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ABSTRACT

An airborne short-pulse radar system to measure ice thickness was designed and operated during the 1973-74 and 1974-75 ice seasons. This system supported a joint effort among NASA, the U. S. Coast Guard and NOAA to develop an all-weather Great Lakes Ice Information System which aids in extending the winter navigation season. This paper describes experimental studies into the accuracy and limitations of this short-pulse radar system. A low power version of this system was built and operated from an all-terrain vehicle on the Straits of Mackinac during March 1975. The vehicle allowed rapid surveying of large areas and eliminated the ambiguity in location between the radar system and the "ground truth" ice auger team which is unavoidable for the airborne versions of the system. These in situ measurements also permitted an assessment of the effects of snow cover, surface melt water, pressure ridging, and ice type upon the accuracy of the system. Over 25 sites were explored which had ice thickness in the range of 29 to 60 cm. The maximum radar overestimate was 9.8 percent, while the maximum underestimate was 6.6 percent. The average error of the 25 measurements was 0.1 percent.

INTRODUCTION

During the past three years NASA, in conjunction with the U. S. Coast Guard, National Weather Service, National Oceanographic and Atmospheric Administration, and U.S. Army, has been developing an all-weather Great Lakes ice information system to aid in extending the winter navigation season. An extended season has the potential of saving millions of dollars in coal and ore shipping costs, since cargo must now be shipped by more costly rail or truck routes or stored until spring thaws. The entire operational ice information system is scheduled to be turned over to the U.S. Coast Guard by the end of the 1975-76 ice season.

The Great Lakes ice information system primarily uses a side-looking airborne radar (SLAR) aboard a U.S. Coast Guard C-130 aircraft. This X-band radar is an improved version of the system flown on Army OV-1 aircraft in Viet Nam. The SLAR provides an all-weather aerial view of the ice cover which is than transmitted to SMS (synchronous meteorological satellite). From the satellite the information is retransmitted to a NOAA station at Wallops Island, and then via telephone lines to the U.S. Coast Guard's Great Lakes Ice Center at Cleveland for interpretation. Detailed ice maps are then constructed and sent by radio facsimile to any ship on the Great Lakes with the appropriate recording equipment. This information is updated daily to reflect ice shifts due to wind.

The SLAR system has proved to be very effective in determining ice location patterns and movement on the Great Lakes in virtually all types of weather. The SLAR is very sensitive to surface roughness and discontinuties and readily gives the location of pressure ridges. Because the surface pattern is most often a relic of the early history of the ice, the SLAR imagery cannot be interpreted directly to give ice thickness. To supplement the SLAR data ice auger teams have been used in the past, but these ground truth measurements are laborious, time consuming, expensive, weather dependent, dangerous to personnel and cannot be done on a large enough scale to map an entire lake in a reasonable amount of time. It is for this reason that a short pulse (one nanosecond) S-band radar system was developed to profile the thickness of ice remotely.

The remote ice measuring system was first designed and tested for feasibility during the winter of 1972-73 and flown successfully aboard a U.S. Coast Guard H-53 helicopter at altitudes up to 100 meters [Vickers et al., 1973]. Other radar methods were considered [Page et al., 1973; Iizuka et al., 1971], but appeared to have possible operational and resolution problems.

For the next ice season (1973-74) the nanosecond radar system was redesigned to be used as an ice profiler aboard a C-47 aircraft [Cooper et al., 1974]. This system proved operational at altitudes up to 2300 meters and ground speeds of 75 m/sec. The radar was able to detect ice thickness from 10 cm to 92 cm, the upper limit being the thickest ice found on the Great Lakes in the past two ice seasons.

As thickness data from the short-pulse radar system was utilized in an operational program in support of the SLAR during ice seasons 1973-74 and 1974-75, questions arose as to the radar's accuracy and operational limitations. During some initial helicopter check out flights a small amount of calibration data was taken. Some more calibration of the short-pulse radar system on the C-47 aircraft was done in conjunction with an ice auger team on Brevoort Lake in the upper peninsula of Michigan west of the Straits of Mackinac during the ice season of 1973-74. The lake was of relatively uniform thickness and easy to locate by aircraft. The radar data checked the auger team to within 2 cm. Because it was not possible to exactly locate the ice auger team on a flight line, some uncertainty in the calibration remained.

