Estimation of Incoherent Scattered Field by Multiple Scatterers in Random Media

Dong-Wook Seo, Jae-Ho Lee, and Hyung Soo Lee

This paper proposes a method to estimate directly the incoherent scattered intensity and radar cross section (RCS) from the effective permittivity of a random media. The proposed method is derived from the original concept of incoherent scattering. The incoherent scattered field is expressed as a simple formula. Therefore, to reduce computation time, the proposed method can estimate the incoherent scattered intensity and RCS of a random media. To verify the potential of the proposed method for the desired applications, we conducted a Monte-Carlo analysis using the method of moments; we characterized the accuracy of the proposed method using the normalized mean square error (NMSE). In addition, several medium parameters, such as the density of scatterers and analysis volume, were studied to understand their effect on the scattering characteristics of a random media. The results of the Monte-Carlo analysis show good agreement with those of the proposed method, and the NMSE values of the proposed method and Monte-Carlo analysis are relatively small at less than 0.05.

Keywords: Random media, RCS, scattering, incoherent, coherent, composite.

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I. Introduction

In designing radar and remote sensing systems to detect objects buried in the ground or submerged within a chaff cloud, it is important to accurately grasp the characteristics of wave propagation in a random media. In the case of a chaff cloud, the atmosphere and chaff fibers can be modelled as the host material and inclusions of a random medium, respectively.

In particular, to enhance the detection capability of a radar system, it is essential that the clutter signature from the random media surrounding a target be removed. This clutter signal by the random media should be predicted and reflected in the radar system during the design phase [1]. Even in cases of obtaining synthetic aperture radar images, the image quality is highly dependent on the accurate estimation of the radar clutter signal by the random media [2].

The methods used to estimate the scattered field from a random medium can be classified as Monte-Carlo analysis and effective permittivity calculation. The former method uses multiple estimations of the wave scattering for a large number of inclusions through the use of low-frequency methods such as the method of moments (MoM) and the T-matrix [3]–[7]. The computed results are usually averaged over the realizations; therefore, this method provides an accurate solution through the use of numerical methods, despite suffering from an enormous amount of computation time and computer resources. The latter method, on the other hand, is the most commonly used one, and includes a mixing formula such as the Maxwell-Garnet, Polder-van Sante, or quasi-crystalline approximation with coherent potential [8]–[10]. The mixing formula is based on the concept of low frequency; thus, the analysis frequency is limited. In particular, this type of formula can be applied to calculate the effective permittivity of a random medium with inclusions, which have a formal shape, a uniformly random position, and orientations in all directions. The generalized equivalent conductor (GEC) method has recently been announced; this method can be used to determine the effective permittivity of a randomly oriented media with a probability distribution function [11]–[13]. The obtained effective permittivity of a random medium defines the characteristics of the medium. In tracing the history of an effective permittivity calculation, in most cases, the effective permittivity is only used to obtain the extinction coefficient (or absorption attenuation) and to estimate the attenuation of the field intensity [4], [5].

The scattered field generated by a random medium with random properties consists of a coherent field and an incoherent field. An incoherent field represents fluctuations in the scattered field, and is therefore usually considered trivial or negligible. In general radar systems, the signatures reflected by a target are expressed as the radar cross section (RCS). The average RCS of a random medium is the sum of the coherent and incoherent RCSs due to the coherent and incoherent fields, respectively [14]. From the point of the average RCS, consequently, an incoherent field is also a significant factor that cannot be ignored.

To evaluate an incoherent scattered field, in a conventional random media field, the effective propagation constant and amplitude of the coherent plane wave are gained by solving an integral equation; these values are used to construct a coherent transmitted field, which is used to obtain a coherent scattered field. The incoherent scattered intensity (squared amplitude) is then obtained through a distorted Born approximation [15]. Because the series of procedures for the determination of the incoherent scattered field uses the spherical vector function of the T-matrix approach, obtaining unknown coefficients is cumbersome, and the incoherent scattered intensity can only be obtained by using a coherent transmitted field.

