SEA ICE DISCRIMINATION WITH RADAR SCATTEROMETERS

Albert W. Biggs, Robert M. Haralick, and Richard K. Moore
Center for Research, Inc.
University of Kansas
Lawrence, Kansas 66044

ABSTRACT

Interpretations for backscatter radar returns are presented in terms of surface roughness, volume scatter, effective conductivity, and relative dielectric constant of the scattering media. These interpretations are discussed with respect to statistical analyses of 13.3 GHz backscatter of various categories of sea ice at different angles of incidence. Results indicate that it is possible to identify both water or thin ice and multi-year ice from first year ice without any misidentifications using angles of incidence greater than fifteen degrees. Further it seems possible to identify a few additional ice categories within the first year ice group.

The area coverage requirement of a given sea ice category is described in terms of aircraft operating altitude, speed, antenna patterns, and signal frequency. This description covers the minimum terrain area necessary for discrimination against other sea ice categories.

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I. INTRODUCTION

When electromagnetic waves hit the earth's surface, specular reflection and scatter may occur. Specular reflections follow Snell's law (angle of incidence equals the angle of reflection), and scatter has components over the entire spectrum of incidence angles from vertical to grazing. As the surface changes from a smooth to a rough configuration (a gauge of roughness is the size of surface irregularity or variation in comparison with the wavelength of the incident radio wave), the specularly reflected waves decrease relative to the non-specular or scattered waves. At microwave lengths specular reflection is usually many orders of magnitude less than scatter along the same path as the incident energy are signals returned called the backscatter.

II. THE SCATTEROMETER

A scatterometer is a radar system, which measures the backscattered return, often as a function of incident angle. The surface roughness and subsurface structure determine the angular variation of the backscatter return and its amplitude. A scatterometer may be constructed with a fan beam antenna pattern in both transmit and receive systems. The beam may be very narrow (say, 2-3 degrees) across the direction of the flight path, and very wide(say, 60 degrees forward and 60 degrees behind). Resolution of the backscatter may be achieved by the Doppler frequency shift of signals returned from resolution cells along the flight path. A resolution cell has dimension determined by the half power points of the narrow beam width and by the bandwidth of a filter centered about the Doppler frequency corresponding to a selected angle of incidence.

The results of the scatterometry measurements may be presented as the variation of the differential backscatter cross section (per unit area) versus angle of incidence. Returns from several resolution cells may have to be averaged to decrease the influence of fading. The minimum number of resolution cells for a given category of terrain depends on the angle of incidence, the path length radiated (along flight path), the incident wavelength, and the airplane altitude (2).

Another mode for presenting results is that of backscatter cross section versus distance along the flight path with angle of incidence as a parameter. Thus, in one mode we have σ° (differential scattering cross section) versus Θ (angle of incidence) plots for each group of resolution cells. In the other, we have σ° versus distance for fixed Θ. The first mode describes the roughness of a specific area on the earth's surface over the complete angular range of Θ. Since the variation of backscatter cross section with Θ is a function of the ground geometry and electrical properties, this mode may provide the data needed for identification of terrain features or characteristics (trees, lakes, wheat, corn, or sea ice). The second mode holds the incidence angle fixed and looks at the terrain along the flight path, with variations in backscatter following variations in terrain features. With a fixed Θ, it is like the line trace on a radar image formed in a side scanning operation.

Radar return from ice-free ocean is determined solely by the wave structure on the surface, for the electrical properties of sea water are sufficiently constant that their variations do not influence the return significantly, and the waves transmitted into the sea are absorbed before striking a reflecting surface.

Using the scatterometer for sea ice and glacier snow provides a different situation. Ice and snow have lower dielectric constants and much smaller conductivities than water. The results of backscatter measurements over glacier snow (3) and sea ice (4) presented results which indicated backscatter from other regions than just those of the surfaces. Looking below the surface, the presence of volume scatterers in the form of dielectric spheroids in glacier snow and in the form of brine pockets in sea ice (5) is likely. The dielectric spheroids are ice particles which have a fairly high return, while the brine pockets have a fairly low return (in comparison). Volume backscattering depends upon the density of scatterers, the scatterer size in comparison with signal wavelength, and the contrast in dielectric properties of the scatterers and their surrounding medium.

