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A THEORETICAL STUDY OF RADAR RETURN AND RADIOMETRIC EMISSION FROM THE SEA

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16. Abstract

The applicability of the various electromagnetic models of scattering from the ocean are reviewed. These models include the small perturbation method, the geometric optics solution, the composite model, and the exact integral equation solution. The restrictions on the electromagnetic models are discussed.

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I. INTRODUCTION

During the past four or five years, as significant amounts of radar (and more recently, microwave radiometer) imagery have become available to the scientific public, a substantial literature on the interpretation of this imagery has developed. The greater part of these studies (Refs. 1, 2) have been based upon the identification or recognition of familiar features (drainage patterns, geological lineaments, soil contacts, patterns of land usage, vegetative cover) in the imagery, although there have also been one or two studies (Ref. 3) of surface discrimination by means of the textural quality within homogeneous areas of the image. As yet, however there have been few attempts to use either imagery, or other types of microwave sensor output, to obtain quantitative estimates of surface parameters. There are at least two reasons for this. The first is that, with few exceptions, the imagery itself is not well enough calibrated in grey scale to permit estimates of absolute (or even relative) values of the surface scattering cross-sections or brightness temperatures. The second reason is that most of the useful image interpretation has been made by geoscientists, who are not familiar with the relations between the radar scattering cross-section σ_0, the brightness temperature T_b, and those properties of the surface which control them. It is also true that in many cases the sequence of sensor outputs which would be most useful in establishing a particular surface parameter is not a spatial sequence (i.e., an image) but is of some other kind (e.g., a variation of σ_0 or T_b with look angle -- the scatterometer experiment -- or with polarization, frequency, time of day, etc.)

Thus before any large scale satellite remote sensing program can be undertaken with microwave sensors, a number of interpretive studies should be undertaken. This is of particular importance if it is desired to establish quantitative relations between the sensor output and the surface properties, because these will affect the design of the sensing instrument. This is especially true for the design of a general purpose radar-radiometer sensor because of the wide variety of applications such a system would have. Ideally, these many potential applications should each be validated by carefully controlled, repeatable experiments together with extensive ground truth data and detailed theoretical interpretation. In many cases this process can most effectively be carried out by small scale measurements from towers or trucks, or modelling and theoretical studies under laboratory conditions, rather than by the more expensive programs utilizing aircraft or spacecraft programs.

One application of microwave remote sensing of particular importance is to the estimation of the state of the sea surface (Refs. 4, 5). Among the parameters which might be estimated by suitable choice of sensor and signal design are the r.m.s. wave height, the r.m.s. wave slope, the percentage of foam cover (and thus, perhaps, the local wind velocity), the water temperature and salinity at the surface. The ability to sense such parameters on a synoptic basis would have very important practical applications to global weather forecasting, ship routing, etc., as well as the more obvious scientific applications. However, in order to interpret the sensor output in terms of the surface parameters, one must have detailed models to relate these parameters to the measurable scattering and emission characteristics. It is the purpose of the work reported here to investigate the "composite" model for sea surface scattering, and to provide direct methods for determining the scattering from actual representations of the sea surface. The details of the work reviewed in this final report may be found in the technical reports and papers generated during the contract period (Refs. 12, 13).

II. PAST WORK ON SEA SURFACE CHARACTERISTICS

During the past few years, theoretical and experimental work here and abroad (Refs. 5-9) has led to an understanding of the mechanisms responsible for scattering and emission of microwaves by the ocean. For off-normal backscatter, the "Bragg-scatter" from capillary and short wavelength components of the ocean surface, which can be calculated by perturbation theory, has explained the angular and polarization dependence of the microwave radar return. When combined with the known height spectrum (Ref. 4) of the ocean surface, it explains the weak dependence of backscatter on electromagnetic wavelength and wind velocity. Near the specular direction, i.e., near normal incidence for backscatter, the scattering is controlled by the slope distribution of the large scale structure of the surface. This part of the scattering is calculated by geometrical optics and provides an explanation of the dependence of the brightness temperature of the ocean on incidence angle, polarization and wind velocity (at least at the lower wind speeds). This view, that at microwave frequencies two different mechanisms contribute to the scattering behavior has led to the development of the "composite" model in which the ocean surface height $h(x,y)$ is written as the sum of two statistically independent random processes $h(x,y) = z(x,y) + s(x,y)$ where z represents the large scale structure (scattering calculated by geometrical optics) and s the small scale structure (scattering calculated by perturbation theory). The actual ocean has a continuous height spectrum $W(k)$ such that the mean square height is

