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GIANT ENHANCED BACKSCATTERING FROM ROUGH SURFACES AND RELATED PHENOMENA

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13. ABSTRACT *(Maximum 200 words)*

A combined theoretical and experimental research program on "Giant Enhanced Backscattering from Rough Surfaces and Related Phenomena" has been implemented. The results should have potential application in remote sensing, radar signature, telecommunication, target acquisition and classification.

14. SUBJECT TERMS

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1.0 STATEMENT

Surface Optics Corporation (SOC), in association with U.C. Irvine and CICESE, has been conducting a combined theoretical and experimental research program in the field of Giant Enhanced Backscattering from randomly rough metal and dielectric surfaces. The investigation centers on the subject matter of enhanced backscattering manifested as a narrow peak in the angular distribution of the intensity of diffusely scattered light in the retroreflection direction for any angle of incidence on characterized surfaces which were fabricated by a computer driven laser scanner with controlled statistics. However, both theoretical and experimental investigations have shown that the ratio of the height of the enhanced backscattering peak to that of the background at the position of the peak is close to, or smaller than, a factor of two. Recently we reported the observation of giant enhanced backscattering of light from a randomly weak rough dielectric film on a reflecting metal substrate, in which the ratio of the height of the peak to the background was greater than 10. It was found that this giant enhanced backscattering peak is accompanied by concentric circular interference fringes, whose axis is normal to the mean scattering surface, with both the specular and backscattering peak on the same ring.

Although there has been much work done in enhanced backscattering phenomena, a significant contribution has been accomplished during this contracting period. We have initiated research on the enhanced backscattering from dielectric surface, and have shown enhanced backscattering from a random phase screen on a semi-infinite dielectric, enhanced backscattering from free-standing dielectric film, and enhanced backscattering from semi-infinite dielectric. We have shown the enhanced backscattering from total internal reflection, enhanced backscattering from deterministic quasi-periodic surface, enhanced backscattering from very smooth metal surface and conical scattering.

Speckle statistics and correlations in systems that present multiple scattering is studied. The angle correlation function of speckle patterns scattered from a one-dimensional rough dielectric film on a glass substrate and speckle correlation in double passage configuration were experimentally measured. Scattering from surfaces with more than one scale by reentrant surfaces, partial focusing, and statistics of the stokes parameters are also implemented.

The major goal of this study is to improve our understanding of the mechanism responsible for the enhanced backscattering phenomenon. At the same time, the results should have potential application in remote sensing, radar signature, telecommunication, target acquisition and classification.

2.0 SUMMARY OF THE PROBLEM STUDIED

During the period from 1 April 1993 to 30 September 1996 under U.S. Army Research Office Grant DAAH04-93-C-0014, we have been investigating the "Giant Enhanced Backscattering from Rough Surfaces and Related Phenomena". The advances in our understanding of such phenomena are summarized as follows.

2.1 Giant Enhanced Backscattering

One of the interesting phenomena associated with the scattering of light from a randomly rough surface is that of enhanced backscattering. This is the presence of a well-defined peak in the retroreflection direction in the angular distribution of the intensity of the incoherent component of the light scattered from such a surface. Recently we report the observation of a giant enhanced backscattering. When a polarized beam of light is scattered from a thin, two-dimensional weakly rough dielectric film coated on metal, a significant enhanced backscattering peak is observed in the retroreflection direction with a ratio of peak to background as large as 10.[(1)] This is much larger than the factor of 2 predicted on the basis of the coherent interference of a multiply-scattering optical path with its time-reversed partner. The sample studied in the experiment is a smooth aluminum plate that was coated with a thin Teflon film with a thickness of about 5.2 μm, and the surface which separated the film from the vacuum is a two-dimensionally randomly rough surface with a rms height of approximately 60Å and a $1/e$ correlation length of about 3000Å. It is found that this giant enhanced backscattering peak is accompanied by concentric circular interference fringes, whose axis is normal to the mean scattering surface, with both the specular and backscattering peak on the same ring.

Large enhancements were predicted in a series of paper by Jakeman and his colleagues,[(2)] who studied the enhanced backscattering of light from a deep random phase screen placed in front of a mirror. They predicted that when the mirror is placed close to the random phase screen than the focusing plane of the latter, the height of the enhanced backscattering peak could be much more than twice the height of the background at its position. Giant backscattering enhancement in laser sounding of the ocean was also reported,[(3)] Hoge and Swift recorded in 1983 the strong fluctuations of echo pulses in laser sounding of scattering layers through the rippled surface of the ocean. Due to random focusing of light, the giant enhancement can research 2.5×10^3. However, no systematic research has been done from the rough surface scattering.

Recently the perturbation analysis, thin-phase screen model, and the numerical simulation of the scattering of light from weakly rough dielectric films on the reflecting substrate produce the similar giant enhanced backscattering peaks (see Figure 1).[4] We speculate the giant enhanced backscattering observed may come from two different contributions. One of them is due to the rings which always make one ring lay on the specular and retroreflection directions. It is the result of the interference of two related paths which are only diffusely scattered once. It exists in moderately rough surfaces and only supported by large thickness of the film. The contrast of the ring to its background can be very large, depending on the reflectivity of the rough surface. The other contribution to the observed giant enhanced backscattering peak is the double passage configuration. It is the coherent interference of a given light path which interacts with the rough surface at two different points with its time-reversed partner.

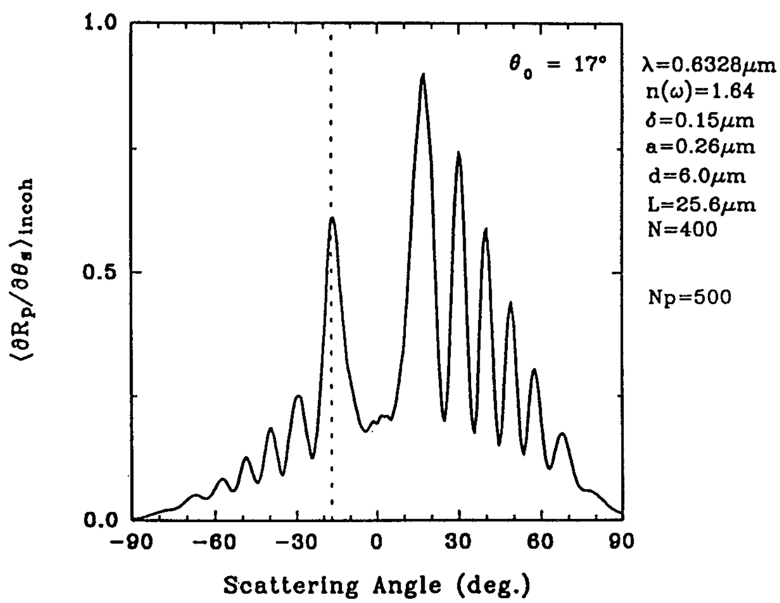

Figure 1. Numerical Simulation of Scattering from Dielectric Film on Metal Substrate.