The method for estimating the coherent field from the effective permittivity can be used to provide a clear prediction, which has been verified by other analysis methods [11], [14]. Few studies on the determination of an incoherent field using the effective permittivity can be found in the literature. In [14] and [16], calculations of the incoherent scattered intensity from the effective permittivity were conducted. However, the calculations were not derived from electromagnetic theory, and the derivation principles were unclear; moreover, some errors in the calculation results can be observed.

In [17], the calculation of the effective permittivity from both an incoherent and a coherent scattered field is proposed. Based on this method, the present paper proposes a direct method for estimating the incoherent scattered intensity and RCS from the effective permittivity, which is obtained using the GEC method. In comparison with the results of [14] and [16], the results of the proposed method are derived from the original concept of incoherent scattering. Additionally, since the proposed method uses the effective permittivity estimated with the GEC method, it can estimate the incoherent RCS of scatterers with arbitrary orientation distribution. The potential of the proposed method is verified through comparison with the results from a Monte-Carlo analysis using the MoM. To investigate the characteristics of coherent and incoherent scattering, we also estimate the RCS of a random medium for various inclusion densities.

The remainder of this paper is organized as follows. In Section II, the coherent, incoherent, and average RCSs of a random medium are briefly explained, and the proposed approach for directly calculating an incoherent RCS is presented. The results of the RCS with respect to the depths of a random medium are shown in Section III, using the orientation distribution and the inclusion density. Finally, Section IV summarizes this work and provides some concluding remarks.

II. Formulations

1. Review of Scattered Field and Average RCS in Random Media

Consider multiple identical scatterers distributed randomly and oriented arbitrarily within volume V of a free space, as shown in Fig. 1. Volume V is regarded as a random medium owing to the random characteristics of the multiple scatterers. The magnitude and phase of the scattered field of the random medium fluctuate randomly in space and time; hence, the scattered field is a function of position r, time t, and the number of realizations m. For a total of M realizations, the scattered field by the mth realization is represented by the sum of the coherent and incoherent scattered fields, which can be given as follows:

$$E_{\mathrm{s}}^{(m)} = E_{\mathrm{coh}} + E_{\mathrm{incoh}}^{(m)}, \tag{1}$$

where the coherent scattered field, E_{coh}, is the average scattered field for each realization. That is, the coherent scattered field is irrelevant to any particular realization. On the other hand, the incoherent scattered field, $E_{\mathrm{incoh}}^{(m)}$, indicates fluctuations, and its sum is zero. Therefore, the coherent and incoherent scattered fields can be expressed as

$$E_{\mathrm{coh}} = \frac{1}{M}\sum_{m=1}^{M} E_{\mathrm{s}}^{(m)}, \tag{2}$$

$$\sum_{m=1}^{M} E_{\mathrm{incoh}}^{(m)} = 0. \tag{3}$$

If the scatterers are totally random, then the scattered field

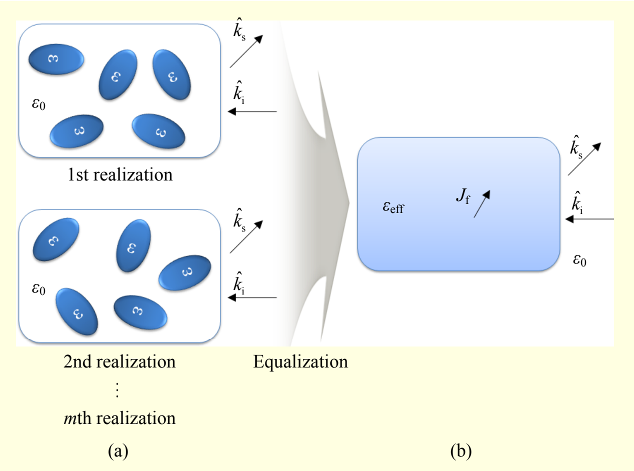

Fig. 1. Equalization model of random medium: (a) realizations of random medium with multiple identical scatterers and (b) homogeneous media with volume current and effective permittivity.

will have nearly incoherent components, and the coherent scattered field will be diminished. The more the scatterers tend toward having an arbitrary orientation or position, the more the coherent scattered field increases. Based on the same principle, in the line-of-sight problem, the coherent scattered field is almost the only field in the proximity of the transmitter. However, at a farther distance from the transmitter, there is a strengthening of the incoherent scattered field [18].

