

River Ice Conditions Determined from ERS-1 SAR

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ABSTRACT

CRREL has received digital data for 15 European Space Agency (ESA) European Remote Sensing (ERS) Satellite-1 synthetic aperture radar (SAR) images of the St. Marys, Connecticut and White Rivers, acquired from 16 December 1992 to 5 May 1993. Satellite-borne SARs such as those onboard ERS-1 acquire radar image data in all weather conditions and at night. Data for four of the 15 images have been processed to determine ice conditions on the rivers as detected by this satellite-borne SAR. Extensive data bases of past ice conditions on these rivers, ground observations, ice thickness measurements and low-altitude aerial photographs collected during or within three days of ERS-1 overpasses were used to evaluate SAR image patterns resulting from the river ice on the four images. The preliminary results of these evaluations suggest that satellite-borne SARs will provide data on river ice conditions that are necessary for navigating through ice and for evaluating the potential for river ice jams and ice erosion along shorelines.

INTRODUCTION

Background

The Corps of Engineers is responsible for managing navigable waterways throughout the United States. As part of its management duties, the Corps must operate locks and dams throughout the year on some rivers and must deal with the special problems of winter navigation when rivers are partially or completely ice covered. On the St. Marys River in Michigan, the locks located at Sault Ste. Marie are usually operated until mid- to late January. Ice conditions at

this time have usually become severe enough to prohibit ship passage without ice-breaking operations. Thus, around this time each year, the locks are closed and ships cannot navigate through the locks until about mid- to late March when the locks re-open.

Before the locks are closed and after they are re-opened, the St. Marys River is usually ice covered to some extent. Nearshore ice made mobile during ship passage may erode banks and uproot and break plants along the river shoreline, causing loss of lands and nearshore emergent wetland habitats. There is also considerable concern that as ships navigate through the ice in the spring, ship-induced waves and currents in the nearshore zone may cause increased concussion of ice with fish habitats, leading to premature hatching of fish eggs at a time when the food supply for larval fish is very low and their survival would be clearly jeopardized. The increased agitation and re-suspension of nearshore, river-bed sediment caused when ships pass while ice is on the river may also cause fish egg burial and mortality. On the Connecticut River and many other New England rivers, ice jams are a major concern nearly every spring. Some of the worst floods of record in New England occur as a result of ice jams.

The capability to use a satellite-borne, synthetic aperture radar (SAR), such as that onboard the ERS-1, for monitoring river ice conditions would prove useful in providing data for navigating through ice on inland waterways, operating locks and dams in the winter, evaluating environmental effects of winter navigation along river shorelines, evaluating the potential for ice jam occurrence and carrying out emergency operations during ice jams. The objective of this study was to determine if ERS-1 images could be used for monitoring river ice conditions for such ice

engineering applications. This study constitutes a "first-look" determination because I used unsophisticated image analysis techniques and had a limited number of sample sites. In-depth study is necessary to determine the operational utility of the ERS-1 SAR imagery.

Previous Research

Results of previous studies confirm that airborne SARs distinguish river and lake ice features such as hummocked ice covers, ice jams, smooth and level ice, overflows onto ice and open water leads. Melloh and Gatto (1990a, b, c, 1992) used the radar backscatter measured by the Jet Propulsion Laboratory's SAR for studies on the Tanana River in Alaska, and Leconte and Klassen (1991) used the Canadian Centre for Remote Sensing's SAR for studies on the Burntwood River in northern Manitoba. These SARs measure radar backscatter in four bands, C, L, P and X, and four polarizations, VV, VH, HH and HV.

My initial interpretations of river ice patterns shown on a European Space Agency's (ESA) European Remote Sensing Satellite (ERS)-1 C-band, VV, SAR image of the Sagavanirktok River in Alaska, taken on 20 February 1992, suggest that surface characteristics of river ice, such as reaches of rough and smooth ice, are apparent (Gatto et al. 1992). Chacho and others (1992) also used ERS-1 SAR images and ground-based, short-pulse radar to map subsurface water beneath ice along the Sagavanirktok River floodplain. These initial results suggest that the ERS-1 SAR may provide data on river ice characteristics as useful as those obtained from airborne SARs.

FRESHWATER ICE AND ERS-1 RADAR WAVE INTERACTIONS

The ERS-1 SAR obtains strips of high-resolution imagery along the right side of the satellite. The SAR's 10-m-long antenna, aligned parallel to the flight track, directs a narrow radar beam onto the Earth's surface over a 100-km-wide swath along the ground. The imagery is built up from the time delay and strength of the returned signals (ESA 1992a, b). The radar return received by a SAR is determined by the polarization, depression angle and wavelength of the radar system and the complex dielectric constant, surface roughness, subsurface roughness or volume scatterers within the target terrain and the range (distance) of the target from the satellite.

The dielectric constant of freshwater ice is between 3.0 and 3.2, depending on the amount of air inclusions present in the ice (Vickers 1975). Freshwater

ice is also a low-loss dielectric, i.e., little incident microwave radiation is absorbed, because it generally does not contain high concentrations of ionic impurities that strongly interact with incident microwave energy (Leconte and Klassen 1991). Thus, much of the incident microwave energy can penetrate a smooth surface layer of freshwater ice and be scattered within the ice at interfaces between materials of dielectric differences, such as air bubbles and sediment within the ice. If the microwaves penetrate deeply enough, they can be scattered from the ice-water interface or ice-sediment interface if the ice is grounded near the shore. The ice-water interface is a strong reflector because water has a dielectric constant of about 80.

