage to allow trained ice observers to view and map the ice conditions below. In the early years of SLAR, these observations were important in validating the radar imagery and observations. In later years after personnel, both in the air and on the ground, became more familiar with the radar imagery the SLAR imagery became more of a stand-alone product. SLAR imagery was often used as the only source of ice condition data for input into the creation of ice charts during periods of low visibility.

In addition to observation facilities, the Electras were equipped with other, non-radar, sensors, such as an infrared (IR) scanner, Vinten 70mm cameras, a laser profilometer and Airborne Radiation Thermometers (ARTs). These sensors collected data at other wavelengths, which aided in the creation of the ice chart and the validation and understanding of the radar data. Although not all were side looking, as was the radar, they did allow understanding of the general conditions present. The flight tracks occasionally overlapped, so that non-radar and radar data of the same area at nearly coincidental times was obtained.

A third SLAR was obtained by AES in late spring 1986 and was installed in the Ministry of Transport Dehavilland DASH-7 aircraft. The SLAR was built by Canadian Aer-

onautics Ltd. (CAL) and named the SLAR-100. It had a number of new innovations, such as latitude and longitude grid overlay on the imagery and digital operation and data collection. The SLAR-100 was flown on 6 June 1986 and has flown over 400 flights to date. After the APS-94E system in CF-NAY was retired in 1988, a second SLAR-100 was mounted in CF-NAY for a short time. Specifications for these and other SLAR and SAR systems are found in Table 1. A

