Scattering in Volumes and Surfaces
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MEASUREMENTS OF ANGULAR SCATTERING BY RANDOMLY ROUGH METAL AND DIELECTRIC SURFACES

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Measurements of the light scattering by three well-characterised random rough surfaces are presented. The surfaces studied include one- and two-dimensional gold-coated samples and a one-dimensional dielectric sample. Measurement wavelengths are 633 nm and 10.6μm. The purpose of these measurements is to provide a reliable database to aid theoretical understanding of multiple light scattering from rough surfaces.

1. INTRODUCTION

There is no shortage of experimental and theoretical studies of angular scattering from randomly rough surfaces. However, experiment and theory rarely have the opportunity to be compared in a critical way, for two reasons; first, theoretical analyses frequently make quite specific assumptions on the nature of the surface (e.g. gaussian probability density of height to all orders, or perhaps perfect conductivity) and on the nature of the scattering process (e.g. "shadowing" or multiple scattering ignored); second, experiments are frequently carried out on surfaces whose properties do not match the theoretical assumptions. In the optical region, there have been few experiments on controlled, well-defined randomly rough surfaces and the results of Reneau[1,2] are of particular note.

From the point of view of assisting our understanding of light scattering, there seems little point in measuring the angular scatter from low-sloped surfaces whose correlation length is much greater than the optical wavelength, since this situation is explained adequately by scalar Kirchhoff diffraction theory (except at grazing incidence). However, scattering from high-sloped surfaces is inherently more interesting, since multiple scattering occurs, and until recently no controlled surfaces were available for visible light experiments. In 1987, Mendez and O'Donnell published experimental results for the angular scatter from well

characterised high-sloped metallic gaussian surfaces[3,4] which have stimulated a large number of theoretical and numerical studies[5–11]. The experiments of Mendez and O'Donnell were prompted by the question: is it possible to observe, from rough surfaces, enhanced backscattering of the type observed from dense volume media and which is attributed to coherent co-operative effects resulting from multiple scattering? Enhanced backscattering was observed in the pioneering experiments of Mendez and O'Donnell (and subsequently from many other surfaces prepared in our laboratory) although it is still not clear whether the coherent co-operative effect that gives the effect in dense volume media is the dominant cause of the enhancement for rough surfaces.

In this paper, new experimental results[12–14] are presented for two-dimensional metallic rough surfaces and one-dimensional metallic and dielectric surfaces — in both cases, results at visible (633nm) and infrared (10.6μm) wavelengths are presented. The one-dimensional results (random gratings) are given to assist comparisons with analytical and numerical calculations which are frequently limited to this case; however, no detailed comparisons with theory are made here.

2. SCATTERING EQUIPMENT AND SURFACE PREPARATION

Figure 1 shows the essential features of the scatterometer used to measure the angular dependence of the scattered intensity. In the present work, wavelengths of 0.633 μm (He-Ne laser) and 10.6 μm (CO_2 laser) were used for illumination. Only scattering in the plane of incidence is measured, the incident (θ_i) and scattered (θ) angles being both measured from the surface normal, i.e. $\theta = \theta_i$ in the specular direction. A photomultiplier was used to detect the visible wavelength and a pyroelectric detector for the infrared radiation. The measurement of intensity involved some angular averaging, approximately 0.5° for visible and 1.0° for the infrared. Since the speckle size was on the order of 5 arc seconds for the visible and 1 arc minute for the infrared, speckle noise was effectively eliminated and the results are equivalent to ensemble averages blurred by the (small) angular cone of measurement.

The measured intensity is normalised by the incident power and is thus the mean normalised differential scattering cross-section; for a perfect lambertian diffuser, the variation of intensity with angle would be cos(θ). Measurements of a smoked Magnesium Oxide surface[13] show this cosine law is obeyed approximately

