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MICROWAVE BACKSCATTERING THEORY AND ACTIVE REMOTE SENSING OF THE OCEAN SURFACE

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FINAL REPORT

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16. Abstract

This report reviews the status of electromagnetic scattering theory relative to the interpretation of microwave remote sensing data acquired from spaceborne platforms over the ocean surface. Particular emphasis is given to the assumptions which are either implicit or explicit in the theory. The multiple scale scattering theory developed during this investigation is extended to non Gaussian surface statistics. It is shown that the important statistic for this case is the probability density function of the small scale heights conditioned on the large scale slopes; this dependence may explain the anisotropic scattering measurements recently obtained with the AAFE Radscat. It is noted that present surface measurements are inadequate to verify or reject the existing scattering theories. Surface measurements are recommended for qualifying sensor data from radar altimeters and scatterometers. Additional scattering investigations are suggested for imaging type radars employing synthetically generated apertures.

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1.0 INTRODUCTION

Active microwave remote sensing of the ocean surface is rapidly moving out of the realm of research and into a nearly operational status. However, this movement does not necessarily mean that all the problems associated with interpreting microwave sensor data have been resolved. By the same token, it is becoming increasingly obvious that neither electromagnetic nor oceanographic researchers, working in isolated environments, can separately solve the significant problems. However, with a joint effort, it is felt that significant strides can be made in this area. For example, the electromagnetic researcher needs to know, from the oceanographer, which scattering model assumptions are not valid for the ocean surface while, conversely, the oceanographer must know what measurements are necessary to validate the electromagnetic scattering theory.

The purpose of this investigation was to review the current state of affairs in the area of microwave scattering theory as applied to the ocean surface and to point out those problems requiring further investigation. In particular, the areas addressed were basic rough surface electromagnetic scattering theory, sensor-specific scattering theory, and requirements for supporting oceanographic research. The remainder of this section comprises a summary of results and a list of recommendations for additional research. These recommendations are based upon apparent shortcomings in the present state of microwave remote sensing as identified in this study.

1.1 Summary of Results

Existing theories for microwave backscatter from the ocean surface are reviewed from the point of view of their fundamental assumptions about the surface. A new multiple scale surface scattering theory is developed which overcomes some of the limitations of the conventional composite surface theory.* The implications of this theory are discussed and its limitations are presented. Existing surface measurements are inadequate for validating this scattering theory.

Three specific microwave remote sensors are studied from the standpoint of deficiencies in our understanding of their data outputs. For radar altimetry, sea state bias and the response of the radar to swell dominated conditions appear to warrant further theoretical and experimental research. Understanding wide angle scatterometry data requires further oceanographic research into the behavior of the high frequency waveheight spectrum. Recent scatterometer measurements are shown to be at variance with existing interpretations of some oceanographic data and theory as to the nature of the capillary range of the spectrum. Finally, the brief study of synthetic aperture radars indicates the need for a complete reevaluation of the scattering models which are presently used to interpret the data. A short discussion of the deficiencies in the existing models is presented.

1.2 Recommendations For Future Studies

The following list encompasses those areas which were identified during this study as requiring additional investigation.

1. The new composite surface scattering theory developed during this study should be extended to dielectric surfaces and numerical computations should be carried out to determine the degree of depolarization to be expected for very rough surfaces.

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* This material is documented in a separate report [1] for the jointly Gaussian surface. Results for the more general surface are summarized here.

2. Measurements of the joint slope probability density function should be made for the large scale surface. This also implies that techniques will have to be developed for filtering the slope data to remove the effects of the small scale structure. It is also desirable to know how the large scale slopes and the small scale heights are correlated.

3. In order to better understand microwave scattering theory and measurements, it is absolutely essential that experimental and/or theoretical descriptions of the behavior of the high frequency height spectrum be obtained. This is crucial to the qualification of the scatterometer as a valid wind vector sensor.

4. Additional theoretical microwave scattering research is necessary before a complete understanding of synthetic aperture radar data is possible.

5. GEOS-3 waveform data under high sea state conditions should be carefully examined to determine possible sea state bias effects. An extension of Seltzer's analysis [20] to non-Gaussian surface statistics should be made to assess their altitude bias potential. Supporting oceanographic measurements on the joint height and slope density function would be most beneficial.

6. GEOS-3 data for swell dominated surface conditions should be examined and compared to theoretical models for the purpose of determining the effect upon automated waveform processing models.

Quite obviously, some of these areas are multi-year efforts, however they are considered essential to furthering our understanding of the scattering of microwave energy by the sea surface. In addition, it is essential that the efforts of radar and oceanographic specialists be very well coordinated. It must be remembered that there is probably a certain degree of hesitancy on the part of the user community to accepting radar-derived oceanographic information. This is probably due to the fact that the basic radar data requires interpretation by extremely skilled specialists; a situation which is significantly different from that of visible or infrared photography. Furthermore, microwave remote sensing has the potential of providing, on a synoptic scale, much more information on the state of the ocean's surface than was ever before possible. However, one of the points which came up repeatedly during this initial study was the fact that qualification of microwave sensor data requires a much more extensive knowledge of the surface; thus the need for a closely coupled joint effort.

2.0 REVIEW OF THE SURFACE ASSUMPTIONS IN SCATTERING THEORY

The interpretation of microwave scattering measurements nearly always involves some model for how the scattering object alters the incident electromagnetic field. This model, whether it be empirical or analytical, must be based upon the physics of the scattering process. In the case of an analytical model, certain assumptions are usually made in order to simplify the mathematical details, and these assumptions involve some relative characteristic of the scattering object. This approach has great merit for it not only results in mathematically compact answers but also provides a solution which more complicated models must equal under the same surface assumptions. Even for empirical models, which are based upon a finite number of prior observations, there is usually some known limiting form. Thus, solutions which are strictly only valid for certain configurations of the scatterer are essential to understanding the more general problem.

The conventional model for scattering from rough surfaces at microwave frequencies has evolved from the combination of two surface restricted solutions. These two solutions will be examined for the purpose of determining their limitations and how they might be extended to more general surfaces. This same type of examination will also be applied to the scattering model developed during this investigation [1]. In addition to pointing out the limitations of existing scattering models, this study will also show what specific surface characteristics need be measured in order to verify the adequacy of the models.

The present trend in the analysis of electromagnetic scattering problems is toward the use of numerical techniques and large computers to solve the basic integral equation for the current induced on the scattering object. While this approach has significant merit when applied to deterministic scattering problems, it is not particularly attractive for random scattering problems. That is, because of the number of computer runs that would be required to generate a meaningful result, the approach is necessarily limited relative to random scattering problems. Even given the time, money, and computer necessary to accomplish such a task, extreme care must be exercised in translating the details of the basic problem to the simulation. For these reasons, the search for analytical solutions is not only justified but essential.

This report is not intended as a comprehensive review of all the theoretical and experimental work in the field of rough surface scattering. For such material, the reader is referred to the excellent report by Barrick and Peake [2].

