THEORIES FOR THE INTERACTION OF ELECTROMAGNETIC AND OCEANIC WAVES - A REVIEW

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Abstract. This paper reviews analytical methods in electromagnetic scattering theory (i.e., geometrical and physical optics, perturbation, iteration, and integral-equation) which are applicable to the problems of remote sensing of the ocean. In dealing with Earth's surface (in this case, the weakly non-linear ocean), it is not possible to have a complete and exact description of its spatial and temporal statistics. Only the first few moments are generally available; and in the linear approximation the statistics are assumed homogeneous, stationary and Gaussian. For this case, the high-frequency methods (geometrical and physical optics) and perturbation (Rayleigh–Rice), or a combination of them, provide tractable analytical results (i.e., the specular-point, the slightly-rough Bragg scattering and the composite-surface models). The applicability and limitations of these models are discussed. At grazing incidence and for higher frequencies, other scattering mechanisms become significant; and shadowing, diffraction and trapping must be considered.

The more exact methods (integral-equation and Green's function) have not been as successful in yielding tractable analytical solutions, although they have the potential to provide improved theoretical scattering results in the future.

1. Introduction

Satellite technology has developed rapidly in the last few years and presently is being used for gathering information about the atmosphere and the Earth's surface. Presently the possibility of using spacecraft in remote sensing of oceanographic parameters is being fully assessed. To implement this application, it is necessary to have a clear picture of the physical processes involved in the *electromagnetic ocean-surface interaction*, and a reasonably accurate analytical description of the processes must be available in order to extract the desired ocean variables (e.g., wind speed, wave height, wave slope, ocean-wave spectrum, mean sea level, and apparent surface temperature).

Fortunately with the last two decades, significant advances have been made in understanding the basic phenomena involved in the interaction by means of experimental investigations of electromagnetic (e.m.) scatter from the ocean (Crombie, 1955; Braude, 1962; Bass *et al.*, 1968; Ward, 1969; Long and Trizna, 1973) and in controlled wave tank experiments (Wright, 1966; Wright and Keller, 1971; Duncan *et al.*, 1974; Keller and Wright, 1975). From these investigations, it has been established that the most important mechanism contributing to the e.m. wave ocean-surface interaction is *resonant, or Bragg, scattering*. An exception is in the specular direction (normal incidence for backscatter) where specular scatter predominates (Semyonov, 1966; Barrick and Peake, 1968).

To predict the e.m. scatter from the ocean for radio waves and microwave frequencies (400 MHz–30 GHz), one should not only be familiar with classical e.m.

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scattering theories as applied to random rough surfaces (Beckmann and Spizzichino, 1963; Shmelev, 1972), but also with the hydro-dynamics of ocean waves (Phillips, 1966; Hasselmann, 1968). The statistical distribution of the surface displacement of a wind-wave system is Gaussian in the linear approximation of a superposition of non-interacting sinusoidal water waves. The non-linear coupling of the ocean waves produces a continuous redistribution of energy and momentum of the waves causing the statistics of the ocean surface to be non-Gaussian, non-stationary and non-homogeneous (Longuet–Higgins, 1963). Furthermore, the energy balance of the ocean waves is controlled by several competing processes: the input from the wind, the energy transfer by non-linear wave-wave interactions and the energy lost by viscosity and wave breaking. Even today, efforts continue in oceanographic research to understand the overall energy balance of the ocean wave system (Hasselmann *et al.*, 1973).

The emphasis in this paper is on the e.m. backscattering from the ocean and water surfaces to establish the present state of analytical techniques and scattering models of use in remote sensing of oceanographic parameters.

2. E.M. Scattering from Random Rough Surfaces

Both the *direct* and the *inverse* scattering problems are of interest in remote sensing. In the *direct* problem, the current distribution on a body is given and one wishes to determine the scattered fields at a distance from the body. On the other hand, in the *inverse* problem – the scattered fields are given and one desires the current distribution on the body, or the body itself. Here, the emphasis is on the classical methods of e.m. theory for the solution of direct scattering problems from *statistically rough surfaces* for given source (or incident) fields.

The literature on the scattering of e.m. waves from deterministic bodies and corrugated surfaces is of particular interest because these same techniques are used in the scattering from random rough surfaces. Most of the analytical techniques (geometrical optics, physical optics, iteration, perturbation and integral-equation methods) apply to the scattering from statistically rough surfaces, with the added complexity that the scattered fields are now statistical quantities and appropriate ensemble averages over the statistics of the surface are taken to obtain their mean values. General purpose reviews of scattering from random surfaces are those of Beckmann and Spizzichino (1963) and Shmelev (1972).

It is well known in e.m. theory that the fields (**E** the electric and **H** the magnetic fields connected by Maxwell's equations and two constitutive equations) in a domain V enclosed by a simply connected surface S (Figure 1a), may be determined by the Stratton–Chu integral equations (Stratton, 1941):

$$\mathbf{E}(\mathbf{r}) = \mathbf{E}_i(\mathbf{r}) - \oint \{i\omega\mu_0(\mathbf{n}\times\mathbf{H})G + (\mathbf{n}\times\mathbf{E})\times\nabla G + (\mathbf{n}\cdot\mathbf{E})\nabla G\}\,\mathrm{d}S \tag{2.1}$$

$$\boldsymbol{H}(\boldsymbol{r}) = \boldsymbol{H}_i(\mathbf{r}) + \oint \{i\omega\varepsilon_0(\mathbf{n}\times\mathbf{E})G - (\mathbf{n}\times\mathbf{H})\times\nabla G - (\mathbf{n}\cdot\mathbf{H})\nabla G\}\,\mathrm{d}S \tag{2.2}$$

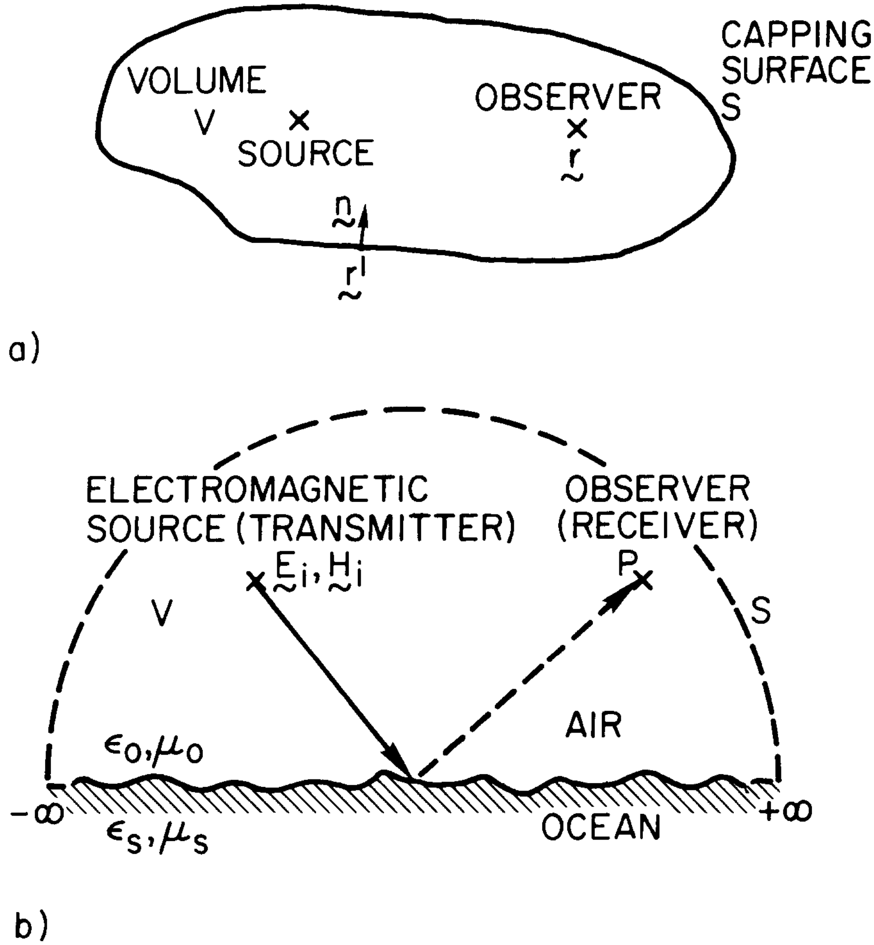


Fig. 1. Geometrical configuration of the electromagnetic scattering problem. (a) General interior (volume) scattering; (b) ocean surface scattering.

if the surface fields are known. Here ε_0 and μ_0 are the electric permitivity and magnetic permeability of the medium (free space in our case), ω is the angular frequency of the incident e.m. radiation ($\mathbf{E}_i$, $\mathbf{H}_i$), $G = \exp(ikR)/4\pi R$ is the Green's function of free space, $k = 2\pi/\lambda$ is the wave number of the e.m. radiation, R is the distance from the observation point $\mathbf{r}$ to the scattering point $\mathbf{r}'$ on the surface, $\mathbf{n}$ is the positive unit normal vector to the surface, ∇ is the gradient vector operator with respect to $\mathbf{r}$ and $\exp(-i\omega t)$ is the time dependence.

Once the surface fields in the integrands are known, the scattered fields $\mathbf{E}_S = \mathbf{E} - \mathbf{E}_i$ and $\mathbf{H}_S = \mathbf{H} - \mathbf{H}_i$ may be determined from (2.1) and (2.2). From these fields, the mean scattered power density $P_S = \frac{1}{2}\,\mathrm{Re}\,\langle \mathbf{E}_S \times \mathbf{H}_S^* \rangle$ and the radar cross-section $\sigma = \lim_{R\to\infty} (4\pi R^2 \langle |\mathbf{E}_S|^2 \rangle / |\mathbf{E}_i|^2)$ may be derived. $\mathbf{H}_S^*$ is the complex conjugate of $\mathbf{H}_S$ and $\langle \cdots \rangle$ denotes the ensemble average of the quantity inside the brackets. In scattering from the ocean surface, the appropriate domain (geometrical configuration) is shown in Fig. 1b.

Usually in scattering problems, one is interested in the fields far from the surface, in the so-called *far-zone*. For a surface of linear dimensions X and Y, the *far zone* is defined as the zone which is at a mean distance $R_0 \gg XY/\lambda$ from the surface. Accordingly, for the *far zone* the following approximations apply

$$G \sim \exp(ikR)/4\pi R_0 \tag{2.3}$$

$$\nabla G \sim -ikG\mathbf{n}_2 \tag{2.4}$$

where $R = R_0 - \mathbf{n}_2 \cdot \mathbf{r}'$, $\mathbf{n}_2$ is the unit vector in the scattered direction.