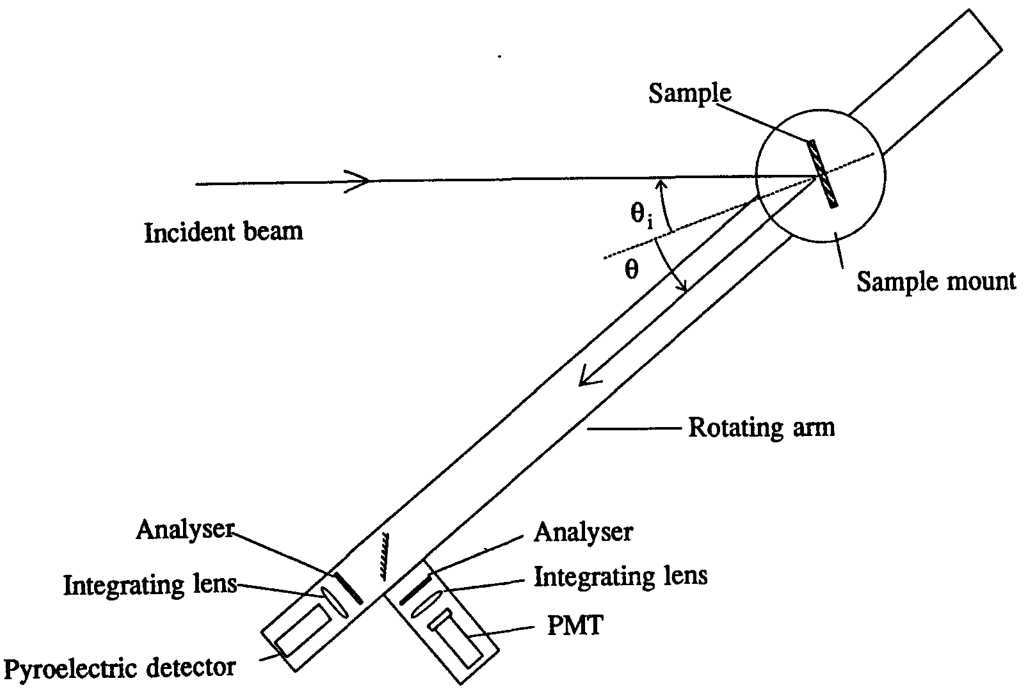

FIGURE 1

for small angles of incidence, except for the presence of the enhanced backscatter peak due to coherent effects within the scattering volume.

Random rough surfaces were prepared by exposing photoresist (Shipley S1400-37 in the most recent experiments) to laser speckle patterns, following the method of Gray[15]. Both one- and two-dimensional surfaces have been made. In the case of the "one-dimensional" surfaces, correlation lengths are typically microns in the direction of interest and millimetres in the orthogonal direction. Surfaces have been replicated[12] by first forming a copy in silicone rubber (Dow Corning Sylgard 182) and then casting in epoxy resin (Araldite MY 778 + HY 956). The resin copy is a positive replica of the original surface. Surfaces are coated with a gold layer ≈90 nm thick; the dielectric results shown in Section 4 were obtained using the silicone rubber intermediate (refractive index 1.43).

Measurements of the surface profile were made with a stylus instrument (Rank Taylor Hobson "Talystep") equipped with a special stylus. For the case of the one-dimensional surfaces, a chisel-shaped stylus was used, of approximate dimensions 0.6 by 2.0 μm. The probability density function of surface height and correlation function are both gaussian to a good approximation. Figure 2 shows an example for a one-dimensional surface #39. Surfaces are therefore characterised by their

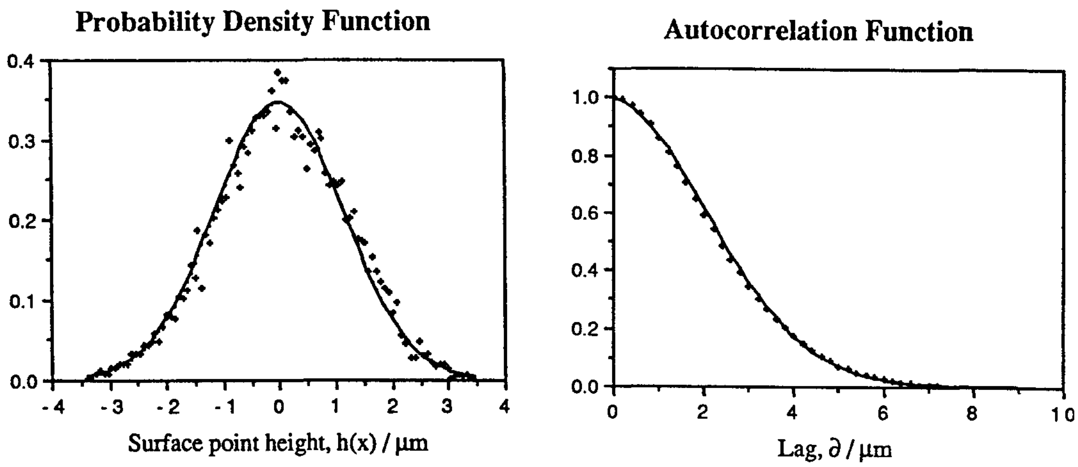

FIGURE 2. Probability density and autocorrelation function of surface height for one-dimensional surface #39.

root-mean-square (rms) surface height σ and 1/e correlation length τ. The measurements on one-dimensional surfaces are considered to be much more reliable than those made on the two-dimensional surfaces because the effect of stylus on the measurement is much smaller. In this paper, results are presented on three surfaces (note that the errors given are statistical errors):

(i) Surface #313: two-dimensional, gold-coated; $\sigma = 1.0 \pm 0.1$ μm, $\tau = 2.9 \pm 0.2$ μm

(ii) Surface #440: one-dimensional, gold-coated; $\sigma = 1.2 \pm 0.1$ μm, $\tau = 2.0 \pm 0.2$ μm

(iii) Surface #39: one-dimensional, dielectric and gold-coated, $\sigma = 1.18 \pm 0.13$ μm, $\tau = 2.97 \pm 0.05$ μm.

