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A THEORY OF SEA SCATTER AT LARGE INCIDENT ANGLES E 7.6 - 1 0.1 8.3.

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A THEORY OF SEA SCATTER AT LARGE INCIDENT ANGLES

A. K. Fung H. L. Chan

ABSTRACT

A theory for sea scatter at large incident angles ($\theta \ge 30^{\circ}$) is developed using a two-scale roughness model. The assumed small scale waves are to satisfy the small perturbation assumptions and the large scale waves to satisfy the physical optics approximations. Measured sea surface slope density and sea spectra reported by oceanographers are incorporated into the theory to explain effects of incident angle, polarization, frequency, wind speed and anisotropic characteristics of the sea surface.

It is observed that the increase of the backscattering coefficients with the wind is due primarily to the growth of the sea spectrum and, to a lesser extent, to the interaction between the two scales of roughness. This interaction effect is also the cause of the shift of the minimum of the scattering coefficient around the crosswind direction towards the downwind direction. The difference between the upwind and the crosswind observations is the result of the anisotropic characteristics in the sea spectrum, while the difference between the upwind and downwind observations is the consequence of the skewness in the slope probability density function of the large scale waves. Comparison with some experimental data shows satisfactory agreements.



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1.0 INTRODUCTION

It has been generally agreed¹⁻⁵ that the scattering properties of the sea surface can be explained reasonably well in terms of a two-scale roughness model where the small scale waves are assumed to satisfy the small perturbation assumptions while the large scale waves are to satisfy the Kirchhoff approximation. The basic approach is to use the first order result of the small perturbation method to compute the scattering coefficient due to small scale waves and to account for the tilting effect of the large scale waves by averaging this scattering coefficient over the slope distribution of the large scale waves. This averaged scattering coefficient is such that for near grazing incidence the vertically polarized scattering coefficient so computed is always larger than the corresponding horizontally polarized coefficient. Since recent experimental data⁵ indicate that there are cases where the converse is true, it is clear that such a theory may not be applicable near grazing incidence. However, for incident angles between 30° and 80° the theory is expected to be valid.

2.0 THE SCATTER THEORY

Many authors 1, 2, 6 have shown that for a slightly rough surface which satisfies the small perturbation assumption, the backscattering coefficient is given by (Figure 1)

$$\sigma_{\rm Tr} (\Theta, \phi) = 8 \, \kappa^4 \sigma_1^2 | \, \propto {\rm pp} |^2 \, W (\Theta, \phi)$$

(1)

where for horizontal polarization, p=h and

$$x_{hh} = \cos^4 \Theta |R_h|^2$$

 R_h is the Fresnel reflection coefficient for horizontal polarization and for vertical polarization, p = v and

$$V_{vv} = Rv \cos^2 \Theta + (k'^2 - k^2) Tv^2 \sin^2 \Theta / (2k'^2)$$

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where Rv and Tv are the Fresnel reflection and transmission coefficients for vertical polarization. In α_{pp} , k is the wave number in air; k' is the wave number in sea water and θ is the angle of incidence. W(θ , ϕ) is the normalized anisotropic sea spectrum and σ_1^2 is the variance of the small scale sea waves. To include the tilting effect of the large scale waves, it is necessary to average σ_{pp} over the slope distribution (as viewed by the receiver) of the large scale waves. Thus, the incident angle in (1) becomes the local incident angle (denoted by θ^1 in (2)) and the averaged scattering coefficient is (Figure 1)

$$\int_{-\infty}^{\infty} \phi(\Theta, \phi) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \sigma_{pp}(\Theta', \phi) P_{\theta} (Zx', Zy') dZxdZy$$

$$= \int_{-\infty}^{\infty} -\cot \theta$$
(2)

Note that the local incident angle θ' is a function of the incident angle θ and the surface slopes, Zx and Zy. In (2) P_{θ} (Zx¹, Zy¹) is the slope distribution of the large scale waves as viewed at an incident angle θ and is defined in the prime coordinates whose $x^{1} - axis$ is parallel to the wind direction. It is assumed that the plane of incidence is the XZ plane and that the angle between the x - axis and the x' - axis is ϕ so that an upwind observation occurs when $\phi = 0$.

