slower cutoff of the total second-order spectrum. The contribution from the third part σ_{S3} is effective only at a few isolated Doppler frequencies.

It may be mentioned here that the above plots are based on the assumption that the sea is fully developed in the scattering region including the region surrounding the radar. In case the radar is located on the beach or near the shore, the second part may not be wholly present. Also, the third part may be neglected. Thus the second-order cross section reduces to the first part only. On the other hand, when the radar is based on a ship or on an offshore platform, σ_{S2} may be quite effective. The peaks at $\pm 2\omega_B$ have been observed in the Doppler spectra measured by Barrick [10] with an offshore platform-based radar. Hence, in such a condition, σ_{S2} may modify the second-order cross section predicted by σ_{S1} alone.

IV. Conclusions

An alternative analysis of HF scattering from a rough surface using a dipole source is presented. The technique clearly provides the solution for the scattered electric field in the form of various ground waves (depending upon the order of scattering) with modified surface impedances. The results are applied to a model of the ocean surface. Based on the model, predictions are made of backscattered radar cross section of the ocean surface for a narrow-beam receiving antenna. The second-order cross section contains new results in addition to those derived by other investigators. These additional results may be very significant when the radar is completely surrounded by ocean. Some of the new results of this analysis have been verified experimentally.

References

[1] S. O. Rice, "Reflection of electromagnetic waves from slightly rough surfaces," in *Theory of Electromagnetic Waves,* M. Kline, Ed. New York: Interscience, 1951, pp. 351-378.

[2] R. K. Rosich and J. R. Wait, "A general perturbation solution for reflection from two dimensional periodic surfaces," *Radio Sci.,* vol. 12, pp. 719-729, Sept.-Oct. 1977.

[3] D. E. Barrick, "Remote sensing of sea state by radar," in *Remote Sensing of the Troposphere,* V. E. Derr, Ed. Washington, DC: U.S. Govt. Printing, 1972, ch. 12.

[4] ——, "The ocean waveheight nondirectional spectrum from inversion of the HF sea echo Doppler spectrum," *Remote Sens. Environ.,* vol. 6, pp. 201-227, 1977.

[5] J. Walsh, "On the theory of electromagnetic propogation across a rough surface and calculations in the VHF region," Memorial Univ. of Newfoundland, St. John's, Nfld., Canada, O.E.I.C. Tech. Rep. N00232 (available from Ocean Engineering Information Centre, Memorial University of Newfoundland, St. John's, Nfld., A1B 3X5, Canada), 1980.

[6] S. K. Srivastava, "Scattering of high-frequency electromagnetic waves from an ocean surface: An alternative approach incorporating a dipole source," Memorial Univ. of Newfoundland, St. John's, Nfld., Canada, Ph.D. dissertation (available from Canadian theses on microform service, National Library of Canada, 395 Wellington Street, Ottawa, Ont., K1A 0N4, Canada), 1984.

[7] J. R. Wait, *Electromagnetic Waves in Stratified Media.* New York: Pergamon, 1970, ch. 2.

[8] D. D. Crombie, "Doppler spectrum of sea echo at 13.56 M c/s," *Nature,* vol. 175, pp. 681-682, Apr. 16, 1955.

[9] B. L. Weber and D. E. Barrick, "On the nonlinear theory for gravity waves on the ocean's surface, Part I: Derivations," *J. Phys. Oceanogr.,* vol. 7, pp. 3-10, Jan. 1977.

[10] D. E. Barrick, Ocean Surface Research, Boulder, CO, private communication, 1984.

Satish K. Srivastava received the B.Sc.Eng. degree in electronics from the Banaras Hindu University, India, in 1972 and the M.Eng. degree in electrical engineering from the Memorial University of Newfoundland, St. John's, Canada in 1977. He received the Ph.D. degree also from the Memorial University of Newfoundland in 1984 on the subject of electromagnetic scatter from the ocean surface. His Ph.D. thesis received the Dean of Graduate Studies award for thesis excellence.

Until 1975 and from 1977 to 1979 he was employed with All India Radio, India as a Radio Engineer. Subsequently he served as a Lecturer in the Department of Electronics Engineering at Banaras Hindu University. He is presently working as a Research Fellow in the radar group of the Faculty of Engineering and Applied Science at Memorial University of Newfoundland. His current work involves ground-wave scatter from rough surfaces and the measurement of the directional ocean wave-height spectrum using ground-wave Doppler radars.

★

John Walsh received the B.Eng. degree in electrical engineering from the Technical University of Nova Scotia, Halifax, Canada in 1968 and the Ph.D. degree from the University of Calgary, Calgary, Alta., Canada in 1971.

He worked as an Assistant Professor in the Electrical Engineering Department at Concordia University, Montreal, Que., Canada from 1971 to 1972. In 1972 he joined the Faculty of Engineering and Applied Science at Memorial University of Newfoundland, St. John's, Canada, where he is presently working as a Professor. His earlier research involved analysis of transmission lines and antenna systems. In 1980 he initiated a group in conjunction with C-CORE for conducting research on the ground-wave radar remote sensing of the ocean surface, sea ice, icebergs, and ships. His major accomplishments include development of analytical techniques for the propagation and scatter from rough surfaces, mixed paths and layered media, and the application of the results in ground-wave radar detection of ocean surface parameters and surface targets. He is author or coauthor of various technical reports and open-literature publications.