3. RESULTS FOR TWO-DIMENSIONAL SURFACES

Mendez and O'Donnell[3,4] have reported measurements of enhanced backscattering on gold-coated high-sloped surfaces. Apart from the backscatter peak, the scattered intensity also has an interesting polarisation structure that strongly suggests that multiple scattering plays an important rôle. To investigate this further, we measured the Stokes' parameters of the scattered intensity for a few fixed angles of scattering. For linearly polarised incident light, it was found that the scattered light had only two non-zero Stokes' parameters (to within the experimental error of 5% of the first Stokes' parameter), corresponding to components that were (a) linearly polarised in the direction of the incident light and

(b) unpolarised. It should be stressed that, although a single surface was used in the experiment, the measurement involved angular averaging over many speckles and thus was equivalent to an ensemble average. In this context, "unpolarised" means that there was no preferred direction of polarisation averaged over all speckles.

As a consequence of this result, it is possible to re-plot the usual co- and cross-polarised intensity measurements as polarised, I_{pol}, and unpolarised, I_{unpol} intensities; for example, for s-polarised incident radiation (s-polarised means that the electric vector is perpendicular to the plane of incidence):

$$I_{pol} = I_{ss} - I_{sp} \quad ; \quad I_{unpol} = 2\,I_{sp} \quad . \tag{1}$$

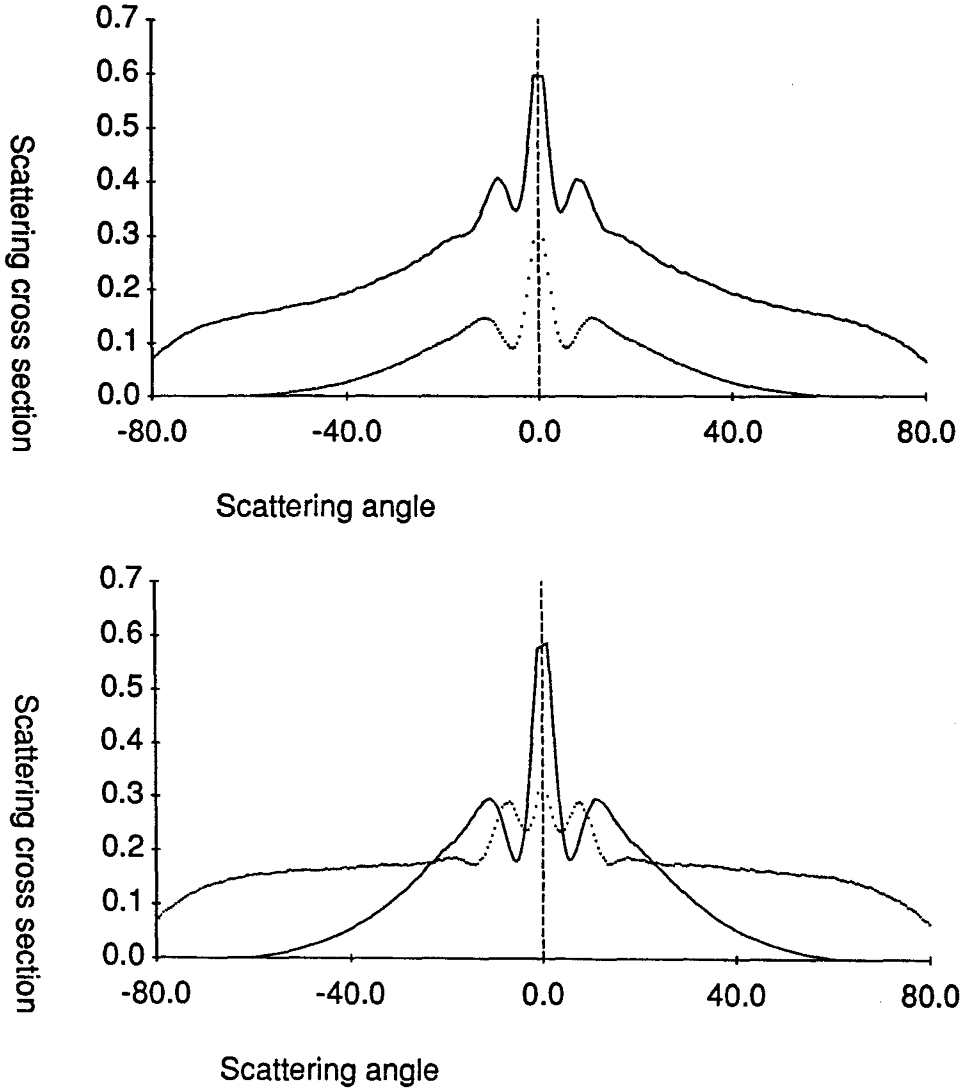

FIGURE 3. Two-dimensional surface #313, normal incidence.

The upper parts of Figures 3 and 4 show the angular scattered intensity for surface #313 ($\sigma = 1.0 \pm 0.1$ µm, $\tau = 2.9 \pm 0.2$ µm) for s-polarised incident light ($\lambda = 633$ nm) and s- and p-polarised scattered light at angles of incidence of 0° and -10° respectively (in these and subsequent Figures, the enhanced backscatter peak is situated on the right hand side and the specular peak — if any — on the left). In each case the solid line is the co-polarised return and the broken line is the cross-polarised return. These measurements clearly show the enhanced backscatter peak and side-lobe structure reported by Mendez and O'Donnell[3,4]. The lower parts of Figures 3 and 4 show these results re-plotted in terms of the polarised (broken line)