2.2 Enhanced Backscattering from Very Smooth Metal Surfaces

The enhanced backscattering of light from a mirror-like randomly rough surface was predicted early in 1985 by A.A. Maradudin, etc., in the scattering of p-polarized light when the plane of incidence was perpendicular to the generators of the surfaces. To test this theory, recent experimental investigations of scattering from very smooth surfaces were conducted.[5] The glass plate substrate is extremely smooth with about 2Å rms roughness which was coated with a Gold film of the thickness about 1000Å. By controlling the time of the cooling, the rms roughness and 1/e correlation length vary. Four groups of 40 samples (with rms roughness $\sigma \leq 10$Å) show the enhanced backscattering phenomenon for the scattering of p-polarization of wavelength $\lambda = 0.6328\ \mu m$. Based on the characterization of the sample with Atomic Force Microscope, the analytical calculation shows similar results.

We feel one of the mechanisms responsible for the enhanced backscattering from very smooth metallic surfaces is the micro-structure of the crystalline grain on the surfaces. Due to the multiple scattering of the surface polaritons, which is excited by the incident light passing through the hills and valleys on the surface before they are converted back into volume waves in the vacuum propagating away from the surface, the coherent interferences of such a scattering sequence and its time-reversed partner leads to the enhanced backscattering.

2.3 Enhanced Backscattering at Vacuum/Dielectric Interface

Early attention to enhanced backscattering has been focused on rough metallic surfaces. There are four kinds of enhancement reported:(6) enhanced backscattering, enhanced transmission, enhanced reflection, and enhanced refraction. Recently enhanced backscattering from randomly rough dielectric surfaces has become an active research topic. We have measured the enhanced backscattering from a characterized randomly rough 1-D vacuum/dielectric interface for p- and s-polarizations.

Three kinds of enhanced backscattering from vacuum/dielectric interfaces were measured; they are enhanced backscattering from a random phase screen on a semi-infinite dielectric;(7) enhanced backscattering from free-standing dielectric film;(8) and enhanced backscattering from semi-infinite dielectric.(9) It is believed that the observed enhanced backscattering results from the coherent interference of multiply scattered optical paths with their time-reversed partners when the wave vectors of the incident and scattered light are oppositely directed. This coherency is lost for scattering into directions other than the retroreflection direction.

2.4 Enhanced Backscattering from Total Internal Reflection

We have reported the observation of enhanced backscattering in the scattering of light from a photoresist film with a one-dimensional randomly rough interface deposited on a flat parallel glass plate. The random interface is illuminated from the photoresist side, entering the sample through the glass plate.(10) Strong backscattering peaks both with p- and s-polarized illumination were observed. Angular scattering measurements for this sample are compared with results obtained numerically using two approximate models to describe the interaction between the light and the sample. The overall shape of the curves of both measurement and numerical calculation agree quite will. The observed backscattering enhancement is believed to be due to multiple scattering processes at the photoresist-air interface, where total internal reflection can take place.

2.5 Enhanced Backscattering from Quasi-periodic Surface

Up to now most experimental studies of the enhanced backscattering of light from rough surfaces have focused on randomly rough surfaces. Now we have observed the enhanced backscattering of light from one-dimensional deterministic surface, consisting of a photoresist film with a rough interface deposited on a plane parallel glass plate, when the light illuminates the rough surface from the dielectric side, entering through the glass.[11] We have also observed the enhanced backscattering from deterministic metallic surfaces when the light directly illuminates the rough surface from vacuum. Angular scattering measurements for these samples are compared with the numerical simulations. As with random systems, it is believed that the observed enhanced backscattering is due to the constructive interference of multiple-scattered optical waves.

2.6 Conical Scattering

The term conical refers to the case in which the plane of incidence makes an oblique angle with respect to the generators of the surface (see Figure 2). The light scattering from a well-characterized randomly rough gold-coated surface in a conical configuration is measured.[12] The surface profile of our sample constitutes a good approximation to a Gaussian random process with a Gaussian correlation function. Effects related to the backscattering enhancement and small but noteworthy amounts of cross-polarized scattered light are measured.

2.7 Partial Focusing of Optical Waves by Randomly Rough Objects

We have studied the scattering of light in a double passage configuration using point source illumination. It has been found that, after averaging, the diffuser-mirror combination appears to focus the scattered light on a point conjugate to that of the point source. The phenomenon is due to the enhancement in the backscattering direction, and the peak disappears very rapidly as one moves away from the focal position. Our calculations were verified experimentally.

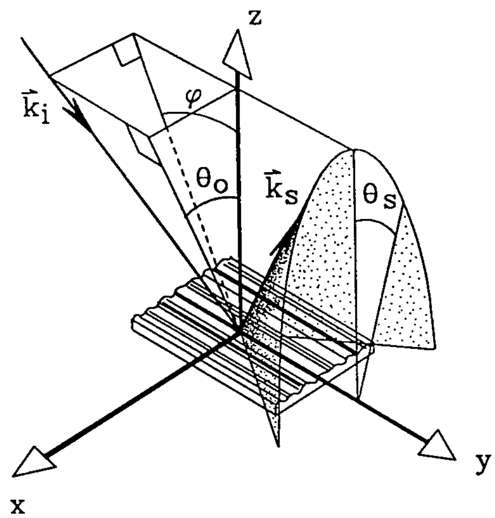

Figure 2(a). Schematic of Conical Scattering Geometry.