Thus, the amount of backscatter reflected from freshwater ice results primarily from surface and subsurface interfaces encountered by the transmitted wave. Rough ice surfaces or bubbly ice could produce high backscatter while smooth or clear ice itself would cause little return while interfaces below such ice could reflect substantial microwaves.

APPROACH

I chose the St. Marys, Connecticut and White Rivers for this evaluation because field data are available and the rivers are very different and thus afford an excellent opportunity to compare ice conditions from three distinct river regimes. The White River is the smallest and steepest, the Connecticut is intermediate and the St. Marys is the widest and flattest (Table 1). The gradient of the St. Marys river changes at the St. Marys Falls north of Sault Ste. Marie; upstream of the falls to Lake Superior the gradient is $.7 \times 10^{-5}$; downstream to Lake Huron the gradient is $.3 \times 10^{-5}$.

Image data for three SAR scenes of the St. Marys River and one of the Connecticut and White Rivers (Fig. 1) were processed for this evaluation. The computer techniques used to produce the images I interpreted included contrast stretching, image brightness changes and despeckling. The patterns on the images produced by the river ice on the Connecticut and White Rivers were then compared to the ice conditions as documented by field observations, photographs and ice thickness measurements. In the case of the St. Marys River ice, low-altitude, oblique aerial photographs and measured ice thicknesses were provided by the Detroit District of the Corps of Engineers for the comparisons. The Corps measured the ice thickness and observed the general ice conditions at six sites along an 11.3-km reach downstream from Sault Ste. Marie, Michigan.

Table 1. Rivers evaluated.

| River | Drainage Area (km ²) | Typical Jan-Feb Discharge (m ³ /s) | Average Stream Gradient | Stream Width (m) |
|-------------|----------------------------------|---|--|------------------|
| White | 1820 | 13-25 | $.12 \times 10^{-2}$ | 50-150 |
| Connecticut | 8780 | 84 | $.3 \times 10^{-3}$ | 100-500 |
| St. Marys | (Lake Superior) | 1680 | $.7 \times 10^{-5}$ $.3 \times 10^{-5}$ | 91-12,000 |

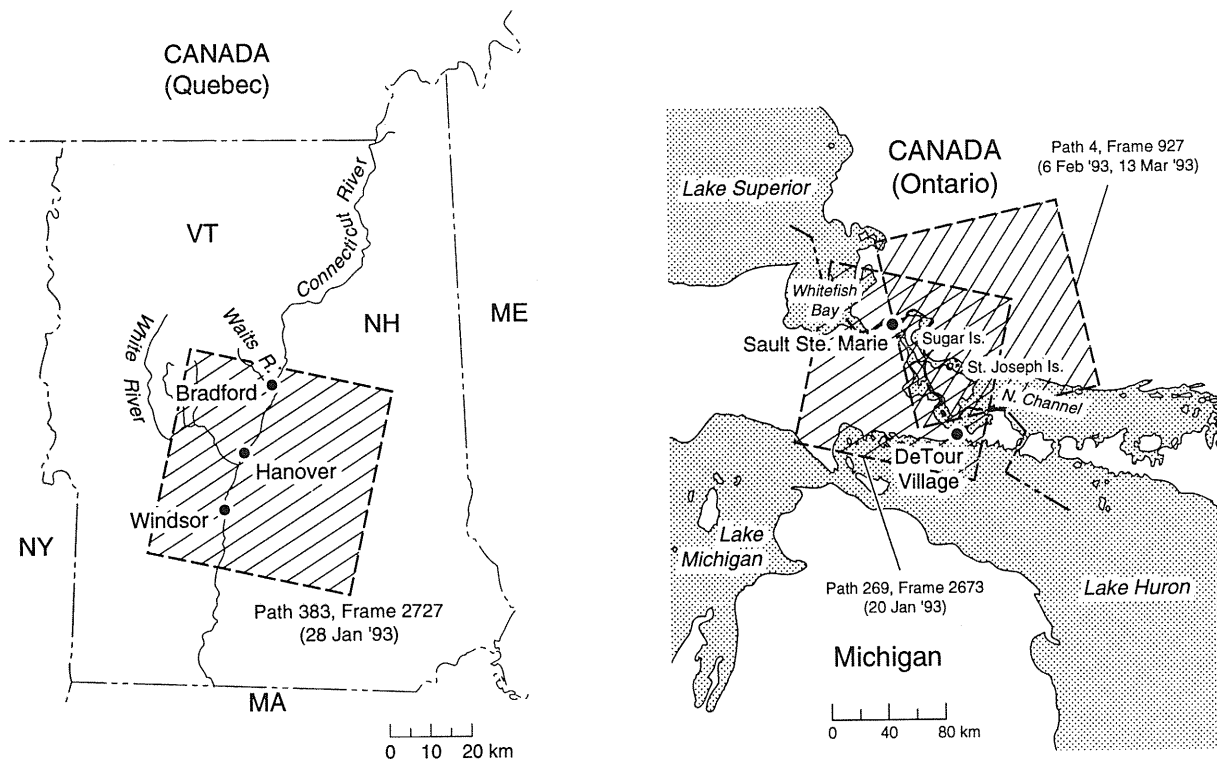


Figure 1. Location maps.

RESULTS

White River

The SAR image was acquired on 28 January when the air temperature was approximately -8°C and had been below freezing since the late afternoon of the previous day. The high temperatures from 25 to 27 January were 3.9, -1.7 and 4.4°C, respectively. Snow cover on the ice was patchy and generally less than 2 cm deep and its temperature would be below freezing on 28 January. Cold, dry snow is virtually transparent to the C-band microwave radiation of the ERS-1

SAR and the snow would produce virtually no signature on the SAR image.

