Experimental light-scattering measurements from large-scale composite randomly rough surfaces

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We present experimental measurements of the angular distribution of light scattered from large-scale composite randomly rough surfaces (oceanlike surfaces) with different statistical parameters illuminated at small and large angles of incidence. The surfaces are composed of a small-scale roughness superimposed on a slowly (large-scale) varying surface. The large-scale surfaces are diamond-machined periodic surfaces made on aluminum substrates and have either a sinusoidal or a Stokes wave profile. The small-scale roughness is added with microlithographic techniques, and the surfaces are then gold coated. For a linearly polarized incident beam, it is found that the diffusely scattered light is strongly depolarized and that its pattern is rather different for each large-scale surface profile. Enhanced backscattering is also observed. © 2002 Optical Society of America

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1. INTRODUCTION

The scattering of electromagnetic waves can be utilized in several fields to determine properties of the surface or the material of objects. Optical tomography, remote sensing, microscopy, and surface characterization are some of these applications.

The problem of light scattering by rough surfaces has been the object of renewed interest because of the discovery of effects unknown until just a few years ago, such as enhanced backscattering.1,2 Since then, significant advances have been made in the study of light scattered from rough surfaces.

There are many studies of scattering from or through different media using electromagnetic waves (see the references in Nieto-Vesperinas3 and in reviews by Valenzuela4 and Shmelev5). One of the methodologies that has been used to address theoretically the electromagnetic scattering problem is the integral equation approach.6,7

This method consists in using Maxwell’s field equations to derive an integral equation for the scattered field at any observing point.6,8 This approach contains the boundary conditions of the problem implicit in the formulation. A key point for the derivation of an expression for the scattered field is Green’s theorem.6

It has been possible to obtain analytic results in two limiting cases. One of them, the Kirchhoff approximation, applies when the radius of curvature of the surface structure is large compared with the wavelength of radiation and the angle of incidence is not large. The second approach, the perturbation method, occurs when the surface is slightly rough, that is, when the surface irregularities are small in comparison with the wavelength of radiation.

The Kirchhoff approximation consists in approximating the field at any point of the surface by the field that would be present on an infinite tangent plane at that point. It also usually includes a far-field approximation (detailed reviews can be found in Beckmann and Spizzichino,9 Bass and Fuks,10 and Ogilvy11).

The Kirchhoff approximation is in good agreement with experiments conducted with rough surfaces whose local radius of curvature is large compared with the wavelength,5,12 This means that the local slope is not large in comparison with the illuminating wavelength. A sufficient criterion broadly accepted is that the correlation length be greater than the incidence wavelength,9,11,13 However, the limitations and the accuracy of this approximation have been the subject of discussion.14–16 When we deal with slightly rough surfaces where the irregularities are small in comparison with the wavelength, the Kirchhoff approximation is no longer suitable. However, the perturbation method has been used with some success in this case.

The perturbation method has been used to obtain the scattered field from slightly rough surfaces.17 For this method, it is important to have gentle slopes $|\nabla \zeta(x, y)| \ll 1$ and small heights $k|\zeta(x, y)| \ll 1$, where $\zeta(x, y)$ represents the surface heights. The essential part of this method consists in expanding both the boundary conditions and the scattered field in powers of the small parameter $k \sigma_{\zeta}$ ($k$ is the wave number, and $\sigma_{\zeta}$ is the stan-
Experimental studies with surfaces within this regime have been reported by West and O'Donnell. In 1987 O'Donnell and Méndez reported enhanced backscattering and depolarization with surfaces with a correlation length of twice the wavelength. These effects were not predicted by the Kirchhoff approximation or any other theory known at that time. These new effects stimulated the search for new approximations or improvements of the existing scattering theories.

It is now widely accepted that the main mechanism of enhanced backscattering and depolarization from very rough surfaces is due to multiple-scattering effects. Chen and Ishimaru and Bruce and Dainty have studied the role of multiple scattering with this kind of surface. Using the Kirchhoff approximation, they separated the single- and double-scatter terms in the total scatter pattern, and they also have included shadowing effects, finding out that the double-scatter term is responsible for the enhanced backscattering peak and that its strength decreases with increasing angles of incidence.

