Experimental Study of Non-specular Wave Scattering from 3-D Building Surface Roughness

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Abstract: This paper presents experimental study for non-specular scattering from 3-D building surface roughness. Superresolution method was applied as an approach to handle signal parameters (DOA, TOA) of the individual incoming waves reflected from building surface roughness. In order to comprehend in detail the microscopic mechanisms of scattering, signal parameters are to be incorporated into the geometrical ray tracing. The results show that the multiple paths can be detected from many scatterers, such as ground, window glass, window frame, bricks surface, as well as directly from the transmitter. Most of the scattered waves arrives closely from specular directions. The calculation of glass and bricks reflection coefficient can be performed based on data measurement.

Keywords: Multipath Propagation, Reflection Coefficient, Building Surface, ESPRIT

1 Introduction

In urban area, buildings are the dominant scatterers determining propagation properties. The propagation prediction must reliably predict the influence of buildings and other obstructions. Microscopic scattering models are required to reflective properties of the environmental objects. If they are not adequately modeled, the propagation prediction can result in large errors. On the other hand, reflection, diffraction, and scattering of the electromagnetic waves on the building surfaces in the radio environment give rise to multipath propagation. Consequently, the transmitted signal reaches the receiver through different propagation paths. Multipath prediction on a building surface was conventionally based on an assumption that reflection from the surface has a substantial specular direction. However, the multipaths are also generated by scattered wave propagating in non-specular direction [1]. This paper presents experimental study for multipath characteristics of non-specular wave scattering from 3D building surface roughness based on the experimental results. The antenna element was scanned spatially to detect the directions of arrival (DOA) and the carrier frequency was scanned to obtain the times of arrival (TOA). Super resolution method was applied as an approach to handle the signal parameters (DOA, TOA) of the individual incoming waves scattered from building surface roughness. In order to comprehend the microscopic mechanism of scattering, the signal parameters are to be incorporated into the geometrical ray-tracing. The results show that the multiple path can be detected at many scatterers, such as ground, window’s glass, window’s frame, bricks surface, as well as directly from transmitter. The signal parameters of the arrival waves from the building scatterer have a tendency to be distributed around the angle of specular direction. It was also shown that the glass and bricks reflection coefficient were well bounded by the theoretical Fresnel reflection formulas for smooth surfaces and rough surface using the scattering correction of the modified Gaussian rough surface.

2 Environment Under Consideration

2.1 Equipment Arrangement

Equipment arrangement of the experiment is shown in figure 1. Transmitter and receiver antennas were linearly polarized rectangular microstrip antennas with ground plane size of 0.08 × 0.08m². The patch size was 0.0179 × 0.0179 m² on dielectric substrate with \(\varepsilon_r = 2.55\). Center frequency of the antennas is 4.95 GHz with bandwidth of 180 MHz. The wavelength was comparable with or smaller than depth of building surface roughness. The receiver antenna was shifted spatially by X-Y positioner to obtain field strength at each point in the scanning region. The X-Y positioner was used for automatically shifting. It has an accuracy of 1 mm. Both antennas were aligned to transmit and receive vertical polarization. The height of transmitter antenna was 1.9 m above from ground. The height of transmitter antenna was 2.7 m away in front of the building surface. The transfer function between transmitter and receiver antennas was measured using Vector Network Analyzer (VNA). The measurement of the frequency characteristics of transfer function and the shifting of receiver antenna are operated automatically using personal computer through the positioner controller and General Purpose Interface Bus (GPIB) to achieve high accuracy and easy measurement. The spatial scanning was configured to resemble an array antenna called synthesized uniform rectangular array (URA). Measurement points during the spatial
scanning were discretized for every 0.025 m toward the horizontal and vertical directions. The measurement was performed along 0.5 m in vertical direction. The middle of vertical direction scanning region is the same as height of transmitter antenna. Figure 2 illustrates the spatial scanning of the receiver antenna. It performs the measurement along 8.125 m to horizontal direction. The transmitter antenna is positioned facing toward the bricks surface of the building. The first vertical direction of measurement is 0.7 m away from the transmitter antenna, which corresponds to 10° incident angle in specular direction. Figure 3 shows profile of the building surface. The profile was taken from one of the buildings in Tokyo Institute of Technology. The surface of building has non-uniformity due to the roughness, as well as the wall surface. Position of the windows are made up of the sidewall, aluminum frames and plain glasses, which in principle are the building frames (aluminum), and wall (bricks). The surface of wall has periodical irregularity of five length-periods. One period of the surface equals 3.7 m. The windows are made up of the sidewall, aluminum frames and plain glasses, which in principle are the building roughness, as well as the wall surface. Position of the windows are elevated 1.5 m from the ground. The wall surface that has periodical roughness in both horizontal and vertical directions is made of 0.1 × 0.05 m² bricks with 0.01 m gap among each other.

