NOAA Technical Memorandum ERL GLERL-Y

AN ANALYSIS OF GREAT LAKES ICE COVER FROM SATELLITE IMAGERY

Brenda Blanton Hagman

Great Lakes Environmental Research Laboratory
Ann Arbor, Michigan
April 1976

UNITED STATES DEPARTMENT OF COMMERCE
Elliot L. Richardson, Secretary

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
Robert M. White, Administrator

Environmental Research Laboratories
Wilmot N. Hess, Director

CONTENTS

FIGURES

TABLES

AN ANALYSIS OF GREAT LAKES ICE COVER FROM SATELLITE IMAGERY

Brenda Blanton Hagman

Remotely sensed satellite data present a synoptic view of the distribution and extent of the Great Lakes ice cover. Although there are several reasons for extracting ice-cover information from satellite imagery, the major reason is the desire to extend the navigation season on the Great Lakes. One method of obtaining this type of information is to measure satellite transparency density and then correlate calculated surface reflectance with ice-cover concentration. But the use of transparencies presents several difficulties, such as the problem of variable film densities. Because of the variability inherent in satellite transparencies and inaccurate ground verification data, it is desirable to find a better method of extracting ice-cover information.

1. INTRODUCTION

The present method used to construct Great Lakes ice-cover charts is undesirable because it is time consuming and because missing data can cause inaccurate depiction of the ice cover. In considering alternative methods which could be used to supplement visual aerial reconnaissance data, a study was conducted to investigate the feasibility of using density measurement* from satellite imagery to identify various ice-cover concentrations.

The purpose of this study was to formulate an ice-cover concentration scheme based on calculated surface reflectance* as related to conventional ice-cover classes. The density of an ice field on the satellite imagery was used to determine the surface reflectance of a known ice concentration Surface reflectance was then correlated to the ground verified ice-cover data. A more objective and efficient method for interpreting ice data was thus achieved.

Imagery from the NOAA-2, -3, and -4 meteorological satellites (0.6-0.7 μm) was selected because of the coverage – twice daily. The criteria for selecting the passes to be used were: amount of cloud cover, availability of ground verification data, and number of lakes visible. Ice concentration is charted by the United States Coast Guard and the Canadian Department of the Environment. The concentration classes used here are identical to those used in ground verification aerial reconnaissance flights.

2. METHODS

The satellite signal is an indicator of surface reflectance. Variations in surface reflectance are due to changes in solar illumination, sun angle, atmospheric transmission, and the path radiance. These effects must be calculated for each frame; this can be achieved by measuring the image densities of two surfaces with known surface reflectances, one light and one dark. For this study the light surface, a snow field near Hudson Bay, Canada, and the dark surface, an open water area, were assigned reflectance values of 0.85 and 0.1, respectively. Values of atmospheric and solar variations can be determined (Grum et al., 1973) as follows:

$$S = X\rho + Y, \tag{1}$$

where S = flux received by the satellite (densitometer reading)
X = influences of atmospheric transmission (two ways), solar illumination, and sun angle
ρ = known surface reflectance value
Y = path radiance.

Once X and Y were calculated for each frame, unknown surface reflectance values were determined by using equation (1) with ρ as the unknown term.

The procedure for analysis was as Follows:

1. Construct ice-cover charts and identify the various areas of ice cover.

2. Determine densities of the two areas with known reflectance values.

3. Determine the densities of the areas with unknown reflectance values.

4. Calculate atmospheric, solar, and sky variation* from equation (1).

5. Calculate surface reflectance* for the area* measured in step 3 "sing the correction factors obtained from step 4.

6. Correlate calculated surface reflectance* with available ice concentrations from ground data.

An error analysis was performed with a ± 10 percent error in X and Y. The results indicate that path radiance (Y) has the greatest influence on reflectance. A 10 percent error in X resulted in a 8.6 percent error in reflectance; in comparison, a 10 percent error in Y resulted in a 24.1 percent error in reflectance.