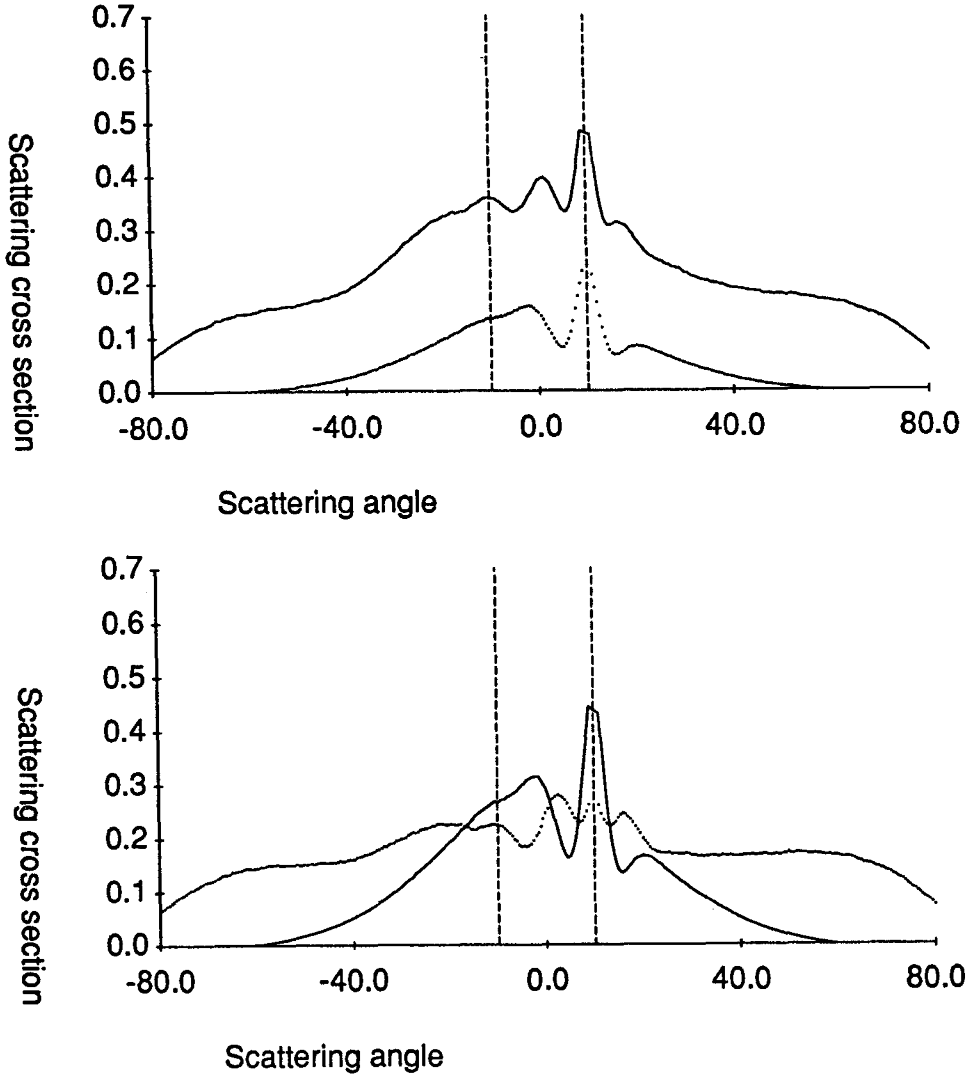

FIGURE 4. Two-dimensional surface #313, −10° incidence.

and unpolarised (solid line) cross-sections, as defined by Eq.(1). *Note that the enhanced backscatter peak is present only in the unpolarised intensity.*

To a first approximation, the polarised component is the result of single scattering and the unpolarised component due to multiple scattering. Thus the above result implies that it is *multiple scattering* that is the dominant cause of enhanced backscattering for these high-sloped metallic rough surfaces.

4. RESULTS FOR ONE-DIMENSIONAL SURFACES

Whilst experimental measurements for two-dimensional surfaces are interesting, particularly as regards the polarisation behaviour of the scattered light, they are of limited value for verifying theoretical predictions since these are almost always limited to the one-dimensional case (i.e. to random gratings). Since the principal aim of our work is to provide experimental data for comparison with theory[5–11], we have measured the light scattering from a number of well characterised one-dimensional random rough surfaces.

Figures 5 – 8 show the measurements of the angular scattering for surface #440 ($\sigma = 1.2 \pm 0.1$ µm, $\tau = 2.0 \pm 0.2$ µm) for several angles of incidence. Figures 5 & 6 are for visible light ($\lambda = 633$ nm) and Figs 7 & 8 for infrared radiation ($\lambda = 10.6$ µm), and Figs 5 & 7 are for s-polarised incident light and Figs 6 & 8 for p-polarised incident light. There was no measurable cross-polarised scattering. In all of the Figures, the circles represent the experimental measurements and the solid (noisy) lines represent the results of numerical calculations (see below).

