NOAA Technical Memorandum ERL GLERL-13

ON THE USE OF MICROWAVE RADIATION FOR GREAT LAKES ICE SURVEILLANCE

Brenda Blanton Hagman

Great Lakes Environmental Research Laboratory
Ann Arbor, Michigan
May 1976

UNITED STATES
DEPARTMENT OF COMMERCE
Juanita M. Kreps, Secretary

NATIONAL OCEANIC AND
ATMOSPHERIC ADMINISTRATION
Robert M. White, Administrator

Environmental Research
Laboratories
Wilmot N. Hess, Director

NOTICE

CONTENTS

TABLES

FIGURES

ON THE USE OF MICROWAVE RADIATION* FOR GREAT LAKES ICE SURVEILLANCE

Brenda Blanton Hagman

With the desire to extend the Great Lakes shipping season to year-round operation comes the need for up-to-date information on ice conditions. One method being investigated uses microwave (radar) remote sensing for ice surveillance. Microwave systems are advantageous because they can penetrate cloud cover, operate day or night, and provide greater areal coverage at aircraft altitudes than can optical systems. For ice surveillance, radar "sees" a world of edges and interfaces that correspond (in gray tones) to relative amounts of backscattered radiation. Radar has been shown effective in classifying certain ice types, conditions, and features, and for aiding ships in ice-covered waters or during severe weather. Future microwave studies should concentrate on making various radar systems operational, collecting and correlating ground verification data with radar data, and investigating the use of satellite platforms for microwave remote sensing.

1. INTRODUCTION

In the past, extensive ice cover around the Great Lakes has forced all shipping to cease for at least 1 month each year. (The exception was 1974-75, which was an extremely mild winter.) Several United States Government agencies, including the U.S. Coast Guard jointly with the National Aeronautics and Space Administration (NASA), are conducting research and development programs to extend the Great Lakes shipping season to year-round operation. But successful navigation through ice-covered waters requires up-to-date information. For this reason and because there is a need for accurate ground data on the physical properties of ice and snow (so that the qualitative studies can be conducted), the Federal Government has appropriated funds for ice surveillance research. In relation to this research, several organizations have investigated the use of microwave radiation remote sensing. The purpose of this report is to describe microwave projects that have been conducted and possibilities for future investigations in the area of ice surveillance.

Microwave systems have two major advantages over optical systems; first, microwave radiation can penetrate all but the most severe weather, day or night, and second, the areal extent obtained from aircraft altitudes is much greater from microwave systems than is possible from optical systems. Optical images obtained from the National Oceanic and Atmospheric Administration's (NOAA) satellites yields the maximum useful area1 coverage extending over the Great Lakes, but almost constant cloud cover during the winter months obscures the ice and hinders interpretation.

*GLERL Contribution No. 92.

Microwave investigations of ice cover utilize short pulsed radar for measuring ice thickness and side looking airborne radar (SLAR), with either real or synthetic antenna apertures, for monitoring ice-cover conditions. Many problems are encountered when determining ice thickness from radar because of multiple reflections from subsurface layers, surface roughness, snow cover, and interference by off-axis reflectors that act as corner reflectors. However, short pulsed radar has proven accurate for measuring multiple reflection layers in smooth ice sheets and providing information on the structure of rough surface or broken ice (Vickers et al., 1973). The investigations of SLAR systems for monitoring ice-cover conditions have proven valuable from both experimental and operational viewpoints. Therefore, the emphasis of this report will be on the application of real and synthetic aperture SLAR systems for monitoring Great Lakes ice-cover conditions.

2. INITIAL SLAR INVESTIGATIONS

A number of microwave studies have been conducted to investigate the feasibility of using SLAR to monitor freshwater ice conditions, but they were limited by a general lack of ground verified data regarding ice types, surface features, internal structures, and crack patterns and were limited by a general lack of ground verified data regarding ice types, surface features, internal structures, and crack patterns and by equipment design which restricted the swath width to rather narrow coverage. However, the results of these studies have demonstrated the ability of microwave radiation to sense various ice types and surface features.

