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13. ABSTRACT (Maximum 200 words) During 1991 Kevin O'Donnell at Georgia Tech made new measurements of light scattering from gold surfaces, which were well characterized and known to be nearly one-dimensional (1-D). In anticipation of these new data, numerical simulations of the scattering experiments were undertaken in this project for comparison with the data and with results of other investigators.					
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NUMERICAL SIMULATIONS OF LIGHT SCATTERING FROM ROUGH
ONE-DIMENSIONAL GOLD SURFACES

FINAL REPORT

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I. Problem Statement

At the International Workshop on "Modern Analysis of Scattering Phenomena" (held in Aix en Provence, France in September 1990) differences between experimental and numerical scattering cross sections for light scattering from 1-D gold surfaces were reported by Dainty et al. (Imperial College, London). During 1991 Kevin O'Donnell at Georgia Tech made new measurements of light scattering from gold surfaces, which were much better characterized and known to be much more nearly one-dimensional (1-D). In anticipation of these new data, numerical simulations of the scattering experiments were undertaken in this project for comparison with the data and with results of other investigators.

The gold surfaces were assumed to be 1-D and randomly rough with Gaussian statistics. The roughness spectrum was taken as Gaussian with an rms surface height fluctuation of 1.95 micrometers and a correlation length ($1/e$ length) of 3.57 micrometers. Calculations were done at wavelengths of 1.152 and 3.392 micrometers for both "s" and "p" polarizations, and at incident angles of 0, 10, and 30 degrees. Complex refractive indices for gold, $0.312 + 7.93i$ at 1.127 micrometers and $1.958 + 20.7i$ at 3.35 micrometers, were used for the wavelengths 1.152 and 3.392 micrometers, respectively. Gold is a good conductor and the accuracy of using the perfect conductor approximation was also investigated.

II. Summary of Results

Integral equation codes were implemented for both s and p polarization following Maradudin et al.¹ Initial test calculations for p polarization showed significant dependence on the fineness of the surface partitioning. At the wavelength of 3.392 micrometers, 40 partitions per wavelength were found necessary to obtain reasonable results using the method directly as outlined in Ref.1, whereas to be practical no more than about 10 points per wavelength can be used. The problem was traced to rapid variations of the integral equation kernel due to the complex index in the conductor. In particular, diagonal matrix elements for the second of the two coupled integral equations cannot be computed by the usual small argument expansion keeping only a few terms. However, numerical studies showed that the surface fields could still be considered constant over the partition interval Δx . Thus, we used numerical integration of the kernel over Δx to compute diagonal matrix elements for the second equation. With this method, a partition of 10 points per (vacuum) wavelength was at least as accurate as 40 points per wavelength using the method from Ref.1. The same difficulty could affect the s polarization calculations, but numerical results showed direct use of the method given in Ref. 1 to be adequate for s polarization.

For the calculations, a tapered plane wave incident field² was used (taper parameter $g = L/4$ where L = total surface length). The cross section was normalized so that the integral over all scattering angles yields unity for perfect conductors. The number of surface partitions was 400 and the cross sections were obtained by averaging over results for 500 surfaces for each case studied.

The accuracy of the perfect conductor approximation was examined first. When the gold surface is considered a good conductor, the integral equation solution is obtained using coupled equations for two media. When considered a perfect conductor, the integral equation solution is

found using Dirichlet (for s polarization) or Neumann (for p polarization) boundary conditions. For s polarization, the perfect conductor approximation was found to be very good (Figure 1). It was found that the good conductor scattering cross sections could be very accurately estimated from perfect conductor results by first calculating cross sections both ways for a 50 surface set, obtaining the cross section ratio for each scattering angle, and then using this ratio to correct other perfect conducting results (with the same incident angle, etc.). Fig. 2 shows estimated and actual good conductor results for one 50 surface set, the estimate based on perfect conductor results corrected using another 50 surface set. The 500 surface results for s polarization were obtained in this way. For each wavelength and incident angle, the cross section ratio was found using 50 surfaces. Then 500 surface perfect conductor results were corrected using the ratio. A considerable computer time saving is made using this method. For p polarization the perfect conductor model was not as good an approximation (Fig. 3) and the full two media calculations were done.

Cross section plots for the two polarizations, two wavelengths (1.152 and 3.392 micrometers), and three incidence angles (0, 10 and 30 degrees) are given in Figs. 4-15. These results were presented at a workshop on backscattering enhancement on January 9-10 in Boulder, CO sponsored by ARO. The results in Figs. 4-15 agreed very well those of several other investigators.

In order to facilitate comparison with experimental data which tends to be smoother than computer simulations with 500 realizations, an attempt was also made to smooth the results. Running least square fits to cubic polynomials were used to generate smoothed cross sections. An example of smoothed and unsmoothed results is shown in Fig. 16. The smoothing was not applied near the backscattering enhancement peak. Plots of smoothed results as well as tabulations of both smoothed and unsmoothed cross sections were made and are available.

References

1. A.A. Maradudin, T. Michel, A.R. McGurn, and E.R. Mendez, Enhanced Backscattering of Light from a Random Grating, *Annals of Physics* **203**, 255-307 (1990).
2. E.I. Thorsos, The Validity of the Kirchhoff Approximation for Rough Surface Scattering Using a Gaussian Roughness Spectrum, *J. Acoust. Soc. Am.* **83**, 78-92 (1988).