Some general comments on these experimental measurements are in order. (i) At the visible wavelength, there is a pronounced enhanced backscatter peak and sidelobe structure at small angles of incidence (< 20°), similar to that exhibited by two-dimensional surfaces. This peak is above a broad plateau of scattering as in the two-dimensional case. (ii) The differences between the curves for incident light that is s-polarised (Fig 5) and p-polarised (Fig 6) are small. (iii) The angular scattering curves for the infrared do not show any obvious backscattering peak; however, given that the angular width of the backscatter peak is wavelength-dependent[4,14], this is not surprising. For s-polarisation, the scattering is fairly symmetrical around the origin with a little more than 50% of the radiation in the specular half-plane, whereas for p-polarisation a little more than 50% goes into the backscatter half-plane.

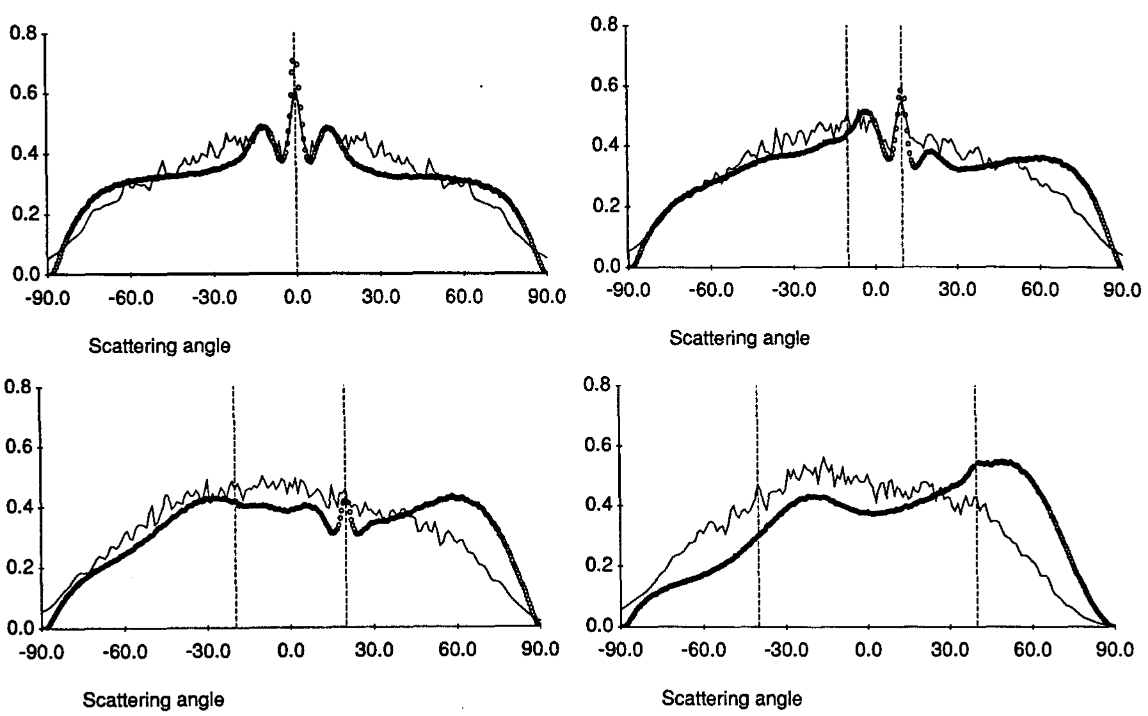

FIGURE 5. Surface #440, λ = 633 nm, gold-coated, s-polarisation, angles of incidence 0°,-10°,-20° and-40°. Circles represent measurements, solid (noisy) line is numerical calculation. Vertical axis is scattering cross-section