Larrowe et al. (1971), jointly with the U.S. Lake Survey District of the U.S. Army Corps of Engineers, investigated the use of a synthetic aperture radar (SAR) system, at 3-cm wavelength, to make preliminary assessments of the radar's discriminating potential. The results showed that SAR has the ability to differentiate between open water and/or broken ice and to distinguish the following surface features and ice types: ship tracks, dividing lines between ice packs, brash ice, thin ice, rough ridges of ice, hard lake ice, and shadows.

This initial investigation paved the way for additional microwave research by NASA and the U.S. Coast Guard. During the 1971-72 winter, NASA attempted to correlate SLAR imagery with various ice types, features, and patterns as part of the Winter Navigation Program (U.S. Coast Guard, 1972a and b). The SLAR data was stored in memory during flight and processed upon landing. The generated SLAR imagery provided information from which ice types could be inferred. Processed SLAR prints accompanied by hand-drawn interpretative charts were then facsimile transmitted to vessels operating on the Lakes via the Great Lakes Marine VHF Network. The results demonstrated the broad area ice survey capability of the SLAR-SAR system (Jirberg et al., 1973). Thus, SLAR was demonstrated to be a practical means of obtaining accurate, all weather, and timely ice information of benefit to shippers in planning vessel routes and in reducing vessel delays. However, a time lag of over 12 hours between the SLAR flights and receipt of the information by the user rendered this information useless on an operational basis. Because dynamic weather conditions can cause major changes in the Lakes' ice cover in a few hours, for maximum utility, the delay between collection and dissemination needed to be reduced.

3. PRESENT SLAR INVESTIGATIONS

3.1 Federally Conducted Studies

In conjunction with the Winter Navigation Program, the U.S. Coast Guard flew SLAR missions over the Lakes during the 1974-75 and 1975-76 seasons. A real antenna aperture was used because it allowed ice data to be disseminated more quickly to the user. The SLAR data collected while in flight were transmitted to the NOAA-GOES satellite via a UHF link-up and then relayed, via S-band down-link, to the NOAA/NESS Command and Data Acquisition Station at Wallops Island, Virginia. The phase modulated data were next converted to a 5-mHz I.F. output and synchronously phase demodulated. Finally, the digital data were synchronized, buffered, and transmitted via telephone lines to the U.S. Coast Guard Ice Information Center in Cleveland, Ohio. At Cleveland, experienced ice interpreters constructed ice charts from the SLAR imagery.

NASA, in cooperation with the U.S. Coast Guard, is presently testing a Motorola AN/APS-94C system for operational use (Schertler et al., 1975). The system operates at X-band frequency (9.245 GHz) and uses a real aperture antenna that transmits and receives horizontal polarized radiation.

3.1.1 Image Interpretation

Interpretation is based upon correlations between ice types, surface features, and patterns with associated tones and textures in the radar imagery. The radar "sees" a world of edges and interfaces; therefore, various shades of gray correspond to relative amounts of backscattered microwave radiation. Light-toned surfaces indicate areas with large amounts of backscattered radiation. Areas exhibiting this type of return are those with cracks, rafted and ridged pieces of ice, and such ice types as brash. Dark-toned surfaces are those with less backscatter, such as open water or smooth ice.