2.2 Description of Data Measurement

Since the VNA measured transfer function of the cable and amplifier simultaneously, calibration of the data measurement system was required to eliminate the effect of equipment. Transfer function of the signal was measured using network analyzer with the frequency range of 4.85 to 5.05 GHz. The transfer function of the VNA can be expressed as follows,

\[ X(f) = H(f) \times G(f) \]  \hspace{1cm} (1)

where \( G(f) \) is transfer function of the cable, amplifier and antenna complex directivity at broadside, and \( H(f) \) is Friis free space transfer function, which is given as,

\[ H(f) = \frac{\lambda}{4\pi d} \exp\left(-\frac{2\pi f \lambda}{c}\right) \]  \hspace{1cm} (2)

where \( d \) is propagation path, and \( \lambda \) is wavelength. All measurement data resulted from this experiment were already calibrated by applying function \( G(f) \), which is obtained from the measurement using the transmitter and receiver antennas positioned face-to-face with 1 meter distance to each other in an open space.

In order to obtain the signal parameters of the arrival wave, measurement data are formulated. Suppose, it was assumed that the \( L \) waves impinging at the receiver that have three parameters of azimuth angle (\( \phi_l - \frac{\pi}{2} \)), elevation angle (\( \frac{\pi}{2} - \theta_l \)) and delay time \( \tau_l \), where \( 1 \leq \tau_l \leq \tau \). With X-Y positioner, the receiver antenna performs scanning spatially both in horizontal and vertical directions where the interval of the sampling points are \( \Delta_x \) and \( \Delta_y \). The numbers of sampling points are \( M_1 \) and \( M_2 \), respectively. At each sampling point, it carries out \( M_3 \) points of sampling over frequency where the interval of sampling is \( \Delta_f \) and the center frequency is \( f_c \). If the electrical lengths of the aperture of array \( \frac{\lambda}{4} M_1 \Delta_x \) and \( \frac{\lambda}{4} M_2 \Delta_y \), are both small enough to be assumed as constant within the bandwidth \( M_2 \Delta_f \), i.e, \( M_1 \Delta_x \cdot M_2 \Delta_f \ll c \), and \( M_2 \Delta_y \cdot M_3 \Delta_f \ll c \), where \( c \) is a light velocity, the measured data \( y_{k_1,k_2,k_3} \) can be expressed as,

\[ y_{k_1,k_2,k_3} = \sum_{l=1}^{L} \left[ s_l \prod_{r=1}^{3} e^{j \theta_l(r)} \right] + n_{k_1,k_2,k_3} \]  \hspace{1cm} (3)