The surface fields, in principle, may be obtained from the limiting forms of (2.1) and (2.2) as $\mathbf{r}$ approaches the surface along the unit normal (Maue, 1949, Müller, 1957; Mitzner, 1967). The resultant integral equations decouple for *perfectly conducting* surfaces (for this case $\mathbf{n} \times \mathbf{E} = 0$ on the surface) and the magnetic field satisfies

$$\tfrac{1}{2}\mathbf{n} \times \mathbf{H}(\mathbf{r}'') = \mathbf{n} \times \mathbf{H}_i(\mathbf{r}'') - \mathbf{n} \times \int_{\bar{S}} (\mathbf{n} \times \mathbf{H}) \times \nabla G \, dS \tag{2.5}$$

where $\mathbf{r}''$ is on S and $\bar{S}$ is the punctured surface S such that $\mathbf{r}'' \neq \mathbf{r}'$. For *highly conductive* surfaces, the magnetic field is still obtained from (2.5), but the electric field $\mathbf{E}(\mathbf{r}'')$ on the surface is derived from an impedance boundary condition (Senior, 1961)

$$\mathbf{n} \times \mathbf{E} = z_S \mathbf{n} \times (\mathbf{n} \times \mathbf{H}) \tag{2.6}$$

where the surface impedance $z_S = (\mu_S/\varepsilon_S)^{1/2} \ll 120\pi$ ohms (the impedance of free space).

A numerical solution of the integral equations for the surface fields is possible for deterministic bodies of dimensions not too large compared to the wavelength of the e.m. radiation (Andreasen, 1965). However, in scattering from random rough surfaces (the ocean, for example), this procedure is not possible and recourse is made to reasonable approximations for the surface fields based on e.m. scattering theory for deterministic bodies (Siegel, 1958; Ruck *et al.*, 1970). The scattered fields are then obtained from these surface fields using (2.1) and (2.2). Afterwards, the scattering results are checked with experiments on known surfaces or against exact analytical scattering results applying in a well-defined limit (e.g., geometrical optics and perturbation scattering).

DeSanto (1974) has investigated the e.m. scattering from random rough surfaces using the dyadic Green's method where the statistical properties of the scattering are included in the Green's function (the response to a point source) of the rough surface boundary-value problem. From the Green's function, the scattered fields may be determined from the incident fields by integration over a plane surface. Thus far, no explicit new scattering results for general use have been obtained with this method; even the first two moments of the Green's function are given in integral equation form. Nevertheless, the method yields a rigorous diagrammatic formulation for the computation of high-order corrections to the scattering from a random rough surface. Soviet work on this method is given in Shmelev (1972).

In the next few sections, a review of the more useful and tractable scattering models developed for random surfaces is given. These scattering models have already been used to obtain oceanographic parameters (Long and Trizna, 1973; Tyler *et al.*, 1974; Walsh, 1974) and in controlled wave-tank experiments have furnished new knowledge on the dynamics of high frequency wind-waves (Larson and Wright, 1975; Keller and Wright, 1975).

3. Geometrical and Physical Optics

Whenever the body or surface has a radius of curvature ρ large compared to the wavelength of radiation (surfaces with discontinuities in slope are excluded), the surface fields may be approximated by the fields which would be present were a flat tangent plane introduced at each point on the surface (*tangent-plane approximation*). Notice that for perfectly-conductive surfaces, the tangent-plane approximation for the surface fields is equivalent to using the first term in an iterative solution of (2.5).

Whèn the scattered fields are obtained from Equations (2.1) and (2.2) with the tangent-plane approximation for the surface fields, the procedure is denoted as *physical optics* or the *Kirchhoff* method in scattering. The result is a high-frequency solution to the scattering which becomes exact for the limiting case that the wavelength of the e.m. radiation vanishes (*geometrical optics* limit) and the surface is of infinite extent so that no edge effects exist.

The condition for the applicability of the *physical optics* scattering results was given by Brehkovskikh (1952)

$$\rho k \cos^3 \theta \gg 1 \tag{3.1}$$

where θ is the angle of incidence of the e.m. radiation with respect to the normal surface.

The geometrical-optics cross-section for a perfectly conductive facet with principal radii of curvature R_1 and R_2 is well known (Siegel, 1958)

$$\sigma_F = \pi R_1 R_2 \,. \tag{3.2}$$

For gently undulating random rough surfaces, Kodis (1966), finds, with *physical optics* and the method of stationary phasė of integration, that the back-scattering cross-section σ_{K0} is independent of the polarization of the e.m. radiation and given by

$$\sigma_{\mathrm{K0}} = \pi \overline{R_1 R_2} \langle N \rangle \tag{3.3}$$

where $\overline{R_1 R_2}$ is the average of the product of the principal radii of curvature of the rough surface and $\langle N \rangle$ is the average number of specular points per unit area.

Barrick (1968) derived scattering results for *finitely* conductive rough surfaces. In this work, the cross-section per unit area of the surface is proportional to the joint-probability density of slopes $p(\zeta_X, \zeta_Y)$ of the rough surface ζ; $\zeta_X = \partial\zeta/\partial X$, $\zeta_Y = \partial\zeta/\partial Y$ are the slopes of the rough surface in two orthogonal directions. General bistatic results are derived by Barrick; for backscattering, the cross-section per unit area reduces to

$$\sigma_{BA} = \pi \sec^4\theta \, p(\zeta_X, \zeta_Y)|_{Sp.} \times |R(0)|^2 \tag{3.4}$$

where $R(0)$ is the Fresnel reflection coefficient for normal incidence and the probability density of slopes is evaluated at the specular points. Accordingly, only surface *facets normal* to the direction of the incident radiation contribute to backscattering (Hagfors, 1964). Equation (3.4) is independent of wavelength and polarization of the e.m. radiation except for implicit dependencies in the Fresnel reflection coefficient and in the mean-square slopes of $p(\zeta_X, \zeta_Y)$. For an isotropic rough surface of Gaussian statistics, (3.4) becomes

$$\sigma_I(\theta) = \frac{|R(0)|^2}{s^2} \sec^4\theta \exp(-\tan^2\theta/s^2) \tag{3.5}$$

where s^2 is the total variance of slopes and θ is the angle of incidence.

To apply (3.5) to the ocean, one must keep in mind that only a portion of the total mean-square slopes of the ocean surface in included in s^2, these being the mean-square slopes contributed by ocean waves whose lengths are greater than the wave-length of the e.m. radiation.

Daley *et al.* (1973), Daley (1973) and Barrick (1974) obtain relatively good agreement with measured cross-sections at normal incidence when the total mean-square slopes for a *clean* ocean surface (Cox and Munk, 1954; Phillips, 1966) and the Fresnel coefficient are used in (3.5) to predict the cross-section. However, when the prediction with the same value of the parameters is extended to angles away from normal incidence, one finds considerable disagreement. To remedy this using the same model, Equation (3.5), we find that the reflection coefficient should be modified and that the mean-square slopes for an ocean with *slicks* (one where the gravity-capillary and capillary waves have been suppressed) applies. For 3-cm e.m. radiation, the reflection coefficient required to match the data is given in Figure 2a. The corresponding backscattering cross-section per unit area is in Figure 2b. Yapley *et al* (1971) find that the backscattering cross-section of the sea at normal incidence is two or three times greater on the trough than on the crest of the dominant wave on the ocean for light winds, and the ratio increases with wave height and wind speed. In part this may be due to a larger concentration of short gravity waves on the crest of the wave reducing the reflection properties of the facets there. It is well known that the reflection properties of a surface are modified by the amplitude of the roughness present (Valenzuela, 1970). The reflection

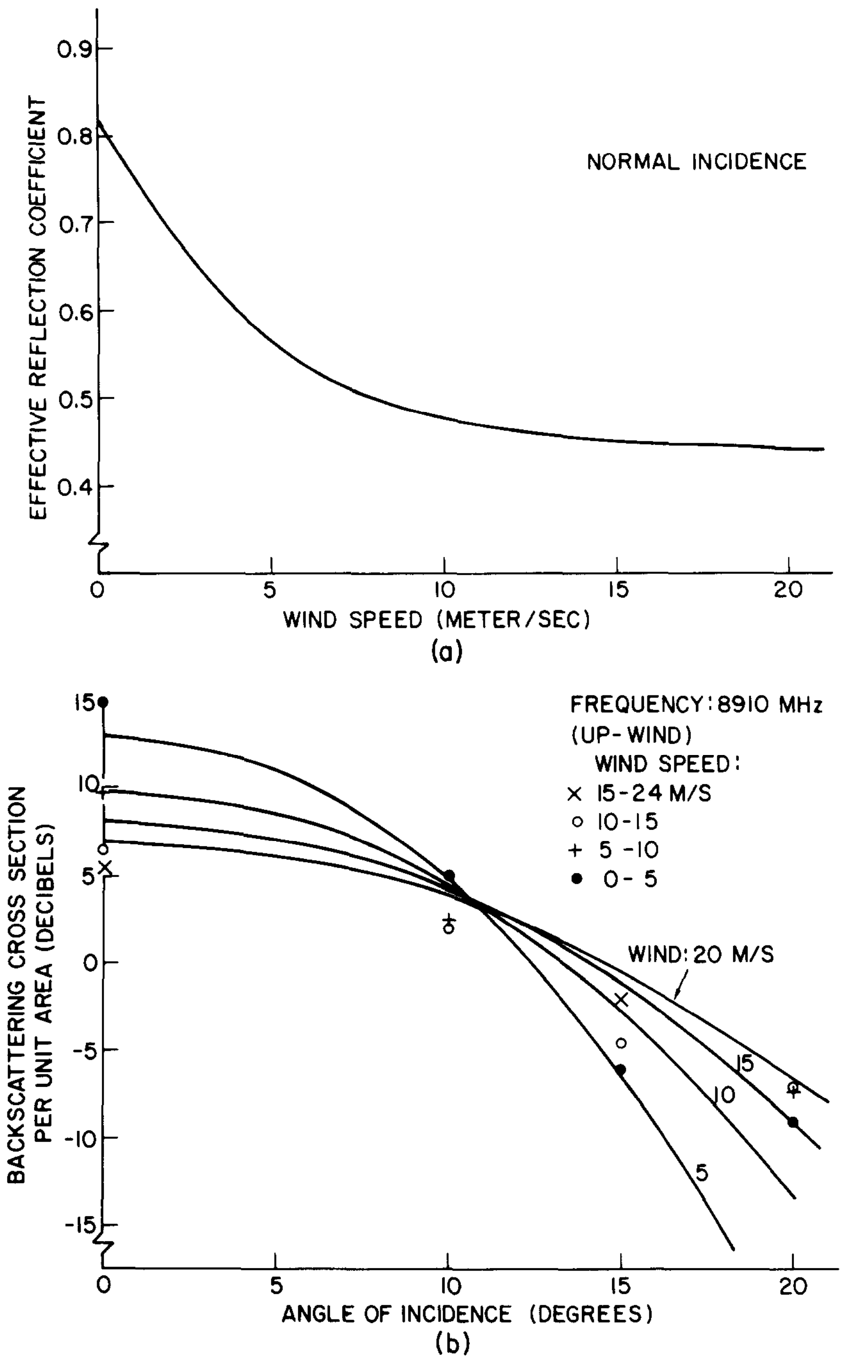


Fig. 2. Application of the specular-point model to the radar backscatter from the ocean. (a) Reflection coefficient obtained from 3-cm e.m. radiation measurements (Barrick, 1974); (b) comparison of measured and theoretical cross-sections per unit area. Theory (Barrick, 1968): —— Isotropic Gaussian specular-point model (with the reflection coefficient given in (a) and with the mean-square of slopes for an ocean with 'slicks'). Experiment (Daley *et al.*, 1968–1973): ●, +, ○, × for various winds. The cross-section data have been converted to mean values with a Rayleigh hypothesis for the envelope of the return and it has been renormalized to a two-way antenna pattern.