III. Participating Scientific Personnel

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Patricia A. Oakley

Kate M. Bader

All participating personnel are at the Applied Physics Laboratory, University of Washington, Seattle, WA 98105

S Polarization
 $\lambda = 3.392 \mu\text{m}$
 $\theta_i = 30^\circ$

50 Surface Average

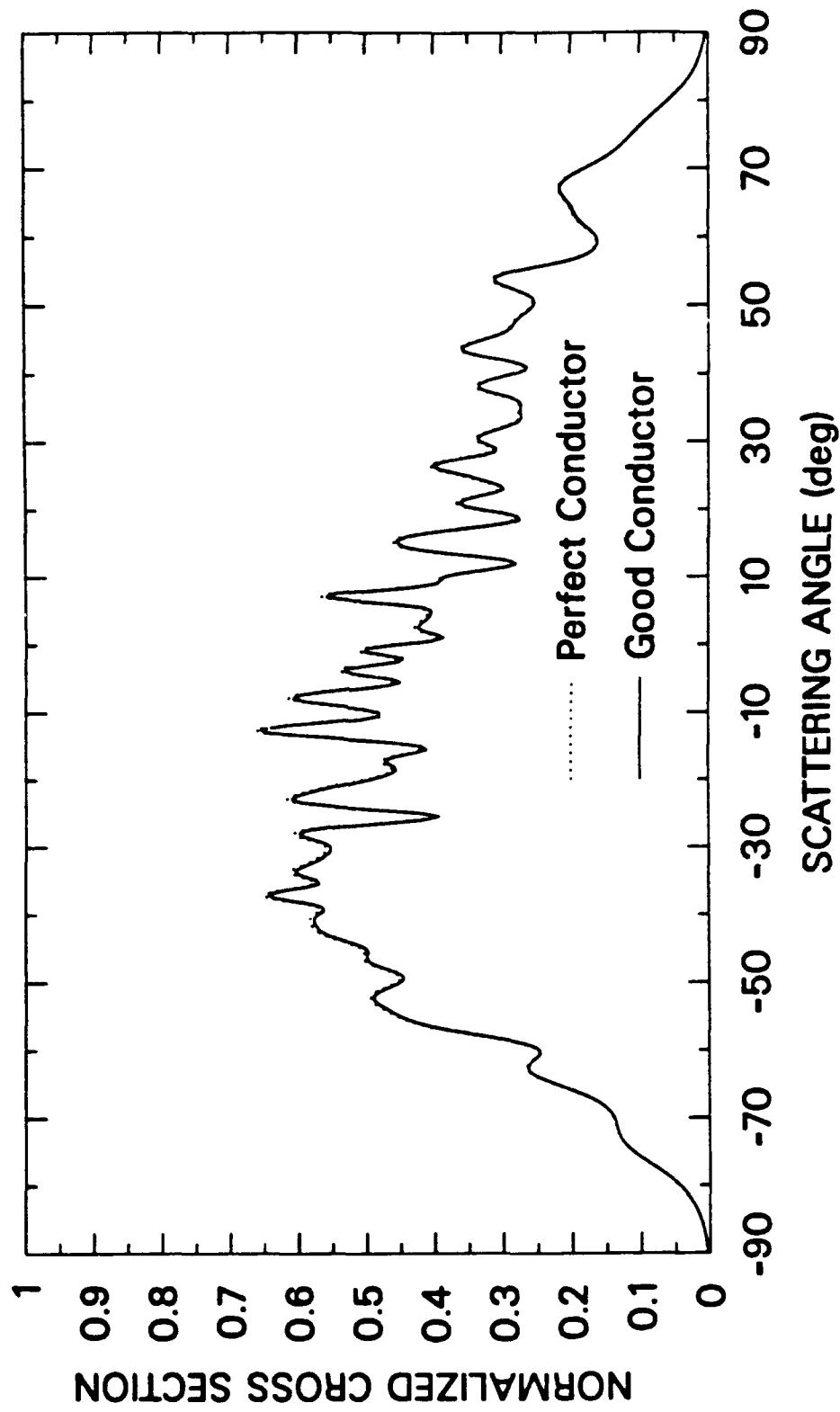


Figure 1.

