JOINT APPLICATION OF IEM AND RADIATIVE TRANSFERT FORMULATIONS FOR A 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. The overall scattering response of such surfaces is composed of surface and volume scattering components. In this paper Integral Equation Method (IEM) is used to work out the surface scattering and Radiative transfer theory (RTT) is applied to model the volume scattering.*

INTRODUCTION

Systematic characterization of scattering behavior of natural (oceans, snow, sand) and manmade (roads…) rough surfaces is required in many radar applications. In general, it is found that the overall scattering response of such surfaces is composed of surface and volume scattering components. At 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: Integral Equation Method (**IEM**) is used to work out the ***surface scattering*** and the Radiative Transfer Theory (**RTT**) is applied to model the ***volume scattering.***

First applications of our work are focused on road surfaces such as asphalt and concrete. The scattering elements of such surfaces have complex geometry and are randomly distributed; their radar scattering involves complex interactions. The bistatic scattering coefficients are calculated from the nadir *to the hardly ever developed grazing incidence, even at millimeter-waves frequencies*, in response to large requirements in modeling from remote sensing up to safety in road traffic.

ROUGH SURFACE DESCRIPTION

An appropriate description of the surface is required for all surface modeling. Its roughness is usually described by a statistical distribution. Most modeling methods assume that the surface roughness exhibits a Gaussian height distribution p(z). Nevertheless, surface roughness is not totally described by the statistical distribution p(z) as it tell us nothing about the density of the irregularities. This last is described by the autocorrelation function $\rho(r)$. Gaussian and exponential functions are often proposed in theoretical modeling. Thus, two principal parameters characterize the surface: the standard deviation of the heights s_z and the correlation length l_c which describe respectively the degrees of vertical and horizontal roughness; l_c is the distance for which $\rho(r)$ will drop to the value 1/e = 0.368. More precisely, these aforementioned parameters are expressed in terms of the wavelength λ and the scattering behavior depends on the values of ks_z and kl_c, where k is the wave number given by $2\pi/\lambda$.

SURFACE SCATTERING CALCULATION

Classical Asymptotic Methods [1], [2], [3]

The choice of the appropriate model depends on the values of the normalized parameters ks_z et kl_c.

The *Small Perturbation Method* (SPM) assumes that the scattered electromagnetic field could be represented by a superposition of plane waves of unknown amplitudes which are propagated towards the receiver. This model is suited for only smooth surfaces ($ks_z < 0.3$ and $kl_c \leq 3$).

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 for surfaces having a moderate roughness which satisfy the following restrictions: $ks_z \leq 1.5$ and $kl_c > 2\pi$.

Thus these two methods which are commonly used to calculate surface scattering involve limited domains of applicability. Previous limitations are circumvented by using the *Integral Equation Model* (IEM) for the surface scattering coefficient. Fig.1 shows that the validity field of this method overlaps widely those of SPM and KM and ensures the continuity between them.

The Integral Equation Method (IEM) [4], [5]

This method gives a rigorous solution of the Stratton-Chu integral equation. The scattered electric field is obtained by a reformulation of the tangential field through two components : the Kirchhoff term and a complementary term which takes into account the wave interaction with the surrounding roughness (1).

$$E_{qp}^{s} = E_{qp}^{sk} + E_{qp}^{sc} \tag{1}$$

With the field expression given by (1), the average scattered power is (2) :

$$P_{qp}^{s} = \frac{1}{2\eta}\left\langle E_{qp}^{s} E_{qp}^{s\,*}\right\rangle = \frac{1}{2\eta}\left[\left\langle E_{qp}^{sk} E_{qp}^{sk^*}\right\rangle + 2\Re e\left\langle E_{qp}^{sc} E_{qp}^{sk^*}\right\rangle + \left\langle E_{qp}^{sc} E_{qp}^{sc^*}\right\rangle\right] \tag{2}$$

p et *q* respectively denote the polarization of the emitting and receiving antennas; η is the intrinsic impedance of the medium.