coefficients obtained (except for a typographical error) are:

$$R_{\perp\text{effective}} = R_\perp + \frac{1}{2}\frac{k^2 \cos\theta(\varepsilon_r - 1)I_\perp}{[\cos\theta + (\varepsilon_r - \sin^2\theta)^{1/2}]^2} \tag{3.6}$$

$$R_{\|\text{effective}} = R_\| - \frac{1}{2}\frac{k^2 \cos\theta(\varepsilon_r - 1)\varepsilon_r I_\|}{[\varepsilon_r \cos\theta + (\varepsilon_r - \sin^2\theta)^{1/2}]^2} \tag{3.7}$$

where $R_\perp$ and $R_\|$ are the Fresnel reflection coefficients for e.m. radiation polarized *perpendicular* and *parallel* to the plane of incidence, respectively, ε_r is the relative dielectric constant of the surface (ocean), θ is the angle of incidence of the e.m. radiation with respect to the surface normal, and $I_\perp$, $I_\|$ are linear functionals of the energy spectral density of the surface roughness explicitly given in Valenzuela (1970). The reflection properties of the surface may also be modified by other parameters, e.g., by the mixed layer of *spray* and *foam* usually found at the ocean surface.

In an alternative approach, one could introduce a more general joint probability density of slopes in (3.4) to attempt to predict the measured backscattering cross-section of the sea. Accordingly, for up-wind and a non-isotropic Gaussian rough surface, we obtain from (3.4)

$$\sigma_{\text{N.I.}}(\theta) = \frac{|R(0)|^2}{2s_u s_c} \sec^4\theta \exp(-\tan^2\theta/2s_u^2) \tag{3.8}$$

where s_u^2 and s_c^2 are the mean-square slopes for up-wind and cross-wind, respectively. To match the measurements, however, one still finds that s_u^2 is of the order of the mean-square slopes for up-wind for an ocean with *slicks*. Thus, in using either (3.5) or (3.8) to predict the backscatter from the ocean near normal incidence, one needs a realistic reflection coefficient and the mean-square slopes of the longer waves.

Recently, Seltzer (1974) has included third-order phase corrections to the specular-point model. Higher-order amplitude corrections to the scattering may also be obtained with *physical optics*. However, these corrections are wavelength and polarization dependent; and as the wavelength of the e.m. vanishes, Equation (3.4) is the *limiting* result for backscattering.

Specular-point models have been used in investigations by Cox and Munk (1954) on the distribution of slopes of the sea from *glitter* patterns, in the satellite ocean radar-altimeter problem (Berger, 1972; Hasselmann, 1972; Barrick, 1972b) and in the radar emission from the ocean (Stogryn, 1967; Lynch and Wagner, 1970).

The backscatter of e.m. waves from the ocean is specular near normal incidence; and away from normal incidence the scattering is *diffuse*, being produced by the smaller scale roughnesses. Toward grazing incidence, other more complex mechanisms become significant at the higher radar frequencies: shadowing

(Wagner, 1967; Smith, 1967; Seltzer, 1972), diffraction (Kalmykov and Pustovoytenko, 1976), and trapping by atmospheric ducts and surface waves (Brekhovskikh, 1960) (Figure 3).

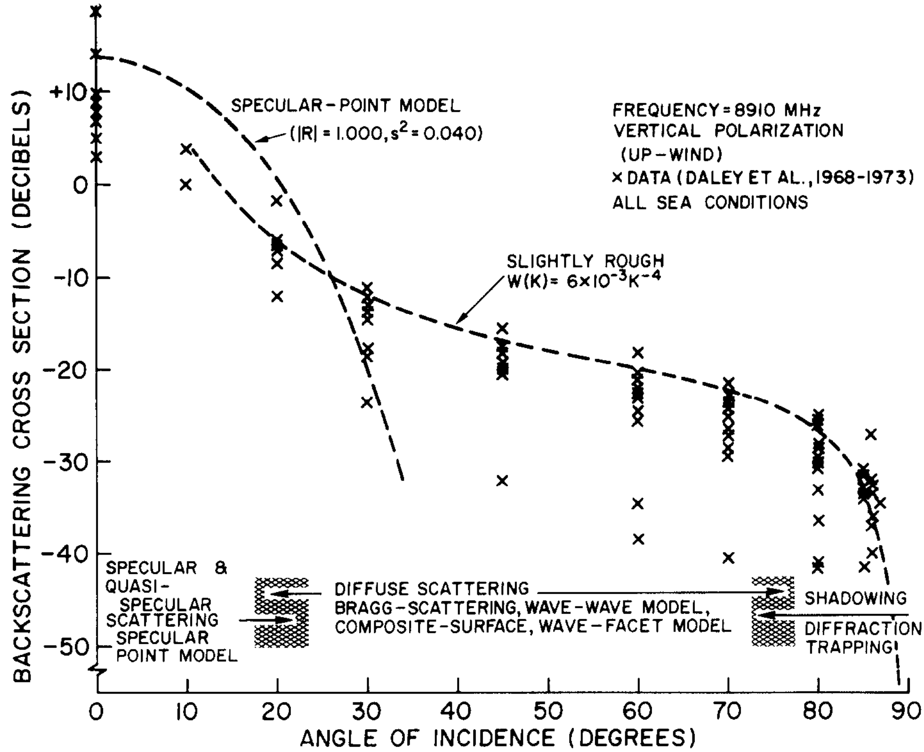


Fig. 3. Illustration of mechanisms which predominate in the radar backscatter from the ocean at the various angles of incidence.

4. Resonant, or Bragg, Scattering (Wave-wave Model)

Crombie (1955) correctly identified the backscatter from the sea of 22.1-m radio waves as being produced by a *grating* scattering mechanism. That is, at grazing incidence, water waves one-half the radio wavelength are the scattering ocean waves. The Doppler shift produced by these waves is equal to the wave freauency. Later, in controlled wave-tank experiments with mechanically-generated water waves of small amplitude, Wright (1966) found that the backscatter of 3-cm e.m. radiation is polarization dependent. The return for vertical polarization is greater than that for horizontal polarization, and the ratio increases with angle of incidence θ and the relative dielectric constant of the fluid. For backscatter, *only water waves of wave number* $2k \sin\theta$ (the Bragg resonance condition) *travelling parallel to the line of sight* contribute. The angle of incidence θ and the polarization dependence of the measured backscatter cross-section are in agreement with first-order perturbation scattering theory (Peake, 1959; Wright, 1966).

Perturbation scattering theory was used by Lord Rayleigh (1894) to investigate the scattering of sound from sinusoidal corrugated surfaces. Subsequently, the method was applied to the scattering of *planar* e.m. waves from statistically rough surfaces ξ of gentle slopes and small surface heights compared to the e.m. wavelength λ (i.e., $|k\xi|\sim|\nabla\xi|\ll 1$ a *slightly rough surface*). Rice (1951) obtained explicit first- and second-order scattered fields for a perfectly conducting slightly rough (random) surface for horizontal and vertical polarization. For a dielectric surface, explicit first-order scattered fields were given only for horizontal polarization. Peake (1959), using Rice's method, obtained first-order backscattering cross-sections for a dielectric slightly rough surface for both polarizations.

It is worthwhile to comment in more detail on the philosophy of perturbation scattering methods. The small-scale roughness is in fact replaced by effective surface currents on the mean surface (a flat surface in Rice's formulation). Mitzner (1964) developed a general perturbation formulation for arbitrarily shaped mean surface. The surface fields are expanded in the series

$$\mathbf{H}=\mathbf{H}^{(0)}+\mathbf{H}^{(1)}+\mathbf{H}^{(2)}+\cdots \tag{4.1}$$

$$\mathbf{E}=\mathbf{E}^{(0)}+\mathbf{E}^{(1)}+\mathbf{E}^{(2)}+\cdots \tag{4.2}$$

where $\mathbf{E}^{(0)}$, $\mathbf{H}^{(0)}$ are the surface fields when the small-scale roughness is absent and $\mathbf{E}^{(i)}$, $\mathbf{H}^{(i)}$ are the higher-order fields dependent on powers of the amplitude ξ. Mitzner (1964) derived expressions for the first- and second-order fields. In first order

$$\mathbf{n}\times\mathbf{E}^{(1)}=-\mathbf{n}\times\left\{\Delta(\mathbf{n}\times\mathbf{E}^{(0)})\nabla_T\xi+\xi\left[\Delta\left(\frac{\partial \mathbf{E}^{(0)}}{\partial n}\right)\right]\right\} \tag{4.3}$$

$$\mathbf{n}\times\mathbf{H}^{(1)}=-\mathbf{n}\times\left\{\Delta(\mathbf{n}\times\mathbf{H}^{(0)})\nabla_T\xi+\xi\left[\Delta\left(\frac{\partial \mathbf{H}^{(0)}}{\partial n}\right)\right]\right\} \tag{4.4}$$

where $\Delta(\cdots)$ denotes the discontinuity of the quantity at the mean surface, $\mathbf{n}$ is the unit normal to the mean surface and ∇_T is the transverse gradient operator. Hence, in first order the perturbed fields are linear functions of ξ and the higher-order fields corresponding to higher powers of ξ.

Rice's (1951) perturbation method, although different in mechanics is equivalent to Mitzner's (1964); the small-scale roughness is random with a Gaussian distribution of zero mean value and with a two-dimensional energy spectral density $W(\mathbf{K})$ (normalized according to $4\langle\xi^2\rangle=\iint W(\mathbf{K})\,d\mathbf{K}$). Then, the amplitude of the scattered fields is obtained from the boundary conditions.

In *weak-interaction theory* of statistical hydrodynamics (Hasselmann, 1968) a perturbation formulation is also used to investigate the scattering of water waves. Thus, in that context, the e.m. scattering from random rough water surfaces may be interpreted by means of a *wave-wave interaction* model involving e.m. waves and surface water waves (Hasselmann and Schieler, 1970). In the complete interaction picture, one should include electromagnetic and hydrodynamic interaction processes.