As a result of new computing techniques and computing processing power, the exact solution to the scattering equations was established numerically, first for the case of a perfect conductor and later for metals and dielectrics. These approaches use the Monte Carlo numerical method for calculating the scattering intensity due to a finite section of a rough surface, which is then averaged over several samples of the surface. The main restriction of this method is due to the limited speed and memory of present-day computers. In consequence it is often possible to consider only a one-dimensional surface and a small illuminated section of the surface.

Many rough surfaces of interest can be modeled as a superposition of two independent components: a small-amplitude, high-frequency roughness superimposed on a low-frequency, large-amplitude component (Fig. 1). The latter can be a periodic surface. Examples of such surfaces at optical frequencies are those that have a granular appearance and still have microscopic irregularities, while the sea and certain types of terrain are well described by such a model at microwave frequencies.

There has been a surging interest in scattering of waves from multiple-scale (composite) surfaces because of its application in remote sensing and radar imaging, that is, to interpret radar data and to relate them to oceanic parameters. Radar scattering from the sea surface, particularly at large angles of incidence, remains a poorly understood phenomenon. One of the main problems is the modeling of the sea surface itself. The most common way to represent the sea surface is to treat it as composed of small capillary waves riding on top of larger gravity waves. Well-controlled experimental studies in this area will contribute to a better understanding of scattering by sea surface and terrain and will help to develop models that can reproduce the features of radar scattering.

Analytical approaches such as the Kirchhoff approximation and the perturbation method have been used in order to understand the statistical characteristics of scattering by double-scale surfaces. The composite model has been used widely in interactions of electromagnetic and oceanic waves. In this approach, the rough surface and the sea surface are a superposition of two independent, random, surface-height distributions. Thus the composite model approximates the rough surface by small patches of slightly rough surfaces that ride the large waves. Each patch is small enough to be considered planar. The scattering of an electromagnetic wave from the small-scale surface is modeled by using the perturbation approach. The total scattered field is an incoherent average of the scattered field from single rough patches over the distribution of slopes of the large-amplitude components.

To our knowledge, no experimental scattering measurements from well-characterized large-scale composite randomly rough surfaces have been reported. Thus the aim of the research reported in this paper is an experimental investigation of light scattering from well-characterized double-scale surfaces, i.e., surfaces having a small-scale random component on a large-scale periodic grating, illuminated at small and large angles of incidence. This will show trends in scattering behavior and provide physical insight for the scattering processes occurring on composite rough surfaces that will provide the ground for testing the two-scale theoretical approaches. Currently, this problem cannot be rigorously solved either analytically or numerically.

Furthermore, this kind of experiment can be related to a scaled-down sea scattering problem, that is, to undertake laboratory optical frequency experiments to investigate the in-plane angular scattering properties of ocean-like surfaces with well-controlled statistical parameters that can aid in understanding the features of radar sea scattering.

2. MODELING THE OCEANLIKE SURFACE

The mathematical description of waves on the sea surface has evolved over the years (Lamb has collected the early developments of the subject). Hydrodynamic theory is limited to the study of idealized problems with tractable solutions. A simple mathematical equation cannot describe a real sea with waves of different periods propagating in different directions and interacting with one an-
other. Nonetheless, the theoretical modeling has been able to describe the basic properties of the surface waves.

A simple wave theory that considers the sea surface as a single sinusoidal wave cannot completely describe the real ocean surface. However, this approach has had success in describing, with considerable accuracy, the basic properties of ocean waves, particularly in relation to the dynamics of their propagation. The fact that for small-amplitude waves the linear theory is adequate has encouraged the adoption of the pragmatic approach of regarding the irregular sea surface as a composite of many ideal sinusoidal wave components.\(^{31}\)

Thus our first model for a sea surface shall be a large-scale surface with a sinusoidal profile (gravity wave). The gravity wave is thus given by\(^{31,33,34}\)

\[
\zeta(x) = A_p \sin(Kx),
\]

where \(K = 2 \pi/\Lambda\) is the wave number, \(\Lambda\) is the period, and \(A_p\) is the amplitude of the wave. A condition for the validity of the linear wave solution treated above is that the wave slope be small \((A_p/\Lambda < 1/7)\).\(^{34}\)

While the linear wave theory is adequate for many applications, it may be necessary to model the sea more closely with nonlinear solutions. This is because the basic dynamics are in fact nonlinear, and the linear equation presented earlier is only an approximation.