A Physical Radar Cross-Section Model for a Wind-Driven Sea with Swell

STEPHEN L. DURDEN AND JOHN F. VESECKY, MEMBER, IEEE

(*Invited Communication*)

Abstract—**A new spectrum model for the ocean surface is proposed. We determine the two unknown parameters in this spectrum by fitting it to radar observations. We find that this spectrum combined with two-scale scattering theory can predict much of the observed dependence of the radar cross section on radar frequency, polarization, angle of incidence, and wind velocity at incidence angles in the 0°-70° range. The spectrum model is combined with a model for swell to examine the effect of swell on the radar cross section. We find that the effect of swell is significant for low radar frequencies (*L* band) and near normal incidence**

Manuscript received February 13, 1985; revised July 11, 1985. This work was supported in part by the Office of Naval Research under an ONR Fellowship and in part by NASA.

The authors are with the Department of Electrical Engineering, STARLAB/SEL, Stanford University, Stanford, CA 94305.

0364-9059/85/1000-0445$01.00 © 1985 IEEE

but can be nearly eliminated by using higher frequencies (K_u band) and large angles of incidence ($\approx 50°$).

I. INTRODUCTION

Over the past two decades considerable effort has been devoted to the understanding of how the radar cross section is related to ocean surface winds. The composite or two-scale model first proposed by Wright [1] and Bass *et al.* [2] in the 1960's describes many aspects of scattering from the ocean surface. This theory has been used in various models [3]–[7] to predict the variation of radar cross section with wind speed and direction. A significant step in this effort was the work of Fung and Lee [8]. Their model can account for variations in cross section with radar frequency, polarization, angle of incidence, and wind velocity. However, their model is restricted to angles of incidence $\geq 20°$ and uses empirically derived slope variances, as opposed to slope variances calculated from their ocean spectrum model.

In this paper we propose a new spectrum model for the wind-driven ocean surface. All surface statistics are derived from the model spectrum rather than outside measurements. Also, we include quasi-specular scattering, so that our calculations are valid over a large range of incidence angles (0°–70°). We compare our model predictions with K_u-, X-, and L-band observations. Finally, we include a model for swell and calculate its effect on the cross section.

II. ROUGH SURFACE SCATTERING

In the two-scale model [1], [2] the ocean surface is divided into a large-scale, gently undulating surface height fluctuation h_l and a small-scale surface height fluctuation h_s. The total height fluctuation (about the mean sea level) is equal to $h_l + h_s$. We assume that the two surfaces are uncorrelated. In this case the surfaces can also be separated in wavenumber space. If the wave-height spectrum for the total surface, defined in [9], is denoted by $\Psi(K)$, the spectrum for the large-scale surface by $\Psi_l(K)$, and the spectrum for the small-scale surface by $\Psi_s(K)$, then we have

$$\Psi(K_x, K_y) = \Psi_l(K_x, K_y) + \Psi_s(K_x, K_y) \tag{1}$$

where

$$\begin{aligned} \Psi_l(K_x, K_y) &= \Psi(K_x, K_y), \qquad K < K_d \\ \Psi_s(K_x, K_y) &= \Psi(K_x, K_y), \qquad K \geq K_d \end{aligned} \tag{2}$$

$K = (K_x^2 + K_y^2)^{1/2}$ and K_d is the transition wavenumber. The spectrum is normalized so that its integral over K space is equal to the height variance.

The normalized radar cross section is defined by $\sigma^0 = \lim_{R\to\infty} 4\pi R^2 \langle E_s^2 \rangle / \Delta S$, where R is the distance to the radar and E_s is the field scattered by a patch of area ΔS when illuminated by an incident field of unit intensity. In the two-scale model the total cross section of the surface is a combination of the cross sections for the large- and small-scale surfaces, as discussed below. The cross section due to the large-scale surface fluctuation is found by the method of physical optics, which requires that the parameter $\kappa \equiv \lambda^2 C_u^2$ be $\ll 1$. Here, λ is the electromagnetic wavelength and C_u^2 is the upwind curvature variance. The upwind direction is chosen because the curvature is a maximum in this direction. Physical optics leads to quasi-specular scattering [10]:

$$\sigma_{QS}(\theta) = \frac{|R(0)|^2}{2S_x S_y} \sec^4 \theta \exp\left(-\tan^2 \theta / 2S_x^2\right) \tag{3}$$

where θ is the angle of incidence, $R(0)$ is the normal incidence reflection coefficient, and S_x and S_y are the slope standard deviations of the large-scale surface in the x and y directions, respectively. The x and y axes lie in the plane of the (mean) ocean surface, with the y axis perpendicular to the plane of incidence.

The small-scale surface cross section is found by perturbation theory. In order that the cross section be well approximated by the first-order (Bragg) term in the perturbation expansion, the parameter $\beta \equiv 4k^2\langle h_s^2 \rangle$ must be $\ll 1$ [11]. Here, k is the electromagnetic wavenumber and $\langle h_s^2 \rangle$ is the small-scale height variance. The cross section of a slightly rough surface tilted by an angle ψ in the x direction and δ in the y direction was derived by Valenzuela [12] and is given by

$$\begin{aligned} \sigma_{\text{Bragg}}(\theta, \psi, \delta) = {} & 16\pi k^4 \cot^4 \theta_i |\alpha(\theta, \psi, \delta)| \\ & \cdot \Psi_s(2k \sin(\theta+\psi),\ 2k \cos(\theta+\psi) \sin \delta) \end{aligned} \tag{4}$$

where θ is the angle of incidence relative to the (x, y) plane, θ_i is the local angle of incidence defined by $\cos \theta_i = \cos(\theta + \psi) \cos \delta$, k is the electromagnetic wavenumber, and α is a complex-valued function of the local angle of incidence, the polarization, and the dielectric constant. The dielectric constant for the ocean may be found in [13].