The coherent scattered field depends on the size and shape of the entire analysis volume containing multiple scatterers, and can be calculated by assuming the entire analysis volume as a homogeneous material with an effective permittivity. On the other hand, an incoherent scattered field is caused by fluctuations in the dielectric constant between the inclusions/spaces and the background of the random medium. For a different arrangement of the scatterers for each realization, a fluctuating scattered field arises from spatial variations in the dielectric constant between the inclusions/spaces and the background [17].

When a unit plane wave is incident on the random medium, the instantaneous RCS of the mth realization becomes [14]

$$\begin{aligned}\sigma^{(m)} &= 4\pi E_{\mathrm{s}}^{(m)} E_{\mathrm{s}}^{(m)*} \\ &= 4\pi E_{\mathrm{coh}} E_{\mathrm{coh}}^{*} \\ &\quad + 4\pi\left[E_{\mathrm{coh}} E_{\mathrm{coh}}^{(m)*} + E_{\mathrm{incoh}}^{(m)} E_{\mathrm{coh}}^{*} + \left|E_{\mathrm{incoh}}^{(m)}\right|^2\right],\end{aligned} \tag{4}$$

where the first term on the right-hand side arises from the coherent scattered field, and the second term arises from both the coherent and incoherent scattered fields. For a total of M realizations, the average RCS is therefore given by

$$\begin{aligned}\langle\sigma\rangle &= 4\pi\left\langle\left|E_{\mathrm{s}}^{(m)}\right|^2\right\rangle = 4\pi\left|E_{\mathrm{coh}}\right|^2 + 4\pi\left\langle\left|E_{\mathrm{incoh}}^{(m)}\right|^2\right\rangle \\ &= \sigma_{\mathrm{coh}} + \sigma_{\mathrm{incoh}}.\end{aligned} \tag{5}$$

Contrary to the instantaneous RCS, the average RCS is expressed as the sum of the coherent and incoherent RCSs. To obtain the average RCS of a random medium, the coherent scattered field and incoherent scattered field are both needed.

2. Formulation of Incoherent Method

As mentioned above, the fluctuations in a scattered field are caused by spatial variations of the dielectric constant between the inclusions/spaces $\varepsilon(x, y, z)$ and the background, $\varepsilon_{\mathrm{eff}}$. Such variations operate as the volume current density, J_{f}. Thus, the wave equation can be summarized as follows [17]:

$$\begin{aligned}\nabla\times\nabla\times\vec{E}_1 - \kappa_{\mathrm{eff}}^2\vec{E}_1 &= \omega^2\mu\left(\varepsilon-\varepsilon_{\mathrm{eff}}\right)\vec{E}_1, \\ &= \mathrm{j}\omega\mu\vec{J}_{\mathrm{f}},\end{aligned} \tag{6}$$

where $\vec{E}_1$ is the electric field in the boundary enclosing the random medium, and μ and κ_{eff} denote the permeability of the equivalent volume and extinction coefficient of the incoherent field, respectively. Additionally, ε and $\varepsilon_{\mathrm{eff}}$ are the permittivity of the inclusions/space and the effective permittivity of the equivalent homogeneous volume, respectively. The volume current density J_{f} is the current density induced by the incident field on the equivalent volume. That is, J_{f} can be considered an equivalent current source that generates the incoherent scattered field. If the effective permittivity of the random medium is defined using a non-dimensional parameter, such as s, then we have

$$\varepsilon_{\mathrm{eff}} = \varepsilon_0\left(1-\mathrm{j}s\right). \tag{7}$$

Then, the volume current density J_{f} becomes

$$\vec{J}_{\mathrm{f}} = \mathrm{j}\omega\left(\varepsilon_{\mathrm{eff}}-\varepsilon_0\right)\vec{E}_1 = \omega\varepsilon_0 s\vec{E}_1. \tag{8}$$