We shall consider a Stokes wave to the fourth order as a nonlinear solution to the wave theory.\(^{31,33,34}\) A Stokes wave is a series solution expressed as an infinite power series in terms of a parameter related to the slope \((A_p/\Lambda)\). To the fourth order, the sea wave profile is given by\(^{31}\)

\[
\zeta(x) = -A_p \cos(Kx) + \left(\frac{1}{2}KA_p^2 + \frac{17}{24}K^3A_p^3\right) \cos(2Kx) - \frac{3}{8}K^2A_p^3 \cos(3Kx) + \frac{1}{3}K^3A_p^3 \cos(4Kx). \tag{2}
\]

Spectral analyses have been carried out to determine the spectrum of the wave components present in a real sea.\(^{31,33}\) From these we have taken a wavelength of \(\Lambda = 100\) m and an amplitude of \(A_p = 2.5\) m. These are representative values of a fully developed sea, that is, an equilibrium energy state, appropriate to a given wind speed, in which the waves have ceased to grow or change period.

We have already mentioned two ways of constructing a mathematical model to describe the sea surface, taking into account the fact that the linear theory is acceptable for many conditions, but they can be improved.

With certain restrictions, the wind-driven sea is best thought of as random ripples (capillary waves) on top of large gravity waves. If the ripples are formed from many contributions arising from relatively unrelated forces, it is then reasonable to assume the summation of all these contributions to be statistically independent. In fact, this physical situation is governed by many additive, independent events. Such a process can be described by employing Gaussian statistics, by virtue of the central limit theorem.\(^{25}\) The distribution of ripple heights is thus assumed to be Gaussian. A fully developed sea falls into this category. For most purposes, the Gaussian distribution is satisfactory, although in the context of radar imaging the skewness of the height distribution may be important. From the experimental point of view, it is more convenient to consider a Gaussian distribution, since a technique for fabricating this kind of surface is well-known.\(^{36}\) Therefore we shall consider a Gaussian process for the random ripples riding on top of gravity waves, and its probability density function is given by\(^{37}\)

\[
p(\xi) = \frac{1}{\sqrt{2 \pi \sigma^2}} \exp\left(-\frac{\xi^2}{2 \sigma^2}\right), \quad -\infty < \xi < \infty, \tag{3}
\]

where \(\sigma\) is the standard deviation of heights of the capillary waves.

While the probability density function gives information about the statistics of a single point, information about lateral structure in space is also of importance. In our surface model, we are going to consider the autocorrelation function of two points at different positions at a fixed time to be a Gaussian function given by\(^{37}\)

\[
W(|x - x'|) = \exp\left(-\frac{(x - x')^2}{a^2}\right), \tag{4}
\]

where \(a\) is the correlation length and describes the horizontal scale of the random roughness.

Thus, within our model, an oceanlike surface would appear as illustrated in Fig. 1.

### 3. FABRICATION OF ROUGH SURFACES

There have been many experimental investigations of surface scattering, and many different types of rough surfaces have been used for this purpose, such as ground glass plates, gold-coated sand paper,\(^{24}\) and chemically etched glass plates.\(^{25}\) However, such surfaces are difficult to characterize and fabricate in a well-controlled way. Since theoretical studies of light scattering from rough surfaces generally employ a particular statistical model, a critical comparison between experiments and theory can be conducted only when well-characterized surfaces are available, and therefore the fabrication of such surfaces becomes important.

Several methods exist to make randomly rough surfaces, but the most suitable for our purposes is a photolithographic technique. This fabrication technique, as developed by Gray,\(^{36}\) leads to two-dimensional isotropic surfaces with Gaussian statistics and has been used with success by Méndez and O’Donnell\(^{1,2}\) and Kim\(^{12}\) in scattering experiments. This method consists in exposing photoresist-coated plates to laser speckle patterns. It is suitable for the fabrication of, in general, randomly rough surfaces with a gamma probability density distribution of surface heights, with the Gaussian distribution being a limiting case.

Most of the scattering theories consider surfaces whose height variation depends on one Cartesian coordinate only; therefore the manufacture of those surfaces is of interest. There has been some work by Kim\(^{12}\) and Sant,\(^{38}\) who developed a technique to manufacture quasi-one-dimensional surfaces. Later, Méndez \textit{et al.}\(^{39}\) suggested...
another method that produces highly one-dimensional surfaces. It consists in scanning a photoresist-coated plate under a narrow line of light, obtained by focusing an expanded laser beam with the help of a cylindrical lens. A better method, at least for making one-dimensional randomly rough surfaces, was suggested by Knots et al.\(^{40}\) and is a combination of the techniques of Kim\(^{12}\) (elongated speckles) and Méndez et al.\(^ {39}\) (scanning).

