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4 to 18 GHz Rader Backscatter Model of First-Year Sea Ice

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Abstract

Microwave remote sensing plays a major role in areas where cloud cover and darkness prevail. In this and the next papers, models are described for the radar backscatter from two major types of sea ice in an attempt to specify optimum sensor parameters and to allow the most reliable image interpretation possible.

Here, the physical-optics model using an exponential correlation function is shown to be able to predict the signatures of first-year ice under cold conditions. The effect of volume scattering by small inclusions in the first-year ice is shown to be negligible using a semi-empirical volume scattering model.

1. Introduction

Since 1962, considerable experimental data on the microwave signatures of sea ice have been collected with both active and passive remote sensors. Scattering theories have been developed to describe the interaction of electromagnetic waves with nature, assuming that the nature can be described with certain average statistical parameters. Recently the surface and volume scattering theories have been applied to remotely sensed ground targets, including snow, vegetation, soil, ocean waves, etc.

Parashar(1974) applied to sea ice the general theory, developed by Fung(1969), of wave scattering by a horizontally weakly inhomogeneous medium. The model includes small-scale roughness of the air-ice interface and also a bilinear mean vertical permittivity profile for sea ice, with anisotropic small random perturbations in the ice volume. Parashar had some success in matching the 0.4 and 13 GHz scatterometer data by arbitrarily adjusting the model parameters (necessary because there were no surface measurements accompanying the data). The small-perturbation method was possibly applicable to thick first-year ice and thinner ice types, but did not show satisfactory results for multiyear ice.

Fung and Eom(1982) developed a radiative-transfer theory which combines rough surface and volume scattering effects, and applied it to backscatter measurements of snow and sea ice. The surface-scattering effect is accounted for by the Kirchhoff model, and the inhomogeneous layer is modeled by either the Rayleigh phase matrix or a continuous random medium with a cylindrically symmetric correlation function for its permittivity. By assuming several model parameters, the theoretical like- and cross-polarized curves provided satisfactory agreements in level and trend to the measured first-year and multiyear ice data at 9 and 13 GHz. Their model is further studied in this paper. By assuming that the volume scattering contribution can be neglected, the signatures of first-year ice are tested against the predictions of surface scattering theories. By using the measured surface-height correlation length and standard deviation, it is shown that the physical-optics model, using an exponential correlation function, provides a good fit to measured angular and frequency behaviors of the backscattering coefficient for first-year ice.

The volume scattering contributions of the brine pockets and the air bubbles in the first-year ice are also calculated using a simple semi-empirical model, and it is shown to be negligible for most cases.

2. Dielectric Constant of Sea Ice as a Function of Frequency, Salinity, and Temperature

Physical parameters of sea ice, such as salinity and temperature, affect the dielectric properties of sea ice, which in turn determine the backscattering behavior of sea ice in combination with other parameters like surface roughness, size of scatterers inside the ice, etc. In general, the magnitude of the real part of the dielectric constant of sea ice is far greater than that of the imaginary part. Therefore ϵ' largely determines the Fresnel reflection coefficient at the ice surface while ϵ'' largely determines the penetration into the ice, as well as the backscattering contribution due to the inclusions inside the ice medium.

Both ϵ' and ϵ'' of sea ice decrease as frequency is increased from 1 to 18 GHz. This occurs because the very high dielectric constant of brine decreases with frequency(Vant et al., 1978), although that of pure ice may increase in the frequency range of interest(Ulaby et al., 1986). Hallikainen(1982) derived a set of empirical constant multipliers for ϵ' and ϵ'' at different frequencies relative to the values at 500MHz. The equations are:

$$\varepsilon'(18\,\text{GHz}) = 0.98\,\varepsilon'(5\,\text{GHz}) = 0.93\,\varepsilon'(1\,\text{GHz}) = 0.86\,\varepsilon'(0.5\,\text{GHz}) \quad (1)$$

$$\varepsilon''(18\,\text{GHz}) = 0.92\,\varepsilon''(5\,\text{GHz}) = 0.61\,\varepsilon''(1\,\text{GHz}) = 0.46\,\varepsilon''(0.5\,\text{GHz}) \quad (2)$$

In this study, these scale factors from the basis for a linear variation of ϵ with frequency over the 1 to 18 GHz region; once the dielectric behavior of sea ice as a function of salinity and temperature is determined, values are assigned at other frequencies.

