VOL. 78, NO. 33 JOURNAL OF GEOPHYSICAL RESEARCH NOVEMBER 20, 1973

Wind Dependence of Radar Sea Return

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Recently significant progress has been made in modeling sea return by means of a composite surface theory. All of the four-frequency radar sea return data obtained by the Naval Research Laboratory have been incorporated into this theory to provide a more accurate determination of the magnitude of sea return for vertical polarization. A value of the power law for the wave number spectrum of the sea close to that of −3.75 previously found by Kinsman (1965) was determined from the radar data. By means of this spectrum, equations have been developed that model vertically polarized sea return as a function of wind velocity and direction, radar wavelength, and depression angle. A power law dependence of sea return with wind velocity is introduced that is in agreement with the data in many cases.

During the past several years, personnel of the Naval Research Laboratory (NRL) have conducted extensive sea return measurement programs at various locales: Puerto Rico (1965), the North Atlantic (1969), and, as part of the Joint Ocean Surface Study sponsored by the Naval Oceanographic Office, Bermuda (1970, Joss 1) and off the East Coast (1971, Joss 2). The system used was the NRL four-frequency (4FR) system, which is an airborne coherent pulsed radar capable of transmitting and receiving a sequence of four frequencies, X band (8910 MHz), C band (4455 MHz), L band (1228 MHz), and P band (428 MHz), alternately on vertical and horizontal polarization. The components of the return are subsequently labeled XVV, XVH, XHH, XHV, etc., where the first letter identifies the frequency and the following letters denote transmitted and received polarization, respectively. The method of calibrating the system has been described by *Guinard et al.* [1971], and the results of the above programs have been documented by *Daley et al.* [1968, 1970, 1971, 1973]. The data bank so obtained provides comprehensive information on the parametric behavior of the radar cross section of the sea per unit area of the scattering surface, i.e., the normalized radar cross section (NRCS) σ_0 as a function of radar wavelength, polarization, and depression angle for sea conditions ranging from calm to conditions characterized by 24 m/sec winds and 7- to 8-meter wave heights.

In recent years, significant progress has been made in modeling sea return by means of a composite surface consisting of short gravity and capillary waves with lengths comparable to the radar wavelength, superimposed on longer waves. A review of the entire field is not the purpose of this paper; therefore, only work directly applicable will be referenced. The work of *Wright* [1968] has shown that the two-dimensional energy density spectrum of the surface height variations (i.e., the ocean wave height spectrum) is related directly to the vertically polarized NRCS in the microwave region. Using a functional form for a portion of this spectrum derived by *Phillips* [1966], which is defined for a range of frequencies or wave numbers that have attained maximum values (equilibrium range), *Guinard and Daley* [1970] have calculated an upper bound to the NRCS of the sea in agreement with existing measurements. Further work of *Guinard et al.* [1971] incorporating additional data verified the existence of an upper bound or limiting value to the magnitude of sea return and suggested a growth law of the X band NRCS proportional to the square root of the wind velocity for winds greater than 5 m/sec. A later study by *Valenzuela et al.* [1971] related a power law dependence of the NRCS as a function of wind velocity to the form of the ocean wave height spectrum and demonstrated results consistent with the available data in the microwave region.

The purpose of this study is to extend the above work to incorporate all of the data pres-

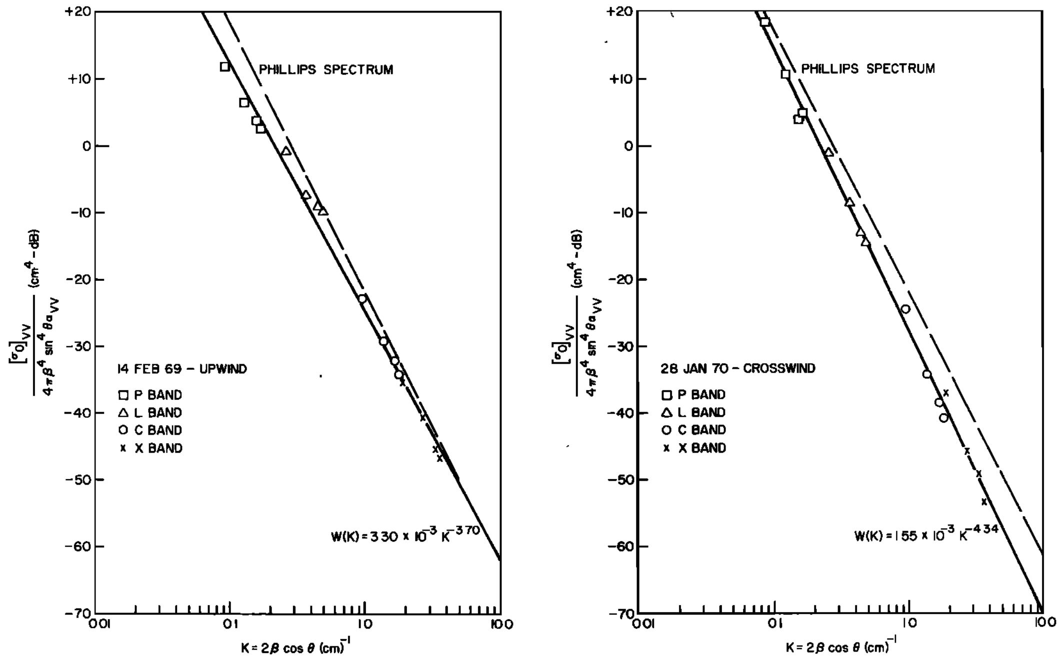

Fig. 1. Ocean spectra calculated from vertical polarization NRCS data.

