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ON THE USE OF MULTISPECTRAL RADAR TO DEFINE CERTAIN CHARACTERISTICS OF GREAT LAKES ICE

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OX THE USE OF MULTISPECTRAL RADAR TO DEFINE CERTAIN CHARACTERISTICS OF GREAT LAKES ICE[1]

S. J. Bolsenga

Synoptic observations of Great Lakes ice cover are often severely hampered by weather conditions. It is possible to overcome these difficulties by using microwave radar. New areas of research using multispectral microwave radar are suggested. It seems probable that detailed structural characteristics of the Great Lakes ice cover can be described with an appropriately sophisticated radar system.

1. INTRODUCTION

Definition of the character and extent of the Great Lakes ice cover has been a problem of serious scientific interest since the advent of large-scale commercial shipping on the Lakes. The Great Lakes Environmental Research Laboratory, NOAA, and its predecessor organization, the U.S. Lake Survey, have conducted visual aerial ice reconnaissance programs in cooperation with the U.S. Coast Guard for several years. Charts of the extent of the ice cover at various times during each winter season have been published on a yearly basis (for example, Assel, 1974, and Randy, 1969). On the Canadian side, the Department of Transport has conducted similar reconnaissance and has cooperated with United States agencies on the composition of ice charts.

The limitations of visual or photographic observations from relatively slow moving aircraft are immediately apparent and, in addition, poor weather is common over the Lakes during the winter season, limiting the amount of available data. Also, a lack of synopticity of the observations presents a problem when comparisons between the Lakes or even between parts of one lake become necessary since only a part of any lake might be observed on any given day.

Information has shown that cloud-cover problems are even more severe with satellites than with aircraft. Hagman (1976), in attempting to correlate satellite transparency density to calculated surface reflectance and ice-cover concentration found the method unworkable due to numerous problems, including variable film densities.

To overcome the difficulties posed by weather problems in remotely observing ice cover, microwave radar systems are being used. Advantages

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[1] GLERL Contribution No. 140.

offered by radar over visual and optical systems include: (1) greater aerial extent coverage and (2) penetration of adverse weather on a day or night basis. Short pulsed systems to measure ice thickness and side looking airborne radar (SLAR) of the real aperture type to monitor ice-cover conditions are currently used on an operational basis. The purpose of this report is to comment on the usefulness in ice characteristics research of a four-channel SLAR designed and operated by the Environmental Research Institute of Michigan (ERIM). Bryan and Larson (1975) have described a classification of freshwater ice from the imagery used here and papers such as that by Johnson and Farmer (1971) have described sea ice signatures. The intention of this paper is not to redescribe ice classifications but rather to analyze and suggest possible areas of new research that will further extend the usefulness of multispectral radar imagery, such as the use of radar to provide information on ice albedo.

2. INSTRUMENTATION AND DATA COLLECTION

The ERIM radar system consists of a dual-frequency, dual-polarization, side looking, X-L airborne radar installed in a C-46 aircraft (X-band, 3 cm, and L-band, 25 cm). Data recording is by 70 mm signal film with a separate unit used for each band. Like and crossed polarized signals are both recorded on the same film for each band (27 mm + 0.5 mm separation) with the signals represented as astigmatic Fresnel zone plates. In effect, half of the cathode ray tube pulse accommodates the horizontally polarized and half the vertically polarized signal for each band. The chirp signal is divided, with one portion proceeding directly to the X-band transmitter and the remainder hetrodyned to L-band by mixing with a reference oscillator. The L-band chirp is one half the length of the X-band chirp. Cross-track resolution is obtained from FM pulse compression and along-track resolution from the synthetic aperture technique. An all inertial navigation system is required as an auxiliary system for the synthetic aperture configuration to guide the aircraft along a straight line track. A motion compensation subsystem is used for a final radar phase correction. Full details of the system can be found in Rawson et al. (1975).

