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OPTIMUM BACKSCATTER CROSS SECTION OF THE OCEAN AS MEASURED BY SYNTHETIC APERTURE RADARS

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ABSTRACT

Microwave remote sensing of rough surfaces (both land and ocean), using moving platforms (aircraft and satellite), as well as ground based measurements has illustrated the need for a better understanding of the interaction of the radar signals with these surfaces. This interaction is particularly important for the ocean surface where the radar modulation can yield information about the long ocean wave field. Radar modulation measurements from fixed platforms have been made in wavetanks and the open oceans. The surfaces have been described in terms of two-scale models. The radar modulation is considered to be principally due to: (1) geometrical tilt due to the slope of the long ocean waves and (2) the straining of the short waves (by hydrodynamic interaction). For application to moving platforms, Synthetic Aperture Radar (SAR) and Side Looking Airborne Radar (SLAR), this modulation needs to be described in terms of a general geometry for both like- and cross-polarization since the long ocean waves, in general, travel in arbitrary directions. In the present work, the finite resolution of the radar is considered for tilt modulation with hydrodynamic effects neglected.

1. INTRODUCTION

The full wave approach is used to determine the modulation of the like- and cross-polarized scattering cross sections for composite models of rough surfaces illuminated by SAR. The full wave approach accounts for both specular point scattering and Bragg scattering in a self-consistent manner. Thus, the total scattering cross section is expressed as a weighted sum of two cross sections (Bahar et al., 1983). The first is the scattering cross section associated with the filtered surface consisting of the large-scale specular components of the illuminated rough surface area. The second is the cross section associated with the surface consisting of the small-scale spectral components that ride on the filtered surface.

Full wave solutions are derived for the scattering cross sections of a relatively small area or resolution cell of the rough surface that is effectively illuminated by SAR. The normal to an arbitrarily oriented mean plane associated with the illuminated cell is characterized by tilt angles Ω and τ in and perpendicular to a fixed reference plane of incidence. It is assumed that the lateral dimension of the resolution cell L_s is much larger than both the electromagnetic wavelength and the surface height correlation distance for the cell. As the SAR scans different portions of the rough surface S, the direction of the unit vector normal to the cell F fluctuates. In this paper the "modulations" of scattering cross sections are determined as the tilt angles Ω and τ fluctuate. In a recent study of "tilt modulation" by Alpers et al. (1981), first-order Bragg scatter due to capillary waves on a tilted plane is considered. It can be shown that if the large scale spectral components of the surface within the cell are ignored, the full wave solutions derived here for tilt modulation reduce to the results obtained by Alpers et al.

$$\bar{n} = \nabla f/|\nabla f| = (-h_x\bar{a} + \bar{a}_y - h_z\bar{a}_z)/(h_x^2 + h_z^2 + 1)^{\frac{1}{2}} \tag{7a}$$

where

$$f = y - h(x,z) \ , \ h_x = \partial h/\partial x \ , \ h_z = \partial h/\partial z \tag{7b}$$

and

$$\bar{n}_s = \bar{v}/v \ . \tag{7c}$$

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The expression for the physical optics (specular point) cross section for the large-scale surface h_ℓ is

$$<\sigma_\infty^{PQ}> = \frac{4k_o^2}{v_y^2}\left[\left|\frac{D^{PQ}}{\bar{n}\cdot\bar{a}_y}\right|^2 P_2(\bar{n}^f,\bar{n}^i|\bar{n})p(\bar{n})\right]_{\bar{n}_s} \tag{8}$$

in which D^{PQ} depends on $\bar{n}^i$, $\bar{n}^f$, $\bar{n}$, the media of propagation above and below the rough surface $h(x,z)$ and the polarization of the incident and scattered waves (Bahar, 1981a,b). The shadow function P_2 is the probability that a point on the rough surface is both illuminated and visible, given the slopes $\bar{n}(h_x,h_z)$, at the point (Smith, 1967; Sancer, 1969). The probability density function for the slopes h_x and h_z is $p(\bar{n})$. The factor $\chi^s(v)$ that multiplies $<\sigma_\infty^{PQ}>$ accounts for the degradation of the contributions from the specular points due to the superimposed small scale rough surface h_s.