TABLE 1. Best Fit to the Ocean Spectrum: $W(K) = AK^{-(4\ -\ \nu)}$

Date	Wind Velocity $U_{19.5}$, m/sec	Upwind $A \times 10^{-3}$	Upwind $(4 - \nu)$	Downwind $A \times 10^{-3}$	Downwind $(4 - \nu)$	Crosswind $A \times 10^{-3}$	Crosswind $(4 - \nu)$
North Atlantic							
Feb. 11, 1969	24.2	4.30	3.69	3.15	3.69	1.91	3.61
Feb. 6, 1969	20.6	6.52	3.74	4.98	3.85	2.76	3.86
Feb. 14, 1969	19.8	3.30	3.70	2.52	3.64	1.31	3.65
Feb. 13, 1969	19.1	3.67	3.85	2.54	3.77	1.56	3.88
Feb. 10, 1969	16.2	2.70	3.79	1.95	3.70	1.98	3.70
Feb. 20, 1969	15.0	2.82	3.51	2.33	3.79	1.63	3.85
Feb. 18, 1969	11.4	1.95	3.82	1.53	3.79	0.65	4.26
Average		3.61	3.73 ± .15	2.71	3.75 ± .13	1.69	3.83 ± .14
Joss 1							
Jan. 22, 1970	12.9	4.36	3.65	3.36	3.58	1.57	3.90
Jan. 28, 1970	11.9	6.47	3.79	5.38	3.86	1.55	4.34
Jan. 20, 1970	10.3	1.63	3.66	1.60	3.80	0.72	4.23
Jan. 27, 1970	8.3	2.14	3.65	1.66	3.91	0.83	4.43
Jan. 26, 1970	7.7	3.95	3.59	3.33	3.66	1.75	3.97
Jan. 27, 1970	7.0	1.51	3.82	1.15	4.04	0.41	4.49
Jan. 23, 1970	5.7	2.13	3.76	1.75	3.75	0.89	4.35
Average		3.17	3.70 ± .11	2.60	3.80 ± .13	1.10	4.24 ± .14
Average of North Atlantic and Joss 1		3.39 ± 3.2	3.72 ± 0.1	2.66 ± 2.5	3.77 ± 0.1	1.69 ± 1.2*	3.83 ± 0.14
Puerto Rico							
July 15, 1965	8.3	3.03	4.03	2.99	4.03	2.09	4.55
July 19, 1965	6.5	3.85	4.18	3.03	4.19		
July 22, 1965	5.7	2.09	4.00	1.75	4.17		
Average		2.99	4.07 ± .20	2.59	4.13 ± .20	...	...

Limits of error equal to two standard deviations about the mean.
*North Atlantic only.

ently available into one model and to obtain a consistent set of equations describing the behavior of the NRCS of the sea within the limits of the composite surface model. This will be done by (1) determining from the radar measurements the best estimate of the ocean wave height spectrum in the equilibrium range, (2) using this spectrum to calculate the NRCS as a function of depression angle and radar wavelength, (3) obtaining from a generalized form of this spectrum a theoretical prediction of the power law dependence of the NRCS as a function of wind velocity, and (4) comparing the power law of this spectrum with empirical results.

DETERMINATION OF THE OCEAN SPECTRUM

For a composite surface *Wright* [1968] has demonstrated that the ocean wave height spectrum can be related to the vertically polarized NRCS. This result, which has been obtained by *Barrick and Peake* [1967], *Valenzuela et al.* [1971], and *Wu and Fung* [1972], can be expressed as

$$[\sigma_0]_{vv} = 4\pi\beta^4 \sin^4 \theta\alpha_{vv} W(K_x, K_y) \quad (1)$$

where β is the radar wave number, θ is the depression angle, K_x, K_y are ocean wave numbers in Cartesian coordinates, $W(K_x, K_y)$ is the two-dimensional energy density spectrum of the surface height variations defined as

$$H_{ms} = \frac{1}{4}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} W(K_x, K_y)\, dK_x\, dK_y \quad (2)$$

where H_{ms} is the mean square height, and

$$\alpha_{vv} = \frac{(\epsilon - 1)[\epsilon(\cos^2\theta + 1) - \cos^2\theta]^2}{[\epsilon \sin\theta + (\epsilon - \cos^2\theta)^{1/2}]^2}$$

where ϵ is the complex dielectric constant of the surface with values of 48.3–34.9i (X band), 57.1–36.3i (C band), 73–85i (L band), and 73–165i (P band). The wave tank observations of *Wright* [1966] demonstrated that the effective mechanism in generating radar backscatter was Bragg scattering, namely, the scattering produced by an equally spaced array of point scatterers when the respective path length differences are an integral number of half wavelengths [*Guinard et al.*, 1971]. This leads to the following wave number relationships between the radar and the ocean:

$$K_x = 2\beta\cos\theta \qquad K_y = 0 \quad (3)$$

For a generalized form of the spectrum

$$W(K) = AK^{-(4-\nu)} \quad (4)$$

where $K = (K_x^2 + K_y^2)^{1/2} = 2\beta\cos\theta$, equation 1 may be written as

$$\frac{[\sigma_0]_{vv}}{4\pi\beta^4\sin^4\theta\alpha_{vv}} = AK^{-(4-\nu)} \quad (5)$$

In this form, A is a constant of proportionality with dimensions (cm)$^\nu$, and $[\sigma_0]_{vv}$ is the measured NRCS (mean value), so that A and ν can be determined by standard least squares fit procedures. The applicable NRCS measurements are those in the range of depression angles from 20° to 60° for sea conditions characterized by winds of 5 m/sec or higher. Also, median values of NRCS must be converted to mean values and the NRCS calculated on the basis of a two-way antenna pattern to remain consistent with $[\sigma_0]_{vv}$ defined by *Wright and Keller* [1971] and *Valenzuela et al.* [1971].