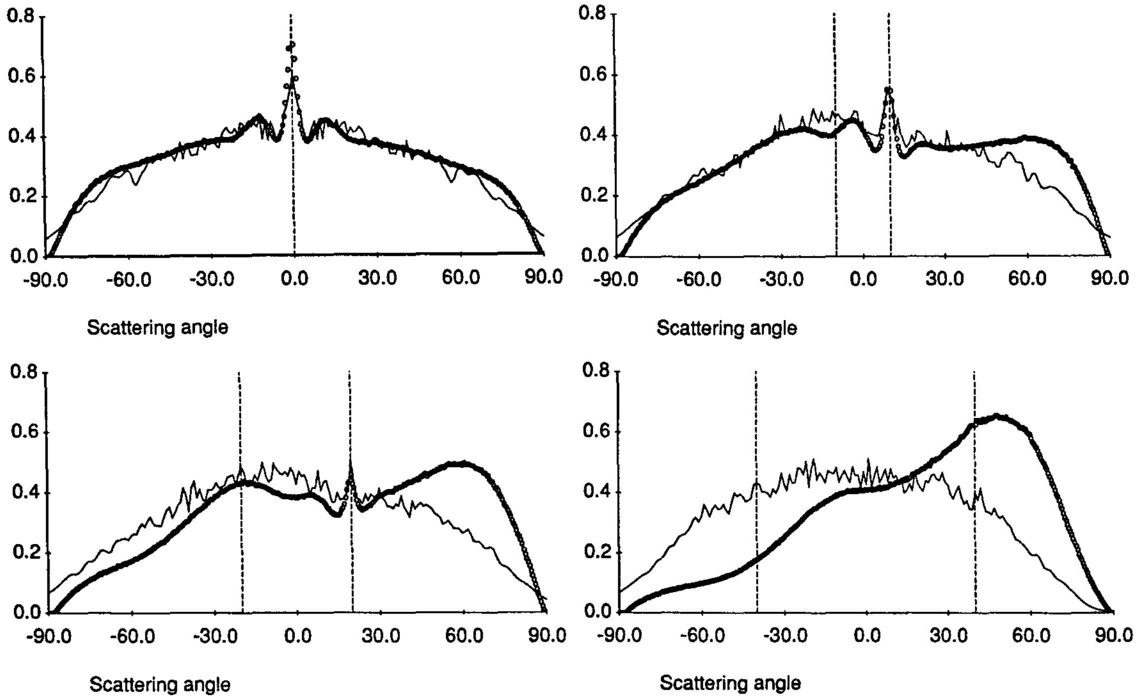

FIGURE 6. Surface #440, as Fig 5, but p-polarisation.

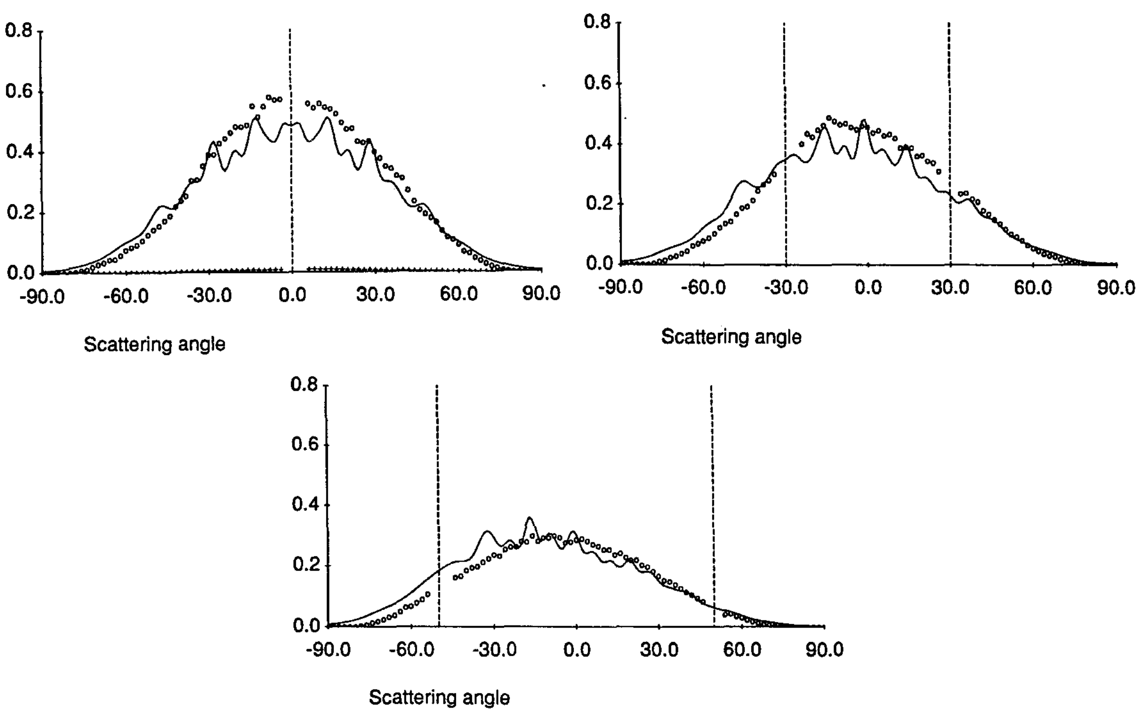

FIGURE 7. Surface #440, λ = 10.6 μm, gold-coated, s-polarisation, angles of incidence 0°,-30°, and-50°. Circles represent measurements, solid (noisy) line is numerical calculation. Vertical axis is scattering cross-section