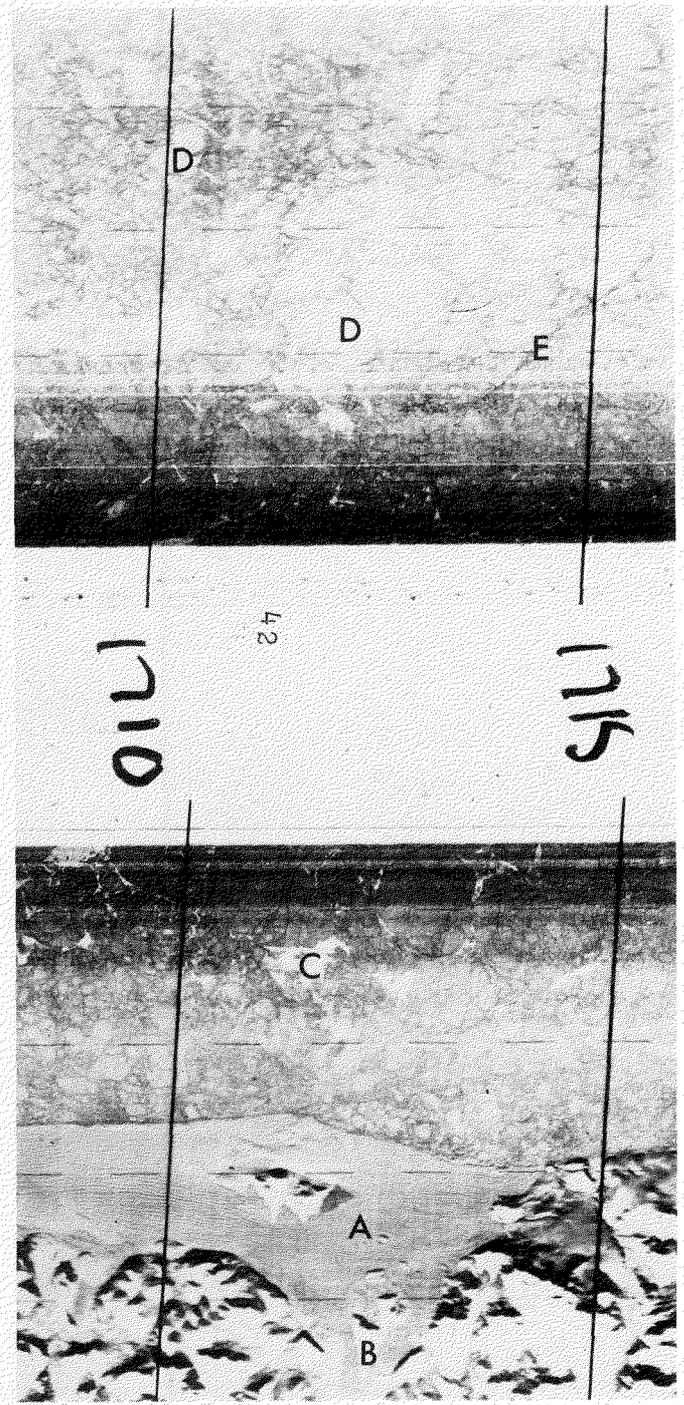


FIG. 1. Motorola APS-94D SLAR image of Ward Hunt Ice Shelf, Ellesmere Island. North is at the top of the image. The aircraft was flying from the west (1710 time mark) to the east (1715 time mark). The image covers the full 100 km swath on each side of the aircraft. An altitude gap of 2x altitude (approximately 12000 feet) and annotation space constitute the centre area between the two swaths. The image was acquired on flight NDZ 1557 on 11/02/85. (Image courtesy of AES.)

CAL SLAR-100 image of the eastern end of Jones Sound is shown in Figure 2, with King Edward Point (A) and Smith Island (B) visible at the top right corner of the image. Fast ice is found along the coast of Devon Island (C), while icebergs in ice (D) (appearing as small dots and dashes) are found in the lee of Kind Edward Point. A mixture of young and first-year ice is found between the two shores (E), while a large area of open water influenced by winds is found at (F) near Prince Edward Point. This is a negative image, the same format produced on board the aircraft.

While AES was operating SLARs for ice reconnaissance, the oil and gas industry operating in the Beaufort Sea was in need of operational imaging radar support. This was provided for several years (1981-83) by an APS-94D SLAR mounted in a Gulfstream G-1 aircraft operated by MARS Inc. This system provided regular coverage of a large area of the Beaufort Sea and had the capability of downlinking radar data in real time, using a downlink system developed by Intera Technologies Ltd., to a ground station for operational and modelling use.

The first commercial digital SLAR was developed by Intera and Terma A/S of Denmark for use in the operational support of oil and gas activities in the Beaufort Sea and for tactical navigation support in the Eastern Arctic. The Intera SLAR is mounted in a Cessna Conquest 441 and has real-time downlinking capability and digital storage on computer-compatible tapes (CCTs) for extra hard copy replay, digital enhancement or analysis on an image analysis system. At present, AES is the largest user of SLAR-equipped aircraft and the main source of SLAR data. The other systems mentioned are operated commercially on demand for client-oriented projects.

SAR IN THE CANADIAN ARCTIC

As with SLAR, American investigators were in the Arctic in the early 1970s using SAR with various systems and wavelengths (Johnson and Farmer, 1971). The first major foray into the Arctic by Canadian investigators was in March and April 1979 in support of the Canadian Surveillance Satellite (SURSAT) project, a program to collect and analyze airborne X- and L-band data in conjunction with the SEASAT satellite data collection and analysis program. An X-L-band SAR had been acquired from the Environmental Research

Institute (ERIM) by the Canada Centre for Remote Sensing (CCRS) and after some modification was mounted in a