Ice types, ice-cover concentrations, ice thickness, location of leads, and other information pertinent to shippers are incorporated in the charts. These, along with the SLAR imagery (SLAR Product) (Figs. 1, 2, and 3), are transmitted to shippers around the Lakes. Note the following interesting features visible on the SLAR imagery:

1. A lead on western Lake Erie, Figure 1.

2. A ship's track on Lake St. Clair, Figure 2.

3. The Mackinaw Bridge and ship track, Figure 3.

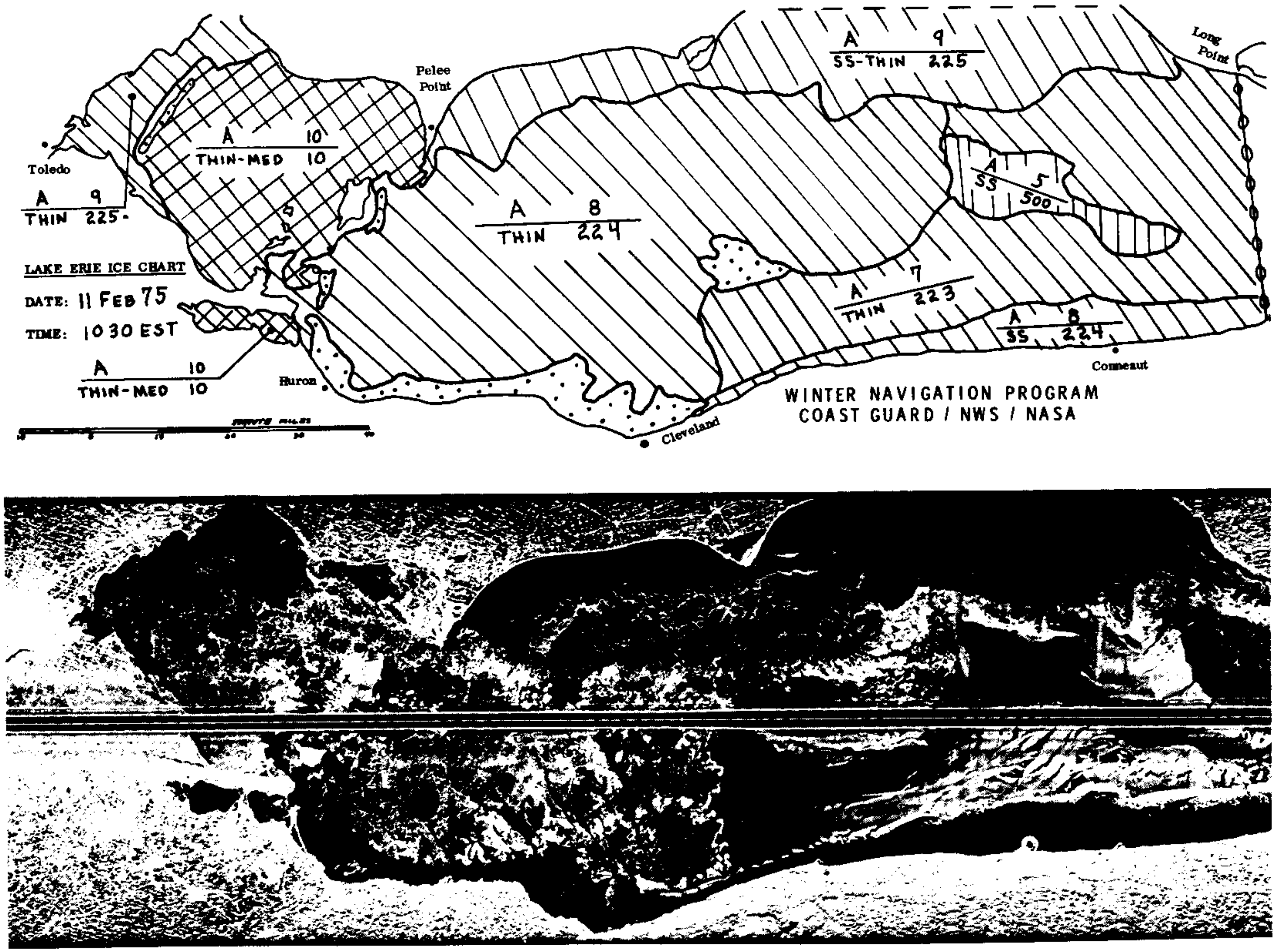


Figure 1. SLAR Image Ice Chart Product for Lake Erie on 11 February 1975. (U.S. Coast Guard, 1972b.)