The White River is the shallowest and narrowest of the three rivers (Table 1) and thus is more difficult to see distinctly on the SAR image (Fig. 2) than the other rivers. I surveyed the White River along the reach included within the area imaged by the SAR (Fig. 1) on 28 January and observed a variety of ice conditions. Near its confluence with the Connecticut River, approximately half the channel was open with frazil pans floating in the open water, but this condition is not apparent on the SAR image. Areas of thin

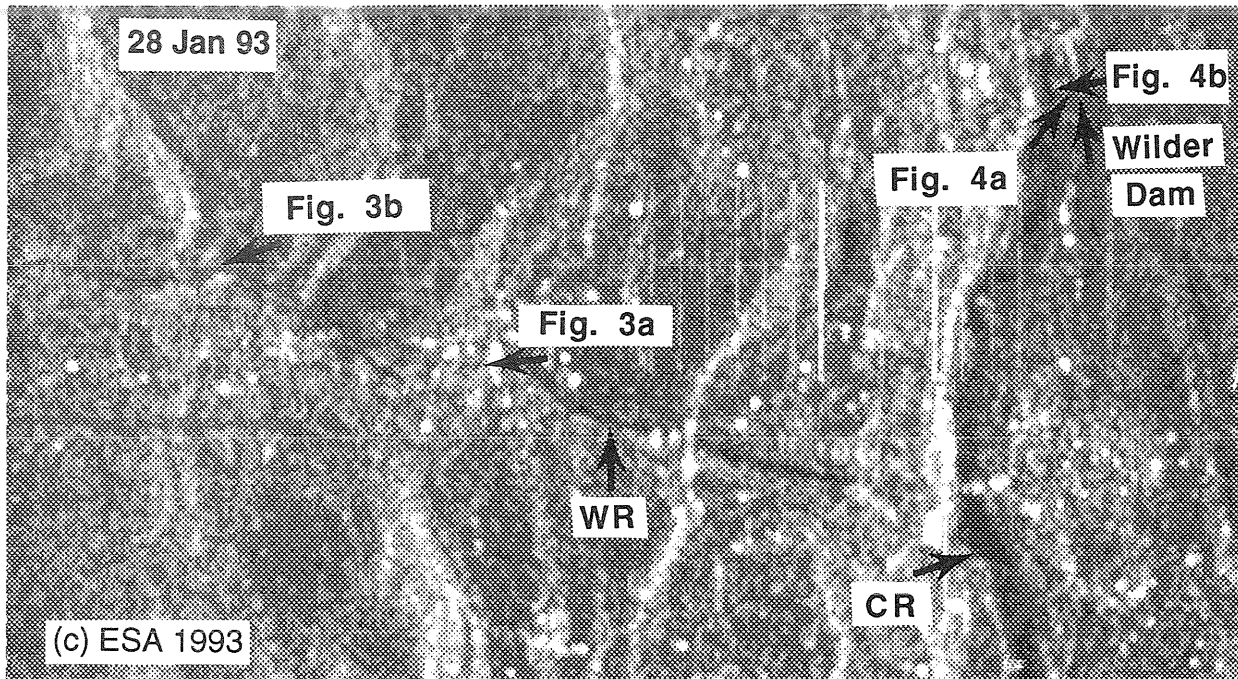


Figure 2. SAR image of the confluence of the Connecticut (CR) and White (WR) Rivers, VT, 28 January 1993.

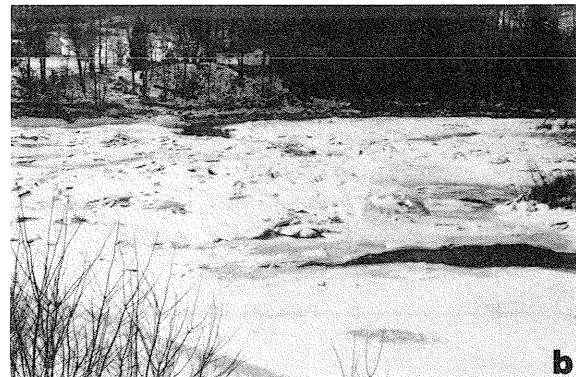
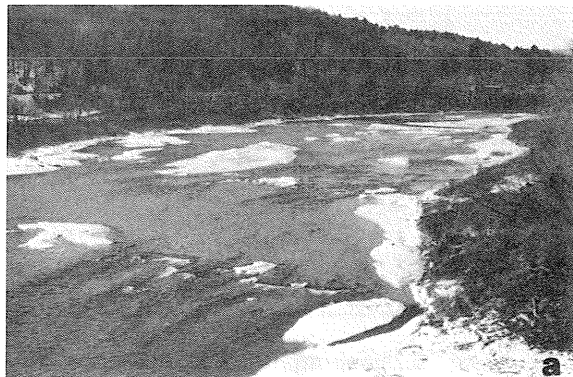


Figure 3. Hand-held photos of the ice conditions on the White River, 28 January 1993.

shore ice and open water (Fig. 3a) appear as dark reaches and it is very difficult to determine if ice is present at all. An ice jam on the river (Fig. 3b) is difficult to distinguish on the SAR image because the river is narrow and there is an island at the jam site. With the spatial resolution of the imagery of about 30 m, the features within narrow reaches of the White River are lost and become indistinct.

