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GREAT LAKES WINTER EXPERIMENT 2002 (GLAWEX 2002)

SYNTHETIC APERTURE RADAR APPLICATIONS TO ICE-COVERED LAKES AND RIVERS

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S. V. NGHIEM (JPL) AND G. A. LESHKEVICH (GLERL)

National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology

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1. INTRODUCTION

The Laurentian Great Lakes with its vast natural resource contribute significantly to economic and social activities of North America. This area provides 20% of the United States gross national product, where one in eight Americans live. Ice cover in the Great Lakes, the most obvious seasonal transformation in the physical characteristics of the lakes, has a major impact on the regional climate, local commerce, and public safety. Information on ice concentration, the areal percentage of ice coverage on the lake surface, is valuable to the shipping industry and to all involved in winter navigation. Extending the winter navigation season can save millions of dollars in coal and ore shipping. Ice can impose navigation hazards in marine ports such as Duluth and Chicago and important waterways such as the St. Mary River and the St. Lawrence Seaway.

In particular, the Great Lakes region has recently suffered anomalous and prolonged Arctic cold conditions. Consequently, three large lakes of the Great Lakes - Lake Superior, Lake Huron, and Lake Erie - have frozen over for the first time in nearly a decade [*CNN/Reuters*, 2003]. The St. Lawrence Seaway officials decided to postpone its opening for almost a week, from March 25 to March 31, and hoped that the ice conditions would be alleviated by then [*ABC/Reynolds*, 2003]. The navigation delay may cause major disruptions down the supply chain and the timing is horrible for manufacturers dependent on materials like steel [*ABC/Reynolds*, 2003]. In the Duluth Harbor, ice was more than 2 feet thick in spots on the Duluth side, and was even thicker across the way in Superior, and this year could have a very difficult opening as indicated by the Executive Director of the Duluth Seaway Port Authority [*NBC/Meryhew*, 2003].

In the world's largest freshwater surface covering an enormous area of 245,000 km^2 with a drainage basin extending 1110 km north-south and 1390 km east-west, the ice cover is inherently a large-scale problem. The nature of the ice cover problem in large lakes and in extensive waterways demands the use of satellite SAR data to satisfy the required high resolution and the large areal coverage simultaneously. The major utility of synthetic aperture radar (SAR) is its high resolution, which is appropriate to monitor ice navigation hazards in shipping lanes in lakes and rivers. Moreover, microwave SAR has the capability to see through clouds with negligible atmospheric effects. The all-weather, day/night sensing capabilities of SAR make it well suited to the short daylight, cloud dominated winter conditions in the Great Lakes region. For applications to ice mapping, the Great LAkes Winter EXperiment (GLAWEX 2002) was carried out in February-March 2002 using the NASA/JPL AIRSAR system aboard the NASA DC-8 Aircraft deployed along the US Coast Guard Mackinaw icebreaker ship tracks over various locations in Lake Superior, Lake Huron, and Lake Michigan. GLAWEX 2002 were conducted by the NOAA Great Lakes Environmental Research Laboratory (GLERL) and the Jet Propulsion Laboratory (JPL) with ship and helicopter supports from the United States Coast Guard (USCG).

2. GLAWEX 2002

The objective of the GLAWEX 2002 experiment is to map the Great Lakes ice cover in three dimensions including ice area, ice type, and ice thickness for scientific and operational applications. The method is to use polarimetric and interferometric SAR together with field observations and in-situ measurements. Results are to be applied to satellite multipolar/polarimetric SARs such as ENVISAT, RADARSAT-2, ALOS, and other future SAR in the long term, and to determine design parameters and use of future interferometric SAR. Results from this experiment and their applications to long-term SAR data help to address direct applications including shipping navigation, recruitment forecast for the fishing industry, and ice hazards in hydropower industry, as well as science topics including ice mass and marine water level change, climate change, ecosystem change and its environmental and biological effects.

Figure 1: NASA DC-8 aircraft carrying AIRSAR system deployed for GLAWEX 2002.