On the other hand, the surface scattering involves two different scattering mechanisms: the coherent and the incoherent scattering. The coherent scattered power (power scattered in the specular lobe), which decreases when the roughness increases, is calculated from the mean squared power (3). The incoherent contribution (power scattered outwards the specular) is obtained by subtracting the previous coherent power from the total power (4). This component increases with the roughness. Fig. 2 presents the different components of the total scattered power.

$$P_{qp_{coh}}^{s} = \frac{1}{2\eta}\left\langle E_{qp}^{s}\right\rangle\left\langle E_{qp}^{s*}\right\rangle = \frac{1}{2\eta}\left[\left\langle E_{qp}^{sk}\right\rangle\left\langle E_{qp}^{sk*}\right\rangle + 2\Re e\left[\left\langle E_{qp}^{sc}\right\rangle\left\langle E_{qp}^{sk*}\right\rangle\right] + \left\langle E_{qp}^{sc}\right\rangle\left\langle E_{qp}^{sc*}\right\rangle\right] \tag{3}$$

$$P_{qp_{incoh}}^{s} = \frac{1}{2\eta}\left[\left\langle E_{qp}^{s} E_{qp}^{s*}\right\rangle - \left\langle E_{qp}^{s}\right\rangle\left\langle E_{qp}^{s*}\right\rangle\right] \tag{4}$$

Finally note that the bistatic scattering coefficient is related to the average power expression by (5).

$$\sigma_{qp}^{s0}(m^2/m^2) = \frac{4\pi R^2 P_{qp}^{s}}{A_0 P_{qp}^{i}} \tag{5}$$

where P_{qp}^{i} is the incident power; A_0 is the illuminated surface and R is the distance to the receiver.

IEM Results

The Monostatic Case

Our first results concern the backscattering response of asphalt and concrete roads at millimeter-waves frequencies (35 and 94GHz). Good agreement is obtained between theoretical results and experimental measurements found in appropriate papers (Fig. 3). We were also interested in 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], [8].

The Bistatic Case

In the bistatic case we calculate the total surface scattering coefficient. Fig.4. shows the variations of the coherent and incoherent components according to the increase of the surface roughness. It is shown clearly that the incoherent scattering increases with the value of s_z.

VOLUME SCATTERING CALCULATION

Radiative Transfer Theory (RTT) [6], [7]

The volume of the rough surface is assumed to be a random medium composed of clusters embedded in a host medium. The *Radiative Transfer Theory* accounts the Stokes vector variations of an electromagnetic wave propagating through it. These variations are due to three different phenomena: absorption losses by the host medium and the particles, scattering losses by the particles and thermal emission by the global inhomogeneous medium (Fig. 5.). The intensity I_q^s scattered in a given direction is found out by solving the radiative transfer differential equation (6) which governs the polarimetric flow of electromagnetic energy through the random medium.

$$\frac{d\vec{I}(\vec{r},\hat{s})}{ds} = -\kappa_e I(\vec{r},\hat{s}) + \vec{J}_e(\vec{r}) + \int_{4\pi} P(\hat{s},\hat{s}') I(\vec{r},\hat{s}') d\Omega' \qquad (6)$$

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.

Finally the volume scattering coefficient is given by (7), where I_p^i is the incident intensity.

$$\sigma_{qp}^0 = \frac{4\pi \cos\theta_s * I_q^s(\theta_s,\varphi_s)}{I_p^i(\theta_i,\varphi_i)} \qquad (7)$$

RTT Results

The Monostatic Case

The top graph in Fig.6 shows the variation of the volume backscattering coefficient of dry asphalt surfaces for the co- and the cross-polarization at 94GHz. The backscattering coefficient is represented at near grazing incidence. Validation is achieved using experimental results in literature [6], [7].

The Bistatic Case

The evolution of the bistatic volume scattering coefficient according to the incidence angle is illustrated on the lower graph in Fig.6.

TOTAL SCATTERING CALCULATIONS

In the case of dielectric surfaces, a strict evaluation of the power scattered by the rough interface in the whole upper half space allowed us to quantify the portion of the incident power which is transmitted in the random medium. The power scattered by the pavement mixtures, in case of road surfaces, i.e the volume scattering, is calculated. Finally, the total scattering coefficient is calculated by summing the surface and the volume scattering coefficients.

The Monostatic Case

Our first application is focused on backscattering from road surfaces such as asphalt and concrete. Fig. 7 shows the comparison between the theoretical prediction and measurements collected in [7] for the HH backscattering coefficient of dry asphalt surfaces at 94GHz. A good agreement is obtained between theory and the experimental values. As the surface roughness is important, the volume contribution can be neglected.

The Bistatic Case

As we did in the monostatic case, surface and volume contributions are summed up to obtain the total bistatic scattering coefficient. Fig. 8 shows that at $s_z = \lambda/3$, the volume contribution could be neglected in comparison with the surface scattering.