Operationally, results from the C-47 flights had shown that the radar was unable to detect less than 10 cm of ice and that measurements were precluded wherever surface melt water exceeded about 1 mm in thickness, because of lack of penetration. Snow cover on the ice was never found to be a problem unless the snow surface was slushy. The S-band radar system worked well in any type of weather except rain which, of course, has the same effect as melt water.

Calibration of the system could not be performed readily in the laboratory because of the large amount of ice and water required to approximate a planar surface. In the laboratory it also would be difficult to make any supporting structure nonreflective to microwaves. The dielectric constant of ice made from pure water has been measured in many laboratory studies [Birks, 1961; Cumming, 1952; Evans, 1965]. Von Hipple [1954] found the dielectric constant of ice to be 3.2 at S-band, decreasing to 3.17 at X-band. Accurate measurements of ice thickness depend on a good knowledge of the dielectric constant of lake ice.

To help facilitate better radar measurements, ten lake ice samples were taken from the Straits of Mackinac and Whitefish Bay during the winter of 1973-73 and analyzed for dielectric constant and loss tangent at Stanford Research Institute [Vickers, 1975]. The diameter of the samples was 7.6 cm with thickness ranging from 30 to 78 cm. Various ice types were in the samples, i.e., clear, milky with small air inclusions, and mostly clear with large layered inclusions. Ice machining to permit the insertion of the sample in the test wave guide was performed in an environmental chamber at -10^{o} C. The relative dielectric constant for lake ice from 1 to 18GHz was found to be 3.17 for clear ice with no inclusions, 3.08 for milky ice with small (less than 5×10^{-2} cm diameter) air inclusions and 2.99 for clear ice with large (greater than 0.6 cm) air inclusions. Whereas these results are in the expected range of values, the laboratory method requires ice storage for long periods of time prior to examining as well as machining which could possibly alter the measured results.

Because locating an ice auger team directly on a flight line for accurate system calibration was considered nearly impossible, it was decided to build a low power radar which could be mounted on an all-terrain vehicle. With this configuration the radar could be easily checked without location ambiguity. A low r.f. power radar was required to insure personnel safety. A portable gasoline generator supplied the auxiliary 115v, 60Hz electrical power. The all-terrain vehicle was borrowed from the Coastal Zone Labs of the University of Michigan at Traverse City, Michigan. The actual research using the all-terrain vehicle on the Straits of Mackinac was performed in the second week of March.

THEORY AND SYSTEM CONFIGURATION

The short-pulse radar system works on the basic radar principle of time delay. From an aircraft the radar pulse may be considered a plane wave which is partially reflected upon incidence at the surface of the air-ice or snow-ice interface. Part of this wave continues on through the ice at a slower velocity due to the increased relative dielectric constant. At the ice-water interface total reflection takes place and the wave continues at its slow rate back to the air-ice or snow-ice interface. The receiver measures the time delay between the partially reflected incident wave and the wave which continued through the ice to the water interface and back before preceeding to the aircraft. To know the velocity of the wave in the ice, the relative dielectric constant must be known. In addition to ice thickness, a measure of the time that the partially reflected incident wave takes to return to the aircraft gives aircraft altitude.

The time delay t in nanoseconds can be directly related to the ice thickness, x in cm, by the following expression if the relative dielectric constant of ice, ϵ_r, is known:

$$x \simeq 14.99\, t \Big/ \sqrt{\epsilon_r}$$

Generally a relative dielectric constant of 3.1 [Vickers, 1975] is assumed for lake ice which yields:

$$x \simeq 8.51\, t$$

The short-pulse radar system has made ice thickness measurements in support of the SLAR imagery during the ice seasons of 1973-74 and 1974-75. As previously mentioned, aircraft location is of prime importance because radar makes measurements at the nadir the aircraft. NASA's C-47 aircraft is equipped with an inertial navigation system (INS) which is accurate to ± 1.85 Km after one hour. While the INS is adequate for making ice charts, good calibration cannot be performed.

Both C and S-band versions have been employed on the C-47 aircraft, but the S-band proved operationally superior because of better system components. The aircraft radar system block diagram is shown in Figure 1.