S Polarization
 $\lambda = 3.392 \mu\text{m}$
 $\theta_i = 30^\circ$

50 Surface Average

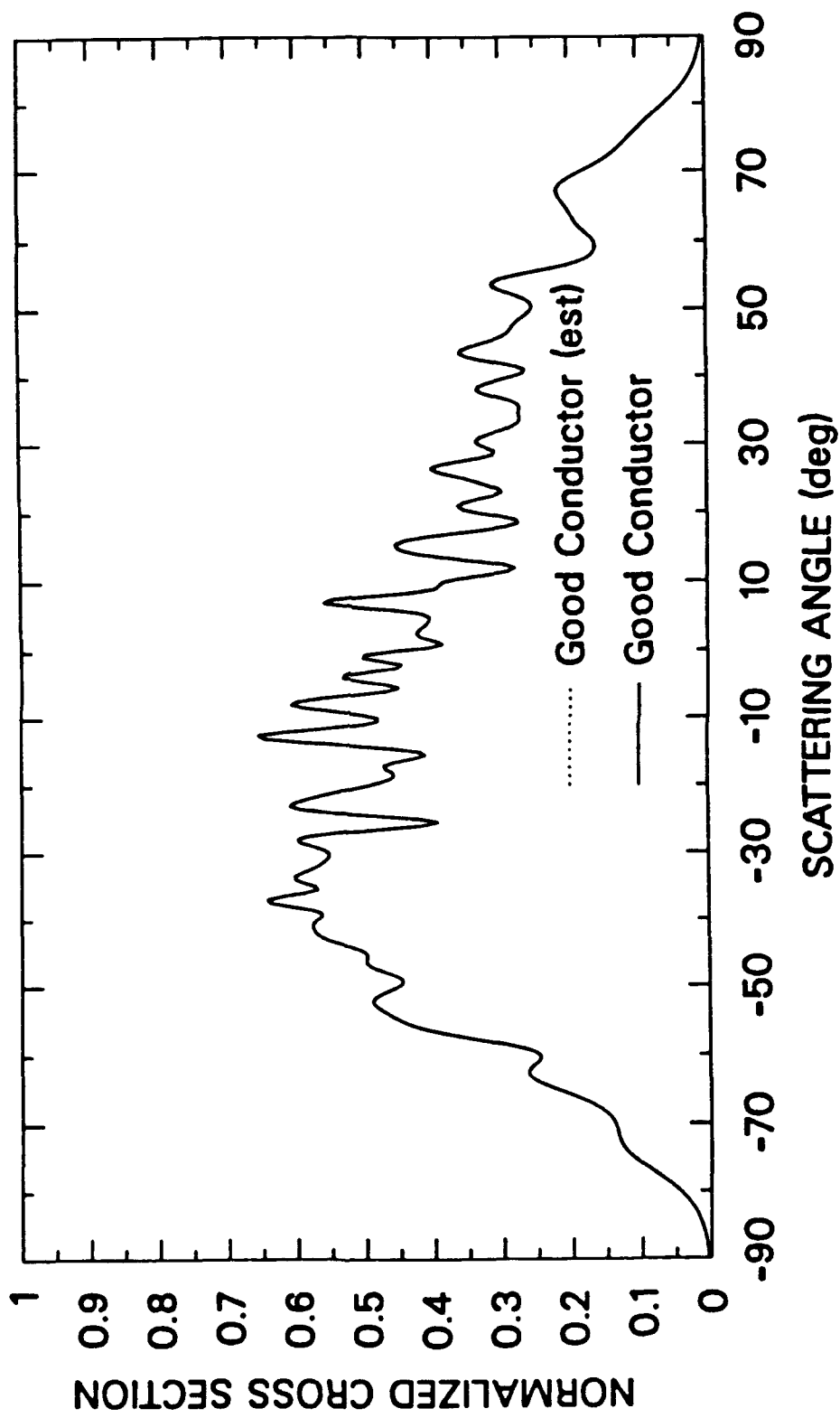


Figure 2.

P Polarization

$\lambda = 3.392 \mu\text{m}$

$\theta_i = 30^\circ$

50 Surface Average

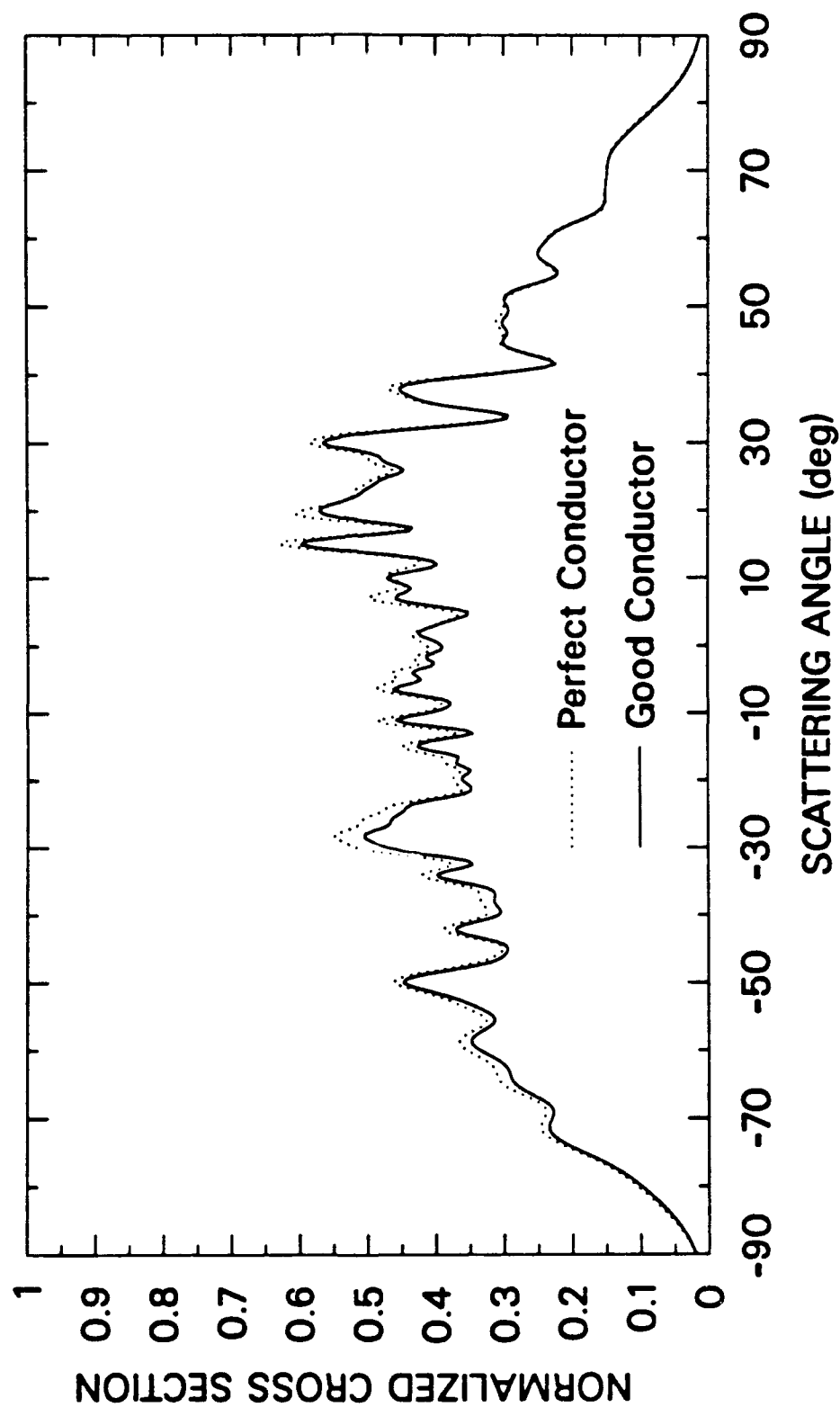


Figure 3.