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. We studied and observed the scattering behavior from road surfaces such asphalt which includes both surface scattering from the rough interface and volume scattering from the asphalt mixtures. Interesting results and a good agreement between theory and measurements found out in appropriate papers were obtained even for the particular case of grazing incidence between 70º and 88º.
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.

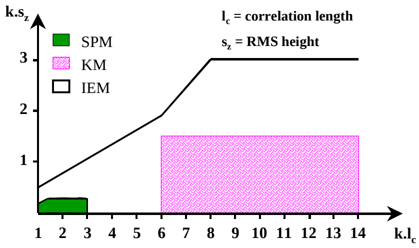

Fig. 1. Range of validity of electromagnetic method

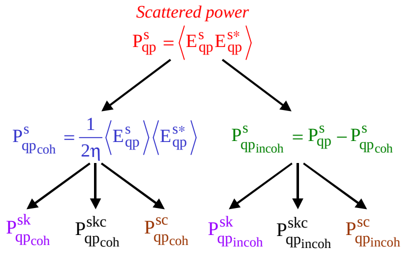

Fig. 2. Total scattered power by IEM model

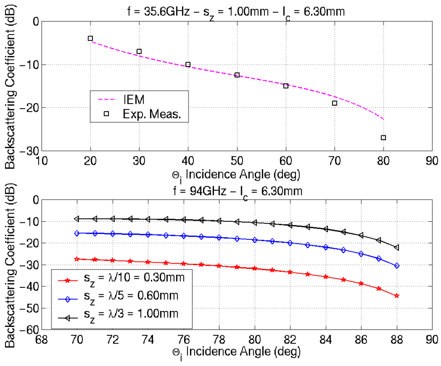

Fig. 3. Backscattering coefficient from an asphalt surface

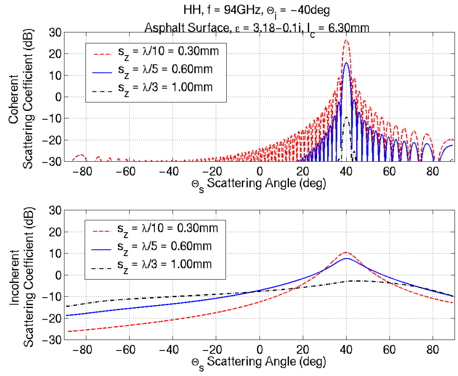

Fig. 4. Bistatic scattering coefficient from asphalt surface

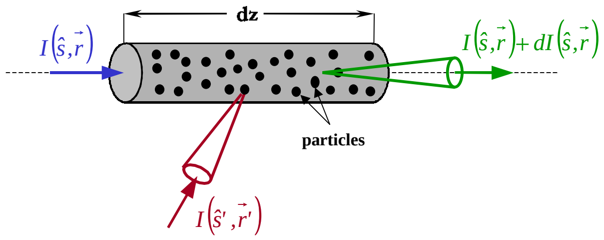

Fig. 5. Transfer of energy in the asphalt road volume

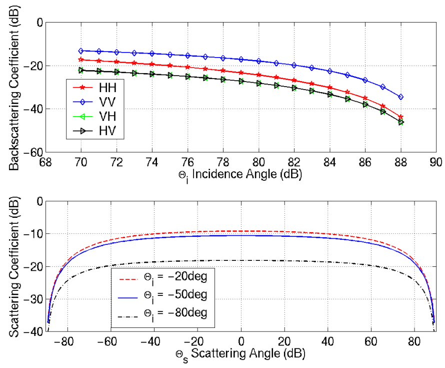

Fig. 6. Volume scattering coefficients from asphalt

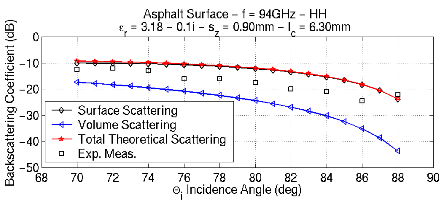

Fig. 7. Asphalt total backscattering coefficient

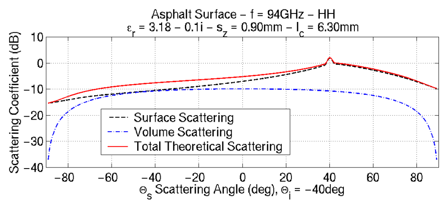

Fig. 8. Asphalt total scattering coefficients

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