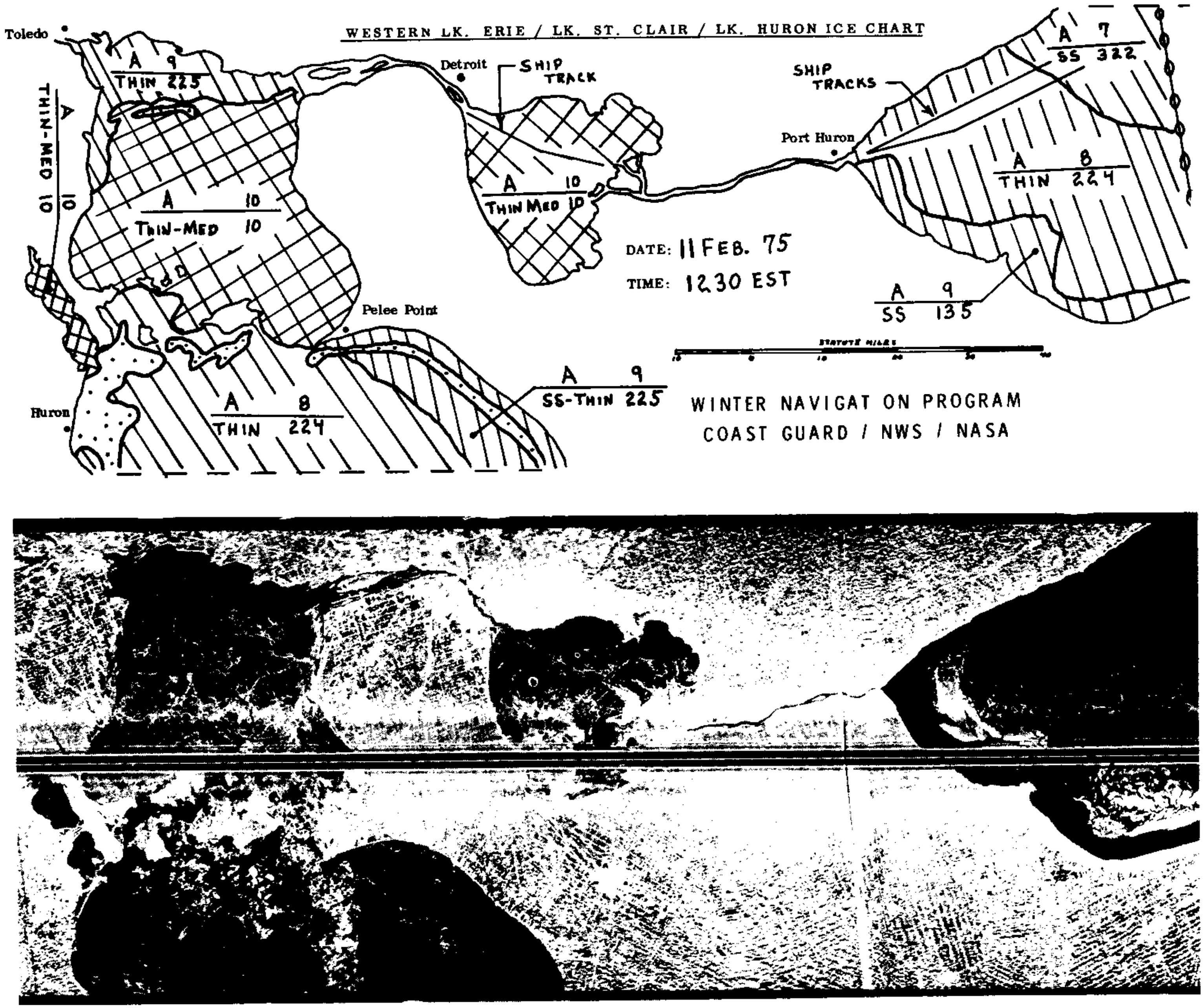