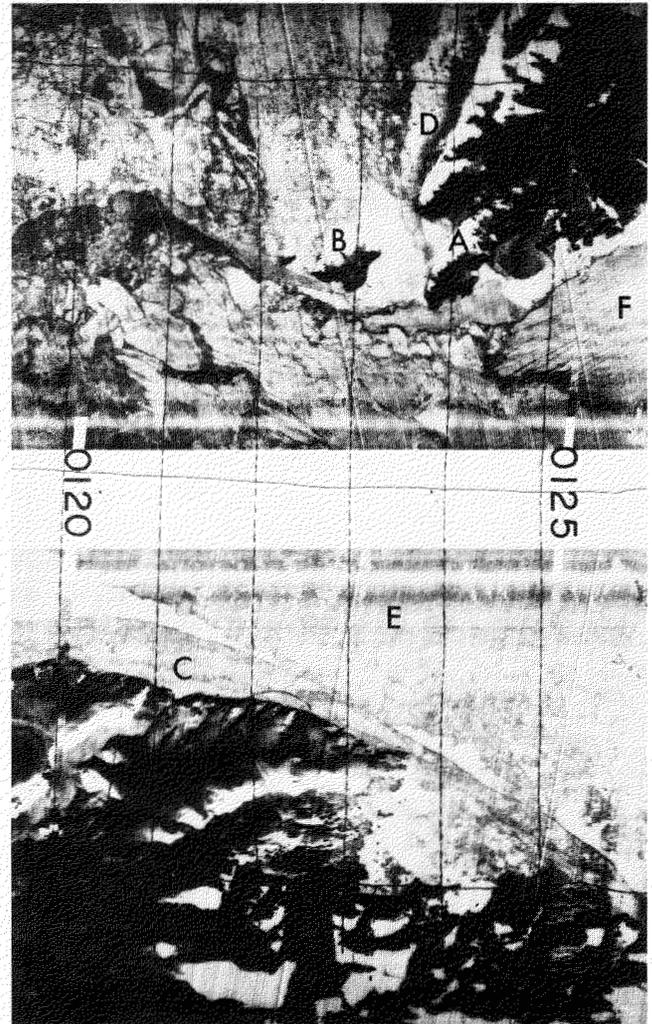


FIG. 2. CAL SLAR-100 image of the eastern end of Smith Sound. North is at the top of the image. The aircraft was flying from west (0120 time mark) to east (0125) down the centre of the sound. A full 100 km for each swath was imaged and a latitude and longitude grid overlay appears on the image. The image was obtained on 01/12/87 on flight CFR 219, 20, 21. (Image courtesy of AES.)

TABLE 1. SLAR and SAR parameters

	APS-94	SLAR-100	X-L CV-580	X-C CV-580	STAR-1	STAR-2 (CIRS)
Wavelength(s)	X (3.1-3.3 cm)	X (3.26 cm)	X (3.2 cm) L (23.5 cm)	X (3.2 cm) C (5.6 cm)	X (3.2 cm)	X (3.2 cm)
Polarization	HH	HH	HH, VV, HV, VH	HH, VV, HV, VH	HH	HH
Resolution	30M+	30M+	1.5/2.1(X) 2.3/2.1(L)	6 x 6 (narrow) 10 x 20 (wide)	6 x 6 (narrow) 12 x 12 (wide)	15 (narrow) 25 (wide)
Swath width(s)	25-50-100 km	25-50-100 km x 2 sides	6 - 23 km	18, 22 or 65 km x 1 side	23 to 46 km x 1 side	65 x 100 km x 1 side
Aircraft platform	Electra (prop)	Dash-7 (prop)	CV-580 (prop)	CV-580 (prop)	Conquest (prop)	Challenger (jet)
Digital data	N	N	Y	Y	Y	Y
Hard copy output	Neg. film	Neg. film	Paper	Paper	Paper or film	Paper or film
Downlink capability	Y	Y	Y	N	Y	Y
Mission duration	10 h	5 h	5 h	5 h	6 h	5 h
Presently operational	N	Y	N	Y	Y	Y

Convair-580 (CV-580). Unlike earlier SLAR flights, the system, known as the SAR-580 (Inkster *et al.*, 1979) was supported by a large number of ground data collection exercises and coincidental flights by other aircraft and sensors. This was done to more fully understand the SAR data to maximize its usefulness for a large research, development and operations community (Intera, 1980).

With the addition of a C-band frequency in 1982, the SAR-580 was operated for a number of CCRS research and development projects throughout the Arctic until 1985. At that point the ERIM X-L SAR was replaced by a system built by MacDonald, Dettwiler and Associates. This system included a number of improvements based on previous experience and operated at X- and C-bands. The focus on C- rather than L-band was due to the intention of the Canadian government to operate a C-band radar satellite (Radarsat) in the future. This sensor was to provide input and understanding of C-band data that had previously been lacking.

The CV-580 aircraft, with either radar system on board, has at times also carried a number of sensors that have been useful in the interpretation and understanding of the SAR data. These sensors have included a side-looking 35 mm camera, a scatterometer, a metric camera and downward-looking video cameras.

Dual channel, multi-polarized data were collected by both systems (Table 1). Initially, the ERIM SAR was used and later the IRIS system recorded all channels on high-density digital tapes (HDDTs). Both systems output data on a real-time basis on dry silver paper. Swath width coverage varied depending on the operation mode from a minimum of 10 km (nadir mode) to a maximum of 26 km (wide swath mode) (ERIM SAR) to 63 km (IRIS). The variability in swath width coverage, polarization and wavelength, along with the capability to record signal and image data, reflected the research and development mandate of the SAR. Unlike most of the SLARs in operation in the Arctic, the SAR-580 only images on one side of the aircraft, although the side chosen can be changed by the operator during a mission. The appendix contains information on data availability and formats.