The magnetic vector potential, $\vec{A}$, based on the volume current density J_{f}, is

$$\vec{A} = \frac{\mu}{4\pi}\iiint_V \vec{J}_{\mathrm{f}}\left(x',y',z'\right)\frac{e^{-\mathrm{j}kR}}{R}\mathrm{d}v', \tag{9}$$

where R is the distance between the source and the observation point. We assume that the observation point is in the far zone from the target, which is located at the origin of the coordinate system. Using this approximation in the integrals for vector potential $\vec{A}$, the incoherent scattered field originating from volume current density J_{f} can be written as

$$\begin{aligned}E_{\mathrm{incoh}}^{\mathrm{s}} &= \frac{-\mathrm{j}\omega\mu}{4\pi r}e^{-\mathrm{j}k_0 r} \\ &\quad\times\iiint_V\left[\vec{J}_{\mathrm{f}}\left(x',y',z'\right)-\left(\vec{J}_{\mathrm{f}}\left(x',y',z'\right)\cdot\hat{r}\right)\hat{r}\right]e^{-\mathrm{j}k\vec{r}'\cdot\hat{r}}\,\mathrm{d}v' \\ &\quad+O\left(\frac{1}{r^2}\right).\end{aligned} \tag{10}$$

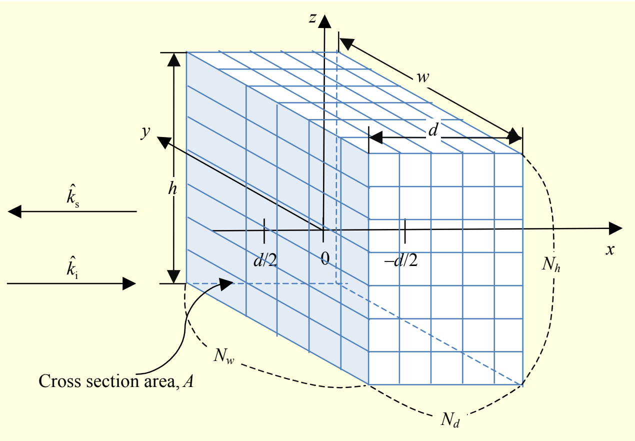

Fig. 2. Geometry of equalized homogeneous media of $w \times d \times h$ (m^3) with N sub-blocks.

Consider that an equivalent homogeneous volume of width w, depth d, and thickness h is illuminated by a uniform plane wave, as shown in Fig. 2. The media is bounded on both sides by air. The propagation direction of the incident plane wave and the direction of the observation point are assumed to be parallel to the x-axis and are defined by $\hat{k}_i = \hat{x}$ and $\hat{k}_s = -\hat{x}$, respectively. Thus, the incident field is given by

$$E^{i} = E_0 \exp(-\mathrm{j}k_1 x). \tag{11}$$

The ratio between the wave number of the effective medium and that of free space, k_1/k_0, can be made as close to $1 - \mathrm{j}s/2$ as desired by making the non-dimensional parameter s sufficiently close to zero [16]. Substituting (8) and (11) into (10), we obtain

$$\begin{aligned} E^{s}_{\text{incoh}} &\approx \frac{-\mathrm{j}\omega\mu e^{-\mathrm{j}k_0 r}}{4\pi r}\iiint_V \left(\omega\varepsilon s E_0 e^{-\mathrm{j}k_1 x'}\right)\cdot e^{-\mathrm{j}k_0 x'}\,\mathrm{d}v' \\ &= \frac{-\mathrm{j}k_0^2 e^{-\mathrm{j}k_0 x} s}{4\pi x}\int_0^h\int_0^w\int_0^d E_0 \cdot e^{-\mathrm{j}(k_1+k_0)x'}\,\mathrm{d}v' \\ &= \frac{-\mathrm{j}k_0^2 e^{-\mathrm{j}k_0 x} s}{4\pi x}\int_0^h\int_0^w\int_0^d E_0 \cdot e^{-k_0\left(2\mathrm{j}+\frac{s}{2}\right)x'}\,\mathrm{d}v'. \end{aligned} \tag{12}$$