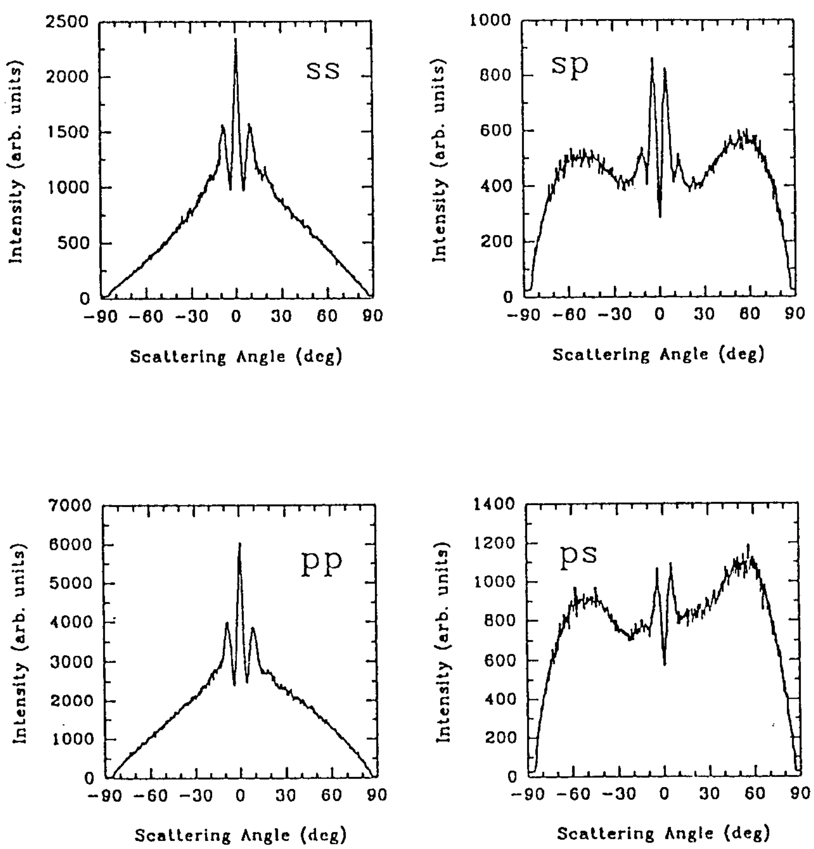

Figure 2(b). Conical Scattering from a 1-D Random Rough Surface.
(λ = 0.6328 μm, ϕ = 5.8°, a = 3.5 μm, σ = 1.55 μm)

We have shown that the width of this backscattering peak is given, approximately by the quantity $\xi = 2\ Z_0/k\omega$, where Z_0 is the distance from the diffuser to the point source, Z_s is the distance from the diffuser to the "focal" plane, ω is the radius of the aperture at the diffuser plane, and $k = 2\pi/\lambda$. With the parameters employed in our experiments, the width of the backscattering peak is about 8 μm (see Figure 3). This suggests that such an arrangement could be used to form high resolution images without the need of using lenses.

2.8 Statistics of the Stokes Parameters of Light Scattered by a One-Dimensional Randomly Rough Surface

We have studied the statistics of the polarization properties of one-dimensional randomly rough surfaces.[13] Based on the assumption that the s and p components of the electric-field vector constitute correlated circular complex Gaussian processes, some first-order statistical properties of the polarization of scattered fields are first established. In particular, results are presented for the probability density function of the Stokes parameters and their correlations.

2.9 Scattering by Reentrant Surfaces

The novel numerical techniques for rough surface scattering based on the integral equation method cannot deal with multivalued surface profiles. We have devised and implemented a modification to this method to handle multivalued and even reentrant surfaces.

To do this we developed a method to parametize self-avoiding curves, such as those that may represent a surface profile. We then consider scattering problems using Green's integral theorem and the formalism developed to parametize the curves. The iteration is carried along the case *ds*, rather than along *dx*, as is done in the usual treatment.

To validate our numerical codes, we first considered cases already reported in the literature. In Figure 4(a), we show a square-wave surface profile. In dimensional units the height $h = 0.4$ and the width $c = 0.8$.

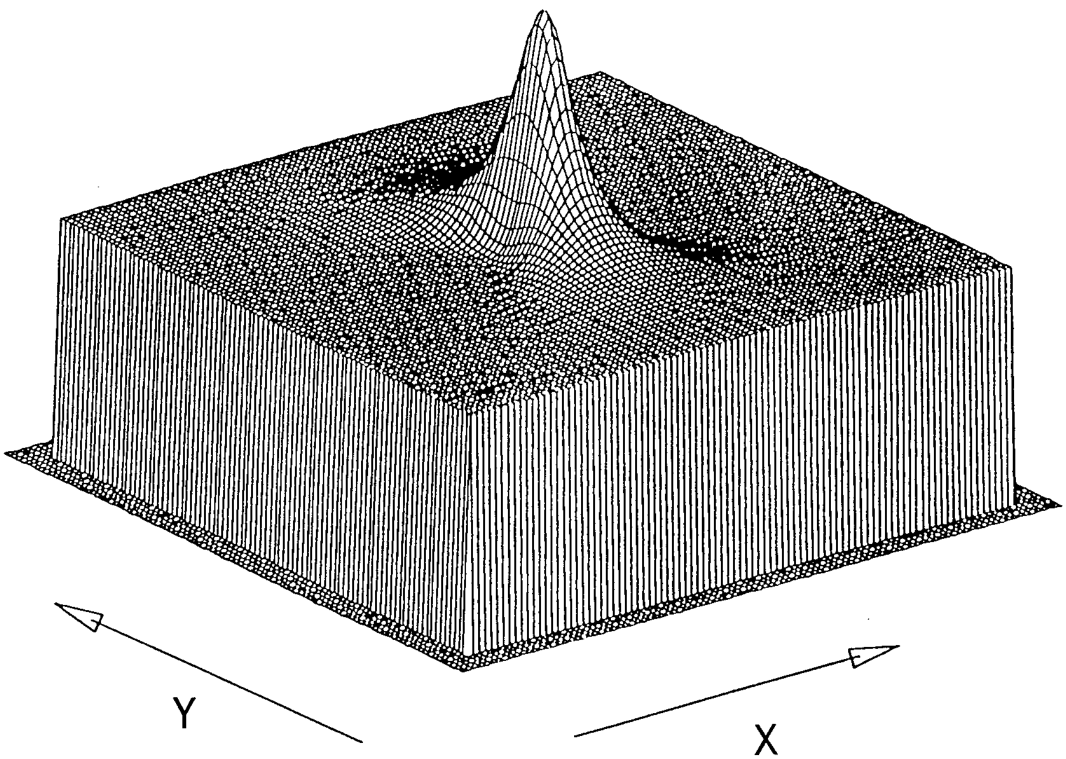

Figure 3(a). Partial Focusing at $Z = Z_0$.