Assuming a Gaussian probability density function for h_s, $<\sigma^{PQ}>_s$ is given by the sum

$$<\sigma^{PQ}>_s = \sum_{m=1}^{\infty} <\sigma^{PQ}>_{sm} \tag{9}$$

where

$$<\sigma^{PQ}>_{sm} = 4\pi k_o^2 \int \frac{|D^{PQ}|^2 \ P_2(\bar{n}^f,\bar{n}^i|\bar{n})}{\bar{n}\cdot\bar{a}_y}$$

$$\cdot \ \exp(-v_{\bar{y}}^2<h_s^2>)\left(\frac{v_{\bar{y}}^2}{2}\right)^{2m} \frac{W_m(v_{\bar{x}},v_{\bar{z}})}{m!} \ p(h_x,h_z)dh_x dh_z \tag{10}$$

in which $<h_s^2>$ is the mean square of the surface height h_s and $v_{\bar{x}}, v_{\bar{y}}$ and $v_{\bar{z}}$ are the components of $\bar{v}$ (6) in the local coordinate system (at each point on the large scale surface) associated with the unit vectors $\bar{n}_1, \bar{n}_2$ and $\bar{n}_3$. Thus $\bar{v}$ can also be expressed as

$$\bar{v} = v_{\bar{x}}\,\bar{n}_1 + v_{\bar{y}}\,\bar{n}_2 + v_{\bar{z}}\,\bar{n}_3 \tag{11}$$

where

$$\bar{n}_1 = (\bar{n} \times \bar{a}_z)/|\bar{n} \times \bar{a}_z| \ , \ \bar{n}_2 = \bar{n} \ , \ \bar{n}_3 = \bar{n}_1 \times \bar{n} \ . \tag{12}$$

The function $W_m(v_{\bar{x}},v_{\bar{z}})/2^{2m}$ is the two-dimensional Fourier transform of $(<h_s h_s'>)^m$.

For $\beta << 1$ and arbitrary $p(h_x,h_z)$ the first term in (9), $<\sigma^{PQ}>_{s1}$ is also in agreement with Valenzuela's solutions that are "mostly based on physical considerations" (Valenzuela, 1968, Valenzuela et al., 1971). For small slopes $\bar{n} \approx \bar{a}_y$ and $\beta << 1$ the first term in (3) reduces to Brown's solution (1978) based on a combination of physical optics and perturbation theory. Since it is assumed (on deriving (3) from the full wave solutions for the scattered fields) that the surface h_ℓ satisfies the radii of curvature criteria as well as the condition for deep phase modulation, it is necessary to choose $\beta = 4k_o^2<h_s^2> \geq 1$ in order to assure that the weighted sum of cross sections (3) remains insensitive to variations in k_d, the wavenumber where spectral splitting is assumed to occur (Bahar et al., 1983).

In order to apply the full wave approach to SAR it is necessary to modify the results presented in this section (a) to account for the filtering of the very

For the illustrated examples presented, the scattering cross sections and their derivatives with respect to the tilt angles are evaluated for all angles of incidence. The modulation of the like cross sections near normal incidence is due primarily to fluctuations in specular point scattering while the modulation of the like cross section for near grazing angles is due primarily to fluctuations in Bragg scattering. Thus, for large angles of incidence the cross sections for the horizontally polarized waves are shown to be more strongly modulated than the cross sections for vertically polarized waves. The relative modulations of the like polarized backscatter cross sections are optimum for incident angles between 10° and 15° depending upon the lateral dimension of the resolution cell and the polarization.

2. FORMULATION OF THE PROBLEM

The full wave solutions for the normalized cross sections per unit area are summarized here for composite rough surfaces. The position vector to a point on the rough surface is expressed as follows:

$$\bar{r}_s = \bar{r}_\ell(x,h_\ell,z) + \bar{n}h_s \tag{1}$$

in which $y=h_\ell(x,z)$ is the filtered surface consisting of the large scale spectral components of the rough surface and h_s, the small scale surface height is measured in the direction of the normal ($\bar{n}$) to the large scale surface $y=h_\ell$. For a homogenous, isotropic surface height the spectral density function is the Fourier transform of the surface height autocorrelation function $\langle h(x,z),h'(x',z')\rangle$.