III. VOLUME SCATTERING

In his study of radar ground return, R. E. Clapp (6) proposed three scattering models with which airborne measurements might provide experimental verifications. The first model was developed from Lambert's Law. This law states that the light scattered from a radiant surface varies in intensity with the direction of radiation, the intensity being proportional to the cosine of the direction of propagation and the surface normal.

Applying this law to radar return, the differential scattering cross section is

$$\sigma = K \sin^2 \Theta \ ,$$

where K is the fraction of power striking the unit area which will be diffusely scattered. The rejection of this model by Clapp was made on a fundamental obstacle. Lambert's Law requires that the scattering pattern have a distribution independent of the incident wave direction. Consider radar backscatter from a forest. The incident wave is broken into wavelets which have so many multiple reflections and refractions that they forget from whence they came. The energy must reverberate from leaf to leaf and branch to branch until every surface of every trunk and twig are uniformly excited. Excitation can vary with depth from the treetops, but the excitation must be identical on opposite sides of a tree (even for low grazing angles). Shadows cannot exist because a shadow indicates the original direction of incidence. Only a ground glass surface can have this shadowless character. A Lambert's Law surface requires a complete reduction of direct reflections in favor of multiple reflections.

Clapp's second model consisted of replacing the terrain by an array of spheres, which scatter equally in all directions, independent of the angle of incidence. This single layer of spheres can be described as a sphere density per unit area. For N spheres per unit area, each with a cross section area A_k the scattering cross section is

$$\sigma = NA .$$

Although the second model did not correspond with his measurements, and because he felt that one layer was not sufficient for terrain with depth as well as transverse character, Clapp also rejected this model. However, it may fit media like a field of oats in head. The scattering cross section is smaller at the lower frequency. The heads of grain are like a single layer of large scatterers.

The third model represents the terrain as many layers of spheres, with the density of spheres given by δ and the cross section per sphere by A. This model agrees with measurements of the return from vegetation. It has a cross section given by

$$\sigma = \delta A \cos \Theta .$$

Although experimental results support the above expression, Ament (7) has been quoted as showing theoretically that this surface cannot physically exist. His proofs are correct for high incidence angles (about 90°).

Other experimental measurements for snow were made by Cosgriff et al (8). These are made at X-Band (10 GHz) and Ka Band (35 GHz) for 4 inches of dry snow above 2 inches of brown grass, and for 4 inches of melting snow above 1 inch of brown grass. The grass was brown because the measurements were made during the winter. Dr. Cosgriff, now at the University of Kentucky, could repeat these for Kentucky Blue Grass.

IV. THE ARCTIC MISSION

In May 1967 the NASA P3A (Electra) remote sensor aircraft flew repeated missions near Pt. Barrow, Alaska to record data from Arctic ice. The primary flights were over selected lines at Pt. Barrow, which were established and documented by CRREL personnel (headed by J. McLerran) and Arctic Institute personnel, and over two lines located approximately 150 nm NNE of Pt. Barrow. One of these lines was documented by a Navy Oceanographic Office team (headed by R. K. Ketchum) camped at the site. In addition, several lines were selected at random during the flights.

The flights at Pt. Barrow provided data on first-year ice during breakup, and bay ice. The ice camp flights and the random flights included data from a variety of ice types including old, first-year, young, and new ice.

The mission was based at Eilson AFB, Fairbanks, Alaska and was operational daily from May 10 through May 17, 1967. During the entire eight-day period the cloud ceiling over the desired flight areas was less than 1500 feet, except for a three-hour period on the afternoon of May 16. The data collected included black-and-white photography, color IR photography, X-band radiometer images, IR images, and 2.25 radar scatterometer measurements. Due to the extreme cloud cover experienced daily during the mission, much of the photography and imagery is degraded, and no data were obtainable above 1000 feet altitude (under clouds). However, the radar data constitute the most highly-controlled radar measurements of Arctic ice existing prior to a comparable mission in 1970, for which results are as yet unavailable.