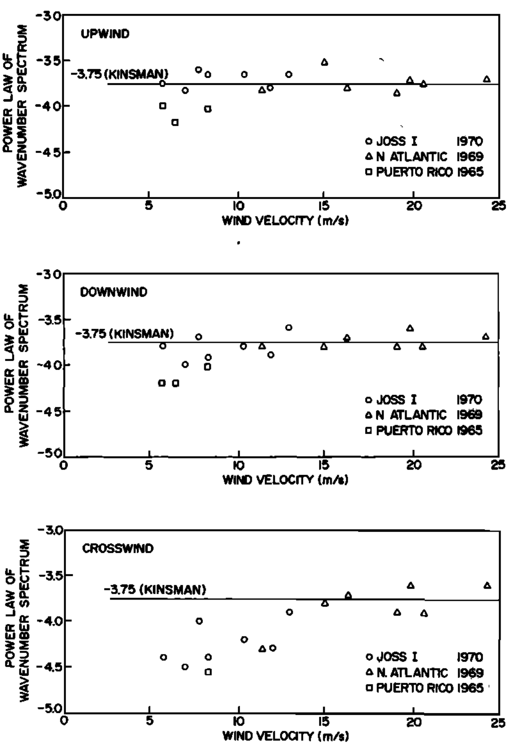

Fig. 2. Power law of sample wave number spectra.

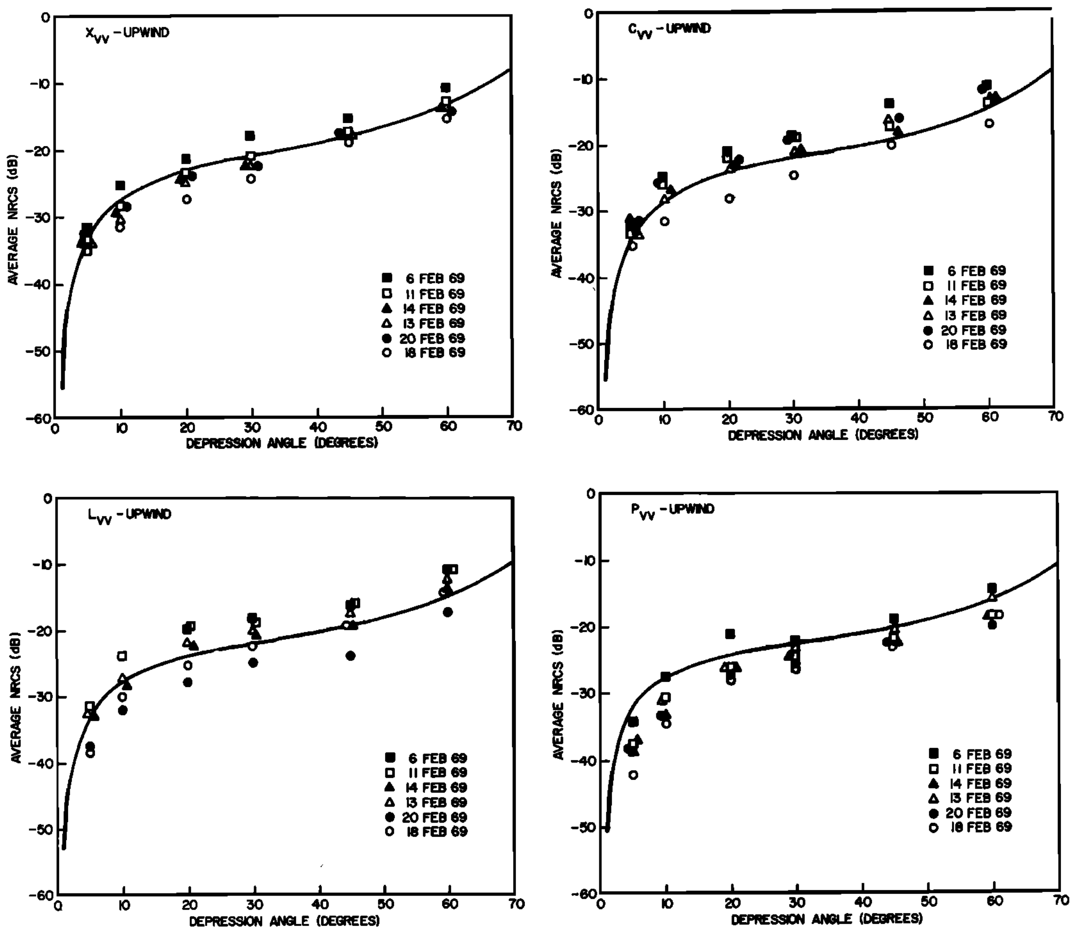

Fig. 3. Average NRCS as computed from spectrum (upwind).

The conversion is easily applied to the four-frequency radar data by the addition of 3.1 db to the published median σ_0 values. This factor includes +1.5 db (corresponding to a factor of $1/(2)^{1/2}$ in the pulse-limited illuminated area) to account for the two-way antenna pattern recalculated by *Daley et al.* [1973]. The factor also includes +1.6 db to convert the measured median values of σ_0 to mean values, which is an assumption of a Rayleigh distribution. The Rayleigh assumption is a first approximation employed to simplify the conversion. It has been shown by *Valenzuela and Laing* [1971] that sea clutter in general is not Rayleigh distributed, although an explicit mean-median relationship has yet to be obtained.

