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GREAT LAKES ALL-WEATHER ICE INFORMATION SYSTEM

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ABSTRACT

This paper describes an all-weather ice information system developed by the NASA Lewis Research Center as part of the twelve federal agency Great Lakes Winter Navigation Program for which the U.S. Army Corps of Engineers is lead agency. This system utilizes an X-band Side-Looking-Airborne-Radar (SLAR) for determining type, location, and aerial distribution of the ice cover in the Great Lakes and an airborne, S-band, short pulse radar for obtaining ice thickness. The SLAR system is currently mounted aboard a U.S. Coast Guard C-130B aircraft. Digitized SLAR data are relayed in real-time via the NOAA-GOES-1 satellite in geosynchronous orbit to the U.S. Coast Guard Ice Center in Cleveland, Ohio. SLAR images along with hand-drawn interpretative ice charts for various winter shipping areas in the Great Lakes are broadcast to facsimile recorders aboard Great Lakes vessels via the MARAD marine VHF-FM radio network to assist such vessels in navigating both through and around the ice. The operational aspects of this Ice Information System are being demonstrated by NASA, U.S. Coast Guard, and NOAA/National Weather Service. Results from the 1974-75 winter season demonstrated the ability of this system to provide all-weather ice information to shippers in a timely manner.

1. INTRODUCTION

The Great Lakes-St. Lawrence Seaway System is a network of navigable waters composed of the St. Lawrence River, the five Great Lakes, and their connecting channels. The highly industrialized cities around the Great Lakes rely heavily on this inland waterway for economic commercial transportation. The Great Lakes ports account for over 17 percent of the United States' domestic and foreign waterborne commerce and over 31 percent of such traffic for Canada, totaling more than 100 billion ton-miles of waterborne freight per year. Considering only domestic commerce movement, these same ports account for 19 percent of the United States' traffic and 46 percent of Canadian traffic (ref. 1).

In 1972 this system carried 214 million tons of cargo, including significant percentages of the United States' waterborne traffic in iron ore (70 percent), coal (22 percent), limestone (78 percent), and gypsum (98 percent).

The Great Lakes-St. Lawrence Seaway system has traditionally been closed to navigation during the winter ice season from mid-December until early April because of the adverse effects of weather and ice. A preliminary investigation of the technical and economic feasibility of extending the navigation season into the winter months on this System was completed in 1969 by the U.S. Army Corps of Engineers (ref. 1). Results of this study concluded that present technology was sufficiently advanced to make extended season operations physically possible. This study further recommended a comprehensive demonstration program be undertaken to demonstrate the practicability of extending the navigation season into the winter months and provide information on the cost effectiveness, and environmental impact of measures to alleviate problems associated with winter navigation. Since 1970, twelve federal agencies led by the U.S. Army Corps of Engineers and the U.S. Coast Guard have participated in a federally sponsored program to demonstrate the practicability of extending the navigation season on the Great Lakes-St. Lawrence Seaway System and to identify the necessary resources for permanent extension. If an extended season is sufficiently cost-beneficial it is expected to be implemented on a permanent basis.

2. ICE INFORMATION REQUIREMENTS

The geographic location and extent of the Great Lakes region is such that it is subjected to a variety of wind and weather patterns and to rapid temperature changes. In this climatic zone the period of freezing temperature is generally not long enough to cause a lake-wide, solid stable ice sheet to form. Consequently, various stages of ice formation and decay often occur simultaneously at different locations within the Great Lakes and can even occur at different locations in the same lake. Storms, winds, current, and other hydro-meteorological factors produce rapid changes in the location and extent of the ice cover on the lakes.

The collection, analysis, and timely dissemination of accurate information concerning the location, areal extent, type, and thickness of the ice within the Great Lakes has been recognized as an essential element in the successful extension of shipping activities into the winter season. Such ice information is necessary to facilitate the safe and efficient vessel transit of ice covered waters (minimize delays caused by ice) as well as to provide a valuable input for the determination of vessel routing and movement schedules. In addition, such ice information will serve as a necessary input into the various scientific studies and analytical models used to predict ice build-up or decay throughout the season.

To meet the operational needs of the lake vessels and other interests during the extended winter navigation season, ice information must not only be frequently updated over the entire system but must also be transmitted in a timely manner to the wheelhouse of vessels operating in the Great Lakes. During periods of rapidly fluctuating ice [illegible]tions such as might occur as the results of the passage of a weather front th[illegible] the Great Lakes region, ice information must be updated daily. Due to the dynami[illegible]ure of the Great Lakes ice cover, information more than 12 to 24 hours old is [illegible]mes of limited value for aiding vessel navigation.

Side-Looking Airborne Radar (SLAR) with its ability to penetrate all but the most severe weather and to map broad lateral distances from aircraft altitudes satisfies the major requirements for an Ice Information System. Winter cloud cover and a limited field of view in relation to the tremendous areal extent of the Great Lakes ice cover generally preclude the use of optical systems operating in the visible and the infrared region of the electromagnetic spectrum.

2.1 Previous Investigations

A number of previous investigations have examined the feasibility of using SLAR to monitor freshwater ice conditions (refs. 2 to 4). Results of these investigations demonstrated the ability of microwave radiation to portray various ice surface features which in turn provide clues to ice type discrimination. Such investigations, however, were hampered by general lack of "ground-truth" information regarding various types of ice, surface features, internal structure and cracking patterns associated with freshwater ice. In addition, these previous SLAR investigations were limited because of their particular equipment design to rather narrow swath width coverages precluding the evaluation of one of the most salient features of the SLAR system; i.e., its ability to provide broad area coverage.

During the winter of 1971-72, the NASA Lewis Research Center initiated an attempt to correlate SLAR imagery with various ice types, features, and surface patterns as part of the Winter Navigation Program. Through a cooperative effort with helicopter teams of the 9th District U.S. Coast Guard, valuable on-the-ice observations and ice thickness measurements were obtained. The SLAR used in this study was the Motorola AN/APS-94C system developed for the U.S. Army and flown aboard a Grumman Mohawk OV-1B aircraft. Preliminary results demonstrated the broad-area ice survey capability of the SLAR (ref. 5). The SLAR imagery provided information from which some ice types could be inferred. With this system no direct correlation could be established between the microwave backscattered radiation and the thickness of an ice sheet. During this same time period a prototype airborne, high resolution, nonimaging short pulse radar for measuring ice thickness was developed. This short pulse radar provided accurate thickness measurements on smooth sheets of ice directly below the aircraft (ref. 6).

During the 1973-74 Winter Navigation Program, three OV-1 Mohawk aircraft equipped with SLAR (AN/APS-94) were regularly flown by the U.S. Army and NASA to obtain criteria for an operational system and demonstrate the usefulness of the information. Microwave signal returns were recorded on photographic film during the flights to be processed upon landing. SLAR prints accompanied by hand drawn interpretative ice charts were facsimile transmitted via the Great Lakes Marine VHF Network to vessels operating in the Great Lakes.

During the 1973-74 winter navigation season, nineteen vessels representing four shipping companies participated in this radio-facsimile demonstration. A total of 137 separate SLAR Image/Ice Chart Products were generated and relayed to the vessels. During this extended winter navigation season (Dec. 16-Mar. 31) 10.63 million tons of commerce were shipped. Short pulse ice thickness radar flights using the NASA C-47 aircraft (ref. 7) were initiated during the spring navigational season opening, commencing around the first of April. Seven such flights were conducted covering primarily the ice covered areas of Lake Superior.

The 1973-74 Ice Information Program demonstrated that: (a) SLAR in conjunction with the ice thickness radar was a practical means of obtaining accurate, all-weather and timely ice information. (b) Up-to-date ice information was very beneficial to the shippers in vessel route planning and in reducing vessel delays. However, results indicated that using the OV-1 aircraft and subsequently processing the SLAR imagery upon the completion of the flight was not an efficient way to provide ice information on an operational basis. First, because of OV-1 range limitations, two processing facilities (one at Saulte Ste Marie, Michigan, and one at Cleveland, Ohio) were required. Second, having to wait until the aircraft had landed to process the SLAR imagery did not always provide the ice information to the shippers in a timely manner. To survey adequately the winter shipping areas, flights were required which caused the information to be 12 or more hours old by the time it reached the wheelhouse of the Great Lakes vessels. Dynamic weather conditions in the Great Lakes can affect major changes in ice cover in a matter of hours. For maximum utility the time between the collection and dissemination of this information must be a matter of a few hours at most.

The results from the 1973-74 Ice Information Program were used to plan Project Icewarn for the 1974-75 and 1975-76 winter navigation seasons.

2.2 Project Icewarn

Project Icewarn is a cooperative program between the U.S. Coast Guard, NOAA/National Weather Service, and NASA to develop and demonstrate an operational all-weather, near real-time ice information system for Great Lakes winter navigation. The ice information system was designed by NASA and jointly demonstrated in an operational mode by NASA, U.S. Coast Guard and NOAA/NWS during the 1974-75 winter navigation season. Various elements associated with Project Icewarn are depicted in figure 1.

A four-engine, U.S. Coast Guard C-130B aircraft equipped with a SLAR system routinely surveyed selected regions of the Great Lakes. The SLAR data were transmitted to the U.S. Coast Guard Ice Navigation Center in Cleveland, Ohio, via two separate communications networks: (1) A continuous real time UHF uplink transmission from the SLAR aircraft to the NOAA-GOES Satellite in geosynchronous orbit and a subsequent S-Band microwave down link to the Wallops Island, Virginia, ground station and on to the Cleveland Ice Center by special dedicated telephone lines. (2) Tape playback data transmission from the SLAR aircraft to selected ground stations by an S-Band microwave downlink and on to the Cleveland Ice Center by special dedicated telephone lines. The satellite link constituted the primary communications network while the S-Band downlink to selected ground stations provide backup capability.

At the Cleveland Ice Center, the SLAR data were used to generate a high quantity SLAR image. These images along with hand drawn interpretative ice charts for the various winter shipping areas in the Great Lakes were transmitted by a facsimile scanner to vessels operating in the lakes.

A nonimaging, short pulse radar, routinely used to measure actual ice thicknesses, is not represented in figure 1. During the 1974-75 season, this radar system was flown in a NASA C-47 aircraft and was capable of measuring ice thicknesses remotely. The use of this short pulse ice thickness radar on a routine operational basis constituted one of the essential elements of the Great Lakes Ice Information System. A more detailed discussion of each of the various elements associated with the Ice Information System will be presented in the following sections of this report.

Operational experience from the 1973-74 Ice Information Program indicated that it generally would not be necessary to obtain SLAR imagery for all Standard Areas during each operational flight due to the absence of significant ice cover in some areas. As mentioned previously, the period of freezing temperatures in the Great Lakes region generally precludes the formation of a solid, lake-wide, stable ice sheet. Consequently various stages of ice formation, growth, movement, and decay often occur simultaneously at different locations throughout the lakes. Day by day SLAR operational planning must remain flexible so as to most efficiently respond to these dynamic ice conditions. During the spring of 1974, for example, flights were tailored to provide SLAR imagery of all of Lake Superior in order to portray the extensive ice cover on this lake. Special Summary Ice Charts of Lake Superior were issued outlining the existing ice types and locations. At this same time Lake Erie was completely ice free. During the 1974-75 season, ice conditions in Lake Superior were such that generally only Whitefish Bay in the eastern end of the lake required routine surveillance. Operational experience gained during the 1973-74 season indicated that SLAR imagery would have to be updated as frequently as once a day during periods of extensive and rapidly fluctuating ice conditions and on the order of three times a week during periods of relatively stable ice and weather conditions.

2.3 Standard SLAR Image/Ice Chart Product Areas

For the 1974-75 Winter Navigation Program, five standard areas were designated for which SLAR imagery and ice thickness measurements would be available. The location of these areas was determined by both the navigational track lines of the major winter shipping routes and the general pattern of the winter ice cover on the lakes. For example, since the Welland Canal and the St. Lawrence Seaway are not yet open into the Great Lakes for winter navigation, the area for Lake Erie includes only the western and central basins to just east of Conneaut. Conneaut is generally the most eastern harbor in Lake Erie used by the major shipping iron ore companies. These standard areas are depicted in figure 2 by the solid outlined areas. The dashed outlines indicate areas where additional coverage was provided on a limited (as needed) basis. The actual width of these standard areas is dictated by the 100 km swath width coverage of the SLAR system (50 km on each side of the aircraft).