$$W(v_x,v_z) = \frac{1}{\pi^2}\int_{-\infty}^{\infty}\langle hh'\rangle \exp(iv_x x_d + iv_z z_d)dx_d dz_d \tag{2a}$$

where $\langle hh'\rangle$ is a function of distance $|\bar{r}_d| = (x_d^2 + z_d^2)^{1/2}$ and

$$x - x' = x_d \text{ and } z - z' = z_d. \tag{2b}$$

The surface $h_\ell(x,z)$ consists of the spectral components $k = (v_x^2 + v_z^2)^{1/2} \leq k_d$ and the remainder term $h_s(x,z)$ consists of the spectral components $k > k_d$. The full wave approach accounts for both specular point scattering and Bragg scattering in a self-consistent manner the total scattering cross section can be expressed as a weighted sum of the cross section $\langle\sigma^{PQ}\rangle_\ell$ for the filtered surface h_ℓ and the cross section $\langle\sigma^{PQ}\rangle_s$ for the surface h_s that rides on the large-scale surface h_ℓ (Bahar et al., 1983)

$$\langle\sigma^{PQ}\rangle = \langle\sigma^{PQ}\rangle_\ell + \langle\sigma^{PQ}\rangle_s \ . \tag{3}$$

The symbol < > denotes statistical average. The first superscript P corresponds to the polarization of the scattered wave while the second superscript Q corresponds to the polarization of the incident wave. To derive (3) using the full wave approach it is implicitly assumed that the large scale surface meets the radii of curvature criteria (associated with the Kirchhoff approximations for the surface fields) as well as the condition for deep phase modulation. Thus the first term in (3) is

$$\langle\sigma^{PQ}\rangle_\ell = |\chi^s(\bar{v}\cdot\bar{n}_s)|^2 \langle\sigma_\infty^{PQ}\rangle \tag{4}$$

in which χ^s is the characteristic function for the small scale surface

$$\chi^s(\bar{v}\cdot\bar{n}_s) = \chi^s(v) = \langle\exp ivh_s\rangle \tag{5}$$

and

$$\bar{v} = \bar{k}^f - \bar{k}^i = k_o(\bar{n}^f - \bar{n}^i) \ , \ v = |\bar{v}| \ . \tag{6}$$

The unit vectors $\bar{n}^f$ and $\bar{n}^i$ are in the directions of the scattered and incident wave normals respectively; thus for backscatter $\bar{n}^f = -\bar{n}^i$. The free space radio wavenumber is k_o. An $\exp(i\omega t)$ time dependence is assumed. The vector $\bar{n}_s$ is the value of the unit vector $\bar{n}$ normal to the surface $h(x,z)$ at the specular points. Thus

large scale spectral component of the rough surface by the SAR that effectively illuminates a relatively small area of cell F of the rough surface S and (b) to account for the normal to a reference plane associated with the illuminated cell which is characterized by arbitrary tilt angles Ω and τ in and perpendicular to the reference plane of incidence. It is assumed here that the lateral dimension of the cell illuminated by the SAR is much larger than the surface height correlation distance for the cell and that as the SAR scans different portions of the rough surface S the direction of the unit vector normal to the cell F fluctuates. Our purpose is to determine the "modulation" of the backscatter cross sections $\langle\sigma^{PQ}\rangle$ (3) as the tilt angles (of the normal to the cell) in and perpendicular to the reference plane of incidence fluctuate.

3. SCATTERING CROSS SECTIONS FOR ARBITRARILY ORIENTED RESOLUTION CELLS OF THE ROUGH SURFACE

Let x,y,z be the reference coordinate system associated with the surface of the cell F that is illuminated by the SAR such that the mean surface of the cell is the y=0 plane. Furthermore, let x',y',x' be the fixed coordinate system associated with the large surface S such that the unit vector $\bar{a}'_y$ is normal to the mean rough surface height h(x',z'). The unit vector $\bar{n}^i = -\bar{n}^f$ is expressed in terms of the unit vectors of the fixed coordinate system (x',y',z'):

$$\bar{n}^i = -\bar{n}^f = \sin\theta'_o\, \bar{a}'_x - \cos\theta'_o\, \bar{a}'_y \,. \tag{13}$$