From a handful of reported measurements available on temperature and salinity dependence of the dielectric constant of sea ice, the following conclusions can be drawn: (1) the dielectric constant of sea ice decreases as temperature is lowered, and (2) it generally increases as salinity increases. All the uncertain variations depend on the ice types and even on the specific sampling and measurement techniques used. Instead of using a complicated mixing formula, simple empirical equations by Vant(1974, 1978) relating the dielectric constant of sea ice to the brine volume are used in this study. These equations seemed to be suited for the study of radar backscatter from sea ice at least for the temperatures below $-5\,^{\circ}$C. The equations have the form $\epsilon' = a + b\,V_{br}$ and $\epsilon'' = c + d\,V_{br}$, where a, b, c, and d are constants depending on ice type and the frequency. The brine volume, V_{br}(o/oo) is estimated from salinity, S(o/oo) and the temperature, T ($^{\circ}$C) using the equation given by Frankenstein and Garner(1967).

$$V_{br} = S\,(-49.185/T + 0.532) \quad (3)$$

The empirical equations given by Vant are:

$$\varepsilon' = 3.05 + 7.2\,V_{br}/1000, \text{ for first-year ice at 4 GHz} \quad (4)$$

$$\varepsilon'' = 0.024 + 3.3\,V_{br}/1000, \text{ for first-year ice at 4 GHz} \quad (5)$$

3. Surface-Scattering Model of First-Year Ice

Due to high loss and the small sizes of various inclusions inside the ice medium, surface scattering can be assumed to be the dominant mechanism for radar return from snow-free first-year ice or even the summer ice. Therefore, the signatures of first-year ice are tested against the predictions of surface scattering theories. The effect of snow cover on sea ice was treated in Kim et al.(1984) and the effect of small inclusions inside the first-year ice will be examined later.

Surface scattering is usually described by the Kirchhoff method for surfaces with large radius of curvature(compared to the wavelength), and by the small perturbation method for surfaces with small scales of roughness (Ulaby et al., 1982). Also, two-scale surface theory has been successfully applied to ocean waves, which can be modelled to have both large and small scales of roughnesses.

The Kirchhoff model assumes that the horizontal scale of roughness, or the correlation length ℓ, is large compared to wavelength while the vertical scale of roughness, expressed as the standard deviation σ of surface height is small enough to maintain the average radius of curvature large compared to the wavelength. When the surface height variation is large compared to the wavelength, the Kirchhoff surface integral is simplified using a stationary phase approximation(geometrical-optics model) and when the surface is smoother, it can be simplified using scalar approximation (physical-optics model). Mathematically, the requirements of the Kirchhoff model are;

correlation length $\ell > \lambda$ .... (6)

average redius of curvature $r_c > \lambda$ .... (7)

surface height stanard deviation $\sigma > \lambda/4 \cos\theta$ .... (8)

rms slope of the surface $m < 0.25$ .... (9)

Eqs. (6) and (7) are the basic assumptions for the Kirchhoff model, Eq. (8) is for the stationary-phase approximation, and Eq. (9) is for the scalar approximation. The backscattering coefficient for the Kirchhoff surface was derived in Ulaby et al.(1982), and the effect of varying model parameters or choosing different correlation functions can be found in Eom(1982). With the Gaussian correlation function, $\rho(\zeta) = \exp(-\zeta^2/\ell^2)$, the backscattering coefficient with polarization pp is,

$$\sigma^{o}_{PP}(\theta) = |R_{PP}|^2 (k\ell \cos\theta)^2 e^{-4(k\sigma\cos\theta)^2} \sum_{n=1}^{\infty} \frac{4(k\sigma\cos\theta)^{2n}}{n\,n!} e^{-4(k\ell\sin\theta)^2/n} \quad \cdots\cdots (10)$$