3. AIRCRAFT DATA ACQUISITION

3.1 Side-Looking-Airborne Radar

The SLAR used in this program was the Motorola AN/APS-94C system developed for the U.S. Army. Operating in the X-band at a frequency of 9.245 GHz (3.245 cm wavelength) using a real aperture antenna, this radar transmits and receives horizontally polarized radiation. For the 1974-75 winter season, this radar system was mounted aboard a U.S. Coast Guard C-130B aircraft. For SLAR missions this aircraft was flown at an altitude of 3.35 kilometers (11,000 ft) and at an average ground speed of 280 knots. Figure 3 is a photograph of the C-130B flying a mission over the Straits of Mackinac which connect Lake Michigan and Lake Huron. Note the 6.1 meter (20 ft) SLAR antenna mounted on the tail section of the aircraft parallel to the longitudinal axis of the aircraft. A ground clearance of only 0.58 meter (23 in.) precluded mounting the antenna under the forward sections of the fuselage.

A schematic of this SLAR system is presented in figure 4. Narrow 0.5 degree wide beams of pulsed microwave radiation were alternately radiated from the left and right sides of the antenna at a rate that permits simultaneous mapping of the ice cover on both sides of the aircraft. The range resolution of the system was 80 meters while the azimuth resolution was proportional to range varying from approximately 45 meters at a range of 5 km to 450 meter at 50 km. Backscattered radiation was received by the antenna and routed to the receiver where the return signals were amplified and converted to video signals. These analog signals were used to modulate the intensity of traces of a cathode ray tube (CRT) on the aircraft; they were also simultaneously sent to a digitizer and signal encoder. The image on the CRT exposed a moving film whose speed was synchronized to the forward motion of the aircraft to provide a continuous image on the film. The SLAR image in this figure portrays the ice cover in Lake Erie on February 11, 1975. A radar "altitude hole" exists down the center of the track directly beneath the aircraft.

The SLAR has a pulse repetition rate of 750 pulses/second. The returns from these transmitted pulses were divided into 400 equal right antenna and 400 equal left antenna time segments or range bin intervals. During each range bin interval, the SLAR video signal was sampled and digitized into a six-bit data word. A digitizing unit accumulates the digitized SLAR video data in a memory, range bin by range bin, and continuously performed exponential averaging in the along-track direction.

Auxiliary data including aircraft drift, ground speed, altitude and heading were multiplexed with the averaged video data and the appropriate synchronization words to form a real time Bi-ϕ-L digital output at a rate of 6032 bits/second. These data were subsequently recorded, on magnetic tape. These SLAR data were either simultaneously transmitted in real-time to the NOAA-GOES satellite or transmitted at a later time by tape playback as described in Section 4.0.

3.2 Short Pulse Ice Thickness Radar

A key element of the 1974-75 ice information system was the routine operational use of an S-Band (2.8 GHz) short pulse radar to measure actual ice thicknesses. Profiling the ice immediately beneath the aircraft, this microwave system is capable of measuring ice thickness with an accuracy of 5 centimeters (±2.5 cm) from altitudes up to 2 kilometers (6500 ft).

Below 10 GHz electromagnetic waves generally exhibit low attenuation with a resultant high penetration in both ice and snow. For example, at 3 GHz measurements on fresh water ice give a signal attenuation of 0.44 decibels per meter for ice with a dielectric constant of 3.2 while results for snow range from 0.067 decibels per meter to 0.3 decibels per meter, depending upon the density of the snow (ref. 6). These values assume no losses from scattering processes. Such minimal losses indicate that a plane parallel layer of ice and snow should give rise to multiple returns from the various interfaces when illuminated by a microwave pulse. For example, consider a horizontal layer of snow, ice, and water. The reflection coefficients to be expected at 3 GHz at the various interfaces are as follows (ref. 6).

Air/snow interface	0.10
Snow/ice interface	0.19
Air/ice interface	0.28
Ice/water interface	0.67

The presence of either surface roughness or a surface water film would of course modify these values.

Figure 5 is a schematic illustration of this short pulse radar system. A nanosecond pulse of microwave energy is generated and directed toward the ice immediately beneath the aircraft. The return signal is composed of a pulse returned from the top of the ice (air-ice interface) and another, delayed in time, from the bottom of the ice (ice water interface). The delay time between these two pulses gives the ice thickness when calculated for the slower microwave propagation time through the ice.

The velocity of propagation of an electromagnetic wave is a function of the dielectric constant of the transmitting medium. Dielectric measurements on a number of fresh water ice samples (ref. 8) show a range of values between approximately 3.0 and 3.2 for the real part of the dielectric constant at a frequency of 2.8 GHz. Using a value of 3.1 for the dielectric constant of ice, the velocity of propagation in ice is 17 centimeters per nanosecond.

A typical pulse radar return is illustrated in figure 5. The delay time of 8 nanoseconds corresponds to a double transit of an ice layer 68 centimeters thick. Details concerning the electronic system design and operation can be found in reference 7.

Test results indicated that ice thicknesses as thin as 10 cm could be accurately measured in the case of a single unbroken ice sheet. For ice thinner than 10 cm the time separation between the return pulses from the air-ice and ice-water interfaces was not resolvable. The accuracy of these measurements was approximately 5 cm (±2.5 cm). Typical flight altitudes of 1.22 km (4000 ft) were used. Very rough or broken ice areas such as brash rafted or ridged areas cannot be profiled accurately because multiple off-axis surface reflections interfere and obscure the ice-water interface reflections. Measurements are not affected by snow storms, fog or snow covered ice; however, water on the ice surface from melting or rain precludes measurements at these locations because the microwave pulse is unable to penetrate the surface water.

Thickness results from typical Short Pulse Radar flights in Lake Superior from the 1973-74 winter shipping season are shown in figure 5. The dashed lines in this figure indicate the flight lines. On March 28, the western end of the lake was sampled by a pattern of across-the-lake flight lines. A complete west to east traverse of the lake was carried out on March 29 along with selected traverses in Whitefish Bay. Flight lines for such flights were prepared in advance from an examination of the most current SLAR imagery. Use of the SLAR imagery helps to insure that all major ice areas will be sampled. Thickness information from such short pulse radar flights was facsimile transmitted to the ships in a form similar to the Lake Superior chart depicted in figure 5. The data were also incorporated into the hand drawn interpretative ice charts described in Section 5.3.

4. DATA RELAY FROM AIRCRAFT TO ICE CENTER

During the 1974-75 Winter Navigation Program, the SLAR equipped aircraft was flown out of the NASA Lewis Research Center in Cleveland, Ohio. This aircraft could conduct the SLAR survey and return to base at the completion of each day's flight. As previously mentioned SLAR data were relayed to the USCG Ice Navigation Center in Cleveland via the two communication networks described in Sections 4.1 and 4.2.

4.1 NOAA-GOES Satellite Link

The digital SLAR data was transmitted to the NOAA-GOES satellite via a UHF uplink. The UHF transmitter consisted of a ±70 degree phase modulator followed by a RF amplifier. The transmitter center frequency was at 402 mHz and the RF output level was 150 watts. The transmitting antenna was mounted on the top of the aircraft fuselage just forward of the wing. The portion of this antenna that was used consisted of crossed dipoles fed by a 90 degree phase shift coupler. The GOES Satellite was utilized as a transponder for the uplinked data. The data were relayed via S-Band Downlink at 1.6 GHz to the NOAA/NESS Command and Data Acquisition Station at Wallops Island, Virginia. The phase modulated information was down converted to a 5 mHz I.F. output by the station and synchronously phase demodulated. The digital data were then synchronized, buffered and sent via telephone lines to the U.S. Coast Guard Ice Information Center in Cleveland, Ohio.

4.2 S-Band Data Link

Aircraft SLAR data after being tape recorded were played back and transmitted via an S-band link at a frequency of 2.2605 GHz and a bandpass of ±5 mHz. The primary ground receiver site was located at Saulte Ste Marie, Michigan, with another site at the Ice Center in Cleveland, Ohio. Data were transmitted to the receiving site at a 48,256 bit per second rate at the completion of a flight over one or two Standard Areas. For instance, SLAR data from both the Straits of Mackinac and Whitefish Bay were relayed to the Saulte Ste Marie station in approximately 7 minutes. On the ground the Bi-ϕ-L data were synchronized and recorded on magnetic tape. At the completion of the data dump, the data were relayed to the Cleveland Ice Center of the Coast Guard through dedicated telephone lines at a 6400 bit per second data rate.

5. DATA PROCESSING AND SHIPPER PRODUCE PREPARATION

5.1 SLAR Ice Information

The broad mapping coverage of the SLAR is illustrated in figure 6 which shows the ice cover on Lake Erie on February 22, 1973. In this figure the ice covered areas of the lake can be distinguished from the surrounding land areas by referring to the schematic boundary outline of Lake Erie accompanying this figure. Basically the radar "sees" a world of edges and interfaces rather than the bulk forms seen in the visible. The various shades of gray in the SLAR image correspond to the relative amounts of backscattered microwave radiation from the area within the antenna's field of view. Light toned (white) areas indicate areas of relative large amounts of backscattered radiation as might be expected from features exhibiting surface roughness such as cracks, rafted and ridged pieces of ice as well as broken pieces of ice (brash) possessing multiple edges. Dark toned areas on the other hand, represent areas of minimal backscattered radiation such as open water areas or smooth surface ice areas. From such areas the incident microwave pulse is specularly reflected away from the receiving antenna.

Figure 6 provides an example of many of the ice features identifiable from the SLAR imagery. The dark toned area along the north shore of the lake, east of Pelee Point, is open water. Directly south of Pelee Point, belts and patches of broken ice (brash) in areas of open water can be recognized by their very bright radar tone and their associated teardrop shaped patterns. The multiple edges of such brash features provide for excellent radar reflection. To the west of Pelee Point, along the northern edge of the lake, the generally dark toned region laced with a network of bright lines is associated with thin ice (less than 15 cm) which has developed extensive cracks as a result of wind stress. The very bright toned area along the southern shore between the islands in the lake and Toledo is a region of medium ice between 15 and 30 cm thick. The ice patterns north and east of Cleveland portray a large area of dark toned, smooth surface floes of medium thickness surrounded by bright toned edges composed of broken pieces of ice.

Often the ice along the open water boundary of the ice pack consists of brash pieces broken by wind and wave action. Such pieces, possessing multiple edges, provide a very bright radar return allowing the edge of the ice cover to be delineated from the open water areas. For example, the bright toned area southeast of Long Point in the eastern end of the lake illustrates the ice edge delineation. The dark toned area around Buffalo is a relatively smooth surface fast ice sheet of medium thickness. Such dark toned areas are distinguished from similar dark toned open water areas by the bright tone lines lacing the area which represent a series of ridges. Much data and imagery were collected in establishing the correlation between the various ice types and surface features with the tones, textures, and patterns found in SLAR imagery. These correlations will be reported in a subsequent paper by the authors.

The value of sequential SLAR imagery in following the large scale movement of ice in the Great Lakes is illustrated in figure 7. SLAR images from the Straits of Mackinac for the 27th, 29th, and 31st of March 1975 are presented along with an accompanying geographic sketch of the surrounding land areas.

On the 27th of March the area of the Straits between Beaver Island and Bois Blanc Island remained primarily ice covered with thickness between 15 and 50 cm. The dark toned area along the northern shore between St. Ignace and Port Inland was 70 percent covered with thin ice between approximately 10 to 15 cm thick. The area east of Bois Blanc was largely ice free. Between Beaver Island and Green Bay bright tone patches of brash ice can be seen in primarily open water areas. The southern part of Green Bay below Washington Island remained ice covered with only a few cracks discernible. Winds from the east later shifting around to the southwest succeeded in driving the ice out of inner area of the Straits around Mackinaw City, breaking it into pieces of brash in the process. The imagery on the 29th reveals the belts of brash which fill the Straits. Bright toned brash pieces were concentrated along the northern boundary of the Straits in response to the southwest winds. On this same day a large area of ice in Green Bay had broken off and moved in a northeasterly direction. Fast shore ice areas remained essentially unaffected by these current wind shifts. On the 30th the winds shifted around to the west, northwest. SLAR imagery taken on the 31st dramatically illustrates its effect on the ice cover. Broken pieces of ice completely clog the inner areas of the Straits, resulting in rafted, ridged, and windrowed areas of ice that make vessel navigation extremely difficult.

At the present time ice interpretation is still based on a qualitative correlation between the various ice types, surface features and patterns, and the associated tones, textures and patterns portrayed in the SLAR imagery. Preliminary research has been conducted to establish a quantitative correlation between the amount of backscattered microwave radiation and the various ice types and features. As part of this program a high resolution, multiplexed synthetic aperature SLAR system, developed and operated by the Environmental Research Institute of Michigan (ref. 9) was used. This system simultaneously imaged the "terrain" with X-band (3.2 cm) and L-band (23.0 cm) radar wavelengths recording both parallel and cross polarization backscattered returns. Preliminary results defined the dynamic range of backscattered microwave signals from the various ice types and features found in the Great Lakes to be within 20 dB of the minimum detectable signal. Additional details from this study will also be published in a subsequent paper by the authors.