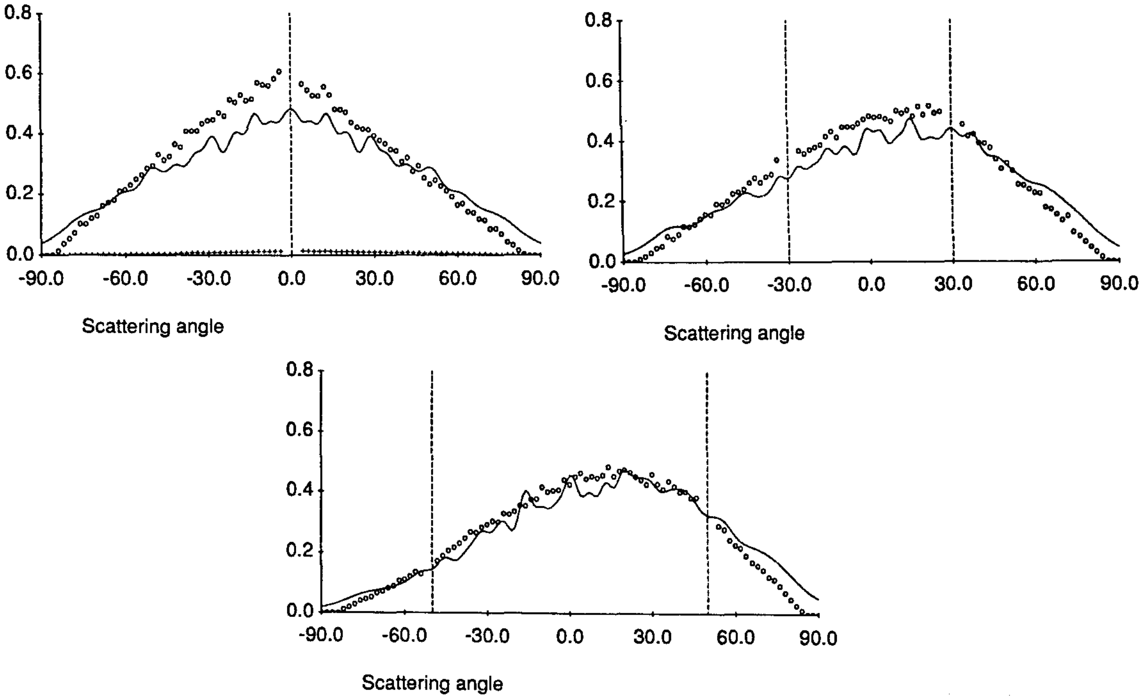

FIGURE 8. Surface #440, as Fig 7, but p-polarisation.

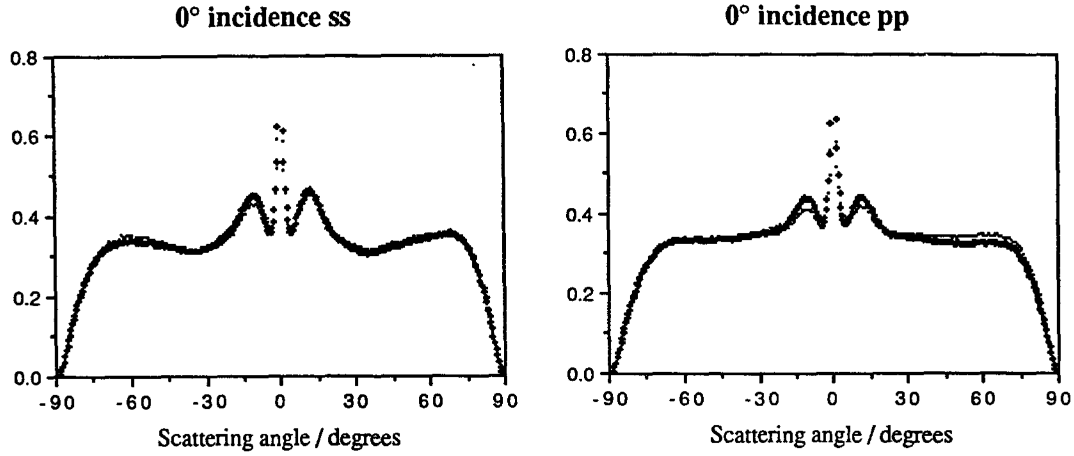

FIGURE 9. Surface #39, relative scattering cross-sections (vertical axis) for the original and epoxy replica, both gold-coated, for normal incidence (λ = 633 nm).

Also plotted in Figs 5 – 8 are the results of numerical calculations *for a perfect conductor* based on the method of Nieto-Vesperinas[6] (solid noisy lines). Good agreement is obtained for the infrared wavelength and for small angles of incidence at the visible wavelength. It is not known at the present time whether the discrepancies observed in the other cases are due to deficiencies in the calculation or to the assumption of a perfect conductor.

In order to compare the scattering by metallic and dielectric surfaces, replicas of surface #39 (σ = 1.18 ± 0.13 μm, τ = 2.97 ± 0.05 μm) were made. Figure 9 compares the scattered intensity for the original and epoxy replica, for s-polarised and p-polarised normally incident light of wavelength λ = 633 nm; in both cases the surfaces were gold-coated. The agreement between the light scattering curves for the original and replica is excellent, indicating that the replicating process faithfully reproduces the surface structure of the original. Figure 10 shows the angular scattering of the original surface for angles of incidence of-20° and-40° for both incident polarisations. Both Figs 9 & 10 show features (i) and (ii) of Figs 5 & 6 for surface #440 described above — in particular, note that the light scattering is not strongly dependent on the incident polarisation.

Figure 11 shows the angular scattering by the dielectric intermediate used to cast the epoxy replicas; since the surface has a gaussian probability density function of height, the statistics of this intermediate are identical to those of the original and

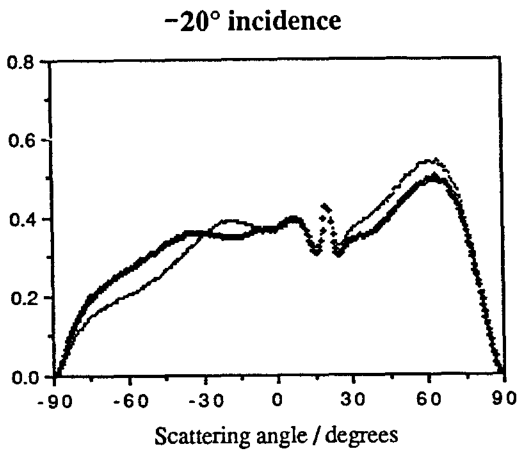

FIGURE 10. Surface #39, relative scattering cross-sections (vertical axis) for the gold-coated original for angles of incidence of-20° and-40° for s-polarisation (bold) and p-polarisation (light). λ = 633 nm.

epoxy replica. The most important feature of Fig 11 is the large difference between the angular scattering for s- and p-polarisations of the incident light. As might be expected from the Fresnel reflection coefficients for a flat surface, the scattered light is always greater for s-polarised incident light. For s-polarised incident light, most of the scattered energy lies in the specular half-plane, whereas it lies in the backscatter half-plane for the p-polarised case.