V. ARCTIC SEA ICE

The polar pack that covers much of the Arctic Ocean is a dynamic, changing mass of sea ice. Polynyas and leads are continually opening and closing to form hummocks and ridges. The motion of sea ice and ice islands (land or fresh water ice from Greenland or the islands in the Arctic Ocean) combine with the forces of wind, underwater currents, and thermal stresses to create a daily changing scene.

Ice types are divided into numerous categories, usually by thickness or nature of formation. "Multi-year" or "old" describes the perennial sea ice, of more than one winter's growth. It is usually less than 4 meters thick and generally weathered to an undulating surface topography. First-year ice has many subcategories depending on thickness and formation, but in all cases the term applies to ice of one winter's growth or less. It ranges in thickness between 0.2 meters and 2 meters, depending on the severity of the winter. First-year ice is frequently hummocked due to pressure, and even in smooth regions is characterized by blocks of ice seemingly strewn on its surface. "New ice" is less than 0.2 meters thick. Slush, shuga, frazil ice, and grease ice are stages of freezing of new ice.

The physical properties of sea ice depend on a number of factors, such as the salinity of the original sea water, the temperature of the ice, pressure, and porosity. The speed of ice formation, the age of the ice, and other factors concerned with the history of the ice determine its structure.

The salinity of sea ice is always less than the salinity of the original sea water because part of the brine trapped between ice crystals escapes during freezing. With melting, the enclosed salts go into solution first, and H_2O crystals follow. The melt cells grow and the ice becomes porous, thus permitting brine to escape: hence old ice (polar ice), which undergoes surface thawing and refreezing, is less saline than new ice (winter ice). In summer the upper layer of old ice may be reduced in salinity to the point that it can be used for drinking water. Sea ice, especially old ice, can be very inhomogeneous and its dielectric constant may very greatly with depth (4).

VI. STATISTICAL ANALYSES OF THE ARCTIC MISSION SCATTEROMETRY

We wanted to determine whether it was at all reasonable to expect that certain basic ice types could be differentiated on the basis of their 2.5 cm radar backscattered-return profiles. Each return profile ($\sigma°$ vs. Θ curve) contained values of $\sigma°$ at incidence angles of 2-1/2°, 3°, 7°, 15°, 25°, 35°, 45°, 50°, and 65°. From the Arctic mission, there were 363 backscattered profiles, each taken of a small-area (30 m x 30 m) ground patch of an ice type reliably identified by ground or air observers. Initially, we divided the ice identifications into three major ice categories: water or thin ice, multi-year ice, and first year ice. If ice types could be distinguished on the basis of their radar-backscattered-return profiles, certainly these three major groups would be distinguished.

One approach (and an optimum one at that) to the discrimination problem involves the use of a simple Bayes decision rule. Such a rule assigns the cross-section profile to the most "likely" ice category. That is, if d is a nine-dimensional vector whose first component is the backscattered cross-section at incidence angle 2-1/2°, whose second component is the backscattered cross-section at incidence angle of 3° and whose ninth component is the backscattered cross-section at incidence angle of 65°, and if c is any ice category, then the Bayes decision rule assigns the profile measurement d to measurement category c* if and only if the conditional probability of c* given d is greater than or equal to the conditional probability of c given d for any category c. If we denote the conditional probability of category c given measurement profile d by $P_d(c)$, then the above condition may be written as

(1) $P_d(c^*) \geq P_d(c)$ for every category c.

Now, by Bayes formula,

(2) $P_d(c) = \frac{P_c(d)P(c)}{P(d)}$ where $P_c(d)$ is the conditional probability of d given c and P(c) is the probability of c.

