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Controlled Millimeter Wave Experiments on the Enhanced Backscattering from Rough Surfaces

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Abstract

We present experimental results on the scattering of electromagnetic waves at millimeter wave frequencies from one–dimensional very rough conducting surfaces with controlled surface roughness statistics. Very rough surfaces are defined as surfaces with rms height and correlation length on the order of a wavelength such that the rms slope is at least unity. It is expected that scattering experiments using these surfaces can provide useful insights since their statistics lie outside the range of validity of the present theories, namely, the Kirchhoff and perturbation theories. Strong backscattering enhancement at different incident angles, both in the TE and TM polarizations, is observed experimentally. Numerical calculations based on the exact integral equation method for cylindrical beamwave antennas compare favorably with the experimental results. The agreement between measurements and numerical calculations is good over a wide range of incident angles and for all scattering angles. The close agreement between the experimental results and numerical simulations indicates that this controlled experimental setup can be used to study scattering phenomena from one–dimensional very rough surfaces with different roughness statistics and from two–dimensional rough surfaces.

1. Introduction

Recently, there has been interest in the phenomenon of backscattering enhancement in the scattering of electromagnetic waves from very rough surfaces. As indicated in Figure 1, most of the conventional theories available are applicable in limited regions of validity and break down when the roughness of the surface becomes comparable to the wavelength of the incident wave. Few analytical solutions exist for such a problem and those are only suitable for one–dimensional surfaces in which the height is a random function of position in one direction. Furthermore, in order to compare any theory to experimental results, accurate knowledge of the true statistics of the surface characteristics must be available and all the parameters of the experimental conditions must be known accurately. Satisfying the above requirements proves to be a very difficult task, if not an impossible one. Nevertheless, if the wavelength of the incident radiation is on the order of a millimeter, the accuracy of the desired surface roughness statistics is more easily obtained. Moreover, the assumption of perfect conductivity at this range of wavelengths is more easily achieved and verified compared with the optical method.

The research reported here represents controlled experimental work on the scattering of millimeter waves from one–dimensional perfectly conducting rough surfaces. Both the Gaussian statistics and Gaussian roughness spectral density of each surface are known exactly. This is more useful than the previous optical experiments using metallic surfaces because of the ease in controlling the relative rms roughness of the surface. At optical wavelengths, many optical methods exist to determine the surface profile directly such as optical interferometry, profilometry, surface plasmon method, tunneling electron microscopy, and the scattering method. However, the measured surface statistics may not always compare well among different instruments because at the sub–micron range the measured characteristics depend on the type of instrument used. This is especially true for the autocovariance function of the surface height where both the vertical and horizontal resolutions are important. In the case of a surface profilometer which is a direct contact measurement, the hardness of the surface relative to the probing stylus may affect the measured surface roughness statistics. The importance of the effects of the surface roughness characteristics on the measured scattering cross section should not be underestimated since it was shown that the scattering from rough surfaces with Gaussian spectrum and those with non-Gaussian spectrum may differ appreciably.

Scattering experiments are carried out for several different statistically independent surfaces in order to obtain adequate representative average results. The copolarized scattered cross section as a function of the observation angle is compared with numerical results based on an exact integral equation method. The agreement between experimental results and numerical calculations is good over all scattering angles for both small and large angles of incidence.

2. Scattering Experiments

Bistatic reflectance measurements of the scattering cross sections of rough surfaces are performed using a millimeter wave scatterometer. The scatterometer is a HP8510-based millimeter wave network analyzer system operating in the 75–100 GHz frequency band. Figure 2 shows the three–dimensional geometry of the experimental setup including the transmitting antenna and the receiving antenna. Both the transmitter and receiver scan in the same scattering plane. The scattering cross section can be measured at all scattering angles except those which are within the range of the blind angle of the receiver. For all the experimental results, the specular direction is given by $\theta_s = \theta_i$ and the backscattered direction is given by $\theta_s = -\theta_i$. Both incident TE and TM polarizations are also included in the figure. Each surface sample is painted with several coatings of conducting nickel paint to ensure good conductivity. The reflectivity and transmissivity of the conducting paint are measured at millimeter wave frequencies using the standard waveguide transmission line method. The conducting paint is found to be highly conducting at millimeter wave frequencies. The rms height h and the correlation length l of the surfaces are both equal to 1λ at 100 GHz.

Scattering experiments are carried out for both TE and TM polarizations at angles of incidence $\theta_i = 0°$, $20°$ and $40°$. Backscattering enhancement exists for all angles of incidence for the TE case and also for small angles of incidence for the TM case, namely, $\theta_i = 0°, 20°$.

No backscattering enhancement exists for the TM case when $\theta_i = 40°$. Experimental results are compared with the numerical calculations based on exact integral equation formulations. Figures 3 and 4 depict the comparison between the numerical simulations and the experimental results for both TE and TM polarizations at $\theta_i = 20°$. The experimental results are shown in solid lines with symbols and the numerical simulations are shown in thick broken lines. The agreement between the experimental results and numerical calculations is good over the entire range of scattering angles.