To perform our experimental study to investigate the in-plane angular scattering properties of double-scale surfaces, we fabricated several large-scale composite randomly rough surfaces. We shall present the results from two of them.

For the manufacturing of the large-scale composite randomly rough surfaces, we started with large-scale, slowly varying, diamond-machined periodic surfaces made on 5.0-cm \(\times\) 5.0-cm aluminum substrates. One of the surfaces has a sinusoidal profile \([\text{Eq. (1)}]\) with a period of \(\Lambda = 1.0\) mm and an amplitude of \(A_p = 25.0\) \(\mu\)m. The other long-period surface has a Stokes wave to the fourth-order profile, described by \(\text{Eq. (2)}\), where the period is \(\Lambda = 1.0\) mm and the distance from peak to valley is 50.0 \(\mu\)m.

To include the small-scale randomly rough surface on top of the large-scale periodic surface, we used the speckle technique for surface fabrication described by Gray.\(^{36}\) After the substrates had been cleaned, an immersion photoresist coating was used. This consists of dipping the substrates for 30 min at 90 °C.

The photoresist-coated substrates were exposed to eight independent laser speckle patterns produced by the 442-nm line of a helium–cadmium laser with equal exposure times. When the exposures were completed, the photoresist was developed in a Shipley developer and allowed it to dry overnight, apply a second immersion coating, and then pull it upward at constant speed. The following procedure was found to give good results for the dipping coating technique: Immerse the aluminum substrate in the photoresist, pull up the substrate at constant speed \((\approx 130\) \(\mu\)m/s), allow it to dry overnight, apply a second immersion coating at the same speed, dry for 24 h, and bake the substrates for 30 min at 90 °C.

The photoresist-coated substrates were exposed to eight independent laser speckle patterns produced by the 442-nm line of a helium–cadmium laser with equal exposure times. When the exposures were completed, the photoresist was developed in a Shipley developer and coated with a nontransparent layer of gold.

The characterization of the surfaces was carried out by using two profilometers. Figure 2(a) shows the trace for the surface with a sinusoidal profile, and Fig. 2(b) shows the trace for the Stokes waves to the fourth-order surface. We first used a Rank Taylor-Hobson from TalySurf model 112/0. This TalySurf has enough vertical and horizontal dynamic range to measure the main features of the large-scale component without having problems of nonlinearity. Also, this TalySurf allowed us to start a new scan exactly where a previous one was finished. That is why it is possible to present traces as shown in Fig. 2. It is worthwhile noting the difference between the two kinds of slowly varying periodic surfaces.

To measure the small-scale component roughness, we used a Rank Taylor-Hobson TalyStep model 223-7. This TalyStep has a much higher resolution than that of the previous one. We took several scans along the grooves of the large-scale surface at three regions: crest, trough, and middle part (a point between the peak and the valley).

Table 1 shows the parameters for the large and small features of the two large-scale composite randomly rough surfaces. As we can see, the standard deviation of heights of the small-scale component is not the same in the three regions. The surfaces are rougher at the trough. Also, because of the thickness of the photoresist layer, the peak-to-valley distances are shorter than those of the uncoated aluminum substrates.

Given the profilometer traces, it will be useful to have a mathematical expression to describe the final slowly vary-

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**Table 1. Surface Parameters for the Large and Small Components of the Large-Scale Composite Randomly Rough Surfaces**