Sample spectra determined from (5) are shown in Figure 1 along with a spectrum with the Phillips power law:

$$W(K) = 6 \times 10^{-3} K^{-4} \qquad (6)$$

The values of A and $(4 - \nu)$ are listed in Table 1 for each of the sea conditions under consideration along with the average value of wind velocity measured at 19.5 meters above the surface, $U_{19.5}$. No spectra are included from the Joss 2 program because of the absence of NRCS measurements at 20° and 30°. The behavior of the exponent $-(4 - \nu)$ as a function of wind velocity is shown in Figure 2, where it is compared to a value of −3.75 previously found by *Kinsman* [1965]. Large departures from the Kinsman result occur in

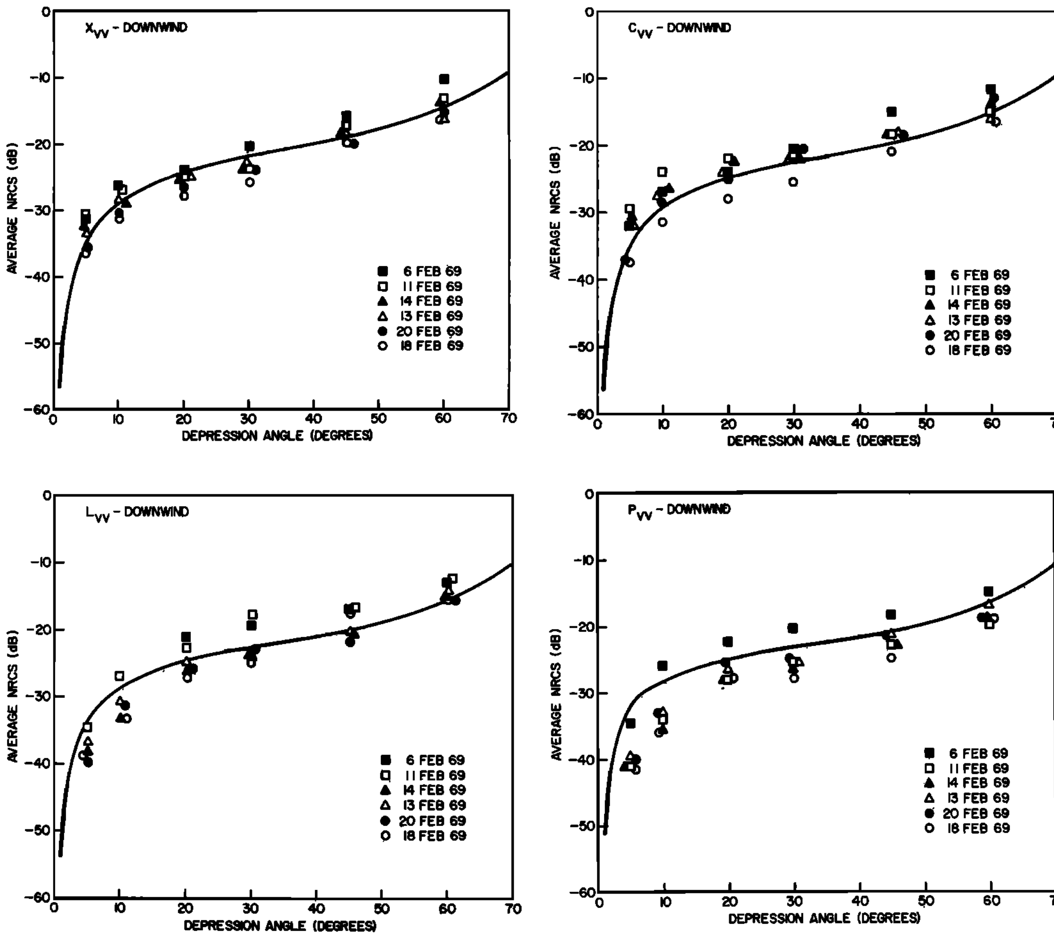

Fig. 4. Average NRCS as computed from spectrum (downwind).

the crosswind direction during Joss 1 (Figure 2*c*) and at Puerto Rico. The high values of the exponent $(4 - \nu)$ at low winds are due to a dip in the spectrum at the short wavelengths (X and C bands). This effect was reported for the wave tank measurements of *Wright and Keller* [1971] and verified for the open sea by *Valenzuela et al.* [1971]. It is explained by wave-wave interactions that produce a null in the wave number region around 3.5 cm^{-1} for light winds (Figure 1*b*). The average values of A and $(4 - \nu)$ for each of the major measurement programs are given in Table 1. In the upwind and downwind directions the average spectrums for the North Atlantic and Joss 1 are in close agreement and approximate the power law found by *Kinsman* [1965] of $W(K) \sim K^{-3.75}$. Therefore these results are combined for subsequent steps in the model as shown in the table.

NRCS COMPUTED FROM THE SPECTRUM

The work of *Guinard and Daley* [1970] has shown that the combination of (1) with (3) and (6) provides a theoretical upper bound to the sea return, which has been experimentally verified. From the results obtained above a more accurate empirical determination of the ocean spectrum is now possible, namely,