In addition to errors which can occur in equation (1), errors which can be related to image development and ground verification also occur. Image development is the process of converting the received satellite signal into a panchromatic transparency. The initial 2 years of data processed (for the winters of 1972-73 and 1973-74) were not calibrated. The satellite project was still in the experimental stage, resulting in a wide range between the light and dark signal values (table 1) used for solving equation (1). The data processing systems were calibrated during the last year; hence, signal difference* for that period are more consistent.

Table 1. Differences Between Light and Dark Signal Values (Dimensionless)

1972-73			1973-74			1974-75		
Light	Dark	Difference	Light	Dark	Difference	Light	Dark	Difference
1.08	1.50	0.42	0.86	1.34	0.58	0.65	1.10	0.45
0.65	1.10	0.45	0.56	1.43	0.87	0.51	1.15	0.64
1.01	1.33	0.32	0.50	1.30	0.80	0.82	1.60	0.78
0.57	1.47	0.90	0.51	1.15	0.64	0.52	0.86	0.34
0.62	1.25	0.63	0.74	1.40	0.66	1.35	1.92	0.57
0.57	1.20	0.73	0.70	1.61	0.89			
			0.50	1.37	0.87	0.98	1.93	0.95*
						0.66	1.55	0.89*
						0.59	1.35	0.74*
						0.60	1.46	0.86*
						0.83	1.70	0.87*
						0.88	1.82	0.94*
						1.00	1.90	0.90*
						0.41	1.29	0.88*
						0.38	1.29	0.91*
						0.39	1.31	0.92*
						0.46	1.44	0.98*
						0.74	1.68	0.94*
						0.34	1.22	0.88*
						0.44	1.33	0.89*

* Data processing systems recalibrated.

The data processing systems were calibrated during the last year; hence, signal differences for that period are more consistent.

A second image development error is related to the film used to produce transparencies. Since each piece of film has a unique unexposed density, a film density curve (fig. 1) is used to determine optimum exposure time. When exposure is within the straight line segment of the density curve, variations can be minimized. However, it is too time consuming and costly to determine the unexposed density of each piece of film.

Ground verification errors relate to the process of correlating calculated surface reflectances with corresponding ground data. Inconsistencies found between the ground verification sources can be minimized by standardizing data collection parameters and procedures followed by the organizations involved. In addition, large areas of the lakes are not observed for long periods of time. The dynamic nature of ice can cause errors when ground data collected more than 2 days after the satellite pass is correlated with reflectance data.

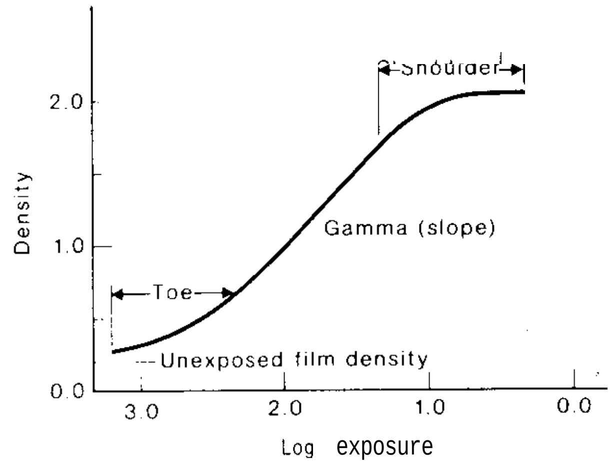

Figure 1. Representative film sensitometric curve.

3. DISCUSSION

Radiation incident on an ice field interacts with the surface in three modes: reflection, absorption, and transmission. Several ice-cover features can drastically alter the amount of radiation reflected by the ice surface. The magnitude and mode of change are determined by the various characteristics of the influencing feature. The magnitude of these interactions can be determined by direct field measurements; however, the measured values will change continuously, depending upon the prevailing atmospheric, solar, and physical conditions. In addition, there is a noticeable lack of qualitative information with respect to the amount of radiation reflected, absorbed, and transmitted by fresh water ice in the visible portion of the electromagnetic spectrum. One can only speculate as to the influence these three interactions have with respect to ice types, thickness, topographic features, and snow cover. Therefore, with currently available information, only the type of interaction taking place and the direction of change between an ice feature and the incident radiation can be determined.