The need for a commercial SAR system in support of oil exploration and navigation in the Arctic was perceived by Intera in the early 1980s during its development in the SURSAT program and other SAR projects and experiments. In conjunction with ERIM and MDA, the Sea Ice and Terrain Acquisition Radar (STAR-1) was developed. Much of the experience and data from previous work (Lowry and Hengeveld, 1980; Hengeveld, 1980; Hawkins *et al.*, 1980) showed that the optimal polarization and band for ice-related work was HH (horizontal transmit, horizontal return) X-band (3.2 cm wavelength).

STAR-1 consists of the radar system mounted in a fuel-efficient Cessna 441 Conquest aircraft. The system has two main modes of operation: standard mode with a 46 km swath width and 12 m resolution, and narrow swath (23 km) mode with 6 m resolution. Real-time downlink capabilities and digital data recording are also available.

STAR-1 has been used for a number of research projects in the Arctic (e.g., Mould Bay, the Beaufort Sea), but most of the data collection has been in support of commercial clients, such as Dome and Gulf for drilling in the Western Arctic and Canarctic for navigation purposes in the Eastern Arctic. STAR-1 has been involved in multi-year programs in

support of drilling in the Beaufort Sea. Figure 3 shows a full swath STAR-1 image.

The success of STAR-1 led to the development of an improved SAR, STAR-2, based on MDA's IRIS system. This system, also mounted in a Conquest aircraft, included improved data collection and accuracy capabilities and came on stream for a two-year period in 1987 (Akam, 1988). An agreement between AES and Intera for Intera to provide a Comprehensive Ice Reconnaissance Service (CIRS) using a dual-sided SAR mounted in a Canadian Challenger jet aircraft led to the decommissioning of the original STAR-2 and its inclusion after some modification in the CIRS system, also known as STAR-2 (Mercer, 1989).

The jet-mounted, dual-sided SAR is based around the IRIS system and is fully digital for downlink recording and data output purposes. CIRS came on line for AES in January 1990 and had flown over 60 missions as of April 1990. The system has dual 100 km swaths at 25 m resolution or narrower swaths (65 km) at 15 m resolution (Mercer, 1989), a single channel (X-band) and polarization (HH).

Recently, the SAR-580 has been used in the Arctic for occasional experiments on sea ice in the Beaufort Sea, while STAR-1 has been used in the Eastern and Western Arctic, mostly in support of ship navigation and climatology work. With the advent of STAR-2 (CIRS) in the Challenger jet, it appears that this system will provide most of the Arctic SAR data collected in the immediate future. Figure 4 shows the Challenger CIRS aircraft.

Apart from the airborne SAR systems mentioned here, a large amount of data was collected, although over a limited period, by the first satellite SAR, known as SEASAT. The data were collected in September and October 1978. SEASAT operated at an altitude of 800 km with one channel L-band (23.5 cm wavelength), HH polarization and a nominal resolution of 25 m. The swath width was 100 km.

IMAGING RADARS ADVANTAGES AND DISADVANTAGES IN AN ARCTIC ENVIRONMENT

Imaging radars, like many other sensors, have their advantages and disadvantages. SLAR and SAR have many common characteristics but differ in resolution. In terms of advantages over optical wavelength sensors, both SAR and SLAR have day/night capabilities, since the radar provides its own illumination and does not require solar illumination. This is especially useful in the Arctic during the long periods of darkness for any application. Of special importance, especially to geological and terrain applications, is the capability of providing illumination from directions other than that provided by the sun. Shadow effects from non-solar orientations can be used to highlight surface features and provide a perspective and information otherwise unobtainable.

Imaging radar, X-band, at 3.2 cm or longer wavelengths has an almost all-weather capability in terms of cloud and rain penetration. The wide swath coverage of up to 100 km on each side of the aircraft, combined with a flying speed of 200-450 knots/h, depending upon aircraft type, allows large areas to be imaged under similar conditions.