In GLAWEX 2002, the NASA DC-8 aircraft (Figure 1) carrying the NASA/JPL AIRSAR system was deployed to the Great Lakes in multiple flights from Madison, Wisconsin. AIRSAR collected polarimetric and interferometric SAR data over various ice types. The SAR frequencies include P, L, and C bands, which are consistent with many past, present, and future satellite SAR such as ERS, RADARSAT, ENVISAT, and ALOS so that results from GLAWEX 2002 can be applicable these satellite SARs.

Furthermore, AIRSAR data with multi-frequency polarimetric and interferometric modes can be analyzed to determine optimal SAR modes for a future SAR system for lake and river ice remote sensing. Under NASA support, AIRSAR was deployed in three phases in February and March 2002 to acquire data along US Coast Guard (USCG) Mackinaw icebreaker ship tracks. Figure 2 presents the map of AIRSAR data collection areas in Lake Superior, Lake Huron, Lake Michigan, and St. Mary River.

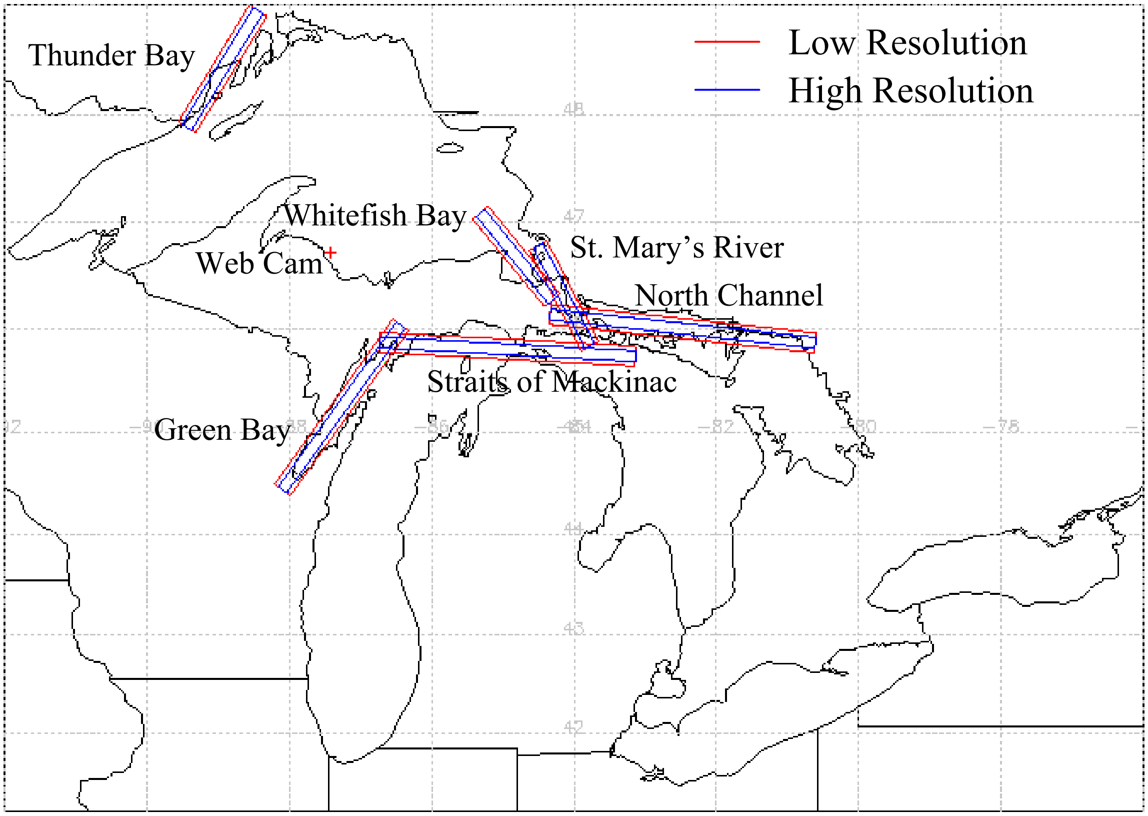

Figure 2: AIRSAR data collection areas in low and high resolutions over the Great Lakes