In the two-scale model the quasi-specular cross section and the Bragg cross section are combined to yield an approximate cross section for the total surface:

$$\begin{aligned} \sigma^0(\theta) = {} & \exp(-\beta)\sigma_{QS}(\theta) \\ & + \int \frac{\sigma_{\text{Bragg}}(\theta, \psi, \delta)}{\cos \psi \cos \delta} p(\tan \psi, \tan \delta) d(\tan \psi) d(\tan \delta) \end{aligned} \tag{5}$$

where $p(\tan \psi, \tan \delta)$ is the slope probability density function for the large-scale surface. This expression has been derived from physical arguments [3]. It can also be derived rigorously from electromagnetic theory and is *identical* to the expression for a composite surface derived by Bahar [14] using his full-wave theory.

There is some controversy concerning the probability density function for the slope of the ocean surface. Cox and Munk [15] find that the slope density is skewed toward the upwind direction. On the other hand, Tang and Shemdin [16] find almost no skewness in the slope density. In this study we take the surface height, slope, and curvature to be Gaussian. The slope density function is

$$p(\tan \psi, \tan \delta) = \frac{1}{2\pi S_x S_y} \exp\left(-\frac{\tan^2 \psi}{2S_x^2} - \frac{\tan^2 \delta}{2S_y^2}\right) \tag{6}$$

where S_x and S_y are the same as in (3). These variances can be found from the ocean spectrum using the following expression:

$$S_p^2 = \int_0^{2\pi} \int_0^{K_d} \Psi(K, \phi) K^3 C(\phi)\, dK\, d\phi \tag{7}$$

where $C(\phi) = \cos^2 \phi$ for S_x^2 and $C(\phi) = \sin^2 \phi$ for S_y^2. In order to account for the upwind/downwind difference observed in the radar cross section, we include a term due to Jones *et al.* [17] for hydrodynamic modulation. The portion of the spectrum contributing to Bragg scattering is multiplied by the factor $(1 + 0.20 s_u / S_u)$, where s_u is the large-scale upwind slope and S_u is the large-scale upwind slope standard deviation. This term models the enhancement of the small-scale spectrum on the downwind face of the large-scale waves.

We have now specified all values needed in (5) to calculate the radar cross section, except for K_d and the wave-height spectrum $\Psi(K, \phi)$. Based on numerical studies reported by Fung [18] and Lentz [19], it appears that the two-scale model will be valid if $\beta < 1$ and $\kappa < 1$. We choose K_d so that both of these conditions are well satisfied. In particular, we choose K_d so that β takes on a maximum value of 0.5. We find that for the spectrum described below, κ remains below 0.002. This method of choosing K_d means that both K_d and the large-scale slope variances will change with the radar frequency, as expected physically. This effect is not included in the model of Fung and Lee [8], since they use empirically derived slope variances. With K_d specified, the only remaining unknown is the wave-height spectrum.

III. Ocean Wave-Height Spectrum

A fully developed ocean may be described by the Pierson–Moskowitz spectrum [8]:

$$\Psi(K, \phi)=\frac{B}{2\pi} K^{-4} \exp\left(-0.74(K_c/K)^2\right)\Phi(\phi) \tag{8}$$

where $B = 0.004$, Φ is an unknown function of the wind direction, and $K_c = g/U_{19.5}^2$. $U_{19.5}$ is the wind speed (in meters per second) measured at 19.5 m above the water surface. For $K \gg K_c$ this spectrum approaches the Phillips [9] K^{-4} equilibrium spectrum. This spectrum is derived by assuming a balance between the wind input and the dissipation due to wave breaking. Then, the spectrum will depend only on the gravitational constant g, the ocean wavenumber K, and the friction velocity u_*, which is defined as the square root of the ratio of surface stress to air density. Dimensional considerations require the spectrum to be of the following form:

$$\Psi(K, \phi)=K^{-4}f(\phi, Ku_*^2/g) \tag{9}$$

where f is an unknown function. If $Ku_*^2/g \ll 1$, this form reduces to the Phillips spectrum. However, if this condition is not satisfied, the spectrum will depend on the friction velocity, and thus on the surface wind speed. Physically, this corresponds to a growing surface wind drift layer. Banner and Phillips [20] have shown that this wind drift layer can significantly reduce the height at which a wave will break. Thus when $Ku_*^2/g \ll 1$ is not satisfied the form of the spectrum must be different from the K^{-4} dependence. Deviation from the Phillips spectrum has been observed in [21]–[23]. To incorporate the effect of the wind drift layer on Ψ, we replace f by a power law and derive the following form for the wave spectrum:

$$\Psi(K, \phi)=\frac{1}{2\pi K} S(K)\Phi(\phi) \tag{10}$$

where

$$S(K)=BK^{-3}(bKu_*^2/g_*)^{r(K)} \tag{11}$$

and $r(K)$ is an unknown exponent which depends on K, b is a constant, and $g_* = g + \gamma K^2$. γ is the ratio of surface tension to water density and has a value of 7.25×10^{-5} m^3/s^2. The use of g_* in the capillary range was first suggested by Mitsuyasu [21]. The exact form of $r(K)$ is not known. However, the frequency variation of wind speed dependence [8], [24] suggests that r may have a logarithmic dependence on K. Hence, we take $r = a \log (K/K_t)$, where K_t is the wavenumber where $Ku_*^2/g \ll 1$ is no longer satisfied. Depending on u_* this condition probably becomes invalid for K between 1 and 10. In lieu of more exact information, we choose $K_t = 2$ m^{-1}.

The other function to be chosen is $\Phi(\phi)$. We follow Fung and Lee [8] and choose

$$\Phi(\phi)=1+c(1-e^{-sK^2}) \cos 2\phi. \tag{12}$$

As in Fung and Lee, we choose c so that the ratio of crosswind to upwind slope variances for the entire spectrum is equal to the Cox and Munk measured value [15]. Thus

$$c=\frac{(1-R)/(1+R)}{(1-D)} \tag{13}$$

where

$$R=\frac{0.003+1.92\times 10^{-3}U_{12.5}}{3.16\times 10^{-3}} \tag{14}$$

and

$$D=\frac{\int_0^\infty K^2S(K) \exp(-sK^2)\, dK}{\int_0^\infty K^2S(K)\, dK}. \tag{15}$$

The constant s is taken to be 1.5×10^{-4} m^2.

