Radar Image Studies of Scattering from Random Rough Surfaces

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Abstract—

In this paper electromagnetic scattering from deterministic rough surfaces is described through analysis of radar images. Backscatter results are considered for 1-D random rough surfaces which satisfy an impedance boundary condition (IBC). Radar images of single realizations of random surfaces are formed through back-projection tomography. Detailed investigations of the images are also provided to clarify major and secondary scattering events, angular dependencies, and polarization effects, and a ray tracing analysis is performed to predict multiple scattering images. For an ocean-like surface, effects of surface length scale components are discussed.

1. INTRODUCTION

In recent years several analytical models for rough surface scattering have shown promising results for specified ranges of surface statistics [1]. No approximate solutions, however, clearly explain all possible scattering mechanisms for a single surface realization since evaluation of analytical theories is typically based on results for cross sections averaged over surface realizations. Due to lack of information on the physical behavior of scattering from rough surfaces, a more descriptive approach is necessary to understand the existing theories. Imaging techniques offer a unique tool for analysis and understanding of rough surface scattering phenomena [2].

Recent development of efficient numerical methods for back-scattering predictions enable radar image formation. Exact numerical results can provide useful information on important scattering features from single surface realizations when the existing analytical models are not valid any longer. Also, images formed from numerical scattering models can be used as a reference solution to evaluate the performance of the existing models, and to develop more accurate analytical scattering models.

In Section 2, the scattering geometry for deterministic rough surfaces is described. In Section 3, the theoretical background for an efficient numerical model and construction of 2-D inverse synthetic aperture radar (ISAR) images is included. In Section 4, various scattering features captured from the images are examined.

2. SCATTERING GEOMETRY

One dimensional realizations of Gaussian random process surfaces with Gaussian or Pierson-Moskowitz (P-M) spectra are considered in this paper. Surfaces with a Gaussian spectrum can be characterized by the rms height ($\sigma$) and correlation length ($l_c$). A 1.92 m surface with rms height 2.0 cm and correlation length 7.5 cm is used for the Gaussian surface case.

Unlike the Gaussian surface, the P-M ocean-like surface has a multi-scale roughness controlled by maximum and minimum scale cutoff frequencies ($k_{du}$ and $k_{df}$) in the surface spectrum. A single realization of a P-M ocean-like surface is generated for 6 m/sec wind speed with $k_{du} = 587$ rad/m and $k_{df} = 0.001$ rad/m so that all important length scale variations at X- to Ku-bands for a 7.68 m surface length are included. Large and small scale roughness effects of the P-M surface at large incidence angles will be discussed.

The medium is assumed to be described by an impedance boundary condition (IBC) with a relative permittivity of $(39.7 + i40.2)$ to approximate sea water. The surface is truncated at $x = L/2$ and $-L/2$ and a phase-corrected tapered beam with spot size $g = L/5$ is used to confine the incident field to this area so that edge effects can be avoided.

3. BACKGROUND THEORIES

An iterative method of moments based on the forward-backward (FB) method has been successfully applied to scattering from 1-D surfaces with relatively large rms heights. Several fast techniques have been proposed to accelerate the computational efficiency for the 1-D FB method. To improve the efficiency of the 1-D FB computation, the novel spectral acceleration (NSA) algorithm has been developed [3]. A spectral domain representation of the scalar Green’s function and the source current is
used to compute the coupling between points separated by wide distances. For a large number of unknowns, the resulting computation count and memory requirement reduce to $O(N)$ for fixed surface statistics.

A 2-D ISAR image of a deterministic surface is constructed from a set of frequency and angular swept complex backscatter field data. Back projection tomography using an inverse Fourier transform is employed to generate the images [4]. Backscatter data were collected over 4 GHz frequency bandwidth (10 - 14 GHz) and a 20° angular bandwidth corresponding 3.75 cm down- and 3.65 cm cross-range resolution in the image domain, respectively. Frequency and angle steps are appropriately chosen so that unambiguous ranges include the possible ranges of secondary scattering sources in cases involving multiple scattering. To reduce the side-lobe level, the Hamming window is used.

4. RESULTS AND DISCUSSIONS

First, we investigate ISAR images of the Gaussian roughness surface for aspect angles centered at normal incidence. The two images in Figure 1 show the horizontal (HH) and vertical (VV) polarization images constructed from the exact numerical results (FB/NSA). Each image is expressed within the dynamic range of 60 dB and composed of 200 × 160 pixels in a 2 m × 1.6 m range so that each pixel size is much smaller than the range resolution.

Note that the images have a maximum scattering level near the center of the surface due to the tapered wave illumination on the surface. The surface profile is also overlaid to match the scattering centers and the corresponding surface points. The scattering centers come primarily from the near specular points with maximum image levels of about -3.4 dB for both polarizations, showing very little polarization dependence as expected. The images for both polarizations show additional scattering sources below the surface, possibly from multiple scattering effects.

To study the origin of these additional scattering points, a ray tracing analysis is carried out to predict the locations of points which occur due to double reflection. In this analysis, we draw three rays which represent the incident ray on one point, the horizontally propagating ray connecting two points and the scattered ray on the other point, respectively. Once possible double reflection points are found, the corresponding time delays of each ray is calculated. The time delayed points are then placed along the down-range from the middle of two points as shown in Figure 2. Overlayed by the images of Figure 1, the predicted points match the time-delayed images from multiple scattering effects. The intensity of the secondary scattering images becomes higher as the rms height increases due to the strong near specular interactions.

As a second example, the ocean-like rough surface is investigated through radar images at incident angles centered at 70°. Due to the wide range of length scales in the surface roughness, radar images are expected to show contributions from both long scale and small scale portions. As shown in Figure 3, some polarization differences are observed unlike the Gaussian surface case at normal incidence. As indicated in the dynamic range, VV polarization is about 15 dB above HH polarization in the overall backscatter level.

Another important difference between polarizations is that the scattering source distribution over the entire surface. As observed in the figure, most of the single scattering returns for HH backscatter come from portions with large local slopes and show little contribution from the backside of the surface. On the other hand, for VV returns the scattering sources are more evenly distributed over the surface showing some contributions even from the geometrically shadowed regions. These phenomena have been addressed from the statistics of ocean backscatter study by Donohue [5], in which examination of induced current distributions and local radar cross sections revealed different scattering behavior between polarizations, similar to the results observed in the radar images.

In addition to the strong single scattering returns due to the Bragg components of the surface, some multiple scattering effects are also observed below the surface for both polarizations. By filtering the spectrum contents of the surface, the origin of these multiple scattering effects can be analyzed. By changing the limit of high or low cutoff frequencies of surface spectrum, it is found that multiple scattering events and the overall backscattering levels are closely related to the Bragg scattering component of the surface in conjunction with the large scale variations.

5. REFERENCES


Figure 1: 2-D ISAR images for a Gaussian surface: $f = 10 \sim 14$ GHz, $\delta f = 50$ MHz, $\theta_i = -10^\circ \sim 10^\circ$ and $\delta \theta = 0.2^\circ$

Figure 2: Ray tracing prediction for the location of image spots due to multiple scattering at normal incidence

Figure 3: 2-D ISAR images for an ocean-like surface: $f = 10 \sim 14$ GHz, $\delta f = 25$ MHz, $\theta_i = 60^\circ \sim 80^\circ$ and $\delta \theta = 0.2^\circ$