Ship and helicopter supports for GLAWEX were provided by USCG. We coordinate the Great Lakes field campaign for concurrent USCG ship and NASA aircraft deployment. Field observations and in-situ measurements were obtained from USCG ship. Ice thickness, ice and snow characteristics, and environmental data were collected at many locations where the USCG stopped for the field work. Lake ice cores were also taken to measure ice density and ice layer structure. Air reconnaissance flights were also carried out by USCG helicopter for ice observations during GLAWEX 2002. Moreover, RADARSAT SAR images over the Great Lakes were transferred to the ship during GLAWEX via the US Naval and National Ice Center with data subseting, compressing, and posting by the NOAA Great Lakes Environmental Research Laboratory (GLERL). The RADARSAT images were obtained with a JPL setup for an Internet connection via the Iridium Satellite to the USCG ship during GLAWEX. Furthermore, concurrent QuikSCAT images processed by JPL were transferred to the ship in the same manner. Surface data from the Great Lakes Marine Network were obtained and archived for later analysis of GLAWEX data. Surface temperature and wind field over the Great Lakes were produced by NOAA GLERL, which cover the time period of GLAWEX 2002.

We present some initial results here. The left panel of Figure 3 shows an AIRSAR (POLSAR) image of a portion of Whitefish Bay on Lake Superior (March 20, 2002). The X-shaped feature near the bottom of the SAR image is the Sault Ste. Marie Airport, whose aerial photo is in the right of Figure 3 (Sault Ste. Marie Airport Development Corp., http://www.saultairport.com). The SAR synthesized false color image composed of Bands C (HH, blue), L (VV, green), and P (VV, red) reveals different ice types in the ice cover. The color indicates the roughness/ice volume of the different ice types at each respective band. White indicates sufficient roughness/ice volume at all bands. For example, the white colored band of brash ice spanning the lower portion of the bay (northwest of the airport) is at least 4.5 ft. thick (also see Figures 4 and 7).

Figure 3: (a) Left panel is AIRSAR false-color image of the a portion of Whitefish Bay containing various ice types, and (b) Right panel is an aerial photo of the Sault Ste. Marie airport (from http://www.saultairport.com/physicallayout.html) that appears as the X-shaped feature near the bottom of the SAR image.

A close examination of the SAR image in Figure 4 reveals the track of the US Coast Guard icebreaker Mackinaw coming out of the St. Mary's River. This track progresses northwest to the ice floe (white) just southwest of Ile Parisienne. It is clear in the zoomed in SAR image in Figure 4 that that the USCG Mackinaw icebreaker ship track (horizontal arrow) encountered across the thick brash ice areas (vertical arrow), which straddled across the Whitefish Bay. The Sault Ste. Marie Airport also appears with more details and the runways physical layout is clearly observed.

Figure 4: Zoomed-in SAR image revealing the US Coast Guard Mackinaw ship track encountering thick brash ice in the Whitefish Bay.

The Mackinaw is an Arctic class icebreaker ship and yet it experienced significant difficulties in cutting through the thick brash ice area in Whitefish Bay. Figure 5 is a photograph of the USCG Mackinaw icebreaker ship stopped in brash ice in Whitefish Bay. This type of ice can be very thick. Such thickness is caused by strong wind pushing the ice together and piling the ice with much of the ice volume under the surface water level. Figure 6 is another zoomed in SAR image corresponding to the area occupied by a large ice area in the middle of the SAR image in Figure 3. The Mackinaw ship track is the vertical bright line in Figure 6 trailing a bright elongated spot in the middle of the image. The bright spot is actually the USCG Mackinaw ship itself. The Mackinaw is a 290-foot icebreaker run on six diesel engines. When commissioned in 1944, Mackinaw was the most powerful and capable icebreaker in the world.

