1. Introduction

The millimeter-wave band offers significant advantages in supplying enough bandwidth. Millimeter-wave radar-based sensors are being considered for a number of automotive applications including obstacle detection and collision warning, true-speed, and road-surface recognition. The interaction of electromagnetic waves with asphalt road surfaces at millimeter-wave frequencies is studied by Eric and Sarabandi [1]. In high frequency band like millimeter-wave, roughnesses of the surfaces are comparable with the wavelength. So the scattering of wave should be considered. Approximate analytical solutions exist for rough surfaces with small root mean square (rms) height and slope, like small perturbation method (SPM) [2]. Although much effort has been devoted to extend the region of validity of these models, the improved techniques still have the basic limitations of the original models. An alternative approach for evaluation of the scattered field for rough surfaces is Monte Carlo simulation. In this approach, many sample surfaces with the desired roughness statistics are generated and then the scattering solution for each sample surface is obtained using a numerical method. Another issue is that the rough surfaces are the targets of infinite extent that must be truncated appropriately before the numerical scattering solution can be obtained. This can be done either using a tapered illumination or padding the sample surfaces with a tapered resistive sheet. The beam-width of the tapered illumination should be narrow, to suppress the edge contributions at large angles of incidence, which results in an inaccurate solution by excessive smoothing, especially for a relatively smooth random surface with a large correlation length [3]. The tapered illumination approximation is numerically inefficient, because the effective width of the sample surface contributing to the scattered field is much smaller than the width of the surface used in the numerical calculation. Application of the tapered resistive sheet is advantageous. In this method, a relatively small portion of the sample surface is used to suppress the edge currents. This improves the computation time and reduces the required memory [4]. The incident wave is a uniform plan wave. In the following, we have used this method along with the method of moments to calculate some corrections to the Fresnel coefficients for asphalt surfaces in millimeter-wave band. A time factor of $e^{-jwt}$ has been assumed and suppressed.

2. Rough Surface Resistive Loading

First consider a one dimensional perfect conducting rough surface $z = f(x)$ (Fig.1). For TE
case of incident wave, \( E' = \hat{g}e^{ik_0(x \sin \theta - z \cos \theta)} \), we have EFIE equation [5]:

\[
E'(r) = \frac{k_0Z_0}{4} \int J_s(r) H_0^\nu(k_0 |r - r'|) dl'
\]

(1)

\( J_s \) is the unknown induced current. For TM incident case \( H^t = \hat{g}e^{ik_0(x \sin \theta - z \cos \theta)} \), MFIE equation is:

\[
-\hat{n} \times H'(r) = -\frac{1}{2} J_s(r) + \frac{i}{2} \int J_s(r) \times \nabla H_0^\nu(k_0 |r - r'|) dl'
\]

(2)

where \( k_0 \) is the wavenumber, \( Z_0 \) is the intrinsic impedance of the free space, \( H_0^\nu \) is the zeroth-order Hankel Function of the first kind, \( \hat{n} \) is the unit normal vector of the surface, and \( r \) and \( r' \) are the position vectors of observation and source points on the rough surface, respectively. After discretizing a sample surface into sufficiently small cells, EFIE cast into matrix equations using the pulse-basis functions and point-matching technique. The induced surface current for the TE case, exhibits a known singularity near the edges of the surface, which has a significant effect on the back scattered field for normal incidence. However, this is not the case for the TM incidence wave for a one-dimensional perfectly conducting surface. To suppress the singular behavior of the current near the edges, a tapered resistive sheet is added to each end of the surface sample as shown in Fig.1. Using boundary conditions for resistive sheets according to [4] the integral equation for TE case becomes:

\[
E'(r) = R(r)J_s(r) + \frac{k_0Z_0}{4} \int J_s(r) H_0^\nu(k_0 |r - r'|) dl'
\]

(3)

where \( R \) is the resistivity of the surface. (3) applies over all of the surface and is cast into a matrix equation \([Z][I] = [V]\) using the point matching technique. While the elements of the excitation vector \([V]\) are given by

\[
v_n = \exp[ik_0(x \sin \theta - z \cos \theta)]
\]