5.2 Portable Ground Truth Ice Thickness Radar

On-the-ice "ground truth" data have been collected in support of the development of the airborne ice thickness radar as well as in an attempt to correlate ice types thicknesses and surface features with the relative amount of backscattered microwave radiation. In the past on-the-ice thickness measurements were obtained by drilling holes in the ice with an ice auger and measuring the thickness with a tape measure. During the 1974-75 season, a low powered, short pulse ice thickness radar similar to the airborne ice thickness radar was developed and tested in an all-terrain vehicle (ref. 10). This system allowed "ground truth" teams to rapidly collect ice thickness measurements over a large area as well as examine the returned microwave pulses for the effects of snow cover, moisture content, surface water and the physical condition of the ice.

5.3 Shipper's Product Preparation

At the Cleveland Ice Center, the digital SLAR data transmitted from the aircraft were recorded on magnetic tape, decoded and converted to an analog signal for a CRT-Fiber Optics Recorder that employed dry, heat developed, photosensitive paper to generate a high quality SLAR image at a scale of 1:1,000,000. Appropriate recorder controls were provided to match the CRT beam intensity to the dry silver paper which was capable of 9-12 gray levels and 200 lines/inch resolution. Contrast adjustments allowed various ice feature to be selectively enhanced to meet the needs of the interpreter.

The visual interpretations of the SLAR images were presented in the form of hand-drawn ice charts. The ice charts also contained ice thickness measurements obtained from the Short Pulse Ice Thickness Radar when available as well as additional relevant ice information available to the ice center. The combination of a SLAR image and its corresponding interpretative ice chart was referred to as a SLAR Image/Ice Chart Product or SLAR Product.

Examples of these SLAR Products for the five primary Standard Product areas (fig. 2) are shown in figures 8 to 12. The interpretative ice charts attempt to categorize the various areas of ice as to thickness, relative concentration of ice and percentage of various sized pieces of ice using standard Great Lakes ice nomenclature and plotting symbols. As an example of this nomenclature refer to ice chart in figure 8 where the designation $\frac{\text{A} \quad 8}{\text{THIN} \ 224}$ is shown. The "A" is an indicator for the age of the ice while "THIN" designates its thickness is between 5 and 15 cm. The "8" indicates that the total concentration of ice in this area is 80 percent. The "224" designation in the denominator is an indicator of ice floe size: 20 percent of the area is covered by brash or small pieces of ice less than 10 m in diameter; 20 percent is small to medium ice floes, 10 to 500 m in diameter; 40 percent is comprised of big floes greater than 500 meters in diameter.

The Product for the St. Clair/Lower Lake Huron areas (fig. 9) illustrates the ability of the SLAR imagery to display the established ship tracks through the ice as very bright linear features. A similar ship track feature can be noted in the Products of the Straits (fig. 10) and can be followed westward until it has been obliterated by the shifting ice. The very bright line running approximately north-south in the vicinity of Mackinaw City is the Mackinaw Bridge. This bridge was seen earlier in the photograph of the C-130 (fig. 3). Note the incorporation of the pulse radar ice thickness data in the interpretative ice chart (indicated by T*).

The Product for the eastern end of Lake Superior (Area 1) (fig. 11) encompasses only the Whitefish Bay area due to lack of significant ice cover outside of this bay. Ice movement in response to shifting winds combined with rather limited vessel maneuverability render Whitefish Bay along with the Straits as the most treacherous areas for vessel transit during the winter season.

The Product (fig. 12) for the western end of Lake Superior (Area 2), near Duluth is from February 6, 1974. Extensive ice cover such as exemplified here were not encountered in this area of the lake during 1974-75 season due to rather moderate winter weather conditions.

The ice near Duluth is solidly packed and over 30 cm thick. Its relatively smooth surface provides minimal radar return and appears dark on the image. The area of open water depicted in the middle of this image would permit the shippers to select an ice free track in transiting this area of the lake.

6. DATA TRANSMISSION TO GREAT LAKES VESSELS

6.1 Great Lakes Marine VHF-FM Network

The SLAR Products were facsimile broadcast to vessels operating in the Great Lakes over the Great Lakes Marine VHF-FM Radio Network. This network was established by the Maritime Administration (MARAD). Location of the various transmitting sites and the approximate range of each is depicted in figure 13. These indicated ranges do not take into account possible topographic obstructions which would shadow the radio broadcast. For example, Isle Royale in Lake Superior will shadow the Thunder Bay Area. This network consists of stations operated by the Lorain Electronics Corporation of Lorain, Ohio, and Central Radio of Rogers City, Michigan. Lorain Electronics transmitted these products from their stations at Duluth, Minnesota; Copper Harbor, Michigan; Port Washington, Wisconsin; and Lorain, Ohio. New stations at Grand Marais, Michigan, and Sturgeon's Bay, Wisconsin, are expected to become operational for the 1975-76 winter navigation season. Stations at Rogers City, Charlevoix, and Tawas, Michigan, were operated by Central Radio.

In addition to the SLAR Products, Wind and Temperature Forecast Charts and Ice Thickness Charts were also broadcast over the marine radio facsimile network. An example of one of these Forecast Charts is shown in figure 14. The forecast charts were issued daily and were prepared by the National Weather Forecast Office in Detroit. They indicated the winds and temperatures expected at 7 a.m. the next morning and at 7 p.m. the next evening. These charts also showed the expected location of weather fronts at the valid times of the chart. Separate ice thickness charts showing the results of the NASA Short Pulse Ice Thickness Radar were issued when they became available at the completion of such flights.

6.2 Facsimile Receiver

The shipboard facsimile equipment used during the 1974-75 winter shipping season was the Alden Facsimile Recorder. An essential feature of this equipment was its ability to provide an image of at least eight gray levels. An additional feature included its essentially unattended operation by first employing an automatic start/phasing/stop capability requiring only that the facsimile recorder be switched into the proper marine VHF radio channel at the time of the broadcast and second, the use of a continuous roll of recorder paper eliminating the need to reload paper for each product transmission. Facsimile products were received aboard ship at a scale of 1:762,000. Similarly scaled transparent overlays of the Great Lakes Navigation Charts were provided to each vessel equipped with a facsimile recorder. Used in conjunction with the SLAR Image and Ice Chart, these overlays allowed the ice cover to be seen in relationship to various land features and standard Great Lakes vessel track lines.

6.3 Broadcast Schedule

SLAR imagery was continuously generated at the Cleveland Ice Center during data transmission via the satellite communications relay from the SLAR aircraft surveying the ice covered regions of the Great Lakes. Interpretative charts can be made available within 1 hour after the completion of each flight segment. Using a laser facsimile transmitter developed by the Harris Corporation, the SLAR Product was facsimile transmitted as soon as it was completed to the marine radio communications center of the Lorain Electronics Corporation in Lorain, Ohio, over dedicated telephone lines. At Lorain the information was recorded on magnetic tape while simultaneously being broadcast to Great Lakes vessels via a telephone line/VHF-FM network. This ice information was also rebroadcast at other prearranged times throughout the day. A voice announcement on Marine VHF Channel 16 preceded these facsimile transmissions alerting the vessel as to which particular Products would be forthcoming. A detailed schedule of the Product facsimile transmissions from the

1974-75 season is presented in table 1. This table indicates which Products were broadcast from each station as well as the broadcast times and the Product order of broadcast. Each Product required on the average about 6 minutes to be transmitted. During the 1973-74 and 1974-75 these regularly scheduled facsimile broadcasts were provided as a public service by Lorain Electronics Corporation and Central Radio.

7. RESULTS OF THE GREAT LAKES ICE INFORMATION DEMONSTRATION

During the 1974-75 winter navigation season, 25 vessels representing five shipping companies and two U.S. Coast Guard vessels participated in this radio-facsimile demonstration. A total of 158 separate SLAR Products were generated from 56 flights between January 16 and April 6, 1975. These flights were conducted on an average of once every 2 days with daily coverage during times of rapidly changing weather conditions. During this same time period, nine short pulse ice thickness radar flights were conducted surveying ice covered areas primarily in the Straits of Mackinac and Whitefish Bay. These pulse radar flights were conducted with a frequency of approximately once a week for most areas.

During the 1974-75 extended winter navigation season (Dec. 16-Mar. 31), over 15 million tons of commerce were shipped within the Great Lakes. For the first time in the history of the Great Lakes, shipping continued year-round.

The goal of this program to provide all-weather ice information to shippers in a timely manner was achieved during the 1974-75 season. Results demonstrated the operational capability of the Side Looking Airborne Radar and Short Pulse Ice Thickness Radar Systems in conjunction with the satellite data relay and marine facsimile networks to provide comprehensive near real-time all weather ice information to vessels operating on the Great Lakes. The essentially automatic operation features of the shipboard facsimile receiver were highlighted by the shippers as enhancing the utility of the information although the overall quality of the facsimile copy received aboard the ships was only fair. Improvements in the quality of the telephone circuits serving the more remote marine radio transmitter locations should improve the quality of the facsimile transmissions. The coverage provided by the various transmitting stations in the marine VHF-FM radio network was generally adequate with the exception of the Whitefish Bay area of Lake Superior and the St. Mary's River which received only marginal radio coverage. New stations at Grand Marais, Michigan, and Sturgeon's Bay, Wisconsin, expected to be available for the 1975-76 season, will further extend the coverage of the marine radio network. A transmitting station in the vicinity of Saulte Ste Marie, Michigan, would essentially complete the network for winter navigation.

One of the primary goals of the Ice Program was to supply adequate near real time ice information to allow vessels either to avoid areas of ice altogether or to follow the path of least resistance when it becomes necessary to transit the ice fields. The ice charts provide an excellent overall view of the existing ice conditions, but the exact locations of the various regions and floes of ice within the ice field are only portrayed in the SLAR image. Therefore, the SLAR images are necessary for charting a vessel's course through and around the ice.

An example of the use of SLAR imagery by the U.S. Steel vessel Roger Blough in transiting the Whitefish Bay area of eastern Lake Superior during April of 1974 is presented in figure 15. The SLAR imagery during the period was transmitted from the aircraft directly to the Roger Blough. During the early part of April, ice was piled up in the eastern end of Lake Superior along the Canadian shore. By April 7, shifting winds had compacted this ice cover along the southern shore of the lake, west of Whitefish Point as shown in figure 15. The inner regions of Whitefish Bay remained 100 percent ice covered. The high return from the established ship track can be distinguished as a bright line running through the dark tone area of the solid ice pack. The Roger Blough, upbound into Lake Superior on April 7, used the SLAR image to navigate to the north around this ice pack. The Blough's route is indicated by the white line added to the SLAR image. The white toned area of ice in the outer regions of the bay is heavily rafted. On this same day, April 7, the U.S. Coast Guard Icebreaker Southwind attempted to open a new vessel track through the ice pack in the vicinity of Whitefish Point. After making only limited progress through this rafted and highly windrowed region of ice, the ice breaker steered a course toward the open water using the latest SLAR imagery of this area. Three days later on April 10, a south wind had opened this ice pack so that the best route for the Blough to navigate was a southerly one through a series of large leads and open water along the edge of Whitefish Point. Figure 15 portrays the downbound course of the Blough by means of the dashed line added to the SLAR image.

Figure 15 provides another indication of the dynamic movement that can take place in the ice pack in the Lake Superior entrance to Whitefish Bay. The shipper's have reported a number of instances when recently transmitted SLAR imagery has alerted them to both the development as well as the location and extent of newly formed regions of windrowed ice in Whitefish Bay. Similarly, instances have been reported in the Straits of Mackinac where the SLAR imagery has been used for navigational purpose either to initially determine a particular course or alter an existing course. For example, in the early part of the 1974-75 season, the SLAR imagery alerted shippers to the extent and location of ice building up in both the South Channel (near Bois Blanc Island) and Gray's Reef Passage (just east of Beaver Island) so that alternate ice free passages could be taken

In the western end of the Straits, the use of recently transmitted SLAR imagery allowed shippers to take advantage of leads and water opening brought about by recent shifts in the wind. These examples help to point out that even in regions of the lakes such as Whitefish Bay and Straits of Mackinac where vessels have a rather limited number of course alternatives to choose from, SLAR imagery can be extremely valuable for charting a vessel's course. In the more expansive open areas of the lakes there is no question about the utility of SLAR imagery for navigational purposes. This is especially evident during the months of February and March when the ice cover generally reaches its maximum buildup and on through the early part of April when it begins to decay.