The unit vector $\bar{a}_y$ normal to the reference surface associated with the cell is expressed in terms of the tilt angles Ω and τ in and perpendicular to the fixed plane of incidence, the x',y' plane. Thus

$$\bar{a}_y = \sin\Omega \cos\tau\, \bar{a}'_x + \cos\Omega \cos\tau\, \bar{a}'_y + \sin\tau\, \bar{a}'_z \,. \tag{14}$$

For convenience $\bar{a}_x$ and $\bar{a}_z$, the unit vectors associated with the cell, can be chosen such that the plane of incidence in the x,y,z coordinate system is normal to the vector a_z. Thus

$$\bar{a}_z = (\bar{n}^i \times \bar{a}_y)/|\bar{n}^i \times \bar{a}_y|\,, \quad \bar{a}_x = \bar{a}_y \times \bar{a}_z \tag{15}$$

and the expression for $\bar{n}^i$ in the x,y,z coordinate system is

$$\begin{aligned}\bar{n}^i &= (\bar{n}^i\cdot\bar{a}_x)\bar{a}_x + (\bar{n}^i\cdot\bar{a}_y)\bar{a}_y \\ &\equiv \sin\theta_o\, \bar{a}_x - \cos\theta_o\, \bar{a}_y \end{aligned} \tag{16a}$$

where

$$\cos\theta_o = \cos(\theta'_o + \Omega)\cos\tau \,. \tag{16b}$$

The angle ψ^i_F between the plane of incidence in the fixed coordinate system (x',y',z') and the plane of incidence in the coordinate system (x,y,z) associated with the cell is given by

$$\cos\psi^i_F = \frac{\cos\tau \sin(\theta'_o + \Omega)}{\sin\theta_o} \tag{17a}$$

and

$$\sin\psi^i_F = \frac{\sin\tau}{\sin\theta_o} \,. \tag{17b}$$

For backscatter $\bar{n}^f = -\bar{n}^i$. Thus the angle ψ^f_F between the plane of scatter in the fixed coordinate system (x',y',z') and the plane of scatter in the coordinate system associated with the cell is

$$\psi^f_F = -\psi^i_F \,. \tag{18}$$

The matrix that transforms the incident vertically and horizontally polarized waves in the fixed coordinate system to vertically and horizontally polarized waves in the cell coordinate system is therefore (Bahar, 1981a,b)

$$T_F^i = \begin{bmatrix} \cos\psi_F^i & \sin\psi_F^i \\ -\sin\psi_F^i & \cos\psi_F^i \end{bmatrix} . \tag{19}$$

Similarly, the matrix that transforms the scattered vertically and horizontally polarized waves in the cell coordinate system back into the vertically and horizontally polarized waves in the fixed coordinate system is

$$T_F^f = \begin{bmatrix} \cos\psi_F^f & -\sin\psi_F^f \\ \sin\psi_F^f & \cos\psi_F^f \end{bmatrix} . \tag{20}$$

Thus in view of (18), $T_F^f = T_F^i$. The coefficients D^{PQ} in (8) are elements of a 2 x 2 matrix D given by

$$D = C_o^{in}\, T^f\, FT^i \tag{21}$$

in which C_o^{in} is the cosine of the angle between the incident wave normal $\bar{n}^i$ and the unit vector $\bar{n}$ normal to the rough surface of the cell $h_F(x,z)$. Thus

$$C_o^{in} = -\bar{n}^i \cdot \bar{n} = \cos\theta_o^{in} \tag{22}$$

where $\bar{n}^i$ is given by (16) and $\bar{n}$ is given by (7a) with $f_F(x,y) = y - h_F(x,y)$. The elements of the scattering matrix F in (21) are functions of the unit vectors $\bar{n}^i, \bar{n}^f$ and $\bar{n}$ as well as the media of propagation above and below the rough surface S (Bahar, 1981a). The matrix T^i transforms the vertically and horizontally polarized waves in the cell coordinate system $(\bar{a}_x, \bar{a}_y, \bar{a}_z)$ to vertically and horizontally polarized waves in the local coordinate system that conforms with the rough surface, $\bar{n}_1, \bar{n}_2, \bar{n}_3$ (12). Similarly, the matrix T^f transforms the vertically and horizontally polarized waves in the local coordinate system back into vertically and horizontally polarized waves in the cell coordinate system (Bahar, 1981a).