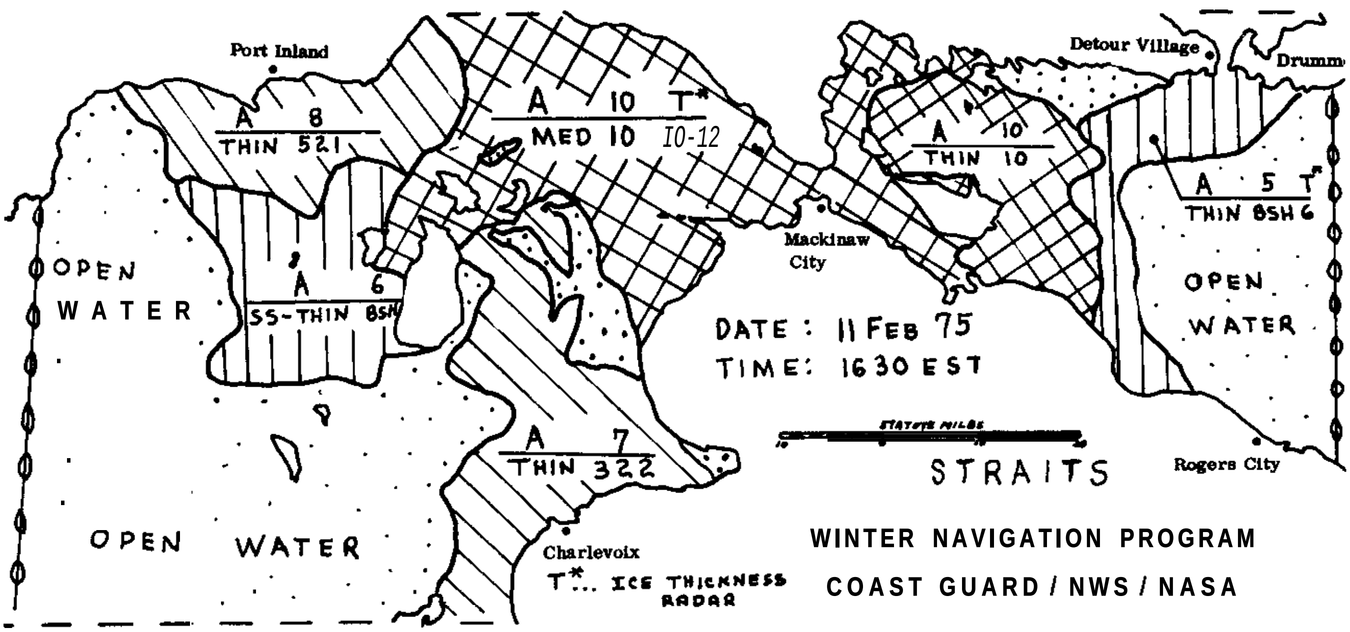