Great Lakes vessels can move with safety and relative ease through thin ice. However, substantial ice fields, especially as the thicknesses become greater than 30 cm begin to preclude all vessel passage. Avoiding heavy concentrations of thick ice in the open lakes is very desirable since icebreaker assistance is not readily available in these open reaches of the lake and operational delays are costly. In addition such ice fields increase the probability of vessel damage.

During the 1974-75 season, the master of one vessel reported that he examined the SLAR image for evidence of the bright return from the established ship track, especially in areas such as the Straits, Whitefish Bay, and Lake St. Clair. If such a track line was delineated on the SLAR image, it suggests generally stable ice conditions. Absence of this well defined return or a shift in its general location alerted him to the fact that wind forces may have shifted the ice pack.

SLAR imagery was also used to provide detailed ice information concerning possible areas and harbors of refuge from severe weather and winter storms. Areas such as Bete Grise Bay of the Keweenaw Peninsula and Isle Royale in Lake Superior are frequently used to provide shelter from severe weather. On those occasions when vessels had to seek refuge from high winds, masters were very anxious to receive the latest ice information Products to see where all the prestorm ice fields had been blown before they got underway again.

Ice information was used regularly by the shipping companies in making vessel dispatch decisions. One shipping company had a facsimile receiver located in their operations office and regularly received all the Products. Accurate up-to-date information on changing ice conditions in the lower regions of the lakes (Lake St. Clair, Detroit River, Lake Erie) allowed them to make dispatch decisions as their vessels reached the southern end of the St. Mary's River at Detour on the advisability of going to Lake Michigan ports versus Lake Erie ports. Such decisions of course take into consideration the availability of ice breaker assistance at each point in time.

In addition to helping to facilitate the safe and efficient transit of vessels through the ice covered waters of the Great Lakes, comprehensive ice information is serving as a necessary data input for scientific and engineering studies concerned with winter ice operations and the environmental impact of such operations. Some of these studies include the development of analytical forecast models for freeze-up, growth rates, maximum ice cover and breakup of ice within the various regions of Great Lakes; the effect of ice cover on the heat budget and evaporation in Lakes Erie and Ontario; monitoring the environmental effects of ice on various shore structures as well as on shoreline erosion; the effect of ice cover on the climatology of various Great Lakes metropolitan areas, especially Buffalo, New York, and the effect of ice cover on water ecology.

8. CONCLUDING REMARKS

The collection, analysis, and timely dissemination of comprehensive, information concerning the location, type, and extent of the ice cover within the Great Lakes has been recognized and repeatedly emphasized as an essential element in the successful extension of the Great Lakes shipping activities during the winter months. An all weather ice information system for the Great Lakes has been developed by NASA and jointly demonstrated by the NASA, U.S. Coast Guard and NOAA/NWS during the 1974-75 winter navigation season in conjunction with the federally funded Winter Navigation Program.

The current system employs a real aperture X-band (3.245 GHz) side looking airborne radar mounted on a U.S. Coast Guard C-130B aircraft to routinely survey ice covered areas of the Great Lakes. Digitized SLAR data were relayed to the U.S. Coast Guard Cleveland Ice Center from the SLAR aircraft via the NOAA-GOES Satellite and dedicated telephone lines. Remote ice thickness measurements were also available to the Ice Center on a regular basis from an S-band (2.8 GHz) short pulse Ice Thickness Radar mounted aboard a NASA C-47 aircraft. At the ice center high quality SLAR images were generated from the SLAR data. These images along with had drawn interpretative ice charts incorporating the remote ice thickness measurements for the various ice covered winter shipping areas were facsimile broadcast in real time to the wheelhouse of vessels operating within the lakes via the Marine VFH-FM radio network.

During the 1975-76 winter season, NASA, the U.S. Coast Guard, and NOAA/NWS will continue to demonstrate the application of both the SLAR and the short pulse ice thickness radar in providing all weather ice information for the Great Lakes in an operational mode. NASA plans to improve the airborne ice thickness radar to provide automatic readout of ice thickness as well as profile ice ridge heights. Additional short pulse radar systems will be built for installation aboard the C-130B SLAR aircraft, the NASA OV-1 aircraft, and a USCG Sikorsky H-53 helicopter. Various technical improvements are also planned for the SLAR system aboard the C-130B. In addition, a UHF communication receiver is being developed for installation aboard the USCG Icebreaker Westwind which normally operates in the Straits of Mackinac during the winter navigation season. During the 1975-76 winter ice season, it is planned to transmit real time SLAR data to the icebreaker directly from the C-130B SLAR aircraft. An image recorder aboard the ice breaker will provide an enlarged 1:250,000) SLAR image of the ice cover in the Straits in a further demonstration of the applicability of SLAR information to assist icebreaker operations.

For the 1975-76 winter navigation season, this Great Lakes all weather ice information system will be operated by the U.S. Coast Guard and NOAA/National Weather Service with some NASA assistance. By the 1976-77 season the transfer of this Ice Information System to the U.S. Coast Guard and NOAA/National Weather Service is expected to be complete.

REFERENCES

1. Great Lakes and St. Lawrence Seaway Navigation Season Extension Survey Report. Detroit District Corps of Engrs., 1969.

2. Larrowe, B. T., et al.: Fine-Resolution Radar Investigation of Great Lakes Ice Cover. Willow Run Labs., Univ. of Mich. (Contract No. DACW35-68-C-0046), 1971.

3. Analysis of SLAR Imagery of Arctic and Lake Ice. DOT-CG-14486-A, U.S. Coast Guard, 1972.

4. Interpretation of Winter Ice Conditions from SLAR Imagery. DOT-CG-14486-1A, U.S. Coast Guard, 1972.

5. Jirberg, R. J., et al.: Application of SLAR for Monitoring Great Lakes Total Ice Cover. Presented at International Symp. on Advanced Concepts and Techniques in the Study of Snow and Ice Resources, Monterey, Calif., Dec. 2-6, 1973.

6. Vickers, R. S.; Heighway, J.; and Gedney, R.: Airborne Profiling of Ice Thickness Using a Short Pulse Radar. Presented at International Symp. on Advanced Concepts and Techniques in the Study of Snow and Ice Resources, Monterey, Calif., Dec. 2-6, 1973.

7. Cooper, D. W., et al.: Remote Profiling of Ice Thickness Using a Short Pulse Radar System Aboard a C-47 Aircraft. Presented at Earth Environment and Resources Conf., Philadelphia, Pa., Sept. 10-12, 1974.

8. Vickers, R. S.: Microwave Properties of Ice from the Great Lakes. Stanford Research Inst. (NAS3-19092), 1974.

9. Rawson, R.; and Smith, F.: Four Channel Simultaneous X-L Band Imaging SAR Radar. International Symposium on Remote Sensing of Environment, 9th, Proc., Volume 1, Environmental Research Institute of Michigan, 1974, pp. 251-270.

10. Cooper, D. W., et al. proposed NASA publication.

TABLE 1. - SLAR IMAGE/ICE CHART PRODUCT BROADCAST SCHEDULE FOR 1974-75 WINTER SEASON

BROADCAST TIMES (EST)				PRODUCT AREAS	MARINE VHF STATIONS						
					DULUTH	COPPER HARBOR	PORT WASHINGTON	ROGERS CITY	CHARLEVOIX	TAWAS	LORAIN
1:00 AM	&00 AM	10 AM - 4 PM	7:00 PM	LAKE SUPERIOR NO. 2 (DULUTH)	●	●					
1:10 AM	&10 AM	BETWEEN 10 AM - 4 PM, NEW PRODUCTS WILL BE BROADCAST AS SOON AS AVAILABLE	7:10 PM	LAKE SUPERIOR NO. 1 (WHITEFISH BAY)	●	●	●	●	●	●	
1:18 AM	&18 AM		7:18 PM	STRAITS OF MACKINAC	●	●	●	●	●	●	
1:25 AM	&25 AM		7:25 PM	LAKE HURON			●	●	●	●	●
1:31 AM	&31 AM		7:31 PM	LAKE ERIE				●	●	●	●
1:37 END	&37 END		7:37 END								

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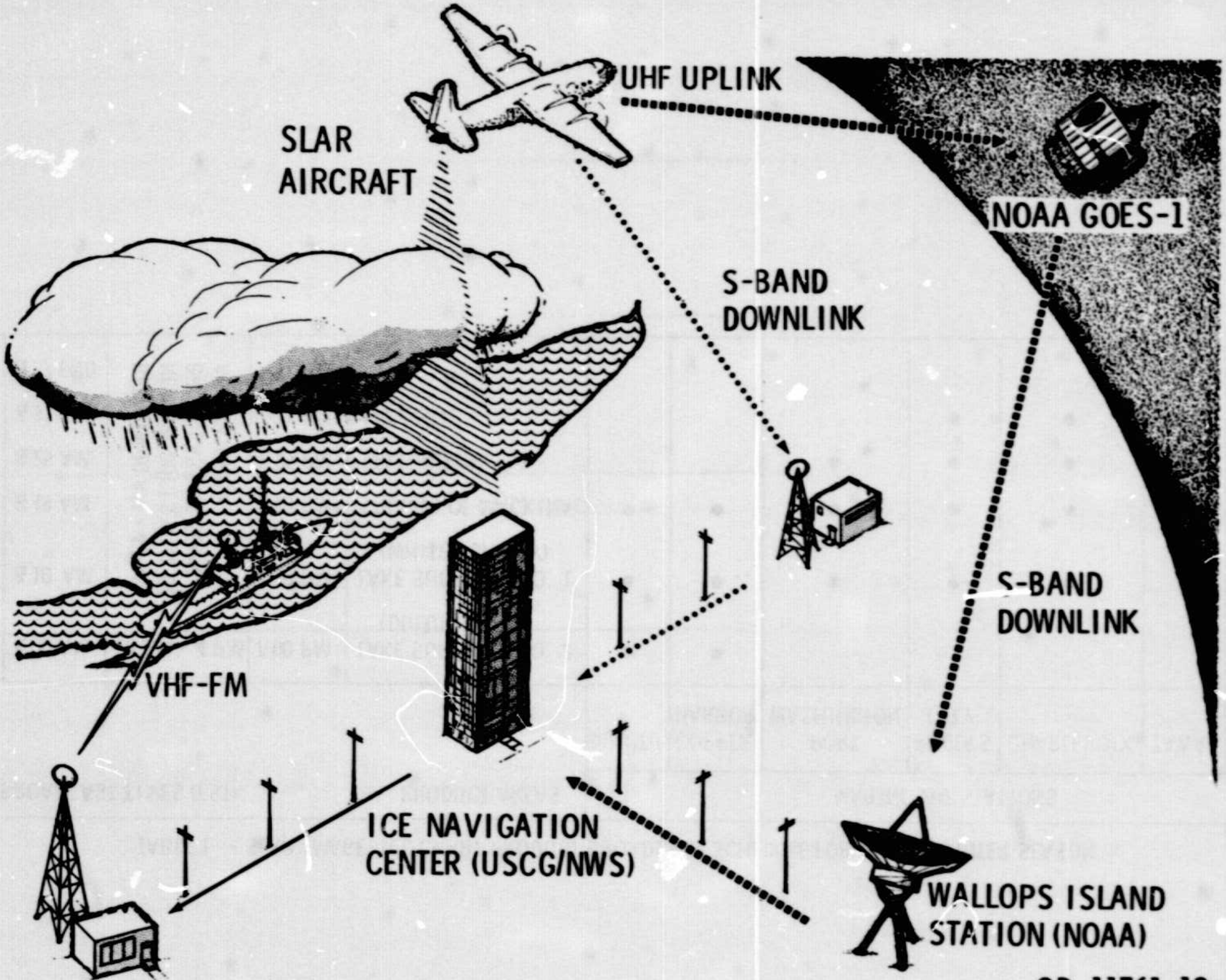

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Figure 1. - Schematic of the Great Lakes Microwave Ice Information Program (Project Icewarn).

