DEFINING AND COMPUTING THE DIFFUSE SCATTERING COEFFICIENT FOR BUILDING SURFACES

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ABSTRCT

Scattering from buildings into non-specular directions is dominated by windows and other architectural features that have a nearly periodic structure. Because these features have predominately vertical and horizontal structure, the directions of the scattered waves lie in Keller cones about the vertical and horizontal directions. Since the exact structure of individual building is not usually known fore inserting into ray codes, we consider each building to be one realization of a random process. Suitable averages of the scattered field lead to a single angle dependent scattering coefficient that is used for all building surface in the ray tracing code.

INTRODUCTION

Ray tracing based on geometric optics and the uniform theory of diffraction has been used to predict characteristics of the urban radio channel. It is thought that non-specular scattering from buildings can also affect the channel characteristics. In order to demonstrate these effects, researchers have assumed the scattering to obey Lambert's law [1-3], which is applicable to rough surfaces that are characterized by a random deviation of the surface height. Unfortunately this assumption does not seem to apply to scattering by a building facade whose windows and other architectural features have a more nearly periodic structure. For individual buildings, this periodic structure generates individual diffraction orders, rather than a continuum of diffuse scattered power. Measurements of the RADAR scattering from the faces of buildings has been measured at 11.2 GHz and compared with the predictions made by assuming the face to be a flat, conducting, rectangular plate [4]. For large buildings with windows, the measurements show a decrease of the peak in the specular direction by 8 - 12 dB, and scattering in non-specular directions that is strong than predicted by theory for a flat plate. However, from the limited measurements it appears that the scattering is concentrated about the specular direction, and therefore is not described by Lambert's law.

The horizontal size and spacing of windows and decorative masonry vary widely from building to building, although the vertical floor heights are more nearly equal. As a result the directions of propagation of the various diffraction orders for each building will be different in the horizontal wave number plane but about the same in the vertical wave number plane. Unfortunately, the databases of buildings used for ray tracing usually do not include detailed information, such as window spacing, for each building. In order to include non-specular scattering into a ray tracing code, we seek a simple description of the scattering that in some average sense is representative of all buildings.

Because the spacing is large compared to the wavelength, there are many diffraction orders that approximate a continuous scattering function. A single continuous function that represents an average over all of the buildings is found by treating each individual building as one realization of a random process. Using the vectorial Kirchhoff-Huygens' integral equation, the scattering pattern is found for each individual building realization. Monte Carlo techniques are then used to create a single statistical model that is used for scattering from all buildings. The resulting scattering law is a smoothed version of the diffraction orders. Since the scattering structures are either vertical or horizontal, scattering takes place primarily along directions such that either: 1) the wave number along the vertical direction is the same as that of the incident wave; or 2) the wave number along the horizontal direction is the same as that of the incident wave. These conditions are satisfied along two cones that are analogous to Keller cones in diffraction theory. The cones intersect along the direction of specular reflection. For normal incidence, the two cones open to become the vertical plane and the horizontal plane. As a result, the smoothed scattering functions exist only for directions lying on the two cones.

BUILDING FACADE MODEL

The generic building facade is showed in Figure 1. The main area of building facade is modeled as a smooth masonry plate with N periodically placed consecutive widows that are separated by a vertical masonry strip protruding from the main surface. The windows are assumed to have metallic frames. Adjacent windows in a group are separated by distance x_d . The window glass has dimensions $d_{xG} \times d_{yG}$, while the outer dimensions of the metallic frames are $d_{xF} \times d_{yF}$. Window glass and window frames are offset from the main brick surface by depth d_{zG} and d_{zF} respectively. The decorative structures are simply modeled as the vertical stripes of width d_{xS} that stick out by d_{zS} from the main brick surface. The periods, along x axis and y axis, are T_x and T_y respectively while the building size is $2L_x \times 2L_y$.