2.1 Boundary Perturbation Approach

Perhaps the most successful of all analytical techniques applied to rough surface scattering problems is perturbation theory. Rice [3] first applied this technique to the problem of scattering of electromagnetic waves by a slightly rough dielectric surface and Peake [5] developed Rice's results into expressions for the scattering cross section of the surface. Bass and Bocharov [4] applied essentially the same technique to scattering by a slightly rough perfectly conducting surface. Valenzuela [6] has obtained expressions for the second order perturbation fields which give rise to depolarization. The basic approach entails expanding both the random surface height and the scattered fields in an eigenfunction series with both the height and the fields having the same eigenfunctions. Satisfaction of the boundary conditions by the total fields at the surface along with the divergence equation on each side of the interface result in a set of self consistent equations. These equations can then be solved to an $n^{\underline{th}}$ order in the height (ζ_s) and slopes (ζ_{sx}, ζ_{sy}), which are assumed to be small, to yield the $n^{\underline{th}}$ order perturbation result. Peake and Bass and Bocharov confined their analyses to the first order perturbation result while Rice and Valenzuela found the second order perturbation fields.

Rice's original approach involves a great deal of algebra and this is common in the classical application of perturbation theory to boundary value problems [7]. This particular drawback has been eliminated by Burrows [8] who recently developed extremely simplified expressions for the perturbation fields based upon an earlier work by Mitzner [9]. Mitzner has also pointed out the very important fact that perturbation theory may yield an asymptotic approximation to the true field rather than a convergent series representation. This particular point has a significant impact upon the importance of perturbation fields of order higher than one and will be discussed later in this section.

Perturbation theory is successful because the perturbation fields satisfy not only Maxwell's equations but also the boundary conditions. The primary conditions imposed upon the surface in addition to stationarity and homogeneity are as follows;

$$|\zeta_s(x,y)| << \lambda_o \tag{1}$$

and

$$|\zeta_{sx}(x,y)| << 1 \qquad |\zeta_{sy}(x,y)| << 1 \quad . \tag{2}$$

In (1), $\zeta_s(x,y)$ is the height of the perturbed surface relative to the mean or unperturbed surface and λ_o is the electromagnetic wavelength. For this case, the mean surface is taken to be the $z=0$ plane and $\zeta_s(x,y)$ is measured along the z-axis. ζ_{sx} and ζ_{sy} are the slopes of the surface in the x and y-directions. Another condition on the perturbed surface is that it contains no edges for this would imply a singularity in the local fields [9], and perturbation techniques are not applicable to singular fields. Some authors [3,6] make the unnecessary assumption that the surface is Gaussian distributed.* That is, if the height of the surface is expressed as a Fourier series, i.e.

$$\zeta_s(x,y) = \sum_{m=-\infty}^{\infty} \sum_{n=-\infty}^{\infty} P(m,n)\exp[ja(mx+ny)] \quad , \tag{3}$$

the coefficients P(m,n) are assumed to be independent, zero mean, Gaussian random variables. This assumption is unnecessary for, as Barrick and Peake [2] have pointed out, as the periodicity of the surface ($L = 2\pi/a$) becomes

*For the first order perturbation fields, the assumption is unnecessary. For the second order fields, the Gaussian assumption does, indeed, allow some simplification in the mathematical detail of the problem.

infinite, the P's become uncorrelated and this condition is sufficient to complete the analysis. Therefore, for the first order perturbation results, it is not necessary for the surface to be Gaussian distributed. This point becomes particularly obvious if Burrows' [8] method of analysis is used.

In order to generate a depolarized component in the scattered field, Valenzula [6] demonstrated that it was necessary to go to the second order perturbation field (using the Rice approach). However, his numerical results indicated that near grazing incidence the depolarized component was stronger than the horizontally polarized component, and this result did not appear to be in agreement with measurements. This fact along with Mitzner's speculation that perturbation theory may yield an asymptotic result, tend to make one slightly suspicious of the use of second order perturbation fields to generate the depolarized component. That is, if the higher order perturbation fields are truly an asymptotic representation for the scattered field, then this fact may be expressed as follows;

$$\vec{E}_s \sim \sum_{i=o}^{\infty} \delta^i \vec{E} \tag{4}$$

where the symbol ~ denotes the asymptotic nature of the series. In (4), $\vec{E}_s$ is the scattered field and $\delta^i \vec{E}$, $i=0,1,\ldots$, is the i th order perturbation field. When the perturbation parameter is sufficiently small, the magnitude of the terms of (4) start by decreasing successively to a minimum and then subsequently increase. For this reason, only the first few terms may be numerically meaningful. For the case of hh polarization near grazing incidence, according to Valenzuela's computations, $|\delta^o \vec{E}|$ and $|\delta^1 \vec{E}|$ are smaller than $|\delta^2 \vec{E}|$ and this may be a result of the asymptotic nature of the solution.

That is, the series should actually be truncated at the $\delta^1 \vec{E}$ term. Conceptually, it is relatively easy to check for divergence of the series in (4); one merely computes the next higher order perturbation $|\delta^3 \vec{E}|$ and compares it to $|\delta^2 \vec{E}|$. If $|\delta^3 \vec{E}|$ is comparable or greater than $|\delta^2 \vec{E}|$, then the series is asymptotic and terms beyond $|\delta^1 \vec{E}|$ should be ignored. Another possibility is that (4) is nonuniformly convergent. That is to say, all terms in (4) may converge near normal incidence, but near grazing incidence only the first two terms are correct, i.e., the successive terms diverge. This particular point should be investigated more thoroughly in order to determine the basic nature of the perturbation solution and the true meaning of the second order perturbation fields. At this time, it is not clear that the second order perturbation fields correctly describe the depolarized field.

The effects of wave-wave interaction, dissipation, and air-sea interaction will cause the probability density function of ζ_s to depart from the Gaussian form predicted by free wave theory [10,11]. Longuet-Higgins [10] has also demonstrated that these nonlinear effects are even more significant in their impact upon the densities of the slopes of the surface. Although the perturbation approach to rough surface scattering does not require a specific density function for ζ_s, the results are dependent upon the waveheight spectrum. When the surface wind has only been blowing for a short time or the fetch is small relative to the decorrelation length of ζ_s, the surface height will no longer be a stationary or homogeneous stochastic process [12]. While this fact does not alter the basic perturbation theory result, it does mean that the "spectrum" will exhibit both temporal and spatial variation. More precisely, strong surface nonlinearities will give rise to a surface height autocorrelation function which depends on both where and when the measurement is made. The impact of this fact will be discussed in section 3.

In view of (1), perturbation analysis gives rise to a low frequency solution for rough surface scattering. That is, for (1) to be satisfied for large wind speeds or surface heights, λ_o must necessarily be large, i.e., low frequency. Thus, except for near calm surface conditions, (1) cannot be truly satisfied for the microwave frequencies, say, above 1 GHz.

2.2 Physical Optics Scattering

Whereas perturbation theory results in a low frequency scattering solution, the so-called physical optics approach yields a solution which is exact in the zero wavelength limit, i.e., $\lambda_o \to 0$, and approximate for $\lambda_o > 0$. In other words, the physical optics technique is an asymptotic approach which only approximately accounts for the true diffraction nature of the problem.