To account for the arbitrary orientation of the cell, the matrix D in (21) must be post-multiplied by T_F^i and pre-multiplied by T_F^f. Thus the elements of the matrix D in (8) must be replaced by the elements of the matrix D_F where

$$D_F = T_F^f\, D\, T_F^i \quad . \tag{23}$$

Furthermore, in view of the effective filtering by the SAR of the very large scale spectral components of the rough surface $f(x',z') = 0$, the spectral density function for the rough surface $f_F(x,y) = 0$ associated with the resolution cell F is given by

$$W_F(v_{\bar{x}}, v_{\bar{z}}) = \begin{cases} W(v_{\bar{x}}, v_{\bar{z}}) & , \quad k \geq k_s \\ 0 & , \quad k < k_s \end{cases} . \tag{24}$$

where $W(v_{\bar{x}}, v_{\bar{z}})$ is the spectral density function for the surface S, $f(x',z') = 0$. The wavenumber k_s is

$$k_s = 2\pi/L_s < k_d \tag{25}$$

where L_s is the width of the area of the cell illuminated by the SAR. The very large scale surface consisting of the spectral components $0 < k < k_s$ are responsible for tilting the resolution cell with respect to the mean sea surface.

Thus on replacing the spectral density function W (2a) for the surface S by the spectral density function W_F for the cell F (24) and on replacing the elements D^{PQ} of the matrix D by the elements D_F^{PQ} of the matrix D_F (23) the expression (3) can be used to determine the normalized backscatter cross section for an arbitrarily oriented cell F. In view of (19) and (20) the expressions for these backscatter cross sections are explicit functions of the tilt angles Ω and τ. For the special

case $\tau = 0$ (tilt is in the plane of incidence) the matrices T_F^i and T_F^f reduce to identity matrices and

$$\cos\theta_o = \cos(\theta_o' + \Omega) \ . \tag{26}$$

Thus for $\tau = 0$

$$\left.\frac{\partial\theta_o}{\partial\Omega}\right|_{\theta_o'=\text{const}} = \left.\frac{\partial\theta_o}{\partial\theta_o'}\right|_{\Omega=\text{const}} \tag{27}$$

and

$$(\partial\langle\sigma^{PQ}\rangle/\partial\Omega)_{\theta_o'=\text{const}} = (\partial\langle\sigma^{PQ}\rangle/\partial\theta_o')_{\Omega=\text{const}} \ . \tag{28}$$

Therefore to obtain $\partial\langle\sigma^{PQ}\rangle/\partial\Omega$ for $\Omega = 0$ and $\tau = 0$ it is sufficient to evaluate $\langle\sigma^{PQ}\rangle$ as a function of θ_o' with both Ω and τ set equal to zero. The value for $\partial\langle\sigma^{PQ}\rangle/\partial\tau$ can either be evaluated analytically since D_F^{PQ} (23) is an analytic function of τ, or the derivative could be evaluated numerically.

4. ILLUSTRATIVE EXAMPLES

For the illustrative examples presented in this section, the following specific form of the surface height spectral density function is selected (Brown, 1978)

$$W(v_{\bar{x}},v_{\bar{z}}) = \frac{2}{\pi}\, S(v_{\bar{x}},v_{\bar{z}}) = \begin{cases} (\frac{2}{\pi})Bk^4/(\kappa^2+k^2)^4 & k \le k_c \\ 0 & k > k_c \end{cases} \tag{29}$$

where W is the notation used by Rice (1951) and S is the notation used by Brown (1978). For the assumed isotropic model of the sea surface

$$\left.\begin{aligned} &B = 0.0046 \\ &k^2 = v_{\bar{x}}^2 + v_{\bar{z}}^2 \ (\text{cm})^{-2} \quad , \quad k_c = 12 \ (\text{cm})^{-1} \\ &\kappa = (335.2\ V^4)^{-1/2} \ (\text{cm})^{-1} \quad , \quad V = 4.3 \ (\text{m/s}) \end{aligned}\right\} \tag{30}$$

in which k_c is the spectral cutoff wavenumber (Brown 1978) and V is the surface wind speed. The wavelength for the electromagnetic wave is

$$\lambda_o = 3.0 \text{ cm } (k_o = 2\pi/3 \ (\text{cm})^{-1}) \ . \tag{31}$$

The relative complex dielectric coefficient for the sea is

$$\varepsilon_r = 48 - i35 \tag{32}$$

and the permeability for the sea is the same as for free space ($\mu_r = 1$).