It is important to note that the probability of occurrence of a slope on a given surface varies with the direction of observation. To illustrate this point consider a piece of one-dimensional surface depicted in Figure 2. The probability of occurrence for slope Z_{x_2} when viewed from an angle θ is

$$F_{\theta}(Z_{x_2}) = \frac{\frac{l_2 \hat{n}_2 \hat{a}}{l_1 \hat{n}_1 + l_2 \hat{n}_2 + l_3 \hat{n}_3} \hat{a}}{(l_1 \hat{n}_1 + l_2 \hat{n}_2 + l_3 \hat{n}_3) \hat{a}} \equiv \frac{l_2 \hat{n}_2 \hat{a}}{L_{\theta}}$$

where $\hat{a} = \hat{2}\cos\theta - \hat{2}\sin\theta$ and \hat{n}_i are unit normal vectors to the surface. On the other hand, it becomes

$$(\mathbb{Z} \times_{2}) = \frac{J_{2}\hat{n}_{2} \cdot \hat{z}}{(l_{1}\hat{n}_{1} + l_{2}\hat{n}_{2} \cdot l_{3}\hat{n}_{3}) \cdot \hat{z}} = \frac{J_{2}\hat{n}_{2} \cdot \hat{z}}{L}$$

when viewed from the vertical. Hence,

$$P_{\theta} (Zx_2) = \frac{L}{L_{\theta}} (\cos \theta + Zx_2 \sin \theta) P (Zx_2)$$

Since the total probability must be one, the ratio L/L_{θ} can be determined by this condition. Similarly, for two-dimensional surface, the slope probability density function viewed from an angle θ can be shown to relate to the slope probability density function tion viewed from the vertical as

 $P_{\theta} (Zx^{i}, Zy^{i}) = (I + Zx^{i} \tan \theta) P (Zx^{i}, Zy^{i})$ (3)

Attempts to measure $P(Zx^1, Zy^1)$ for the ocean surface were made by Cox and Munk⁷ and for a slick sea surface (one which excludes small scale waves) it was reported that

$$P(Zx^{i}, Zy^{i}) = \frac{\overline{F}(Zx^{i}, Zy^{i})}{2\pi\sigma_{v}} exp \left[-\frac{Zx^{i}^{2}}{2\sigma_{v}^{2}} - \frac{Zy^{i}^{2}}{2\sigma_{c}^{2}} \right]$$

where

$$F(Zx^{1}, Zy^{1}) = 1 - \frac{C_{21}}{2} \left(\frac{Zy^{12}}{\sigma_{c}^{2}} - 1 \right) \frac{Zx^{1}}{\sigma_{v}} - \frac{C_{03}}{6} \left(\frac{Zx^{13}}{\sigma_{v}^{3}} - \frac{3Zx^{1}}{\sigma_{v}} \right) + \frac{C_{40}}{24} \left(\frac{Zy^{14}}{\sigma_{c}^{4}} - 6 \frac{Zy^{12}}{\sigma_{c}^{2}} + 3 \right) + \frac{C_{22}}{4} \left(\frac{Zy^{12}}{\sigma_{c}^{2}} - 1 \right) \left(\frac{Zx^{12}}{\sigma_{v}^{2}} - 1 \right) + \frac{C_{04}}{24} \left(\frac{Zx^{4}}{\sigma_{v}^{4}} - 6 \frac{Zx^{12}}{\sigma_{v}^{2}} + 3 \right)$$

1.47 3.6 1.67 3.6 3.6 3.8 3.8 3.8 3.6 1.

Each constant in $F(Zx^i, Zy^i)$ was reported by Cox and Munk to lie within a range of values. Further study by other oceanographers may lead to more refined estimates. For the purpose of illustration only one value is chosen for each constant as follows:

 $\sigma_{\rm u}^2 = 0.007 + 0.78 \times 10^{-3} \text{U}$ $\sigma_{\rm c}^2 = 0.005 + 0.84 \times 10^{-3} \text{U}$ $C_{21} = 0$ Co₃=-0,05 $C_{22} = 0.1$ C40=0.36 C04=0.26

In the expressions for σ_u^2 and σ_c^2 , U is the wind speed in meter per second at an altitude of 41 feet above the sea horizon. The relations between the surface slopes in the primed and unprimed coordinates are as follows (see Figure 1):