The basic assumption in the physical optics technique is that at every point on the surface the radius of curvature is so large that the surface may be considered to be locally planar. If, in addition, it is assumed that there is no multiple scattering, then the field at any point on the surface is determined entirely by the incident field at the point. If a point on the surface is shadowed by another part of the surface, the field at the point in question is assumed to be identically zero. Thus, knowing the fields on the surface, one can construct equivalent currents and the far-zone scattered field is the Fourier transform of these currents. Because of the difficulty involved in determining the illuminated part of the surface, shadowing is approximated in a pure ray optics manner. In the ray or geometrical optics limit, it can be shown [13] that the effect of shadowing is equivalent to multiplying the no-shadowing result b a so-called shadowing function which depends upon the slope statistics of the surface and the angle of incidence.

Thus, the only difference between the physical optics approximation and a pure geometrical optics analysis is that for physical optics the currents are Fourier transformed to find the far-zone fields while the geometrical optics field is determined by the laws of reflection at the surface.

In terms of essential surface assumptions, the above discussion may be summarized as follows; the radius of curvature at every point on the surface must be much larger than the wavelength, i.e.

$$\rho >> \lambda_o \quad , \tag{5}$$

to avoid multiple scattering the slopes must be everywhere small*, i.e.

$$|\zeta_{\ell x}| < 1 \qquad\qquad |\zeta_{\ell y}| < 1 \tag{6}$$

and in order to not deviate too much from the basic geometrical optics character of the solution ($\lambda_o \to 0$) the projected rms surface height should be large relative to the wavelength, i.e.

$$\left(\overline{\zeta_\ell^2}\right)^{\frac{1}{2}} \cos\theta >> \lambda_o \quad , \tag{7}$$

where θ is the angle of incidence relative to the normal to the mean flat surface. If conditions (5) - (7) are satisfied, the physical optics approximation for the scattered fields will be valid. A particular instance where this point was demonstrated using terrain scattering data is given in [14].

It should be noted that both the perturbation and physical optics approaches require that the surface slopes be everywhere small. For the physical

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*For the perturbation approach, ζ_s is used to represent the random height of the surface, while ζ_ℓ is used in the physical optics case. The subscripts are intended to serve as reminders, and they are also convenient for the discussion of the composite surface.

optics approach, this stipulation justified ignoring multiple scattering effects. For the first order perturbation fields, this condition appears to have the same effect; that is, multiple scattering is not included in the first order perturbation solution. This statement is justified by Valenzuela's demonstration [6] that the second order perturbation fields give rise to depolarization and they are also of the same form as deterministic multiple scattering solutions. The reason for raising this point is that in the past some researchers have ignored (7) and applied the physical optics approach to a surface with small height perturbations. For a perfectly conducting surface, the resulting field is identical to the first order perturbation field obtained using the technique of section 2.1 for horizontal polarization. For vertical polarization and backscattering, the physical optics result and the first order perturbation solution only agree near normal incidence. The reason for disagreement between the two solutions for vertical polarization is not due to multiple scattering for, as shown above, neither result includes multiple scattering. The source of disagreement is more fundamental. The physical optics approximation is based upon geometrical optics which is a scalar solution to the scattering problem. Thus, although the physical optics approach appears to retain the vector character of the problem, it really does not properly account for the vector nature of the diffraction problem. The physical optics solution contains the correct asymptotic dependence of the fields on the wavelength, but it does not show the true vector character of the scattered fields for all angles of incidence. This is exactly why there is an angle of incidence dependence in (7). The fact that the physical optics approach, when properly applied, results in no more information than the basic geometrical optics solution has been previously pointed out by Barrick

[15]. Because of this equivalence, the terms physical optics and geometrical optics will be used interchangeably throughout the remainder of this report.

Barrick [15], in a significant contribution to the theory of rough surface scattering, has demonstrated that for physical optics scattering σ° is determined by <u>either</u> the joint probability density function for the surface slopes or the Fourier transform of the joint probability density function of the surface height, i.e., the characteristic function of the joint height density. This result is important because it provides a unifying link between many earlier, and apparently diverse, analytical approaches. From a remote sensing viewpoint the result is even more important because it provides a direct connection between σ° and a directly measurable quantity, the joint slope density function. Furthermore, the result is not restricted to any specific form for the surface height probability density function nor is the basic result altered by surface nonlinearities.

2.3 Composite Surface Scattering

For microwave frequencies, it might seem that scattering from the ocean surface could be analyzed using the physical optics approach since the rms height of the waves are usually large. Unfortunately this is not the case. A wind driven sea comprises many scale of roughness. Although the characteristic of the surface generally satisfy conditions (6) and (7), it is not always possible to satisfy (5). That is, the small ripple-like waves may well exhibit a small radius of curvature relative to the electromagnetic wavelength. Thus, it is not possible to describe the total scattering process entirely by either the physical optics approach or the perturbation technique separately. However, based upon the simple observation that the small amplitude and wavelength waves appeared to "ride" on top of the larger amplitude and wavelength waves, a physical argument was presented [16] to combine the two approaches. In the resulting model, when applied to backscattering, the physical optics approach was assumed to be valid near normal incidence with only the large scale wave structure contributing to the joint slope density function. For an angle of incidence greater than roughly 30°, the scattering was considered to be due to "patches" of small scale waves tilted by the larger scale waves. This model for microwave scattering by the sea surface has come to be known as the composite surface scattering model primarily because of the incoherent addition of the large scale dependent physical optics result with the tilted plane Bragg scattering solution.

During this study, a more rigorous analytical approach to the problem of composite surface scattering was developed [1] for jointly Gaussian surfaces. The resulting solution was an improvement over the more heuristic composite surface scattering model. The analysis was restricted to jointly Gaussian surfaces because only then could the surface height be split into statistically independent large and small scale components. An unfortunate aspect of the jointly Gaussian assumption is that it tends to confuse ones physical insight into the true mechanisms behind the scattering. Furthermore, while the Gaussian height assumption is probably not too unreasonable, the slopes may exhibit a more significant departure from the assumed Gaussian shape for wind driven seas. Of course, such departures would also indicate nonlinearities in the wave generation process and, quite possibly, wave-wave interaction. This, in turn, would probably invalidate the assumption of statistically independent small and large scale height structure. If, for the present, this possibility is ignored, the Gaussian restriction can be relaxed and results of [1] can be generalized. In particular, using the approach given in [1] and the results in [13], it can be shown that the backscattering cross section per unit area, for an incident field with p-polarization and a scattered field with p'-polarization, is given by the following for a perfectly conducting surface;

$$\sigma^{\circ}_{pp'}(\theta,\phi) = \pi\delta_{pp'} \sec^4\theta \; p_\ell\left(\frac{k_{ox}}{2k_o\cos\theta}, \frac{k_{oy}}{2k_o\cos\theta}\right) P_{1\ell}\left(\hat{k}_i \middle| \frac{k_{ox}}{2k_o\cos\theta}, \frac{k_{oy}}{2k_o\cos\theta}\right)$$