$$\langle h^2 \rangle = \int_0^\infty W(k)\, k\,dk$$

It is not clear, however, that the two independent processes $z(x,y)$ with height spectrum $W_\ell(k)$ and $s(x,y)$ with height spectrum $W_s(k)$ (such that $W = W_\ell + W_s$) can always be suitably chosen. This is because the conditions on the use of the perturbation theory are that

$$<s^2> = \int_0^\infty W_s(k)\ kdk << \lambda_e^2$$

$$<\theta^2> = \int_0^\infty W_s(k)\ k^3dk << 1$$

where

λ_e = electrical wavelength

$<s^2>$ = mean square height of small scale process

$<\theta^2>$ = mean square slope of small scale process.

The condition on the use of geometrical optics for the large scale process is that

$$<1/R_\ell^2> \simeq \int_0^\infty W_\ell(k)\ k^5dk << (1/\lambda_e)^2$$

where

$<R_\ell^2>$ = mean square radius of curvature of large scale process.

For the actual ocean surface spectrum one may use W_s alone (i.e., set $W_\ell = 0$) at low frequencies (say f < 5 to 10 MHz), and W_ℓ alone (i.e., set $W_s = 0$) at optical frequencies. However, it is not always possible to make a separation of W(k) into two parts, which satisfy the three conditions above, at frequencies in the microwave region.

Our approach to the development of a complete model (Refs. 10, 11) for the ocean surface has been to use the composite (Ref. 11) model as a starting point, with the radar scattering controlled off normal incidence by the Rayleigh scattering from the capillary waves, and near normal incidence by the physical optics scattering from stationary phase points of the swell component. It has been found that this model is in good agreement with the radar data near vertical incidence, especially for smooth seas, and gives an rms slope in reasonable agreement with oceanographic prediction of slope based on wind velocity. The model also gives good agreement with radar data at the large incidence angles (between 20° and 70°) and is in qualitative agreement with the polarization behavior of the radar data. Furthermore, the predicted brightness temperatures of seas that are not too rough are in reasonable agreement with such data as are available. It is clear, however, that the composite model alone cannot account for the brightness temperature observed over very rough seas, or for all of the polarization properties of the radar return especially near grazing. Thus we have modified the model to include the effect of white caps, foam, or wind driven spray, which can be partly accommodated simply by introducing a new effective dielectric constant proportional to the density of the foam or disturbed water.

Considerable progress has also been made in the computational part of the investigation and is described in detail in References 12 and 13. Computer programs have been developed for three different approaches to one-dimensional random surface scattering. The first, the so-called geometrical optics (G.O.) method, calculates the position and curvature of each stationary phase point on the surface. The scattered field strength for any incident and scattering direction is found by summing the contribution from each specular point (including an extra 90° phase shift for specular points of positive curvature). Shadowing effects may be included if desired. The second program (the physical optics or P.O. approximation) calculates the value of the scattered field from the equivalent surface currents given by the tangent plane approximation (i.e., $\vec{J}_s = 2\vec{n} \times \vec{H}$ for a metal). Again, shadowing may be included if desired. Both of these programs are usable for surfaces of any length (surfaces up to 5000 electrical wavelengths long have been run), and can be easily modified to cover dielectric, as well as perfectly conducting surfaces. The third program is based on solving the integral equation (I.E.) for the surface currents exactly, by numerical methods (i.e., by matrix inversion) using a point matching formulation. At the present, this program is restricted to surfaces of total arc length less than 30 to 60 electrical wavelengths. In all programs the incident wave is a plane wave, with amplitude tapered to zero at the two ends of the surface to minimize edge effects.