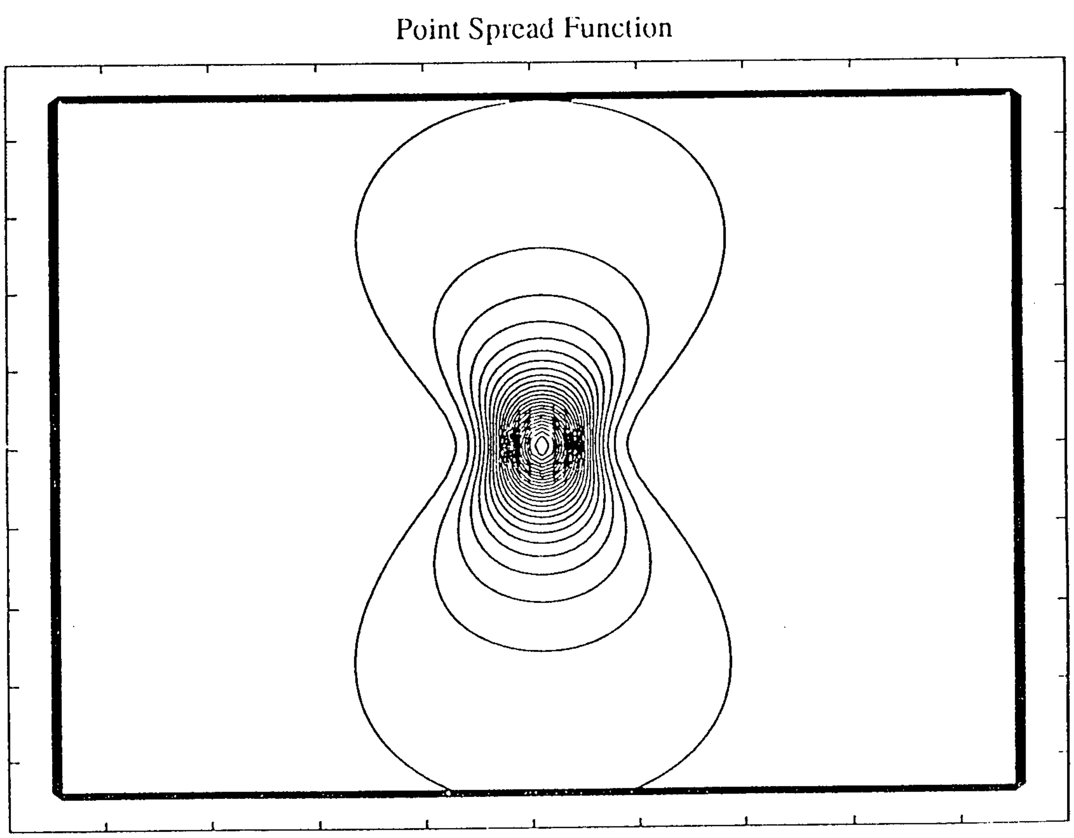

Figure 3(b). Point Spread Function.

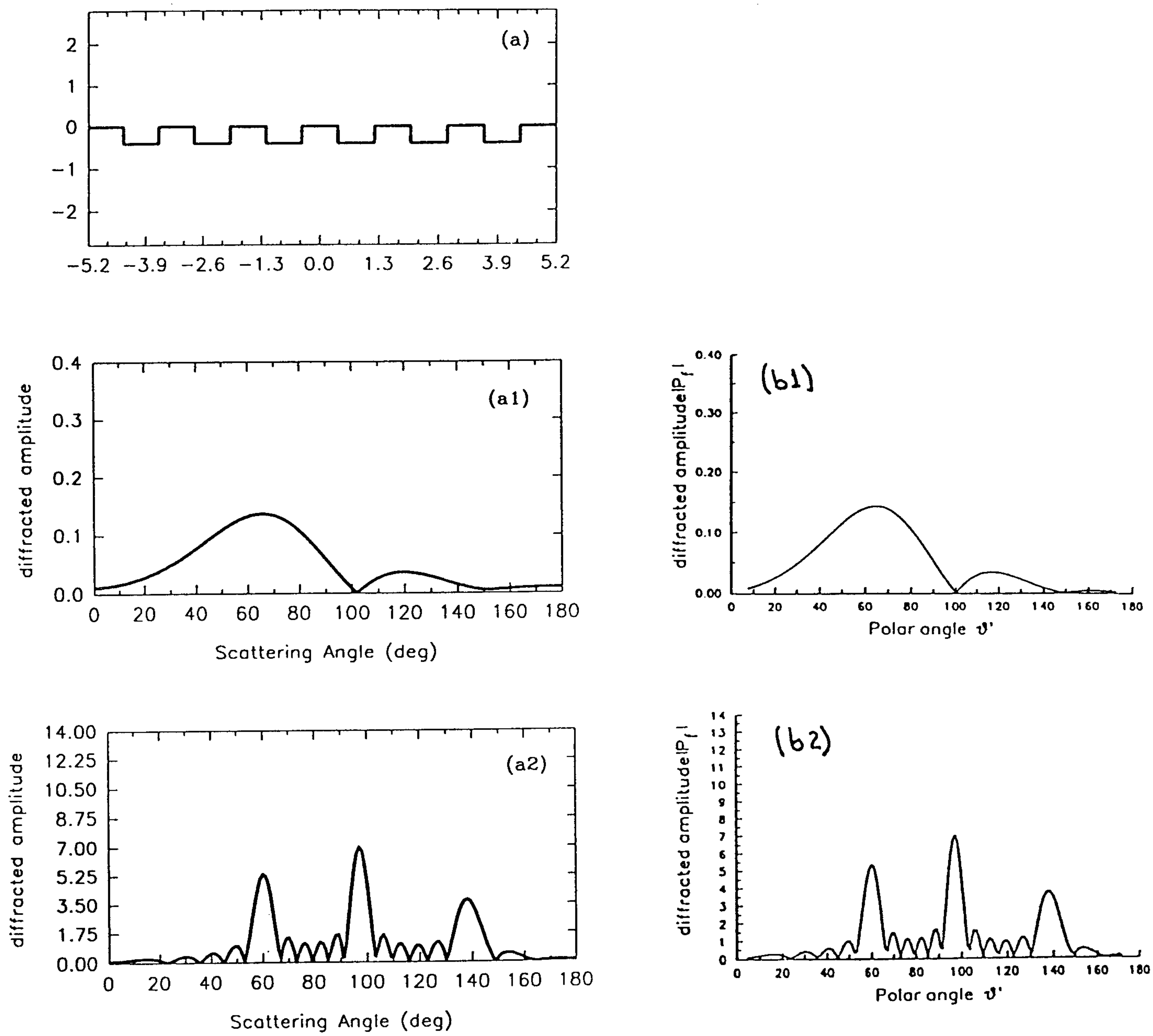

Figure 4. Far-field Scattering Patterns with S-polarization and Perfectly Conducting Surface. The angle of incidence is $\theta_0 = 30°$.