Many of the imaging radars that have operated or are operating in the Arctic have suitable resolution, ranging from 6 to 30 m, to identify ice and terrain features and many types of ice. In addition, radar can penetrate dry snow to the ice surface, allowing features such as floes to be identified on

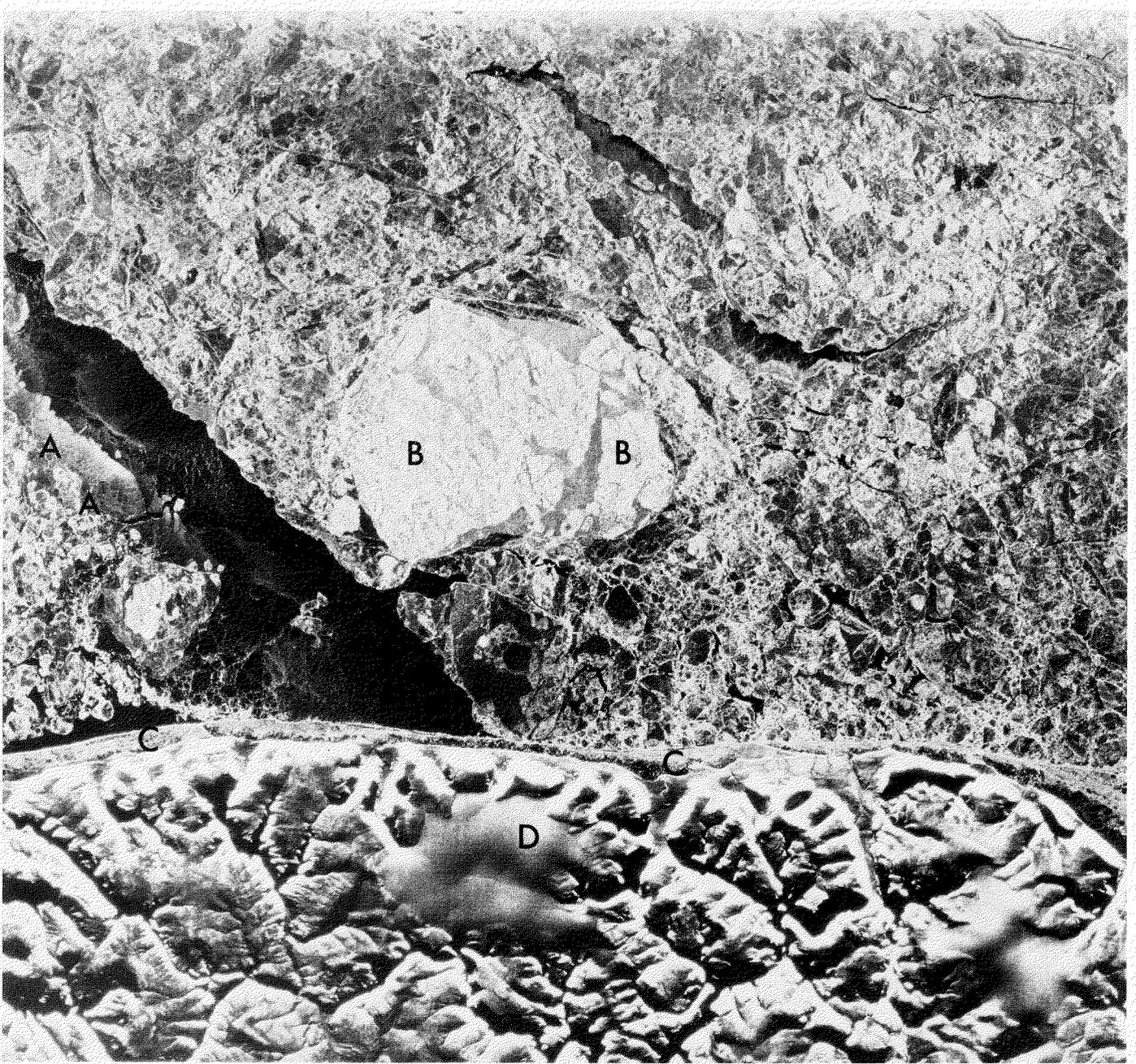


FIG. 3. STAR-1 SAR image of the Sargent Point area of the Brodeur Peninsula, Lancaster Sound. The aircraft was flying from west to east. North is at the top of the image. The full swath image of 46 km is shown. This is a positive image with dark-toned shadows. Ice types range from open water (large black area to left of image) to Nilas and young ice (A), first-year ice over much of the rest of the image and old ice (B). Fast ice (C) is found along the coast. Two large glaciers are located at (D). The image was acquired in late November 1986. (Image courtesy of Intera Information Technologies Corp.)

the radar imagery even though they may not be visible to other non-radar sensors, such as aerial photography.