The complete wave-height spectrum (in m^4) is given by the following expression:

$$\Psi(K, \phi)=\frac{0.004}{2\pi} K^{-4} \cdot \begin{cases} e^{-0.74(K_c/K)^2}(1+c(1-e^{-sK^2})) \cos 2\phi, & K<2 \\ \left(\dfrac{bKu_*^2}{g^*}\right)^{a \log(K/2)} (1+c(1-e^{-sK^2})) \cos 2\phi, & \\ K\geq 2. \end{cases} \tag{16}$$

We note that all parameters in the model are now known except for a and b. Once these parameters are specified we can calculate the cross section as a function of wind speed. The one remaining piece of information needed is a description of the boundary layer so that we may relate the wind at observation level to the friction velocity. According to Pierson [25]

$$U(z)=(u_*/0.4) \ln (z/Z_0) \text{ m/s} \tag{17}$$

where $Z_0 = 0.00684/u_* + 0.428u_*^2 - 0.000443$ m and z is the height above the ocean surface. This equation allows us to do all calculations with $U_{19.5}$.

IV. Determination of Ocean Spectrum from Observations

We use the spectrum of (16) with (5) and related equations to calculate the radar cross section of the ocean surface. The parameters a and b are determined by fitting the cross-section calculations to RADSCAT 13.9-GHz data for HH polarization looking in the upwind direction [26]. Since the calculated wind-speed dependence is primarily determined by a, we varied a until the mean square error between calculated and observed wind-speed exponents was minimized. The wind-speed exponent ν was determined by fitting the power law $\sigma^0 = \alpha U_{19.5}^{\nu}$ to calculations and observations. We found that $a = 0.225$. We then adjusted b until the mean square error in the cross section was minimized. We found that $b = 1.25$. Thus the final spectrum is given by (16) with $a = 0.225$ and $b = 1.25$. Fig. 1 shows the spectrum for $U_{19.5} = 5$ m/s and for $U_{19.5} = 20$ m/s. At large wavenumbers ($K > 1$ m^{-1}) the slope of the spectrum is a function of the wind speed. This agrees with the findings of Lawner and Moore [27] who measured the ocean spectrum using tower-based radar. Table I compares the large-scale slope variances for $K_d \approx 3$ m^{-1} (chosen for 1.2 GHz) and $K_d \approx 60$ m^{-1} (chosen for 13.9 GHz) with the slope variances measured by Cox and Munk for a slick-covered ocean [15]. The measured values are only slightly larger than the calculated values for $K_d \approx 60$ m^{-1} and about twice as large as

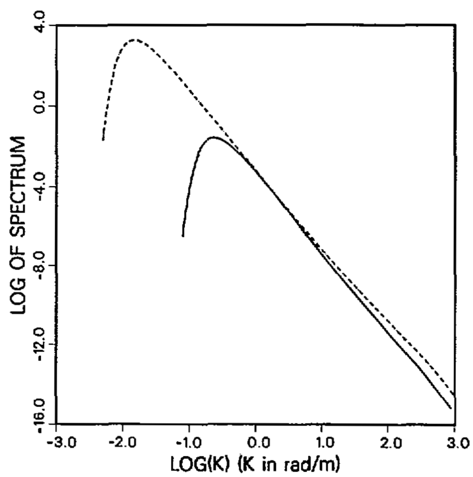


Fig. 1. Log of the wavenumber spectrum $\Psi(K)$ (in m^4) versus log (K) for $U_{19.5} = 5$ m/s (——) and for $U_{19.5} = 20$ m/s (---).

TABLE I
LARGE-SCALE SLOPE VARIANCES ($\times 10^{-2}$)

Source	Wind Speed (m/s) 5	10	15	20
Calculated ($K_d \approx 3\ m^{-1}$)	.8	1.3	1.65	1.88
Calculated ($K_d \approx 60\ m^{-1}$)	1.5	2.2	2.8	3.2
Observed [15]	1.6	2.4	3.1	3.9

those for $K_d \approx 3\ m^{-1}$. It is not known exactly what the cutoff wavenumber was for the Cox and Munk measurements. We assume that surface films damped waves with $K > 10\ m^{-1}$. If this is true, then our calculated variances are somewhat low, but nevertheless similar to their values. Since most of the slope variance comes from the Pierson–Moskowitz portion of the spectrum, the amplitude B cannot be reduced much below its value of 0.004 without causing significant disagreement between calculated and measured slope variances.

Fig. 2 shows the calculated and observed cross sections at 13.9 GHz and 15 m/s as a function of angle of incidence. Only the HH observations were used in determining the spectrum parameters a and b. Both the HH and VV calculated values are within 3 dB of the observed values. We note that the predicted values have a larger polarization difference than the observed values. Fig. 3 shows calculated and observed cross sections at 1.2 GHz and 18 m/s. The observations were taken by the Naval Research Laboratory [28] and are independent of those used in finding a and b. For angles of incidence $\theta \geq 30°$ the HH calculations are within 1 dB of the observations. For this same range of θ the VV values are up to 4 dB greater than the observed values. Thus the predicted polarization ratios are again too high. This phenomenon has also been observed in wave tank experiments [29]. For $\theta < 30°$ the calculated values for both polarizations are up to 10 dB greater than the observed values. Either the observed values near nadir are incorrect or the quasi-specular scattering theory predicts values that are too large.