, where R_{pp} is the Fresnel reflection coefficient for the incidence angle of θ, and $k = 2\pi/\lambda$. With the exponential correlation function, $\rho(\zeta) = \exp|-\zeta/\ell|$,

$$\sigma^{o}_{PP}(\theta) = 2|R_{PP}|^2 (k\ell\cos\theta)^2 e^{-4(k\sigma\cos\theta)^2} \sum_{n=1}^{\infty} \frac{4(k\sigma\cos\theta)}{(n-1)!} \frac{1}{[4(k\ell\sin\theta)^2 + n^2]^{1.5}} \quad \cdots\cdots (11)$$

The summation can usually be truncated at n = 10 with small errors.

For relatively rough surfaces, whose backscattering cross sections show a slowly varying angular behavior near nadir, the geometrical- optics model might be able to predict the backscattering behavior at small incidence angles. For smoother surfaces, the physical-optics model seems better suited. This model usually exhibits faster angular drop-off than the geometrical-optics model does for small incidence angles. For large incidence angles, the rate of decay depends on the choice of the surface correlation function. The Gaussian correlation function shows a fast angular drop-off, while the exponential correlation function shows large tails.

Fig. 1 shows typical backscattering cross sections measured during the melting season for multiyear ice and first-year ice. The surface scattering can be considered to be dominant under summer conditions. From the slow angular drop-offs, one can suspect that the geometrical-optics model with very large rms slope or the physical optics model with an exponential correlation

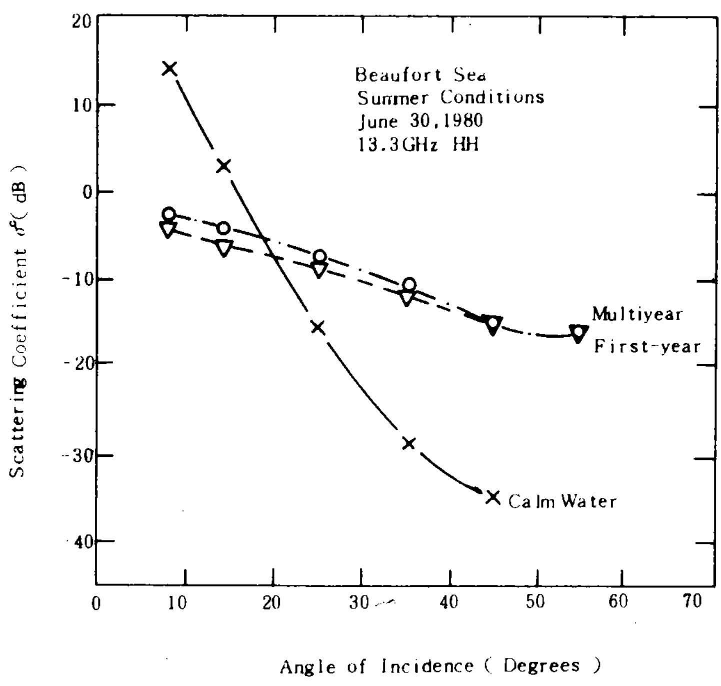

Fig. 1. Measured backscattering cross sections of sea Ice and Water(from Gray et. al., 1982)

function might work. Fig. 2 shows theoretical angular behavior of σ° using the physical-optics model with exponential correlation function. The summer data shown in Fig. 1 are redrawn on Fig. 2, and one can suspect that the data might be explained using the surface scattering model only.

The effect of varying the real part of the dielectric constant is also shown in Fig. 2. The effect of higher salinity or temperature is to raise the dielectric constant of sea ice, and therefore effectively raise the surface-scattered power. The maximum reported variation of ϵ' of first-year ice due to changes in temperature(below about -5°C) or salinity is from 3 to 5. This would change the Fresnel reflection coefficient from 0.27 to 0.38 for vertical incidence and from 0.38 to 0.5 for an incidence angle of 45 degrees with horizontal polarization. With the Kirchhoff surface model, the effect due to the maximum possible change in the values of ϵ' is at most 3 dB(see Fig. 2), and for the normal ranges of values (ϵ' = 3 to 4 for first-year ice) the effect is less than 1.7 dB. This effect is independent of specific choice of surface correlation function. The small variation of ϵ' with frequency as illustrated in Eq. (1) has even smaller effect on surface scattering; it is assumed to be constant in the frequency range between 4 and 18 GHz.