where \( 0 \leq k_r \leq (M_r - 1) \) \( 1 \leq r \leq 3 \) indicates a location of each sampling point, \( n_{k_1,k_2,k_3} \) is a white Gaussian noise of zero mean, \( s_l \) is a complex amplitude of \( l^{th} \)
wave at a reference point and \( \mu_1^{(r)} \) is denoted by,
\[
\mu_1^{(1)} = \frac{2\pi}{\lambda_m} \Delta_y \sin(\phi_i - \frac{\pi}{2}) \cos(\frac{\pi}{2} - \phi_t) \tag{4}
\]
\[
\mu_1^{(2)} = \frac{2\pi}{\lambda_m} \Delta_y \sin(\frac{\pi}{2} - \phi_t) \tag{5}
\]
\[
\mu_1^{(3)} = 2\pi \Delta_f \tau_t \tag{6}
\]
These values include parameters of incident waves so that the target is to obtain these \( L \) sets of 3-D mode parameters. Then vectorization of data measurement can be defined as,
\[
z = [z_{1,1,1} z_{2,1,1} \cdots z_{M_1,1,1} z_{1,2,1} \cdots z_{M_1,M_2,1} z_{1,1,2} \cdots z_{M_1,M_2,M_3}] \in C,
\]
where \( s \in C^L \) and \( n \in C^M (M = M_1 M_2 M_3) \) are the complex amplitude vector and noise vector respectively. The multi-dimensional mode matrix \( A \in C^{M \times L} \) is generated by mode matrices that correspond to each parameter as
\[
A = A(\mu_1^{(3)}) \circ A(\mu_1^{(2)}) \circ A(\mu_1^{(1)}) \in C^{M \times L},
\]
where \( \circ \) denotes the kronecker product of each row of the matrices and
\[
A(\mu_r^{(r)}) = [a(\mu_1^{(r)}) \ldots a(\mu_L^{(r)})] \in C^{M_r \times L}
\]
\[
a(\mu_r^{(r)}) = [1 e^{-j\mu_r^{(r)}} \ldots e^{-j(M_r-1)\mu_r^{(r)}}]^T \in C^{M_r}
\]
The 3D unitary ESPRIT [3] was used to obtain the signal parameter. It is a super resolution direction finding method of the arrival wave. In physical terms, the ESPRIT is equivalent to finding out the parameters of arrival wave by phase difference between groups of uniformly positioned elements of sensor array. The ESPRIT array data had a size of \((10 \times 10) \) or \((0.25 \times 0.25) \) m\(^2\) for each of observation point. The arrival wave analyses were performed at 60 observation points with an interval of 0.125 m. Spatially 4 times and 7 times over frequency were applied for smoothing in the ESPRIT subspace.

3 Reflection Coefficient

3.1 Fresnel Reflection Formula for Semi-infinite Medium

The Fresnel models presented here assume the a homogeneous dielectric material is semi-infinite in extent. Although this is not true for real buildings, the dimensions of the building surface are sufficiently large that they may be approximated as infinite. The Fresnel reflection coefficient (\( \Gamma \)) relates the field reflected from infinite dielectric material to the incident field as,
\[
E_\parallel^i = \Gamma_\perp E_\perp^i \tag{11}
\]
where \( E_\perp^i \) and \( E_\parallel^i \) are the incident and reflected fields, respectively. The subscript \( \perp \) correspond to the vertical polarization, i.e. electric field is perpendicular to incidence plane. As the vertical polarization is used in the measurement, parallel polarization is not considered. The reflection coefficients determined by material properties, angle of incidence (\( \theta_t \)) and frequency, are given by
\[
\Gamma_\perp = \frac{\eta_2 \cos \phi_i - \eta_1 \cos \phi_t}{\eta_2 \cos \phi_i + \eta_1 \cos \phi_t},
\]
where the wave impedance \( (\eta_m) \) and the transmitted wave angle (\( \theta_t \)) are expressed as
\[
\eta_m = \sqrt{\frac{j\omega \mu_m}{\sigma_m + j\omega \epsilon_m}} (m = 1, 2),
\]
\[
\cos \phi_t = 1 - \left( \frac{k_1}{k_2} \right)^2 \sin^2 \phi_t,
\]
where \( \omega \) is the radian frequency and the wavenumbers \( (k_m) \) are
\[
k_m = \omega \sqrt{\mu_m \epsilon_m - \frac{j\mu_m \sigma_m}{\omega}}.
\]
The properties of each of the dielectric materials at the interface are characterized by their permittivity \( (\epsilon_m) \), magnetic permeability \( (\mu_m) \), and conductivity \( (\sigma_m) \).

3.2 Fresnel Reflection Formula for Finite Thickness Medium

Assume that the medium is flat with a finite thickness. The reflection coefficient \( R \) of the medium can be expressed as [2],
\[
R_\perp = \frac{1 - \exp(-2j\delta)}{1 - \Gamma_\perp^2 \exp(-2j\delta)} \Gamma_\perp, \tag{16}
\]
\[
\delta = \frac{2\pi d}{\lambda} \sqrt{\eta_m^2 - \sin^2 \phi_i}, \tag{17}
\]
where \( d \) is the thickness of the material and \( \Gamma_\perp \) is given by equation (12).