Acknowledgements

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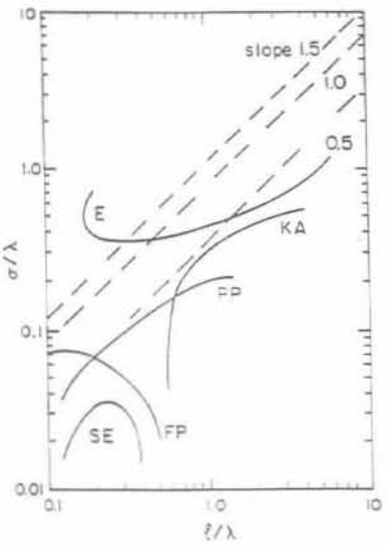

Figure 1. Ranges of validity for Kirchhoff (KA), Phase Perturbation (PP), and Field Perturbation (FP) theories. Enhanced backscattering occurs in the range labeled E. Also, the enhancement due to surface-wave modes occurs in the range labeled SE. σ is the rms height, and ℓ is the correlation distance, of the rough surface.

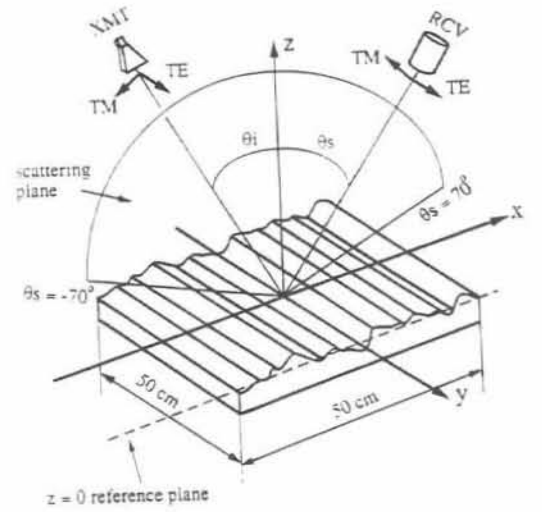

Figure 2. Experimental setup.

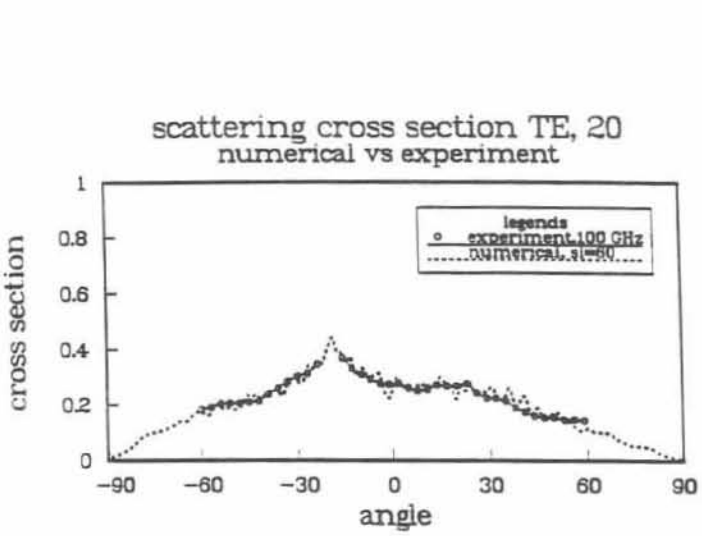

Figure 3. Scattering cross secion for TE, incident angle = 20,$l = 1\lambda$, $h = 1\lambda$.

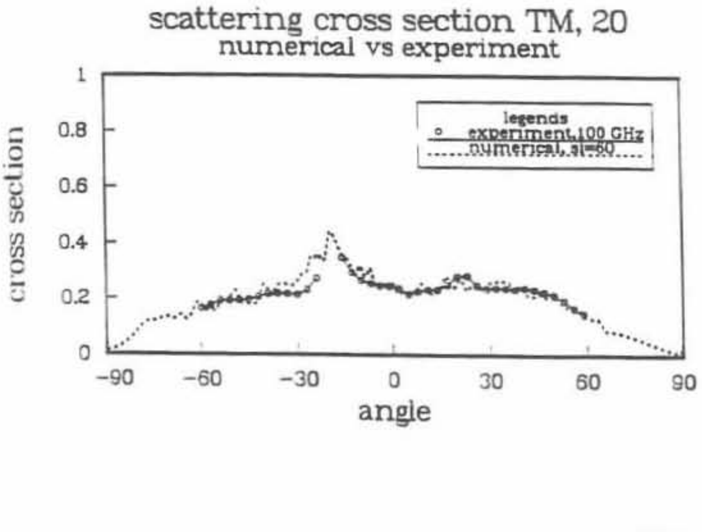

Figure 4. Scattering cross section for TM, incident angle = 20, $l = 1\lambda$, $h = 1\lambda$.