Table II compares the calculated wind-speed exponent ν with the observed values given in [26]. The HH values were used in finding a. For both HH and VV polarizations the calculated and observed values are in good agreement. The largest difference was 0.4 at 20°. Table III compares observed exponents at L-band [24] with calculated values. These exponents are independent of the data used in finding a and b. We see that the observed and calculated values are reasonably close. Fig. 4 shows the calculated and observed values as a function of wind speed for X band (9.0 GHz) at vertical incidence [5].

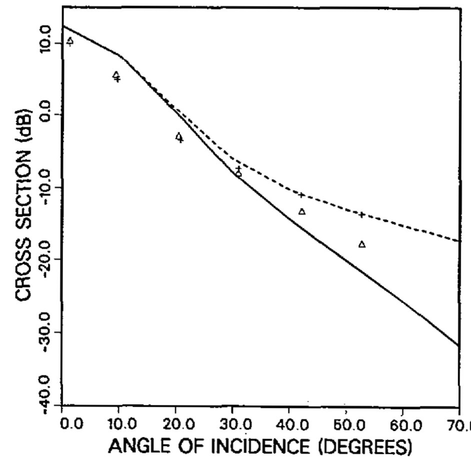


Fig. 2. Variation of the normalized radar cross section (NRCS) with angle of incidence at 13.9 GHz and 15 m/s. (——) Calculated HH polarization. (---) Calculated VV polarization. Values were calculated at 10° increments. The Δ's are observed values for HH polarization, and the +'s are observed values for VV polarization [26].

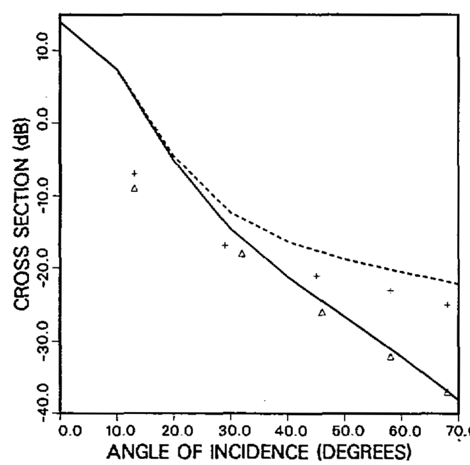


Fig. 3. Same as Fig. 1, except at 1.2 GHz and 18 m/s. Observed values are from [28].

TABLE II
K_u-BAND UPWIND WIND-SPEED EXPONENTS

Source	Angle of Incidence 0^0	10^0	20^0	30^0	40^0	50^0
Calculated HH pol.	-.69	0.15	1.40	1.61	1.69	1.74
Observed HH pol.[26]	-.36	0	1.00	1.65	1.98	1.93
Calculated VV pol.	-.69	0.14	1.36	1.53	1.57	1.60
Observed VV pol.[26]	-.46	0	1.05	1.68	1.77	1.66

TABLE III
L-BAND UPWIND WIND-SPEED EXPONENTS AT $\theta = 30°$

Source	Polarization HH	VV
Calculated	1.20	1.07
NRL-North Atlantic [24]	1.12	1.47
NRL-JOSS I [24]	1.54	0.55

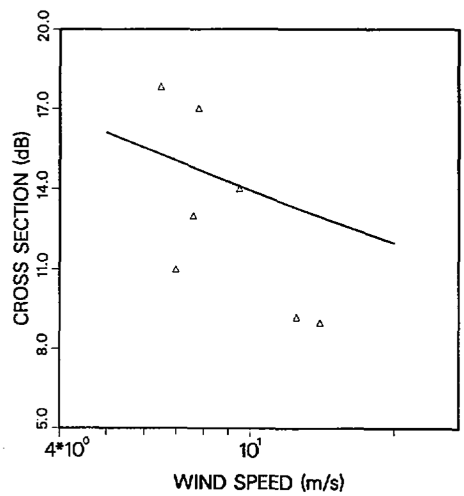


Fig. 4. Variation of NRCS with wind speed at vertical incidence and 9.0 GHz. Δ's are observed values taken from [5].

Because of the scatter in the data, it is difficult to compare the overall wind-speed dependences. However, we see that the level of the observed data is close to the calculated values. We conclude that the new spectrum combined with the two-scale scattering theory can predict (generally, to within a few decibels) the wind-speed dependence of microwave backscatter at a variety of frequencies over the range 0°–70°.

V. Effect of Swell

We use the model to examine the effect of swell on the measured radar cross section. We model the swell as a narrow-band Gaussian process with the following spectrum [30]:

$$\Psi_{\text{swell}}(K_x, K_y)=\frac{\langle h^2\rangle}{2\pi\sigma_{Kx}\sigma_{Ky}} \exp\left\{-\frac{1}{2}\left[\left(\frac{K_x-M_{xm}}{\sigma_{Kx}}\right)^2 + \left(\frac{K_y-K_{ym}}{\sigma_{Ky}}\right)^2\right]\right\} \tag{18}$$

where $\langle h^2\rangle$ is the variance due to swell, K_{xm} and K_{ym} are the wavenumbers of the spectral peak, and σ_{Kx} and σ_{Ky} are the spectrum widths in the x and y directions, respectively. A Gaussian-shaped spectrum was chosen to allow for the fact that real swell is narrow band but not monochromatic. Typical values for swell obtained from synthetic aperture radar images [31] are a wavelength of 300 m and $\sigma_{Kx} = \sigma_{Ky} = 0.0025\ \text{m}^{-1}$. To emphasize the swell effect, we take the rms height to be 4 m, which is a large amplitude swell. We allowed a swell with these parameters to propagate in the radar look direction by adding (18) to (16). Fig. 5 shows the effect on the radar cross section at a frequency of 13.9 GHz. Fig. 6 shows the effect of swell at 1.2 GHz. The maximum effect is at 1.2 GHz and $\theta = 20°$. In this case the swell increases the cross section by approximately 6 dB at 5 m/s and by 3 dB at 20 m/s. This would be significant when attempting to remotely sense surface wind speed using L-band radars such as the SEASAT and the SIR-A and SIR-B synthetic aperture radars. As the frequency or angle of incidence is increased, the effect of swell is decreased, until at 13.9 GHz and 50°, the change in cross section is less than 2 dB at all wind speeds. From our model we conclude that bias in wind measurement may be nearly eliminated by using high frequencies and large angles of incidence.