Connecticut River

I surveyed the Connecticut River from Bradford to its confluence with the White River (Fig. 1) on 28 January and observed that it was predominantly ice covered with intermittent open areas. The ice at all the locations I observed was smooth, with no snow

cover except along the shoreline. Smooth ice produces low backscatter and appears gray on the SAR image. On the upstream side of Wilder Dam (Fig. 2) the ice is smooth in the middle of the river while the nearshore ice is rough and has snow ice at the surface (Fig. 4a). The SAR image shows the gray smooth mid-river zone and a lighter (more backscatter) nearshore zone. The open water downstream of the dam (Fig. 4b) is black due to no radar backscatter (Fig. 2). The ESA SAR image of the river north (Fig. 5a) and west (Fig. 5b) of Hanover shows reaches of smooth ice with low backscatter (gray) in the middle and nearshore areas of the river (Fig. 6). The ice near Ledyard Bridge (Figs. 5b and 6b) is 28 cm thick near shore and 15 cm thick about 30 m offshore.



Figure 4. Hand-held photos of the Connecticut River near Wilder Dam, 28 January 1993.

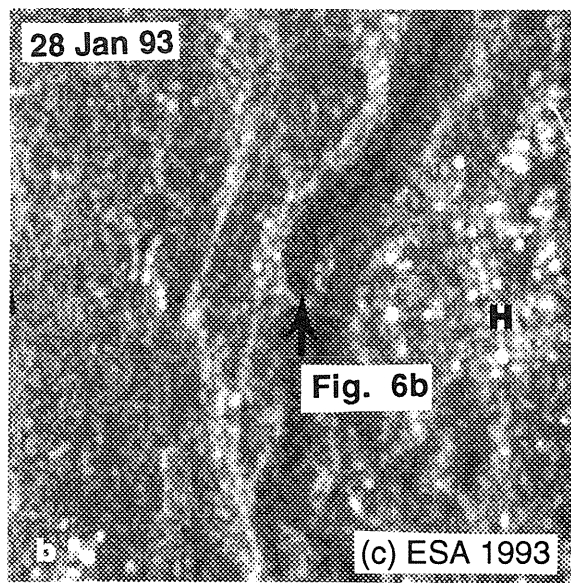
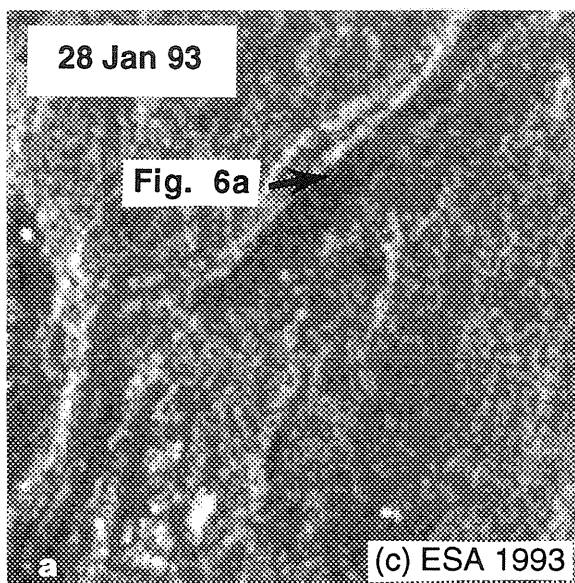


Figure 5. SAR images of the Connecticut River north and west of Hanover (H), NH, 28 January 1993.

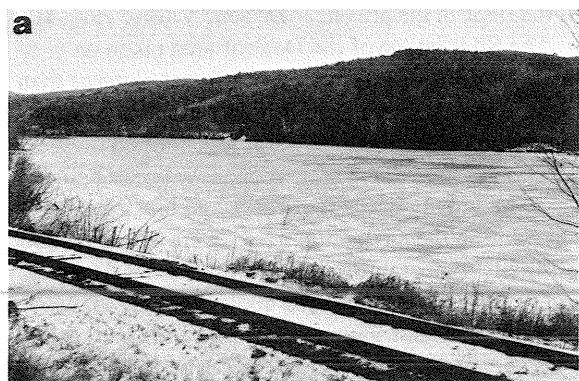


Figure 6. Hand-held photos of the Connecticut River north and west of Hanover, NH, 28 January 1993.

St. Marys River

The St. Marys River is much wider than the Connecticut and White Rivers and thus its ice cover

shows up very distinctly on the SAR. The SAR image taken on 20 January (Fig. 7) clearly shows the open water and snow ice, clear ice, ice cracks and