<table>
<thead>
<tr>
<th>Surface</th>
<th>Large Scale</th>
<th>Small Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Period (mm)</td>
<td>Peak-to-Valley Distance ((\mu)m)</td>
</tr>
<tr>
<td>SIN-A</td>
<td>1.0</td>
<td>20.0 (\pm) 0.01</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>STOKES-A</td>
<td>1.0</td>
<td>20.0 (\pm) 0.02</td>
</tr>
<tr>
<td></td>
<td></td>
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ing component of the manufactured surfaces. In the case of the sinusoidal surfaces, the analytical expression is given in Eq. (1) with $A_p = 10 \mu m$ and $K = 6.28 \text{mm}^{-1}$. For the case of the manufactured surfaces, we shall fit the data to a polynomial function of the form

$$\zeta_{\text{fit}}(x) = c_1 + c_2 \cos(Kx) + c_3 \cos(2Kx) + c_4 \cos(3Kx)$$

$$+ c_5 \cos(4Kx),$$

where the constants $c_1 - c_5$ are the appropriate coefficients to fit our data and $K$ is given in Section 2. Using a standard least-squares-fitting technique, we found that the best-fit parameters are $c_1 = -2.19$, $c_2 = -9.36$, $c_3 = 1.94$, $c_4 = -0.38$, and $c_5 = 0.18$.

If we assume that we can treat the waves of the ocean surface as a composition of small random waves (capillary waves) on top of long-period waves (gravity waves), as mentioned in Section 2, the manufactured surfaces discussed in the present section can be considered a scaled-down sea surface. Therefore, according to our sea surface model, our surfaces can be related to a large (gravity) wave with a period of 100.0 m and a wave height (distance between the wave crest and the wave trough) of 2.0 m. The small random capillary waves have a standard deviation of heights comparable with the wavelength ($\lambda \approx 3.4A$ and $\sigma_z \approx 0.9A$) and therefore with a smaller mean free path for multiple scattering. The strong backscattering peak is known as enhanced backscattering. The latter observations are in agreement with O’Donnell and Méndez and Sant. There are also small sidelobes on both sides of the backscattering peak in the co-polarized scattering, but they are not distinct. These maxima are also present in the cross-polarized component, but they are better defined and in different angular positions. The envelope of the co-polarized scattering is broader than the cross-polarized one.

Figure 4 shows the scattering pattern when the surface is illuminated with a $p$-polarized incident beam. Again, it is possible to observe considerable depolarization. Both the co- and cross-polarized components show a strong backscattering peak (enhanced backscattering). No obvious secondary maxima are observed in the $pp$ scattering component. However, they are present in the $ps$ component. In comparing the $sp$ and $ps$ scattering components, we see that they are similar.

4. EXPERIMENTAL RESULTS

In this section, we present the experimental results of light scattering from large-scale composite randomly rough surfaces at different angles of incidence.

We first describe the scattering measurements for the surface SIN-A [surface with a sinusoidal long-period component, shown in Fig. 2(a)]. The surface parameters are given in Table 1. Figures 3 and 4 show the angular distribution of the co- and cross-polarized mean scattered intensity at normal incidence ($\theta_{\text{inc}} = 0^\circ$) for $s$ and $p$ incident polarization, respectively.

Let us consider first the case of an $s$-polarized incident beam (Fig. 3). It can be seen that there is considerable depolarization; the cross-polarized component ($sp$) reaches approximately 25.0% of the co-polarized ($ss$) intensity at some scattering angles (mainly at $|\theta_{\text{sca}}| < 30^\circ$). A strong backscattering peak is present in both co- and cross-polarized scattering components, and the angular width is approximately $12.0^\circ$. This behavior can be attributed to multiple-scattering effects and is expected for a surface with a correlation length and a standard deviation of heights comparable with the wavelength ($\lambda \approx 3.4A$ and $\sigma_z \approx 0.9A$) and therefore with a smaller mean free path for multiple scattering. The strong backscattering peak is known as enhanced backscattering. The latter observations are in agreement with O’Donnell and Méndez and Sant. There are also small sidelobes on both sides of the backscattering peak in the co-polarized scattering, but they are not distinct. These maxima are also present in the cross-polarized component, but they are better defined and in different angular positions. The envelope of the co-polarized scattering is broader than the cross-polarized one.

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![Fig. 3. Angular distribution of the measured mean scattering intensity from surface SIN-A with $s$-polarized incident light at normal incidence.](image)

![Fig. 4. Same as Fig. 3 but for $p$-polarized light.](image)
In Figs. 5 and 6, we present the experimental results of a series of angular mean scattering intensity measurements (vertical axis) at different angles of incidence for s- and p-polarized incident beams, respectively. Figure 5(a) shows the measurements for the co-polarized component, and Fig. 5(b) shows those for the cross-polarized component.