S Polarization
 $\lambda = 1.152 \mu\text{m}$
 $\theta_i = 0^\circ$

500 Surface Average
(symmetrized)

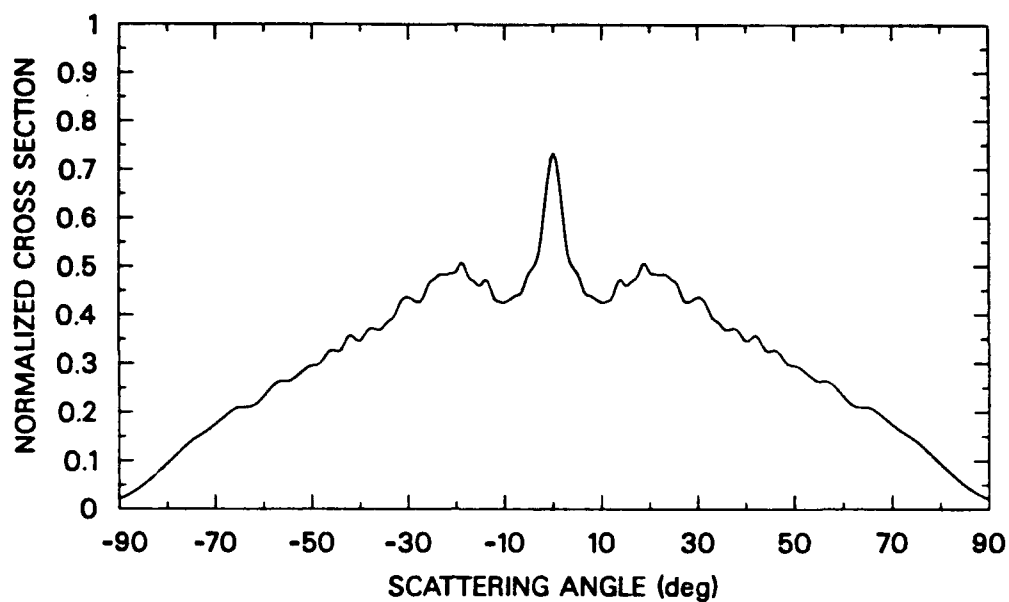


Figure 4.

S Polarization
 $\lambda = 1.152 \mu\text{m}$
 $\theta_i = 10^\circ$

500 Surface Average

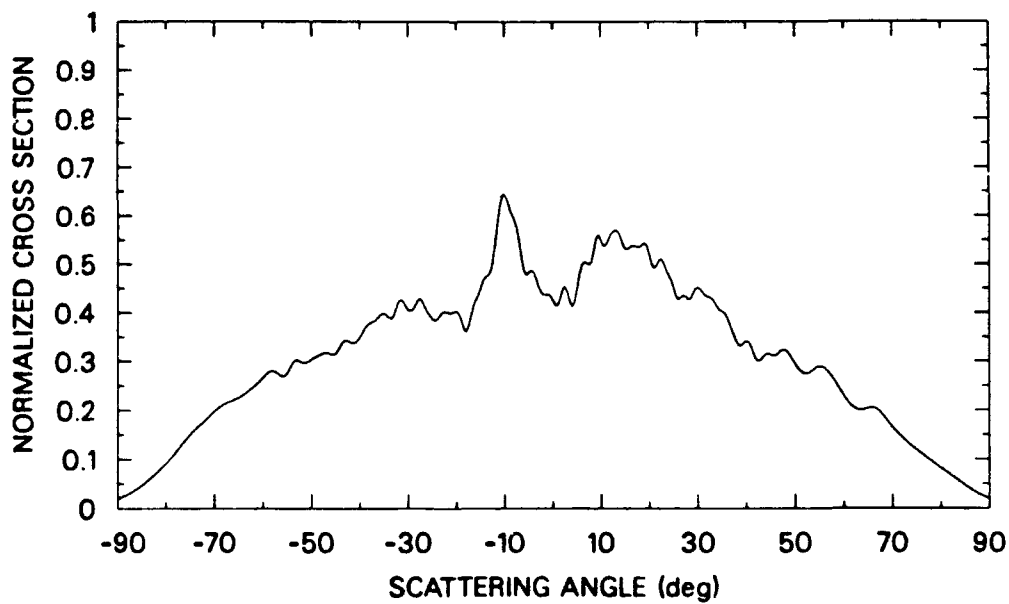


Figure 5.

S Polarization

500 Surface Average

$\lambda = 1.152 \mu\text{m}$

$\theta_i = 30^\circ$

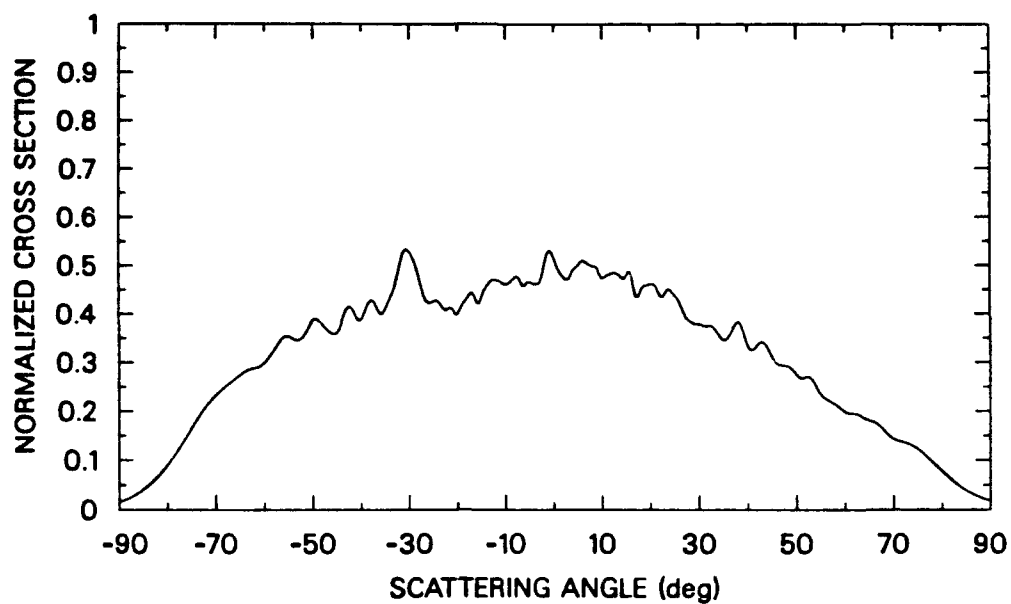


Figure 6.