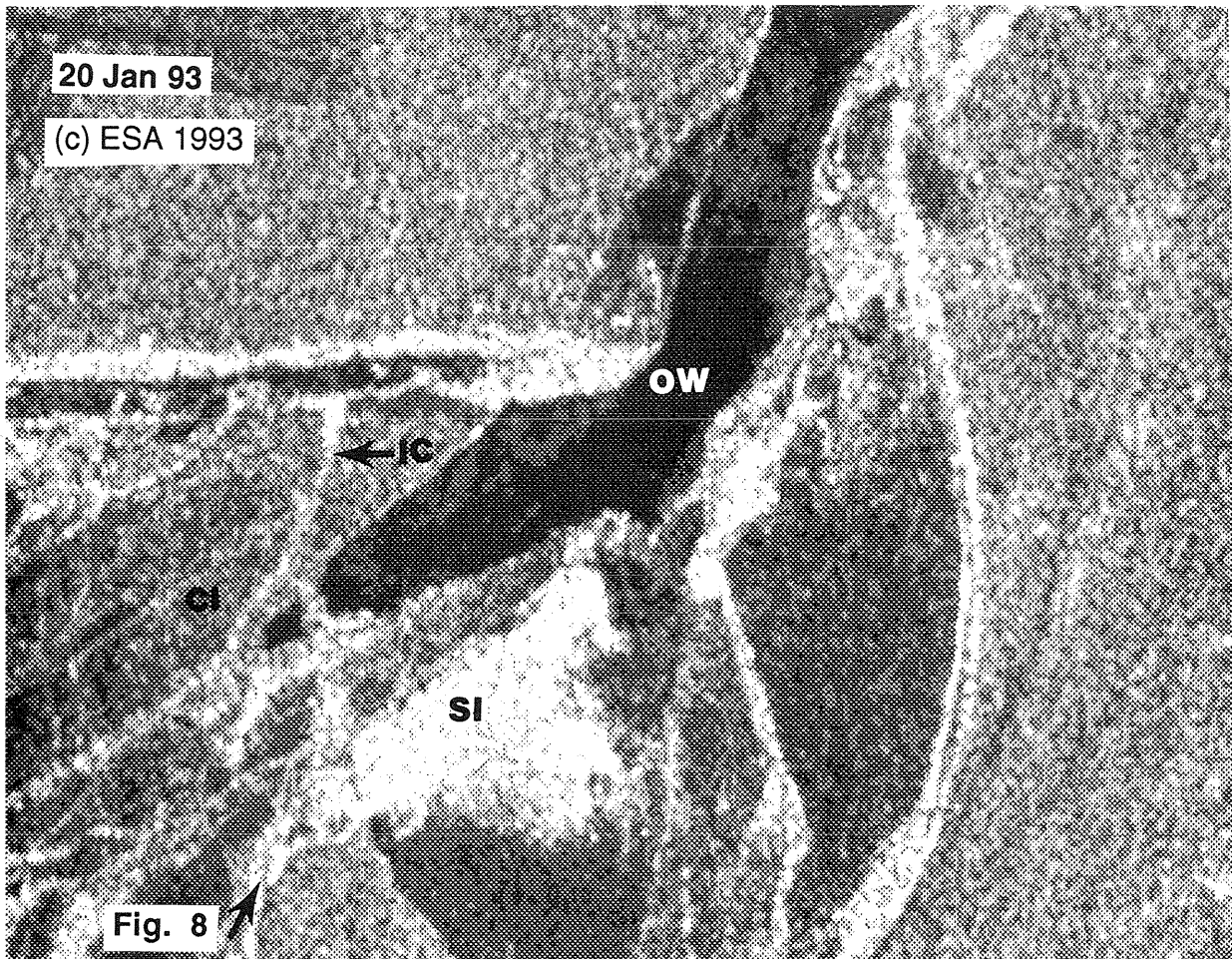


Figure 7. SAR image of the St. Marys River upstream of the Soo Locks, MI, 20 January 1993; OW-open water, SI-snow ice, CI-clear ice, IC-ice cracks.

associated ice ridges through the narrow reach upstream of the Soo Locks. The aerial oblique photograph (Fig. 8) used to compare with this image was taken on 19 January; weather conditions were similar on both days. Snow cover on the ice was windblown and patchy and varied from no snow away from shore to unknown depths near the shoreline where the snow had drifted. Snow cover on the ground was 38 cm deep. Air temperature on the morning of 20 January around the time the SAR image was acquired was about -5.6°C and had been below freezing for about the previous 15 days. The snow was dry and cold and contributed very little to the backscatter reflected from the ice. Thus, the ice signatures made on the image resulted from the backscatter from the ice alone and was not a combination of reflections from the snow and ice.

This 20 January SAR image also distinguishes the open water, the new ice recently formed along the west side of DeTour Passage (Fig. 9), the upbound

and downbound navigation tracks through the ice around the island, and the clear ice that covers most of the river in the area near DeTour Village (Fig. 10).

The SAR image of the DeTour area taken on 6 February (Fig. 11) shows very different patterns than the 20 January image (Fig. 9). The distinction between the land and the ice is far less defined on the 6 February image; the area of open water was much larger and many of the ice cracks and brash ice features within the navigation tracks were not as distinct. The daily temperatures for each of the four days before 6 February had reached above freezing and about 3 cm of snow and some of the surface ice had melted. This changed the surface characteristics of the ice and the snow on the ground enough to alter the backscatter from these areas. Air temperature on the morning of 6 February around the time the image was acquired was about -25°C ; thus, the ice and snow surfaces between 20 January and 6 February had been changed substantially.