Incorrect identification of ice concentrations from surface reflectance calculations can result from variations in ice thickness and type; ice topography, including cracks, puddles, and thaw holes; snow cover; and water overlying ice (table 2).

Table 2. Summary of Ice Features and the Primary Modes of Interaction with Incident Radiation with Respect to the Satellite Sensor

Ice Feature	Reflection	Absorption	Transmission	Scattering	Reflectivity
Ice thickness	thick ice		thin ice		thick ice increases; thin ice decreases
Ice topography		cracks, leads, puddles, thaw holes		ridges, raftings	decrease
Snow cover	new snow	old snow	old snow	new and old snow	increase
Water over ice		water			decrease

The thickness of an ice field determines, in part, the interaction which takes place between the ice and the incident radiation. Thick and/or snow covered ice is relatively light toned, indicating that most of the incident radiation is reflected. In comparison, new or thin clear ice is relatively transparent, implying that most of the incident radiation is transmitted through the ice layer and absorbed by the underlying water. This conclusion is supported by Hutchinson (1957), who stated that transmission of radiation through water is greatest in the red (0.6-0.7 µm) region and that greater than 90 percent of the transmitted radiation is absorbed in the first meter of water. Unfortunately, detailed information with respect to reflection, absorption, and transmission of radiation at various ice thicknesses and for various ice types is not available.

The amount of radiation reflected by an ice field is also influenced by the orientation of topographic patterns with respect to sun angle. Topographic features will decrease reflectance if radiation is scattered away from the sensor due to the orientation of the surfaces. Surface' patterns are caused by wind and wave forces; for example, wind erosion of snow surfaces forms patterns that frequently exhibit vertical and undercut surfaces facing into the wind. Wind and wave forces can combine to force ice sheets into each other, forming pressure ridges and raftings. Each lake displays characteristic topographic patterns depending upon the predominant wind direction and shoreline configuration. Total albedo may be affected by directional reflection from etched patterns and by the movement of snow. Features such as cracks, puddles, thaw holes, and shadows further reduce the radiation reflected due to absorption of radiation by water and obstruction of radiation in the shadow zone. Melt water on top of an ice sheet reduces the amount of reflected radiation by absorbing incident radiation. The magnitude of absorption is determined by the water's depth and consistency (mixed water and snow).

A snow-covered ice surface reflects various amounts of radiation, depending upon the physical characteristics of the snow and the prevailing climatic conditions. Changes in reflectivity are determined by the age of the snow, type of snow, grain form, and solid impurities. Furthermore, changes in reflectivity with azimuth and elevation in direct sunlight are caused by surface irregularities, crusted surfaces, and old metamorphosed snow. Scattering and absorption within the snow layer are determined by grain form, density, and sub-surface ice layers and inhomogeneities. Reflectances also vary with solar angle, time of day and year, and amount of cloud cover. Mellor (1965) determined that reflectance values of various snow types ranged between 46 percent for old snow and 87 percent for new snow. In direct sunlight reflectance increases toward the red end of the electromagnetic spectrum.

Thus, more basic research is needed dealing with the optical properties of fresh water ice during the stages of accumulation, maximum ice cover, and decay and with respect to varying climatic conditions. The information is necessary in order to develop a concise analysis and greater delineation of the ice concentration classes.

The following wintertime lake features can be easily identified on a relatively cloud-free satellite image of good quality:

1. Areas with open water, leads, and cracks.

2. Boundaries between open water and ice cover.

3. Consolidated ice packs with snow cover.

These features can be identified by use of the interpretive tools of tone, texture, pattern, and size. Open water exhibits a characteristic dark tone due to water's high radiation absorption properties. Leads, defined as navigable passages (differentiating them from cracks), can be identified by tone, size, and location, usually along shorelines. Cracks can be identified by tone and pattern orientation. Boundaries between open water and ice cover exhibit a change in tone and texture along the ice-water interface. Consolidated ice packs with snow cover can be identified by their very light tone (due to the snow cover's high reflectance properties), and by location, usually in bays and harbors and along shorelines.