According to e.m. scattering perturbation theory, in first order the backscatter cross-sections per unit area of the ocean are: (Peake, 1959; Wright, 1968)

$$\sigma_0^{(1)}(\theta)_{ij} = 4\pi k^4 \cos^4 \theta |g_{ij}^{(1)}(\theta)|^2 W(2k \sin \theta, 0) \tag{4.5}$$

where $W(\ ,\ )$ is the two-dimensional (Cartesian) wave-number spectral density of the surface roughness (ocean), the incident radiation is in the x–z plane (z being the vertical direction and x, y are the horizontal coordinates), the indices ij denote the polarization of the incident and back-scattered radiation, respectively, and $g_{ij}^{(1)}(\theta)$ are the first-order scattering coefficients. For horizontal polarization

$$g_{\mathrm{HH}}^{(1)}(\theta) = \frac{(\varepsilon_r - 1)}{[\cos\theta + (\varepsilon_r - \sin^2\theta)^{1/2}]^2} \tag{4.6}$$

and for vertical polarization

$$g_{\mathrm{VV}}^{(1)}(\theta) = \frac{(\varepsilon_r - 1)[\varepsilon_r(1 + \sin^2\theta) - \sin^2\theta]}{[\varepsilon_r \cos\theta + (\varepsilon_r - \sin^2\theta)^{1/2}]^2} \tag{4.7}$$

where ε_r is the relative dielectric constant of the ocean (Saxton and Lane, 1952). (For free space, $\varepsilon_r = 1$ and for a perfectly conductive surface, $\varepsilon_r = -i\infty$.) According to (4.5), in first order, only ocean wave of wave-number $2k \sin\theta$ contribute to the radar back-scatter (ocean waves one-half the radar wavelength at grazing incidence, $\theta = 90°$, and corresponding longer waves for smaller angles of incidence). General bistatic conditions may be derived from Rice (1951) or Valenzuela (1967).

At this point, we would like to caution the reader that for short wind-waves, the wave-number spectrum $W(\mathbf{K})$ needed in (4.5) cannot generally be derived from the frequency spectrum of the wave system. For wind-wave systems, the dispersion relation connecting the angular frequency and the wave-number of the water waves includes advective and inertial effects of the coupled shear flow in air and water (Shemdin, 1972; Keller *et al.*, 1974; Valenzuela, 1976).

When the surface is highly conductive, for example the ocean at HF (3–30 MHz) and lower frequencies, it is more convenient to derive scattering coefficients with Rice's method in combination with an *impedance boundary* condition (Barrick, 1971). Also when interpreting experimental measurements (the transmitter is of *finite* dimensions) the backscattering cross-section of the water surface is a convolution of (4.5) with the *angular spectrum* of plane waves of the transmitted radiation (Wright and Keller, 1971).

As the amplitude of the surface roughness increases in relation to the wavelength of the e.m. radiation, second- and higher-order contributions to the scattering become significant. The depolarization of the scattered e.m. radiation in the plane of incidence is of second order for a slightly rough surface (Valenzuela, 1967); and second-order contributions to the scattering represent the interaction of the e.m.

radiation (the horizontal component of the e.m. wave number) with all possible pairs of water waves $\mathbf{K}_1$ and $\mathbf{K}_2$ satisfying (for backscatter)

$$2k \sin\theta = S_1\mathbf{K}_1 + S_2\mathbf{K}_2 \tag{4.8}$$

where S_i ($=\pm$) are sign indices. The second-order scattering coefficients (backscatter) for the polarized return are given in Valenzuela (1968).

The Doppler spectrum of the radar return is also of interest in remote sensing applications, in particular for HF scatter from the ocean. As indicated earlier, in first order the Doppler spectrum has frequency lines displaced from the radar frequency by the frequency of the Bragg resonant water waves $\omega_D = \omega_B = \omega(\mathbf{K}_B)$ (Barrick, 1972a). Accordingly,

$$\sigma_0^{(1)}(\omega_D)_{ij} = \sigma_0^{(1)}(\theta)_{ij}\,\delta(\omega_D - \omega_B) \tag{4.9}$$

where $\delta(\cdot\cdot\cdot)$ is the Dirac delta function and $\sigma_0^{(1)}(\theta)_{ij}$ is given by Equation (4.5); but now the directional properties of the wave-number spectrum (ocean) should be considered. Of course, in practice the first-order Doppler lines are broadened by electromagnetic and hydrodynamic processes.

At second order, the Doppler spectrum (in the wind direction) contains side bands on both sides of the first-order Bragg peaks. They are replicas of the frequency spectrum of the ocean if the Bragg resonant waves are shorter than the dominant waves of the ocean (Hasselmann, 1971). The second-order Doppler spectrum is of the quadratic form

$$\sigma_0^{(2)}(\omega_D)_{ij} = 4\pi k^4 \cos^4\theta\,|g_{ij}^{(2)}(\theta)|^2 \iint T^{(2)} W(\mathbf{K}_1) W(\mathbf{K}_2) \times \delta(\omega_D - s_1\omega_1 - s_2\omega_2)\,\mathrm{d}\mathbf{K}_1 \tag{4.10}$$

where $T^{(2)}$ is the transfer coefficient including e.m. and hydrodynamic contributions and ω_1, ω_2 are the angular frequencies of water waves $\mathbf{K}_1$, $\mathbf{K}_2$, respectively, satisfying Equation (4.8) for backscattering.

Barrick (1972b) investigated in detail the second-order Doppler spectrum for the ground wave at HF frequencies and found $T^{(2)}$ contained singularities at $\omega_D = 2^{1/2}\omega_B$ (second-harmonic resonance) and $2^{3/4}\omega_B$ (corner reflector) adding *spectral lines* to Hasselmann's (1971) mean second-order side bands. At the higher microwave frequencies, the basic scatterers are the shorter gravity-capillary waves that are controlled by surface tension and viscosity. The second-order Doppler contributions from gravity-capillary waves at arbitrary angle of incidence for a lossy dielectric surface and arbitrary polarization were investigated by Valenzuela (1974). Resonant interactions are possible at second order for gravity-capillary waves (Valenzuela and Laing, 1972) and these produce a second-order contribution at the frequency of the first-order Bragg lines. The resonant interactions for gravity waves, the scatterers for the lower HF radar frequencies, occur at third order (Hasselmann, 1962). Figures 4a and 4b are second-order Doppler contributions at HF and 3-cm e.m. radiation as obtained from the *generalized theory*

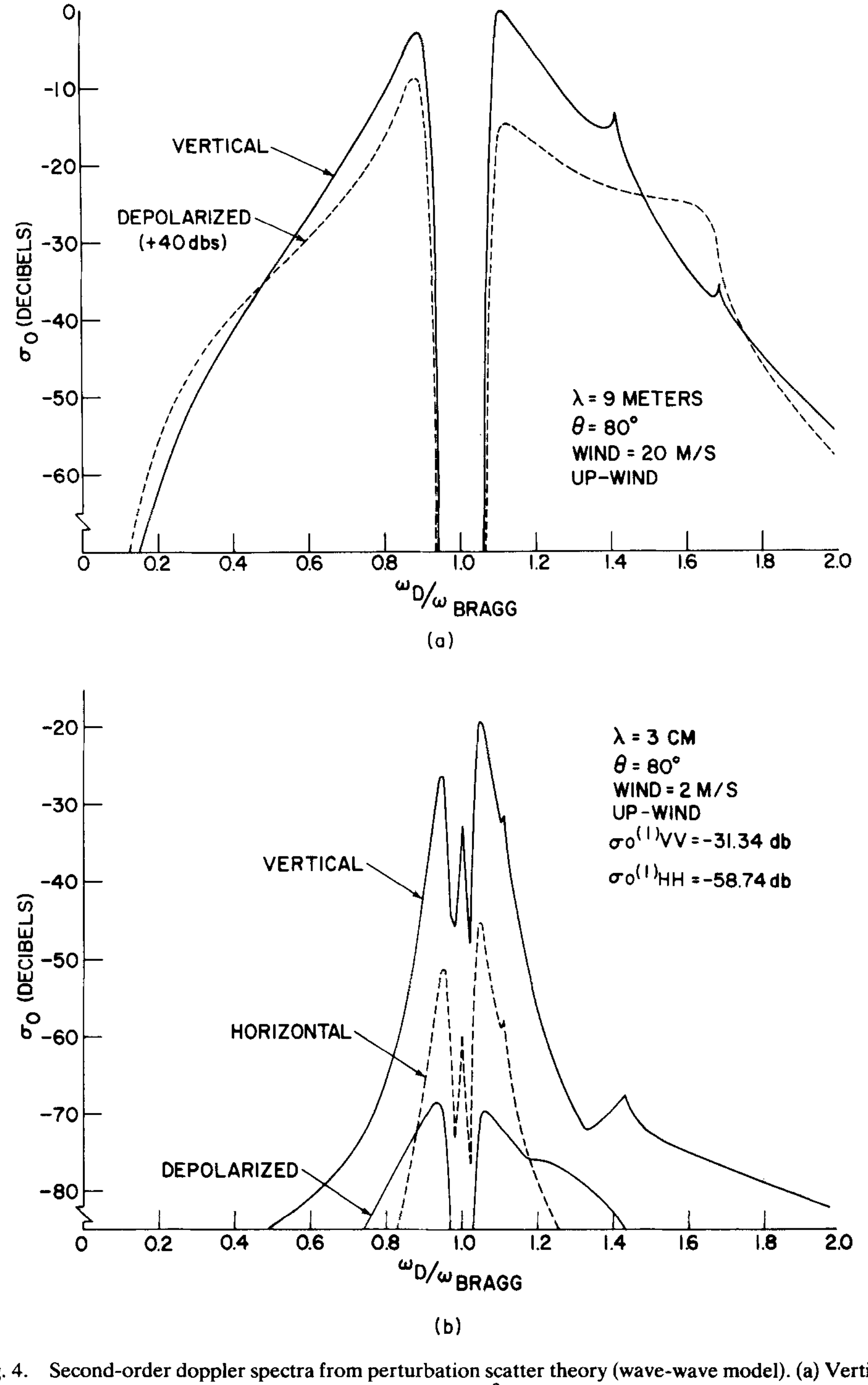


Fig. 4. Second-order doppler spectra from perturbation scatter theory (wave-wave model). (a) Vertical and depolarized spectra for 9-m e.m. radiation and a $\cos^2$ directional distribution of the wavenumber spectrum from generalized theory (Valenzuela, 1974); (b) vertical, horizontal and depolarized spectra for 3-cm e.m. radiation for a semi-isotropic spectrum from generalized theory (Valenzuela, 1974).