Upwind spectra

$$W(K) = 3.39 \times 10^{-3} K^{-3.72} \tag{7a}$$

Downwind spectra

$$W(K) = 2.66 \times 10^{-3} K^{-3.77} \tag{7b}$$

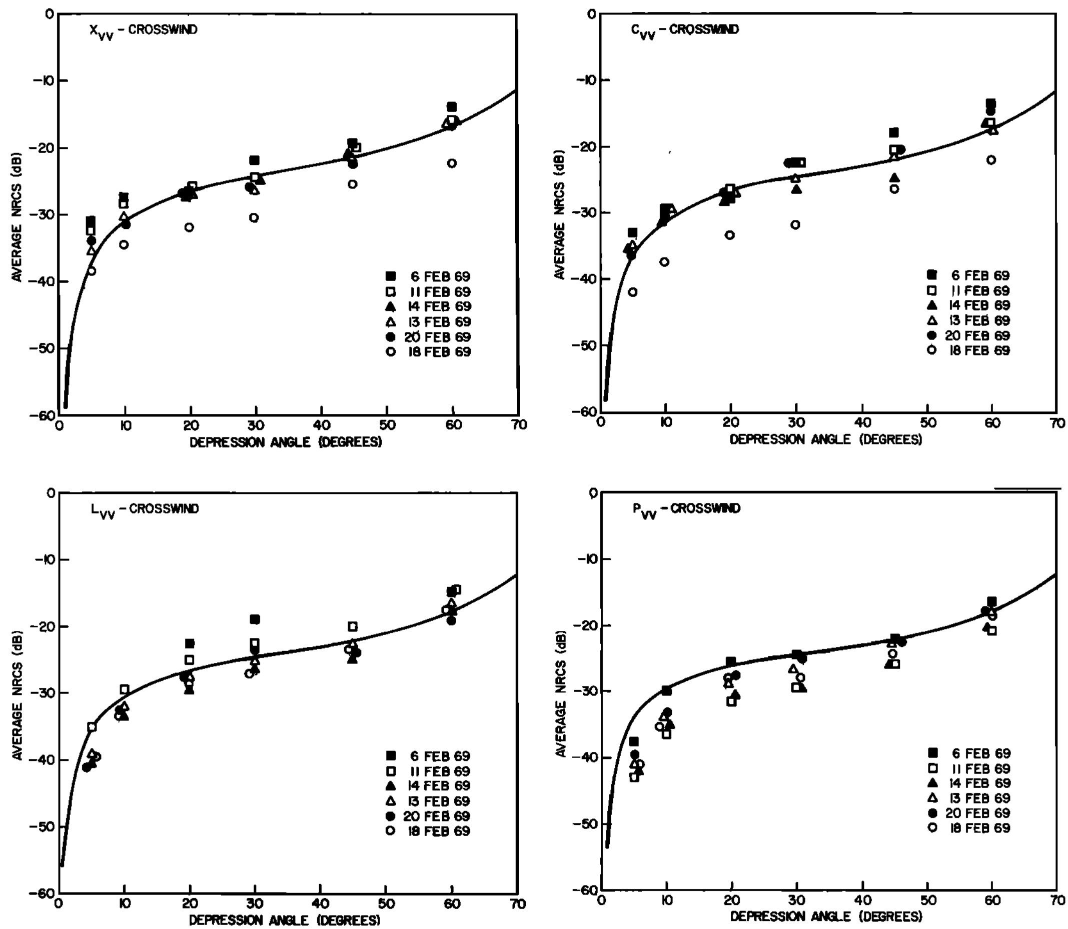

Fig. 5. Average NRCS as computed from spectrum (crosswind).

Crosswind spectra

$$W(K) = 1.69 \times 10^{-3} K^{-3.83} \qquad (7c)$$

where the upwind and downwind spectra are averages of the North Atlantic and Joss 1 results and the crosswind is the average of the North Atlantic results only. When the expressions 7 are combined with (1), the NRCS for vertical polarization is obtained, namely,

Upwind spectra

$$[\sigma_0]_{vv} = 2.66 \times 10^{-3} \alpha_{vv} \tan^4 \theta (2\beta \cos \theta)^{0.28} \qquad (8a)$$

Downwind spectra

$$[\sigma_0]_{vv} = 2.09 \times 10^{-3} \alpha_{vv} \tan^4 \theta (2\beta \cos \theta)^{0.23} \qquad (8b)$$

Crosswind spectra

$$[\sigma_0]_{vv} = 1.33 \times 10^{-3} \alpha_{vv} \tan^4 \theta (2\beta \cos \theta)^{0.17} \qquad (8c)$$

These curves are shown in Figures 3, 4, and 5 with a few data points for each radar wavelength and now include the slight wavelength dependence of σ_0 alluded to by *Guinard et al.* [1971] but not modeled by the Phillips spectrum. Data at 5° and 10° angles are shown to be reasonably close to the model, although the theory does not strictly apply at the lower angles without modification to include such effects as surface tilt and shadowing.

WIND DEPENDENCE OF THE NRCS

The NRCS for an empirically determined form of the ocean spectrum as a function of

TABLE 2. $B = AU^{-2\nu}g^{\nu}$ for Each Spectrum

Date	Upwind, $B \times 10^{-4}$	Downwind, $B \times 10^{-4}$	Crosswind, $B \times 10^{-4}$
		North Atlantic, 1969	
February 11	2.90	2.13	0.64
February 6	7.39	14.18	8.55
February 14	2.74	1.27	0.72
February 13	10.69	3.83	5.82
February 10	5.15	1.83	1.85
February 20	0.64	4.59	5.11
February 18	5.34	3.38	42.15
		Joss 1, 1970	
January 22	3.23	1.48	
January 28	14.04	19.43	
January 20	1.52	3.96	
January 27	2.17	9.21	
January 26	2.85	3.76	
January 27	4.95	14.74	
January 23	5.30	4.11	
Average	4.92 ± 7.1	6.28 ± 18.2	9.26 ± 27.4

Limits of error equal to two standard deviations about the mean.

wavelength and angle having been obtained, it is now desirable to obtain the theoretical prediction of the growth of the NRCS as a function of wind velocity implied by the measured spectra in (7). *Valenzuela et al.* [1971] have pointed out that the generalized form of the ocean spectrum for gravity waves may be expressed as

$$W(K) = BU^{2\nu}g^{-\nu}K^{-(4-\nu)} \tag{9}$$

where g is the acceleration due to gravity, U is the wind velocity, and B is a dimensionless constant. The value of B can be estimated from previous results by substituting

$$A = BU^{2\nu}g^{-\nu} \tag{10}$$

The values of B obtained from (10) for each day are listed in Table 2 along with the average values to be used later. There is a much larger variation in B than in A, since now the errors in both U and ν contribute when B is estimated in this way.