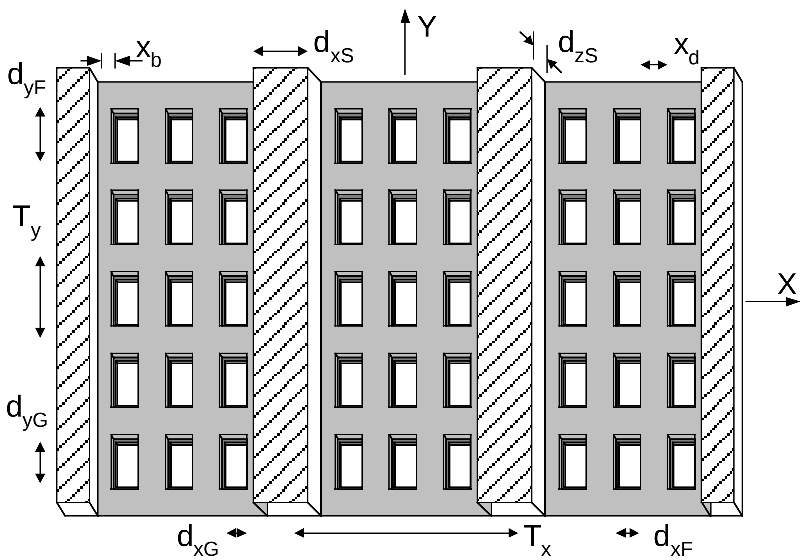

Figure 1 Model of building facade showing 3 consecutive windows within T_x (N = 3).

An oblique plane wave is assumed to illuminate the facade with electric field $\overline{E}_{inc}(\bar{r}')$ in the plane of the facade. The reflected field $\overline{E}_{ref}(\bar{r}')$ in the plane of the facade is assumed to be equal to incident field multiplied by the local reflection coefficient Γ_{TE} or Γ_{TM} for polarization perpendicular (TE) or parallel (TM) to plane of incidence [5]. In addition, it is necessary to account for the phase differences resulting from the depth of the reflecting plane. At the masonry wall the Fresnel reflection coefficients of dielectric half space with $\varepsilon_r = 6$ are used. The windows are modeled as the 2 layers of glass having $\varepsilon_r = 3$ with air in between. The thickness of each layer of glass is 0.3 cm, while the air layer is 1 cm. For simplicity, the metallic window frames are accounted simply using a reflection coefficient $\Gamma = -1$, even though their width may be on the order of $\lambda/2$. With the foregoing approximation for the reflected field just in front of the building surface, the scattered fields far from the building can be found using the vector Kirchhoff-Huygens integral equation.

MONTE CARLO EVALUATION OF THE SCATTERING COEFFICIENTS

Because of the complexity of the various building parameters, we have used Monte Carlo simulations to examine the mean value and standard deviation of the scattered fields. We start our analysis by creating a database of 50,000 realizations of building structures. Since each building is considered to be a realization of a random process, the scattered electric field for each realization is the sum of a mean field $\langle \overline{E}_s \rangle$ and a fluctuating part of the field $\overline{E}_{s,f}$

$$\overline{E}_s = \langle \overline{E}_s \rangle + \overline{E}_{s,f} \tag{1}$$

Here, $\langle \overline{E}_s \rangle$ is the ensemble average of the scattered electric field over all realizations. $\overline{E}_{s,f}$ is the fluctuation of the scattered field away from the mean field, so that $\langle \overline{E}_{s,f} \rangle = 0$ over all realizations.

The directional dependent scattering coefficient $\sigma(\theta,\phi)$ is defined such that when multiplied by the power incident on the building facade and integrated over the hemisphere it gives the ensemble average of the total scattered power. Thus

$$\sigma = \frac{\langle |\overline{E}_s|^2 \rangle 2\pi r^2}{|E_o|^2 A \cos(\pi - \theta_i)} \tag{2}$$

where $< \bullet >$ represents ensemble average and A is the area of the building. The angle of incidence as measured from the outward normal is $\pi - \theta_i$. The Scattering coefficient σ_{co} is similarly defined in terms of the magnitude squared of the mean field $|\langle \overline{E}_s \rangle|^2$. It is found that the scattering coefficient σ_{co} of the coherent fields is limited to the direction of specular reflection. The scattering coefficient for the non-coherent fields is found from the expression $\sigma_{nco} = \sigma - \sigma_{co}$.