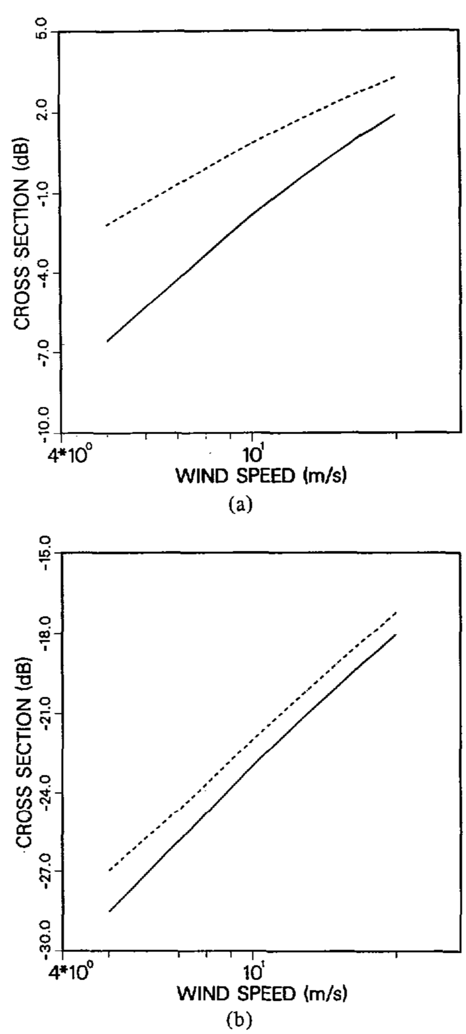


Fig. 5. Variation of NRCS with windspeed when swell is absent (——) and when swell is present (---). Frequency is 13.9 GHZ. HH polarization. Swell height (rms) is 4 m. Swell wavelength is 300 m. (a) Angle of incidence is 20°. (b) Angle of incidence is 50°.

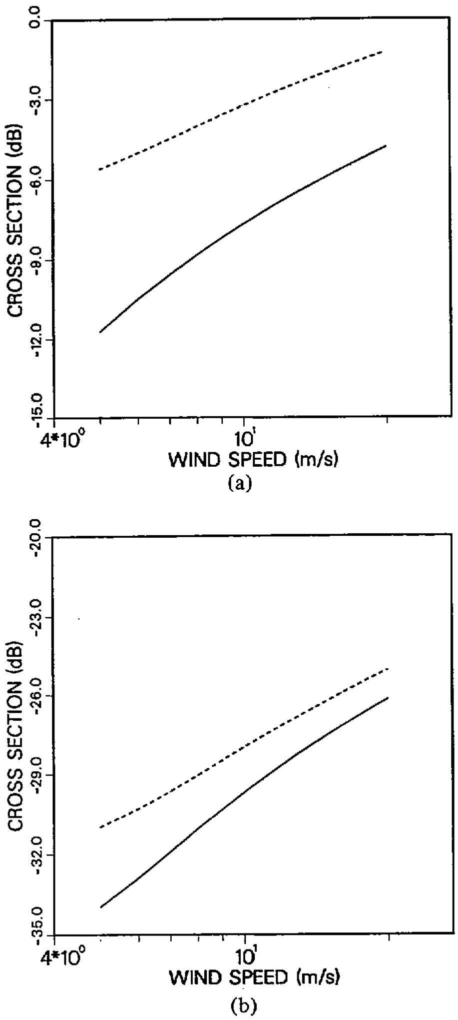


Fig. 6. Variation of NRCS with wind speed when swell is absent (——) and when swell is present (---). Frequency is 1.2 GHz. HH polarization. Swell parameters are identical to those in Fig. 5. (a) Angle of incidence is 20°. (b) Angle of incidence is 50°.

VI. Conclusions

A two-scale scattering model and observations of radar cross section over the ocean under varying wind conditions have been used to infer the free parameters of a simple wind-dependent ocean wave spectrum. The two-scale scattering model combined with this empirical spectrum adequately explains much of the observed dependence of the radar cross section on wind speed, frequency, angle of incidence, and polarization for angles of incidence in the 0°–70° range. We have used this model to examine the effect of swell on wind-speed measurements and have found significant effects at low frequencies (L band) and small angles of incidence. Use of high frequencies (e.g., K_u band) and large angles of incidence nearly eliminates bias in wind-speed measurement due to swell.

Acknowledgment

The authors would like to thank D. Weissman at Hofstra University, H. Dolezalek at ONR, and W. Patzert at NASA for encouragement and guidance during the course of this work.

References

[1] J. W. Wright, "A new model for sea clutter," *IEEE Trans. Antennas Propagat.*, vol. AP-16, pp. 217–223, Mar. 1968.

[2] F. G. Bass, I. M. Fuks, A. I. Kalmykov, I. E. Ostrovsky, and A. D. Rosenberg, "Very high frequency radiowave scattering by a disturbed sea surface," *IEEE Trans. Antennas Propagat.*, vol. AP-16, pp. 554–568, Sept. 1968.