5. CONCLUSIONS

Experimental measurements of the light scattering by three well-characterised high-sloped random rough surfaces at two wavelengths have been presented. For the gold-coated two-dimensional surface, measurement of the Stokes' parameters has shown that for linearly polarised incident radiation, the scattered light has two components, linearly polarised and unpolarised. The enhanced backscatter is exhibited only by the unpolarised component, thus supporting the hypothesis that the enhancement is due to multiple scattering. One-dimensional gold-coated surfaces also exhibit enhanced backscattering. For the gold-coated surfaces, the scattering is similar for both s- and p-polarisations of the incident light, whereas quite different behaviours are observed for dielectric surfaces. The measurements presented for the one-dimensional surfaces are of particular usefulness for comparisons with theory, since the theory is usually only possible for the one-dimensional case.

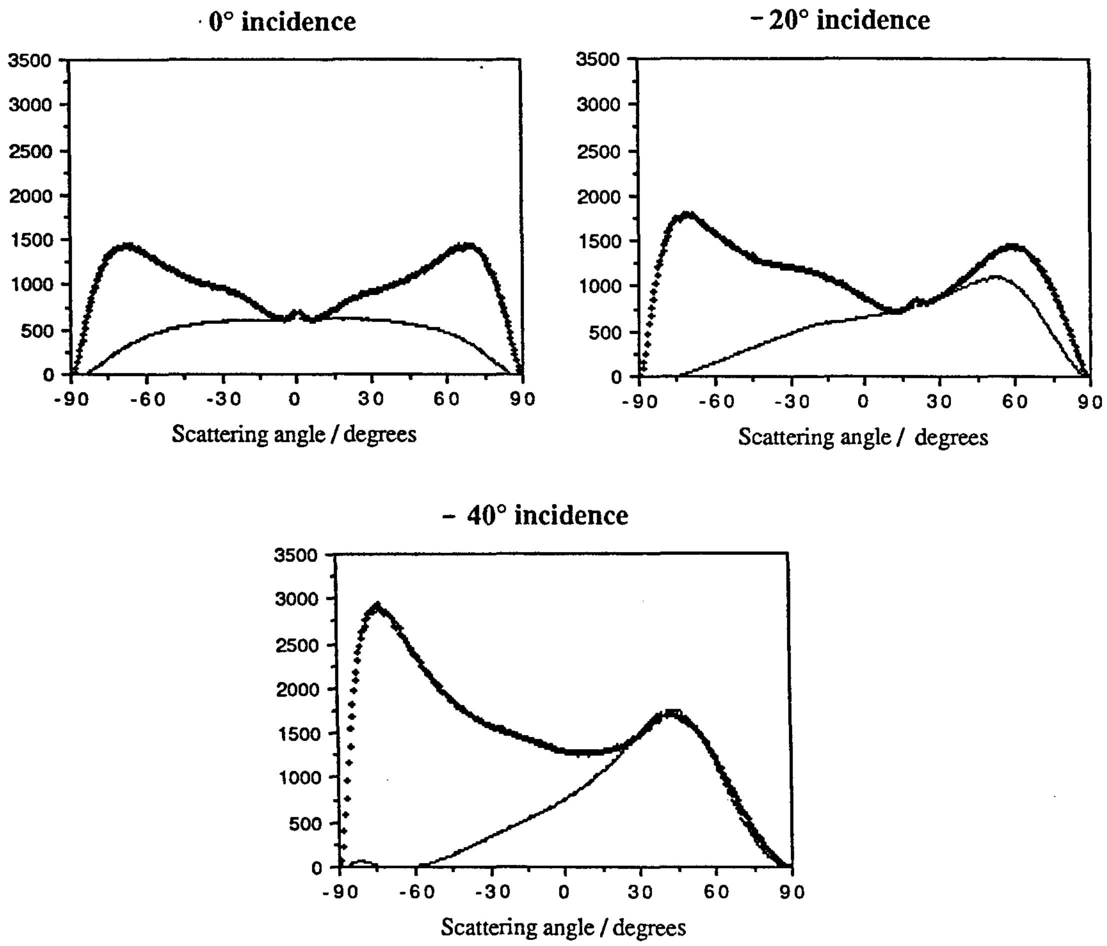

FIGURE 11 Surface #39, relative scattering cross-sections (vertical axis) for a *dielectric* replica (refractive index ≈ 1.43) for angles of incidence of 0°,-20° and -40° for s-polarisation (bold) and p-polarisation (light). $\lambda = 633$ nm.

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