S Polarization

500 Surface Average

$\lambda = 3.392 \mu\text{m}$

$\theta_i = 0^\circ$

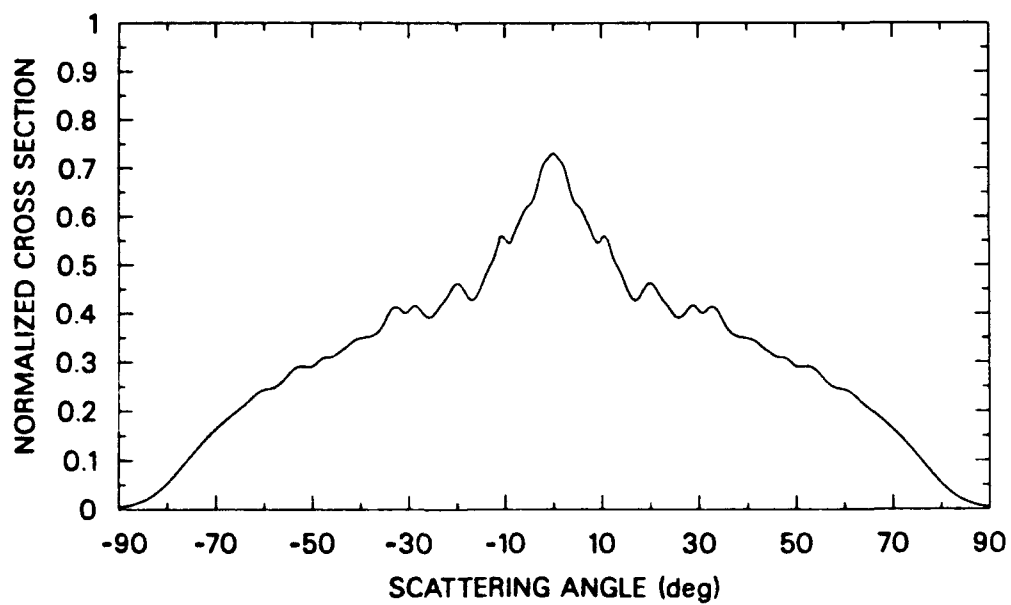


Figure 7.

S Polarization

500 Surface Average

$\lambda = 3.392 \mu\text{m}$

$\theta_i = 10^\circ$

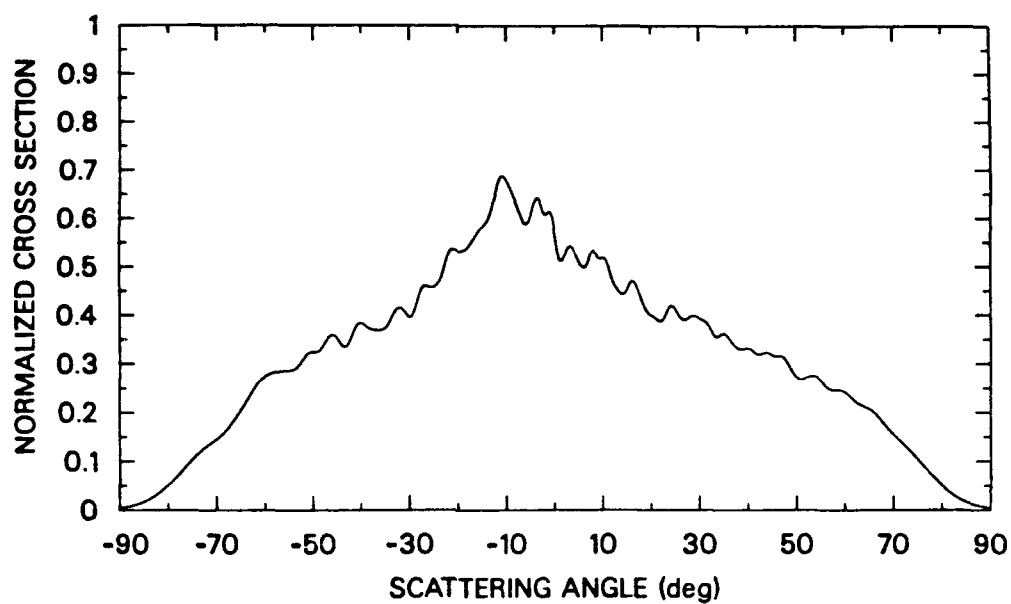


Figure 8.

S Polarization

500 Surface Average

$\lambda = 3.392 \mu\text{m}$

$\theta_i = 30^\circ$

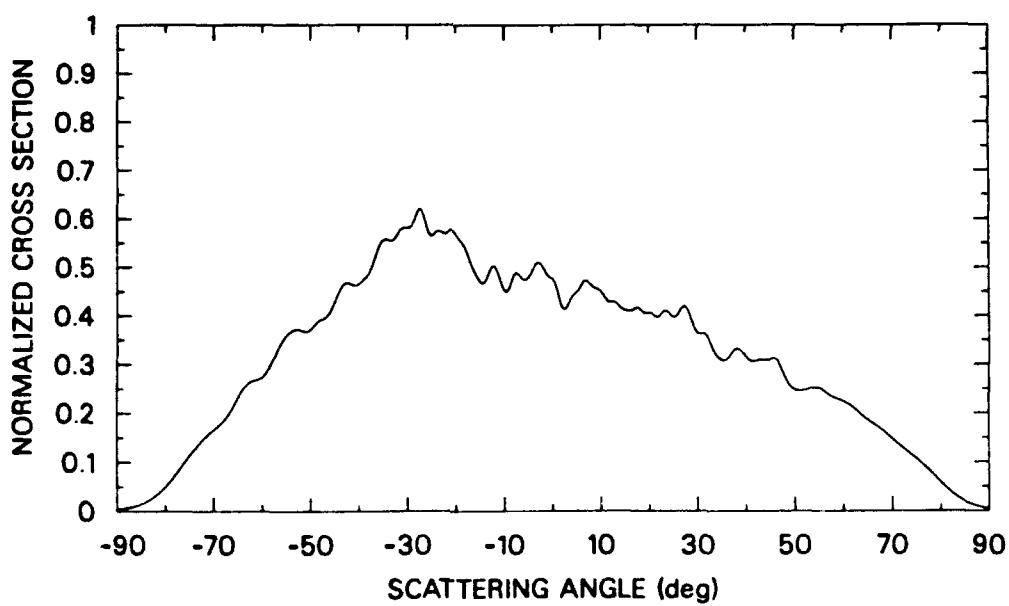


Figure 9.

