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Application of IEM and Radiative Transfer Formulations for Bistatic Scattering of Rough Surfaces

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Abstract* - Systematic characterization of scattering behavior of natural and manmade rough surfaces is required in many radar applications. In general, the overall scattering response of such surfaces is composed of surface and volume scattering components. In this paper Integral Equation Method (IEM) is outlined to work out the *surface scattering* and the radiative transfer theory is applied to model the *volume scattering.

I. INTRODUCTION

Rigorous modeling of electromagnetic waves scattering from natural or artificial rough surfaces (ocean, sand, soils, snow, concrete, asphalt roads, …) is of great interest in many fields of applications. The scattering elements of such surfaces have complex geometry and are randomly distributed. So, their radar scattering involves complex interactions. At the millimeter waves, semi-empirical models and sparse measurements encountered in the literature are not in good agreement and it is not practical to evaluate the scattered fields by exact or asymptotic electromagnetic methods.

In this paper, we propose and set out rigorous analytical formulations to calculate the scattered power by rough surfaces: the IEM method for surface scattering and the radiative transfer theory for volume scattering. These models take into account the statistical description of the surface and are valid over a wide range of surface roughness.

II. ROUGH SURFACE DESCRIPTION

The surface roughness is usually described by a statistical distribution. Two principal parameters characterize the surface [1]: the root mean square of surface heights s_z and the correlation length l_c which describes the density of the irregularities. Most methods usually assume that the surface height distribution p(z) is gaussian. Nevertheless, s_z alone is not enough to completely describe a surface roughness. Several profiles could have the same height distribution but could present noticeable difference in the spatial variation of the irregularities. This difference is characterized by the correlation function ρ(r). Gaussian and exponential functions are often proposed in theoretical modeling. The correlation length l_c is the given distance where the correlation function is equal to $1/e = 0.368$. In fact and more precisely, the scattering behavior respectively depends on the values of ks_z and kl_c, k is the wave number given by 2π/λ.

III. INTEGRAL EQUATION METHOD

A. Classical asymptotic methods [1], [2], [3]

The small perturbation model (SPM) could be used for small values of such aforementioned parameters: $ks_z < 0.3$ and $kl_c \leq 3$. It assumes that the scattered electromagnetic field could be represented by a superposition of plane waves of unknown amplitudes which are propagated towards the receiver.

The Kirchhoff model (KM) considers that each point of the analyzed rough surface belongs to the infinite tangent plane to the surface at this point. This method must be used within the following restrictions: $ks_z \leq 1.5$ and $kl_c > 2\pi$.

Although these methods are the most common techniques for computing the scattered electromagnetic field from rough surfaces, their efficiency is restricted to small roughness or long correlation length surfaces. Fig. 1 summarizes their range of validity. Previous limitations are circumvented by using the Integral Equation Model (IEM) for the surface scattering coefficient. Its range of validity overlaps those of KM and SPM (Fig. 1).

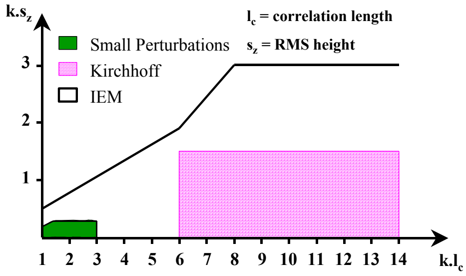

Fig 1: Range of validity

B. IEM formulation [4], [5]

The IEM model gives a solution of the Stratton-Chu integral equation: the scattered field is obtained by a reformulation of the tangential field through two components: the Kirchhoff term and a complementary term (1). Recent formulations from J.L. ALVAREZ-PEREZ [5] have been taken into account. From this consistent IEM formulation, rigorous description of the multiple scattering mechanisms has been developed in order to evaluate the coherent and incoherent scattering coefficients (Fig. 2) and the crosspolarization terms even in the complex monostatic configuration.

$$E_{qp}^{s} = E_{qp}^{sk} + E_{qp}^{sc} \quad (1)$$

p et q respectively denote the polarization of the transmitting and receiving antennas.