Figure 2. SLAR Image Ice Chart Product for western Lake Erie, Lake St. Clair, and lower Lake Huron on 11 February 1975. (U.S. Coast Guard, 1972b.)



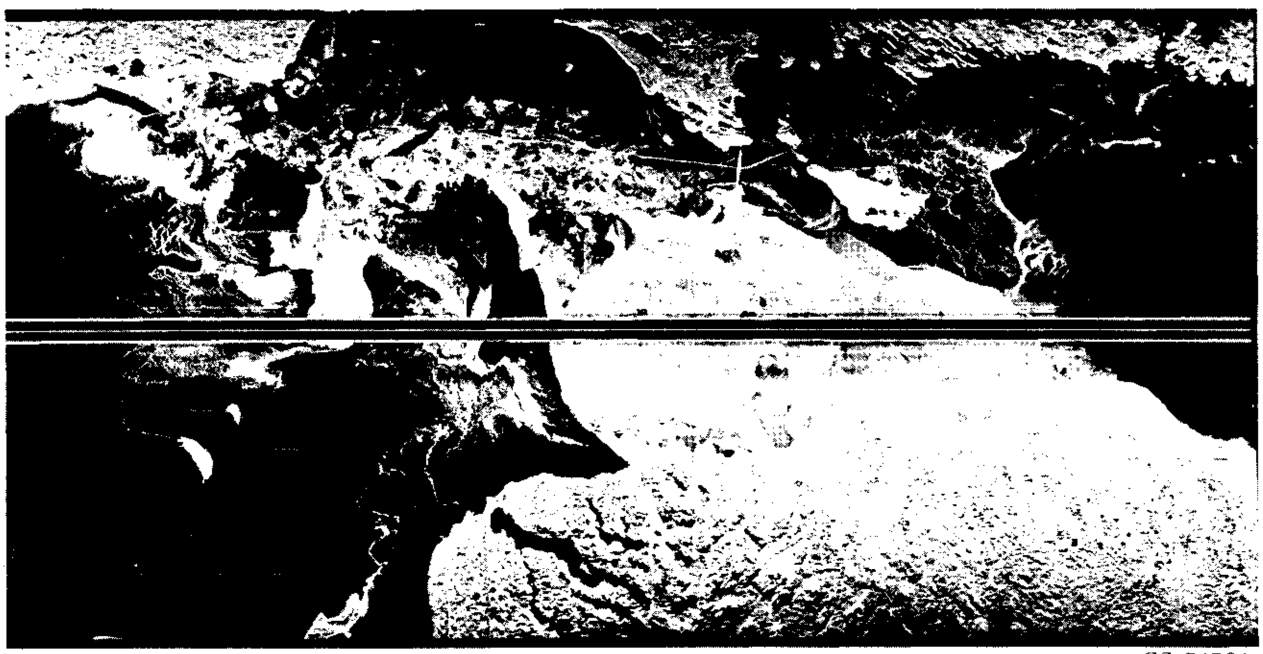


Figure 3. SLAR Image Ice Chart Product for the Straits of Mackinac on 11 February 1975. (U.S. Coast Guard, 1972b.)

3.1.2 SLAR Product Use hy Vessels

The SLAR products are received on board ship at a scale of 1:76,000. Overlays of Great Lakes Navigation Charts are used in conjunction with the SLAR products, allowing the ice-cover to be seen in reference to land features and vessel tracks. In several instances the SLAR products have been used to successfully aid navigation through ice-covered areas. The SLAR products have also alerted shippers of areas to avoid in time for course changes to be made. Other uses of the SLAR products are to provide information concerning areas of refuge in case of severe weather, to support management decisions concerning ship dispatches, and to determine areas where icebreaker activity may be needed.

3.2 Federally Sponsored Studies

The Environmental Research Institute of Michigan (ERIM), under contract from NASA, compared data from NOAA's ERTS-1 (now LANDSAT) satellite with a SAR system for lake-ice surveillance (Bryan, 1975). The SAR system used operates simultaneously at wavelengths of 3 and 26 cm, receiving both parallel and cross-polarized signals. Among other objectives, this study sought: (1) to determine if ground parameters could be identified in the field with accuracy and consistency and (2) to determine if characteristic ice and snow signatures could he obtained from the four separate SAK images.

3.2.1 Ground Parameters

Field measurements were made to determine the dielectric constant and loss tangent at 3- and 26-cm wavelengths (see Table 1), material density, temperature, and moisture content of the ice and snow. Of primary interest was the measurement of the cross-polarized ratio used for determining the moisture content of the earth's surface materials.