(Valenzuela, 1974). For gravity-capillary waves, the second-harmonic resonance line is shifted toward ω_B and the corner reflector line is shifted toward $2^{1/2}\omega_B$; now these lines are much weaker. However, for pure capillary waves (ignoring advection of the waves by surface currents and wind induced drift) the second harmonic resonance should appear at $2^{-1/2}\omega_B$ and the corner reflector line at $2^{1/4}\omega_B$. Measurements of ocean Doppler spectra at HF frequencies have been made by Ward (1969), Long and Trizna (1973) and Tyler *et al.* (1974).

Implicit in all e.m. perturbation scattering results is the *Rayleigh approximation* (only up-going scattered waves from the surface are included); in e.m. scattering theory from corrugated surfaces of sinusoidal profile, it has been shown that the *Rayleigh approximation* is valid for sinusoidal corrugations of slopes less than 0.448 (Millar, 1973). Fortunately, the slopes of gravity waves in the ocean are of order 0.14 (except at the crest of nearly breaking waves); but capillary wave slopes are as large as 0.73 (Schooley, 1958). Accordingly, perturbation scattering results apply to the ocean for a wide range of conditions and radar frequencies. Shadowing effects are already included in perturbation scattering results.

As the surface becomes rougher due to increasing wind speed and in comparison with the wavelength, higher-order contributions to the scattering become evident and ultimately the scattering is typical of a two-scale rough surface.

5. Composite-Surface Scattering (Wave-Facet Model)

Investigations on radar backscatter from the ocean have recognized for some time that the *polarization ratio* (i.e., the ratio of the cross-section for vertical to the cross-section for horizontal polarization), for large angles of incidence, decreases as the ocean becomes rougher with wind speed (Wright, 1966; Daley *et al.*, 1968). This fact, together with fortuitous experimental conditions during backscatter measurements, viz., that the wind speed increased as cross-section data were taken for increasing angles of incidence (the two-scale scattering became more evident), led Wright (1968) to formulate the *composite-surface scattering model* for the ocean.

In this model (the sea is assumed to be composed of an infinite number of *slightly rough patches*), the net back-scattered power density is an average, of the back-scattered power from a single slightly rough patch, over the distribution of slopes of the dominant waves of the ocean (non-coherent assumption). Consider that initially a slightly rough patch is horizontal and accordingly the plane of incidence of the e.m. is in the vertical plane (the angle of incidence is θ). Now assume that due to the passage of long gravity waves, the normal to the patch deviates from the vertical by an angle ψ in the plane of incidence and by an angle δ in a plane perpendicular to the plane of incidence. The resultant angle of incidence is $\theta_i = \cos^{-1}[\cos(\theta+\psi)\cos\delta]$ and the backscattering cross-section per unit area for this slightly rough patch has been obtained by (Valenzuela, 1968; Valenzuela *et al.*, 1971):

for horizontal polarization

$$\sigma_0(\theta_i)_{HH} = 4\pi k^4 \cos^4 \theta_i \left| \left(\frac{\alpha \cos \delta}{\alpha_i}\right)^2 g_{\perp\perp}^{(1)}(\theta_i) + \left(\frac{\sin \delta}{\alpha_i}\right)^2 g_{\|\|}^{(1)}(\theta_i) \right|^2 \times W(2k\alpha, 2k\gamma \sin \delta) \tag{5.1}$$

for vertical polarization

$$\sigma_0(\theta_i)_{VV} = 4\pi k^4 \cos^4 \theta_i \left| \left(\frac{\alpha \cos \delta}{\alpha_i}\right)^2 g_{\|\|}^{(1)}(\theta_i) + \left(\frac{\sin \delta}{\alpha_i}\right)^2 g_{\perp\perp}^{(1)}(\theta_i) \right|^2 \times W(2k\alpha, 2k\gamma \sin \delta) \tag{5.2}$$

and for the depolarized return

$$\sigma_0(\theta_i)_{VH} = \sigma_0(\theta_i)_{HV} = 4\pi k^2 \cos^4 \theta_i \left(\frac{\alpha \sin \delta \cos \delta}{\alpha_i^2}\right)^2 \left| g_{\|\|}^{(1)}(\theta_i) - g_{\perp\perp}^{(1)}(\theta_i) \right|^2 \times W(2k\alpha, 2k\gamma \sin \delta) \tag{5.3}$$

where $\alpha_i = \sin \theta_i$, $\alpha = \sin(\theta + \psi)$, $\gamma = \cos(\theta + \psi)$ and $g_{\perp\perp}^{(1)}$, $g_{\|\|}^{(1)}$ are the first-order scattering coefficients (4.6) and (4.7), respectively. For small tilt angles ψ and δ, (5.1)–(5.3), reduce to Wright's (1968) original expressions.

According to (5.3), depolarization of the e.m. radiation is the result of a tilted slightly rough patch. Therefore, it is possible that the second-order depolarized contribution found by Valenzuela (1967) for a slightly rough surface is an early manifestation of *tilting* and *multiple-scattering*. Depolarization is also produced by volume scattering (Rouse, 1972) for rough surfaces of relatively small dielectric constants. Nevertheless, the dielectric constant of the ocean, even at microwave frequencies, is relatively large and surface scattering should predominate.

Accordingly, the backscattering cross-section per unit area of the sea is obtained from

$$\sigma_0^{SEA}(\theta)_{ij} = \int_{-\infty}^{\infty} d(\tan \psi) \int_{-\infty}^{\infty} d(\tan \delta) \sigma_0(\theta_i)_{ij} p(\tan \psi, \tan \delta) \tag{5.4}$$

where $p(\tan \psi, \tan \delta)$ is the joint probability density of slopes for the large-scale roughness of the ocean. For vertical polarization, the backscattering cross-section per unit area of the sea predicted by (5.4) is approximately equal to (4.5), the cross-section per unit area for a slightly rough surface (Wright, 1968). Guinard and Daley (1970) and Guinard *et al.* (1971) demonstrated that the nature of the radar return from the sea at microwave frequencies is resonant, or Bragg, scattering.

The wave-number spectrum of the ocean may be obtained from radar cross-section data for vertical polarization by inversion of Equation (4.5) (Figure 5). For a light wind of 2.5 m s^{-1}, a *dip* in the spectrum toward 1.7-cm waves is evident in Figure 5. A similar phenomenon has been observed in wave-tanks for wind speeds less than 7 m s^{-1} (Wright and Keller, 1971). The relatively small amplitude of gravity-capillary waves for light winds is produced by the energy transfer of

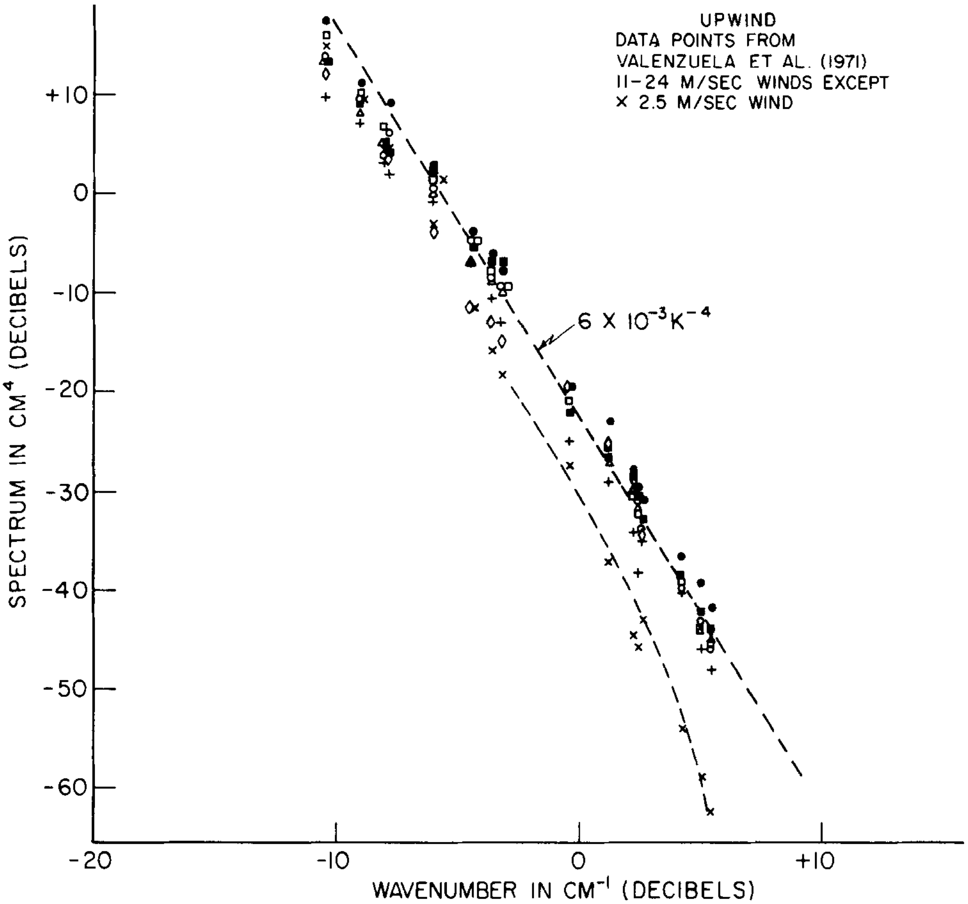


Fig. 5. Ocean wave-number spectra inferred from vertically polarized radar backscatter at 428 MHz, 1228 MHz, 4455 MHz and 8910 MHz for various wind speeds.

gravity-capillary waves by non-linear resonant interactions (Valenzuela and Laing, 1972).

Actually, Equation (5.4) does not apply for angles near normal nor near grazing incidence. Semyonov (1966) and Barrick and Peake (1968) have shown that to obtain the cross-section of the sea in first approximation, one adds the cross-section from the specular-point model, Equation (3.4), and the cross-section predicted for a slightly rough surface, Equation (4.5) (this assumes the large scale roughness ζ and the small scale roughness ξ are not correlated). However, it is more appropriate to add the cross-section from the specular-point model and that predicted by the composite-surface model, Equation (5.4), instead, since *tilts* do significantly modify the cross-section for horizontal polarization and they also yield a depolarized contribution.