$$+ 2k_o^2\sec^2\theta \left\{ \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \left|\Gamma_{pp'}\left(\frac{-k_x+k_{ox}}{2k_o\cos\theta}, \frac{-k_y+k_{oy}}{2k_o\cos\theta}\right)\right|^2 p_\ell\left(\frac{-k_x+k_{ox}}{2k_o\cos\theta}, \frac{-k_y+k_{oy}}{2k_o\cos\theta}\right)\right.$$

$$\cdot P_{1\ell}\left(\hat{k}_i \middle| \frac{-k_x+k_{ox}}{2k_o\cos\theta}, \frac{-k_y+k_{oy}}{2k_o\cos\theta}\right) S(k_x,k_y)dk_x dk_y$$

$$- \int_{-k_d}^{k_d}\int_{-k_d}^{k_d} \left|\Gamma_{pp'}\left(\frac{-k_x+k_{ox}}{2k_o\cos}, \frac{-k_y+k_{oy}}{2k_o\cos}\right)\right|^2 p_\ell\left(\frac{-k_x+k_{ox}}{2k_o\cos}, \frac{-k_y+k_{oy}}{2k_o\cos}\right)$$

$$\left.\cdot P_{1\ell}\left(\hat{k}_i \middle| \frac{-k_x+k_{ox}}{2k_o\cos\theta}, \frac{-k_y+k_{oy}}{2k_o\cos\theta}\right) S(k_x,k_y)dk_x dk_y \right\} \qquad (8)$$

where θ is the angle of incidence relative to the normal to the mean surface and ϕ is the angle relative to the surface oriented x-axis. The unit vector $\hat{k}_i$ specifies the direction of propagation of the incident field and it is given by (see Figure 1)

$$\hat{k}_i = -\sin\theta\cos\phi\,\hat{x} - \sin\theta\sin\phi\,\hat{y} - \cos\theta\,\hat{z}$$

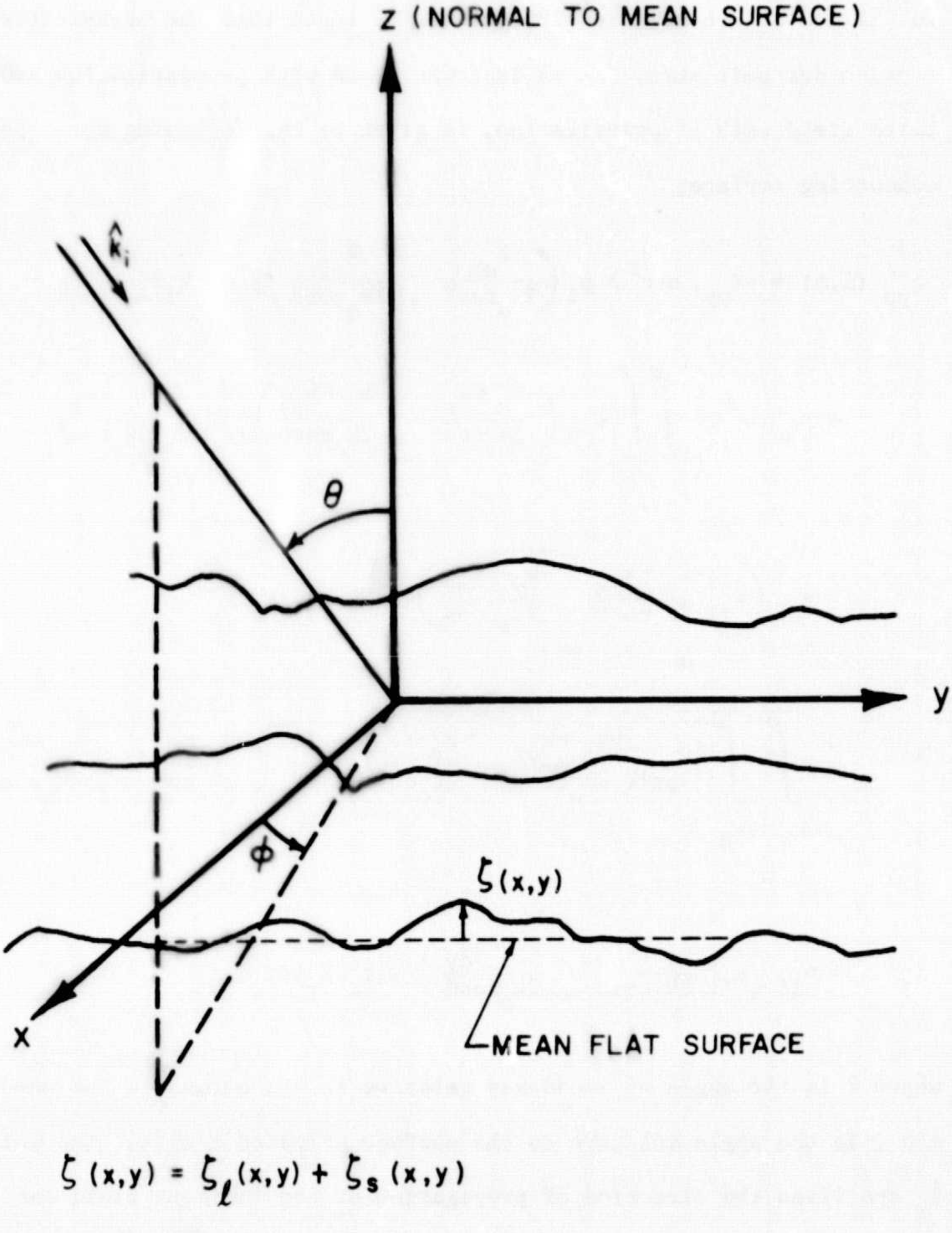

Figure 1. Coordinate system and surface geometry for the condition of backscattering.

The quantity $p_\ell(\zeta_{\ell x}, \zeta_{\ell y})$ is the joint slope probability density function for the <u>large</u> <u>scale</u> surface, $P_{1\ell}(\hat{k}_i | \zeta_{\ell x}, \zeta_{\ell y})$ is the probability that a point on the large scale surface having slopes $\zeta_{\ell x}$ and $\zeta_{\ell y}$ will be illuminated by an incident ray having a direction $\hat{k}_i$, and $S(k_x, k_y)$ is the surface height spectrum. The factor $\Gamma_{pp'}(\zeta_{\ell x}, \zeta_{\ell y})$ depends upon the incident and scattered field polarizations and the slopes of the large scale surface [1]. Also, the quantities $\delta_{pp'}$, k_{ox}, and k_{oy} are defined as follows;

$$\delta_{pp'} = \begin{cases} 1 & p = p' \\ 0 & p \neq p' \end{cases}$$

and

$$\begin{aligned} k_{ox} &= -2k_o \sin\theta \cos\phi \\ k_{oy} &= -2k_o \sin\theta \sin\phi \end{aligned} \tag{9}$$

and an $\exp(j\omega t)$ time convention is used. The wavenumber k_d represents the dividing point between the large scale structure, $(|k_x| \leq k_d) \cap (|k_y| \leq k_d)$, and the small scale structure, $(|k_x| > k_d) \cup (|k_y| > k_d)$. As shown in [1], for a Phillips-type spectrum, the criterion for determining k_d is $4k_o^2 \overline{\zeta_s^2} \approx 0.1$.