4. ANALYSIS

Analysis procedures used included scatter plots, visual inspection, and statistical analysis. The scatter plots of calculated surface reflectance versus ice-cover concentration and visual inspection showed those ice concentrations and surface conditions which could and could not be separated into discrete classes by the use of density measurements and therefore surface reflectances. The statistical analysis verified the scatter plot results.

Figure 2 shows scatter plots for each year's data. Table 3 is a summary of the scatter plot analyses for all years of data. The concentrations are given in proportionate percent coverage, with ten-tenths being total ice cover.

Table 3. Summary of Scatter Plot Analysis for the Six Concentration Classes

Class	Ice Concentration	Reflectance Range	Identification Method
I	open water	0.06-0.19	visual inspection
II	1/10-3/10	0.14-0.50	not identifiable
III	4/10-6/10	0.11-0.50	not identifiable
IV	7/10-10/10*	0.11-0.51	not identifiable
V	7/10-9/10**	0.47-0.81	density measurements, visual inspection
VI	10/10***	0.60-0.93	density measurements, visual inspections

* New or thin ice without snow cover.
** Thick ice with snow cover.
*** Consolidated ice with snow cover.

Class I, open water, could be identified on the imagery by using visual inspection only. The dark toned surface is caused by the high absorption properties of water in the red region of the electromagnetic spectrum (Hutchinson, 1957).

Classes II, III, and IV could not be differentiated on satellite imagery on the basis of density measurements and/or visual inspection. When reflectance values fall within the 0.11 to 0.51 range (provided the surface is not identified as open water), we can only state that the surface is either class II or III with no surface condition restrictions or class IV with new or thin ice. More precise data is needed if greater delineation within these three classes is sought.

Classes II and III have a wide range of reflectance values that are attributed to 1) the fact that exposed water is the major resolution cell element, 2) the fact that the signal is being averaged by the satellite