(a) Surface Profile. In dimensional units the grooves have height $h = 0.4$ and width $c = 0.8$. Results of our modified integral equation method with $\lambda = 6.5$ **(a1)** and $\lambda = 1.0$ **(a2)**. In **(b1)** and **(b2)** we show the corresponding results obtained by Kok[1] with a very different method.

In Figures 4(a1) and 4(a2) we show scattering patterns for the case of a perfect conductor with s-polarization and $\lambda = 6.5$ (a1) and $\lambda =$ (a2). The angle of incidence is $\theta_0 = 30°$. In Figures 4(b1) and 4(b2) we show the results of Kok[1] for comparison.

With the method developed it is also possible to deal with reentrant surfaces, such as fractal ones. An example is shown in Figure 5. We have calculated the scattering patterns associated to Koch prefractals. We generate a sequence of prefractals subdividing progressively the defining sections and, from a certain number of the sequences, we find that the scattering patterns do not change. We can then conclude that this pattern corresponds to the scattering pattern of the fractal, since the finer details on the surface will not be resolved by the wavelength. This is, to our knowledge, the first vigorous results on light scattering by fractal surfaces.

2.10 Speckle Statistics and Correlation in Systems that Present Multiple Scattering

When coherent light is reflected from a rough surface, a complex speckle pattern is formed. This is the result of the interference among the scattered wavelets, each arising from a different microscopic element of the rough surface. The statistics of the speckle patterns produced by scattering from a surface has been widely studied in the past. However, they are all related to the single scattering from rough surfaces. Recently theoretical studies in volume scattering show that there are novel correlations among the speckle patterns in the multiple scattering regime and they can be divided into three types: short-range correlation, long-range correlation, and infinite-range correlations. These three types of correlations play different roles in different scattering system geometries. The short-range correlation, also known as memory effect, is the dominant part in system where the dimension in the direction of the light propagation is much smaller than that in the direction perpendicular to it. The memory effect dictates that even though a laser wave suffers many scattering events upon traversing a thick volume scattering sample, and therefore its wavefront is considerably distorted and seeming random, it still "remembers" the wavefront of the incoming plane wave, so that as the incoming beam direction changes slightly, the transmitted or reflected speckle pattern will move accordingly.[14] The long-range and infinite-range correlations will be the dominate part in the system where the dimension in the direction of the light propagation is larger than in the direction perpendicular to it.

[1] Yon-Lin Kok, "General Solution to the Multiple-Metallic-Grooves Scattering Problem: The Fast Polarization Case", Appl. Opt. 32, 2573-2581 (1993).