The first term on the right hand side of (8) represents the near normal incidence dominant geometrical optics scattering while the second term is due to the (large scale modified) small scale scatter contribution. The form of (8) suggests that near normal incidence measurements could be used to infer the behavior of the joint slope density function and $P_{1\ell}(\cdot)$ together. This measured variation for $\theta \lesssim 20°$ could then be substituted in the second term to determine the spectral behavior using wide angle scattering data ($\theta \gtrsim 40°$). A more detailed discussion of the ramifications of (8) are presented in [1].

It should be noted that in the derivation of (8) it was assumed that (1) and (2) were satisfied for the small scale structure while (5) through (7) were satisfied for the large scale structure. More important, however, is the fact that the two random heights ζ_s and ζ_ℓ were assumed to be statistically independent. As can be shown, the derivation leading to (8) actually requires that the small scale height and the large scale slopes be independent processes. One way of modifying (8) to account for the fact that ζ_s and $\zeta_{\ell x}$ and $\zeta_{\ell y}$ may not be independent is to replace $S(k_x, k_y)$ by the "conditional" height spectrum $\tilde{S}(k_x, k_y)$ where

$$\tilde{S}(k_x,k_y) = S\left(k_x,k_y \,\middle|\, \zeta_{\ell x} = \frac{-k_x+k_{ox}}{2k_o\cos\theta}\ ,\ \zeta_{\ell y} = \frac{-k_y+k_{oy}}{2k_o\cos\theta}\right) \tag{10}$$

That is, since the only contribution to (8) comes from that part of $k_x k_y$-space corresponding to the small scale structure, the spectrum in (8) is the small scale height spectrum when the large scale slopes are as shown in (10), i.e.

$$\zeta_{\ell x} = \frac{-k_x+k_{ox}}{2k_o\cos\theta} \qquad , \qquad \zeta_{\ell y} = \frac{-k_y+k_{oy}}{2k_o\cos\theta} \tag{11}$$

More formally, $\tilde{S}(k_x,k_y)$ is defined as the Fourier transform of the autocorrelation function $\tilde{R}(\Delta x,\Delta y)$ where

$$\tilde{R}(\Delta x,\Delta y) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \zeta_{s_1}(x_1,y_1)\zeta_{s_2}(x_2,y_2)$$

$$\cdot\ f_{\zeta_{s_1}\zeta_{s_2}}\left(\zeta_{s_1},\zeta_{s_2}\,\middle|\,\zeta_{\ell x} = \frac{-k_x+k_{ox}}{2k_o\cos\theta}\ ,\ \zeta_{\ell y} = \frac{-k_y+k_{oy}}{2k_o\cos\theta}\right)d\zeta_{s_1}d\zeta_{s_2} \tag{12}$$

In (12), $f_{\zeta_{s_1}\zeta_{s_2}}$ is the joint probability density function of the small scale heights ζ_{s_1} and ζ_{s_2} conditioned on the fact that the large scale slopes are given by (11). Replacing $S(k_x,k_y)$ in (8) by $\tilde{S}(k_x,k_y)$ is a formal means of accounting for the possibility that the small scale heights and the large scale slopes may not be independent. Assuming that the large scale slopes are reasonably symmetric in the upwind-downwind directions*, any asymmetries in $\sigma°$ for large angles of incidence ($\theta \gtrsim 30°$) would imply a preference by the small scale waves for certain large scale slopes. This, in turn, might permit the determination of the direction of the wind speed. Caution should be exercised, however, in attempting to extrapolate wave tank measurements to open ocean conditions for this type of problem due to the difficulty in generating and sustaining large scale waves in wave tanks. For example, the theory presented here argues that the scattering mechanism is basically Bragg resonance whereas Schooley [17] obtained an upwind-downwind dependence from wave-tank measurements which he attributed to tilted-facet scattering. It is not clear how Schooley's results can be compared to the present theory since his tank was only 70 cm long and this certainly limited the degree of large scale structure present in his experiment.

3.0 THE IMPACT OF SURFACE CONDITIONS ON SPECIFIC SENSORS

The previous section has reviewed the basic surface assumptions which are inherent in existing theories for the backscattering cross section per unit scattering area, $\sigma°$. However, not all active microwave sensors rely on a measurement of $\sigma°$ to infer surface characteristics. For example, of the three active sensors presently being constructed for use on SEASAT, only the

*This assumption can be checked by examining the upwind-downwind dependence in the near normal incidence scattering data.

scatterometer relies on a measurement of σ° to infer specific surface conditions; the radar altimeter and the synthetic aperture radar use different characteristics of the backscattered signal to derive their surface measurements. While it is certainly restrictive to consider only the above three instruments, these are probably the most highly developed and most nearly operational systems. Thus, it is essential that the effects of varying surface conditions on the sensing capabilities of these instruments be fully understood.

3.1 Radar Altimeter

The conventional short pulse, pulsewidth limited radar altimeter accomplished two measurements which are of primary concern in oceanographic remote sensing. The first comprises a time delay measurement which, when coupled with accurate orbit information, can be translated into a measurement of the geoid height. The second entails measuring the shape of the average return waveform which, in turn, can be related to the rms height of the random waves on the surface. The two measurements are coupled in a sense due to the tracking loop in the altimeter; that is, changes in the shape of the average return are also reflected in the basic altitude measurement.

3.1.1 Sea State Bias

When the illuminated area on the surface comprises many surface height decorrelation intervals, the effect of the random height of the waves is equivalent to a convolutional smearing of the radar's point target response [18]. That is, the effective point target response of the system is broadened by the convolution of it and the probability density of the surface height. For automated data processing purposes, it is also convenient to assume that the surface height is Gaussian. Then, simplified algorithms can be designed to process waveform data for rms surface height and estimates of the effect of the surface heights on the tracking loop can be made. The sensitivity of the altimeter's tracking loop to changes in the distribution of the sea surface heights is called sea state bias. That is, changes in the distribution of the sea surface height result in a change in the shape of the average return waveform which, in turn, causes the tracking loop to deviate from its nominal tracking point on the average return. For relatively long pulse systems such as Skylab or GEOS-3, sea state bias only becomes significant under extremely high seas. However, for the SEASAT altimeter where the precision of the altitude data is supposed to be near 10 cm, sea state bias is not negligible and the altitude data should be corrected for this effect.