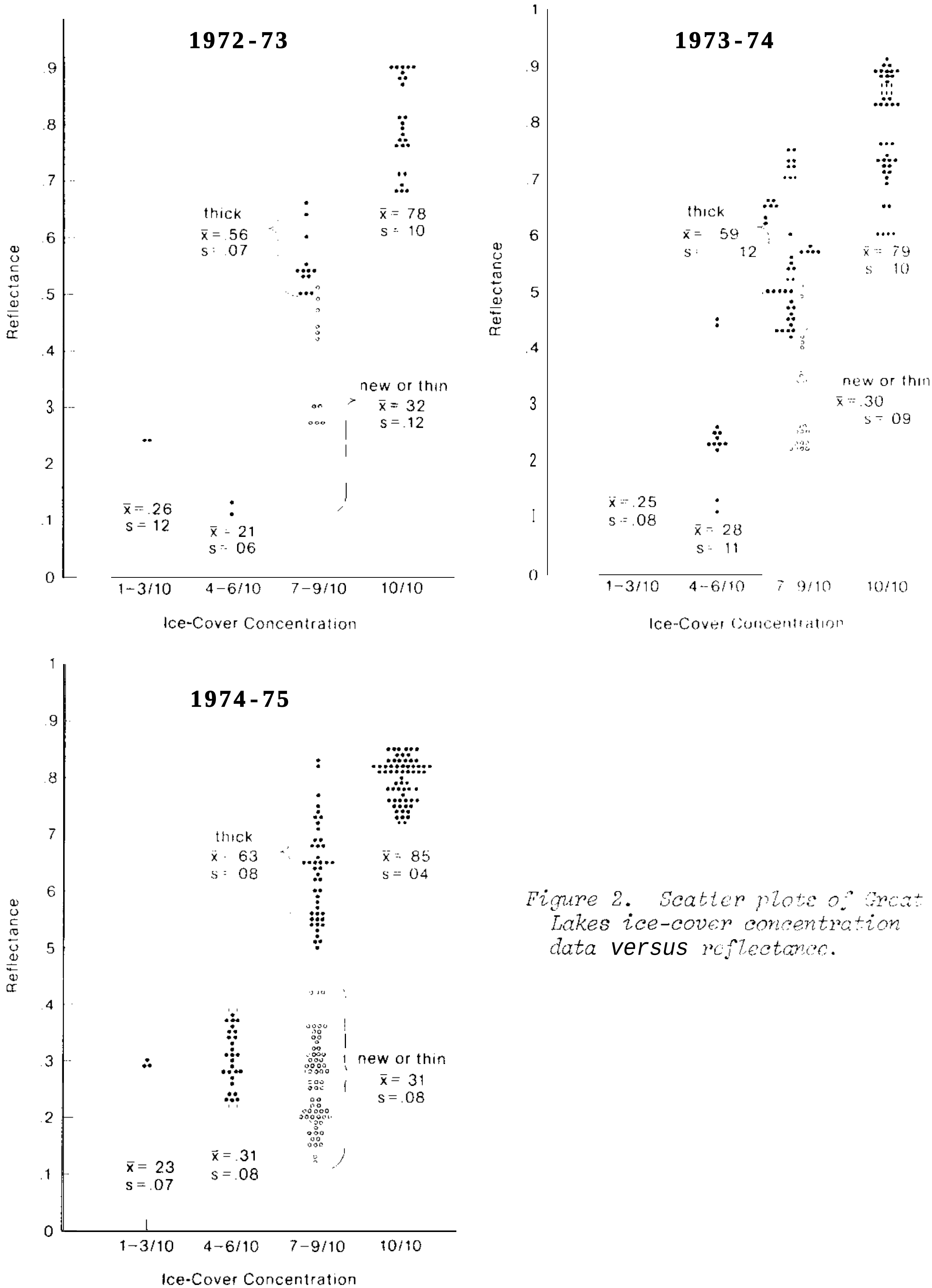

Figure 2. Scatter plots of Great Lakes ice-cover concentration data versus reflectance.

sensor and densitometer, 3) the surface conditon of the ice, and 4) the thickness of the ice. The wide range of reflectance values in class IV is attributed to the high transmission properties of thin ice and high absorption properties of the underlying water.

Classes V and VI could be identified on the imagery from density measurements and visual inspection. The tolerance limits (table 4) of these classes do not overlap the tolerance limits of the other classes. Both classes are very light toned due to the high reflectivity of snow. The presence of small areas of exposed water in class V decreases the integrated reflectance so that it is lower than class VI.

Calculations of reflectance mean, standard deviation, and tolerance limits were made for each class. Student's t-tests were performed on classes II, III, and IV to determine whether or not they were statistically different. Table 4 summarizes reflectance means, standard deviations, and tolerance limits for all classes. Tolerance limits were calculated with a confidence level of 0.95 containing 75 percent of the population (75 percent of the samples taken will fall within the given tolerance limits 95 percent of the time). Tolerance limits were calculated to determine specific reflectance ranges for each class.

The population distributions of classes II, III, and IV showed a normal distribution; therefore, the t-test was used to test the hypothesis that the compared class means were equal (table 5). The t-test was performed at the 95 percent confidence limit with the specified degrees of freedom. If the hypothesis was accepted, the class means were equal; therefore, the compared classes could not be separated. If the hypothesis was rejected, then the compared classes were considered statistically different. Even though the t-test showed some significant differences between classes, the tolerance limits indicated otherwise. Calculated tolerance limits, incorporating all available data, showed major overlapping between reflectance ranges. The probability of differentiating between classes II, III, and IV, by the use oi density measurements and calculated surface reflectance is, therefore, very low.