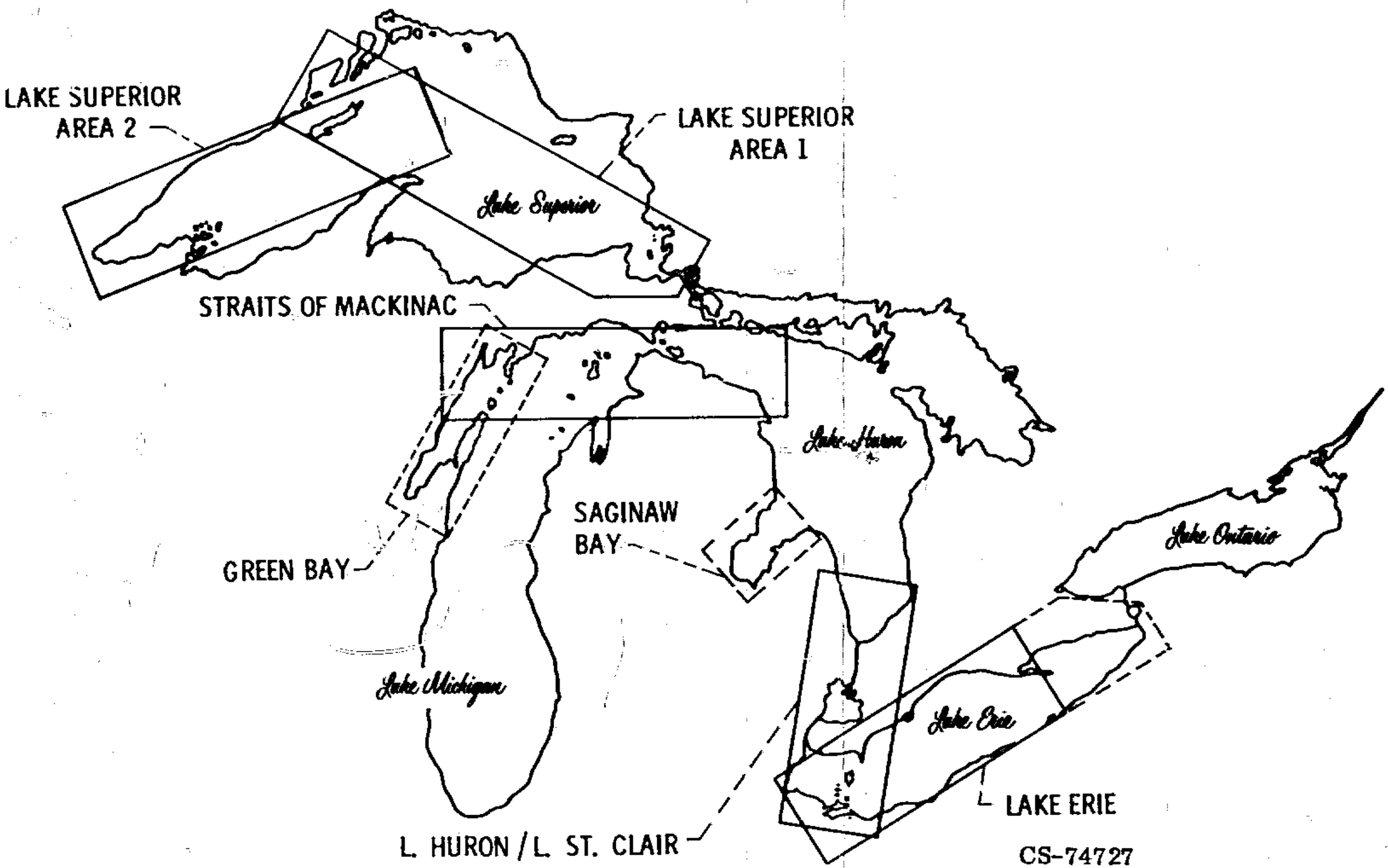

Figure 2. - Location and Identification of the Standard SLAR Image/ Ice Chart Product Areas.

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Figure 3. - Photograph of the U. S. Coast Guard C-130 B SLAR aircraft used in the 1974-75 Winter Ice Program. The ice cover around the Mackinac Bridge is shown in the background.

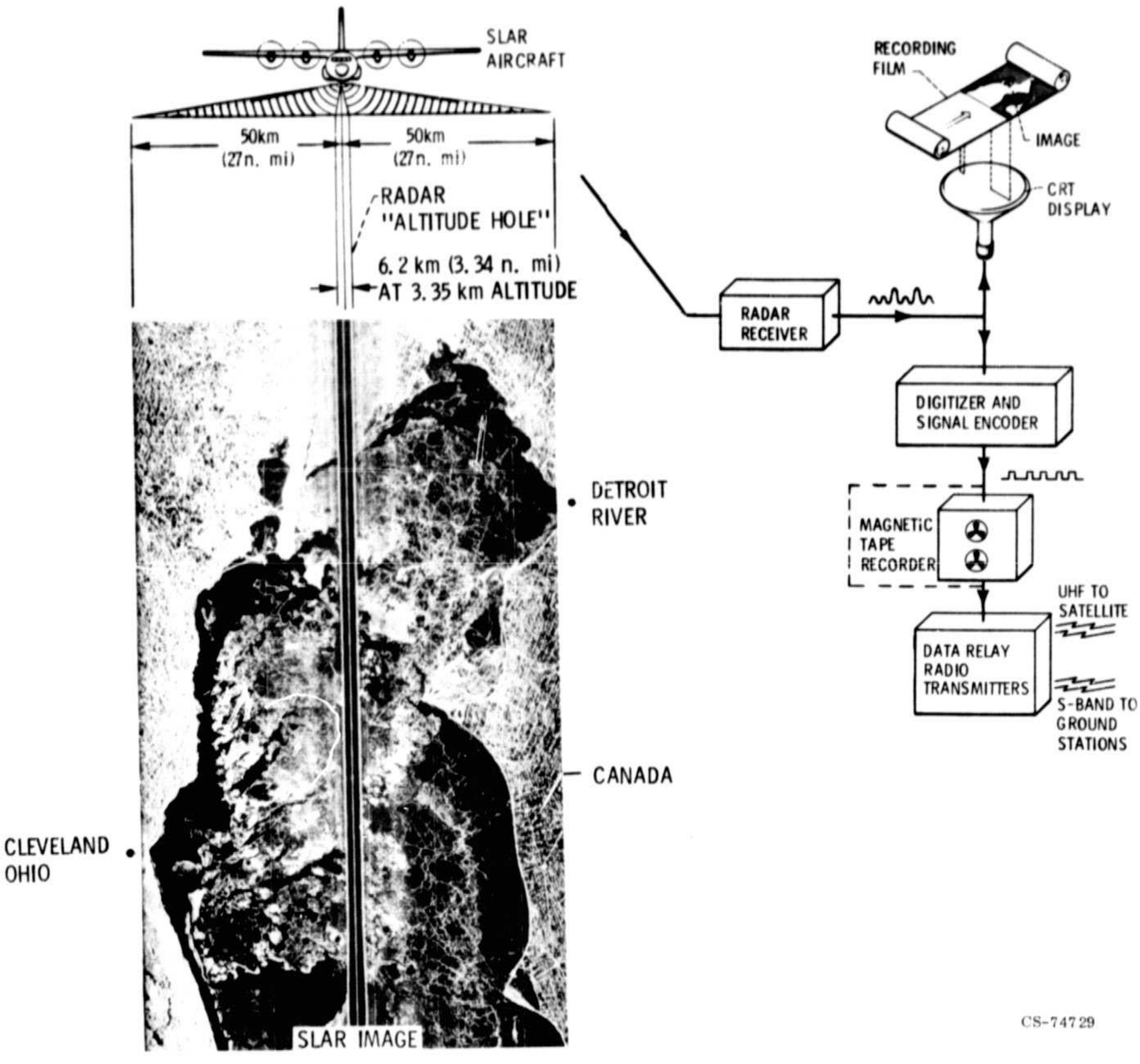
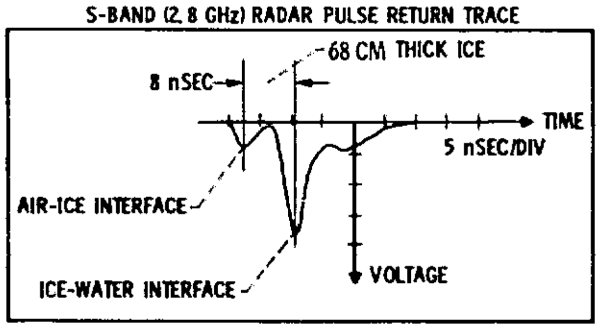


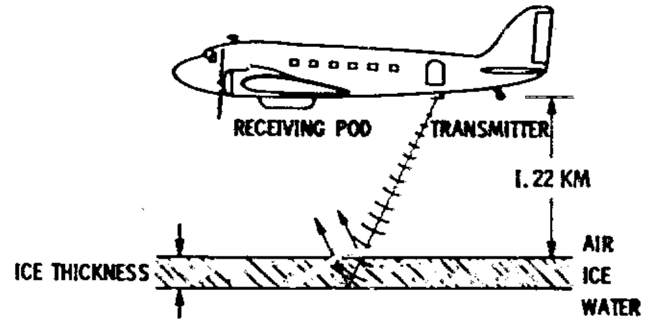
Figure 4. - Schematic of Side-Looking-Airborne-Radar System.

E-8511

ICE THICKNESS RADAR



SCHEMATIC OF AIRCRAFT OSCILLOSCOPE DISPLAY



SCHEMATIC OF PULSE RADAR OPERATION

RESULTS OF AN ICE THICKNESS RADAR FLIGHT

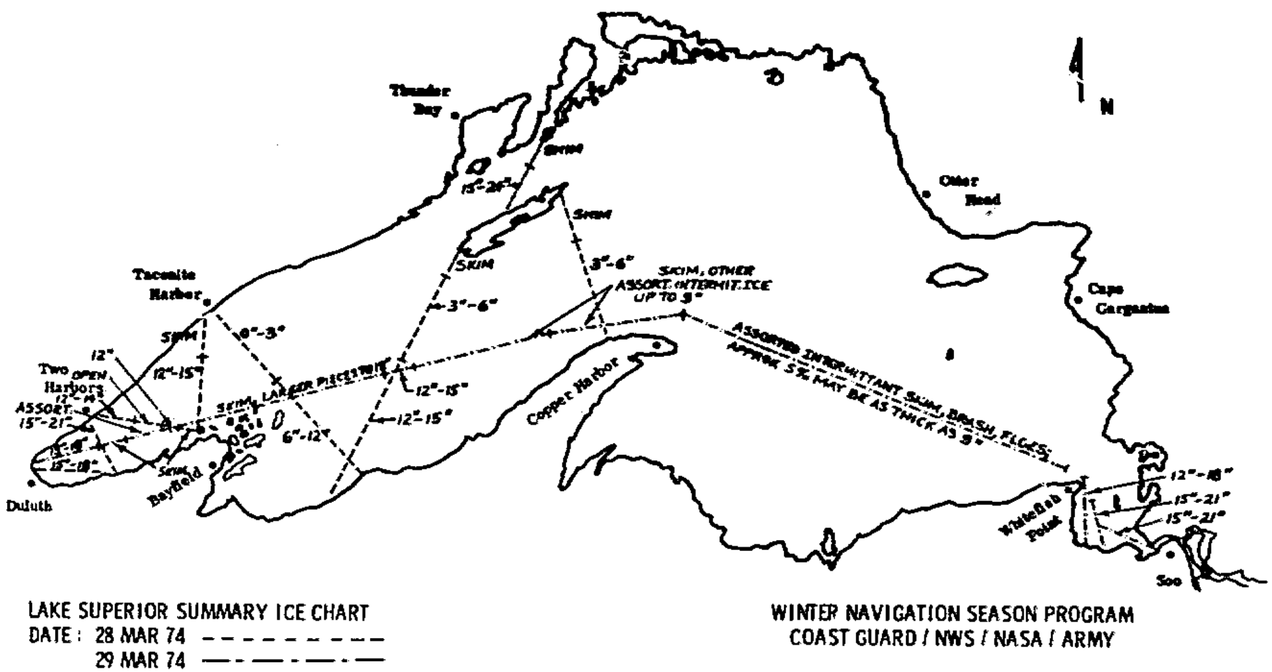


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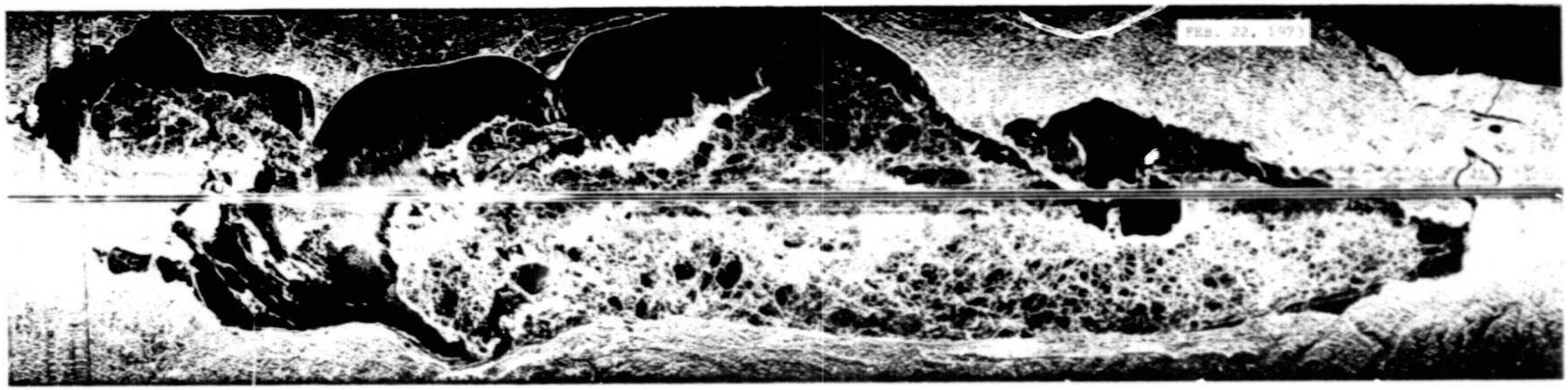
Figure 5. - Results from a typical NASA S-Band (2.8 GHz) Short Pulse Ice Thickness flight.