[3] G. R. Valenzuela, M. B. Laing, and J. C. Daley, "Ocean spectra for the high frequency waves as determined from airborne radar measurements," *J. Marine Res.*, vol. 29, no. 2, pp. 69–84, May 1971.

[4] H. L. Chan and A. K. Fung, "A theory of sea scatter at large incident angles," *J. Geophys. Res.*, vol. 82, no. 24, pp. 3439–3444, Aug. 1977.

[5] D. E. Barrick, "Wind dependence of quasispecular microwave sea scatter," *IEEE Trans. Antennas Propagat.*, vol. AP-22, no. 1, pp. 135–136, Jan. 1974.

[6] M. A. Donelan and W. J. Pierson, "Bragg-scattering and equilibrium ranges in wind-generated waves—with application to scatterometry," submitted to *J. Geophys. Res.*, 1985.

[7] G. S. Brown, "Estimation of surface wind speeds using satellite-born radar measurements at normal incidence," *J. Geophys. Res.*, vol. 84, no. B8, pp. 3974–3978, July 1979.

[8] A. K. Fung and K. K. Lee, "A semi-empirical sea-spectrum model for scattering coefficient estimation," *IEEE J. Oceanic Eng.*, vol. OE-7, pp. 166–176, Oct. 1982.

[9] O. M. Phillips, *The Dynamics of the Upper Ocean.* New York: Cambridge Univ. Press, 1977.

[10] D. E. Barrick, "Rough surface scattering based on the specular point theory," *IEEE Trans. Antennas Propagat.*, vol. AP-16, no. 4, pp. 449–454, July 1968.

[11] G. S. Brown, "Backscattering from a Gaussian-distributed perfectly conducting rough surface," *IEEE Trans. Antennas Propagat.*, vol. AP-26, no. 3, pp. 472–482, May 1978.

[12] G. R. Valenzuela, "Scattering of electromagnetic waves from a tilted slightly-rough surface," *Radio Sci.*, vol. 3, no. 11, pp. 1057–1066, Nov. 1968.

[13] L. A. Klein and C. T. Swift, "An improved model for the dielectric constant of sea water at microwave frequencies," *IEEE Trans. Antennas Propagat.*, vol. AP-25, no. 1, pp. 104–111, Jan. 1977.

[14] E. Bahar, "Scattering cross sections for composite random surfaces: full wave analysis," *Radio Sci.*, vol. 16, no. 6, pp. 1327–1335, Nov.–Dec. 1981.

[15] C. Cox and W. Munk, "Statistics of the sea surface derived from sun glitter," *J. Marine Res.*, vol. 13, pp. 198–227, 1954.

[16] S. Tang and O. H. Shemdin, "Measurement of high frequency waves using a wave follower," *J. Geophys. Res.*, vol. 88, no. c14, pp. 9832–9840, Nov. 1983.

[17] W. L. Jones, Frank J. Wentz, and Lyle C. Schroeder, "Algorithm for inferring wind stress from SEASAT-A" *J. Spacecraft and Rockets*, vol. 15, no. 6, pp. 368–374, Nov.–Dec. 1978.

[18] A. K. Fung, "Review of random surface scatter models," in *Applications of Mathematics in Modern Optics, Proc. Conf., SPIE* (San Diego, CA), Aug. 1982.

[19] R. R. Lentz, "A numerical study of electromagnetic scattering from ocean-like surface," *Radio Sci.*, vol. 9, no. 12, pp. 1139–1146, Dec. 1974.

[20] M. L. Banner and O. M. Phillips, "On the incipient breaking of small scale waves," *J. Fluid Mech.*, vol. 65, pp. 647–656, 1974.

[21] H. Mitsuyasu, "Measurements of the high-frequency spectrum of ocean surface waves," *J. Phys. Ocean.*, vol. 7, no. 6, pp. 883–891, Nov. 1977.

[22] K. K. Kahma, "A study of the growth of the wave spectrum with fetch," *J. Phys. Ocean.*, vol. 11, no. 12, pp. 1503–1515, Nov. 1981.

[23] I. A. Leykin and A. D. Rosenberg, "Sea-tower measurements of wind-wave spectra in the Caspian Sea," *J. Phys. Ocean.*, vol. 14, no. 1, pp. 168–176, Jan. 1984.

[24] W. L. Jones and L. C. Schroeder, "Radar backscatter from the ocean: Dependence on surface friction velocity," *Boundary Layer Meteorol.*, vol. 13, pp. 133–149, 1978.

[25] W. J. Pierson, "The theory and applications of ocean wave measuring systems at and below the sea surface, on the land, from aircraft, and from spacecraft," NASA Contractor Rep. CR-2646, N76-17775, 1976.

[26] W. L. Jones, L. C. Schroeder, and J. L. Mitchell, "Aircraft measurements of the microwave scattering signature of the ocean," *IEEE Trans. Antennas Propagat.*, vol. AP-25, no. 1, pp. 52–61, Jan. 1977.

[27] R. T. Lawner and R. K. Moore, "Short gravity and capillary wave spectra from tower-based radar," *IEEE J. Oceanic Eng.*, vol. OE-9, no. 4, pp. 317–324, Dec. 1984.

[28] N. W. Guinard, J. T. Ransone, Jr., and J. C. Daley, "Variation of the

NRCS of the sea with increasing roughness," *J. Geophys. Res.*, vol. 76, no. 6, pp. 1525-1538, 1971.
[29] P. H. Y. Lee, "Laboratory measurements of polarization ratios of wind wave surfaces," *IEEE Trans. Antennas Propagat.*, vol. AP-26, no. 2, pp. 302-306, Mar. 1978.
[30] D. L. Johnstone, "Second-order electromagnetic and hydrodynamic effects in high-frequency radio-wave scattering from the sea," Ph.D. dissertation, Stanford Univ., Stanford, CA, Mar. 1975.
[31] P. L. Jackson and R. A. Shuchman, "High-resolution spectral estimation of synthetic aperture radar ocean wave imagery," *J. Geophys. Res.*, vol. 88, no. c4, pp. 2593-2600, Mar. 1983.