3.3 Gaussian Scattering Loss Factor

Approximation of reflection coefficient using Gaussian scattering loss factor, equation (12) can be expressed as,
\[
(\Gamma_\perp)_s = \rho_s \Gamma_\perp \tag{18}
\]
In case of rough surfaces, a scattering loss factor \( (\rho_s) \) can be derived to account for diminished energy in the specular direction of reflection. It gives better agreement with measured results [4] when given as,
\[
\rho_s = \exp \left[ -8 \left( \frac{\pi \sigma_h \cos \phi_i}{\lambda} \right)^2 \right] I_0 \left[ 8 \left( \frac{\pi \sigma_h \cos \phi_i}{\lambda} \right)^2 \right], \tag{19}
\]
where \( I_0(z) \) is the modified Bessel function of zeroth order, \( \sigma_h \) is the standard deviation of the surface height about the mean surface height in the first Fresnel zone of the illuminating antenna.
4 The Experimental Results

4.1 Directions of Arrival Wave Profiles

Figure 4 shows the ESPRIT results for azimuthal angle of the arrival wave. The line perpendicular to x-axis depicts the range of the azimuthal angle. Negative azimuthal angle means the wave is coming from the right-hand side of the receiver or source side (see figure 2).

The legends in figure 4 show the type of scatterers estimated from geometrical ray tracing. The number of icons on the vertical line corresponds to the number of multipath signals. Many scatterers can be detected such as from ground (solid circle), window glass & window frame (solid diamond), bricks-I surface (solid box), bricks-II surface (box) and directly from the transmitter (circle). The types of brick scatterer are distinguished between the bricks scatterer with the height between the lower and upper part of the windows, classified as bricks-I, and the bricks scatterer with the height below the windows, classified as bricks-II (see figure 1). The azimuthal angles of the building scattered are concentrated around specular direction. Maximum deviation of the angle is 20°. Figure 5 shows elevation angle of the arrival wave. It can be seen that the value of elevation angle is around 0° for those arrival waves coming from windows and bricks-I scatterers. It implies that most of the scattered waves from building surface arrives closely from specular directions. Figure 5 also shows diffraction effect from windows frame when the distance between transmitter and receiver antenna was 3.5-5 m or its specular point is located around the center of windows. It is found when the arrival waves have large elevation angle. For instance, in the case of the first observation point located 81.25 cm from the transmitter, six arrival waves were obtained, which consisted of two waves that directly arrives, one ground reflection and three waves from building surface. The reason why that the two waves were directly obtained is because the distance between the transmitter and receiver is relatively close. Therefore, the receiver gets the reflection from support equipment of the antenna. This kind of result was only obtained at the first and second observation points.

Figure 4: Azimuth Angle of Arrival Wave from Scatterers

Figure 5: Elevation Angle of Arrival Wave from Scatterers

Figure 6: Power and Delay Time of Arrival Wave for Direct and Ground Reflection

Figure 7: Power and Delay Time of Arrival Wave for Windows Scatterer
of experimental delay time and geometrical ray tracing time delay. In the case of bricks and glass scatterer, the values are larger in comparison to others caused by the occurrence of second order scattering.

### Table 1: Average Difference of experiment delay time with geometrical ray tracing delay time

<table>
<thead>
<tr>
<th>Type of Scatterer</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct</td>
<td>0.25 ns</td>
</tr>
<tr>
<td>Ground Reflection</td>
<td>0.38 ns</td>
</tr>
<tr>
<td>Bricks I</td>
<td>0.83 ns</td>
</tr>
<tr>
<td>Bricks II</td>
<td>0.51 ns</td>
</tr>
<tr>
<td>Glass</td>
<td>0.62 ns</td>
</tr>
</tbody>
</table>