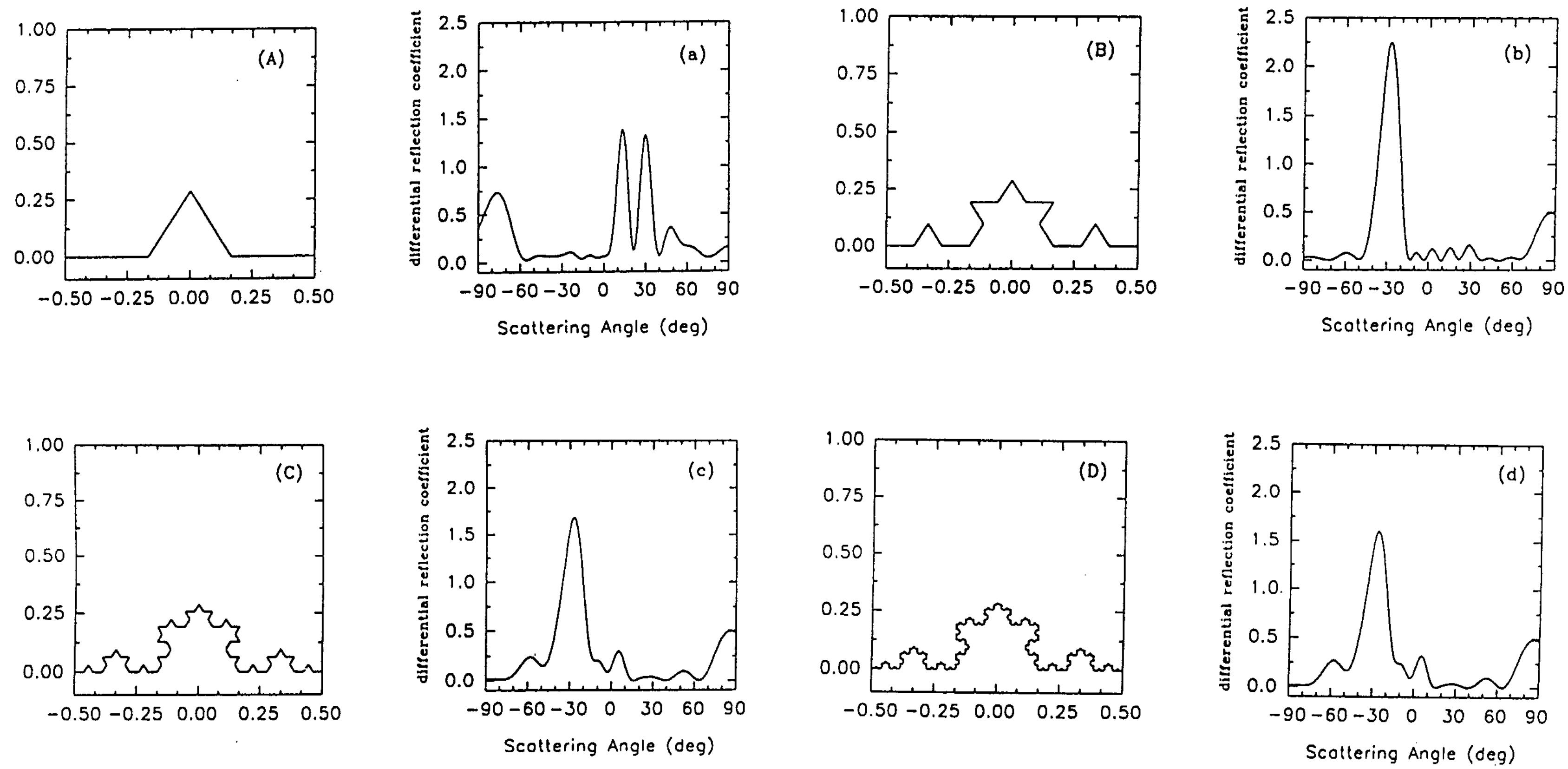

Figure 5. **Angular Scattering Results for a Sequence of Koch Prefractals for the Case of P-polarized Illumination and an Angle of Incidence $\theta_0 = 30°$. With capital letters we denote the surface profile and with small letters the scattering pattern. The length of the surface is $L = 5\lambda$.**

For memory effect, recently we have studied the angular correlation function of far-field speckle patterns scattered by a one-dimensional random rough surface of a thin dielectric film on a glass substrate when a polarized beam of light is incident on the rough surface from vacuum.(15) This surface, which separates the vacuum and the dielectric, is rough enough that only diffused speckles are observed. The experiment for the correlation measurement was set up to use a CCD camera to obtain the image of the speckle pattern in the speckle direction for each given angle of incidence, the cross correlation function is then calculated from the digitized images. It is found that the intensity correlation function exhibits two distinct maxima, one raised from the auto-correlation and the other from the reciprocity condition. It is also found that different scattering processes give rise to quite different correlation functions, where multiple-scattering processes produce narrow peaks with secondary maxima, while single-scattering processes produce relatively broader peaks.

We have also studied experimentally the angular intensity correlation in the double passage of waves through a random phase screen. Assuming as the random medium a deep phase screen that introduces Gaussian-distributed phase fluctions, the motion of the speckles is studied when the source is moved. Controversy to the memory line of memory effect (see Figure 6(a)),(16) we found the line (see Figure 6(b)) does not move for the case where a flat mirror is set behind the phase screen (see Figure 7), while the line is perpendicular to the memory line (see Figure 6(c)) for the case with the phase screen at the center of curvature of a spherical mirror (see Figure 8).

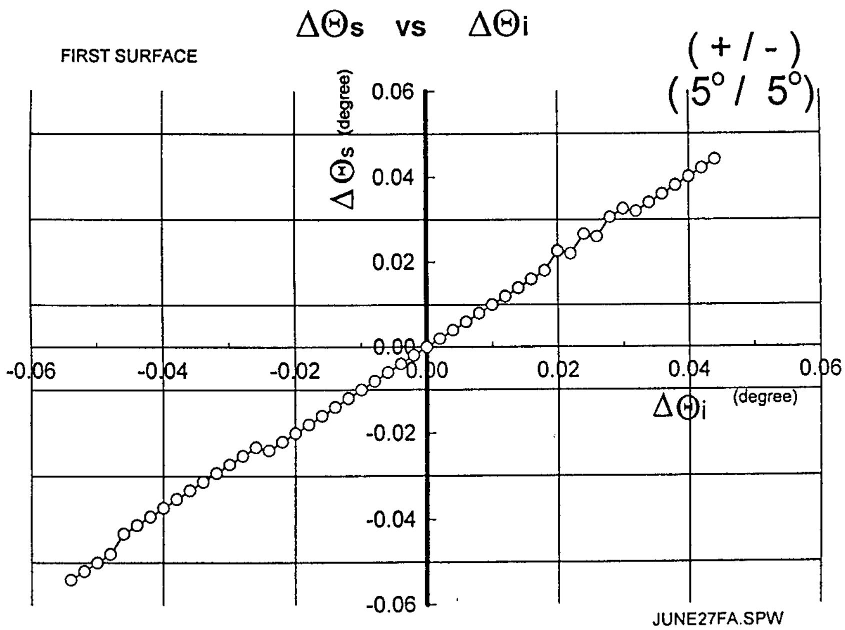

Figure 6(a). A Correlation Line for Memory Effect.

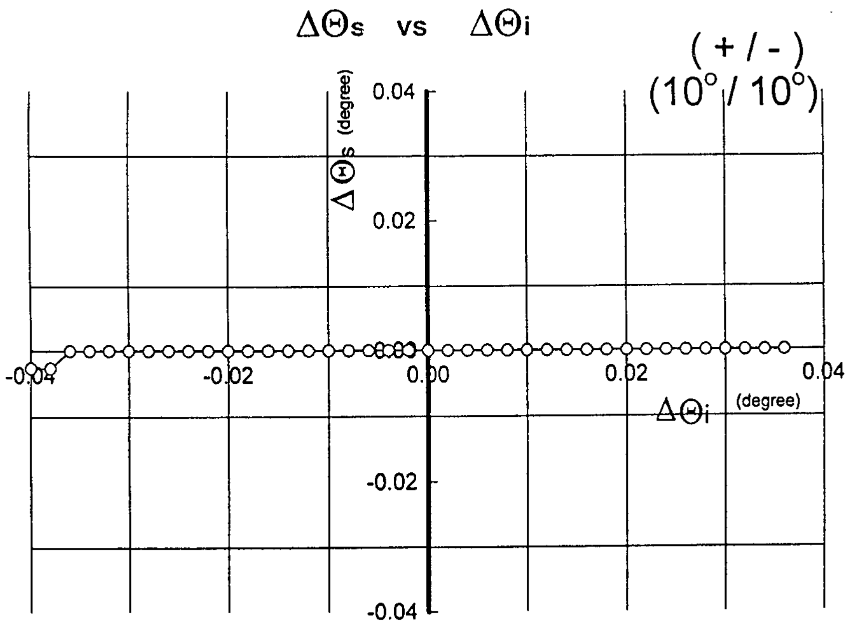

Figure 6(b). A Correlation Line for a Flat Mirror Behind the Random Phase Screen.