In Figures 6 and 7, cross-section data obtained by the U.S. Naval Research Laboratory (Daley *et al.*, 1968–1973) are compared with the prediction of the

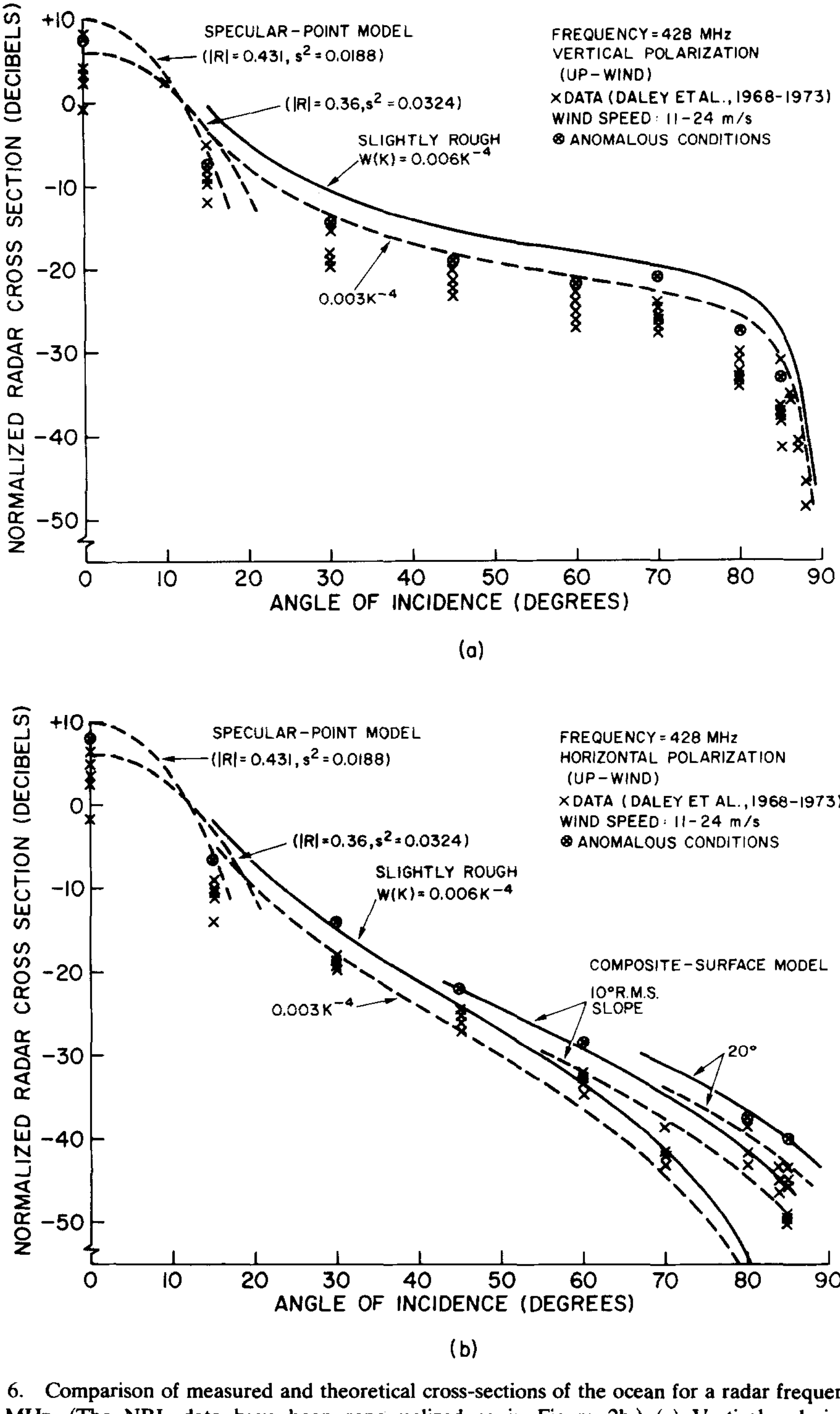


Fig. 6. Comparison of measured and theoretical cross-sections of the ocean for a radar frequency of 428 MHz. (The NRL data have been renormalized as in Figure 2b.) (a) Vertical polarization; (b) horizontal polarization.

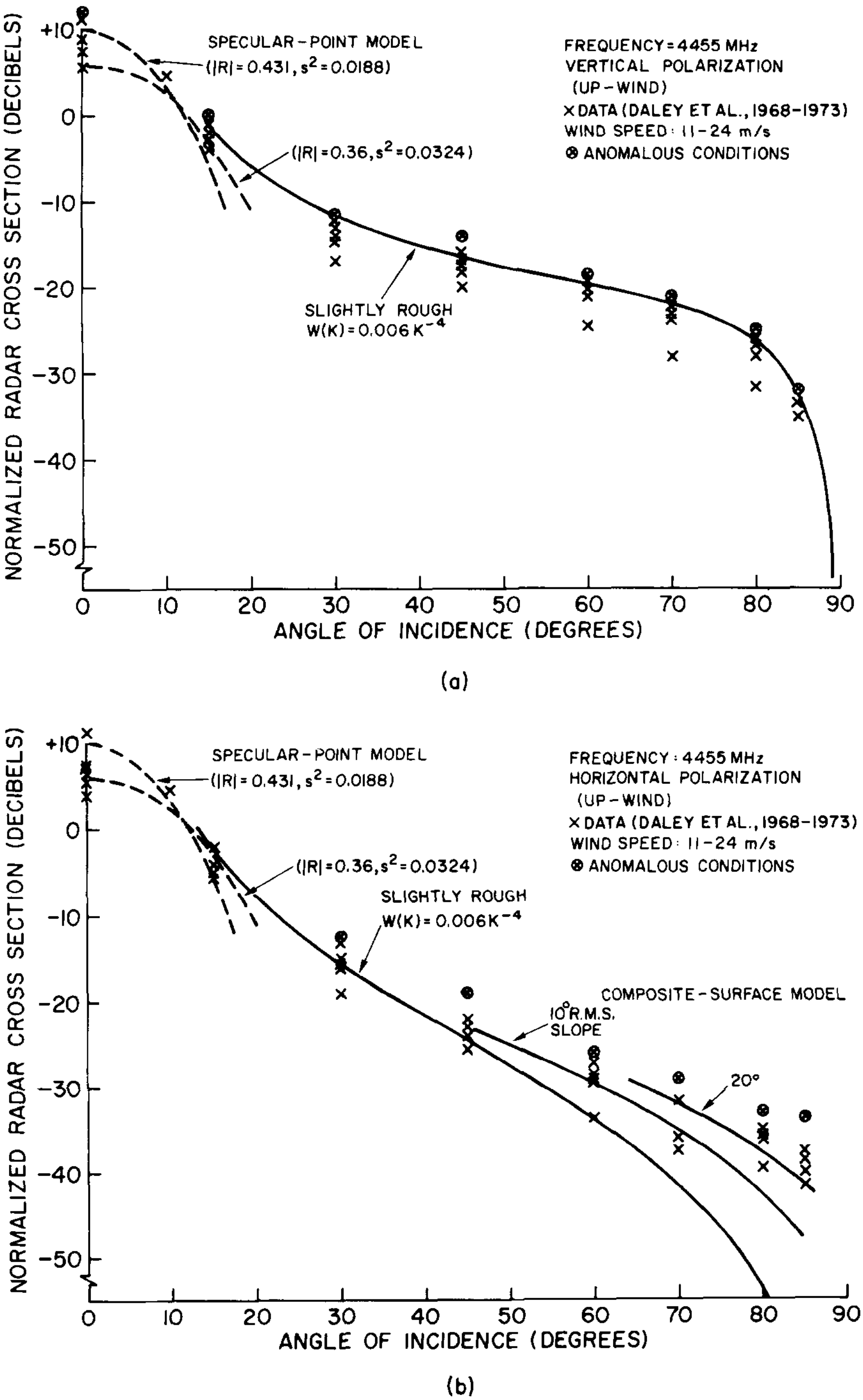


Fig. 7. Comparison of measured and theoretical cross-sections of the ocean for a radar frequency of 4455 MHz. (The NRL data have been renormalized as in Figure 2b.) (a) Vertical polarization; (b) horizontal polarization.

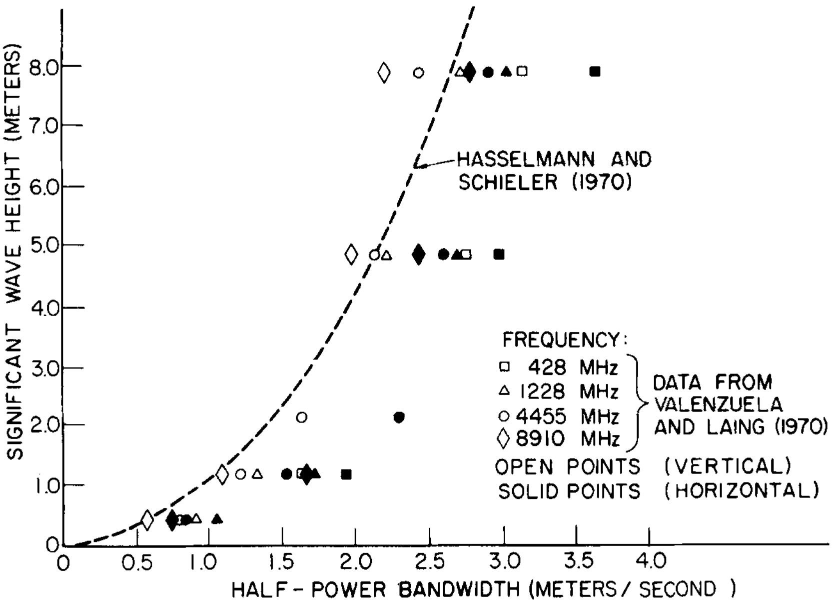
composite-surface scattering model. The composite-surface model is quite adequate for angles of incidence even close to grazing for the lower radar frequency (428 MHz). At the higher radar frequency (4455 HMz), a disagreement for horizontal polarization becomes evident for angles toward grazing. In these Figures, we have also included, about normal incidence, the prediction from the isotropic Gaussian specular-point model using an effective reflection coefficient and the mean-square slopes to match the measurements. The *anomalous conditions* indicated in Figure 6 and 7 refer to a day with precipitation (snow) when the air was colder than the water.

The e.m. scatter from a two-scale rough surface may be obtained in a more formal manner by means of a *local slightly-rough* boundary condition, usually the first two terms in Equations (4.1) and (4.2), for the surface fields on the gently undulating large-scale roughness. The scattered fields are then obtained with the Stratton–Chu integral equations. This procedure has been followed by Soviet scientists (Shmelev, 1972) and Fung and Chan (1969). In the process of obtaining the final results, many mathematical approximations are required. Unfortunately, Fung and Chan's scattering results disagree with available results in well-known limiting conditions (Barrick, 1970).