P Polarization
 $\lambda = 1.152 \mu\text{m}$
 $\theta_i = 0^\circ$

500 Surface Average
(symmetrized)

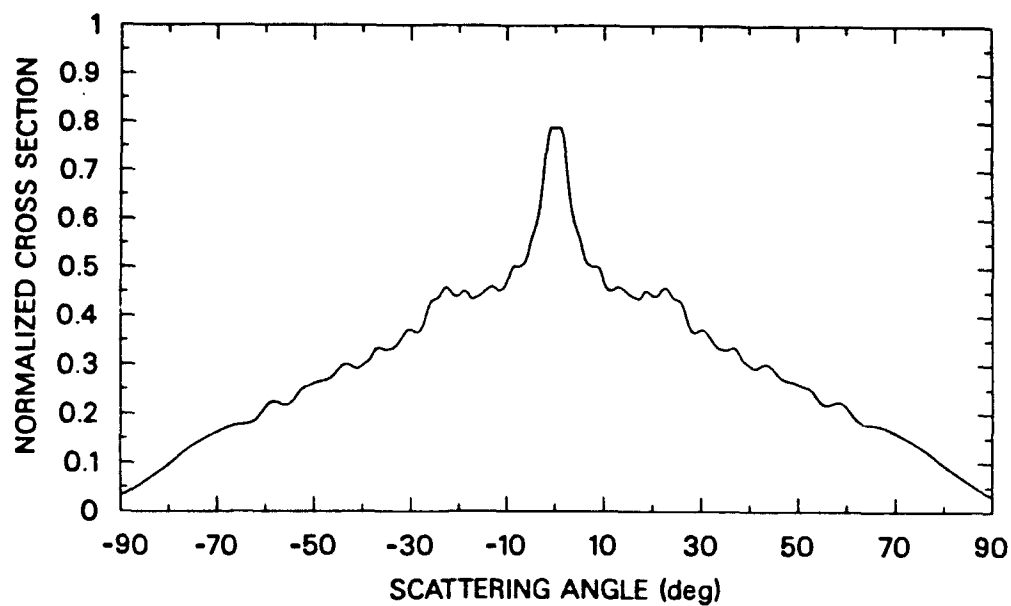


Figure 10.

P Polarization
 $\lambda = 1.152 \mu\text{m}$
 $\theta_i = 10^\circ$

500 Surface Average

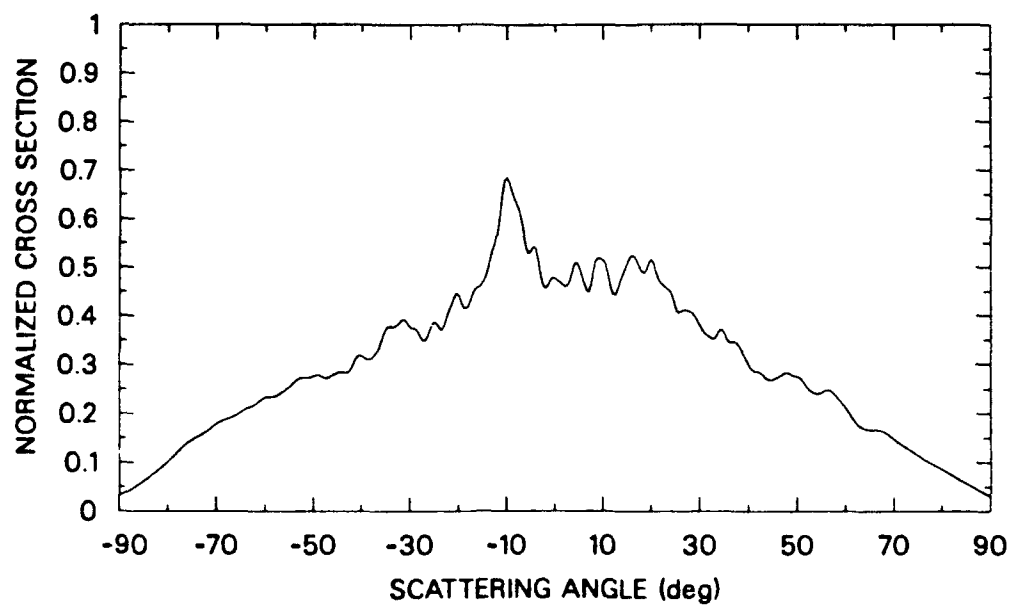


Figure 11.