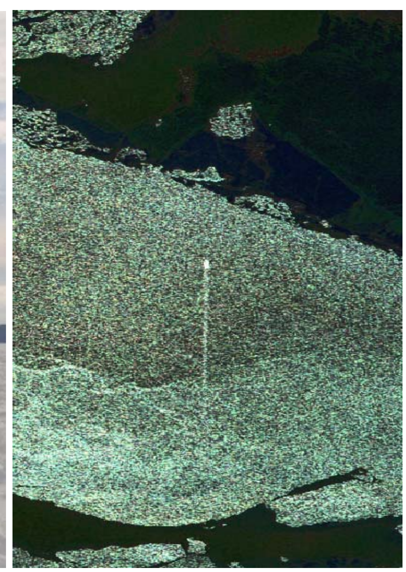

Figure 5: USCG Mackinaw icebreaker stopped in a brash ice area in Whitefish Bay in Lake Superior.

Figure 6: Mackinaw in SAR image with trailing ship track

Figure 7 shows initial results of ice classification in Whitefish bay using cross-polarized backscatter in polarimetric SAR data set. We use red color to represent brash ice, green for patchy snow cover on snow ice over lake ice and rough consolidated ice floes, and yellow for black ice with thin snow. The classification is based on the backscatter library obtain in GLAWEX 1997 using the JPL shipborne C-band polarimetric scatterometer, and the results in Figure 7 are consistent with field observations from the Mackinaw ship. These are initial results and they can be improved when AIRSAR data are better calibrated. This is an illustration of the utility of SAR to identify different ice types for lake navigation in ice-infested areas. Such information will be very useful for USCG icebreaking operations and for monitoring shipping lanes in lakes and rivers.

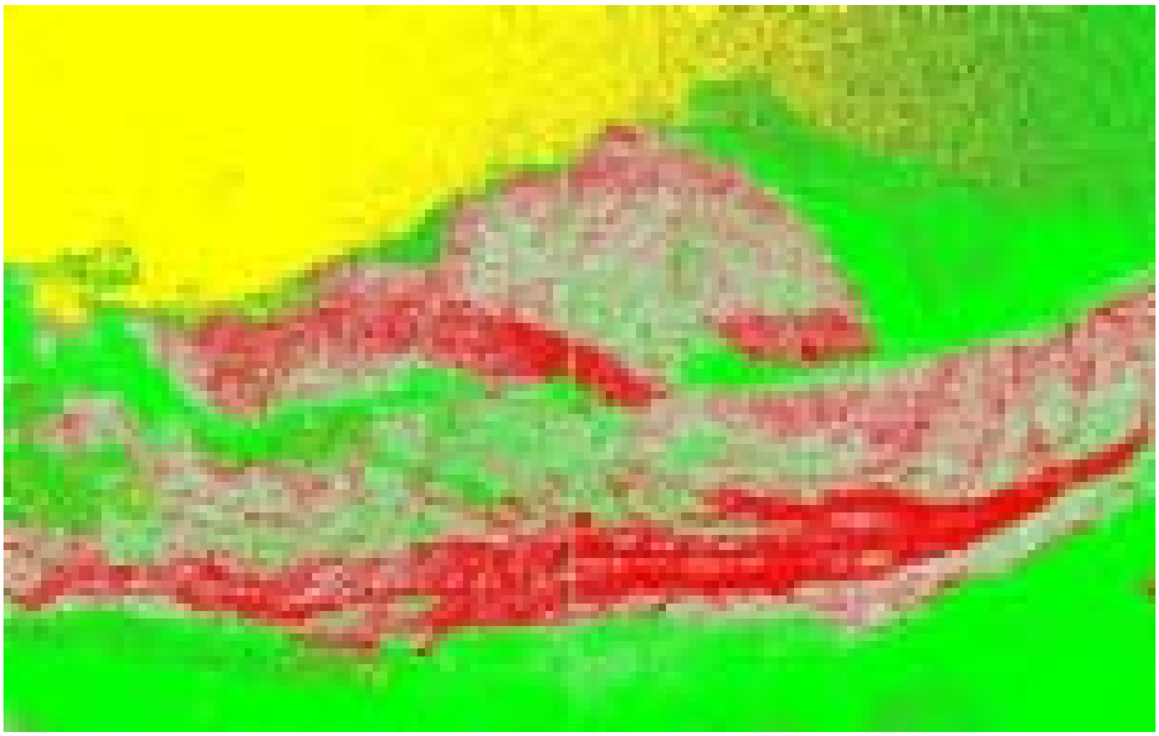

Figure 7: Ice classification results in Whitefish Bay (corresponding to the brash ice area in Figure 4): Red for brash ice, green for patchy snow on snow ice over lake ice and consolidated ice floes, and yellow for black ice with thin snow cover.