For the case of s polarization (Fig. 5), a backscattered peak is present and decreases in strength as the angle of incidence increases; this behavior is noticeable for both co- and cross-polarized components. The backscattering peak is observed up to 30.0° incidence for the co-polarized component and up to approximately 40.0° incidence for the cross-polarized scattering. At the largest angle of incidence (θ_{inc} = 70°), a peak at specular is observed in the co-polarized component, and a maximum seems to develop at θ_{sc} = 0°. The cross-polarized contribution does not show any specular component. As the angle of incidence increases, the degree of depolarization (sp scattering component) gets smaller and the sidelobes, on both sides of the backscattering peak, first become skewed and then disappear.

In the case of a p-polarized incident beam, as shown in Fig. 6, similar behavior is observed, but as we have mentioned for the case of normal incidence, no secondary maxima are noticeable for the co-polarized component. A specular-like peak is also present when the angle of incidence is 70°; the strength of this component is weaker than that in the ss scattering. In comparing both cross-polarized components (sp in Fig. 5 and ps in Fig. 6), we observed nearly identical characteristics.

Now we present the experimental measurements of the angular distribution of the mean scattering intensity from surface STOKES-A, a large-scale composite randomly rough surface with a Stokes wave to the fourth-
order profile as a slowly varying surface component [Fig. 2(b)]. Table 1 shows the statistical parameters of this surface.

In Figs. 7 and 8, we present the mean scattering intensity as a function of angle of observation for s and p polarization at normal incidence, respectively. Both co- and cross-polarized components are also shown.

There are notable aspects of these scattering patterns that are rather different from those for the previous surface. The amount of depolarization is considerable, as there are strong cross-polarized components (sp in Fig. 7 and ps in Fig. 8). A strong peak of finite width is present and is centered about the backscattering direction in both co- and cross-polarized components for both incident polarizations, and the strength of the peak is bigger than that in the previous surface (enhanced backscattering peak due to multiple-scattering effects). On either side of the backscattered peak, subsidiary maxima are observed. The co-polarized component has a broader envelope than that of the cross-polarized component, and also the subsidiary maxima are in different positions for both incident polarizations. It is also noticeable that the mean scattering intensity of the co-polarized component at small angles of scattering ($|\theta_{sc}| < 15^\circ$) is much higher than that of the envelope. In the pp component, the secondary maxima are not as distinct as in the ss component.

In what follows, we present the angular distribution of the measured scattering intensities from surface STOKES-A at different angles of incidence for an s-polarized (Fig. 9) and a p-polarized (Fig. 10) incident beam.

In Fig. 9(a) (ss component), it can be seen that, as at normal incidence, a well-defined peak is observed at different angles of incidence in the retroreflection direction (enhanced backscattering). This backscattering peak decreases as the angle of incidence increases, and it vanishes at approximately an angle of incidence of 50°. Similar behavior is observed for the cross-polarized component (sp). The secondary maxima, observed at normal
incidence, first become skewed as the angle of incidence increases from 0° up to 20° incidence, when one of the peaks has disappeared. The other maximum disappears when the angle of incidence is approximately 30°.

Comparable behavior is observed for the case of a p-polarized incident beam (Fig. 10). However, the pp component differs, mainly, in that it has a slightly weaker scattering where the secondary maxima are. As above, it may be seen that the sp and ps components are nearly identical.

Repeated measurements of the scattered light from the same rough surface were reproducible. To further reduce the speckle noise in this case, we made many measurements with the sample translated by a distance sufficient to cause partial decorrelation between each pair, and the results were averaged.

As we stated in Section 1, it is widely accepted that the main mechanism of the enhanced backscattering from rough surfaces is a multiple-scattering phenomenon, which occurs already in the double-scatter approximation.\textsuperscript{19,20,41} The enhanced backscattering effect can be understood, at least qualitatively, as a coherent interference process. Let us consider the following scenario. When the incident wave hits a point on the surface, a scattered field is produced. Such a scattered field might strike the surface at another point before being scattered into the vacuum, away from the surface. However, some of the incident field might follow the reverse order; that is, the light is scattered from the same points but in the reverse sequence. Then a constructive interference will take place if the wave vectors of the incident and final waves have a nonzero phase difference and rapidly become incoherent.