The S-band system used either random noise or continuous wave modulation at 2.86 GHz. Random noise modulation was used to avoid the possibility of coherent interference between the transmitted pulse and other interfering signals. In actual operation this problem did not occur as theorized.

The heart of the system is the nanosecond pulse generator which when mixed with the S-band oscillator allows only a few cycles of r.f. power to be transmitted. For this purpose, a double mixer system is employed to decrease feed thru from each double balanced mixer. The length of coaxial transmission line to the second mixer is cut to the proper length so both pulses, the output of the first mixer and the output of the pulse generator, arrive simultaneously. The traveling wave tube amplifier gives over 20 watts of peak power. The solid state pre-amplifier maintains a proper input level. The entire system bandwidth must be greater than 1 GHz, as dictated by the nanosecond pulse.

For the purpose of narrowing the receiver antenna pattern, 4 ridged horns feed a combiner and then a low noise (3.8 db noise figure) solid state amplifier, all located in close proximity. After detection a 1 GHz sampling oscilloscope was used for the final display. The radar was initially triggered by the clock which operated from 40 to 250 kHz. The oscilliscope was triggered from a delay unit which started the scope at the precise time that the return pulses were received. A manual adjustment was used on the delay unit which required constant manipulation by the operator as the aircraft altitude changed to keep the data displayed on the oscilloscope face. Recording of data was done with an oscilloscope camera. Typical aircraft ice return displays have been reported [Cooper et al., 1974 Vickers et al., 1973]. A new design is now being formulated which determines the ice thickness electronically and corrects for any aircraft altitude changes. In addition this new system will profile the ice surface, permitting the detection of ice ridges.

ALL-TERRAIN VEHICLE CONFIGURATION

When applying radar principles to an all-terrain vehicle, the nearness of the ice involved new considerations. It was necessary to determine that the ice surface was in the far, not near, field of the transmitting antenna. Near field calculations were made on the S-band pyramidal ridged horn [Harrington, 1961]. At least 20 cm of separation were required between the transmitting horn and the ice surface.

Personnel safety was of primary importance because of long exposure times, so the radio frequency power density in any personnel areas was maintained below 1 mW/cm^2. This was a full decade below usual U.S. safe standards. Fortunately this still allowed sufficient power to make thickness measurements. The 115V, 60 Hz power was supplied from the auxiliary gasoline generator.

The radar for an all-terrain vehicle is simpler than the airborne system because of the lower radio frequency power levels involved. The all-terrain vehicle S-band short pulse radar block diagram is shown in Figure 2. This system differs from Figure 1 in that there was no random noise source, transmitter traveling wave tube amplifier and delay unit. The solid state amplifier was the final transmitter with only 10 dBm output which insured personnel safety. Triggering of the sampling oscilloscope was directly from the clock without a delay unit.

The system was composed physically of four subsystems, i.e., the clock, the sampling oscilloscope, the transmitter and receiving radar module and the two ridged pyramidal horns. The transmitting and receiving module with power supplies weighed 2.7 Kg.

The all-terrain vehicle in operation is shown is Figure 3. This vehicle allowed 3 persons to be carried at speeds up to 48 km/hr. Due to the low bottom of the vehicle, deep snow and high ridges were impassable. Polyethylene bags were placed over the horn antennas to keep mud, snow, and water out of them in transit. With clean bags over the antennas the system was completely operational on the ice. The antennas were extended 1.5 m from the rear deck of the all-terrain vehicle and both were adjusted in the traverse plane while pointing downward to have maximum output. The transmitting horn's source of radiation was taken to be 1.30 m above the ice surface, while the receiving horns point of collection was taken to be 1.14 m above the ice surface. The distance between these points measured parallel to the ice was 1.25 m.

In reducing the data from the all-terrain vehicle, it was necessary to take into account the geometry of the situation. Since the receiving and transmitting horns were in a nonsymmetrical configuration the geometrical theory of diffraction [Kline et al., 1965] was employed in data reduction. Computer iterations using ray tracing techniques at various thicknesses accounted for refraction at the ice surface. The wave propagation was entirely normal in the aircraft model.