We suppose that a number of scatterers, N, divide the equivalent homogeneous volume into N_d, N_w, and N_h in the x-, y-, and z-directions, as shown in Fig. 2, such that N equals the total number of total subvolumes ($N_d \times N_w \times N_h$). The integral in (12) can be expressed in the following Riemann summation form:

$$E^{s}_{\text{incoh}} = -\frac{\mathrm{j}k_0^2 e^{-\mathrm{j}k_0 x} s}{4\pi x}\Delta x\Delta y\Delta z\sum_{n_h=1}^{N_h}\sum_{n_w=1}^{N_w}\sum_{n_d=1}^{N_d} e^{-k_0\left(2\mathrm{j}+\frac{s}{2}\right)m\Delta x}, \tag{13}$$

where Δx, Δy, and Δz are d/N_d, w/N_w, and h/N_h, respectively. In addition, $\Delta x\Delta y\Delta z = V/N$ is the reciprocal of the scatterers' density. Then, (13) becomes

$$E^{s}_{\text{incoh}} = -\frac{\mathrm{j}k_0^2 e^{\mathrm{j}kx} s}{4\pi x\rho}\left(N_h \cdot N_w\right)\sum_{n_d=1}^{N_d} e^{-k_0\left(2\mathrm{j}+\frac{s}{2}\right)m\Delta x}. \tag{14}$$

Substituting (14) into (5) leads us to the following incoherent RCS:

$$\sigma_{\text{incoh}} = \frac{2\pi^2}{\lambda}\frac{sA}{\rho}\left(1-e^{-k_0 sd}\right). \tag{15}$$

Therefore, (15) provides the incoherent RCS of a random medium; this incoherent RCS is defined by the shape of an analysis volume, effective permittivity, and inclusion density at the desired frequency. Equation (15) does not have terms related to the inclusions; the properties of inclusions is reflected in the effective permittivity of the random medium.

III. Simulation Results

To validate the proposed method, simulation results are compared with the incoherent RCS obtained from the Monte-Carlo analysis using the MoM with 50 realizations, employing MATLAB R2013b with a 2.83 GHz Quad CPU and an 8 GB RAM PC. The coherent RCS, meanwhile, is obtained from the GEC method [11] and the Monte-Carlo analysis. The multiple identical scatterers are assumed to be thin, perfectly conducting wire of a half-wavelength in length. These scatterers are also assumed to be uniformly distributed in volume V ($w \times d \times h$), as shown in Fig. 2. The scatterers have two orientation distributions — a uniformly random orientation for all directions and a horizontal orientation (parallel to the horizontal plane). The cross-sectional area of the random medium is fixed as $A = 10\lambda \times 10\lambda$, and its depth, d, varies from 0.1λ to 4λ. Although the total volume V varies, the density of the scatterers is kept at 1.0 [no./λ^3]; thus, the total number of scatterers varies.

As mentioned before, each realization of the Monte-Carlo analysis uses the MoM. For the mth realization, the result when using the MoM is the scattered field of (1). Thus, by substituting the mth scattered field (1) into (4), the instantaneous RCS is obtained for the mth realization. After all realizations, the average RCS is calculated by averaging all the instantaneous RCSs. The coherent field is also calculated by averaging the scattered field over a total of M realizations, as described in (2); then, the coherent RCS is obtained using (5). Therefore, the incoherent RCS can be obtained by subtracting the coherent RCS from the average RCS.

Figures 3 and 4 show the backscattering incoherent, coherent, and average RCSs of the random medium normalized to λ_0^2, in terms of the resonance frequency of the scatterers as a function of the depth of the slab. In terms of the values of peak, null, and level, the proposed method shows good agreement with the Monte-Carlo analysis performed using the MoM.