 $Zx^{i} = Zx \cos \phi + Zy \sin \phi$ $Zy^{i} = Zy \cos \phi - Zx \sin \phi$

3.0 THE SEA SPECTRUM

The spectrum for the small scale waves to be used in this paper is a modification of Pierson and Stacy's sea spectrum⁸. The major change proposed by Pierson⁹ is that their spectrum expression for the capillary region has been replaced by the one reported by Mitsuyasu and Honda¹⁰. The important characteristics to be noted in this spectral model are (1) the spectrum grows with the wind; (2) in the capillary region the larger the K number the faster is the growth; and (3) this model is valid to about 38 knots⁸. In accordance with Mitsuyasu and Honda, their model can be valid to friction velocity as high as 33m/sec at 10 meters above the sea horizon. Thus, the theory may be valid to higher wind speed than the 38 knots when operating frequency is such that only their portion of the sea spectrum is the significant contributor. Also, it should be noted that the definition of $W(\theta, \phi)$ in (4) is not the same as the one used by Pierson and Stacy In that $W(\theta, \beta)$ is defined for all β between 0 and 2π . If Pierson and Stacy's sea spectrum is extended to cover the same angular range, it can be shown that the complete expression of the modified directional sea spectrum is as follows:

$$\sigma_1^2 W(K, \phi) = S(K) (1 + a_{\phi} \cos 2\phi) / K$$
 (4)

where higher order terms in ϕ has been ignored; a_{0} is the only unknown parameter not yet specified; and where

$$S(K) = S_{i}(K), \quad K_{i-1} < K < K_{i}$$

$$S_{1}(K) = \frac{\alpha}{K^{3}} \exp \left[-\frac{0.74g^{2}}{K^{2}U(U_{*})^{4}}\right], \quad 0 < K < K_{1} = \frac{K_{2}U_{*}^{2}m}{U_{*}^{2}}$$

$$S_{2}(K) = \alpha K_{1}^{-1/2} K^{-5/2}, \quad K_{1} < K < K_{2} = 0.359$$

$$S_{3}(K) = S_{4}(K_{3}) (K/K_{3},^{q}, K_{2} < K < K_{3} = 0.942$$

$$S_{4}(K) = 0.875 (2\pi)^{p_{1}-1} \frac{g + 3gK^{2}/13.1769}{(gK + gK^{3}/13.1769)^{(p_{1}+1/2)}} \quad K_{3} < K < K_{4}$$

$$S_{5}(K) = 1.473 \times 10^{-4} U_{*}^{3} K_{m}^{6} K^{-9}, \quad K_{4} < K < \infty$$

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 K_A can be found numerically by settings S_A (K_A) equal to S_5 (K_A).

$$U_{*} = \text{friction velocity, } U_{*} > U_{*m}$$

$$K_{m} = (13, 1769)^{1/2}$$

$$q = \left[\log_{10} S_{2}(K_{2}) / S_{4}(K_{2}) / \log_{10}(K_{2}/K_{3}) \right]$$

$$P_{1} = 5.0 - \log_{10} U_{*}$$

$$z_{o} = 0.684 / U_{*} + 4.28 \times 10^{-5} U_{*}^{2} - 4.43 \times 10^{-2}$$

$$U(U_{*}) = (U_{*}/0.4) \ln (z/z_{o}) \text{ cm/sec}$$

$$a = 4.05 \times 10^{-3}$$

$$g = 980 \text{ cm/sec}^{2}$$

$$U_{*m} = 12 \text{ cm/sec}$$

4.0 THEORETICAL RESULTS AND COMPARISON WITH EXPERIMENTAL DATA

Upon combining (1) (3) and (4) and substituting into (2), we obtain for the backscattered case

$$\sigma_{pp}^{\circ} (\theta, \phi) = \int_{-\infty}^{0} \frac{4K |\alpha pp|^2}{4K |\alpha pp|^2} \left[\frac{(1 + \alpha_0 \cos 2\phi)}{\sin \theta} \right]$$

S(2k sin 0') (1 + Zx' tan θ) p (Zx', Zy') dZxdZy

In (5) the unknown constant a_0 can be estimated by plotting σ^0 versus $\not{\sigma}$ curves and comparing these curves with experimental data. In all Figures 3-8 wind speeds are computed at 19.5 m above the sea horizon. In Figure 3 and 4 σ^0 versus $\not{\sigma}$ curves are plotted for two different wind speeds at $\theta = 30^\circ$ and $\theta = 60^\circ$ and for various choices of a_0 . At $\theta = 30^\circ$ only vertically polarized curves are shown since the difference in σ° due to polarization is small. At 60° the difference in σ° becomes significant and hence σ for both polarizations are shown. The data points in Figure 3 and 4 were obtained from reference 11.

In Figure 4a, the data indicated by circles were taken for σ between 0° and 180° and the squares denote data for σ between 180° and 360°. The square-data were folded back under symmetry assumptions to compare with the circle data. It follows from 3a and 4a that $a_{\sigma} \approx 0.3$ at 12 knots and $a_{\sigma} \approx 0.40$ at 30 knots. It is also noted from these curves that two local maxima occur around the upwind and the downwind directions and a local minimum occurs near the crosswind direction. In addition, the location of σ° minimum tends to shift towards the downwind direction as wind speed or incident angle increases. This effect is most significant for horizontal polarization. The fact that σ° upwind is larger than σ° downwind is due to the skew-ness in the slope density function, $P_{\Theta}(Zx^{1}, Zy^{1})$.