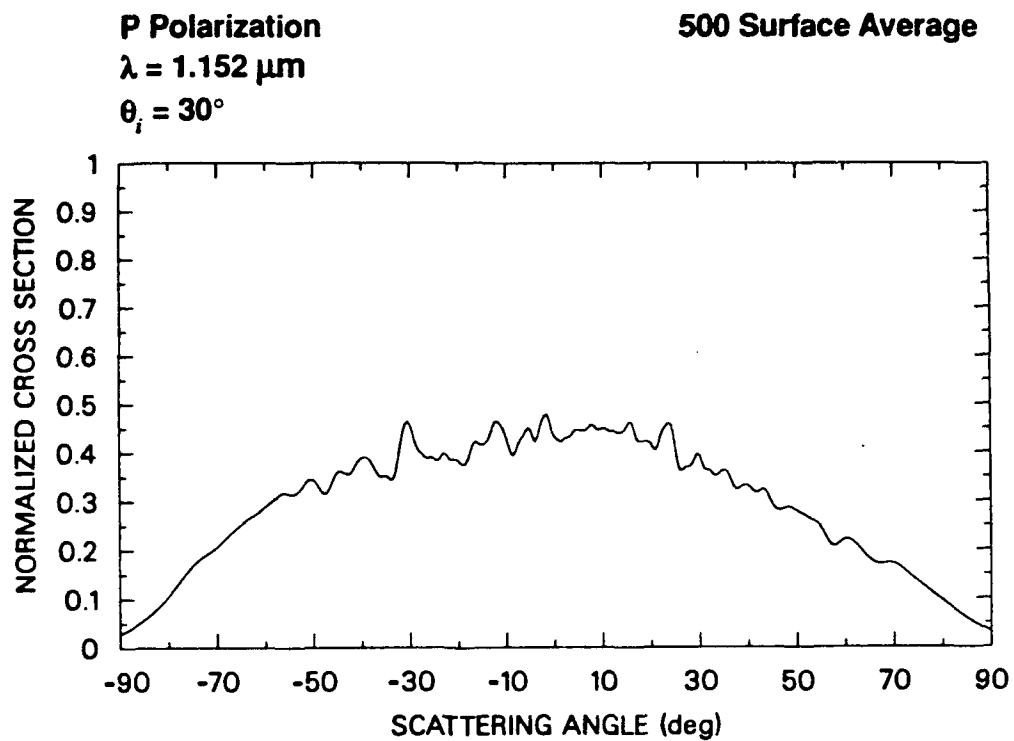


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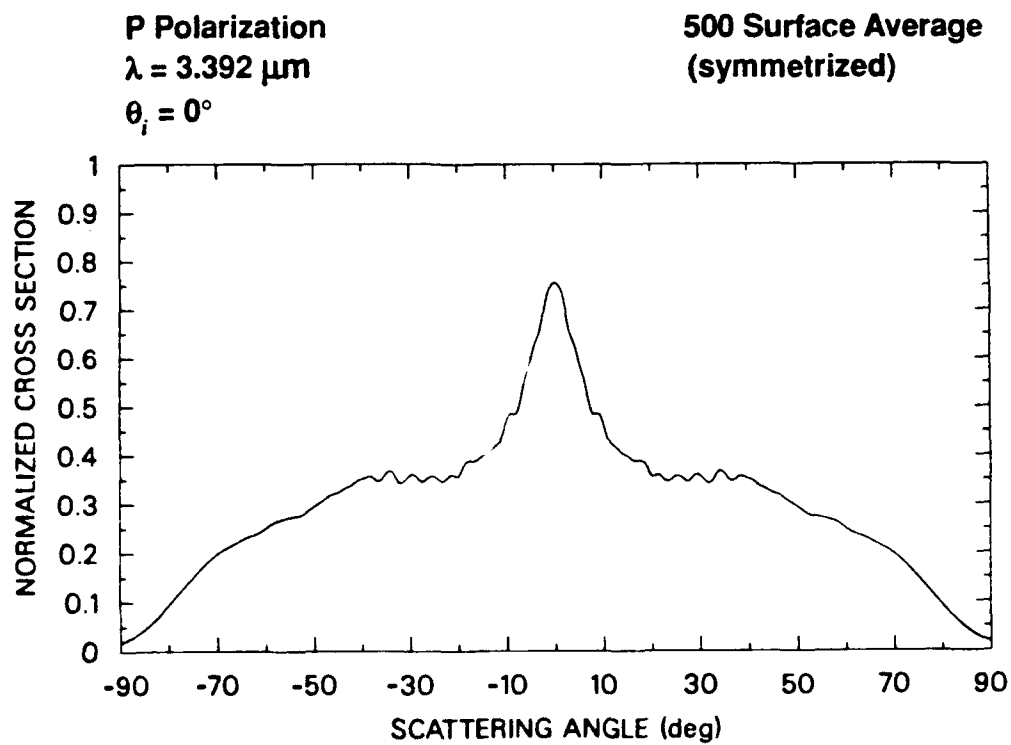


Figure 13.

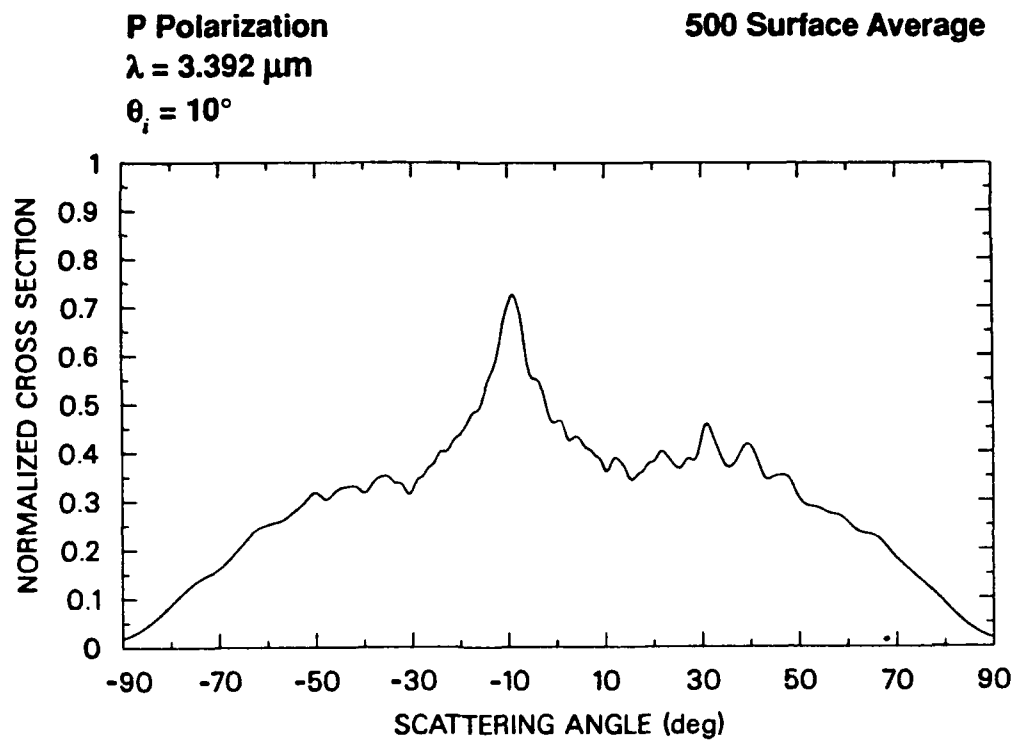


Figure 14.