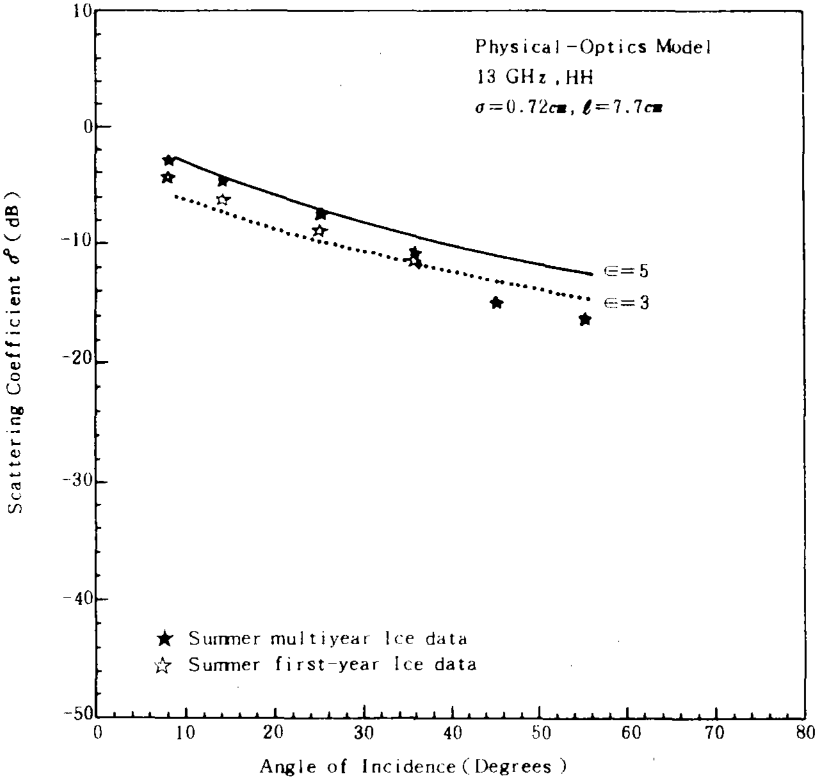

Fig. 2. Theoretical angular behavior of σ°. also shown is the summer Ice data shown in Fig. 1. the surface roughness parameters are real Ice data taken nearly at the same time of the year (June).

Fig. 3 shows the effect of surface roughness(actual measurement results, not arbitrary numbers) under the physical-optics model. The smooth surface gives a little faster angular drop-off than the rough surface, and the surface roughness can make as much as 15 dB difference in the back-scattering cross sections at large incidence angles. If one adds the 2 to 3 dB variation due to the difference in the dielectric constant, the same ice categories with different surface roughness can give up to 18 dB variation with different temperatures or salinities. This large fluctuation has been experienced through many experiments by many investigators, and would severely limit the system capability to discriminate different ice types unless the surface roughness of one type of ice is always different from that of another type of ice, or different ice types have different scattering mechanisms. Multiyear ice is generally understood to have rougher surface than first-year ice due to meltponds, but the small-scale surface roughness characteristics are not well established.

Theoretical frequency behaviors of σ° for a smooth first-year ice and a rough first-year ice