The mean square height for the small scale surface h_s is given by

$$\langle\bar{h}_s^2\rangle \simeq \int_o^{2\pi}\int_{k_d}^{k_c} \frac{W(k)}{4}\, k dk d\phi = \frac{B}{2}\left[\frac{1}{k_d^2} - \frac{1}{k_c^2}\right] \ . \tag{33}$$

The mean square slope for the large scale surface h_ℓ within the resolution cell, is

$$\sigma_{\ell s}^2 = \langle h_{\ell s}^2\rangle = \int_o^{2\pi}\int_{k_s}^{k_d} \frac{W(k)}{4}\, k^3 dk d\phi \tag{34}$$

in which k_s is given by (25). The mean square height for the large scale surface h_ℓ is

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$$\langle h_\ell^2 \rangle = \int_0^{2\pi} \int_{k_s}^{k_d} \frac{W(k)}{4} \, k dk d\phi \tag{35}$$

For $\beta = 4k_o^2 \langle \bar{h}_s^2 \rangle = 1.0$, $k_d = 0.201$. For $L_s = 300$, 1000 and 2500 cm (25)

$$\sigma_{\ell s}^2 = 0.0102, \ 0.0143 \text{ and } 0.0152 \text{ respectively}$$

and

$k_o^2 \langle h_\ell^2 \rangle = 21.9$, 173 and 357 respectively. The slope probability density function within a resolution cell is assumed to be Gaussian; thus

$$p(h_x, h_z) = \frac{1}{\pi \sigma_{\ell s}^2} \exp \left| - \frac{h_x^2 + h_z^2}{\sigma_{\ell s}^2} \right| \tag{36}$$

and the physical optics (specular point) backscatter cross section is (8) (Bahar, 1981a)

$$\langle \sigma_\infty^{PQ} \rangle_B = \delta_{PQ} \frac{\sec^4 \theta_o}{\sigma_{\ell s}^2} \exp \left(- \frac{\tan^2 \theta_o}{\sigma_{\ell s}^2} \right) |R_P|^2 \tag{37}$$

in which δ_{PQ} is the Kronecker delta and $R_P(P=V,H)$ is the Fresnel reflection coefficient for the vertically or horizontally polarized waves (Bahar, 1981a,b).

In Fig. 1a, and b $\langle \sigma^{VV} \rangle$, and $-(d\langle \sigma^{VV} \rangle / d\Omega) / \langle \sigma^{VV} \rangle$ are plotted for $\Omega = 0$ and $\tau = 0$ as functions of θ_o' the angle of incidence with respect to the fixed reference system (x', y', z'). In these figures $L_S = 300$, 1000 and 2500 cm.

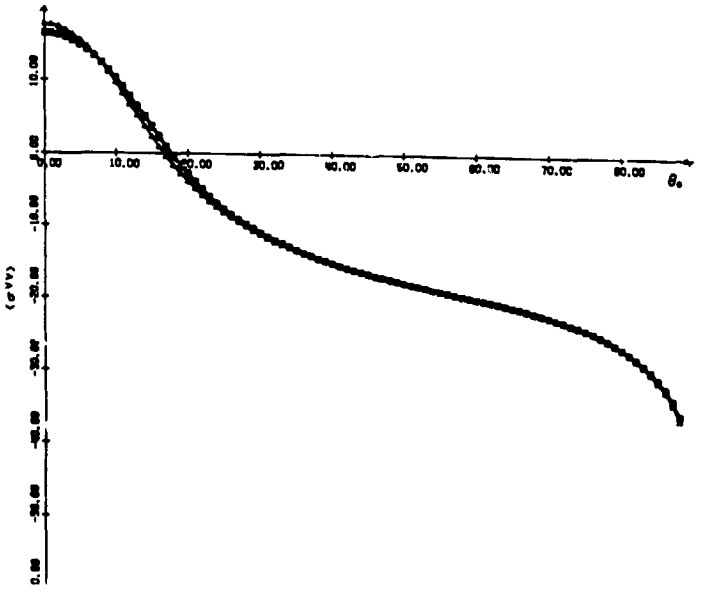

Figure 1a. $\langle \sigma^{VV} \rangle$, for $\Omega = 0$ and $\tau = 0$ as a function of θ_o'. (Δ) $L_s = 300$ cm, (○) $L_s = 1000$ cm, (□) $L_s = 2500$ cm.