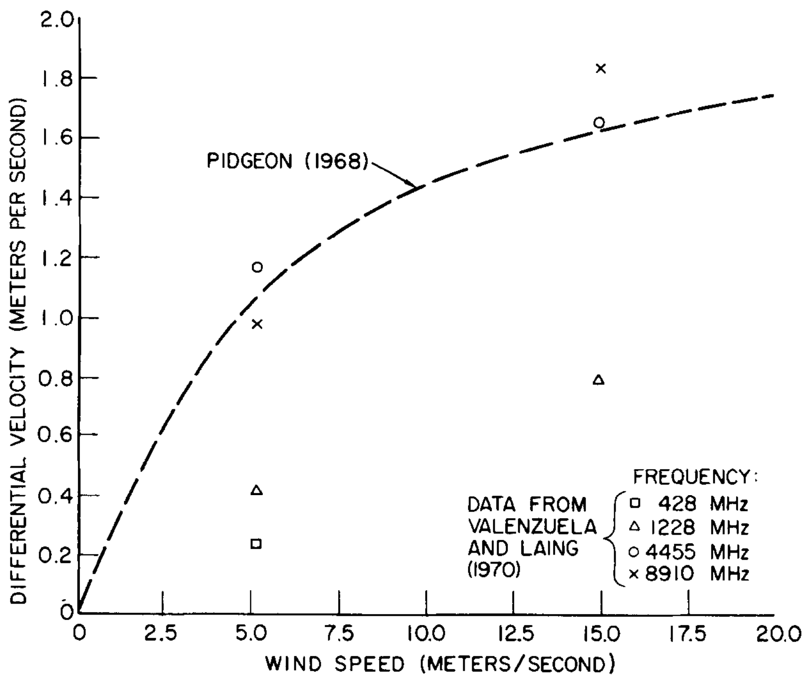
Two-scale scattering models have been used by Wu and Fung (1972) and Wentz (1975) to predict the apparent temperature of a rough sea, and the agreement with measurements is generally better than for the predictions by geometrical optics where the small-scale roughnesses are absent. DeRosa (1972) also uses a two-scale scattering model to investigate fading in communication links between Earth and satellites.

In most two-scale scattering developments, it is assumed that the large-scale roughness is *not correlated* with the small-scale roughness (see, however, Fung and Chan, 1969). However, Keller and Wright (1975) have recently shown that in water-wave systems the large-scale flow modulates the short gravity waves, and accordingly they are *correlated.* This correlation of small and large-scale roughness may contribute to radar backscatter near normal incidence, and the correlation of long and short gravity waves has also hydrodynamic implications in the transfer of energy from the atmosphere to the ocean (Valenzuela and Wright, 1976).

The composite-surface scattering model has been used to investigate the Doppler spectrum of the radar return from the sea for microwaves (Valenzuela and Laing, 1970; Hasselmann and Schieler, 1970) and in wave-tanks (Duncan *et al.*, 1974). Hasselmann and Schieler, in a detailed analysis, find in the zeroth approximation (in terms of the slope of the dominant wave) the Doppler spectrum is Gaussian in shape and they corroborate that the band-width is wave-height dependent (Figure 8a). The polarization and frequency dependencies of the bandwidth of the measured Doppler spectra are not completely explained by the higher-order corrections to the shape of the Doppler spectrum. However, the first-order corrections (through the correlation of wave slope and orbital velocity) do predict the larger



(a)



(b)

Fig. 8. Properties of Doppler spectra of radar backscatter at microwave frequencies. (a) Half-power bandwidth (averages for grazing angles of 5° to 30°); (b) difference in mean Doppler frequency (in velocity units) of horizontal and vertical spectra (grazing angles less than 10°).

mean Doppler shifts for the horizontal spectra, but not as large as observed in the data (Pidgeon, 1958; Valenzuela and Laing, 1970) (Figure 8b).

From the comparisons of the composite-surface scattering-model predictions with measurements from the ocean, Figures 6–8, we may conclude that the model does not explain in a quantitative manner the characteristics of radar backscatter for the higher radar frequencies (toward 3-cm e.m. radiation) and toward grazing incidence. Recently, Kalmykov and Pustovoytenko (1976) have observed, at grazing incidence, that a significant portion of the backscatter of horizontally polarized energy is produced by the crests of the ocean waves, while the backscatter of vertically polarized energy is more distributed over the whole wave. (Also see Long, 1974.) To explain this scattering phenomenon, Kalmykov and Pustovoytenko (1976) propose a scattering model including a combination of *composite-surface* and *wedge* scattering. This combined scattering model supposedly explains the larger horizontal cross-sections at grazing incidence for the ocean driven by high winds, and predicts greater mean frequency shifts in the Doppler spectrum for horizontal than for vertical polarization. However, a final decision on the merits of this combined scattering model awaits more detailed comparisons with experiment.

6. Conclusions

Much progress has been made in understanding the radar scatter from water waves and from the ocean. However, the solution of the ocean radar-scatter problem is by no means complete, in particular for the higher radar frequencies (toward centimetric radiation) and toward grazing incidence.

We have available some useful and tractable analytical scattering models to predict and interpret the radar scatter from a dynamic ocean surface. Oceanographic parameters have already been obtained by *inversion* of the scattering models at HF and microwave frequencies (i.e., wave height, wave spectrum, wind speed, surface currents, and apparent ocean temperature). The *specular-point model* (Barrick, 1968) applies in the neighborhood of the specular direction (normal incidence for backscatter), but one should be careful in using realistic parameters in applying this model to the ocean. For example, only the mean-square slopes of waves longer than the wavelength of the e.m. radiation influences the scatter, and an effective reflection coefficient should be used. The small-scale roughness on the surface and a mixed layer of wind-blown *spray* and *foam* at the air-sea interface modify the reflection properties of the ocean surface.

The *diffuse scatter* away from normal incidence (for backscatter) is explained quite well by *resonant scatter* (wave-wave model) even at grazing incidence for the lower radar frequencies (less than 100 MHz) (Peake, 1959; Wright, 1966; Valenzuela, 1967; Hasselmann, 1971; Barrick, 1972b; Long and Trizna, 1973; Valenzuela, 1974). At the higher radar frequencies (toward centimetric radiation) the radar scatter from the ocean is typical of a *two-scale rough surface* (Wright, 1968; Bass *et al.*, 1968; Valenzuela, 1968; Barrick and Peake, 1968; Hasselmann and

Schieler, 1970; Valenzuela *et al.*, 1971; Wu and Fung, 1972; Wentz, 1975), except near grazing incidence where other mechanisms also become significant: *shadowing, diffraction, and trapping.*

The validity of these scattering models to water waves and to the ocean has been demonstrated from coastal and aircraft measurements. These scattering models should also be applicable to remote sensing of the ocean from satellite, but now the additional effects of *atmospheric absorption* and *refraction* should affect the radiometric and imaging radar systems.

Future advances in scattering theory should be contributed by the more exact methods (integral equations and Green's function, Shmelev, 1972; DeSanto, 1974).

References

Andreasen, M. G.: 1965, 'Scattering from Bodies of Revolution', *IEEE Trans.* AP-**13**, 303–310.

Barrick, D. E.: 1968, 'Rough Surface Scattering Based on the Specular Point Theory', *IEEE Trans.* AP-**16**, 449–454.

Barrick, D. E.: 1970 'Comments on backscattering of Waves by Composite Rough Surfaces', *IEEE Trans.* AP-**18**, 718–719.

Barrick, E. E.: 1971, 'Theory of HF/VHF Propagation across the Rough Sea', *Radio Sci.* **6**, 517–533.

Barrick, D. E.: 1972a, 'First-Order Theory and Analysis of MF/HF/VHF Scatter from the Sea', *IEEE Trans.* AP-**20**, 2–10.

Barrick, D. E.: 1972b, 'Remote Sensing of Sea State by Radar', Chapter 12 in V. E. Derr (ed.), *Remote Sensing of the Troposphere*, Washington, D.C.

Barrick, D. E.: 1974, 'Wind Dependence of Quasi-Specular Microwave Sea Scatter', *IEEE Trans.* AP-**22**, 135–136.

Barrick, D. E. and Peake, W, H.: 1968, 'A Review of Scattering from Surfaces with Different Roughness Scales', *Radio Sci.* **3**, 865–868.

Bass, F. G., Fuks, I. M., Kalmykov, A. E., Ostrovsky, I.E., and Rosenberg, A. D.: 1968, 'Very High Frequency Radiowave Scattering by a Disturbed Sea Surface', *IEEE Trans.* AP-**16**, 554–568.

Beckmann, P. and Spizzichino, A.: 1963, *The Scattering of Electromagnetic Waves from Rough Surfaces*, Macmillan Co., New York, N.Y., 503 pp.

Berger, T.: 1972, 'Satellite Altimetry Using Ocean Backscatter', *IEEE Trans.* AP-**20**, 295–309.

Braude, S. Ya.: 1962, *Radio-Oceanographic Studies of Ocean Waves*, Ukranian Academy of Sciences Press.

Brekhovskikh, L. M.: 1952, 'The Diffraction of Waves by a Rough Surface', *Zh. Eksper. i Teor. Fiz.* **23**, 275–289.

Brekhovskikh, L. M.: 1960, *Waves in Layered Media*, Academic Press, New York, N.Y., 460 pp.

Cox, C. and Munk, W.: 1954, 'Measurement of the Roughness of the Sea Surface from Photographs of the Sun's Glitter', *J. Opt. Soc. Am.* **44**, 838–850.

Crombie, D. D.: 1955, 'Doppler Spectrum of Sea Echo at 13.56 Mc/s', *Nature* **175**, 681–682.

Daley, J. C.: 1973, 'An Empirical Sea Clutter Model', Memorandum Report No. 2668, Naval Research Laboratory, Washington, D.C., 32 pp.

Daley, J. C., Ransone, J. T., Burkett, J. A., and Duncan, J. R.: 1968, 'Sea-Clutter Measurements on Four Frequencies', Report No. 6806, Naval Research Laboratory, Washington, D.C., 42 pp.

Daley, J. C., Davis, W. T., and Mills, N. R.: 1970, 'Radar Sea Return in High Sea States', Report No. 7142, Naval Research Laboratory, Washington, D.C., 46 pp.

Daley, J. C., Ransone, J. T., and Burkett, J. A.: 1971, 'Radar Sea Return – JOSS I', Report No. 7268, Naval Research Laboratory, Washington, D.C., 49 pp.

Daley, J. C., Ransone, J. T., and Davis, W. T.: 1973, 'Radar Sea Return – JOSS II', Report No. 7534, Naval Research Laboratory, Washington, D.C., 15 pp.

DeRosa, J. K.: 1972, 'The Characterization of Multipath and Doppler Fading in Earth Scatter Communication, Navigation, and Radar Links', Ph.D. Thesis, Northeastern Univ., Boston, Mass.

DeSanto, J. A.: 1974, 'Green's Function for Electromagnetic Scattering from a Random Surface', *J. Math. Phys.* **15**, 283–288.

Duncan, J. R., Keller, W. C., and Wright, J. W.: 1974, 'Fetch and Wind Speed Dependence of Doppler Spectra', *Radio Sci.* **9**, 809–819.

Fung, A. K. and Chan, H.: 1969, 'Backscattering of Waves by Composite Rough Surfaces', *IEEE Trans.* AP-**17**, 590–597.

Guinard, N. W. and Daley, J. C.: 1970, 'An Experimental Study of a Sea Clutter Model', *Proc. IEEE* **58**, 543–550.