The basic sea state bias effect encompasses two problems. The first and most obvious is that the surface height density function is not always Gaussian [10]. The second but more fundamental problem is that the height density "seen" by the radar is not necessarily the same density as would be recorded by an _in situ_ device such as a wavepole [19]. Quite obviously, the latter problem must be resolved before the former is even applicable. This latter problem has been discussed by a number of researchers, [19], [11], [20]. Miller and Hayne [19] examined data acquired by a one nanosecond (pulse length) radar operating from the Chesapeake Light Tower [21] and concluded that the radar observed height density was a weighted replica of the true surface height density. The weighting arises as a result of a height dependence in the surface scattering cross section per unit area or σ°. However, it is not at all obvious that the tower experiment is representative of satellite altimetry. For example, the mean height from the radar to the surface was just under 22 meters while the spot size diameter was about one meter. This spot size certainly does not contain many surface height decorrelation intervals! In addition, LeVine [22] has recently demonstrated that, for small separation distances between the radar and the surface, it is possible to have focusing by small concave facets on the surface. Since these concave facets would most likely be concentrated near the troughs of the waves, this would result in a stronger return from the troughs than the crests. It should be noted that this was exactly the type of behavior observed in the data from the tower experiment. In summary, the tower data is probably more applicable to a wave <u>profiling</u> radar rather than a height-averaging radar such as employed in satellite altimetry.

Seltzer [20] has recently pointed out the fact that when the radar range resolution is less than the standard deviation of the surface heights the scattering cross section per unit area should be replaced by the scattering cross section per unit volume. The scattering cross section per unit volume is just the product of the volume density of specular points and the height conditioned mean scattering cross section per unit specular point. Seltzer has shown that for a Gaussian surface, the probability of finding a specular point at a height z above the mean surface is not Gaussian. However, this is not necessarily the final answer because one must also know how the average absolute value of the principal radii of curvature varies with z, since this determines the scattering cross section per unit specular point. In a conversation with Dr. E. J. Walsh of NASA/WFC, Dr. Seltzer has indicated that when this dependence is included, the difference between the scattering cross section per unit volume and the more conventional product of σ° and the probability density of the height is much less significant for the Gaussian surface. It would be most desirable to extend Seltzer's analysis to non-Gaussian surfaces such as might be encountered under extremely wind driven conditions. This would provide some estimate of the degree of sea state bias resulting from surface nonlinearities.

3.1.2 Swell Dominated Conditions

A final problem which deserves consideration is the response of a radar altimeter to swell dominant surface conditions. Under situations where the wind driven sea height is greater than or at least equal to the swell height, it is normally assumed that the rms surface height measured by the altimeter is just the root sum square of the wind driven and swell heights. The justification for this step is based upon the assumption that the two processes are statistically independent. Although wave-wave interaction could certainly weaken the validity of this assumption, the procedure appears to work reasonably well* in practice. However, when the swell is much more dominant than the wind driven sea, the situation is not quite so clear. For example, if there was absolutely no surface wind blowing, the spectral characteristics of the swell would depend upon where and when the swell was created. As the swell propagates away from its driving force, it will become a very unidirectional narrow band process centered about a very low frequency [23] with its amplitude decreasing and its period increasing with propagation distance. Thus, eventually, the surface appears to be a monochromatic sinusoid and the use of random scattering theory is, at best, questionable.

For the more realistic case of both swell and wind driven height components, the analytical approach should be dictated by the bandwidth of the swell. That is, if the swell is sufficiently narrowband, the mean surface

*This statement must be tempered by the fact that the ground truth source for comparison, generally, is NOAA hindcast data and its accuracy is unknown.

should be taken to be sinusoidal rather than planar as in section 2. In this case, the wind driven components can be treated as a random modulation of the sinusoidal mean surface. The same approach given in [1] can be used to compute $\sigma°$, however, the mean surface will be sinusoidal due to the narrowband swell. A procedure for estimating the effect of a sinusoidal mean surface upon the average return waveform is given in [24]. This particular analysis was developed to determine the effect of sinusoidal geoid undulations upon the average return waveform, however, it applies equally well to non random swell. Unfortunately, the calculations in [24] did cover undulation wavelengths of less than 1 km.

It should be noted that there are two motivating reasons for trying to better understand the sea state bias and swell response problems. The primary reason, of course, is to obtain quantitative estimates of the effects of these situations on altimeter data. A second, but no less important, reason is to determine the impact of these surface conditions upon automated data processing algorithms for altimeter data. Of particular importance are algorithms which are incorporated into the altimeter design to reduce telemetry data rates, i.e. such as maximum likelihood processors for waveheight estimation.

3.2 Scatterometers

The scatterometer basically provides measurements of $\sigma°(\theta,\phi)$ as a function of the angle of incidence, θ, and the direction of incidence, ϕ. For $\theta \gtrsim 20°$, recent aircraft measurements [25,26] have shown that $\sigma°$ is a reasonably sensitive function of surface wind speed. Furthermore, for θ constant these same measurements indicate a 2 to 4 dB difference between upwind/downwind and crosswind values of $\sigma°$. Thus, the scatterometer has the potential of providing estimates of the surface wind vector.

For $20° \lesssim \theta \leq 90°$ and microwave frequencies, the mechanism responsible for the scattering is the large scale modified Bragg resonance between the electromagnetic field and the capillary surface components, see section 2.3. Unfortunately, not many in situ measurements in the capillary range of the surface height spectrum have been reported. This, of course, is due to the fact that such measurements are extremely difficult to obtain. Recently, a system has been reported [27] which may be capable of providing spectral data on the behavior of capillary waves at least in the frequency domain. However, difficulties were experienced in attempting to obtain the equivalent spectral information in the wavenumber domain.

The scatterometer measurements reported in [26] imply some rather interesting points about the behavior of capillary waves under wind driven conditions. The fact that $\sigma°(\theta)$, for $\theta \gtrsim 20°$, increases with wind speed seems to indicate that the capillary region of the spectrum is not insensitive to wind speed as has been previously hypothesized [12]. In-Situ measurements presented in [27] also show a similar increase in spectral amplitude in the approximate* capillary range and, as previously noted, these are wave tank measurements. Also, the variation of $\sigma°$ with azimuth angle ϕ indicates that the capillary waves are not omnidirectional in their directional dependence. According to (8), a directional dependence in $\sigma°$ for $\theta > 20°$ could result from either a directionality in the capillary region of the spectrum or a difference between the upwind/downwind and cross wind large scale slopes. However, for $\theta \lesssim 20°$ the measurements given in [26] do not show any asymmetry in $\sigma°$

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*The spectral measurements reported in [27] are given in the frequency domain so, without a well-defined dispersion relation, it is somewhat difficult to pin down the capillary range exactly. However, the wind sensitivity is present up to the frequency limit of the measurements, i.e. ~ 20 Hz.

with the angle ϕ. Using (8), this would imply that the large scale principal slope components are nearly equal. Hence it must be the capillary waves which are spreading in a directional manner. This point is also at variance with previous notions about capillary wave behavior [28]. Finally, Wu [29] has recently reexamined Cox and Munk's classic mean square slope data in an attempt to estimate the spectral constant and the so-called cutoff wavenumber, i.e., the wavenumber at which the waveheight spectrum starts to decay much more rapidly than k^{-4}. For a wind speed of less than about 7 m/sec, Wu found that Cox and Munk's data implied a cutoff wavenumber of about 2.5 $(cm)^{-1}$. This result is definitely not supported by the $\sigma°$ measurements reported in [26]. For an angle of incidence of 30°, the Bragg wavenumber for the AAFE [26] system is 2.79 $(cm)^{-1}$ and this is greater than the cutoff wavenumber proposed by Wu. Thus, $\sigma°(\theta)$ should decay very rapidly with θ beyond 30° if the spectrum were truly cutoff as proposed by Wu; however, the $\sigma°$ measurements did not indicate any rapid decay for wind speeds of 3 and 6.5 m/sec. In fact, the AAFE measurements imply that the cutoff wavenumber would have to be greater than 4.3 $(cm)^{-1}$ since $\sigma°$ data were acquired out to 50°. Thus, the measurements reported in [26] do not support the concept of spectral cutoff below $k = 4.3$ $(cm)^{-1}$ which, incidently, is greater than the neutrally stable wavenumber. This result may also be a clue to the behavior of capillary waves which has previously eluded measurement.