Following a data collection mission, the films are optically processed into strip maps. The processor corrects for change in focus with range, aspect ratio, and eccentricity using a coherent light source, tilted film plane, zoom lens configuration, and spherical and astigmatic lenses. For details of the optical processor, consult Kozma, Leith, and Massey (1972) and Rendleman et al. (1974).

The imagery analyzed was collected on 13 March 1974 over the Whitefish Bay area on the eastern end of Lake Superior. Figure 1 shows the general area of coverage and flight path direction. Nominal flight altitude was 12,000 ft above mean sea level with a depression angle of 26" for the near range and 10° for the far range. Resolution of the imagery was 10 m x 10 m and 3 m x 3 m.

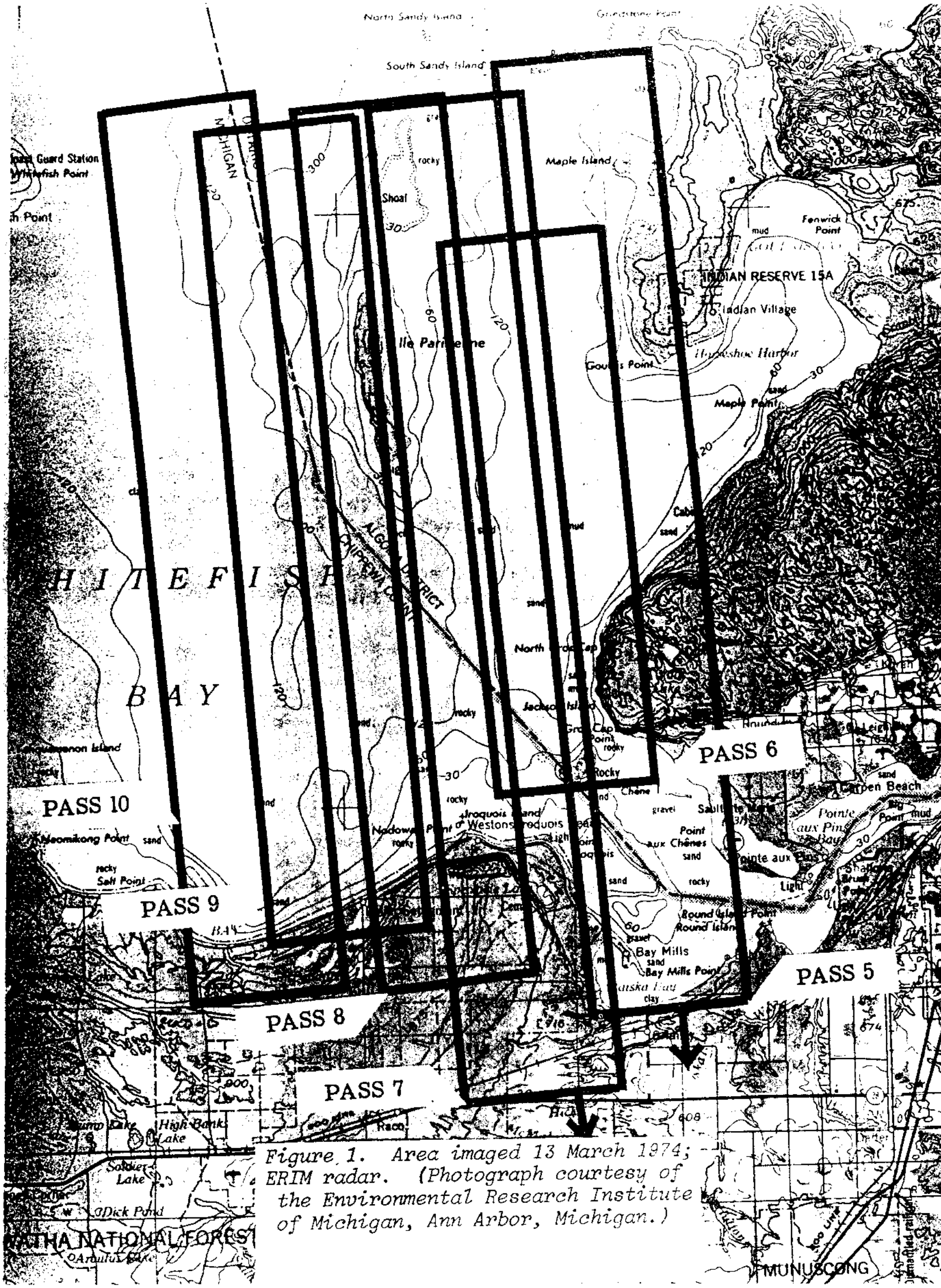
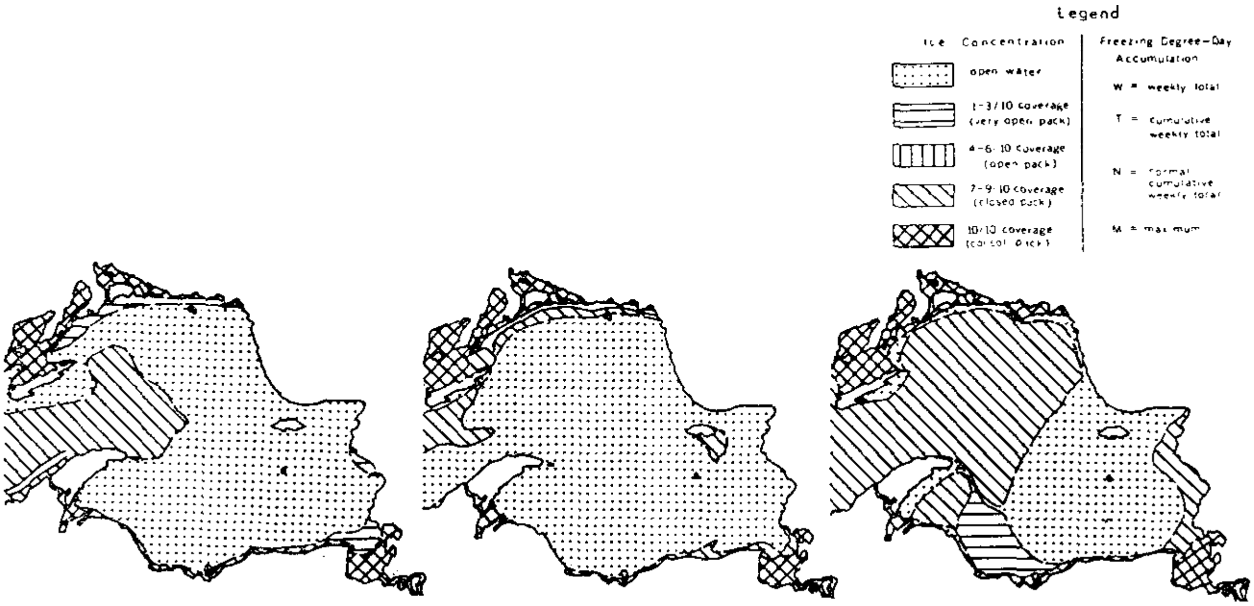