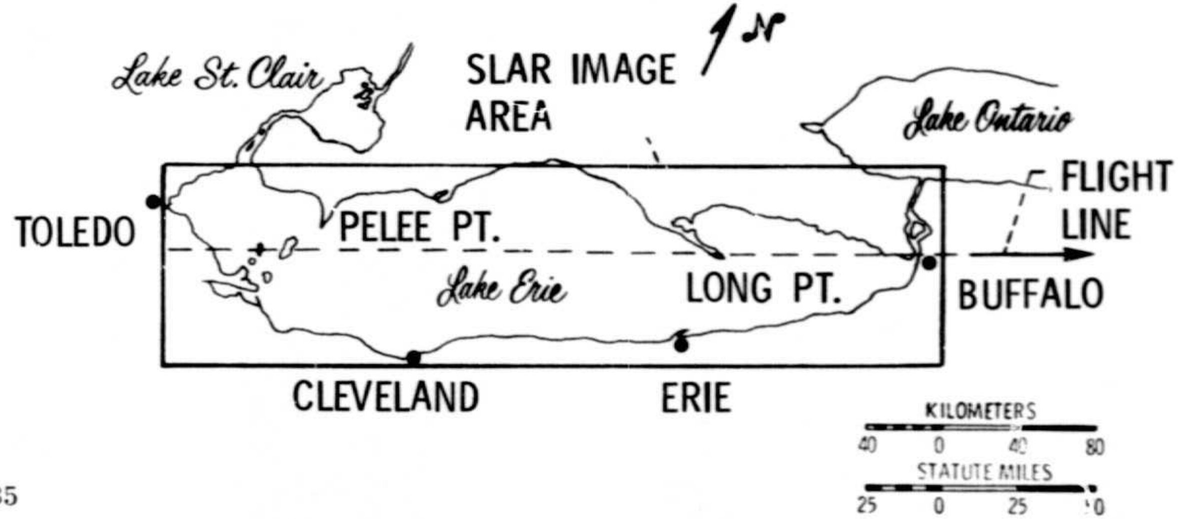


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Figure 6. - SLAR image of Lake Erie ice cover on February 22, 1973.

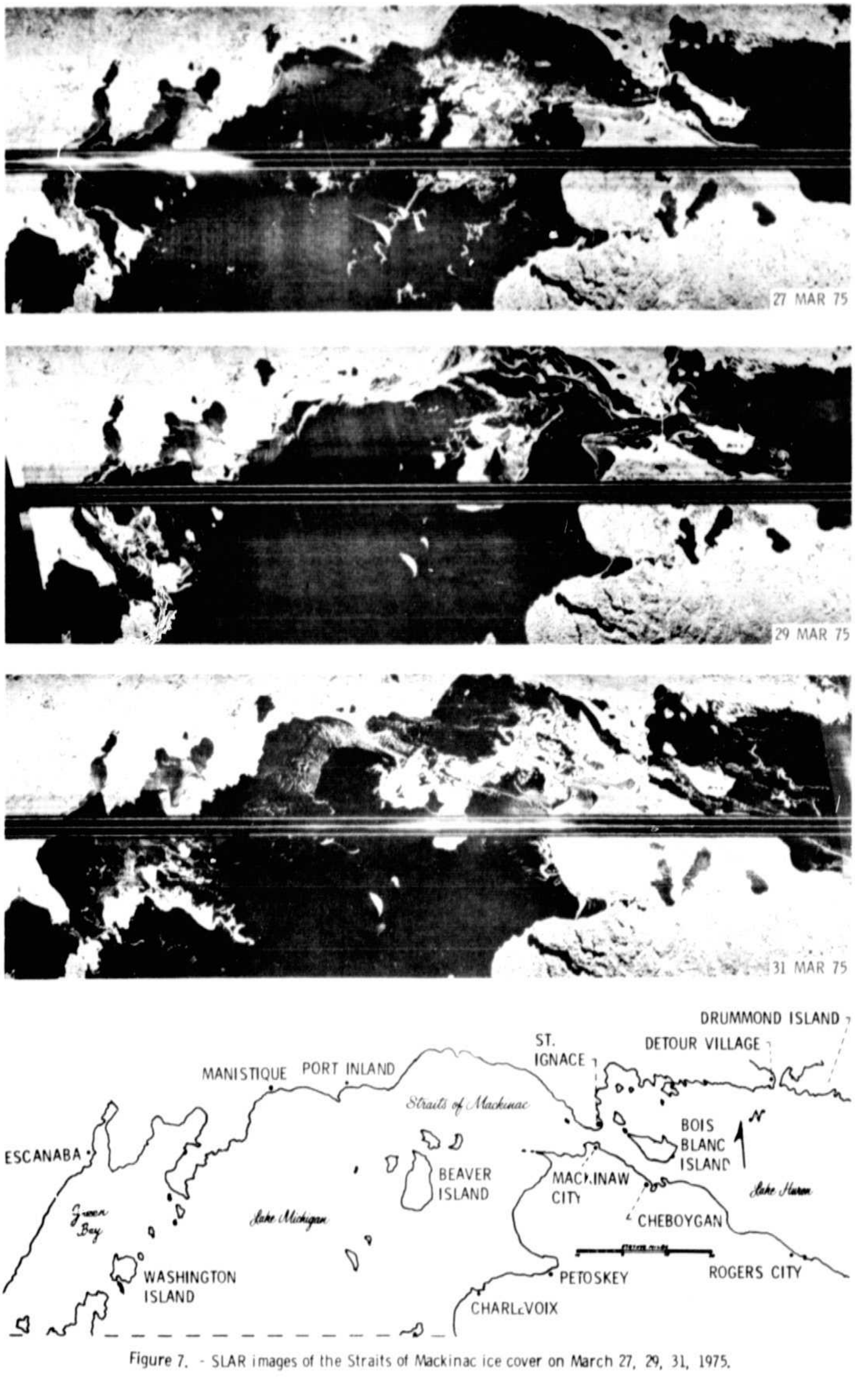

Figure 7. - SLAR images of the Straits of Mackinac ice cover on March 27, 29, 31, 1975.

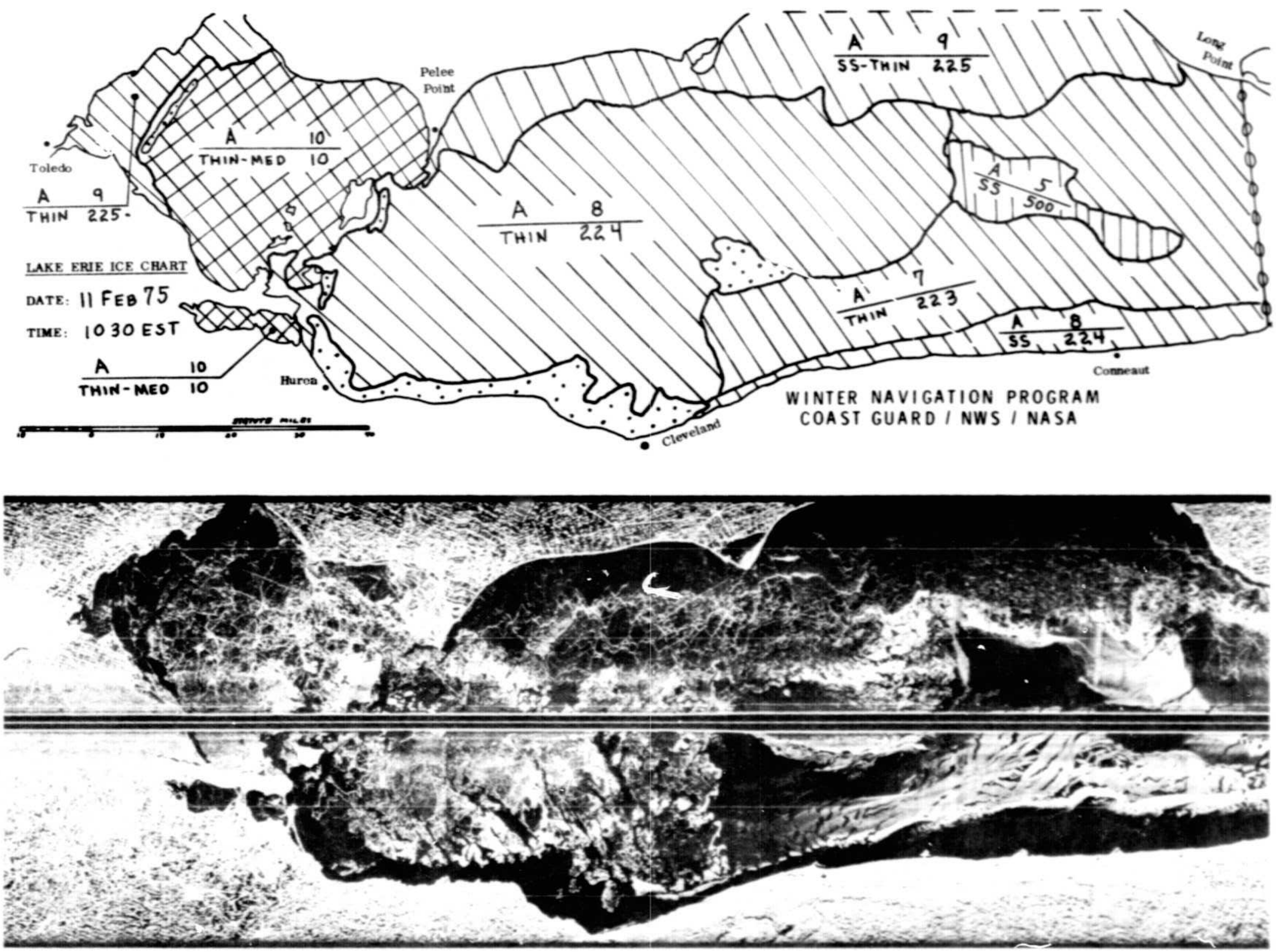

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Figure 8. - SLAR Image/Ice Chart Product for Lake Erie on February 11, 1975.