Since $P(d) \geq 0$,

(3) $P_d(c^*) \geq P_d(c)$ for every c if and only if

$P_{c^*}(d)P(c^*) \geq P_c(d)P(c)$ for every category c.

This is the more usual form in which one sees the defining condition of a Bayes rule written. The probability P(c) is called the prior probability.

Often, the assumption is made that $P_c(d)$ is a multivariate normal, that is,

$$(4)\quad P_c(d) = \frac{1}{(2\pi)^{N/2}\,|\Sigma_c|^{1/2}}\, e^{-1/2(d-\mu_c)'\,\Sigma_c^{-1}(d-\mu_c)},^{+}$$

where $\Sigma_c = E[(d-\mu_c)(d-\mu_c)']$ is the covariance matrix for measurement profiles d coming from category c and $\mu_c = E[d]$ is the mean value of the $\sigma°$ vs Θ curve coming from category c.

The covariance matrix is estimated by

$$(5)\quad \Sigma_c = \frac{1}{N}\sum_{n=1}^{N} (d_n - \mu_c)(d_n - \mu_c)'$$

and the mean is estimated by

$$(6)\quad \mu_c = \frac{1}{N}\sum_{n=1}^{N} d_n,$$

where $d_1, d_2, \ldots d_n$ are all backscatter measurements coming from ice patches of ice category c.

From the data sample of 363 measurements, 195 measurement profiles were selected at random for the training set. Assignment of ice categories was made on the basis of airphoto interpretation and comments during flight by U.S. Navy ice observers. Twenty-five were from patches of water or thin ice, eighty-seven were from patches of first year ice and eighty-three were from patches of multi-year ice. The category probabilities were estimated by the proportions 25/195, 87/195, and 83/195. The corresponding estimates of the mean and covariance matrices were made and used to construct the decision rule. The prediction set consisted of the remaining 168 measurements. Nine were from water or thin ice, eighty-one were from first year ice, and seventy-eight were from multi-year ice. Each measurement was assigned an ice category by the

+We denote the transpose of a vector d by d'.

constructed decision rule. Figure 1 illustrates the resulting contingency table of true ice identifications versus assigned ice identifications. About 92 per cent of the measurements were identified correctly; however, 44 per cent of the assignments to water or thin ice were wrong, about 4 per cent of the assignments to first year ice were wrong, and about 8 per cent of the assignments to multi-year ice were wrong. These results indicated that further examination of the radar scatterometry ice data was warranted, particularly considering some probable errors in the "ground truth."

In another experiment having 182 samples in the training set and 181 samples in the prediction set, we formulated the decision rule differently. For each angle of incidence, we took the range of the back-scattered return for every other data sample and divided it into three equal parts: small returns, medium returns, and large returns. Each back-scattered profile in this training half of the data was then quantized so that each component in the profile could take on only one of three values 0, 1, or 2. The conditional probability of a category c given any quantized measurement was estimated as the proportion of such measurements identified in category c. Then for each angle of incidence the range of the remaining half of data was similarly quantized to three levels and the decision rule defined by the inequalities of (1) was applied to the prediction half of the data. The quantized measurements for which conditional probability estimates were not available were identified by a nearest neighbor rule. The nearest neighbor rule assigns such a quantized measurement to that category of a quantized measurement in the training set closest to it.

Figure 2 illustrates the contingency table of the true category identification versus the assigned ones. Eighty-one per cent of the quantized measurements were correctly identified and only 9 per cent of those assigned to water or thin ice were wrong, 27 per cent of those assigned to first year ice were wrong, and about 4 per cent of those assigned to multi-year ice were wrong. Even though the proportion of correct identification was 10 per cent less than under the multivariate normal assumption, the discrimination between water or thin ice and multi-year ice was better under the crude quantization. This behavior is important because it implies that discrimination between water or thin ice and multi-year ice may be achieved with relatively unsophisticated equipment and a small amount of noise will tend not to have a very great effect on performance.