(4)

for the incident uniform plane wave. Method of moments is used for finding \( J_s \) in (1) and (2) [6]. The resistivity profile plays an important role in suppression of the edge current. It is [4]:

\[
R(x) = \begin{cases} 
0 & \text{if } |x| \leq \frac{rL}{2} \\
Z_\varepsilon \left( \frac{rL/2 - |x|}{r2} \right)^4 & \text{if } \frac{rL}{2} \leq |x| \leq \frac{rL}{2} + r2
\end{cases}
\]

(5)

where \( rL \) is the width of the sample surface and \( r2 \) is the width of the resistive section. (see fig.1)

3. Dielectric Approximation with Resistive Sheet

In millimeter-wave band, the electromagnetic wave does not penetrate into the materials so much. It can be seen by the fact of the depth of penetration \( \delta (\delta = 1/\sqrt{\varepsilon \mu \sigma}) \). Also the resistive sheet is simply a thin dielectric layer, capable of supporting electric currents. The electric current on the sheet is proportional to the tangential electric field. This proportionality is represented by a complex resistivity \( Z_s \), given by [5]:

\[
Z_s = \frac{Z_0}{jk_0(\varepsilon - 1)}
\]

(6)

where \( \varepsilon \) and \( \varepsilon_c \) are thickness and the dielectric constant of the dielectric layer. A good choice for \( \varepsilon \) in millimeter-wave band is the fourfold of the depth of penetration, \( \delta \). Using the tapered resistive techniques we can derive the new EFIE equation (for TE case):

\[
E'(r) = (R(r) + Z_s J_s(r)) + \frac{k_0Z_0}{4} \int J_s(r) H_0^\nu(k_0 |r - r'|) dl'
\]

(7)

The equation has an extra \( Z_s J_s(r) \) term compared to (3). In fact by replacing the perfect conducting surface with dielectric, we must just modify the induced current by adding \( Z_s J_s(r) \) to the first part.

For the TM case, there is no need for resistive loading as explained before:

\[
Z_s J_s(r) = E'_{\alpha = \beta}(x) - \frac{k_0Z_0}{4} \int J_s(r)(1 + \frac{1}{k_0^2 \cdot \partial^2}) H_0^\nu(k_0 |r - r'|) dl'
\]

(8)

The behaviour of the asphalt surfaces on the propagation of the electromagnetic waves is an attractive topic of research and experiments. Different asphalt contents make different types of
scattering patterns. Credible data about the dielectric constants are extracted and used here. By considering Gaussian distribution for roughness, two parameters; rms height, $\sigma$, and correlation length, $l_c$, indicate the roughness. The order of roughness of the typical asphalt is reported in the literatures like [7, 8]. Table 1 shows the extracted parameters. The roughness parameters of these types of asphalt are in the region that the main part of the wave scattered in the specular direction [2]. (rms slope $\alpha = \sqrt{2}\sigma / l_c$ is smaller than 1).

<table>
<thead>
<tr>
<th>Asphalt surface type</th>
<th>$\sigma$ (mm)</th>
<th>$l_c$ (mm)</th>
<th>$\varepsilon_r$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type1 (semi-coarse asphalt concrete)</td>
<td>0.25 &lt; $\sigma$ &lt; 0.73</td>
<td>$\approx$ 2.2</td>
<td>2.5 + j0.6 ($\theta = 34\text{GHz}, T = 18\text{C}$)</td>
</tr>
<tr>
<td>Type2 (thin asphalt concrete)</td>
<td>0.25 &lt; $\sigma$ &lt; 2</td>
<td>$\approx$ 1.5</td>
<td></td>
</tr>
</tbody>
</table>