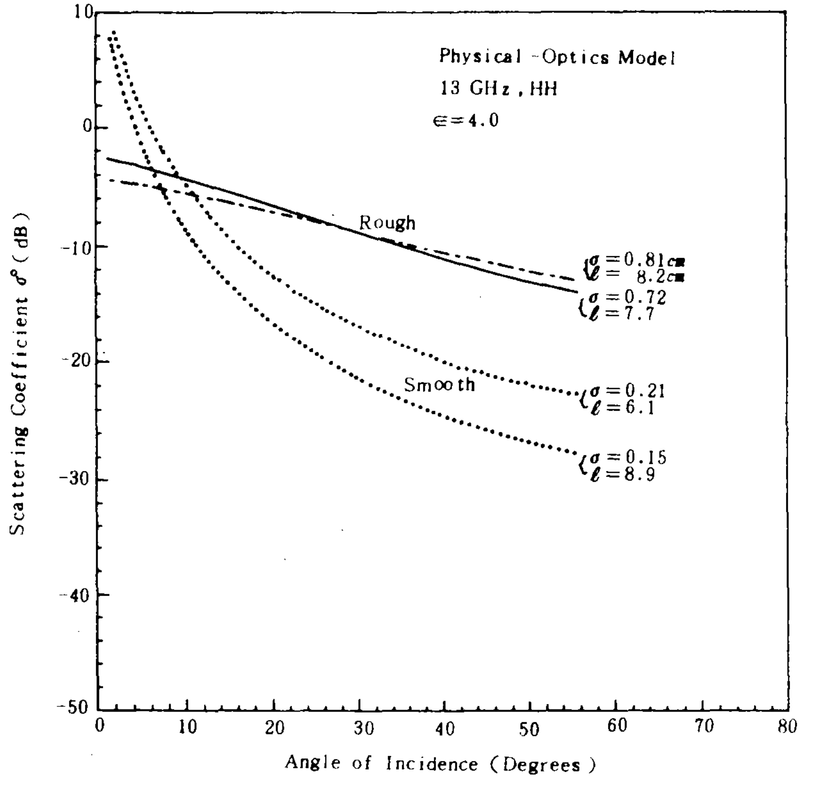

Fig. 3. Theoretical angular bahavior of σ° for smooth and routh Ice.

under the exponential surface correlation function are shown in Fig. 4, together with several reported measurements at the incidence angles of about 40 degrees. Both the calculation and the measurements show gently increasing frequency behaviors, and a good general match can be seen. σ° decrease with frequency for the Gaussian surface correlation(Kim, 1984), and therefore the exponential correlation function seems to be better suited to predict both the angular- and the frequency-behaviors of σ° for first-year ice.

The model is tested for the data taken from the grey ice (about 15 cm thick). Fig. 5 shows the predicted and measured frequency behavior of σ°. The air temperature was about -20°C, and the salinity data were not available, although salinity is usually high for thin types of sea ice. Therefore, the dielectric constant was set to be 3.5. The small scale surface roughness was not measured, so it was adjusted to match the data at $\theta = 40^{0}$. At other incidence angles, the match was not as good. This is not surprising, because most of the multi-frequency data were taken using the frequency-stepping scheme while flying over an ice floe with varying degrees of deformation. Fig. 6 shows the measured angular response and the model behavior using the same surface characteristics as in the frequency response(Fig. 5). The shape of the model prediction matches that of the data reasonably well.