Since the main application of the discrimination of such ice types lies in the airborne implanting of instrumentation packages in either Arctic water or ice in conditions where a low level cloud cover is virtually perpetual, we wanted to examine the discrimination capability of the scatterometer in a look-ahead mode, that is, using those incidence angles greater than 15°: 25°, 35°, 45°, 50°, and 65°. In this way information about ice types ahead of the plane could be received on the plane in enough time to allow the instrument package to drop onto a particular identified patch of ice or water.

Repeating the first discrimination experiment with the conditional multivariate normal assumption, we obtained about 79 per cent correct identification with 69 per cent of water or thin ice assignments wrong, 7 per cent of first year ice assignments wrong, and 23 per cent of the multi-year ice assignments wrong. Repeating the second discrimination experiment with the crude 3 levels of quantization, we obtained about 75 per cent correct identification with no error on assignments made of patches of first year ice. These respective contingency tables are illustrated in Figures 3 and 4.

Finally, to determine what kind of finer discrimination capability there was, we divided the first year ice into three subtypes: first year smooth ice, first year broken and/or snow covered ice, and first year weathered broken and snow covered ice. Then we quantized the 9 angle data to 3 quantized levels and constructed the decision rule using half the data and identified the ice types for the remaining half. Figure 5 illustrates the resulting contingency table. A total of about 75 per cent correct identification was obtained: the major sources of confusion were between multi-year ice and first year smooth, and between first year broken and/or snow covered ice and the first year smooth, and between first year weathered broken snow covered ice.

VII. CONCLUSION

Studies indicate a capability to identify water or thin ice and multi-year ice from first year ice with scatterometry data. The presence of volume scattering is considered to be a factor, but further studies are needed to determine its effect.

	Water, Thin Ice	1st-Year Ice	Multi-Year Ice
Water, Thin Ice	5	3	1
1st-Year Ice	4	71	6
Multi-Year Ice	0	0	78

Figure 1. Illustrated contingency table for prediction set using all 9 angles of scatterometer data. Rows are true category identification and columns are category identifications assigned by a Bayes decision rule based upon multivariate normal conditional distribution.

	Water, Thin Ice	1st-Year Ice	Multi-Year Ice
Water, Thin Ice	10	6	1
1st-Year Ice	1	83	1
Multi-Year Ice	0	25	84

Figure 2. Illustrates contingency table for prediction set using all 9 angles of scatterometer data. Rows are true category identifications and columns are category identifications assigned by a Bayes decision rule based upon three level quantized data.

	Water, Thin Ice	1st-Year Ice	Multi-Year Ice
Water, Thin Ice	4	1	4
1st-Year Ice	9	53	19
Multi-Year Ice	0	3	75

Figure 3. Illustrates a contingency table for prediction set using 5 angles of scatterometer data above 15°. Rows are true category identification and columns are category identification assigned by a Bayes decision rule based upon multivariate normal conditional distribution.

	Water, Thin Ice	1st-Year Ice	Multi-Year Ice
Water, Thin Ice	5	12	0
1st-Year Ice	0	85	0
Multi-Year Ice	0	34	45

Figure 4. Illustrates a contingency table for prediction set using 5 angles of scatterometer data above 15°. Rows are true category identification and columns are category identification assigned by a Bayes decision rule based on three level quantized data.

	Water, Thin Ice	1st-Year Smooth Ice	Multi-Year Ice	1st-Year Broken, Snow Covered Ice	1st-Year Weathered Broken Snow Covered Ice
Water, Thin Ice	10	5	1	1	0
1st-Year Smooth Ice	1	39	0	45	2
Multi-Year Ice	0	20	55	3	1
1st-Year Broken Snow Covered Ice	0	1	1	20	0
1st-Year Weathered Broken Snow Covered Ice	0	0	0	4	12

Figure 5. Illustrates a contingency table for prediction set using 9 angles of scatterometer data. Rows are true category identifications and columns are category identification assigned by a Bayes decision rule based on three level quantized data.

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