The present plans for the SEASAT scatterometer $\sigma°$ data entail using empirical relations between wind speed and $\sigma°$ to convert the basic data into estimates of surface wind speed. The empirical relationships are based on the aircraft derived measurements reported in [26]. While such a data interpretation procedure may be acceptable for an experimental program where the sensor measurements are to be compared with ground truth data, it is not clear that such a system would be acceptable from an operational standpoint. It therefore appears that there is a very definite need for further oceanographic research into the behavior of the capillary portion of the waveheight spectrum. In addition, it would seem that another point of importance is the extrapolation of wave tank measurements to open ocean conditions. Hopefully, the SEASAT program will provide sufficient high quality ground truth data to better understand some of the problems associated with properly interpreting scatterometer data.

As previously noted, the high frequency portion of the waveheight spectrum is very difficult to measure using in-situ mechanical devices. Wright and his co-workers at the Naval Research Laboratory have made great strides in this area [33-39]. Ironically enough, these measurements have been accomplished using radar techniques [35]. The key to their success has been the use of a very controlled situation in which the assumptions of the scattering theory are known to be valid. Their basic approach comprises the use of a doppler radar system with precisely controlled illumination of the surface. For such a system, the observed doppler shift in the backscattered signal is equal to the frequency of the water wave, and the output of the radar is proportional to the waveheight spectral density evaluated at the Bragg resonance wavenumbers, i.e.

$$\Psi(k_x = 2k_o \sin\theta,\ k_y = 0, \omega)$$

where Ψ and $S(k_x, k_y)$ are related by [12]

$$S(k_x, k_y) = \int_{-\infty}^{\infty} \Psi(k_x, k_y, \omega)\, d\omega \quad . \tag{13}$$

One of the most significant measurements accomplished with this system related to wave straining [37] or the preference of capillary waves for a particular slope of the large scale wave structure. These are the type measurements which are required to explain upwind/downwind dependent scattering [26]. Also, these data are essential to validating such theories as indicated by equation (8) in which one needs to know the relationship between the small scale heights and the large scale slopes. One can only hope that a system such as this will eventually be used on towers or ships for open ocean measurements.

3.3 Synthetic Aperture Radar

Synthetic aperture radar sensors have recently received a great deal of attention because they appear to have the potential to provide very wide coverage and near photographic-like, high resolution images of the ocean surface [30]. Their image-like data product seems to be particularly appealing to earth scientists who are used to dealing with visible and infrared images of the earth's surface. There is no basic argument with the fact that synthetic aperture radar (SAR) has a high resolution, wide swath coverage capability. However, the fundamental question with this type system when operated over the ocean is what exactly is it imaging? Quite apart from the fact that the SAR system responds to backscattering while most optical photographs represent bistatic scattering, the more basic question has to do with what exactly the SAR is responding to on the surface.

A recent paper by Elachi and Brown [31] provides an excellent review of some of the analytical models that have been proposed as means for answering the above question. Two of these models are based upon incoherent scattering theory, while another two are based upon the effect of the surface motion on the coherent signature of the surface. Quite frankly, it is difficult to understand how incoherent scattering models apply to a coherent system like the SAR. That is, for typical resolutions of 10 to 30 m and coherent integration times of from 0.4 to 1 sec., it is doubtful that the scattering from a given resolution cell or pixel can be considered to be random. For moderate to high sea states, the resolution cell would certainly not comprise many surface height decorrelation intervals, nor would a one second observation time encompass many temporal decorrelation intervals. Thus, at the very best, the measured backscattered power from a single resolution element would comprise only a few statistically independent samples. Hence, the given measurement would have a very high variance and it would be difficult to relate it to σ°, which is proportional to the <u>mean</u> value of the return power. Quite possibly this is why some of the images reported in [31] show a "wave" pattern regardless of the look angle of the radar relative to the direction of travel of the large scale surface waves. That is, the imaged "wave" pattern may be nothing more than statistical "noise" in the process due to under sampling the return power from a given resolution cell. It is worth noting that this is not the case with an optical photograph because the bandwidth of the illumination and reeceiver are so wide as to comprise many independent samples of a given resolution cell [32]. For the SAR system, this situation could be improved by either using a larger transmitted signal bandwidth or frequency hopping; however, these options may be limited by signal-to-noise and system complexity considerations.

The SAR performance also suffers from the motion of the surface; however, this effect is reasonably well understood [31] and thus it becomes a basic system limitation. The problem of image interpretation is much more fundamental and requires a greater in-depth theoretical electromagnetic scattering examination than it apparently has received to date. Given the degree of correlation between the aircraft based SAR images and ground truth data reported in [31], it will be most fortuitous if the SEASAT SAR system makes a significant contribution to the field of microwave remote sensing.

REFERENCES

1. Brown, G. S.; "Scattering By A Perfectly Conducting, Gaussian Distributed Rough Surface," Tech. Memo., Contract No. NAS6-2520 (Task 3.11), Applied Science Associates, Inc., Apex, N. C., 15 February, 1977.
2. Barrick, D. E.; and Peake, W. H.: "Scattering From Surfaces With Different Roughness Scales; Analysis and Interpretation," Research Report No. BAT-197A-10-3, Battelle Memorial Institute, Columbus Laboratories, Columbus, Ohio, AD662751, 1967.
3. Rice, S. O.; "Reflection Of Electromagnetic Waves From Slightly Rough Surfaces," Commun. Pure Appl. Math., Vol. 4, pp. 361-378, 1951.
4. Bass, F. G.; and Bocharov, V. G.: "Toward A Theory Of Electromagnetic Wave Scattering From Statistically Rough Surfaces," (in Russian), Radiotekhn. i Elektron., Vol. 3, p. 180, 1958.
5. Peake, W. H.; "Theory Of Radar Return From Terrain," IRE Convention Record, Vol. 7, pg. 27, 1958.
6. Valenzuela, G. R.; "Depolarization Of EM Waves By Slightly Rough Surfaces," IEEE Trans. Ant. & Propg., Vol. AP-15, pg. 552-557, July, 1967.
7. Morse, P. M.; and Feshbach, H.: Methods of Theoretical Physics, Part II, Chapter 9, McGraw-Hill Book Co., New York, 1953.
8. Burrows, M. L., "A Reformulated Boundary Perturbation Theory In Electromagnetism And Its Application To A Sphere," Can. J. Phys., Vol. 45, pp. 1729-43, May, 1967.
9. Mitzner, K. M.; "Effect Of Small Irregularities On Electromagnetic Scattering From An Interface Of Arbitrary Shape," J. Math. Phys., Vol. 5, pp. 1776-1786, December, 1964.
10. Longuet-Higgins, M. S., "The Effect Of Non-Linearities On Statistical

Distributions In The Theory Of Sea Waves," J. Fluid Mech., Vol. 17, pp. 459-480, 1964.