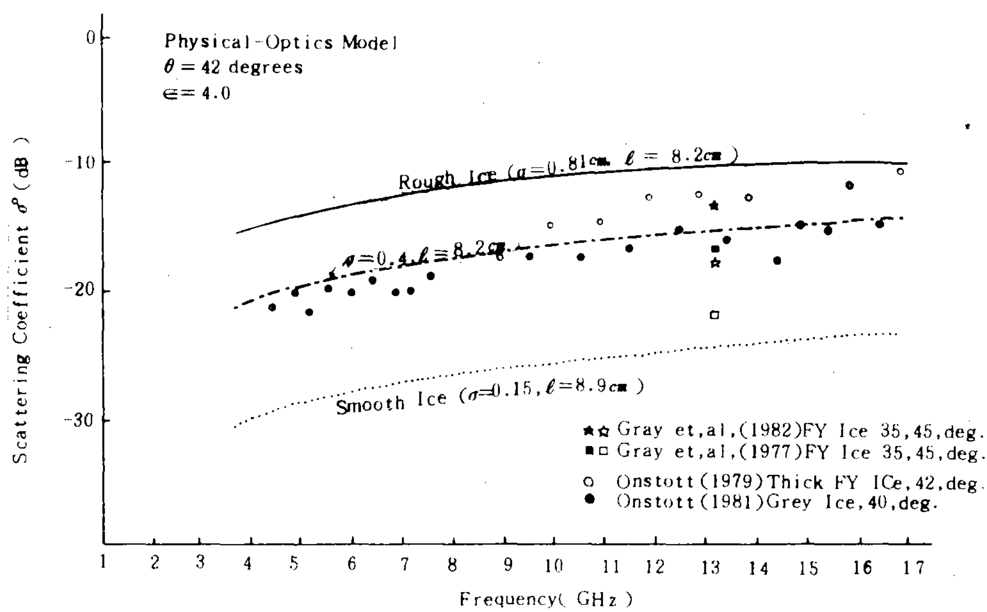

Fig. 4. Physical-Optics model frequency behavior. Also shown are several reported measurements. With proper choice of sur face parameters, the model can fit the data very well.

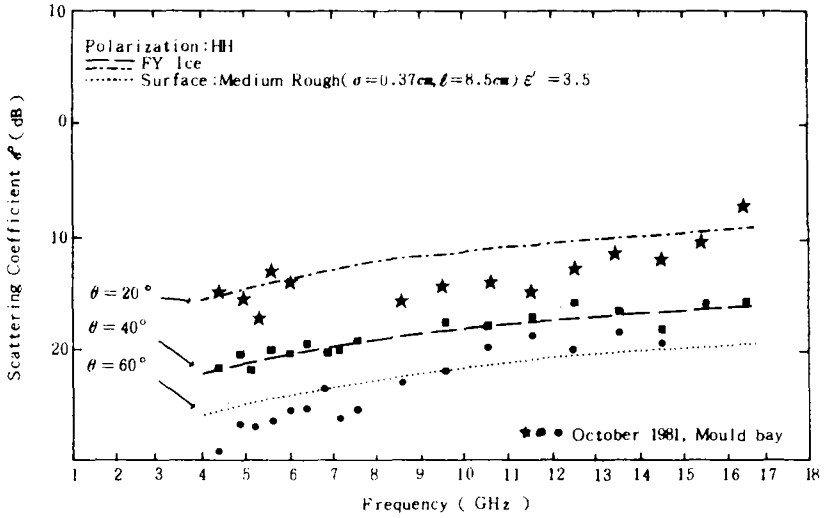

Fig. 5. Measured and predicted σ° of grey Ice. The model parameters are chosen to match the data at 40°.

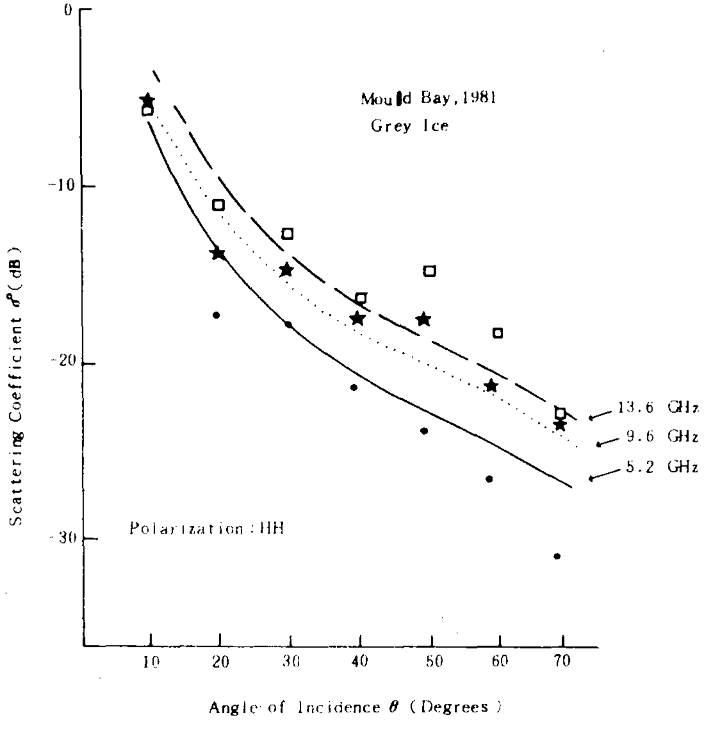

Fig. 6. Measured and predicted σ° of grey Ice. The model parameters are same as those shown in Fig. 5.