COMPUTATIONAL RESULTS

A stem plot of the scattering coefficient σ_{nco} for $\theta_i = 150^o$, $\phi_i = 30^o$, and f = 900 MHz is shown in Figure 2. Since the value of σ_{nco} in many direction is negative when expressed in dB units, for plotting we have added 10 dB to σ_{nco}, and have not shown resulting values that are less than 0 dB. The axes $\sin\theta\cos\phi = k_x / k$ and $\sin\theta\sin\phi = k_y / k$ in Figure 2 represent the projection into (x,y) plane of the unit vector in the direction of propagation of the scattered wave, where the *x* axis is horizontal and parallel to the face of the building, while the *y* axis is vertical. The scattering coefficient of the incoherent fields has the greatest value in the direction of specular reflection, which is about 10 dB smaller than the scattering coefficient of the coherent field. Thus the non-coherent scattering coefficient in the specular direction can be neglected. It is also seen that the scattered power is concentrated in the neighborhood of the specular direction and is significant only in directions such that $k\sin\theta\sin\phi = k_{yi}$ or directions such that $k\sin\theta\cos\phi = k_{xi}$. The scattered power for $k\sin\theta\sin\phi = k_{yi}$ results from the (n,0) grating modes, while the scattered power for $k\sin\theta\cos\phi = k_{xi}$ results from the (0,m) grating modes. Similar results were found for other angles of incidence.

The total power carried by the scattered fields has been integrated over the hemisphere. Table 1 shows the fraction of the incident power that goes into the coherent (specular) scattered fields and the incoherent fields for various frequencies and directions of the incident wave. For the case when $\phi_i = 0^o$, the incident plane wave has TE polarization, the specular power increases monotonically as $\pi - \theta_i$ approaches 90^o (glancing incidence). The specular power is nearly independent of frequency since most of the building dimensions are large compared to wavelength. In contrast, the total non-specular power decreases as $\pi - \theta_i$ approaches 90^o, and has small variation with frequency. For the case when $\phi_i = 90^o$, the incident plane has TM polarization, so that the specular power decreases until the incident angle $(\pi - \theta_i)$ reaches the Brewster angle, after which it increases. The non-speular power for $\phi_i = 90^o$ decreases as $\pi - \theta_i$ approaches 90^o, just as in the case $\phi_i = 0^o$. It is easily shown that P_{co} / P_{inc} in (53) approaches unity as $\pi - \theta_i$ approaches 90^o. However, it is not obvious from (55) that P_{nco} / P_{inc} vanishes for glancing incidence.

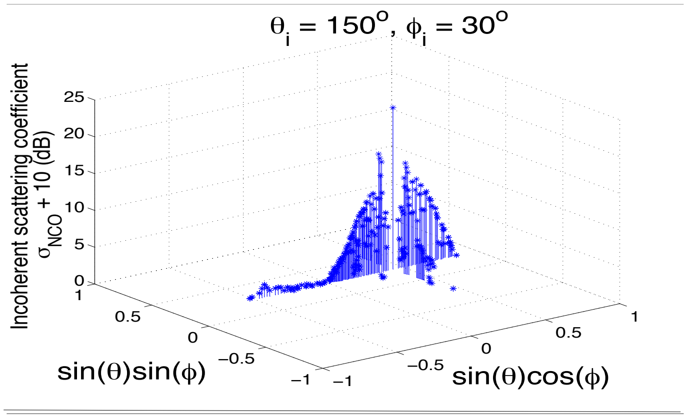

Figure 4 3D plot of scattering coefficients σ, σ_{co} and σ_{nco} with respect to the angles θ and ϕ as $A \rightarrow \infty$, $\theta_i = 150^o$, $\phi_i = 30^o$ for a frequency of 900 MHz. All plots are offset upwards by 10 dB.

Table 1 Percentage of the incident power secattered into specular and non-specular directions, for various angles of incidence and at frequencies 900 MHz - 4 GHz.

		$\phi_i = 0^o$		$\phi_i = 90^o$	
$\pi - \theta_i$	f	P_{co}	P_{nco}	P_{co}	P_{nco}
0°	900MHz	6.50%	17.77%	6.50%	17.77%
	1GHz	6.64%	17.63%	6.64%	17.63%
	2GHz	6.00%	23.22%	6.00%	23.63%
	3GHz	6.62%	23.84%	6.62%	23.84%
	4GHz	6.48%	23.39%	6.48%	23.39%
40°	900MHz	9.95%	14.61%	3.17%	6.44%
	1GHz	9.47%	15.29%	3.17%	6.79%
	2GHz	9.44%	18.13%	3.99%	7.96%
	3GHz	8.77%	21.19%	3.47%	9.75%
	4GHz	9.63%	20.13%	3.46%	10.00%
80°	900MHz	40.30%	5.65%	7.51%	0.51%
	1GHz	40.01%	5.43%	7.36%	0.55%
	2GHz	39.04%	4.71%	6.08%	0.98%
	3GHz	39.83%	4.62%	6.24%	1.23%
	4GHz	33.44%	4.50%	5.89%	1.36%

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