Figure 1. Area imaged 13 March 1974; ERIM radar. (Photograph courtesy of the Environmental Research Institute of Michigan, Ann Arbor, Michigan.)

3. INTERPRETATION AND ANALYSIS

Imagery was interpreted only by the unaided eye. A limited amount of ground truth information was available and was used where appropriate in the interpretation. An effort is made to highlight possible ambiguities in the interpretation of other imagery where ground truth would be lacking. The ice cover in Whitefish Bay often moves quickly due to winds and currents. It appears, however, that the cover remained stable for a considerable period both before and after the radar imagery was collected (Figure 2).

One of the most striking features show" by the radar imagery is the extent *to* which the roughness of *the* surfaces of the various ice types and multiple reflections within certain ice types influence the strength of the pulse return. The advantages of this property are numerous. For example, a large portion of the total ice cover on the Great Lakes consists of brash ice and this ice type is one of the more easily detected features on the imagery. The interplay between a return due t" surface roughness and multiple internal reflection of the radar signal can be traced to the major role that water movements, both nearshore and offshore, play in the formation of a brash ice field. Initially, relatively thin ice might form in a sheltered bay or other quiet water area. On large lakes subsequent water movements will likely break up and move or



WEEK ENDING: MARCH 10, 1974 MARCH 17, 1974 MARCH 24, 1974

Figure 2. ***Ice-cover chronology before and after the radar*** *flight (after Assel, 19741.*

compact this ice cover brash ice unless there is extreme turbulence. The angular surfaces of the old fragments of ice scatter the radar pulse from the surface blocks, the interior of the ice pack, and at the ice/water interface. The size of individual ice blocks will vary greatly from field to field, with the smaller and thinner blocks representing fragmented young ice. It would seem that quantitative evaluation of the strength of radar returns from brash ice fields would provide an index to the age of the ice from which the brash field was developed. Additional data collection would be necessary, including extensive ground truth, to evaluate this possibility. Such a program, coupled with the results of the first study on iake-scale ice movements being conducted by Rumer (1977), could provide an avenue for recreating ice-pack histories. It is important to note that the brash ice discussed here is solid ice and not. freely floating blocks in an unfrozen matrix. In the former case, the fragments would be floating in positions resembling their original formation as opposed to on edge as is common with frozen brash ice. A different radar return would result from each of the two different forms.

On radar imagery the bright returns from pressure ridges and the outer extremities between fields of different ice types are even more obvious than the brash ice fields. The high strengths of the returns are due to surface roughness and multiple reflection within the ridge or ice-field edge. The importance of the illumination angle of the radar is emphasized when pressure ridges are viewed as opposed to brash ice. Since the radar pulse is transmitted at an angle perpendicular to the flight path of the aircraft, it follows that the strongest signals will be received from reflectors most nearly parallel to the flight path. Unfavorably oriented surfaces provide either weak returns or no returns at all (noted particularly with respect to the X-HH band). An interesting possibility for further defining illumination angle dependence would be to fly two sets of flight lines orthogonal to each other.

Since maximum return results when the incidence angle is 90°, it is not surprising that ice foot surfaces also produce strong radar returns with proper illumination. The ice foots in the study area were not particularly well developed by Great Lakes standards, but they nevertheless produced strong returns. Most were 3-4 m in height, with one being only 0.5 m, whereas ice foots of over 5 m are not uncommon in the Great Lakes. Development of ice foots in the Lake Superior region is particularly strong if the shoreline is properly aligned with wind and wave patterns. The location of the radar beam with respect to the ice foot orientation is critical to identification of an ice foot. If radar is flown on the lakeside edge of the ice foot, a strong return will result due to development of a cliff-like edge. However, if it is flown from the land side, where the transition from the land to the ice mass is relatively smooth, the return might appear similar to other ice areas on the lake or to a snow-covered shoreline (Fahnestock et al., 1973).

An attempt was made to distinguish, from the radar imagery alone, as many as possible of the various ice types common to the Great Lakes. The types considered were clear lake ice, bubbly lake ice, ball ice, refrozen pancake, slush curd ice, slush ice. brash ice. and snow ice (Marshall, 1966). Descriptions of clear, pancake, and brash ice are well known. Bubbly lake ice is formed due to surface melting of clear ice. Subsequent refreezing after slight candling produces the opaque appearance of the ice. Extremely turbulent waters in the offshore zone shape slush and frazil into lumps and balls that subsequently refreeze into ball ice. Slush curd ice is formed when wind action on a thick slush layer produces a coagulated pattern with intervening clear ice areas. Slush ice, sometimes classified as a type of snow ice (Ager, 1962), forms due to freezing of a slush layer resulting from an over-water snowfall. Snow ice, milky white in color and containing various sizes and concentrations of air bubbles, is most commonly formed by snow loading an existing ice cover, with refreezing of water seeping upward through stress cracks in the old ice cover into the snow layer.