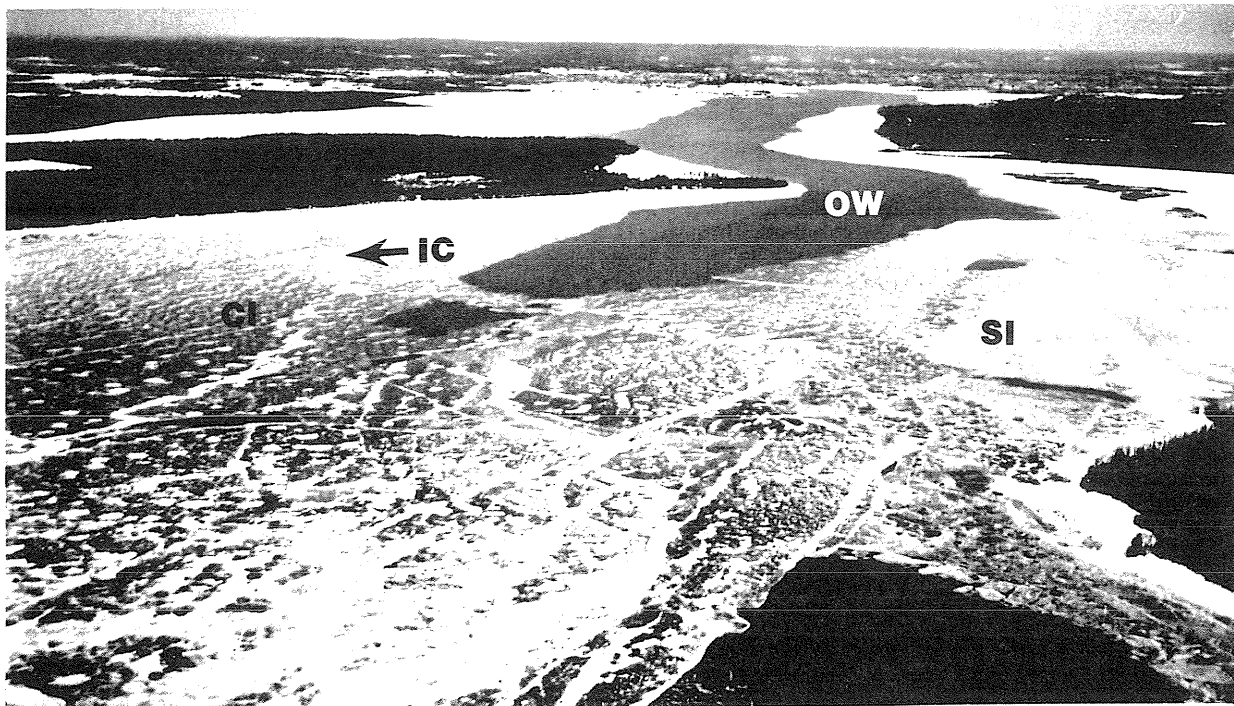


Figure 8. Aerial photo of the area in Figure 7, 19 January 1993.

The SAR image taken on 13 March (Fig. 12) shows the large area of open water, an area of thin ice along the north shore and a zone of broken ice along the south shore within the Sault Ste. Marie harbor. The ice in this zone has snow ice that is 25 cm thick on 18 to 38 cm of clear ice. The open water through the navigation channel downstream of the harbor is also well defined on this image. The downstream end of the open water is composed of refrozen floes and brash ice and has a ridged and rough surface. The nearshore ice along this open reach is 8 to 13 cm of snow ice on 10 to 28 cm of clear ice.

CONCLUSIONS

It is important to reemphasize that the results discussed herein are from a preliminary analysis using simple image processing techniques. More complicated methods are available that may improve the quality of the imagery to be interpreted and therefore increase the information that can be derived from them. Those methods remain to be tried. However, I believe it is appropriate to enumerate two potential limitations of the SAR imagery.

First, the spatial resolution of the SAR may be too small to provide images that distinctly show ice cover on rivers less than 30 to 35 m wide and on rivers so shallow that boulders in the flow channel are above

water level, such as occurs regularly in the White River. On these rivers the backscatter from the ice is integrated with that from the other surrounding terrain features, thus obscuring the ice-unique information. As the river width gets larger the information on the ice conditions is more apparent because more of the imagery pixels of the river ice are composed of backscatter from the ice only and not from the ice and bed and shoreline features. These "combined pixels" are difficult to interpret and the river ice information becomes less than useful for river ice engineering applications.

Second, the single radar band (C) and polarization (VV) of the ESA ERS-1 SAR may limit the differences in the ice that it can differentiate. Having said that and within the context of the above limitations, I believe that this SAR clearly provides imagery that differentiates river ice conditions on a variety of river types and provides for a better initial test of the potential utility of satellite-borne SAR images for monitoring river ice in all weather and at night than would the data from a more complex multiple bands and polarizations SAR instrument.

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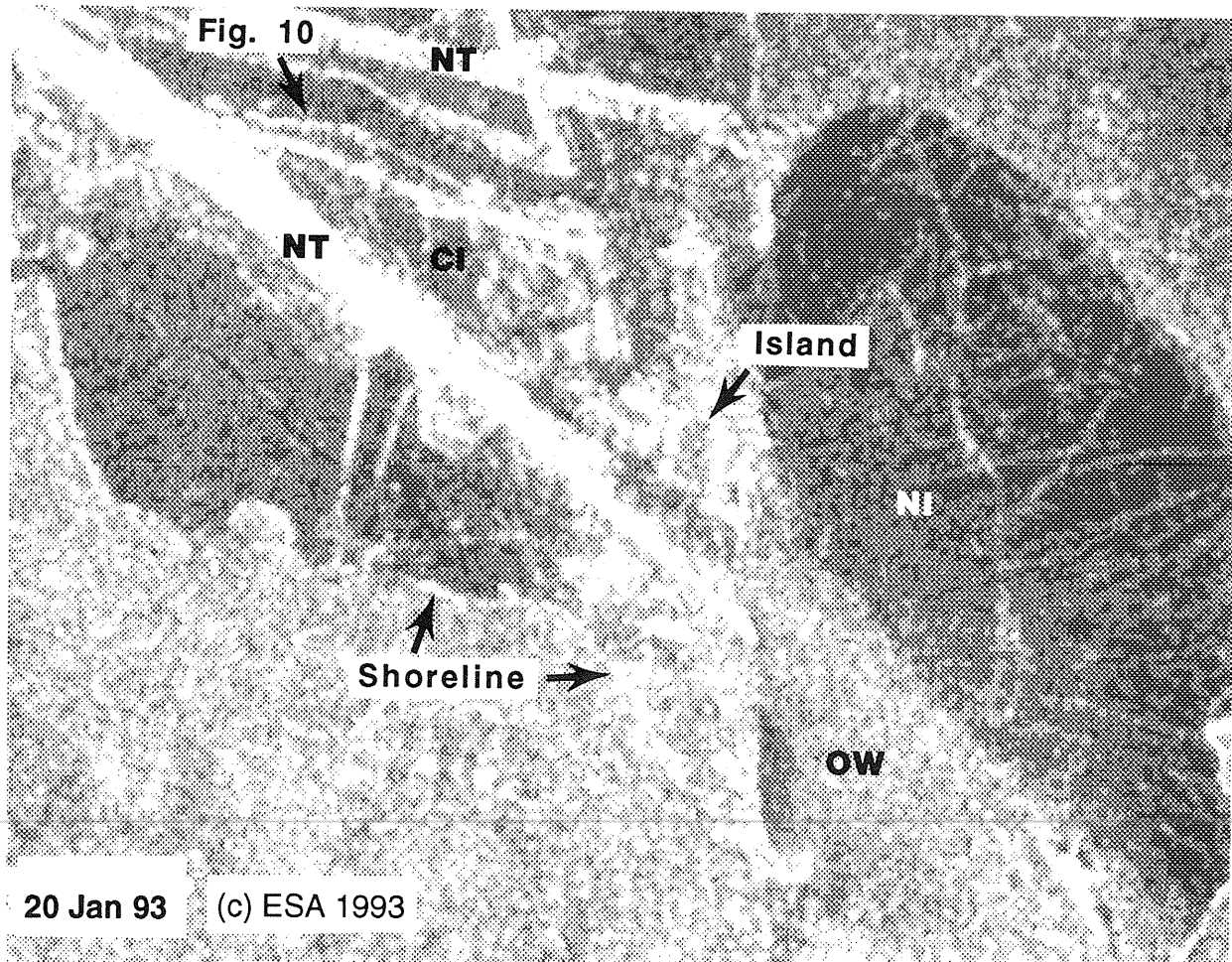