Guinard, N. W., Ransone, J. T., and Daley, J. C.: 1971, 'Variation of the NRCS of the Sea with Increasing Roughness', *J. Geophys. Res.* **76**, 1525–1538.

Hagfors, T.: 1964, 'Backscattering from an Undulating Surface with Applications to Radar Returns from the Moon', *J. Geophys. Res.* **69**, 3779–3784.

Hasselmann, K.: 1962, 'On the Non-linear Energy Transfer in a Gravity-Wave Spectrum', *J. Fluid Mech.* **12**, 481–500.

Hasselmann, K.: 1968, 'Weak-Interaction Theory of Ocean Waves', in M. Holt (ed.), *Basic Developments in Fluid Dynamics*, Academic Press, New York, pp. 117–182.

Hasselmann, K.: 1971, 'Determination of Ocean Spectra from Doppler Radio Return from Sea Surface', *Nature* **229**, 16–17.

Hasselmann, K.: 1972, 'The Energy Balance of Wind Waves and the Remote Sensing Problem', in Proc. Sea Surface Topography from Space, Nat. Oceanic and Atmospheric Admin. tech. Rep. ERL-228, Boulder, Col.

Hasselmann, K. and Schieler, M.: 1970, 'Doppler Spectra of Electromagnetic Backscatter from the Sea Surface at Centimeter-Decimeter and Decameter Wavelengths', Proc. VIIIth Naval Hydrodyn. Symp. pp. 361–388.

Hasselmann, K. *et XV al.*: 1973, 'Measurements of Wind-Wave Growth and Swell Decay during the Joint North Sea Wave Project (JONSWAP)', *Deutsche Hydrogr. Z.*, Suppl. A (8°), No. 12.

Kalmykov, A. I. and Pustovoytenko, V. V.: 1976, 'On Polarization Features of Radio Signals Scattered from the Sea Surface at Small Grazing Angles', *J. Geophys. Res.* **81**, 1960–1964.

Keller, W. C. and Wright, J. W.: 1975, 'Microwave Scattering and the Straining of Wind-Generated Waves', *Radio Sci.* **10**, 139–147.

Keller, W. C., Larson, T. R., and Wright, J. W.: 1974, 'Mean Speeds of Wind Waves at Short Fetch', *Radio Sci.* **9**, 1091–1100.

Kodis, R.: 1966, 'A Note on the Scattering from an Irregular Surface', *IEEE Trans.* AP-**14**, 77–82.

Larson, T. R. and Wright, J. W.: 1975, 'Wind-Generated Gravity-Capillary Waves: Laboratory Measurements of Temporal Growth Rates using Microwave Backscatter', *J. Fluid Mech.* **70**, 417–436.

Long, M. W.: 1974, 'On a Two-Scatterer Theory of Sea Echo', *IEEE Trans.* AP-**22**, 667–672.

Long, A. E. and Trizna, D. B.: 1973, 'Mapping of Northern Atlantic Winds by HF Radar Sea Backscatter Interpretation', *IEEE Trans.* AP-**21**, 680–685.

Longuet-Higgins, M. S.: 1963, 'The Effect of Non-Linearities on Statistical Distributions in the Theory of Sea Waves', *J. Fluid Mech.* **17**, 459–480.

Lynch, P. J. and Wagner, R. J.: 1970, 'Rough-Surface Scattering: Shadowing, Multiple Scatter and Energy Conservation', *J. Math. Phys.* **11**, 3032–3042.

Maue, A. W.: 1949, 'Zur Formulierung eines allgemeinen Beugungsproblems durch eine Integralgleichung', *Z. Physik.* **126**, 601–618.

Millar, R. F.: 1973, 'The Rayleigh Hypothesis and a Related Least-Squares Solution to Scattering Problems for Periodic Surfaces and Other Scatters', *Radio Sci.* **8**, 785–796.

Mitzner, K. M.: 1964, 'Effect of Small Irregularities on Electromagnetic Scattering from an Interface of Arbitrary Shape', *J. Math. Phys.* **5**, 1776-1786.

Mitzner, K. M.: 1967, 'An Integral Equation Approach to Scattering from a Body of Finite Conductivity', *Radio Sci.* **2**, 1459–1470.

Müller, C.: 1957, *Grundprobleme der Mathematischen Theorie Elektromagnetischer Schwingungen*, Springer-Verlag, Berlin, 344 pp.

Peake, W. H.: 1959, 'Theory of Radar Return from Terrain', *IRE National Convention Record* **7**, 27–41.

Phillips, O. M.: 1966, *The Dynamics of the Upper Ocean*, Cambridge Univ. Press, Cambridge, 261 pp.

Pidgeon, V. W.: 1968, 'Doppler Dependence of Radar Sea Return', *J. Geophys. Res.* **73**, 1333–1341.

Rice, S. O.: 1951, 'Reflection of Electromagnetic Waves from Slightly Rough Surfaces', *Comm. Pure Appl. Math.* **4**, 351–378.

Rouse, J. W., Jr.: 1972, 'The Effect of Subsurface on Depolarization of Rough Surface Backscatter', *Radio Sci.* **7**, 889–895.

Ruck, G. T., Barrick, D. E., Stewart, W. D., and Kirshbaum, C. K.: 1970, *Radar Cross-Section Handbook*, Plenum Press, N.Y.

Saxton, J. A. and Lane, J. A.: 1952, 'Electrical Properties of Sea Water', *Wireless Eng.* **291**, 269–275.

Schooley, A. H.: 1958, 'Profiles of Wind-Created Water Waves in the Capillary-Gravity Transition Region', *J. Marine Res.* **16**, 100–108.

Seltzer, J. E.: 1972, 'Spatial Densities for Specular Points on a Gaussian Surface', *IEEE Trans.* AP-**20**, 723–731.

Seltzer, J. E.: 1974, 'A Third-Order Specular-Point Theory for Radar Backscatter', in Electromagnetic Wave propagation Involving Irregular Surfaces and Inhomogeneous Media, AGARD Conf. Proc. 144, The Hague, Netherlands, Ref. No. 2, 16 pp.

Semyonov, B.: 1966, 'Approximate Computation of Scattering of Electromagnetic Waves by Rough Surface Contours', *Radio Eng. and Electron. Phys.* **8**, 1179–1187 (Translation).

Senior, T. B. A.: 1961, 'Impedance Boundary Conditions for Imperfectly Conductive Surfaces', *Appl. Sci. Res.* B **8**, 418–462.

Shemdin, O. H.: 1972, 'Wind-Generated Current and Phase Speed of Wind Waves', *J. Phys. Oceanogr.* **2**, 411–419.

Shmelev, A. B.: 1972, 'Wave Scattering by Statistically Uneven Surfaces', *Usp. Fiz. Nauk* **106**, 459–480.

Siegel, K. M.: 1958, 'Far Field Scattering from Bodies of Revolution', *Appl. Sci. Research* B **7**, 293–328.

Smith, B. G.: 1967, 'Geometrical Shadowing of a Random Rough Surface', *IEEE Trans.* AP–**15**, 668–671.

Stogryn, A.: 1967, 'The Apparent Temperature of the Sea at Microwave Frequencies', *IEEE Trans.* AP–**15**, 278–286.

Stratton, J. A.: 1941, '*Electromagnetic Theory*', McGraw-Hill, New York, N.Y., 615 pp.

Strutt, J. W. (Lord Rayleigh): 1894, '*The Theory of Sound*', Macmillan, London, 480 pp.

Tyler, G. L., Teague, C. C., Stewart, R. H., Peterson, A. M., Munk, W. H., and Joy, J. W.: 1974, 'Wave Directional Spectra from Synthetic Aperture Observations of Radio Scatter', *Deep-Sea Res.* **21**, 989–1016.

Valenzuela, G. R.: 1967, 'Depolarization of E.M. Waves by Slightly Rough Surfaces', *IEEE Trans.* AP-**15**, 552–557.

Valenzuela, G. R.: 1968, 'Scattering of Electromagnetic Waves from a Tilted Slightly Rough Surface', *Radio Sci.* **3**, 1057–1066.

Valenzuela, G. R.: 1970, 'The Effective Reflection Coefficients in Forward Scatter from a Dielectric Slightly Rough Surface', *Proc. IEEE* **58**, 1279.

Valenzuela, G. R.: 1974, 'The Effect of Capillarity and Resonant Interactions on the Second-Order Doppler Spectrum of Radar Sea Echo', *J. Geophys. Res.* **79**, 5031–5037.

Valenzuela, G. R.: 1976, 'The Growth of Gravity-Capillary Waves in a Coupled-Shear Flow', *J. Fluid Mech.* **76**, 229–250.

Valenzuela, G. R. and Laing, M. B.: 1970, 'Study of Doppler Spectra of Radar Sea Echo', *J. Geophys. Res.* **75**, 551–563.

Valenzuela, G. R. and Laing, M. B.: 1972, 'Nonlinear Energy Transfer in Gravity-Capillary Wave Spectra, with Applications', *J. Fluid Mech.* **54**, 507–520.

Valenzuela, G. R. and Wright, J. W.: 1976, 'The Growth of Waves by Modulated Wind Stress', *J. Geophys. Res.* **81**, 5795–5796.

Valenzuela, G. R., Laing, M. B., and Daley, J. C.: 1971, 'Ocean Spectra for the High Frequency Waves as Determined from Airborne Radar Measurements', *J. Marine Res.* **29**, 69–84.

Wagner, R. J.: 1967, 'Shadowing of Randomly Rough Surfaces', *J. Accoust. Soc. Amer.* **41**, 138–147.

Walsh, E. J.: 1974, 'Analysis of Experimental NRL Radar Altimeter Data', *Radio Sci.* **9**, 711–722.

Ward, J. F.: 1969, 'Power Spectra from Ocean Movements Measured Remotely by Ionospheric Radio Backscatter', *Nature* **223**, 1325–1330.

Wentz, F. J.: 1975, 'A Two-Scale Scattering Model for Foam-Free Sea Microwave Brightness Temperatures', *J. Geophys. Res.* **80**, 3441–3446.

Wright, J. W.: 1966, 'Backscattering from Capillary Waves with Application to Sea Clutter', *IEEE Trans.* AP-**14**, 749–754.

Wright, J. W.: 1968, 'A New Model for Sea Clutter', *IEEE Trans.* AP-**16**, 217–223.

Wright, J. W. and Keller, W. C.: 1971, 'Doppler Spectra in Microwave Scattering from Wind Waves', *Phys. Fluids* **14**, 466–474.

Wu, S. T. and Fung, A. K.: 1972, 'A Noncoherent Model for Microwave Emissions and Backscattering from the Sea Surface', *J. Geophys. Res.* **77**, 5917–5929.

Yaplee, B. S., Shapiro, A., Hammond, B. D., and Uliana, E. A.: 1971, 'Nanosecond Radar Observations of the Ocean Surface from a Stable Platform', *IEEE Trans.* GE-**9**, 170–174.