Radar imagery is available in a near-real-time basis on board the aircraft. Depending on the radar system, hard copy film or paper imagery is available 4-15 minutes after a target or area has been imaged. In addition most systems now record digital data on board the aircraft in the form of high-density digital tape, computer-compatible tape or Exabyte 8 mm tape. The digital data can be used to create more hard copy images, either on board the plane or at a replay station. Digital data can be used in image analysis systems, where the data can also be enhanced or corrected for geometric and radiometric distortion.

Specific Advantages (SAR vs. SLAR)

SAR systems generally yield higher resolution, ranging from 6 to 25 m, depending on the system and configuration used, than SLAR systems, which have a resolution of 30 m or more. SLAR resolution degrades outward (across track) from the aircraft at a rate of approximately 8m/km, whereas the across-track resolution of a SAR remains constant.

SAR systems, in particular the CCRS SAR-580, provide data for more than one polarization or wavelength. In the SAR-580's case, data are provided at C- and X-band using both like- and cross-polarizations. There are presently no multi-band or multi-polarized SLAR systems in operation

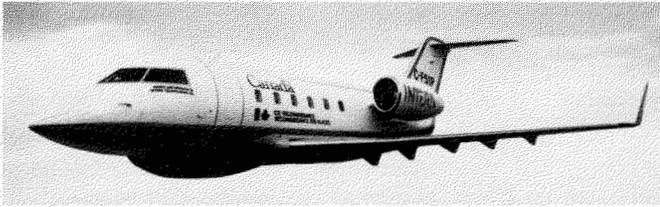


FIG. 4. The Challenger jet aircraft used as a platform for STAR-2, a dual-sided 100 km swath SAR, to provide a Comprehensive Ice Reconnaissance Service (CIRS) for AES. The radar antenna is mounted forward of the wing, under the aircraft, and is covered by a large fibreglass radome (black bubble on the picture). Other SLAR and SAR aircraft radar antennas are located in similar locations on their respective aircraft platforms. SAR antennas are usually bubble shaped, while SLAR antennas are long and narrow. (Image courtesy of Intera.)

in the Arctic. The multi-band, multi-polarized SAR systems are more useful for research purposes than for large-area data acquisition.

SAR systems are optimized for higher data collection altitudes, usually 8000 m and above depending on the aircraft used, while SLAR systems generally operate between 2000 and 5000 m, again depending on the type of system and aircraft used.

Common Imaging Radar Disadvantages

The X-band (3 cm wavelength) signal can sometimes be attenuated by heavy rain or wet snow squalls. This effect is usually temporary and the area affected can be reflown, often in the same mission, if required.

In some cases, such as when the ice is melting, having only one wavelength, e.g., 3 cm and polarization (e.g., HH, horizontal transmit and horizontal receive), can make ice type identification difficult. When wet, most types of ice are difficult to characterize as to type and sometimes to distinguish from calm water.

Small features such as bergy bits, small floes or terrain features cannot be imaged by the radar if below the resolution of radar – i.e., features smaller than 6 m or less than 6 m apart may not be resolved with 6 m resolution. Very rough areas (e.g., rubble fields) and some cultural targets (e.g., metal building or equipment) may appear very bright and saturate the image, giving a loss in detail or information.

RESEARCH, DEVELOPMENT AND APPLICATIONS

Research

Much of the research on imaging radars has focused on the interaction of microwave energy (SLAR, SAR airborne and satellite) and sea and glacial ice of various ages. It is important to consistently identify possible hazards and extraordinary conditions that could be of advantage or present problems to navigation or operations. Some of the main research areas involved the identification of ice types and features, forecasting ice motion, providing ice floe statistics, climatological research and iceberg detection.

In ice type identification, research has focused on the characteristics of different ice types as they appear on a radar image. Considerable success has been shown by many investigators in identifying and separating old ice, first-year ice and younger ice based on tone, texture and shape under cold conditions (Hawkins *et al.*, 1980; Intera, 1980). Unfortunately, ice identification is less reliable under warm ice conditions,

when the ice is melting or covered with water. The use of multiple wavelengths and polarizations for radar or other non-radar sensors can increase the reliability of identification of various types of ice (Hawkins *et al.*, 1980; Lapp, 1982; Pearson *et al.*, 1980).