As presented in Figure 2, AIRSAR collected data over various areas over many ice types. We show examples of quick-look images in several locations. Figure 8 is an AIRSAR image (top panel) for an ice area in Green Bay (Lake Michigan), where brightness corresponds to the radar cross-section at L-band (1.3 GHz) and the color proportional to the ratio of the HH and VV polarimetric channels suggesting that more ice types can be identified using multiple polarization data. The area identified by the green color in the middle of the SAR image is Chambers Island. Compared with an aerial photograph (bottom panel) of the same area, the SAR image reveal more ice types with more features than the optical observation in the photograph. This photograph was taken by the USCG from a helicopter in an ice reconnaissance flight mission during the first phase of GLAWEX 2002.

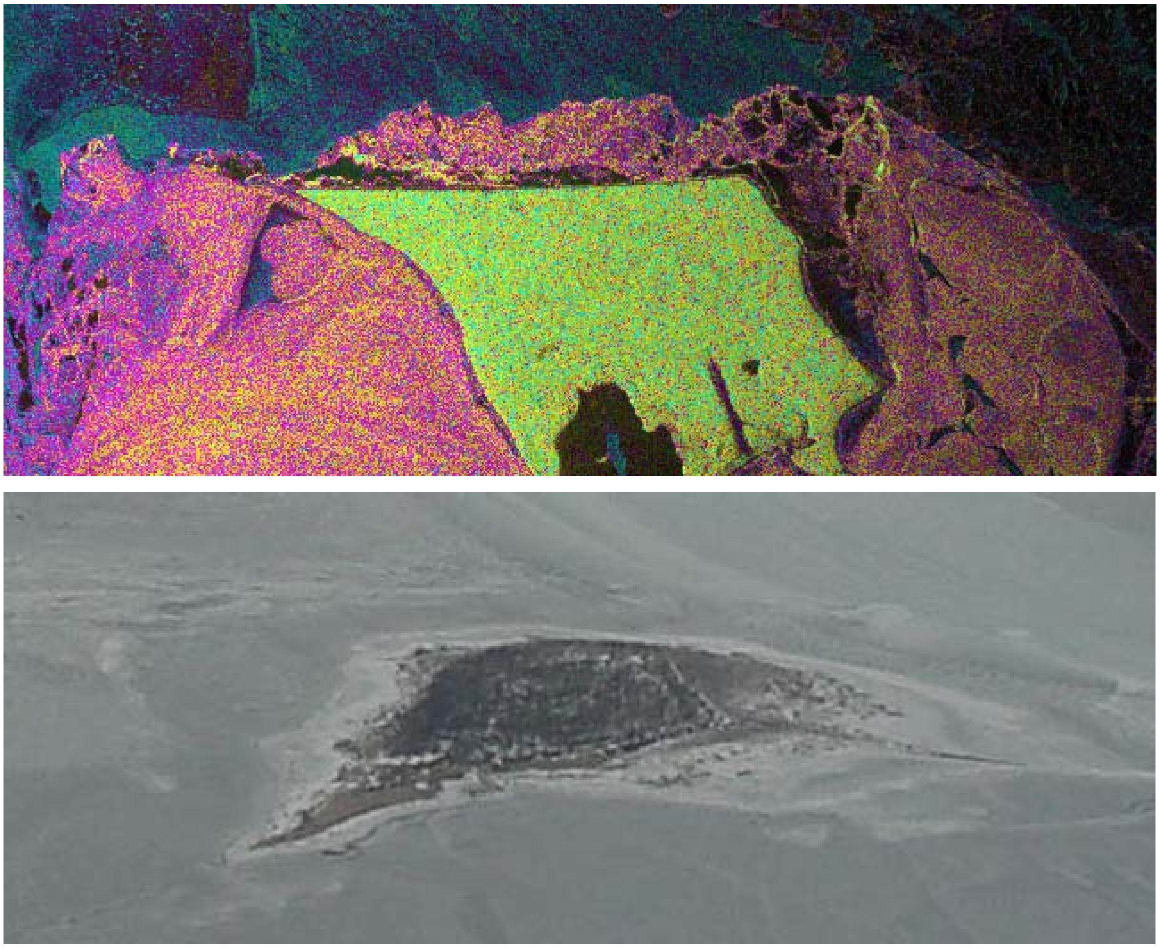

Figure 8: Images of ice surrounding Chambers Island in Green Bay, Lake Michigan: (a) Top panel is and L-band AIRSAR image for an ice area in Green Bay with color proportional to the ratio of the HH and VV polarimetric channels, and (b) bottom panel is an aerial photograph of the same location. Note that the look angles and azimuth orientations are different between the two images.