Figure 9. SAR image of the St. Marys River near DeTour Village, 20 January 1993; NI-new ice, NT-navigation track, CI-clear ice, OW-open water.

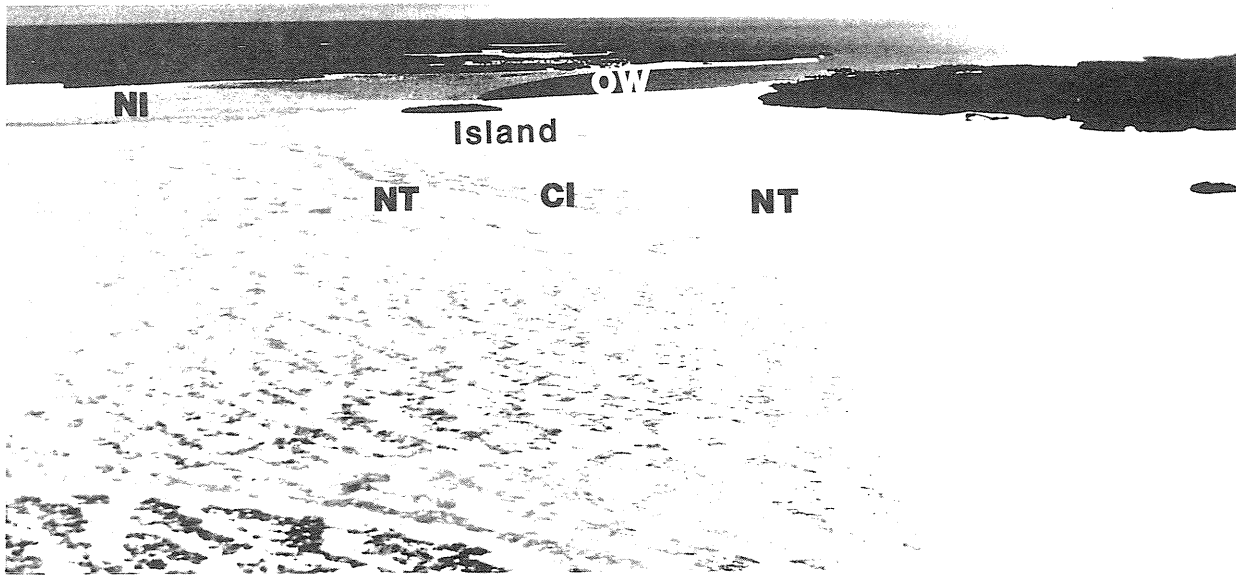


Figure 10. Aerial photo of the area in Figure 9.