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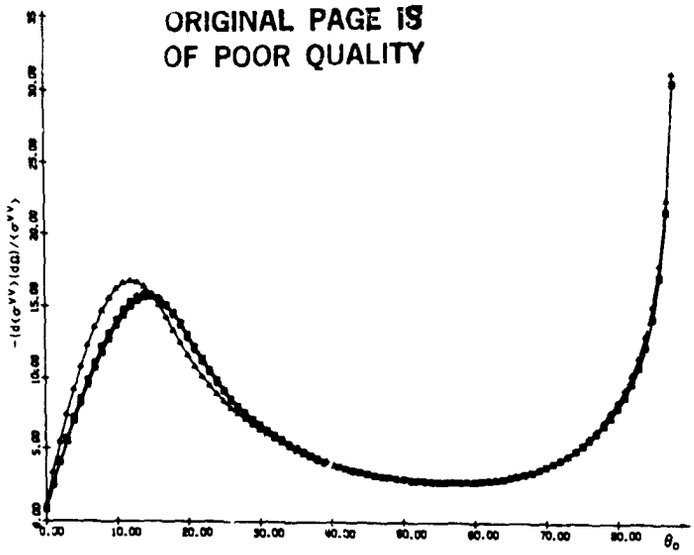

Figure 1b. $-(d\langle\sigma^{VV}\rangle/d\Omega)/\langle\sigma^{VV}\rangle$ for $\Omega = 0$ and $\tau = 0$ as a function of θ_o'. (Δ) $L_s = 300$ cm, (○) $L_s = 1000$ cm, (□) $L_s = 2500$ cm.

In Fig. 2a, and b these results are repeated for $\langle\sigma^{HH}\rangle$. It is interesting to note that the effective filtering of the very large scale spectral components of the rough surface ($0 < k < k_s$) by the SAR does not significantly change the value of σ^{PQ} unless $L_s < 300$ cm. As one may expect, the modulation of the scattering cross sections in the plane of incidence $|d\langle\sigma^{VV}\rangle/d\Omega|$ is strongest for the SAR corresponding to the narrowest effective beam width $L_s = 300$ cm. Except for near-normal incidence the relative modulation $|d\langle\sigma^{PQ}\rangle/d\Omega|/\langle\sigma^{PQ}\rangle$ is larger for the horizontally polarized waves than for the vertically polarized waves. The largest relative modulation of the like polarized cross sections occurs in the transition region where the contribution to the cross section due to Bragg scatter becomes larger than the contribution due to specular point scatter namely at about 10°-15° (see Figs. 1b and 2b).

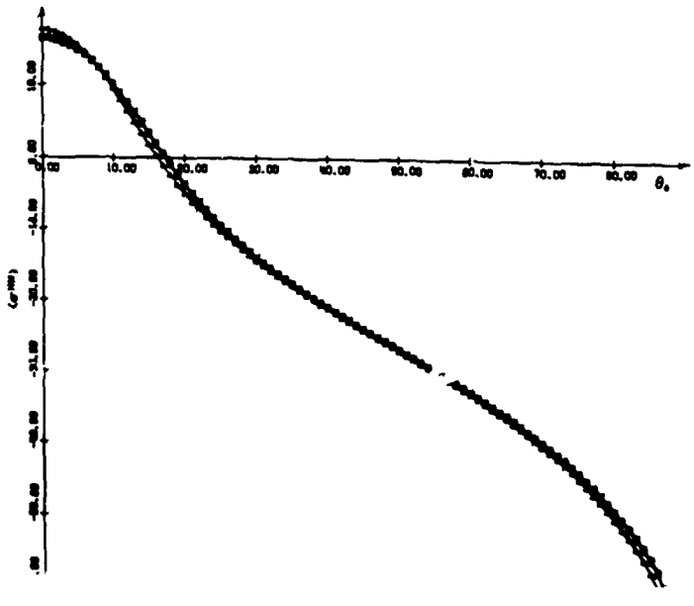

Figure 2a. $\langle\sigma^{HH}\rangle$, for $\Omega = 0$ and $\tau = 0$ as a function of θ_o'. (Δ) $L_s = 300$ cm, (○) $L_s = 1000$ cm, (□) $L_s = 2500$ cm.