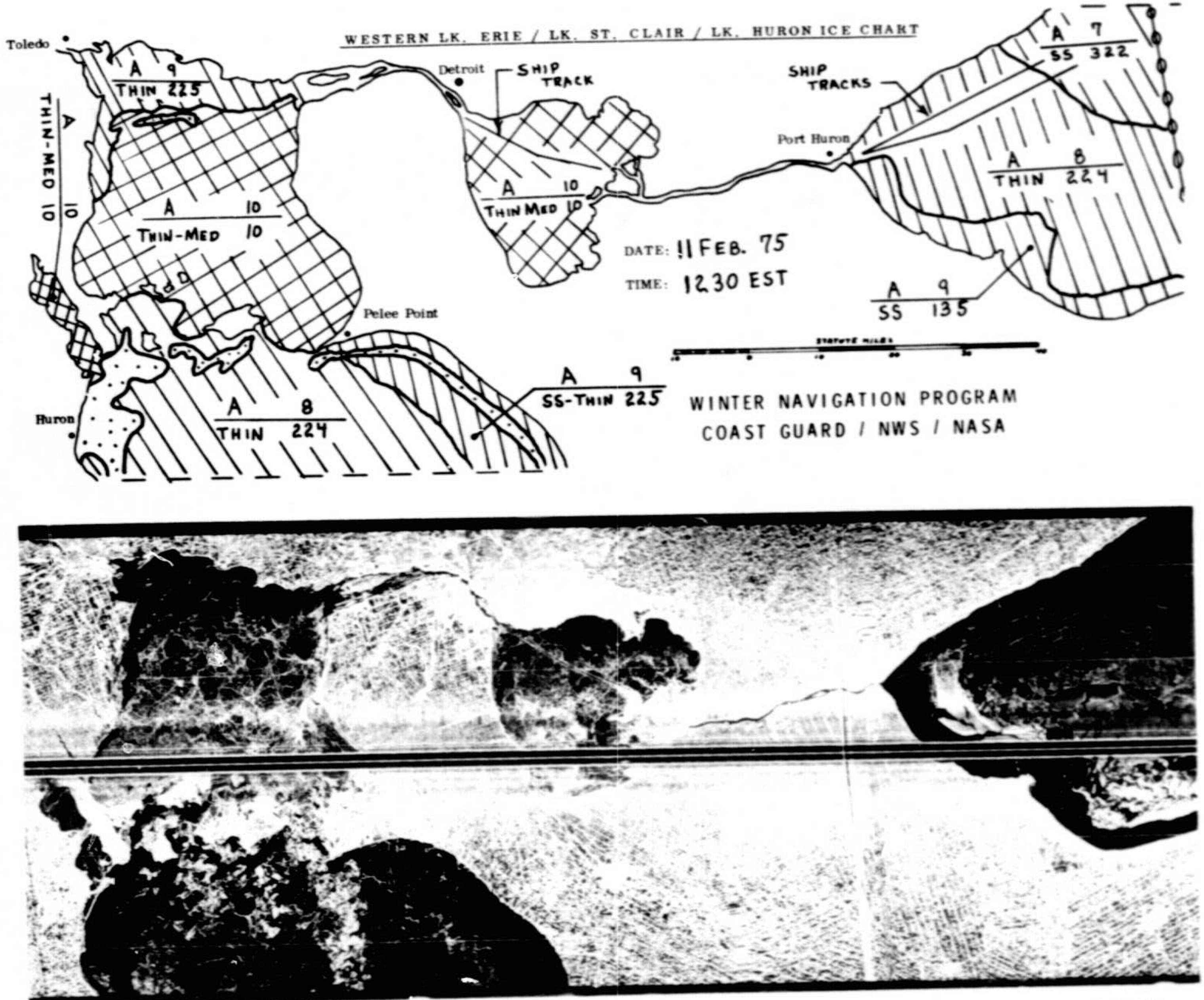

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Figure 9. - SLAR Image/Ice Chart Product for western Lake Erie, Lake St. Clair, and lower Lake Huron on February 11, 1975.

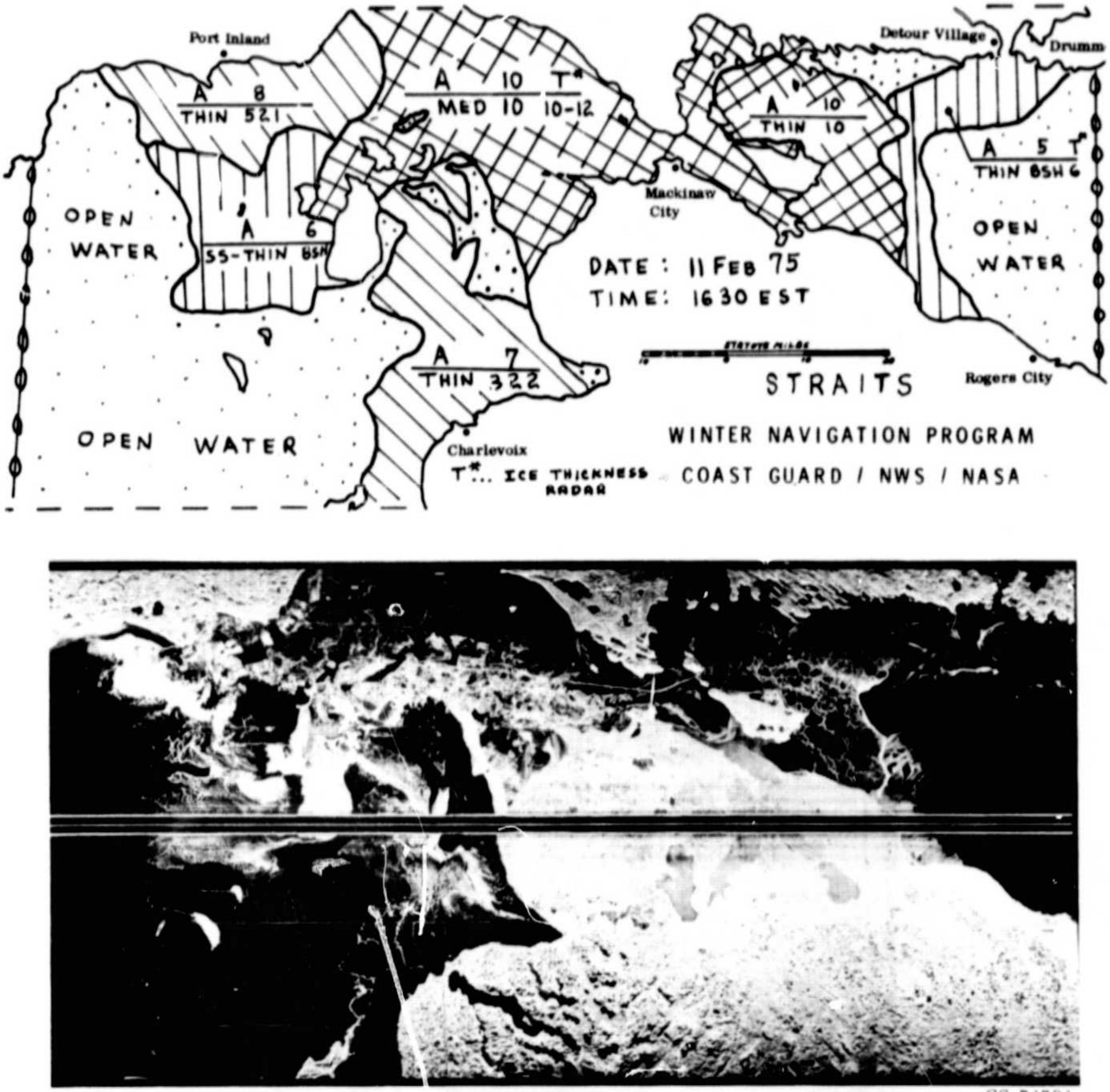

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Figure 10. - SLAR Image/Ice Chart Product for the Straits of Mackinac on February 11, 1975.

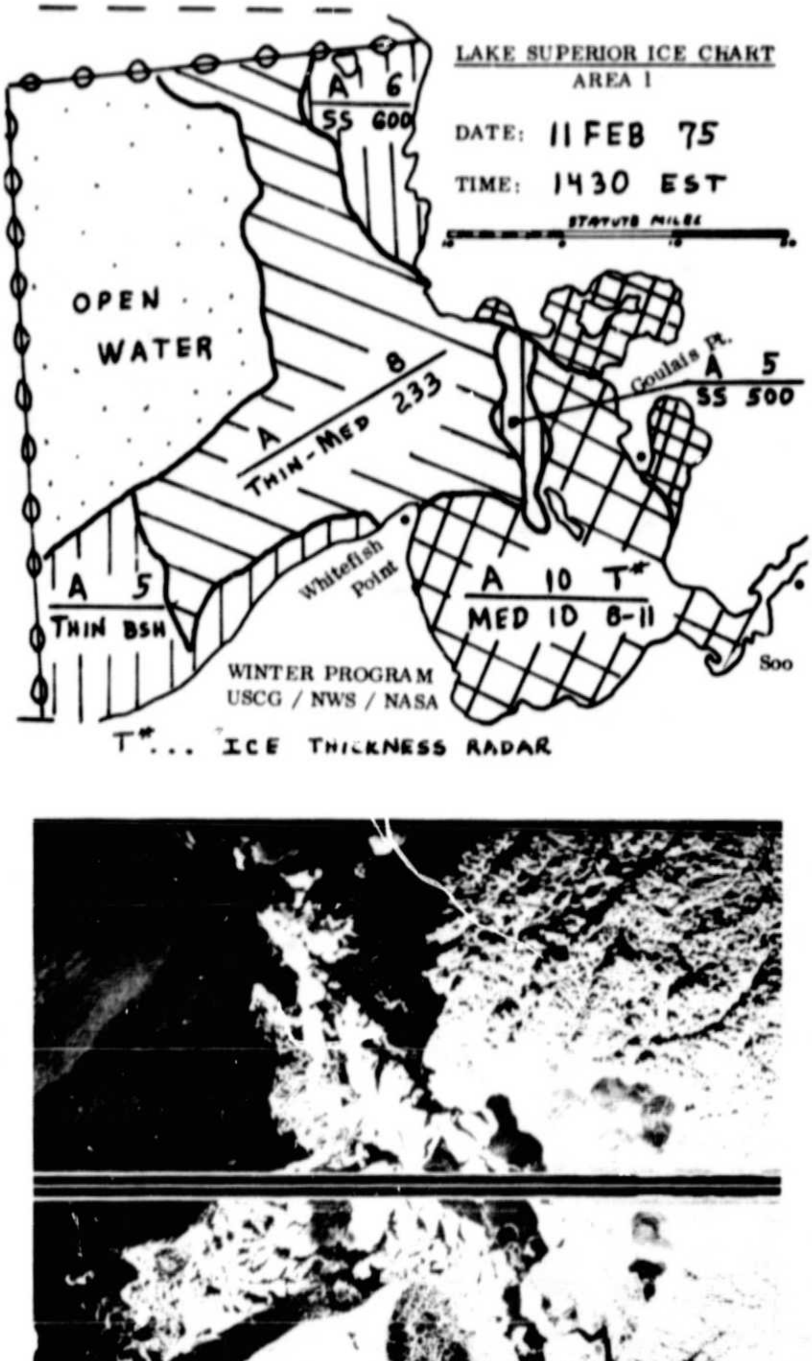

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Figure 11. - SLAR Image/Ice Chart Product for Whitefish Bay area of Lake Superior on February 11, 1975.

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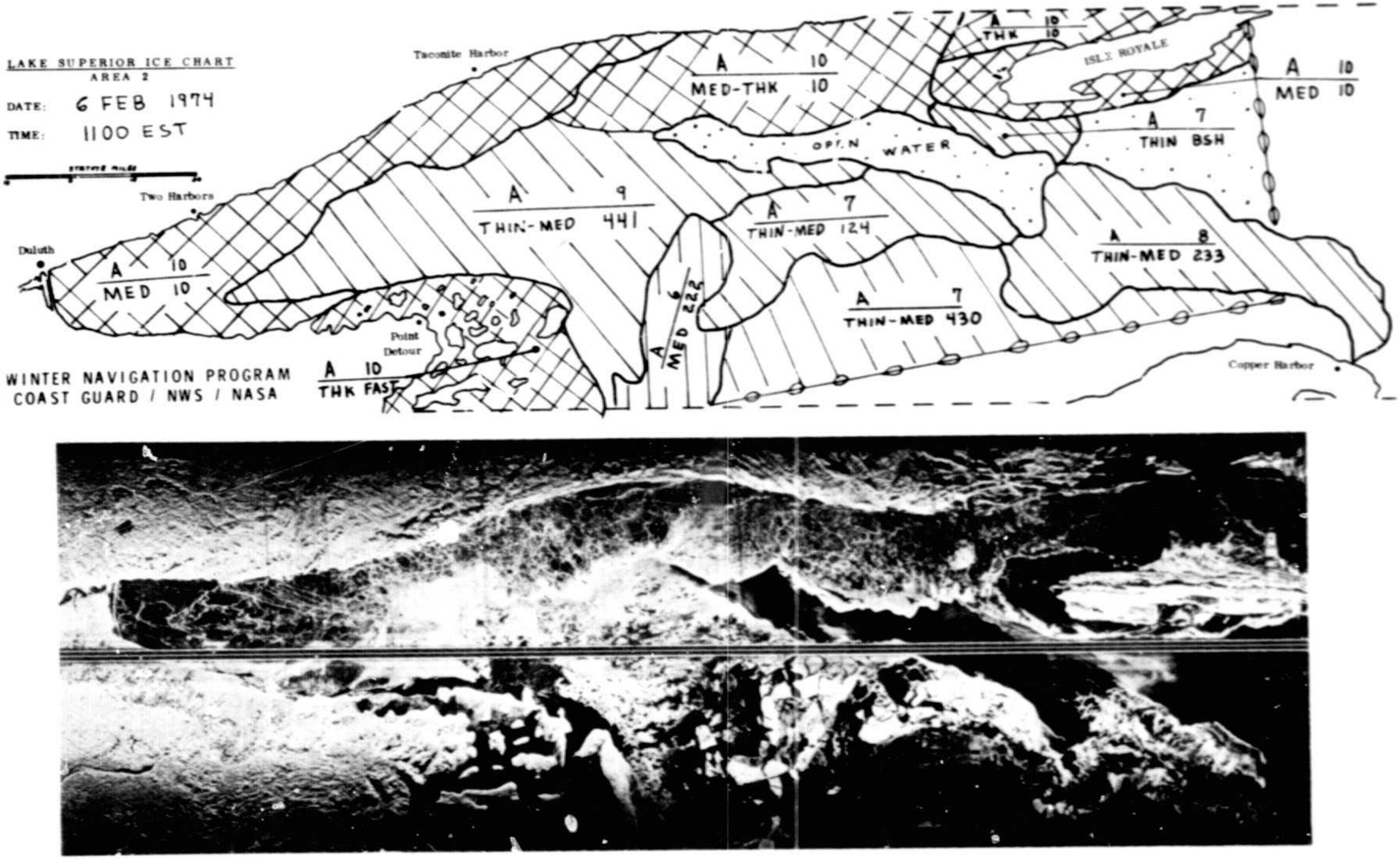

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Figure 12. - SLAR Image/Ice Chart Product for the Duluth area of Lake Superior on February 16, 1974.