This study concluded that variations in the electrical properties of snow are sufficient to give multiple reflections from internal layers. Therefore, one should expect reflections from the following: air/snow interface, snow/ice interface, air/ice interface, water/ice interface, and in some cases ice/ice interface. Table 1 summarizes the parameters which influence the power received by an imaging radar, that is, the dielectric constant (ϵ), penetration depth (S_d), and loss tangent (propagation loss); all are characteristic of the substance being imaged. The relative dielectric constant and loss tangent indicate that penetration of active microwave radiation into ice and snow is on the order of 10 and 60 m for the 3- and 26-cm wavelengths, respectively. This penetration depth is large enough to encompass all interface reflection layers mentioned above, thus making image interpretation more difficult. Due to the numerous problems encountered, no conclusions on ice monitoring were formed from this study.

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

Aperature	Wavelength	Material	Loss Tangent	ε[1]	X_d[2]	Polarization
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	30 cm	Ice	110	3	3-4 m	HH, HV
Synthetic	30 cm	Snow	10^{-3}	2	60 m	HH, HV
Real[5]	10 cm	Ice	0.9 x 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.

3.2.2 Using Radar to Classify Ice

Bryan and Larson (1973) proposed classifying lake ice based on electrical properties and radiation penetration depth into the ice and the resulting ice/water interface reflection (hackscatter). The measured hackscattered energy is a function of wavelength, polarization, and surface roughness.

Penetration into the ice layer is possible at both 3- and 26-cm wavelengths. Two-way energy loss in the ice is not excessive at 26-cm wavelength; therefore, energy reflected from the ice/water interface should he received by the radar antenna. Estimates of reflection coefficients were calculated to he approximately the same at the air/ice and ice/water interfaces; at 3-cm wavelength the penetration is 40-50 cm, while at 26-m wavelength the penetration is 3-4 m (Bryan and Larson, 1973). If the air/ice interface is considered smooth at the operating frequency, then hackscattered energy comes from the ice/water interface for ice thickness less than 50 cm and 3-4 m, respectively. If ice thicknesses are greater than these values, then primary backscatter is from the air/ice interface.

The classification of ice in this study was based on relative backscattered radiation and inferred surface roughness. Table 2 is a summary of some ice types and surface features identified on the radar imagery. This study concluded that more ground base information is needed before ice classification based on backscattered radiation can he accomplished on an operational basis.

Table 2. Classification of Ice Types and Features on Radar Imagery

Feature	Thickness	Tone	Surface Roughness
New ice	<1 m	Black	Rough
Brash ice	<1 m	Bright	Very rough
Smooth ice	Variable	Black	Smooth
White ice	65-70 cm	Bright	Very rough
Ice foots	3-4 m	Bright	Rough
Pressure ridges	3-4 m	Bright	Rough
Drifted snow	Variable	Bright	Rough
Open water, leads		Black	Smooth

4. FUTURE MICROWAVE INVESTIGATIONS

A study was conducted by the National Environmental Satellite Service (NESS) to investigate the potential use of a microwave sensing satellite for hydrological measurements (Alishouse et al., 1971). There is little or no atmospheric attenuation at frequencies lower than approximately 10 GHz (Haroulus and Brown, 1970). This fact, along with the ability of microwave radiation to penetrate clouds, makes the potential use of satellite platforms for ice surveillance very desirable.

Microwave satellites can be of two types, according to whether they have passive or active sensors. Passive sensors utilize radiation emitted by the earth, while active sensors generate signals that are reflected by the earth. The most useful satellite microwave system would be an active system, powered by solar energy, with a synthetic antenna aperture. The SAR system would achieve the best resolution possible from the range of the orbiting satellite. The most desirable frequency of coverage would be at least once a day with a sunsynchronic polar orbit around the Great Lakes, so that sea state studies could also be conducted from data received from the Arctic region. By utilizing imagery obtained from microwave and optical satellites, a more complete representation of the ice cover could be made. A microwave satellite could also be used to continue investigations performed by Strong and Fleming

(1970), in which a 19.4-GHz radiometer was utilized to measure brightness temperatures of various sea ice conditions from an aircraft. An electric scanning 19.4-GHz radiometer is scheduled for inclusion on NIMBUS E, and a 37-GHz radiometer has been proposed for inclusion on NIMBUS F (Alishouse et al., 1971).