For winds greater than 5 m/sec the measured NRCS for X and C bands can be well approximated by a power law of the form

$$\sigma_0 \sim U^{2\nu} \tag{11}$$

the same form being applicable to L and P bands without restriction on wind velocity. Sample least squares fits of (11) are shown in Figure 6 for a 20° depression angle. The values of 2ν obtained for all cases are listed in Table 3. The table also includes the results of fitting horizontal and cross polarizations and indicates a higher power law dependence on these polarizations. In order to compare the empirical values of 2ν (Table 3) for vertical polarization with those implied by the spectrum the values of 2ν have been averaged over the angular region 20°–60°. The comparison is shown in Table 4, and good agreement is seen in the upwind and downwind directions. The exception at crosswind is not surprising in view of the spectral results previously obtained.

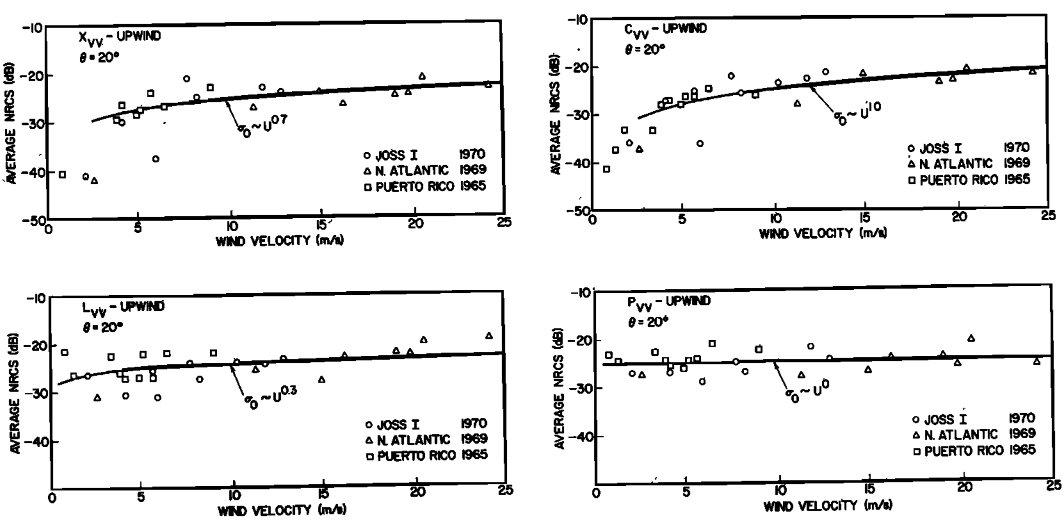

Fig. 6. Variation of NRCS with wind velocity (upwind) $\theta = 20°$.

TABLE 3. Values of 2ν from Best Fit of $\sigma_0 \sim U^{2\nu}$ for $U > 5$ m/sec on *X* and *C* Bands

θ	XVV	CVV	LVV	PVV	XHH	CHH	LHH	PHH	XVH, HV	CVH, HV	LVH, HV	PVH, HV
							Upwind					
5°	0	0.5	0.4	-0.1	0.5	0.6	1.8	1.5	0.2	1.2	0.6	0.4
10°	0.3	0.7	0.3	0	0.6	0.8	0.8	0.8	0.9	1.4	0.8	0.6
20°	0.7	1.0	0.3	0	1.4	1.1	0.7	0.5	1.9	1.4	0.8	0.6
30°	0.6	1.0	0.5	0.2	1.0	1.1	0.7	0.5	1.4	1.4	0.8	0.5
45°	0.8	1.2	0.3	0.1	1.2	1.0	0.3	0.5	1.7	1.9	0.6	0.2
60°	0.3	0.5	0.4	0.2	0.6	0.7	0.4	0.4	1.1	1.6	0.6	0.3
							Downwind					
5°	0.2	0.8	0.4	0	1.5	1.1	1.3	1.8	0.8	1.6	0.6	1.2
10°	0.7	1.3	0	-0.2	1.6	1.7	0.1	0.2	1.3	1.9	0.3	0.6
20°	0.8	1.0	0.2	0	1.5	1.4	0.3	0.4	1.0	0.8	0.6	0.5
30°	0.4	0.8	0.2	0.1	1.1	1.0	0.1	0.3	1.3	1.1	0.4	0.4
45°	1.0	1.1	0	0.2	1.3	1.0	0.1	0.4	1.8	1.8	0.3	0.3
60°	0.4	0.5	0.3	0.2	0.5	0.5	0.2	0.3	1.2	1.5	0.5	0.1
							Crosswind					
5°	1.6	0.9	0	-0.5	1.4	1.5	1.1	1.5	1.1	1.4	0.3	0
10°	1.0	1.0	0	-0.4	1.1	0.7	0.6	0.5	1.6	2.0	0.2	0.1
20°	0.9	1.1	0	-0.3	1.3	1.0	0.2	0.2	1.8	1.6	0.5	0.1
30°	1.1	1.5	0	-0.3	1.4	1.2	0.2	0.1	1.6	1.8	0.3	0
45°	1.2	1.2	-0.3	-0.3	1.8	0.7	-0.2	-0.1	2.0	1.8	0	-0.2
60°	0.4	0.3	0.1	-0.1	0.8	0.2	0.2	0.3	1.7	1.7	0.6	0.2

Limits of error equal to two standard deviations about the mean: ±0.6 for *X* and *C* bands and ±0.2 for *L* and *P* bands.

To obtain a representation that includes the above power law dependence of the NRCS with wind, (10) is combined with (4) and (5) to yield

$$[\sigma_0]_{vv} = \frac{\pi}{4} B g^{-\nu} \alpha_{vv} \tan^4 \theta (2\beta \cos \theta)^\nu U^{2\nu} \quad (12)$$

where B and ν have been obtained by measurement and are functions of upwind, downwind, and crosswind. The comparison of (12) with the data is shown in Figures 7 and 8 for *L* and *P* bands. In these examples we have used the average values of B given in Table 2 and values of ν as determined from the spectrum (Table 4) for the appropriate wind direction.