The wave bending as it enters the ice may be obtained from Snell's law for electromagnetic waves [Harrington, 1961]. The angle to the normal in air at the ice surface, θ, may be related to the angle to the normal in ice, φ, by the relative dielectric constant of ice, ϵ_r.

$$\sin \varphi = \sqrt{\frac{1}{\epsilon_r}} \sin \theta$$

For this all-terrain vehicle radar system, the computerized ray tracing technique yielded the following approximate equation for ice thickness over 10 cm:

$$x \approx 8.77\, t \text{ if } \epsilon_r = 3.1$$

A series solution can also be obtained [Cooper et al., to be published 1976] that yields the same result. Where ice is not identifiable, a dielectric constant of ice, ϵ_r of 3.1 was assumed.

On the C-47 aircraft a refracted wave, directly from the transmitter to receiver, was an inconsequential problem because essentially it occurred microseconds prior to the two return pulses separated only by nanoseconds. It could readily be removed from the receiver return.

On the other hand, in the all-terrain vehicle configuration due to the short distances, this refracted pulse exists in all the data and therefore must be disregarded. The first pulse is the refracted pulse, the second pulse is a surface reflected wave, while the third pulse is reflected from the water as shown in Figure 4.

Data were originally to be taken with a polaroid oscilloscope camera. The severe cold caused the shutter to stick and visual data could only be taken with a 35 mm camera. A typical ice return is shown in

Figure 5. This photograph was taken on the Straits of Mackinac near St. Helena where the auger team measured 39 cm. The feed-thru pulse occurs first followed by the pulse from the ice surface and finally by the pulse from the ice-water interface. The measured radar delay is 4.2 nanoseconds or 36.8 cm of ice if the relative dielectric constant is 3.1. This ice was covered by 8 cm of snow which is not detectable. The ice appeared milky with some similar air inclusions.

TEST RESULTS

The short pulse radar was calibrated by comparing actual auger and radar measurements. This calibration was done on the Straits of Mackinac from March 12-14, 1975.

Over twenty-five sites were examined and measurements were compared. Considerable effort was made to find varied sites, i.e., different ice types and thicknesses. Ocassionally deep snow made the all-terrain vehicle inoperable. Essentially all the encountered ice was snow covered as shown in Figure 3. Up to 25 cm of snow was found at one site but it did not affect any of the radar measurements except when the snow had a slushy crust which was only found at one location. Snow was usually removed around the site to help identify the ice type. Large blocks were not removed as had been in previous ice studies at the Straits of Mackinac. Usually a dielectric constant of 3.1 was assumed.

Previously the airborne radar sometimes became inoperable in warm temperatures. Surface melting was theorized as the problem. Experiments were performed which verified the fact that melt water prevents penetration of the radar wave into the ice. Tests showed that de-ionized water was as effective as lake water in preventing penetration.

The all-terrain vehicle was very limited in crossing ridges due to its low underside. Because there was fear of becoming immobile in deep snow, hourly check-ins by marine radio were made to the local U.S. Coast Guard.

Near the Mackinac Bridge, a pressure ridge was studied where two slabs of ice had refrozen, one over the other. The radar quickly revealed an ice step from 29 cm to 50 cm. Auger measurements supported this finding. A high rafted area 82 cm thick gave inaccurate radar results of about 35 cm but investigation revealed that the ice had a slushy interior. Another rafted area measured 110 cm with the auger, but the radar gave a reading of only 93 cm. Large air pockets were present indicating that the relative dielectric constant, ϵ_r, was assumed too high at 3.1.

For uniform ice with small air inclusions the radar and auger measurements were in close agreement assuming $\epsilon_r = 3.1$ in over 25 different sites as shown in Figure 6. The line represents exact agreement between auger and radar measurements. These sites had ice thickness in the range from 20 to 60 cm.

DISCUSSION OF ERROR

Some of the data scatter in Figure 6 was directly attributable to the ice auger team. The ice auger measurements could be up to ± 1 cm in error due to tape reading, a local convexity or concavity at the bore hole and top and/or bottom surface roughness. This estimate has taken into account considerable past ground truth experience which has shown the bottom surface of lake ice to be relatively smooth and flat.

The radar measurements shown in Figure 6 were normalized to the auger measurements for comparison. The maximum radar overestimate was 9.8 percent, while the maximum underestimate was 8.6 percent. The average error of the 25 measurements was 0.1 percent.