It is important to note that the component parts of each type of ice (individual pancakes, balls, etc.) are always smaller (1 m or less) than the resolution of the radar. On the other hand, the ice types, at least in aggregate form, can be identified from good quality aerial photography. As indicated below, a signature catalog including information on scattering of the radar pulse from both the ice/air and ice/water interfaces night provide an aid to radar identification of ice types. This is currently not possible without extensive additional research.

The surfaces (ice/air) of most of the ice types, with the exception of brash and pancake ice, are smooth and tend to produce specular rather than diffuse radar returns. The ice/water interface is another matter. Bryan and Larson (1975) describe an area of intensive study in connection with the same imagery used here where 65-70 cm thick pancake ice was embedded in a 25-35 cm thick matrix of clear ice producing a very rough ice/water interface. It is clear that one cannot assume that a smooth ice/air surface implies a smooth ice/water surface. In this imagery, numerous cases were observed in which smooth surfaced ice produced strong radar returns owing to reflection of the L-band signal from the ice/water interface. Little is known, however, of the ice/water configuration of any of the ice types. Additional research is necessary to describe ice/water roughness and to relate this to the radar return.

Bryan (1075) reports on field measurements to determine the dielectric constant and loss tangent of both the X- and L-bands according to the density, temperature, and moisture content of ice and snow (Table 1). He concluded that variations in the electrical properties were sufficient to provide radar reflections from air/snow, snow/ice, air/ice, ice/water, and within certain surfaces of ice and snow layers. Penetration into snow layers is considerable for both 3 and 25 cm wavelengths. Penetration into ice layers is also possible at both wavelengths. Bryan and Larson (1973) report 40-50 cm penetration for the 3 cm wavelength and 3-4 m penetration for the 25 cm wavelength (Table 1). Two-way energy loss is not excessive in the L-band mode so that backscattered energy will be received at the antenna. At greater ice thicknesses, backscatter is primarily from the ice/air surface. For additional information on measurements of the dielectric constant and loss tangent of ice, see Hoekstra and Spanogle (1972).

Table 1. Summary of Radar, Ice, and Snow Parameters

Aperture	Wavelength	Material	Loss tangent	ε[1]	X_d[2]	Polarization
Real	3 cm	Snow	5×10^{-4}	2	10 m	HH[3]
Synthetic	3 cm	Ice	110	3	40-50 cm	HH, HV[4]
Synthetic	3 cm	Snow	5×10^{-4}	2	10 m	HH, HV
Synthetic	25 cm	Ice	110	3	3-4 m	HH, HV
Synthetic	25 cm	Snow	10-3	2	60 m	HH, HV
Real[5]	10 cm	Ice	0.9×10^{-3}	3.2	'0.44 dβ/m	HH

1 Dielectric constant of the material.
2 Penetration depth of the radiation.
3 Horizontal transmit and receive.
4 Horizontal transmit, vertical receive.
5 Short pulsed radar.

It is also possible to identify certain ice types by association with a known mode of formation. As pointed out above, slush balls form in turbulent nearshore waters. Figure 3 shows a field of non-frozen slush balls that were identified not due to the resolution of the radar (individual balls are usually less than 1/2 m in diameter) or from the ice/water interface return but from the wavey appearance of the ice field. The observations were made with a SAR X-band radar in 1968 and have been reported by Larrowe (1971). Results of this early study demonstrated the ability of radar to differentiate between open water and broken ice and to identify vessel tracks, brash ice, and dividing lines between ice packs.

Thus, it can be concluded that classification of individual ice types is severely limited, since the radar resolution is not sufficient to distinguish between the component parts of an ice type. However, additional information on such items as the roughness characteristics of the ice/water interface of the various ice types and the internal scattering properties of ice types such as snow ice with varying bubble contents might provide the tools necessary for more complete ice-type identification.