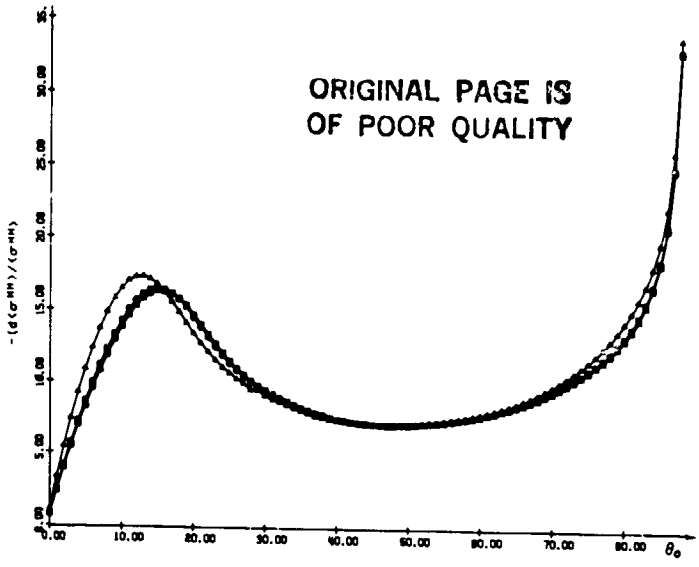

Figure 2b. $-(\langle\sigma^{HH}\rangle/d\Omega)/\langle\sigma^{HH}\rangle$ for $\Omega = 0$ and $\tau = 0$ as a function of θ_o'. (Δ) $L_s = 300$ cm, (○) $L_s = 1000$ cm, (□) $L_s = 2500$ cm.

5. CONCLUDING REMARKS

The full wave approach is used to determine the scattering cross sections for arbitrarily oriented resolution cells on random rough surfaces illuminated by synthetic aperture radars. The purpose of this analysis is to determine the modulation of the like polarized scattering cross sections as the normal to the cells tilt in and perpendicular to the plane of incidence. The full wave approach accounts for shadowing and both specular point scattering as well as Bragg scattering in a self-consistent manner. Thus, the scattering cross sections are expressed as weighted sums of two cross sections. The first cross section is associated with the filtered surface consisting of the large-scale spectral components of the rough surface. The second cross section is associated with the surface consisting of the small-scale spectral components. It can be shown that if the large-scale spectral components of the surface of the cell are neglected, the second cross section accounts for first order Bragg scattering and the results are in agreement with earlier published results (Alpers et al., 1981). However, for typical terrain or sea surfaces, the large-scale spectral components are not negligible.

By using the full wave analysis, the modulation of the like and cross polarized cross sections can be determined for all angles of incidence and tilt angles. On the other hand, first order Bragg scatter theory does not account for backscattering near normal to the surface of the cell (Alpers et al., 1981). The results based on the two-scale model indicate that the relative modulation of the like polarized backscatter cross section is maximum for angles of incidence between 10° and 15° (depending on polarization and effective width of the resolution cell, L_s). The analyses based on first order Bragg scatter do not provide these results. It is also shown that as the angle of incidence approaches zero, the modulation of the scattering cross sections in and perpendicular to the plane of incidence becomes comparable.

When the normal to the cell is tilted in the direction normal to the plane of incidence ($\tau \neq 0$), the full wave analysis not only accounts for the change in the local angle of incidence θ_o^i but also takes into account the fact that the local planes of incidence (or scatter) are not parallel to the reference planes of incidence for scatter), namely $\psi_F^i = -\psi_F^f \neq 0$.

Since Alpers et al. (1981) do not account for the effects of the large scale spectral components of the surface within the resolution cell the results presented here for the modulation of the like polarized scattering cross sections near normal incidence are significantly different from those given by Alpers et al.

6. REFERENCES

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