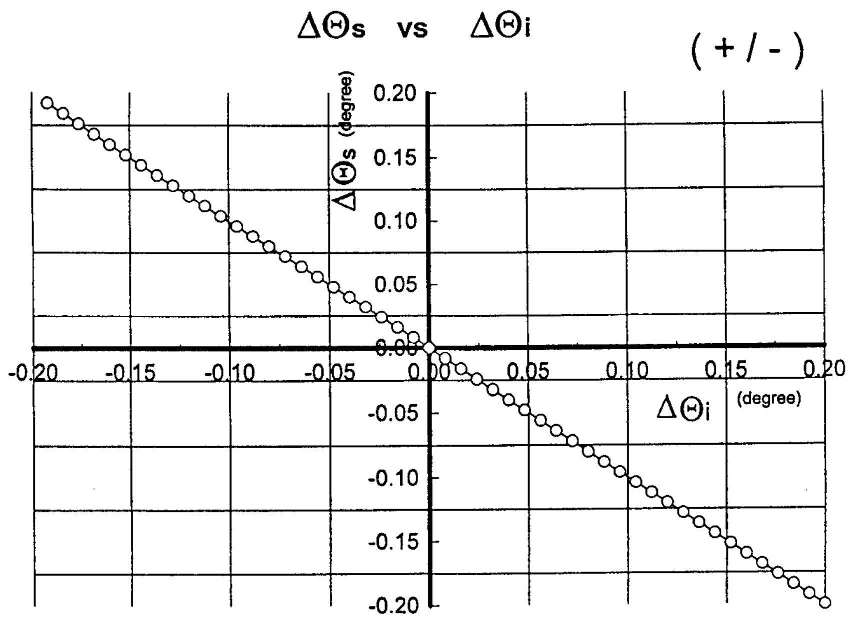

Figure 6(c). A Correlation Line for a Spherical Mirror Behind the Random Phase Screen.

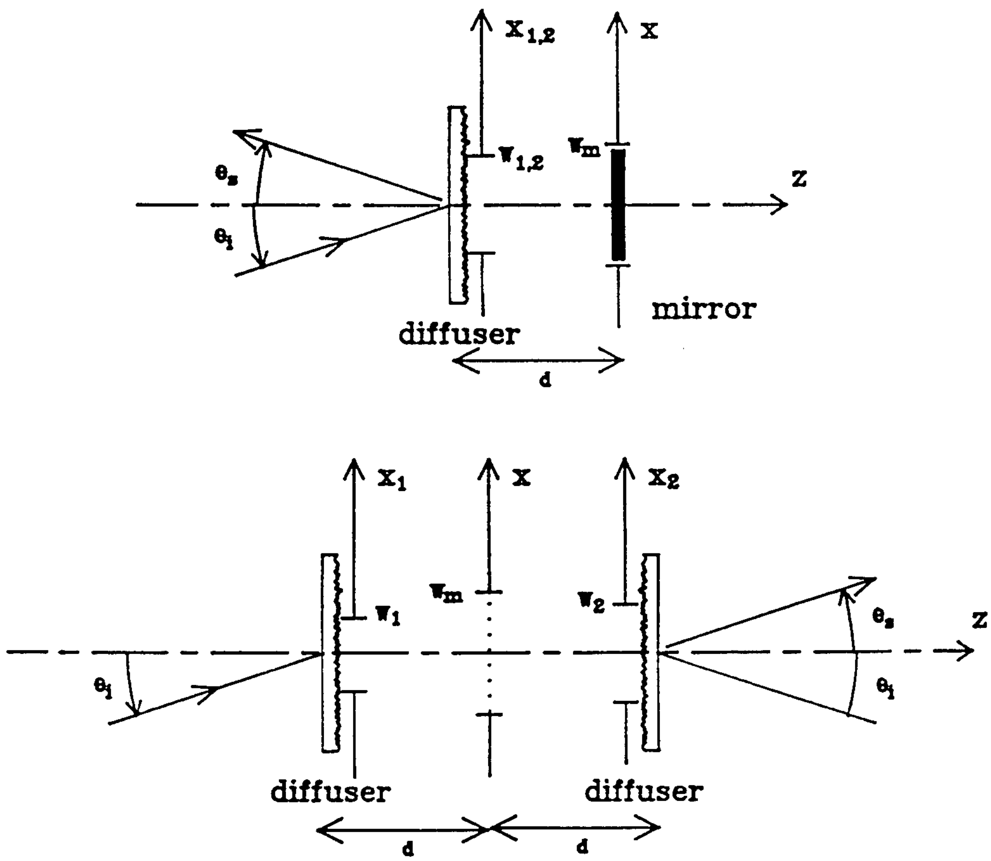

Figure 7. **A Schematic of a Flat Mirror Behind a Diffuser.**

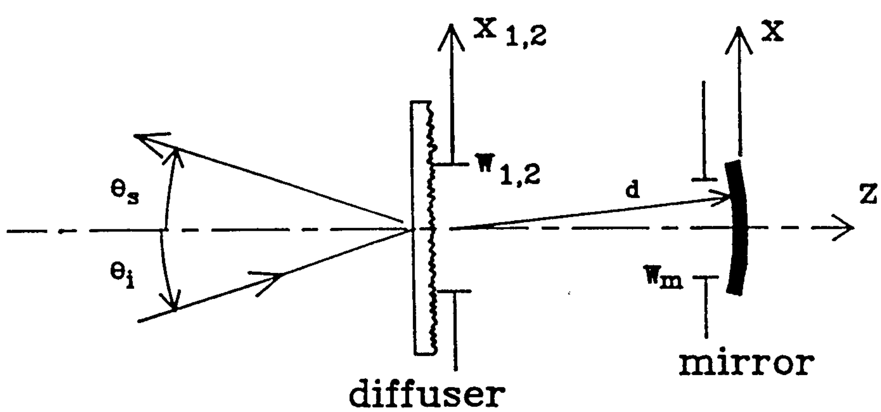

Figure 8. **A Schematic of a Spherical Mirror Behind a Diffuser.**

3.0 LIST OF ALL PUBLICATIONS FOR ARO GRANT

3.1 Publications in Journals

1. Zu-Han Gu, Jun Q. Lu, and A.A. Maradudin, "Enhanced Backscattering of Light from a Rough Dielectric Film on a Glass Substrate", J. Opt. Soc. Am. A, Vol. 10, No. 8, 1753-1764 (1993).

2. Zu-Han Gu and Z. Lin, "Design Review of a Unique Monostatic Bidirectional Reflectometer", SPIE 1995, 131-142 (1993).

3. Zu-Han Gu, Jun Q. Lu, Amalia Martinez, E.R. Mendez, and A.A. Maradudin, "Enhanced Backscattering from an One-dimensional Rough Dielectric Grating on a Glass Substrate", Optics Letters, Vol. 19, No. 9, 604-606, (May, 1994).