The coherent scattered power (power scattered in the specular lobe) is calculated from the mean squared power (2) and the incoherent contribution is obtained by subtracting the previous coherent power from the total power (3).

$$\begin{aligned} P_{qp_{coh}}^{s} &= \frac{1}{2\eta}\left\langle E_{qp}^{sc}\right\rangle\left\langle E_{qp}^{sc*}\right\rangle = \frac{1}{2\eta}\left\langle E_{qp}^{sk}\right\rangle\left\langle E_{qp}^{sk*}\right\rangle \\ &\quad + \frac{1}{2\eta}2\Re e\left[\left\langle E_{qp}^{sc}\right\rangle\left\langle E_{qp}^{sk*}\right\rangle\right] + \frac{1}{2\eta}\left\langle E_{qp}^{sc}\right\rangle\left\langle E_{qp}^{sc*}\right\rangle \end{aligned} \quad (2)$$

$$P_{qp_{incoh}}^{s} = \frac{1}{2\eta}\left[\left\langle E_{qp}^{s}E_{qp}^{s*}\right\rangle - \left\langle E_{qp}^{s}\right\rangle\left\langle E_{qp}^{s*}\right\rangle\right] \quad (3)$$

η is the impedance in the medium.

Note that the dimensionless scattering coefficient, depending on the scattered and incident power, is given by (4).

$$\sigma_{qp}^{s} = \frac{4\pi R^2 P_{qp}^{s}}{A_0 P_{qp}^{i}} \quad (4)$$

where P_{qp}^{i} and P_{qp}^{s} are respectively the incident and scattered power; and A_0 is the illuminated surface. Fig. 2 presents the different components of the total scattered power.

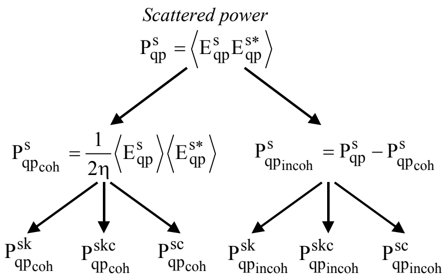

Fig. 2 : Total scattered power by IEM model

C. IEM results

1) Backscattering

Our first application results concern the backscattering coefficient formulation at millimeter wave frequencies (35 and 94 GHz) for asphalt and concrete roads. Good agreement between theoretical results and measurements found out in literature is established (Fig. 3) [4]. Interesting results are also obtained for the particular and original case of grazing incidence between 70º and 88º (Fig. 3). Sparse results are present in relative bibliography concerning this incidence. So, validation is still under investigation [2], [4], [6].

2) Bistatic scattering

In bistatic scattering problem, Fig. 4 shows the variations relative to roughness of the coherent and incoherent components of the scattered power from an asphalt road at 94 GHz. The incident angle is -40˚. On smooth surface, total incident power is scattered in the main lobe of reflection. Higher roughness leads to lower coherent diffracted power and an increasing of the incoherent component.

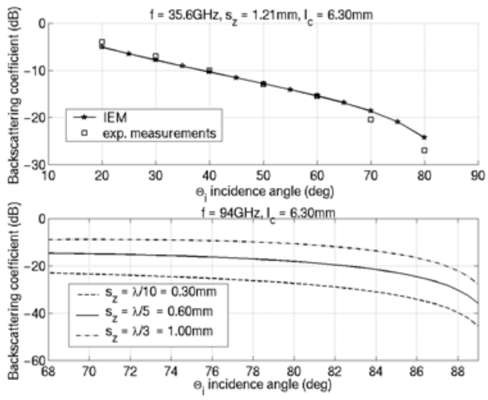

Fig. 3 : Backscattering coefficient from asphalt

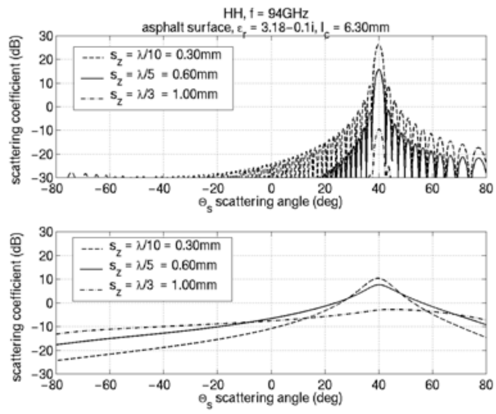

Fig. 4 : Coherent and incoherent bistatic scattering from asphalt at 94GHz

IV. RADIATIVE TRANFERT THEORY

A. Formulation [4], [6]

The radiative transfer theory deals with the transport of energy through a medium containing particles. It accounts the Stokes vector variations of an electromagnetic wave propagating through a random medium composed of clusters embedded in a host medium. These variations are due to different phenomena: absorption losses by the host medium and the particles, scattering losses by the particles and thermal emission by the global inhomogeneous medium. The scattering coefficient is obtained by solving the radiative transfer differential equation (4) which governs the wave propagation in the medium.