In Figure 4b and 4c σ° versus $\not{\sigma}$ curves using only the first order small perturbation theory are also plotted. Results correspond to the case when there is no tilting effect due to large scale waves. Comparison between these curves and those obtained by using (5) indicates that the use only of the first order small perturbation theory fails to account for (1) the difference between the upwind and the downwind scattering coefficients (ii) the possible shift of the minimum of σ° towards downwind and (iii) the true σ° values around the crosswind direction which are higher due to the interaction between the two scales of roughness.

With a_0 chosen to be 0.3, 0.4 and 0.50 at wind speeds at 6.2, 12.6 and 18 m/sec respectively, σ^0 versus wind speed curves are computed for two different frequencies, polarizations and incident angles as shown in Figure 5 through Figure 8. In general, upwind scattering coefficient, σ_0^0 , is found to increase faster with wind speed than the downwind coefficient, σ_D^0 , which in turn increases faster than the crosswind coefficient, σ_C^0 . All three scattering coefficients are found to increase faster with the wind speed as either the incident frequency or the incident angle increases. The rate of increase of the scattering coefficients with wind speed is larger for horizontal polarization than for vertical polarization. For incident angles beyond 60° the level differences between these coefficients also increases with wind speed. When the theoretical σ^0 versus wind speed result is fitted over the wind speed range from 12.5 knots to 25.4 knots by the equation $\sigma^0 = AU$ where A is a constant; U is wind speed and γ is the wind speed power coefficient, a table for γ can be constructed for different frequencies, directions, polarizations, and incident angles. Such a table for two different frequencies is given below.

		THEORETICAL y						
	· · · · · · · · · · · · · · · · · · ·	8,9 GHz INCIDENT ANGLES			13.9 GHz INCIDENT ANGLES			
DIRECTION	POLARIZATION							
		40°	50 ⁰	60 ⁰	40°	50 ⁰	60 ⁰	
Ų	W S	1.40	1.48	1.55	1,63	1.80	1.81	
D in the second		1.38	1.45	1,49	1.6	1.75	1,75	
C		1.07	1.16	1.2	1.3	1.3	1,45	
U	НН	1.47	1.62	1.73	1.70	1,93	2.01	
D		1.42	1.51	1.56	1.65	1.82	1.83	
Ç		1.11	1.26	1.36	1.34	1,43	1,64	

To see that the wind dependence predicted from the present theory is in general agreement with experimental data, a table showing the γ values reported by Jones, et al., ¹¹ and Moore, R. K., et al ¹² is reproduced below. Comparison between these tables shows that general agreement is, indeed, obtained for the 13.9 GHz data.

		2						
	POLARIZATION	NRL (0.9 GHz)		AAFE (13.9 GH2) INCID. NI ANGLE		SKYLAB 5-193 (13,9 GHz) INCIDENT ANGLE		
DIRECTION								
•	n da an seo an seo An seo an seo An seo an se	40°	50 ⁰	46.4	50°	40°	°02	
Ų	₩.	0.65	0,73	1.77	1.65	1.28	1,82	
ant po D i de la se		0.80	0.80	1.62	1,55		li internet de	
C				1.52	1.51			
U	ЯН	0.87	1.03	1,93	1.93	1.63	2,11	
D (1997)		1.04.	1,30	1.97	1,96			
C				1,46	1,48			

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5.0 CONCLUSION

A growing sea spectrum^{9,10} and a two-scale roughness model¹⁻⁵ recommended by many investigators for studying radar sea scatter have been extended to include anisotropic characteristics of the sea surface. From such a theory, the following observations may be made:

- In the o^o versus ø'curves the local minimum occurs around the crosswind direction and tends to shift towards the downwind side as the incident angle increases. This is particularly true for horizontal polarization.
- (2) Stronger wind dependence occurs at larger incident angles and higher frequencies.
- (3) The wind dependence of σ° upwind is stronger than σ° downwind which in turn is stronger than σ° crosswind.

(4) Major factors contributing to anisotropy are the anisotropic sea spectrum and the nonzero mean slope in the large-scale-wave slope density function defined with respect to the plane perpendicular to the look direction.

 $\sum_{i=1}^{n} (1+i) \sum_{i=1}^{n} (1+i) \sum_{i=1}^{n$

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