4. The Volume Scattering Considerations for First-Year Ice

Although surface scattering is considered to be the dominant backscattering mechanism for first-year ice, the possible volume scattering contributions to radar return from first-year ice is also examined here. The volume scatterers can be the snow layer on top of the ice, or the inclusions like air bubbles and the brine pockets.

The effect of snow cover on backscattering from sea ice were considered in(Kim et. al., 1984). The backscattering coefficient of dry snow is much higher than that of smooth ice surface, and the net effect of dry snow cover on smooth first- year ice can be severe(5 cm of dry snow can raise σ° by 8 dB at 9 GHz). The effect is less when the snow is on rough ice surface whose σ° can be as high as that of dry snow layer.

The air bubbles found in first-year ice are small, with diameter of up to 1 mm(Poe et. al., 1974). The brine pokets are approximately spherical in shape in the frail-ice zone(Ramseier et. al., 1974) and the average diameter is far less than 1 mm(Pounder, 1965) (Anderson, 1960), although this is highly variable depending on salinity and temperature. The brine pockets found in the columnar ice zone are reported to be elongated in the vertical direction with average length of 3 to 5 mm(Poe et al., 1974). However, due to the high loss of the frazil-ice zone, the columnar ice with elongated brine pockets is not expected to be seen with microwave frequencies. With the empirical dielectric constant model by Vant (1978), the penetration depths are estimated to be less than about 15 cm for the frequencies above C-band. Therefore only the spherical inclusions are considered here.

The volume backscattering coefficient of the first-year ice is calculated using a semi-empirical equation of the form,

$$\sigma^{\circ}(\theta) = T^2(\theta)\ \sigma_V^{\circ}(\theta') \qquad (12)$$

, where $T(\theta)$ = power transmission coefficient of the ice surface.

θ' = the angle of refraction in the ice medium.

$\sigma_V^{\circ}(\theta')$ = volume backscattering coefficient of the ice.

$$\cong \frac{N\ \sigma_b \cos\theta'}{2\,k_e}\left[1 - \frac{1}{L^2(\theta')}\right] \qquad (13)$$

N = number of scatterers per unit volume.

σ_b = backscattering cross section of a single scatterer.

$L(\theta')$ = $\exp(k_e d \sec\theta')$, which represents one-way loss through the layer with extinction coefficient k_e and depth d.

The details can be found in(Kim, 1984). This type of model has been used for snow(Stiles and Ulaby, 1980, 1981) and for a vegetation canopy(Attema and Ulaby, 1975). In the above equation, all the scatterers are assumed to be of same size, and the multiple scattering is neglected. Kim (1984) showed that the semi-empirical model behavior matches very well with that of the radiative-transfer model for all the frequencies considered.

Figs. 7 and 8 show the calculated volume scattering term due to air bubbles and brine pockets in first-year ice compared to the surface scattering term calculated with the physical-optics model. It can be seen that the volume scattering term can generally be neglected compared to the surface scattering term in the frequency range below about X-band. Only when the surface is smooth, and when the density of first-year ice is low(about 0.85 gm/cm^3), the large air bubbles of 1 mm in diameter can give the volume scattering contribution comparable to that of surface scattering at frequencies above Ku-band at angles well away from vertical.