One of the most critical problems encountered in implementing ice-cover breakup forecasts is the constantly changing albedo during the melt period. An albedo value entered into a forecast model might well be entirely incorrect in a few days or even a few hours owing to mild weather. Since radar returns vary greatly from "dry" ice to "wet" ice,

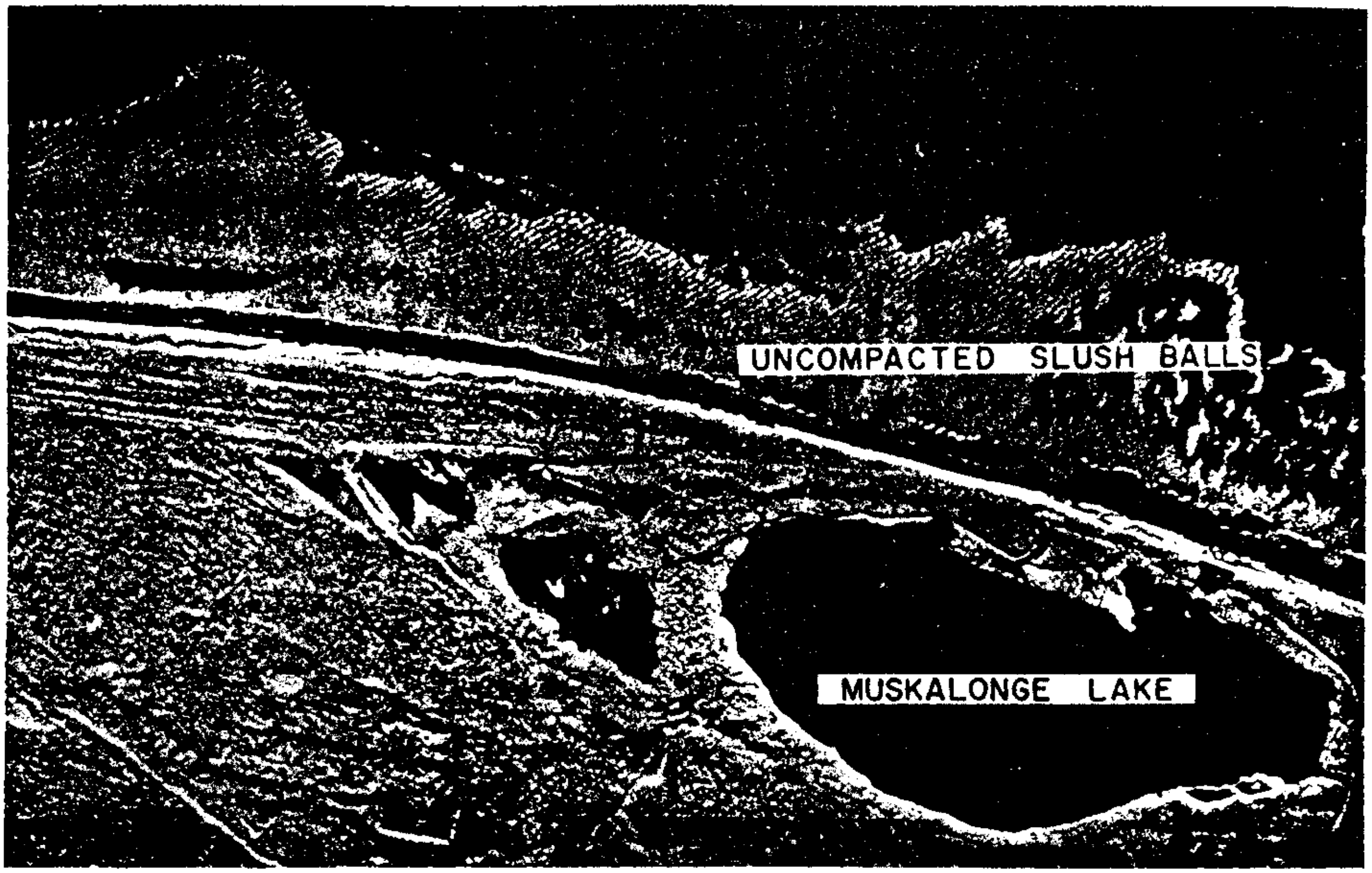


Figure 3. Radar imagery of slush halls (possible ball ice formation) on Lake Superior. (Photograph courtesy of the Environmental Research Institute of Michigan, Ann Arbor, Michigan.)

it would seem that radar, when associated with ice albedo measurements, would provide an excellent all-weather tool to parameterize this condition.