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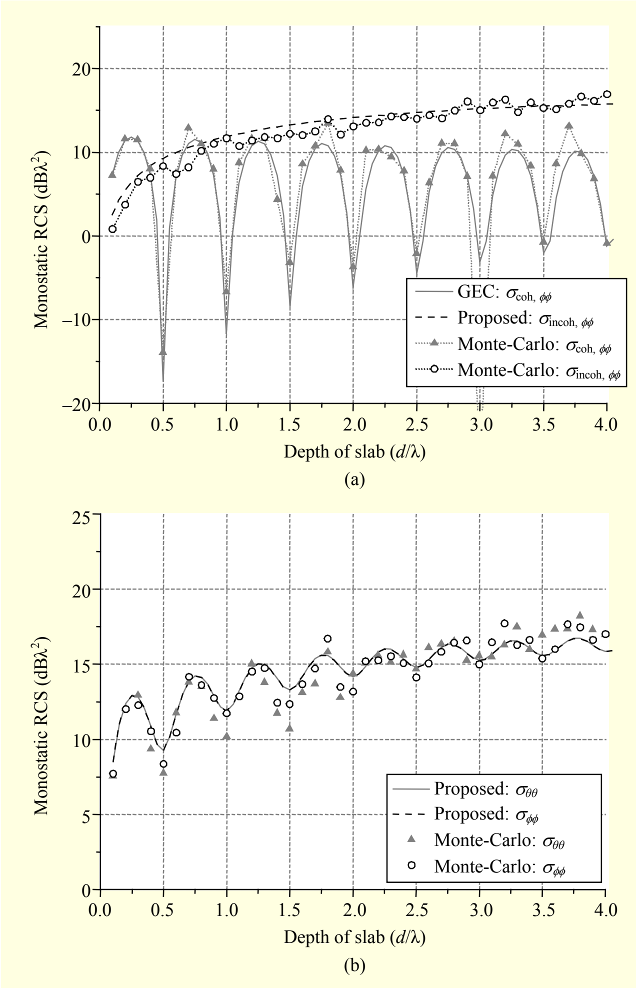

Fig. 3. Monostatic RCS of scatterers with uniform orientation: (a) incoherent RCS and coherent RCS, and (b) average RCS.

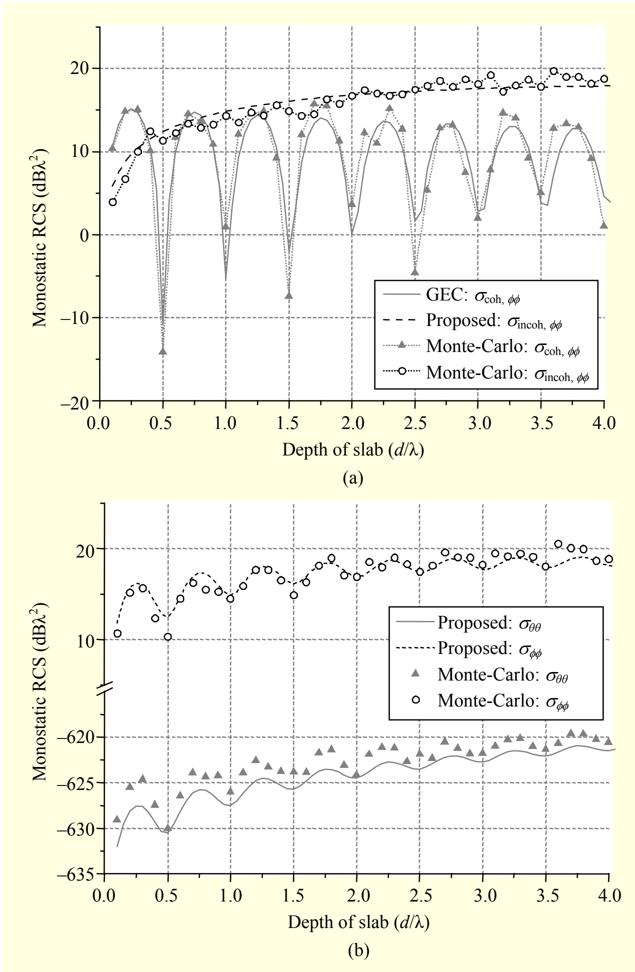

Fig. 4. Monostatic RCS of scatterers with horizontal orientation: (a) coherent RCS and incoherent RCS, and (b) average RCS.

The coherent RCSs shown in Figs. 3 and 4 have nulls at points where the depth of media are multiple half-wavelengths, but maintain constant peak value. When a plane wave is incident normally on the random medium, the phase difference between the fields reflected from the front and rear of the equivalent media generates nulls and peaks. These patterns mean that the coherent RCS can be calculated from the equivalent homogeneous medium of the random medium, as mentioned earlier. On the other hand, as the number of scatterers increases, the incoherent RCS also increases. The incoherent RCS even becomes larger than the coherent RCS when there is an increase of the depth of the equivalent homogeneous medium. Therefore, as illustrated in Figs. 3 and 4, the average RCS, which is the sum of the coherent and incoherent RCSs, has an increasing value with oscillating form as a function of depth.