In addition to the customary checks on flat plates and sections of circular cylinder, a number of surfaces of the type

$$h(x) = \sum_{1}^{N} A_m(s) \sin(K_m x + \phi_m)$$

have been run (Ref. 12). By choosing K_m and A_m appropriately (K_m's not harmonically related to avoid periodicity, distributed approximately uniformly in K space; A_m approximately proportional to $1/m^2$) surfaces rather similar (in appearance and spectrum) to a wind driven water surface have been generated. By comparing the scattered fields given by the three programs we have found that I.E., P.O. and G.O. fields agree well as long as all but a small fraction of the surface has radius of curvature R greater than about 2.5 electrical wavelengths. If $R < 2.5\ \lambda_e$ over a significant fraction of the surface the G.O. and P.O. fields rapidly deviate from the correct value. However, the G.O. method gives zero scattered field if no appropriate specular points exist, and infinite field if the specular point coincides with a point of inflexion of the surface. Since the "statistical" theories of P.O. scatter from random surfaces actually yield results identical to G.O. (essentially because the P.O. integral can only be evaluated in closed form by stationary phase methods) it is clear that direct numerical integration of P.O. currents can significantly extend the range of surfaces for which a spectrum $W_{\ell}(k)$ may be chosen. (For example, if $<1/R^2> \underline{\sim} BK_c^2/2$ where $B \underline{\sim} .006\ cm^4$ and K_c is some appropriate cutoff, such that $W_{\ell}(k) = 0$ for $K > K_c$, say $K_c = 3\ cm^{-1}$, one might expect to use the P.O. integral to calculate scatter for electrical wavelengths smaller than about 2 cm.

Another set of computations has compared (Ref. 12) P.O. with I.E. fields for surfaces of very small mean square height. The two methods agree well and furthermore, as the surface height is increased (by increasing by the same factor all amplitudes in the Fourier series representation of the surface) all the scattered fields increase in exact proportion, with the scattered energy concentrated in the direction specified by the Bragg condition. Thus for small surface amplitudes the I.E. and P.O. fields also agree with the results of the perturbation theory. The fields cease to be proportional to surface height when $<h^2> \underline{\sim} (\lambda_e/10)^2$ and this is also, approximately, the point where the coherent reflected wave contains only half the total energy. Thus one may use the perturbation theory as long as $<h^2>$ (perturbation theory alone) or $<s^2>$ (perturbation part of composite theory) is less than $(\lambda_e/10)^2$.

By comparing the correct scattered fields from exact current distribution from the I.E. solution with those calculated from physical optics, geometrical optics, and perturbation theory we have established directly (Ref. 12) the surface requirements for the several theories to give good results. Because of the simplicity of the direct integration of physical optics current distributions, and the fact that for certain ocean surface states there is a range of microwave frequencies for which the curvature requirement $R < 2\lambda_e$ can be satisfied, it appears feasible to calculate the backscattering cross section for the ocean directly from the surface height h(x,y). This is particularly significant in view of the results summarized in Ref. 13, in which it is pointed out that the actual sea surface has a number of significant features that are not adequately characterized by a simple gaussian process.

III. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

On the basis of the work reported above and presented in Refs. 12, 13, it may be concluded that a variety of direct methods can be used to calculate the scattering from ocean like surfaces under appropriate conditions. In the future, it would be desirable to compare the results of the standard theories of rough surface scattering with the results of direct calculation based on the physical and geometrical optics programs already developed. This will require the running of a large number of surfaces (preferably dielectric rather than perfect conductors) and subsequent statistical averaging. It would also be desirable to develop specific realizations of the actual sea surface which take into account the actual behavior of the surface, in order that the direct calculations of scattering and emission properties be more realistic.

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