For *X* and *C* bands the spectrum of (9) does not strictly apply, since the ocean scatterers involved are in the capillary wave region where the wind dependence is not known. The comparison of (12) with the *X* and *C* band data is shown in Figures 9 and 10.

Disagreement is most apparent at low wind speeds and at $\theta = 20°$, although, as an empirical fit, (12) provides a good estimate in most cases. In the examples the same power law dependence with wind was used for all four radar wavelengths. For a given wave-

TABLE 4. Comparison of Power Laws of NRCS in Angular Region 20° to 60°

Wind Direction	Spectrum			Values of 2ν from Best Fit of σ_0			
	ν	2ν		*X* band	*C* band	*L* band	*P* band
Upwind	0.28	0.56	±0.26	0.6	0.9	0.4	0.1
Downwind	0.23	0.46	±0.2	0.7	0.9	0.2	0.1
Crosswind (North Atlantic)	0.17	0.34	±0.2	0.9	1.0	-0.1	-0.2

Limits of error equal to ±0.3 for *X* and *C* bands and ±0.1 for *L* and *P* bands.

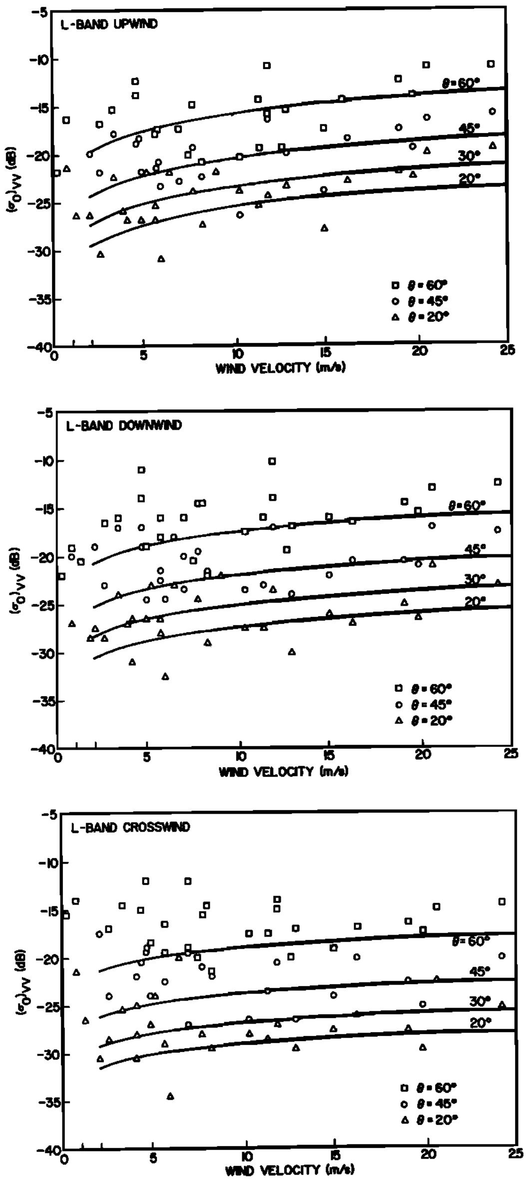

Fig. 7. Variation of NRCS with wind velocity computed from spectrum (L band).

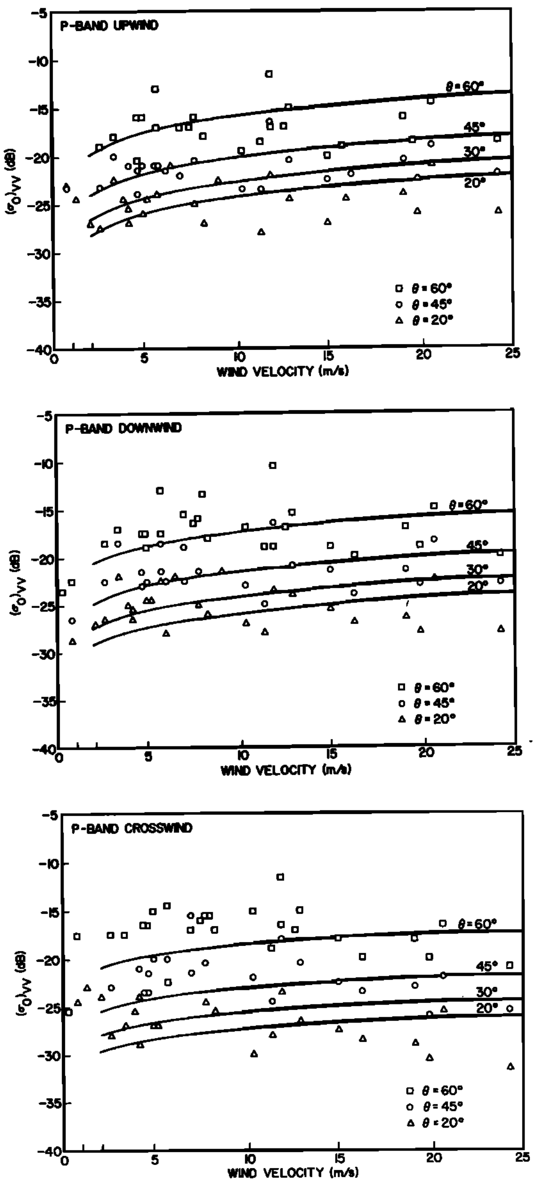

Fig. 8. Variation of NRCS with wind velocity computed from spectrum (P band).

length, better agreement could be obtained by using an estimate of 2ν from Table 3.