A major unknown in the radar mesurements is the true dielectric constant of the ice. In fact, all measurements could be considered exact if the dielectric constant of the ice varied from 2.8 to 3.8. As can be seen by the magnitude of these numbers, they are out of range of what ice is thought to be and other factors are contributing to the errors.

In the present configuration the pulse time delay can only be accurately read to about 0.2 nanosecond which corresponds to a 1.75 cm thickness error which is about 5% pf a 35 cm measurement.

Another concern is the location of the actual, electrical interface. It could be above the actual ice-water interface or the ice and water could have an air pocket between them.

The aircraft system has not been able to measure ice below about 10 cm because it is not possible to separate the two return pulses. This limit has not been verified with the all-terrain vehicle radar system because no ice was found at the proper thickness. A measurement of 92 cm of lake ice has been detected from an aircraft, which is the thickest lake ice we have found in the past two ice seasons.

CONCLUSION

The short pulse radar system has been demonstrated to be an accurate remote lake ice measuring device. Snow cover or adverse weather generally did not interfere with making measurements. Surface melting and rain however preclude measurements.

Further studies are necessary to establish the variability of the relative dielectric constant for lake ice. The best means to do this is in situ, possibly with the short pulse radar and an auger team. For next ice season a radar system is being built for the U.S. Coast Guard's HV-16 helicopter stationed at Traverse City, Michigan. This could allow many different types and ages of ice to be studied throughout the ice season.

NASA's OV-1 and Coast Guard's C-130 aircraft will have C-band versions of this radar system for next winter. At the higher frequency, smaller antennas will be used, but surface roughness may be more of a problem. A half nanosecond pulser will be used to increase the resolution of the instrument.

Electronic processing of the data will be done and manual setting of the oscilloscope trigger delay will no longer be required. Pressure ridges will be studied by noting any rapid changes in the first return pulse. Knowing the pressure ridge height relative to the surrounding ice field should yield ridge thickness, assuming that the ridge is in isostatic balance, i.e., its weight is supported by its bouyancy, not by stresses in the surrounding ice field.

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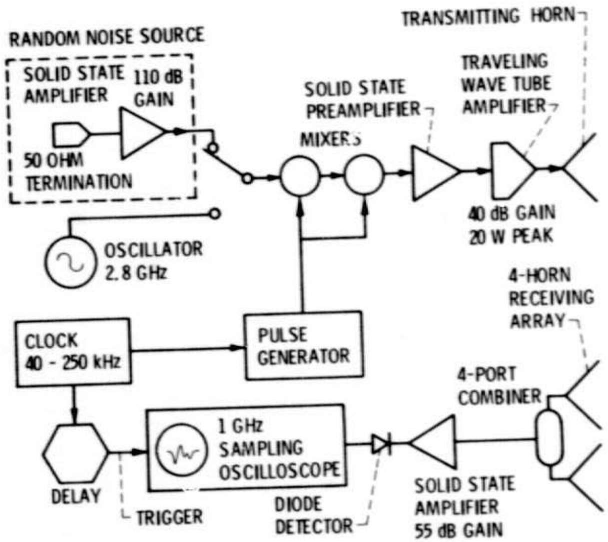

Figure 1. - Block diagram of NASA's C-47 short pulse radar system - S-band.

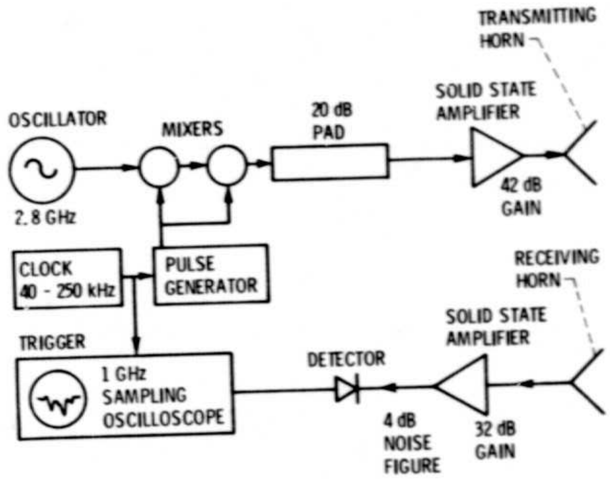

Figure 2. - Block diagram of S-band short pulse radar system used on the all-terrain vehicle.