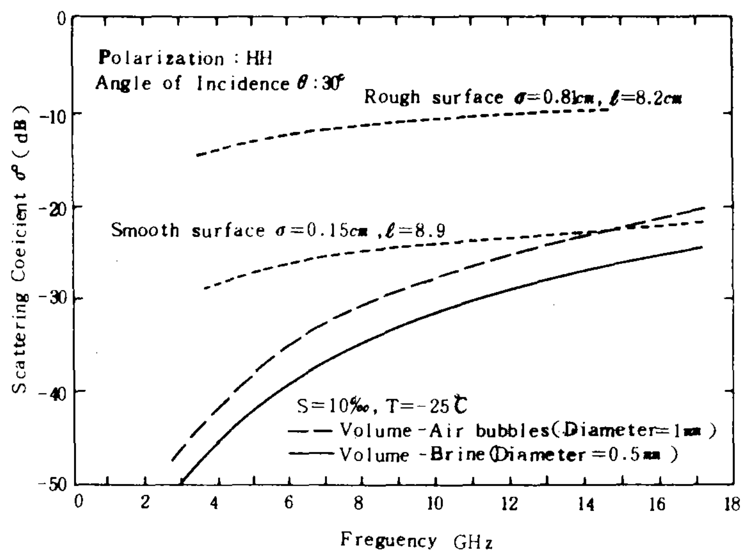

Fig. 7. Volume scattering due to air bubbles and brine pockets in the First-year Ice. Also shown is the surface scattering term using the physical-optics model.

5. Conclusions

The discussions in this paper considered only the surface scattering. This would be the primary effect for a snow-free first-year ice. Snow cover on sea ice contribute backscattering by itself,

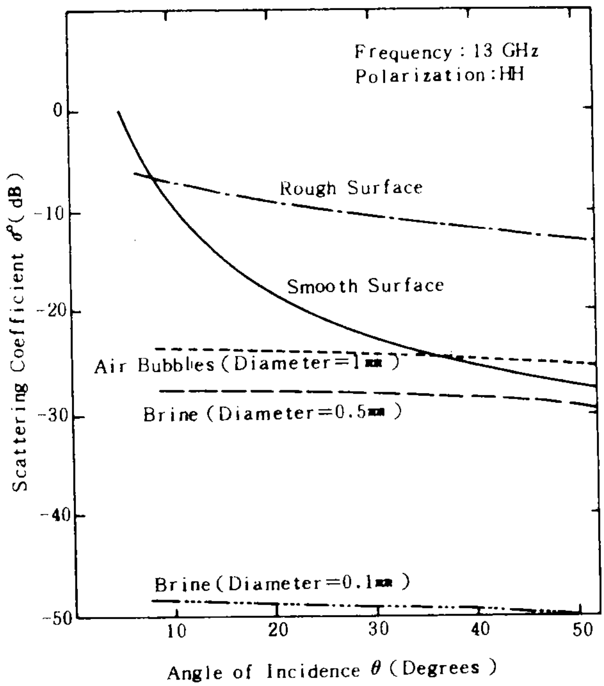

Fig. 8. Angular behavior at 13 GHz. the effect of air bubbles and brine pockets in the first-year ice is shown. All the parameters are same as shown in Fig. 7.

and modify the ice surface scattering as well as the ice-volume scattering by changing the temperature of ice. These factors were considered in(Kim et al., 1984).

Under the assumption that the surface scattering is the dominant backscattering mechanism, the signatures of first-year ice were tested against the predictions of surface scattering models. The measurements of small scale surface roughness satisfy the requirements of the Kirchhoff model for the frequencies between 4 and 18 GHz; and it was shown that the physical-optics model, using an exponential correlation function, provides a good fit to measured angular- and frequency behaviors of the backscattering coefficient of first-year ice. However, the model does not adequately explain the polarization dependence of the backscatter from first-year ice. This is partly due to the lack of cross-polarized data for the whole frequency range considered(4 to 18 GHz), and partly due to the inability of the first-order surface scattering theory to predict the depolarization. The difference between the two like-polazrizations also needs to be studied further, both experimentally and theoretically.

Using a simple semi-empirical model, the volume scattering contributions of the air bubbles and the brine pockets inside the first-year ice was calculated. Compared to the surface-scattering term, it is negligible for most of the cases.

Under summer conditions, the surface scattering can be considered to be dominant for both the multiyear ice and the first-year ice. The macro-scale roughness and snow-cover differences between first-year and multiyear ice may result in different σ°,s, even though the small scale roughness for both ice types can be similar. During winter, the marked difference between the signatures of first-year ice and multiyear ice is better understood from the point of view of different scattering mechanisms. Surface scattering is dominant for first-year ice, but volume scattering might be dominant for multiyear ice and these two are distinguishable. The models for the radar return from multiyear ice will be considered later.

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