Figure 9 consists of two panels showing an ice-covered area in Thunder Bay (Lake Superior) where the Mackinaw ship track is seen as the straight lines. The top panel is a color combination of C-band horizontal co-polarized backscatter (HH) and vertical co-polarized backscatter (VV) together with total radar brightness. Water appears as yellow while different ice types show up as blue to purple. The bottom panel in Figure 8 is the same image type in Thunder Bay for L-band VV, HH, and total brightness combination. The results at different frequencies suggest that more ice types can be detected using multiple frequencies. Note that the ship tracks appear differently in the two images at L and C bands. Moreover, the high resolution of SAR enables applications to river ice. An example of the survey product from AIRSAR flight on 10 March 2002 is shown in Figure 10, which clearly reveals the ship track in the frozen St. Marie River. These AIRSAR data are not fully calibrated and to date only a very small fraction of this unique valuable data have been processed.

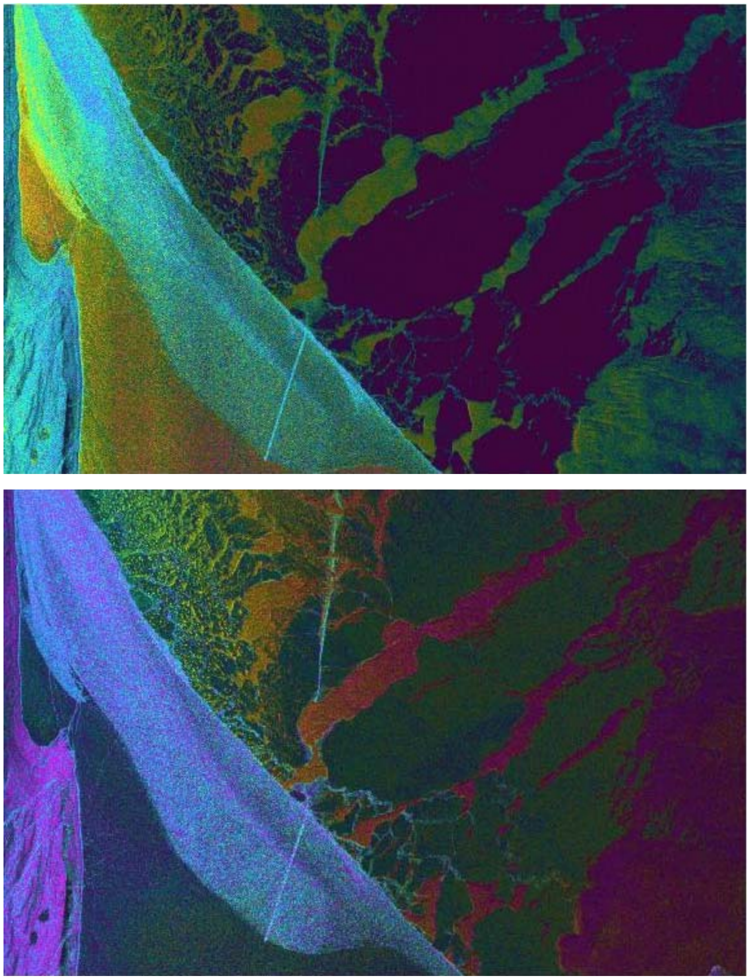

Figure 9: Thunder Bay image for combination of HH, VV, and total radar brightness at C band (top panel) and L band (bottom panel).