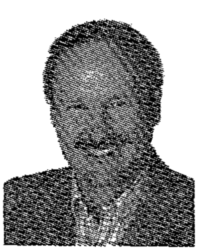
★

Stephen L. Durden was born in Houston, TX, on July 25, 1958. He received the B.S.E.E. degree from Rice University, Houston, TX, in 1980 and the M.S. degree in electrical engineering from Stanford University, Stanford, CA, in 1983.

He currently is an Office of Naval Research Fellow at Stanford University and is a candidate for the Ph.D. degree in electrical engineering. His research interests are in electromagnetic scattering and radar oceanography. He was employed during 1980-1981 by Exxon Production Research Company, Houston, TX, in the area of seismic data acquisition.

Mr. Durden is a member of the American Geophysical Union, Tau Beta Pi, and Phi Beta Kappa.

★



John F. Vesecky (S'61-M'67) received the B.A. and B.S. degrees in electrical engineering from Rice University, Houston, TX, in 1962 and 1963, respectively, and the M.S. and Ph.D. degrees from Stanford University, Stanford, CA, in 1965 and 1967, respectively.

He was a Research Fellow in Astronomy (1967-1969) at Leicester University, U.K., and later taught there in the Astronomy Department (1971-1976) specializing in radio, radar, and X-ray observations of the sun and planets. He did research in radio wave propagation at the Communications and Radiophysics Laboratories at SRI International (1965-1971) and has been with the Electrical Engineering Department of Stanford University in several capacities from 1969-1971 and 1976 to date. He is presently Professor of Electrical Engineering (Research) at Stanford working in radar astronomy and radar remote sensing. His current research interests include radar remote sensing of sea ice, ice sheets, and ocean winds and waves, wave scattering from rough surfaces, and spacecraft-earth radar observations of the solar corona and solar wind.

Field Trials of an Optical Scanner for Studying Sea-Surface Fine Structures

STEPHEN P. HAIMBACH AND JIN WU

(*Invited Communication*)

Abstract—**Field trials of an optical scanner for measuring directional slopes of the sea surface have been carried out at the Research Pier of the Coastal Engineering Research Center (CERC). Preliminary results include upwind-downwind and crosswind components of the mean-square slopes under various wind, swell, and atmospheric stability conditions.**

Manuscript received December 17, 1984; revised June 7, 1985. This work was supported in part by the Physical Oceanography Program, in part by the National Science Foundation under Grant OCE-8214998, and in part by the Mechanics Division, Office of Naval Research under Contract N0014-83-K-0316.

The authors are with the Air-Sea Interaction Laboratory, College of Marine Studies, University of Delaware, Lewes, DE 19958.

I. Introduction

There has been a great deal of interest in determining statistical patterns of fine structures of the sea surface and their variation with wind, swell, and atmospheric stability conditions. Ripples, composing these structures, not only are involved in wind-wave interaction processes [1] but also scatter microwave energy impinging on the sea surface [2]-[4]. Slope distributions of the sea surface have been determined previously from the glitter pattern [5] and with a rather complex optical arrangement [6]. In the present study, a technique, which is much simpler than the former method in data analysis and the latter method in data collection, has been tested. Preliminary results of the mean-square sea-surface slopes also show some interesting trends.

II. Experiment and Data Analysis

A. Instrument

The instrument, shown in Fig. 1(a), consists of essentially a collimated light source and a photomultiplier tube, each directed to a mirror supported on a shaft. The latter was rotated at 2000 rpm during the experiment to direct a laser beam to scan the sea surface from above. The beam, focused on a 1.2-mm-diameter spot at the water surface, was reflected back to the scanner by the surface normal to the beam to produce a light pulse. The angle of the system is adjustable, and the scanning path is illustrated in Fig. 1(b). A time exposure of the laser beam reflected from the water surface is shown in the figure, where the trace of the beam appears black.

The light pulse detected at tilt angle ψ and azimuth ϕ indicates a directional slope with the following components:

$$\theta_{ud} = \tan\psi \cdot \cos\phi$$
$$\theta_c = \tan\psi \cdot \sin\phi \tag{1}$$

where θ is the water-surface slope, and subscripts ud and c indicate, respectively, the upwind-downwind and the crosswind components. From measurements obtained with the scanner set at various tilt angles, relative frequencies of occurrence of various water-surface slopes can be determined. The sensor has been fully tested in a laboratory wind-wave tank [7], [8]; details of its design, signal processing, and data acquisition of the scanner were reported elsewhere [8], [9].

B. Experiments

The experiments were conducted at the Research Pier operated by the Coastal Engineering Research Center (CERC) near Duck, North Carolina. A swing arm was mounted at the end of the pier about 500-m offshore, where the water depth is 8 m [10]. The instrument shown in Fig. 1(a) was supported on the arm extending 4 m beyond the end of the pier, and about 10 m above the mean water level. The experimental conditions [10], [11] are listed in Table I, where U_{19} is the wind velocity measured at 19.5 m above the mean sea surface, H_s is the significant wave height, τ_s are the wave periods, and T_a and T_w are, respectively, the temperatures of air and water. The mean-square slope σ^2 that was measured under these conditions is also listed.

The tests were performed on either Moonless or overcast nights with onshore winds. The choice of night conditions was necessary in order to make certain that the reflected light from the water surface originated from the laser. The onshore wind obviously provided the minimum distortion of wind and wave fields.

0364-9059/85/1000-0451$01.00 © 1985 IEEE