The identification of ice features such as ridges and leads is important to shipping and offshore drill operations (Mercer *et al.*, 1980). Statistical studies of mean and maximum ridge dimensions, distributions and ridge orientations have been undertaken to provide input into the design of offshore structures and ships navigating in ice. Localized effects often limit the extrapolation of data from one part of the Arctic to another. Many ridge studies have included data from other sensors, such as stereo-photography or laser profilometers, along with ground and below-ice measurement (Kirby and Sutton, 1981).

Ice motion forecasting is an important consideration in the Arctic and as such has received considerable study by both government and industry, which have combined their efforts on modelling projects for both sea ice and iceberg motion. Initial efforts focused on the Beaufort Sea, where imaging radar was the main input into the development of several forecast models. The higher resolution of SAR data allowed features such as leads, cracks and small floes to be spotted and monitored more easily than with SLAR data. Illumination was also more even across the image than with SLAR, although the swath widths were narrower. As with other research into various aspects of ice, regional and local variations make it difficult to use one regionally specific model in another region without major modifications (Intera, 1981).

Floe statistics generated from the analysis of SLAR and SAR imagery have provided information on the distribution of floe sizes in relation to ice type and location. This data has been used in design considerations for the design of ships' bows and in navigation criteria and operational windows for different parts of the Arctic (Canarctic, 1988).

Climatological research into ice types present over a long period of time in certain areas has led to improvements in the understanding of the ice regime present and has paid off in direct applications to ship navigation in ice (Norland, 1986).

Iceberg detection has been studied using both SLAR and SAR (Kirby and Lowry, 1979; Lapp, 1982). The radar parameters such as aspect and incidence angle, position in the swath and general target characteristics are well known, but the variability of the actual target characteristics, sea state and the presence of non-iceberg targets, such as ships, still present problems in the correct identification of icebergs and their separation from other targets under difficult conditions.

Increasing emphasis has been placed on the study of ice and icebergs by digital methods using image analysis systems as opposed to older visual methods (Kirby, 1980). While visual interpretation is still important, digital data allow more in-depth analysis. Radiometric and geometric correction are possible on digital data but are much more difficult, if not impossible, on analogue data, such as the older SLAR film outputs.

Research in recent years has been focused somewhat away from the Arctic to the less well-known marginal ice zone in the Labrador and Greenland seas. Experiments such as LIMEX (Labrador Ice Marginal Experiment) have improved our understanding of the marginal ice zone.

Development

A number of developments have been made in the improvement of SAR and SLAR hardware, software, display and downlinking capabilities. Data outputs have improved from the film negative from the Motorola SLAR to digitally downlinked near-real-time data available in soft or hard copy wherever the receiving equipment is located. Some of the major developments related to SAR and SLAR that were brought about due in part or completely to arctic requirements are the development of a real-time hard copy display for the CV-580, real-time downlinking of data and the integration of airborne and marine data.

A real-time hard copy paper display for use on the CV-580 was developed to monitor data quality, coverage and navigational accuracy. Initially this hard copy output was sent down to a shipboard receiving station by a video downlink. Copies of the dry silver paper strips were mosaicked together to provide an overall perspective for use on board the drill ships in the Beaufort Sea. Later developments increased the quality of the hard copy output and made it available in positive or negative format and in digital format for direct downlinking.

Real-time downlinking of data provided data to the ships in the quickest possible way and did away with risky low-level data drops from aircraft or the need to have data flown out by helicopter when the aircraft landed at base. Any number of suitably equipped ships or ground stations within range could receive digital data and hard copy output during the flight. The initial downlink stations consisted of a hard copy replay unit, receiver, data formatter and storage capability in the form of 1600 bpi, 9 track tapes and associated tape drive. STAR-VUE, a more recent, much improved downlink station, has increased display and archiving capabilities along with improved hard and soft copy units and is in use on a number of Canadian Coast Guard ships. STAR-VUE has also been used on a commercial basis.

Airborne radar data were integrated to marine radar to extend the life and usefulness of the SAR data. Initially using the Radar Image Display System (RIDS), data were presented on separate screens for review by the user for features (e.g., floes, ridges and leads) in common on both data sets. Later work has integrated the two radar displays even more closely.