11. Hasselmann, K.; "The Energy Balance Of Wind Waves And The Remote Sensing Problem," in "Sea Surface Topography From Space, Vol. II", NOAA Report ERL 228-AOML 7-2, pp. 25-1 - 25-55, May, 1972.

12. Phillips, O. M.; The Dynamics Of The Upper Ocean, Cambridge University Press, London, 1966.

13. Sancer, M. I., "Shadow-Corrected Electromagnetic Scattering From A Randomly Rough Surface," IEEE Trans. Ant. & Propg., Vol. AP-17, pp. 577-585, September, 1969.

14. Brown, G. S. (Editor); "Skylab Radar Altimeter Experiment Analyses and Results," NASA CR-2763, Applied Science Associates, Inc., Apex, N. C., May, 1976.

15. Barrick, D. E.; "Relationship Between Slope Probability Density Function And The Physical Optics Integral In Rough Surface Scattering," Proc. of IEEE, pp. 1728 - 1729, October, 1968.

16. Wright, J. W.; "A New Model For Sea Clutter," IEEE Trans. Ant. & Propg., Vol. AP-16, pp. 217-223, March, 1968.

17. Schooley, A. H.; "Upwind-Downwind Ratio of Radar Return Calculated From Facet Size Statistics of a Wind-Disturbed Water Surface," Proc. IRE, Vol. 50, pp. 456-461, April, 1962.

18. Brown, G. S.; "The Average Impulse Response Of A Rough Surface and Its Applications," IEEE Trans. Ant. & Propg., Vol. AP-25, pp. 67-74, January, 1977.

19. Miller, L. S.; and Hayne, G. S.: "Characteristics of Ocean Reflected

Short Pulses With Applications to Altimetry and Surface Roughness Determination," in Sea Surface Topography From Space, Vol. 1, J. R. Apel, Ed., NOAA Tech. Rept. ERL 228-AOML 7, pp. 12-1 to 12-17, May, 1972.

20. Seltzer, J. E.; "Spatial Densities For Specular Points On A Gaussian Surface." IEEE Trans. Ant. & Propg., Vol. AP-20, pp. 723-730, November, 1972.

21. Yaplee, B. S.; Shapiro, A.; Hammond, D. L.; Au, B. D.; and Uliana, E. A.: "Nanosecond Radar Observations Of The Ocean Surface From A Stable Platform," IEEE Trans. Geosc. & Elect., Vol. GE-9, pp. 170-173, July, 1971.

22. LeVine, D. M.; "The Scattering Of Obliquely Incident Plane Waves From A Corrugated Conducting Surface," IEEE Trans. Ant. & Propg., Vol. AP-24, pp. 828-832, November, 1976.

23. Kinsman, B.; Wind Waves, Chapter 6, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1965.

24. Miller, L. S.; and Brown, G. S.: "Engineering Studies Related to the GEOS-C Radar Altimeter," NASA CR-137462, Applied Science Associates, Inc., Apex, N. C., May, 1974.

25. Jones, L. W.; Grantham, W. L.; Schroeder, L. C.; Johnson, J. W.; Swift, C. T.; and Mitchell, J. O.: "Microwave Scattering From The Ocean Surface," IEEE Trans. Microwave Theory & Tech., Vol. MTT-23, pp. 1053-1058, December, 1975.

26. Jones, W. L.; Schroeder, C. L.; and Mitchell, J. L.: "Aircraft Measurements of the Microwave Scattering Signature of the Ocean," IEEE Trans. Ant. & Propg., Vol. AP-25, pp. 52-60, January, 1977.

27. Guthart, H.; Taylor, W. C.; Graf, K. A.; and Douglas, D. G.: "Correlation Techniques and Measurements of Wave-Height Statistics," Final Report,

Contract NAS1-10681, Stanford Research Institute, Palo Alto, California, May, 1972.

28. Longuet-Higgins, M. S.; Cartwright, D. E.; and Smith, N. D.: "Observations Of The Directional Spectrum Of Sea Waves Using The Motions Of A Floating Buoy," Ocean Wave Spectra, pp. 111-131, Prentice-Hall, Englewood Cliffs, N. J., 1963.

29. Wu, J.; "Sea-Surface Slopes and Equilibrium Wind Wave Spectra," Phys. of Fluids, Vol. 13, pp. 741-747, July, 1972.

30. Brown, W. E.; Elachi, C.; and Thompson, W. T.: "Radar Imaging of Ocean Surface Patterns," J. Geophys. Res., Vol. 81, pp. 2657-2667, 1976.

31. Elachi, C.; and Brown, W. E.: "Models of Radar Imaging of the Ocean Surface Waves," IEEE Trans. Ant. & Propg., Vol. AP-25, pp. 84-95, January, 1977.

32. Moore, R. K.; and Thomann, G. C.: "Imaging Radars For Geoscience Use," IEEE Trans. Geoscience Elect., Vol. GE-9, pp. 155-164, July, 1971.

33. Wright, J. W.; and Keller, W. C.: "Doppler Spectra In Microwave Scattering From Windwaves," Phys. Fluids, Vol. 14, pg. 466, 1971.

34. Duncan, J. R.; Keller, W. C.; and Wright, J. W.: "Fetch and Wind Speed Dependence Of Doppler Spectra," Radio Science, Vol. 9, pp. 809-819, October, 1974.

35. Larson, T. R.; and Wright, J. W.: "Wind Wave Studies : Part 2 - The Parabolic Antenna As A Wave Probe," NRL Report 7850, NRL, Washington, D. C., December, 1974.

36. Keller, W. C.; Larson, T. R.; and Wright, J. W.: "Mean Speeds of Wind Waves at Short Fetch," Radio Science, Vol. 9, pp. 1091-1100, December, 1974.

37. Witting, J. M.; and Wright, J. W.: "Microwave Scattering and the Dynamics of Short Wind Waves," in NRL Report of Progress, NRL, Washington, D. C., February, 1975.

38. Wright, J. W.; and Keller, W. C.: "Modulation of Microwave Backscatter by Gravity Waves in a Wave Tank," NRL Report 7968, NRL, Washington, D.C., March, 1976.

39. Wright, J. W.; "The Wind Drift and Wave Breaking," J. Phys. Oceanog., Vol. 6, pp. 402-405, May, 1976.