$$\frac{d\vec{I}(\vec{r},\hat{s})}{ds} = -\kappa_e I(\vec{r},\hat{s}) + \vec{J}_e(\vec{r}) + \int_{4\pi} d\Omega' P(\hat{s},\hat{s}') I(\vec{r},\hat{s}') \qquad (4)$$

This equation is formulated in terms of three constitutive functions:

- κ_e, the extinction matrix, describes the attenuation of the intensity due to absorption and scattering.
- $\vec{J}_e$ is a source function that accounts for self thermal emission in the medium. In radar remote sensing, its contribution is small in comparison with the other terms and it is neglected.
- P is the 4x4 phase matrix. It specifies the angular distribution of the incident intensity from a given direction into other directions.

The intensity I_q^s scattered in a given direction is found out by solving the radiative transfer differential equation above. With the incident intensity I_p^i, equation (5) below gives the volume scattering coefficient [6].

$$\sigma_{qp}^0 = \frac{4\pi \cos\theta_s * I_q{}^s(\theta_s,\varphi_s)}{I_p{}^i(\theta_i,\varphi_i)}, \qquad (5)$$

B. Radiative transfer equation results

The backscattering (HH, VV, HV, VH) and bistatic scattering coefficients obtained from (4) and (5) are shown on Fig. 5.

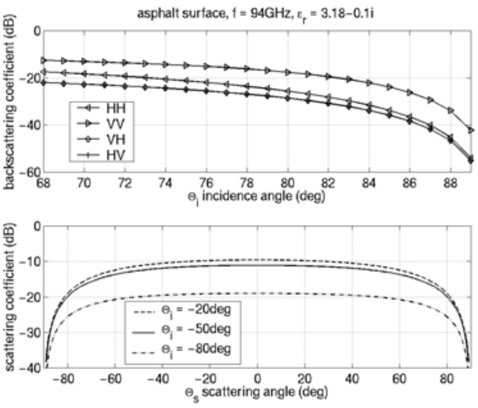

Fig 5 : Asphalt volume scattering coefficients

V. Total backscattering coefficient

A. Grazing incidence in backscattering

In response to large requirements in modeling from remote sensing up to safety in road transportation, bistatic scattering coefficients are calculated from the nadir to the hardly developed grazing incidence, at millimeter waves. Thus, the first application is focused on road surfaces such as asphalt and concrete. Surface and volume contributions are summed up to obtain the total backscattering coefficient [6]. For the volume contribution calculations, the incident power is only the part of power transmitted in the host medium. Results are shown on Fig. 6. Validation is achieved using experimental results in literature [6].

B Bistatic scattering case

Surface and volume contributions are summed up to obtain the total bistatic scattering coefficient. Fig. 6 shows that the volume contribution is preponderant in directions far away from the specular direction. The incident angle is -40°. At $s_z = \lambda/3$, volume scattering is lower than the surface scattering. For higher values of s_z, the volume scattering could be neglected in comparison with the surface scattering.

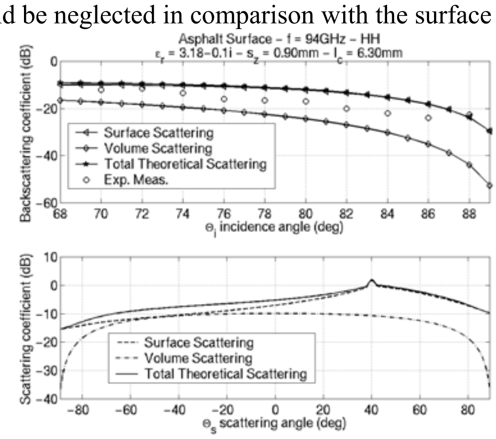

Fig 6 : HH asphalt total scattering coefficients

VII. Conclusion

In this paper, a general bistatic scattering electromagnetic model derived from the IEM (surface scattering) and the radiative transfer formulation (volume scattering) has been evaluated. Interesting results were obtained even for the particular case of grazing incidence between 70º and 88º. Theoretical results and measurements found out in appropriate papers are in good agreement. Theoretical modeling of radar sensor usually deals with the modeling of the Radar Cross Section (RCS) of targets and the modeling of the terrain scattering coefficient. Our current studies investigate the coupling of the targets and their immediate environment using both the bistatic scattering coefficients from the target and the terrain around it.

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