Investigations using SLAR and SAR from aircraft altitudes should also be continued. Much progress has been made in the last 5 years toward operational use of the SLAR and SAR systems. Further emphasis should be placed on the collection and documentation of accurate ground verification data. Also, research should continue with the goal of reducing the delay time between data acquisition and dissemination.

5. CONCLUSIONS

In an effort to gather relevant Great Lakes ice information, several studies were conducted to research and develop operational uses of microwave radiation remote sensing systems. At present the U.S. Coast Guard and NASA are investigating a system employing X-band (3-cm wavelength) real antenna aperture radar, the most operationally useful system because data can be disseminated while the aircraft is in flight. Through a system of relays, ice-cover information is disseminated to shippers in only a few hours. This microwave system has proved useful in aiding all phases of navigation through ice-covered areas and in severe weather. Limitations are evident in the areas of ground data collection and verification.

Due to the dynamic nature of ice cover and persistent cloud cover during the winter months, microwave remote sensing is the only reliable means for continuously monitoring Great Lakes ice cover. Future microwave investigations should concentrate on ground data collection and correlation for both SLAR and SAR systems. Also under investigation is possible satellite microwave remote sensing. The use of satellites would be highly desirable because of the synoptic view of all lakes attained at satellite altitudes.

6. REFERENCES

Alishouse, J. C.; Baker, D. R.; McClain, E. P.; and Yates, H. W. 1971. *Potential of satellite microwave sensing for hydrology and oceanogaphy measurements.* NOAA Technical Memorandum NESS 26, COM-71-00544.

Bryan, M. L. 1975. *A comparison of ERTS-1 and SLAR data for the study of surface water resources.* Final report prepared for NASA by the Environmental Research Institute of Michigan under Contract No. NASA-CR-ERIM-193300-59-F.

Bryan, M. L., and Larson, R. W. 1973. Application of dielectric constant measurements to radar imagery interpretation. Paper presented at the Second Annual Remote Sensing of Earth Resources Conference, 26-28 March 1973, Tullahoma, Tennessee.

Haroules, G. G., and Brown, W. E. 1970. Simultaneous investigation of attenuation and emission by the earth's atmosphere of wavelengths from 4 centimeters to 8 millimeters. *J. Geophys. Res.* 74:4453-4471.

Jirberg, R. J., et al. 1973. Application of SLAR for monitoring Great Lakes total ice cover. Paper presented at the International Symposium on Advanced Concepts and Techniques in the Study of Snow and Ice Resources, 2-6 December 1973, Monterey, California.

Larrowe, B. T., et al. 1971. *Fine resolution radar investigation of Great Lakes ice cover.* Final report prepared for the Great Lakes Research Center, U.S. Lake Survey District, U.S. Army Corps of Engineers by the Environmental Research Institute of Michigan.

Schertler, R. J., et al. 1975. *Great Lakes all-weather ice information system.* NASA Technical Memorandum NASA-m-71815. (Also presented at the 10th International Symposium on Remote Sensing of the Environment, 6-10 October 1975, Ann Arbor, Michigan.)

Strong, A., and Fleming, M. 1970. *Aircraft microwave measurements of the Arctic ice pack.* ESSA Technical Memorandum NESCTM 25.

U.S. Coast Guard. 1972a. *Analysis of SLAR imagery for Arctic and lake ice.* Report DOT-CG-14486-A.

U.S. Coast Guard. 1972b. *Interpretation of winter ice conditions from SLAR imagery.* Report DOT-CG-14486-1A.

Vickers, R. S.; Heighway, J.; and Gedney, R. 1973. Airborne profiling of ice thickness using short pulse radar. Paper presented at the International Symposium on Advanced Concepts and Techniques in the Study of Snow and Ice Resources, 2-6 December 1973, Monterey, California.