5. CONCLUSIONS

The results of this study indicate that it is not feasible to use density measurements for identifying Great Lakes ice-cover concentrations on existing satellite transparencies. Many factors not originally taken into account drastically influence the reflectance information obtained. Future remote sensing ice-cover studies must take into account such factors as film density, topographic patterns, snow cover, and atmospheric and solar influences, so that the data collected is representative of the specific populations under consideration. Two modifications are recommended in the areas of ground verification. First, one standard operating procedure should be followed when collecting and charting ice-cover information from aerial reconnaissance flights in order to construct an overall picture of the ice conditions. Second, the ground verification sources should be coordinated so that maximum coverage on all lakes is achieved.

Table 4. Summary of Reflectance Mean, Standard Deviation, and Tolerance Limits for all Classes

Class	Ice Concentration	Year	Reflectance Mean	Standard Deviation	Tolerance Limits
I	open water	all	*	*	
II	1/10-3/10	1972-73	0.26	0.12	0.26 ± 0.22
II		1973-74	0.25	0.08	0.25 0.14
II		1974-75	0.23	0.07	0.23 ± 0.10
II		all	0.24	0.09	0.24 0.12
III	4/10-6/10	1972-73	0.21	0.06	0.21 0.09
III		1973-74	0.28	0.11	0.28 ± 0.15
III		1974-75	0.31	0.08	0.31 ± 0.10
III		all	0.29	0.09	0.29 ± 0.11
IV	7/10-10/10 (new)	1972-73	0.32	0.12	0.32 0.16
IV		1973-74	0.30	0.09	0.30 0.11
IV		1974-75	0.31	0.08	0.31 ± 0.10
IV		all	0.31	0.09	0.31 0.11
V	7/10-9/10 (thick)	1972-73	0.56	0.07	0.56 ± 0.1"
V		1973-74	0.59	0.12	0.59 0.15
V		1974-75	0.63	0.08	0.63 0.10
V		all	0.60	0.10	0.60 . 0.11
VI	10/10	1972-73	0.78	0.10	0.78 0.13
VI		1973-74	0.79	0.10	0.79 ± 0.13
VI		1974-75	0.85	0.04	0.85 ± 0.05
VI		all	0.81	0.08	0.81 ± 0.09

* Not ca

This study has provided a basic understanding of the properties of ice cover and the manner in which they influence the remotely sensed data used. It has also revealed the need for basic field research in which the optical properties (reflection, absorption, and transmission) of fresh water ice are

Table 5. Summary of t-test Results for Testing the Hypothesis that Comparative Class Means are Equal at the 95 Percent Confidence Level

Class II	Class III DF*	Class III t	Result	Class IV DF*	Class IV t	Result
1972-73	24	1.170	Accept Hypothesis	13	1.004	Accept Hypothesis
1973-74	29	0.666	Accept Hypothesis	70	1.347	Accept Hypothesis
1974-75	52	2.950	Reject Hypothesis	81	3.080	Reject Hypothesis
Class III						
1972-73				29	2.830	Reject Hypothesis
1973-74				89	1.360	Accept Hypothesis
1974-75				104	0.000	Accept Hypothesis

* Degrees of freedom

examined with respect to the physical condition of the ice cover and its surface features under varying climatic conditions.

6. ACKNOWLEDGMENTS

The author gratefully acknowledges the advice and guidance of Dr. Frank H. Quinn, Head, Lake Hydrology Group, Great Lakes Environmental Research Laboratory; Mr. S. J. Bolsenga, Lake Hydrology Group; and Dr. Charles E. Olson, Jr., Chairman, Remote Sensing Program, The University of Michigan.

7. REFERENCES

Grum, F. R.; Hunt, W. G.; and Huboi, R. W. 1973. Color photography. In *SPSE Handbook of Photographic Science and Engineering*, ed. T. Woodief, Jr., p. 434. New York: John Wiley and Sons, Inc.

Hutchinson, E. G. 1957. The optical properties of lakes. In *A treatise on limnology*. New York: John Wiley and Sons, Inc.

Mellor, M. 1965. *Optical measurements of snow*. U.S. Army Cold Regions Research and Engineering Laboratory Research Report 169.