The scatterers in Fig. 3 orient uniformly in all directions, whereas those in Fig. 4 have a horizontal orientation. In other words, all scatterers are parallel to the *xy*-plane. For a uniformly oriented distribution, the $\hat{\theta}\hat{\theta}$ -polarization RCS is equal to the $\hat{\phi}\hat{\phi}$ -polarization RCS. Otherwise, for a perfectly horizontal orientation, the $\hat{\phi}\hat{\phi}$ -polarization average, coherent, and incoherent RCS are about 3 dB larger than those of the scatterers with a uniform orientation, and the $\hat{\theta}\hat{\theta}$ -polarization RCS has a very small level of less than –600 dBλ^2. These results can be also confirmed through the relative effective permittivity of Table 1. Similar to the monostatic RCS, $\varepsilon_{\theta\theta}$ is identical to $\varepsilon_{\phi\phi}$ for a uniform orientation. In the case of horizontal orientation, $\varepsilon_{\theta\theta}$ of 1.0-j0.0 means that the scatterers have no electrical effect on a θ-polarized wave.

To illustrate the differences between the calculated RCSs and the reference RCSs, the normalized mean square error (NMSE) is often used; it can be defined as

$$\mathrm{NMSE} = \frac{\sum_{n=1}^{N}\left|\mathrm{RCS}_n^{\mathrm{p}} - \mathrm{RCS}_n^{\mathrm{r}}\right|^2}{\sum_{n=1}^{N}\left|\mathrm{RCS}_n^{\mathrm{r}}\right|^2}, \tag{16}$$

Table 1. Relative effective permittivity with respect to wave polarization and orientation of scatterers.

	Wave polarization	
	$\varepsilon_{\theta\theta}$ ($\hat{\theta}\hat{\theta}$-pol.)	$\varepsilon_{\phi\phi}$ ($\hat{\phi}\hat{\phi}$-pol.)
Uniform orientation	0.9892 - j0.0195	0.9892 - j0.0194
Horizontal orientation	1.0 - j0.0	0.9842 - j0.0285

Table 2. NMSE between proposed method and Monte-Carlo analysis for uniform orientation distribution.

Method	Monte-Carlo results as reference	
	Type	NMSE
Proposed	Incoherent RCS	0.0331
GEC	Coherent RCS	0.1172
Proposed & GEC	Average RCS	0.0277