DISCUSSION

This method of modeling the NRCS of the sea assumes the existence of an equilibrium range spectrum in the range of ocean wave numbers corresponding to those that produce the scattering in the microwave radar wavelengths from P band to X band. The empirically determined results of the wind dependence of the NRCS listed in Table 3 suggest that the power law of the equilibrium range of the ocean spectrum is wave number dependent, a point already noted by *Valenzuela et al.* [1971]. Recent work by *Pierson and Stacy* [1972] subdivides the above spectral range into regions with power laws from -3.5 to -4 and less.

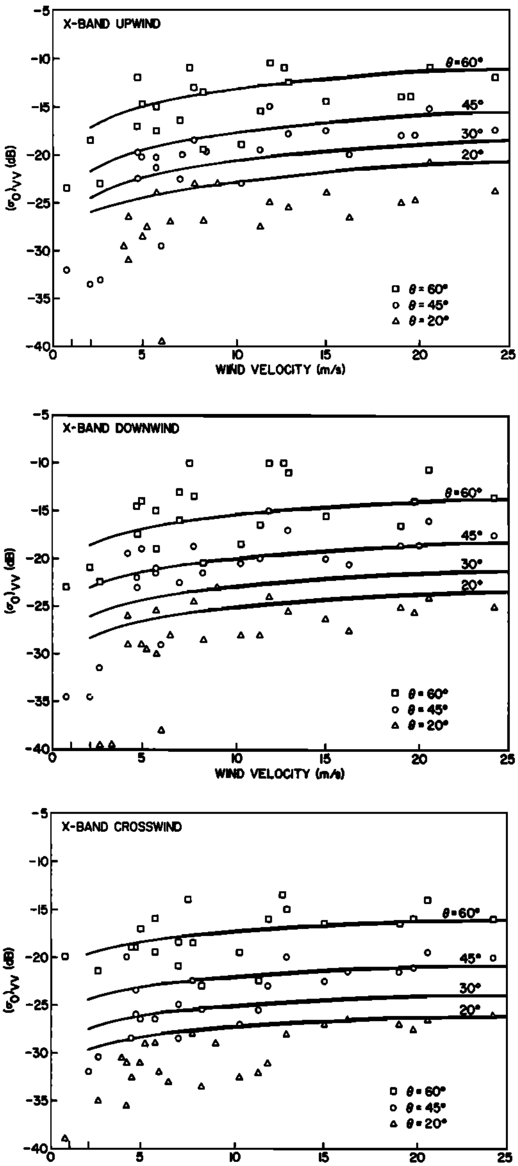

Fig. 9. Variation of NRCS with wind velocity computed from spectrum (X band).

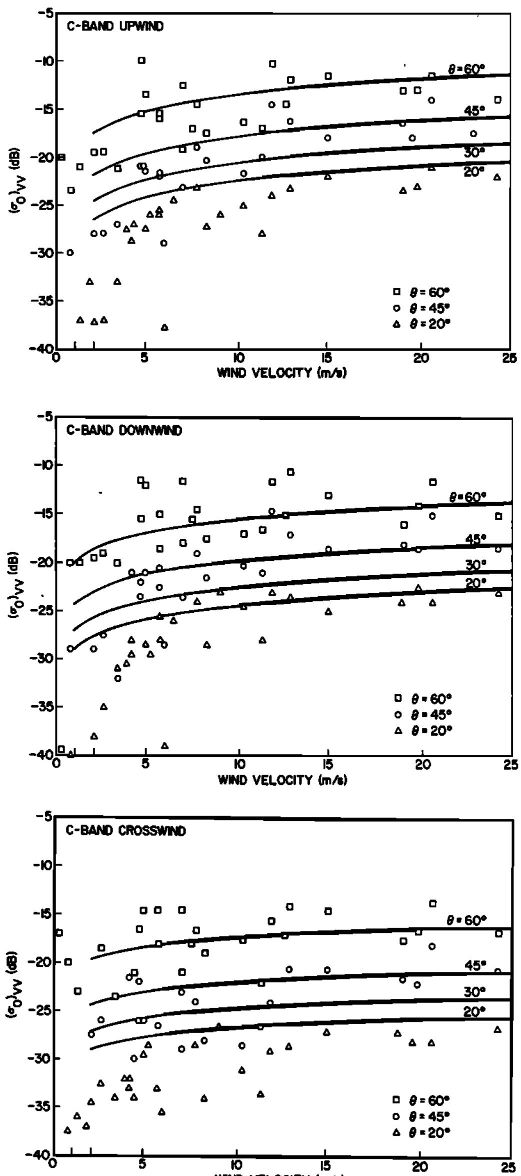

Fig. 10. Variation of NRCS with wind velocity computed from spectrum (C band).

If their model is true, the procedure used here produces a composite power law over this part of the ocean spectrum that may be used to obtain relationships of the NRCS of the sea (vertical polarization) over a range of microwave frequencies. To estimate the NRCS over a narrower band of radar frequencies, a more accurate choice of the spectral form of $W(K)$ could be made, along with a wind dependence indicated by the data of Table 3.

CONCLUSIONS

All of the four-frequency data have been incorporated into the composite surface model in order to provide a more accurate description of the characteristics of the NRCS of the sea for vertical polarization. The Kinsman form of the ocean spectrum has been found to agree with the spectrum determined from radar measurement of the NRCS. By means of this spectrum a more accurate determination of the variation of the NRCS with depression angle has been obtained, which now includes a better fit to the radar wavelength dependence. A further generalization of the spectrum implies a power law dependence of the NRCS with wind velocity that is in good agreement with the data in many cases of interest. Equations have been developed based on these results that model the NRCS of the sea as functions of wind velocity and direction, radar wavelength, and depression angle for vertical polarization.

Acknowledgments. The author wishes to acknowledge the comments and advice of G. R. Valenzuela in the preparation of the paper.

This work was supported by the Naval Air Systems Command, NAIR310-B.

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(Received November 22, 1972; revised July 30, 1973.)