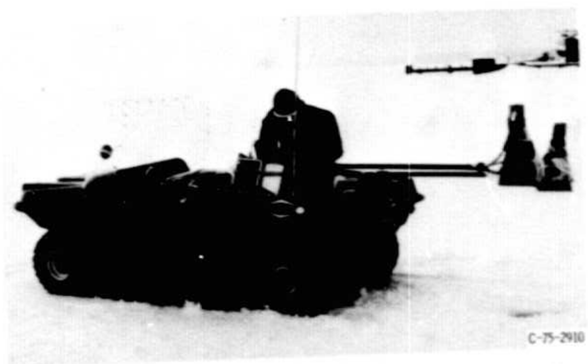

Figure 3. - All-Terrain Vehicle in operation on the Straits of Macinac.

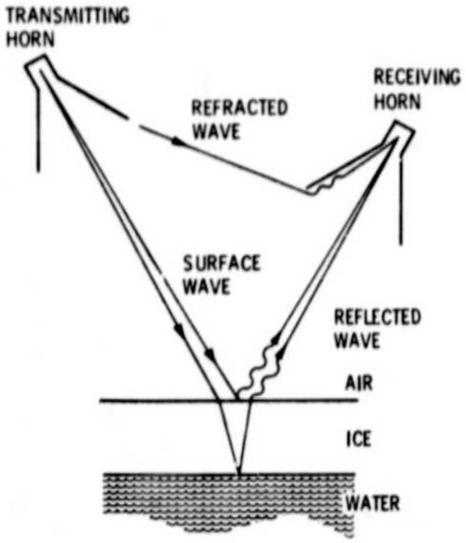

Figure 4. - Short-pulse radar all-terrain vehicle configuration.

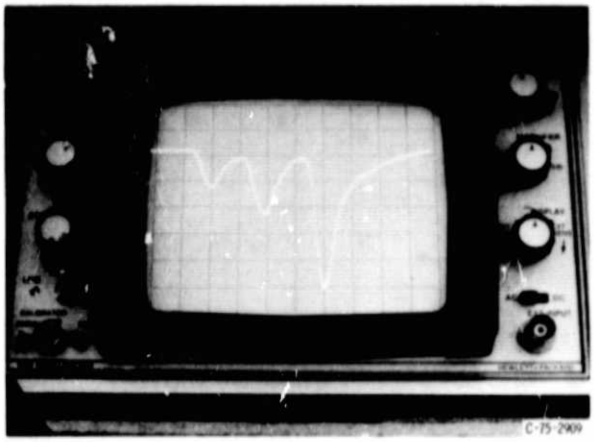

Figure 5. - A typical ice return shown on the face of the sampling oscilloscope (2 nano-sec/div.).

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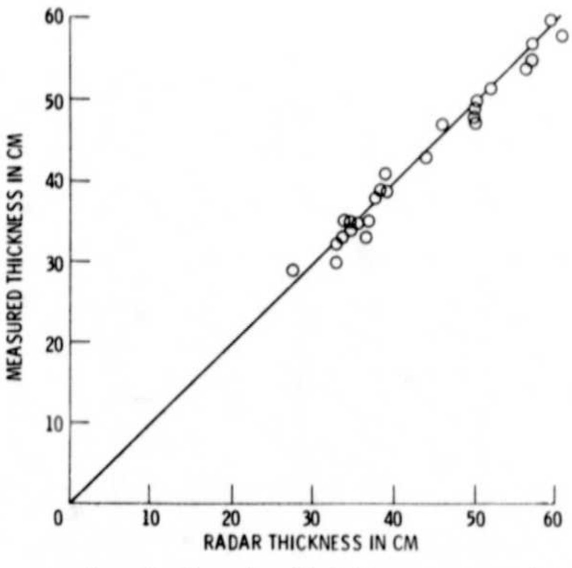

Figure 6. - Comparison of ice thickness measurements between auger and radar assuming $\varepsilon_r = 3.1$.