Applications

There are a number of applications, some of which are ongoing and others that are one-time efforts due to a particular location, feature or need. Applications tend to be related to the need for reliable, readily available data in periods of low visibility, when most other sensors cannot operate. Major applications have been ongoing ice reconnaissance for navigation, historical data base creation, forecasting, trafficability studies and geological data collection.

Ongoing ice reconnaissance flights in support of navigation (Hengeveld, 1980) provide data for ice climatological purposes by the creation of an historical data base to better our understanding of ice conditions over time. This broad mandate has been covered by AES using, until recently, equipment it has either owned or operated and usually using government employees or ice observers. Recently, with the adoption of a commercially provided service, CIRS, AES has brought on an industrial contractor for data acquisition (Mercer, 1989).

In the Eastern Arctic, SAR and SLAR data have been used for tactical purposes in navigating through ice-infested waters. SAR data, in particular, have extended the shipping season and have aided ships such as Canarctic's *MV Arctic* in penetrating farther into the ice than would have been otherwise possible. By creating a data base of SAR, SLAR and NOAA imagery over time, it has been possible to determine the ice conditions in areas where breakup does not occur every year (Canarctic, 1988). In this case, thinner ice is identified in the fall of one year and checked the next year to see if it is still suitably thin for a vessel transit.

Under agreements between the oil and gas exploration companies and commercial suppliers of imaging radar data, large areas of the Beaufort Sea are flown on a regular basis to monitor ice motion and conditions. The data collected are analyzed for input into a model for forecasting purposes. Under most conditions the flights are every few days, but when conditions deteriorate it is a condition of the drilling regulations that data be available on a regular and timely basis. This can often require daily or even twice daily flights and downlinking of data to the affected drill sites.

Other long-term projects have used SAR to collect ice data for analysis of ice types, floe sizes, distributors and ice feature data. These have occurred during most seasons to obtain a reliable data base. Surface trafficability studies have been made using SLAR and SAR in the western and high arctic areas.

Other non-ice applications are becoming more important, especially with the advent of a Canadian Radar Satellite. Data collected over Cornwallis Island by STAR-2 have been used for geological interpretation and for integration with other sensors to give, once digitally combined with other data, more information than any one sensor contained by itself. STAR data of the Houghton meteor crater on Devon Island were collected for geological interpretation and for simulation of how a satellite-borne SAR would view the crater.

CONCLUSIONS

Imaging radar data, in the form of SAR and SLAR data from a variety of government and non-government sources, have played an important role in the support of navigation, resupply missions to northern locations and oil and gas exploration and development in the Arctic. Applications, operations and initiatives that would have otherwise been delayed or put off have been able to proceed safely with savings in time and fuel, along with other decreases in expenses through the use of imaging radar data. Airborne radars have become one of the main sources of information regarding ice conditions in the Canadian Arctic and, while they may be used to supplement any future radar satellites, they are unlikely to be replaced by satellites in the near future due to the fact that airborne data can be collected almost on demand. This is especially useful for applications that may not be able to wait for the next satellite pass. The increased resolution of the airborne SARs, along with multiple channels and polarizations in the case of the CCRS SAR, has expanded the use of airborne radar systems.

APPENDIX — DATA AVAILABILITY AND FORMAT

The largest suppliers of imaging radar data available to the public are AES and CCRS. Much of the data flown by commercial com-

panies was usually of a proprietary nature and is, therefore, not generally available. The following is provided for information purposes only and is subject to change by the agency involved.

AES SLAR and SAR Data: Data from almost 3000 SLAR flights made by AES aircraft from February 1978 to the present are archived by AES, Ice Climatology, at Ice Centre in Ottawa. Data available are in the form of SLAR negatives, flight logs and ice charts. Further information on specifications, coverage areas and ordering procedures and costs can be obtained from: AES, Ice Climatology Division, Mr. D. Mudry, 373 Sussex Drive, Block E, Ottawa, Ontario, Canada K1A 0H3; (613) 996-1550.

CCRS SAR Data Availability: SAR data from CCRS can be broken down to two types: older X-L data, which are recorded on 70 mm B&W film negative and archived at the National Airphoto Library (NAPL) in Ottawa, and X-C data in digital format (HDDT and if transcribed, CCTs) through CCRS, also in Ottawa. Application should be made to: CCRS Airborne Products Order Desk, (613) 991-5532.

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