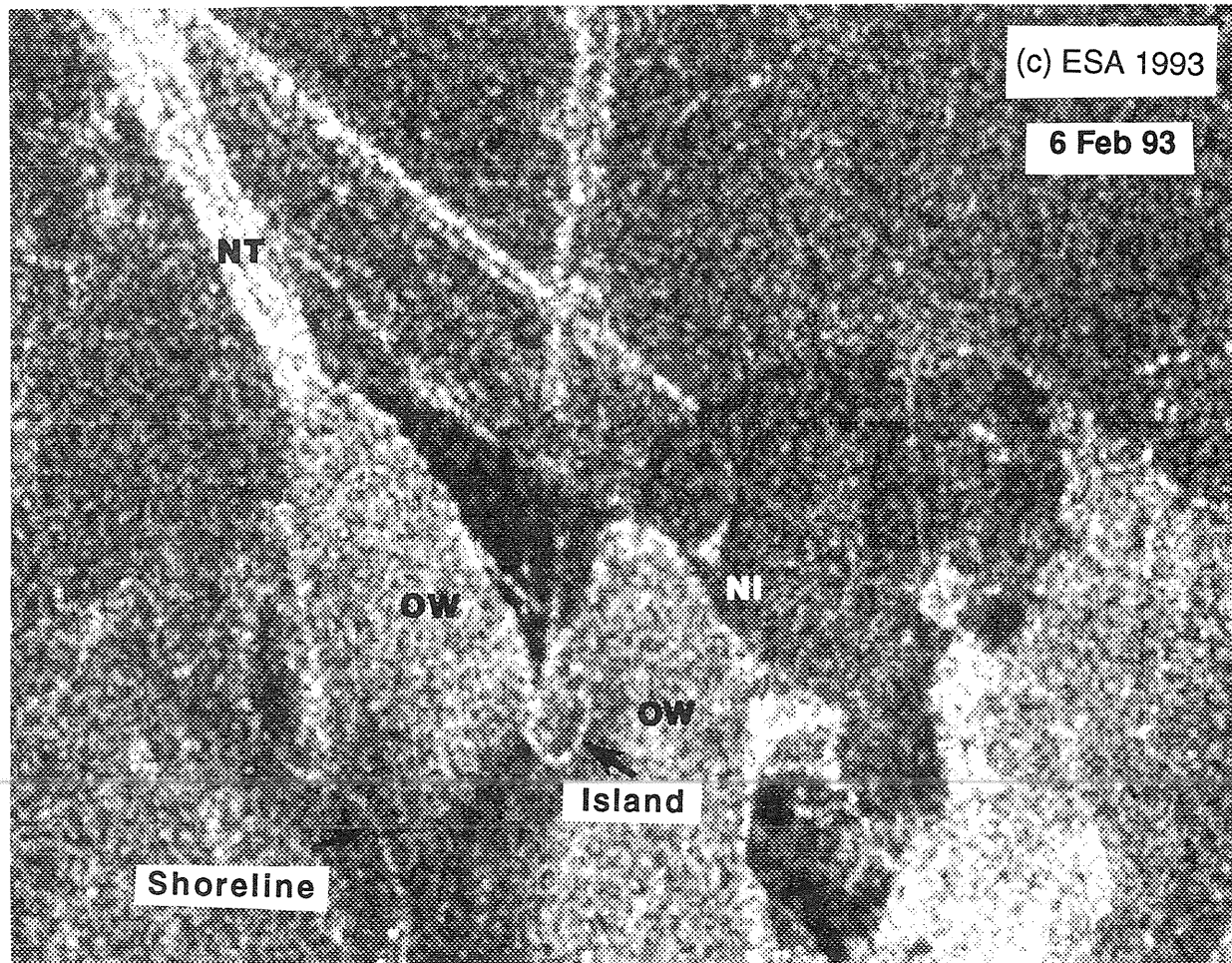


Figure 11. SAR image of the St. Marys River near DeTour Village, 6 February 1993; NI-new ice, OW-open water.

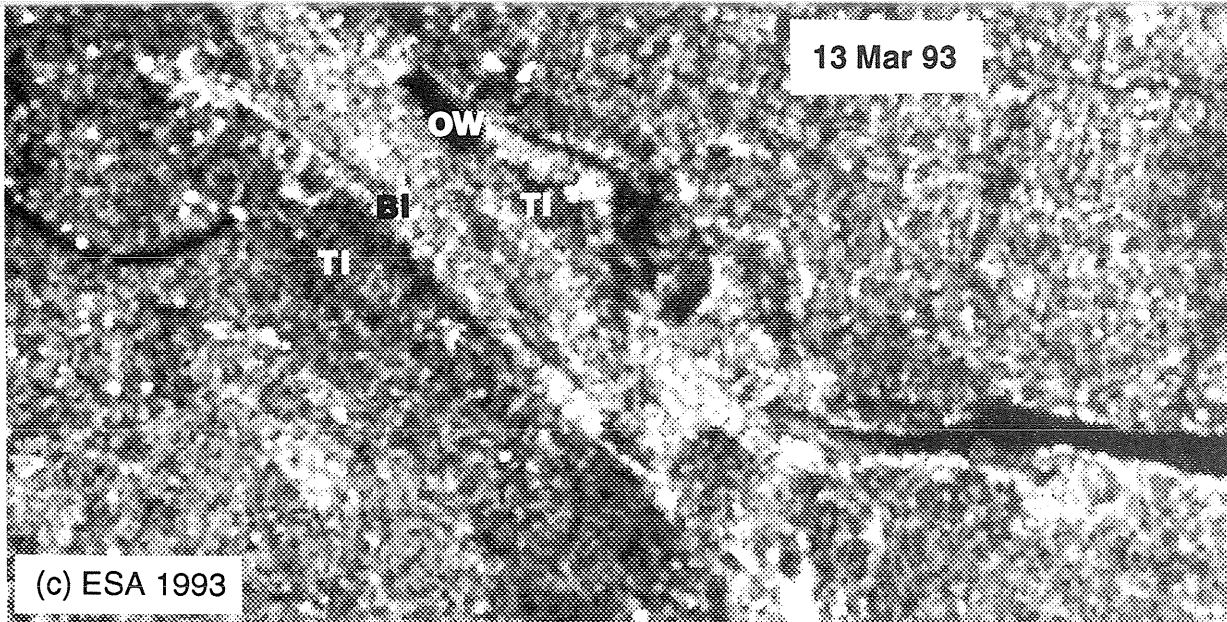


Figure 12. SAR image of the Soo Harbor area, St. Marys River, 13 March 1993; TI-thin ice, BI-broken ice, OW-open water.

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