4. Zu-Han Gu, J. Lu, A. Maradudin, and E. Mendez, "Enhanced Backscattering from One-dimensional Free-standing Dielectric Film", IGARSS, Vol. 1, 264-266 (1994).

5. Michel Josse and Zu-Han Gu, "Fabrication of Two-dimensional Rough Surfaces for Light Scattering and Polarization Measurements", SPIE 2265, 99-104 (1994).

6. Zu-Han Gu, J. Lu, A. Maradudin, and E. Mendez, "Enhanced Backscattering from One-dimensional Free-standing Dielectric Film", SPIE 2260, 145-149 (1994).

7. Zu-Han Gu, R.S. Dummer, P. McKenna, A. Maradudin, J. Estep, "Giant Enhanced Backscattering in Laser Radar Signatures", SPIE 2271, 97-108 (1994).

8. R.E. Luna, E.R. Mendez, J. Q. Lu, and Zu-Han Gu, "Enhanced Backscattering due to Total Internal Reflection at a Dielectric-Vacuum Interface", Journal of Modern Optics, Vol. 42, No. 2, 257-269 (1995).

9. Zu-Han Gu, J. Lu, A. Maradudin, and E. Mendez, "Enhanced Backscattering from a Free-standing Dielectric Film", Applied Optics, Vol. 34, No. 18, 3529-3534 (1995).

10. Zu-Han Gu, J. Lu, and M. Tehrani, "Enhanced Backscattering of a Polarized Beam at Vacuum/Dielectric Interface", Optical Engineering, Vol. 34, No. 6, 1611-1624 (June, 1995).

11. Zu-Han Gu and Jean Bennett, "Enhanced Backscattering from Very Smooth Metal Surfaces", SPIE Vol. 2541, 45-53 (July, 1995).

12. R.E. Luna and E.R. Mendez, "Scattering by One-dimensional Random Rough Metallic Surfaces in a Conical Configuration", Optical Letters, Vol. 20, No. 7, 657-659 (1995).

13. E.R. Mendez, A.G. Navarrete, and R.E. Luna, "Statistics of the Polarization Properties of One-dimensional Randomly Rough Surfaces", J. Opt. Soc. Am. A, Vol. 12, No. 11, 2507-2516 (1995).

14. Zu-Han Gu, M. Josse, and M. Ciftan, "Observation of Giant Enhanced Backscattering of Light from Weakly Rough Dielectric Films on Reflecting Metal Substrates", Optical Engineering, Vol. 35, No. 2, 370-375 (1996).

15. Zu-Han Gu, R.S. Dummer, Jun Lu, and P. McKenna, "Giant Enhanced Backscattering in Ladar Signature", Optical Engineering, Vol. 35, No. 2, 362-369 (1996).

16. Zu-Han Gu and M. Josse, "Fabrication of 1-D Gratings on Photoresist for Light-scattering and Memory Effect Measurements", SPIE 2726, 158-163 (1966).

17. Michel Josse, F. Pincemin, A.A. Maradudin, J.Q. Lu, and Zu-Han Gu, "Enhanced Backscattering from One-dimensional Deterministic Quasi-periodic Surfaces", J. Opt. Soc. Am. A, 1877-1883, Vol. 13, No. 19 (1996).

3.2 Papers Submitted to Journal under Referee

18. Jun Q. Lu, Zu-Han Gu, J.A. Sanchez-Gil, A.A. Maradudin, and E.R. Mendez, "Scattering of Light from a Weakly Rough Dielectric Film on a Reflecting Substrate", Submitted to J.O.S.A.A. (January 1996).

19. Jun Q. Lu and Zu-Han Gu, "Angular Correlation Function of Speckle Patterns Scattered from a One-dimensional Rough Dielectric Film on a Glass Substrate", submitted to Applied Optics (June 1996).

3.3 Papers Presented in Professional Conferences

1. Zu-Han Gu, Jun Q. Lu, R.E. Luna, and E.R. Mendez, "Comparison Between Numerical and Experimental Study of Enhanced Backscattering from a One-dimensional Rough Dielectric Grating on a Glass Substrate", presented at PIES-93 Meeting at JPL, Pasadena, CA (July, 1993).

2. Zu-Han Gu and Z. Lin, "Design Review of a Unique Monostatic Bidirectional Reflectometer", presented at SPIE Annual Meeting, San Diego, CA (July,1993).

3. R.E. Luna, E.R. Mendez, H.M. Escamilla, "Conical Scattering by One-dimensional Randomly Rough Metallic Surfaces", presented at 16th Congress of the ICO Meeting, Budapest, Hungary (August, 1993).

4. H.M. Escamilla, E.R. Mendez, D.F. Hotz, “Angular Intensity Correlation in the Double Passage of Waves through a Random Phase Screen”, presented at 16th Congress of the ICO Meeting, Budapest, Hungary (August, 1993).

5. A.A. Maradudin, Zu-Han Gu, and E.R. Mendez, "Enhanced Backscattering of Light from Rough Surfaces", presented at U.R.S.I. XXIVth General Assembly, Kyoto, Japan (September, 1993).

6. Zu-Han Gu, J.Q. Lu, A.A. Maradudin, and E.R. Mendez, "Enhanced Backscattering from a Dielectric Random Surface", presented at U.R.S.I. XXIVth General Assembly, Kyoto, Japan (September, 1993).

7. Zu-Han Gu, A.A. Maradudin, and Jean Bennett, "Enhanced Backscattering from Very Smooth Metal Surfaces", presented at OSA 93 Annual Meeting, Toronto, Canada (October, 1993).

8. Zu-Han Gu, "Enhanced Backscattering from Vacuum-dielectric and Dielectric-vacuum Interface", presented at ARO Workshop on "Rough Surface Scattering" at Boulder, Colorado (November, 1993).

9. E. Mendez, “Conical Scattering”, presented at ARO Workshop on “Rough Surface Scattering” in Boulder, Colorado (November, 1993).

10. Zu-Han Gu, J. Lu, A.A. Maradudin, and E. Mendez, "Enhanced Backscattering from Vacuum/Dielectric Interfaces", presented at IEEE Antennas and Propagation Society and URSI International Symposium, Seattle, Washington (June, 1994).

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