4.3 Reflection Coefficient Estimation

The building surface reflection coefficient can be estimated using signal parameters of the arrival wave from specular direction. The measured reflection coefficients were compared with the theoretical Fresnel reflection formulas for smooth surfaces and rough surfaces using scattering correction of the modified Gaussian rough surface. Measurement loss can be expressed as follows:

\[
TL = RC + G_t + G_r + 20 \log_{10} \frac{\lambda}{4\pi d}
\]  

(20)

Where $TL$[dB] is total loss of the measurement, $RC$[dB] is reflection coefficient, $G_t$[dB] and $G_r$[dB], are directivities of the transmitter and the receiver antenna, respectively. Table 2 shows the estimated of surface roughness parameters and the measured dielectric properties of bricks, and glass surface. Averaged mean and standard deviation for surface height were obtained from surface height in the first fresnel zone for every arrival wave. Permittivity, permeability and conductivity of material were referred in [4].

### Table 2: Roughness and Dielectric Parameters for Building Surfaces

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Bricks</th>
<th>Glass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean. of Surf. Height (cm)</td>
<td>1.5</td>
<td>14.66</td>
</tr>
<tr>
<td>STD of Surf. Height $\sigma_h$ (cm)</td>
<td>0.267</td>
<td>2.31</td>
</tr>
<tr>
<td>Permittivity ($\epsilon_r$)</td>
<td>4.44</td>
<td>5.0</td>
</tr>
<tr>
<td>Permeability ($\mu_r$)</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Conductivity ($\sigma$) (S/m)</td>
<td>0.01</td>
<td>0.1</td>
</tr>
</tbody>
</table>

4.3.1 Glass Surface Reflection Coefficient

Figure 9 shows reflection coefficient of glass surface. These figures show that the reflection coefficients measurement of the glass surface are well bounded by the
smooth and rough surface reflection coefficient prediction. Smooth surface of the Fresnel reflection coefficient of infinite thickness are applied by equation (12). On the other hand, rough surface of the Fresnel reflection coefficients of infinite thickness and finite thickness are applied by substituting equation (12) and equation (16) to equation (18), respectively. Figure 9 also shows that rough surface of the Fresnel reflection coefficient of finite thickness yields better agreement with measured values compared with the other. Table 3 shows the average difference between predicted reflection coefficients and measured reflection coefficient.

Table 3: Average Difference of Prediction Reflection Coefficient for Glass and Bricks Surface

<table>
<thead>
<tr>
<th>Type</th>
<th>Smooth Ref. Inf.</th>
<th>Rough Inf.</th>
<th>Rough Fin.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass</td>
<td>-4.57 dB</td>
<td>-8.91 dB</td>
<td>-3.91 dB</td>
</tr>
<tr>
<td>Bricks</td>
<td>-5.90 dB</td>
<td>-6.87 dB</td>
<td>-3.79 dB</td>
</tr>
</tbody>
</table>

4.3.2 Bricks Surface Reflection Coefficient

In this section, bricks surface reflection coefficient will be discussed. The reflection coefficients of bricks surface are shown in figures 10. This figure explains that measured the reflection coefficients of the bricks surface are well bounded by the smooth and rough surfaces reflection coefficient prediction. The rough surface of the Fresnel reflection coefficient of finite thickness yields better agreement with the measured values when compared to each other. The averaged-differences for each predicted reflection coefficient with measured reflection coefficient are listed on table 3.

5 Conclusion

This paper has presented multiple paths characteristics of non-specular wave scattering from 3-D building surface roughness. The result shows that many scatterers can be detected such as from ground, window glass, window frame, bricks surface, as well as directly from transmitter. The parameters of the arrival waves from the building surface have a tendency to be around the angle of specular direction. Maximum deviation of the angle is 20° in azimuth and elevation angle. The delay time can be correctly estimated using geometrical ray tracing. The second order scattering was found when the characteristic of signal parameter are low power and large in delay time. The non-specular scattering from building surface are more dominated by window scatterers than brick scatterers. The glass and bricks reflection coefficient were well bounded by the theoretical Fresnel reflection formulas for smooth surfaces and rough surface using the scattering correction of the modified Gaussian rough surface. Moreover, the Fresnel reflection coefficient formula with thickness of the building surface and modified Gaussian scattering correction give better prediction in the glass and bricks surface measurement.

References