The width of the backscattering peak can be found by averaging the phase difference between any given light path and its reverse path partner and is of the order of \(\lambda/a\).\textsuperscript{7} Thus, decreasing the correlation length of our rough surfaces, we shall expect a wider backscattering peak. Furthermore, the subsidiary maxima are expected to appear at angles of observation of the order of \(n\lambda/(d)\),\textsuperscript{41} where \(n\) is the order of interference and \(d\) is the distance between the first and last scattering points. The subsidiary maxima observed in our experiments correspond to \(n = \pm 1\). For \(n = \pm 2\) the phase difference between any given light path and its reverse path partner is sufficiently large to destroy all interference effects in surface scattering, as Maradudin et al.\textsuperscript{41} have found. Thus these effects will be washed out for orders of interference larger than 1.

Since the large-scale surface of our composite surfaces is one dimensional, the contribution to the mean scattering intensity of the cross-polarized component is produced by the two-dimensional small-scale roughness. Consider the scattering of a linearly polarized light by an isotropic two-dimensional surface. Also consider, for simplicity, the surface to be composed of an array of small flat mirrors, each tangent to a point on the surface. When scattering of light from one of these planar mirrors is considered, light scattered in a single direction will be completely polarized. However, because of the detection area of the photodetector, what we are measuring is scattered light integrated over a solid angle. Thus scattered light from several of those flat mirrors, although completely polarized at each point, will not have a preferred polarization state over the detector aperture. This gives rise to a measurement that makes it appear to be unpolarized.

Taking this into account and following Renau et al.,\textsuperscript{13} Dainty et al.,\textsuperscript{42} and Kim et al.,\textsuperscript{43} we shall describe the scattered light in terms of polarized and randomly polarized components and not just in terms of co- and cross-polarized components. Assuming an s-polarized incident beam, it can be shown\textsuperscript{13,42,43} that the polarized \((I_{\text{pol}})\) and randomly polarized \(I_{r\text{-pol}}\) scattered intensities are given by

\[
I_{\text{pol}} = I_{ss}(\theta_{\text{inc}}) - I_{sp}(\theta_{\text{inc}}),
\]

\[
I_{r\text{-pol}} = 2I_{sp}(\theta_{\text{inc}}),
\]

where \(I_{ss}(\theta_{\text{inc}})\) and \(I_{sp}(\theta_{\text{inc}})\) are the mean scattering intensities for the co-polarized \((ss)\) and cross-polarized \((sp)\) components, respectively.

As an outcome of the previous result, we present in Figs. 11 and 12 the scattering intensity of the polarized component (solid curve) and the randomly polarized component (dashed curve) for the two surfaces.

Dainty et al.\textsuperscript{42} and Kim et al.\textsuperscript{43} found that, to a larger extent, the polarized component arises from single scattering and the randomly polarized component arises from multiple scattering. Thus the enhanced backscattering contribution to the light scattering is the randomly polarized component.

With the previous statement kept in mind, the results (Figs. 11 and 12) indicate that the light near the backscattering direction is dominated by randomly polarized
The angle of incidence ranged from normal incidence up to 70° for both s and p polarization. The results show a well-defined peak in the backscattered direction at different angles of incidence. A decrease in the strength of the peak with an increase in the angle of incidence is observed. Also, secondary maxima on both sides of the backscattering peak were observed from the two surfaces. These maxima closely resemble those of the experimental scattering measurements shown in Fig. 9 of O’Donnell and Méndez. This behavior can be attributed to multiple-scattering effects arising from the small-scale roughness. Additionally, strong depolarization was observed at different angles of incidence, as can be seen in Figs. 5, 6, 9, and 10 of the present paper, where the cross-polarized component is shown.

As a result of the combination of a large-scale component and two-dimensional small-scale roughness, the problem is difficult to tackle with rigorous numerical techniques, but two-scale models could be employed to explain some of the results. Scattering from double-scale surfaces is not a simple problem, and we believe that there is not a simple relation between the shapes of the scattering curves and the double-scale surface.

The results are relevant to radar scattering by the ocean surface. Models can be tested. The situation corresponds to a scale problem of scattering of the C band of the microwave spectrum (6.0-cm wavelength) from sea surfaces that are considered fully developed seas with no borders (no coastlines) having a large (gravity) wave period of 100.0 m, a wave height (distance between the wave crest and the wave trough) of 2.0 m, a standard deviation of heights of the order of 2.0 cm, and a correlation length of the order of 21.0 cm for the small random capillary waves.

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