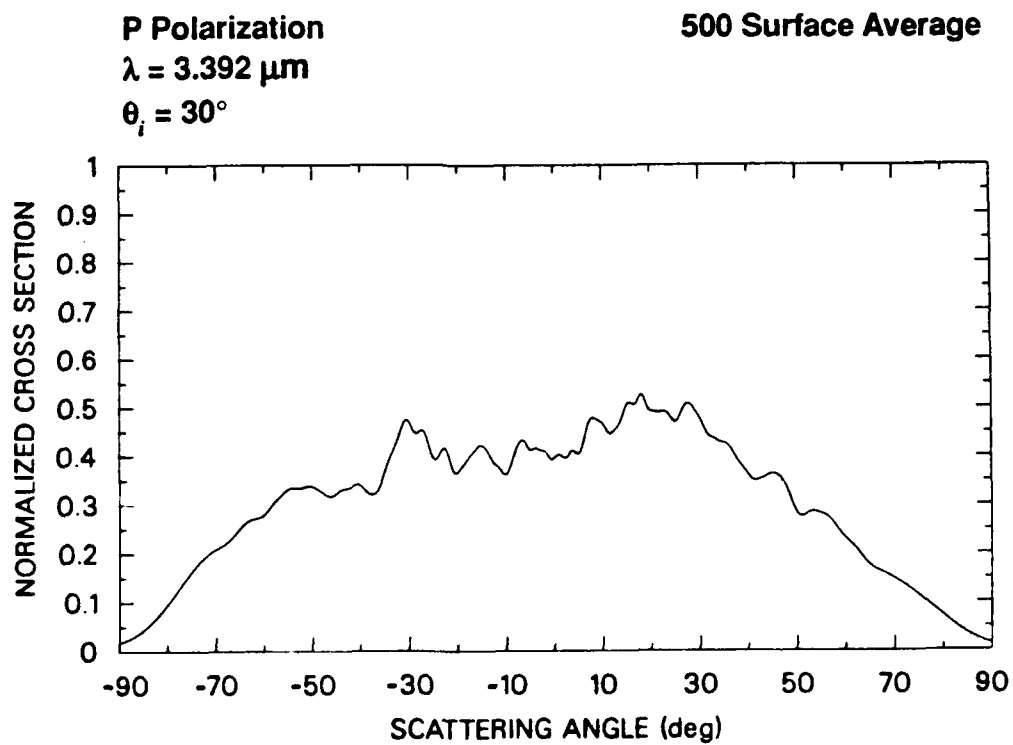


Figure 15.

S Polarization
 $\lambda = 1.152 \mu\text{m}$
 $\theta_i = 0^\circ$

500 Surface Average
(symmetrized)

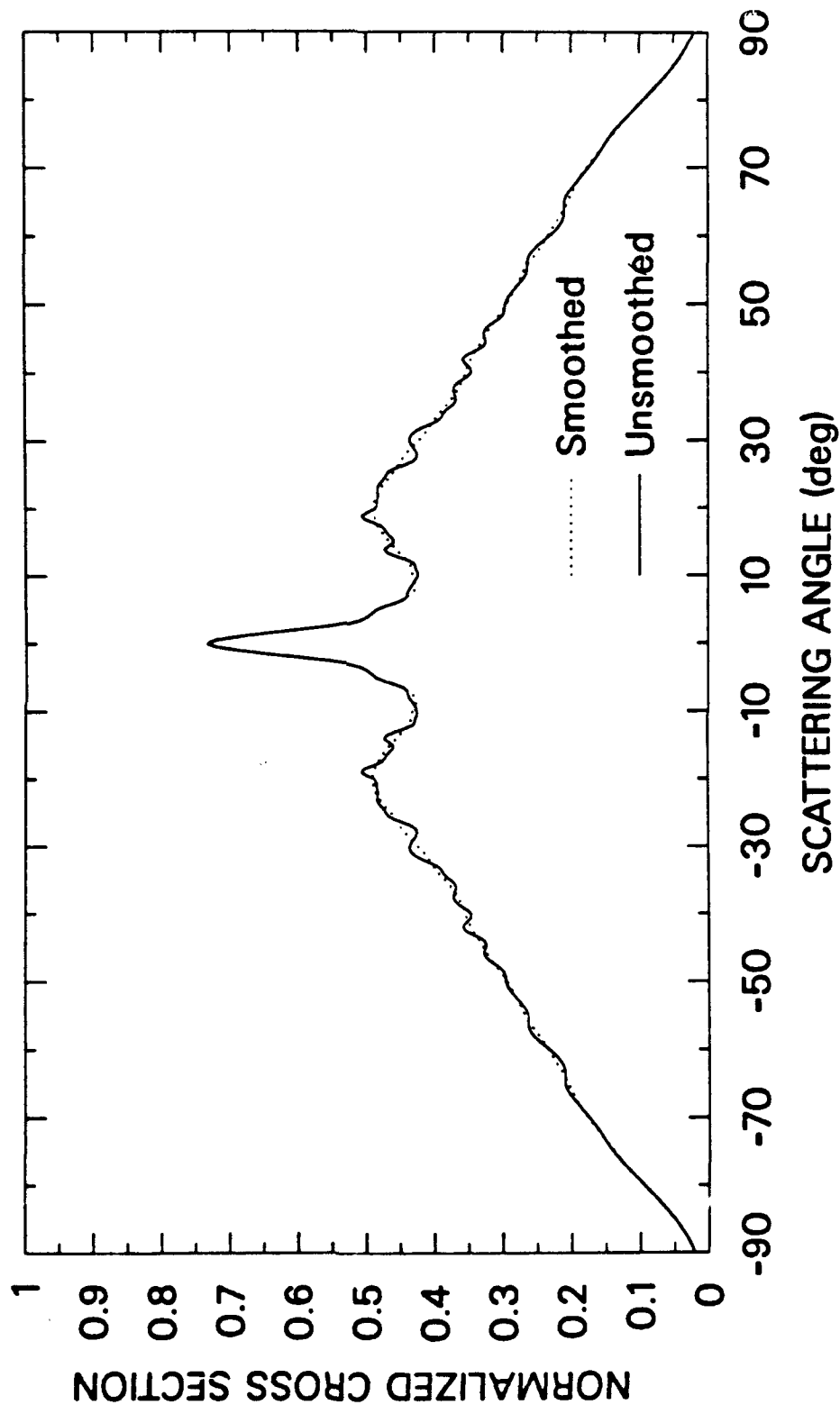


Figure 16.