4. Correction Coefficients

The scattered fields can be obtained from the calculated currents. For TE case it is [6]:

$$ E_i(r') = \frac{2}{\pi kr} e^{j\theta}\varepsilon_r E_i^N, \quad E_i^N = \frac{k_0 Z_0}{4} \int_j \left[ 1 + \left( \frac{dz}{dx} \right)^2 \right] e^{-jl\sin^2\theta j \cos \theta j} dx $$ (9)

and for TM case:

$$ H_i(r') = \frac{2}{\pi kr} e^{j\theta}\varepsilon_r H_i^N, \quad H_i^N = \frac{-ik_0 Z_0}{4\cos \theta j} \int_j \left( \frac{dz}{dx} \right) \sin \theta j - \cos \theta j e^{-jl\sin^2\theta j \cos \theta j} dx $$ (10)

According to (9) and (10) we can use $E_i^N$ and $H_i^N$ parts for correcting. For two different cases: smooth and rough surfaces, two scattered wave in specular direction ($\theta = \theta$) can be calculated. $E_i^N$ and $H_i^N$ can be considered as correction factors for the amplitude and phase of Fresnel coefficients compared to the smooth surface case. For TE and TM case the Fresnel coefficients for infinite and smooth surface are:

$$ \Gamma_{TE} = \frac{E_i}{E_i} = \frac{\eta_2 \cos \theta - \sqrt{\eta_2^2 - \eta_1^2 \sin^2 \theta}}{\eta_2 \cos \theta + \sqrt{\eta_2^2 - \eta_1^2 \sin^2 \theta}} $$ (11)

$$ \Gamma_{TM} = \frac{H_i}{H_i} = \frac{\eta_1 \cos \theta - \sqrt{\eta_1^2 - \eta_2^2 \sin^2 \theta}}{\eta_1 \cos \theta + \sqrt{\eta_1^2 - \eta_2^2 \sin^2 \theta}} $$ (12)

where $\eta_1$ and $\eta_2$ are the intrinsic impedance of the two regions. Table 2 shows results for some incident angels. In this table, $\alpha_a$, $\alpha_p$ are the correction parameters. It means for $\Gamma$ defined in (11) and (12):

$$ \Gamma_{new} = \alpha_a e^{j\alpha_p} \Gamma $$ (13)

5. Results

The results for $\alpha_a$, $\alpha_p$ for all incident angles for TE and TM case and for two types of asphalt surfaces: slightly rough ($\sigma=0.5\text{mm}, l_c=2\text{mm}$) and very rough ($\sigma=1\text{mm}, l_c=1.5\text{mm}$) are obtained. As Fig. 3 shows, by increasing the roughness, $\alpha_a$ becomes smaller (wave scattered in other directions) compared to the slightly rough case (Fig. 2). Also $\alpha_p$ changes into bigger values. These results are attained by 40 realizations using the method of moments and Monte Carlo simulations for $rL = 2m$, $r2=2\lambda$.

<table>
<thead>
<tr>
<th>Asphalt surfaces</th>
<th>$\theta_i = 30^\circ$</th>
<th>$\theta_i = 60^\circ$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\alpha_a$</td>
<td>$\alpha_p$(deg)</td>
</tr>
<tr>
<td>Type1 ($\varepsilon_r = 2.5 + j0.6 @ f = 34\text{GHz}$)</td>
<td>0.693</td>
<td>-9.92$^\circ$</td>
</tr>
<tr>
<td>Very rough asphalt</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\sigma=1\text{mm}, l_c=1.5\text{mm}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Type2 ($\varepsilon_r = 2.5 + j0.6 @ f = 34\text{GHz}$)</td>
<td>0.932</td>
<td>-1.82$^\circ$</td>
</tr>
<tr>
<td>Slightly rough asphalt</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\sigma=0.5\text{mm}, l_c=2\text{mm}$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 2: amplitude and phase correction for slightly rough asphalt $\sigma = 0.5\text{mm}, lc = 2\text{mm}$

Figure 3: amplitude and phase correction for very rough asphalt $\sigma = 1\text{mm}, lc = 1.5\text{mm}$

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References