In one case (Figure 4) above-freezing temperatures prevailed for several days before the albedo was measured. A layer of water had formed on the ice during the previous day, but low nighttime temperatures had solidly frozen this layer by the morning of the measurements. Temperatures were mild during the day of the measurements, causing the ice surface to partially melt. The albedo (300-3000 nm) decreased rapidly from 48 percent at 0847 TST (γ = 22" 01') to 21 percent at 1239 T S T (γ = 36"56'), where γ is the solar altitude and TST is true solar time. At the lowest albedo, water occupied the interstitial spaces between small protruding grains of the ice surface. The albedo was thus a combination of water and ice reflectivity. It should be emphasized that the ice appeared as ice, not water, to the casual observer. Tine visual appearance of the ice varied from white in the early morning to a medium grey tone at 1200 TST. The usefulness of routine SLAR flights in determining ice coverage could be greatly increased if the aircraft were equipped to provide information on characteristics relating to ice albedo. As there was no opportunity to analyze this condition from the ERIM radar imagery, additional flights during proper weather conditions are required.

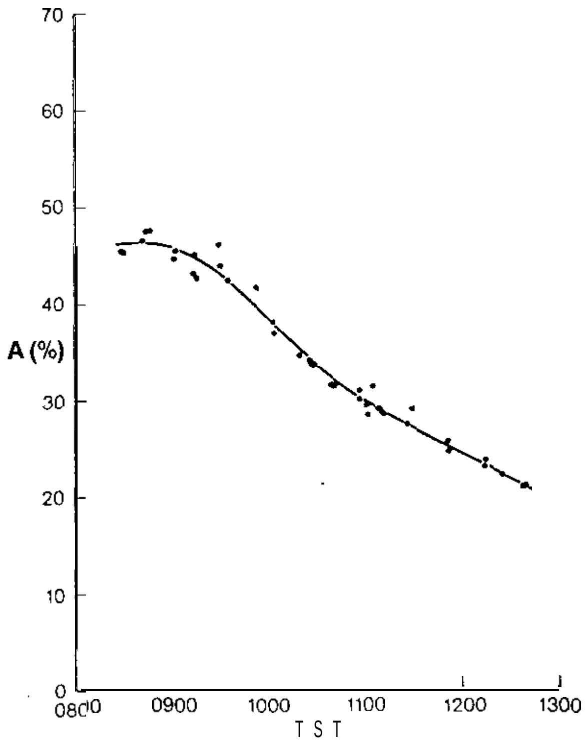


Figure 4. Albedo under decaying ice conditions (after Bolsenga, 1977).

4. CONCLUSIONS

Although the radar technology is available to provide significant information on ice characteristics, the lack of sufficient analysis of the imagery coupled with the lack of ground truth has severely limited advances in this field. SLAR is currently being used in the Great Lakes to define the extent of ice cover. Radar has proven to be an invaluable operational tool for determination of ice extent, but this usefulness can be expanded by additional work.

This brief analysis of some high resolution radar imagery has indicated that certain ice features produce strong and characteristic returns while other features require much additional information for accurate recognition.

Brash ice, owing to its rough ice/air surface, internal structure, and ice/water surface, produces strong returns partially'due to the penetration characteristics in the L-band. Pressure ridges and the outer extremities of ice fields of different types show strong returns owing to surface roughness and multiple internal reflection. The linear pattern of these features and of ice foots contributes to their easy recognition, but also results in a dependence on the radar illumination angle.

An attempt to identify ice types other than brash and pancake ice was unsuccessful and indicated a need for much additional basic information. The possible use of radar to define the degree of deterioration of ice cover deserves further study.

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