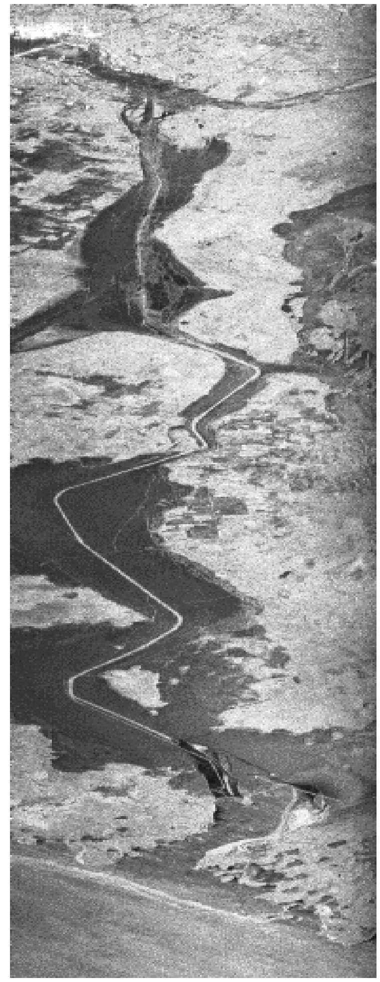

Figure 10: Ship track along the frozen St. Marie River imaged by AIRSAR.

3. SAR APPLICATIONS FOR LAKE AND RIVER ICE

Much of the satellite ice interpretation algorithm development in the Great Lakes region began during the Extension to the Navigation Season Demonstration Study conducted during the 1970's. However, many of the early studies were done by visual interpretation of satellite and other remotely sensed data. Starting in the mid-1970's, a series of studies including field studies and computer digital image processing, explored techniques and algorithms to classify and map freshwater ice cover using LANDSAT, NOAA/AVHRR, ERS-1/2, and RADARSAT SAR data. The goal of much of this work is to develop an automated or semi-automated method to classify and map Great Lakes ice cover using satellite digital imagery.

All single-frequency and single-polarization SAR applications to Great Lakes ice have been for areal mapping which result in the discrimination of a limited number of ice types under favorable conditions. The GLAWEX campaign series provide unique, extensive, and valuable data sets that need to be processed, analyzed, and fully exploited for lake and river ice applications. With results obtained so far, we suggest the following parameters for lake and river ice applications of SAR:

1. **Frequency:** L band or higher (C, X, and Ku band) although L band may have somewhat weak response to certain ice types and more study is needed. Also, multiple frequencies can identify more ice types.
2. **Multiple polarizations:** HH and VV dual polarization, or HH, VV, HV triplet is recommended to have robust ice/water and ice classification algorithms.
3. **Polarimetric data:** Various polarimetric backscattering coefficients in the polarimetric covariance matrix or the Mueller matrix need to be studied. Initial indication suggests polarimetric phase information is useful for ice type identification.
4. **Interferometric data:** not much calibrated data is available. This is a new type of data collected over fresh-water lake and river ice together with surface measurements. Efforts are necessary to investigate and determine the utility of interferometric SAR data for ice types and ice thickness measurements.
5. **Resolution:** 100 m or better for large lake, 30 m or better for river ice.
6. **Revisit frequency and coverage:** 3 days or less, SAR swath of 400 km or larger.

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FOR MORE INFORMATION, CONTACT:

G. A. Leshkevich (GLAWEX PI)
NOAA Great Lakes Environmental Research Laboratory
2205 Commonwealth Boulevard
Ann Arbor, MI 48105
Tel: 734-741-2265
Fax: 734-741-2055
George.Leshkevich@noaa.gov

S. V. Nghiem (GLAWEX Co-PI)
Jet Propulsion Laboratory, 300-235
California Institute of Technology
4800 Oak Grove Drive
Pasadena, CA 91109
Tel: 818-354-2982
Fax: 818-393-3077
Son.V.Nghiem@jpl.nasa.gov