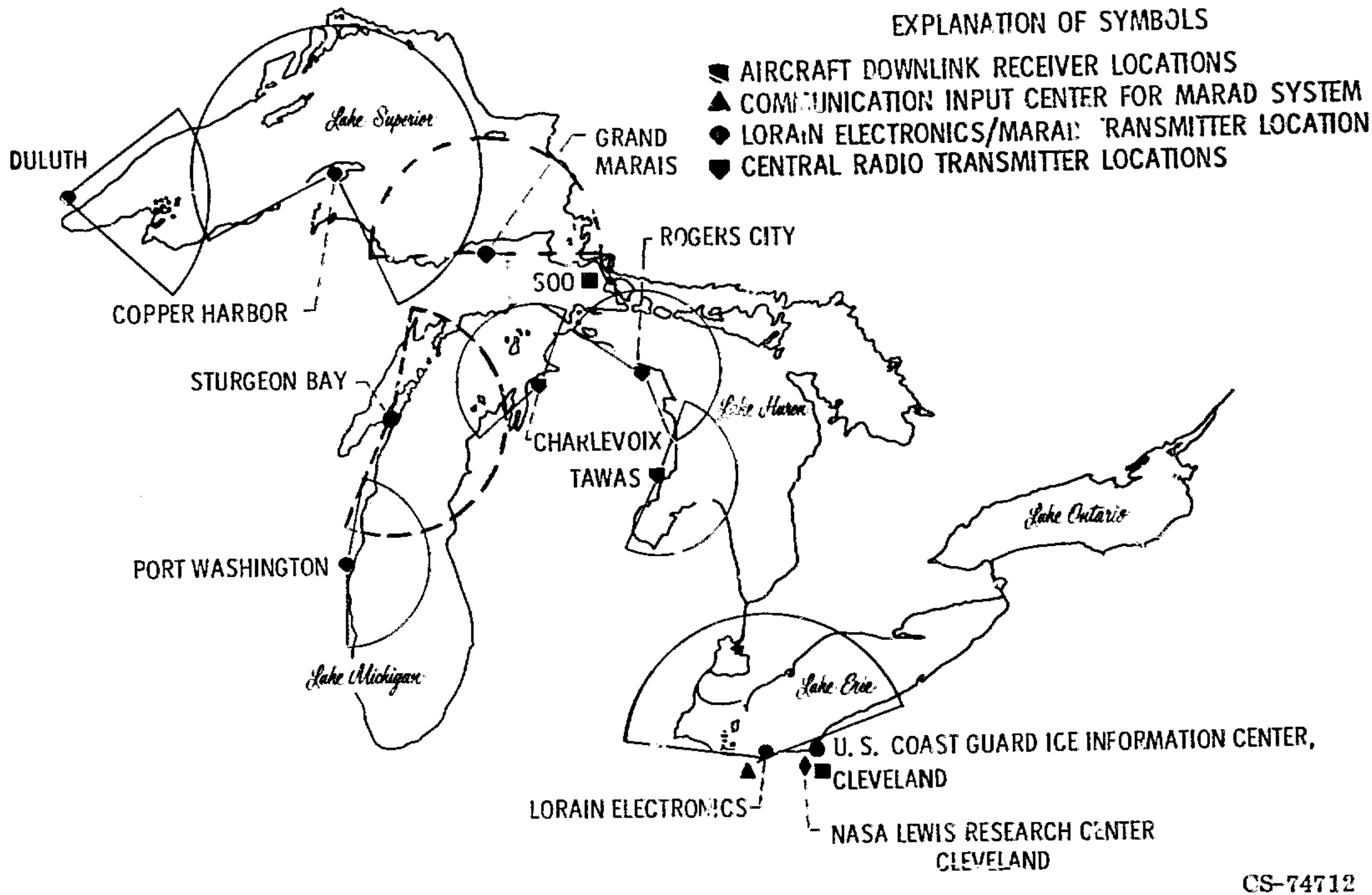

Figure 13. - Great Lakes Ice Information Network.

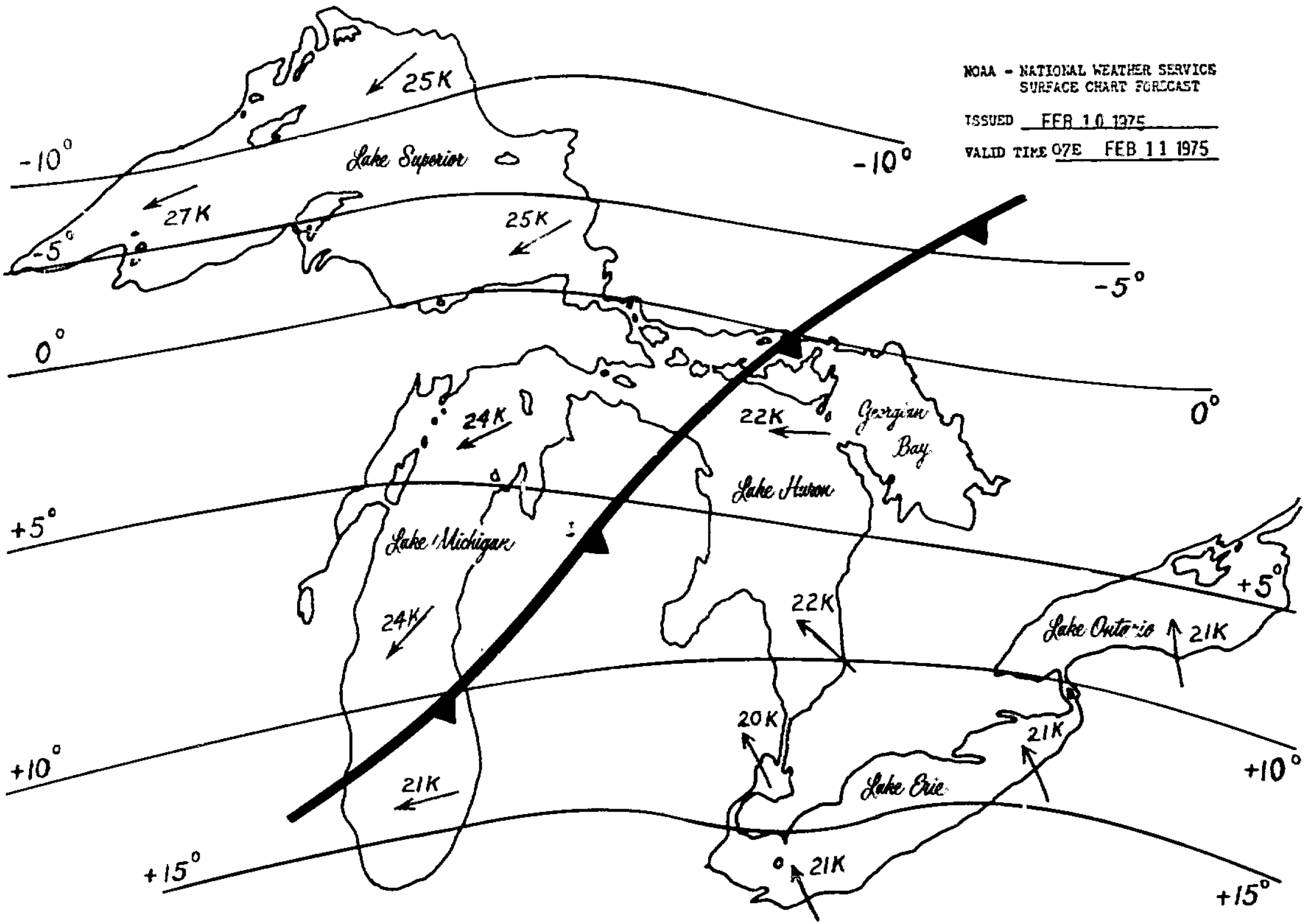

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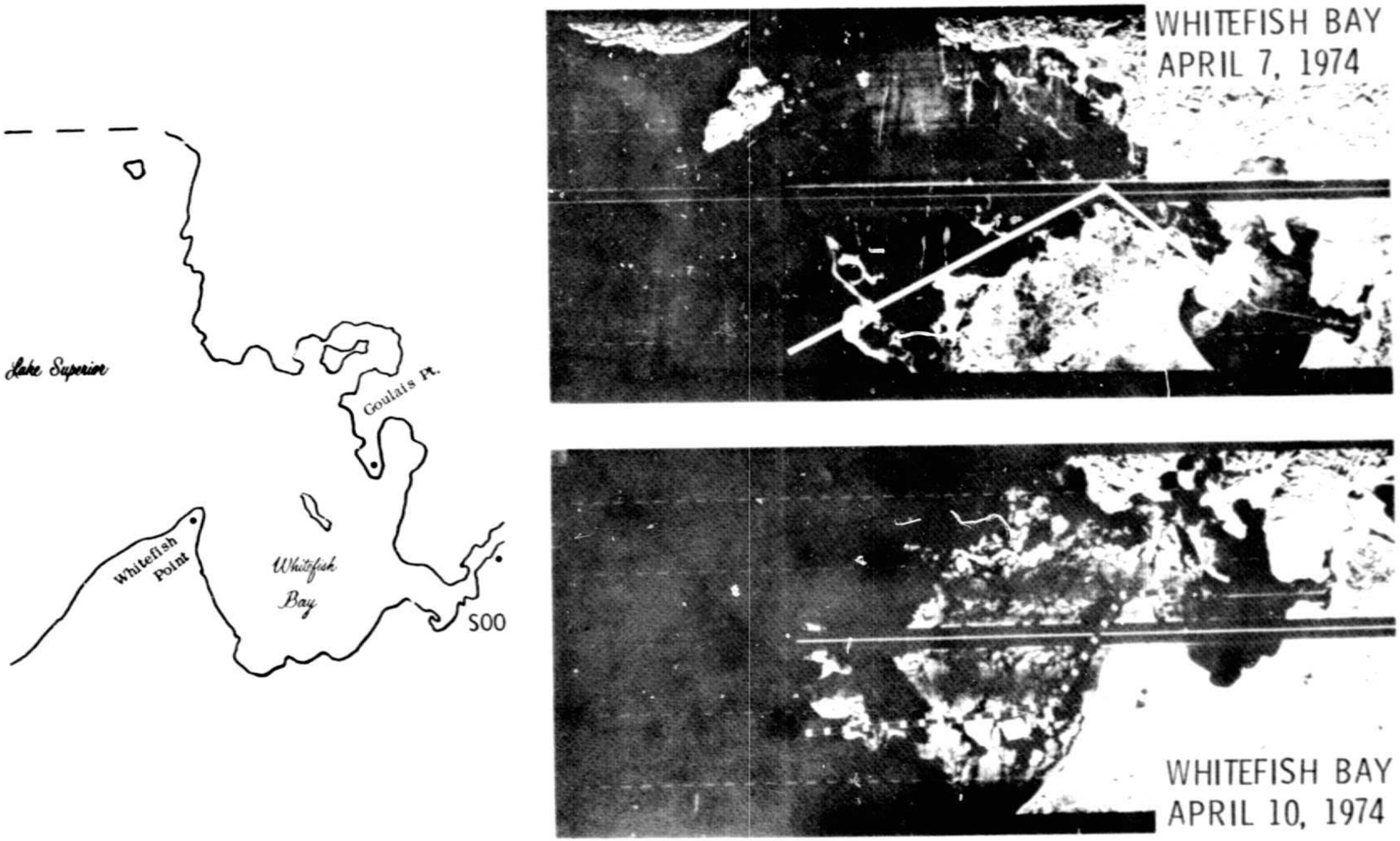
Figure 14. - NOAA/National Weather Service Wind and Temperature Forecast Chart.



ROGER BLOUGH'S	————————	UPBOUND	7 APRIL 1974
VESSEL TRACT	— — —·— · —	DOWNBOUND	10 APRIL 1974

CS-74730

NASA-Lewis

Figure 15. - Use of SLAR imagery for vessel routing under Great Lakes ice conditions.