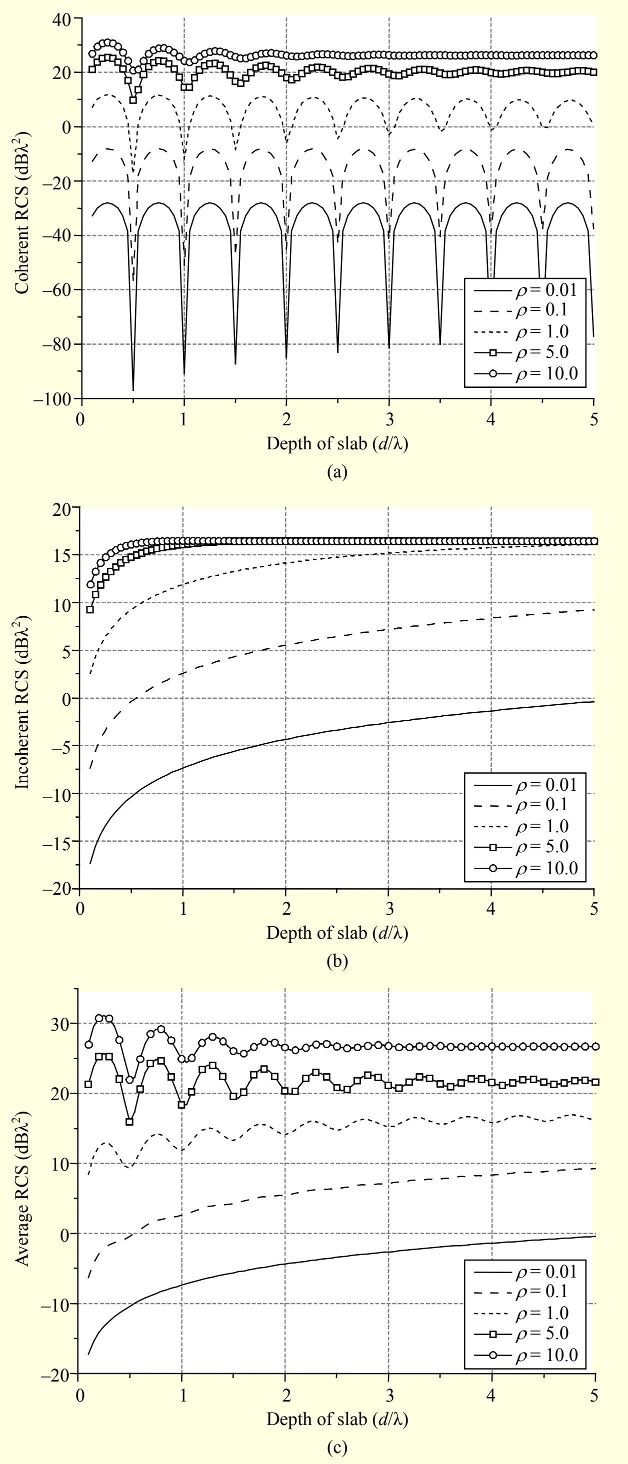

Fig. 5. Monostatic RCS of scatterers with uniform orientation with respect to inclusion density: (a) coherent, (b) incoherent, and (c) average RCS.

where $\mathrm{RCS}_n^{\mathrm{p}}$ and $\mathrm{RCS}_n^{\mathrm{r}}$ are the linear scaled RCS estimated using the proposed method and the Monte-Carlo analysis, respectively, at the nth depth. Table 2 shows the NMSE for the proposed method using the results of the Monte-Carlo analysis as the reference values for uniformly oriented scatterers. It can be seen that the proposed method has a very small NMSE and provides a very accurate value. In particular, the proposed method provides a more accurate solution than does the GEC method in terms of the NMSE.

Figure 5 shows the backscattering coherent, incoherent, and average RCSs for several inclusion densities. The coherent RCS is calculated using an equivalent homogeneous medium, and is significantly affected by the effective permittivity, which is mainly dependent on the inclusion density. The peak values as a function of the inclusion density vary from –30 dBλ^2 to 30 dBλ^2. When the depth of the medium is increased, the peak level decreases slightly and the null level increases slightly. The cause of these behaviors is the attenuation of the reflected field after multiple bounces within the equivalent homogeneous medium. In the same vein, the attenuation in a random medium with a high inclusion density also increases. Therefore, the ripples of the coherent RCS decrease with increases in the depth and inclusion density. These tendencies are clearly confirmed at a higher density.

The incoherent RCS curves of Fig. 5(b) are asymptotic, not oscillatory. For a higher inclusion density or greater depth, the incoherent RCS has a tendency to rapidly converge to a certain level, as indicated in (15).

When the number of scatterers increases, spaces with difference in the effective permittivity and the scatterers' permittivity widen. This situation implies an increase in the incoherent scattering. If the number of scatterers is even greater, the wider space causes a difference between the effective permittivity and the scatterers' permittivity. Owing to the high

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effective permittivity, the difference is lowered. This means a convergence at a particular level. This convergence can be traced to the phenomenon in which a low current is induced to scatterers with small gaps between them. In other words, the problem is whether the predominant scattering is generated by the inter-scatterer coupling or the shielding effect.

From the pattern of the average RCS in Fig. 5(c), we can ascertain the dominant term with respect to the scatterer density. When the scatterer density is less than 1.0 [no./λ^3], the incoherent RCS is dominant. On the contrary, when the scatterer density is larger than 1.0 [no./λ^3], the coherent RCS is dominant. The reference density that determines the dominant factor depends on the shape, orientation, and material properties of the scatterers.

IV. Conclusion

This paper proposed a method for calculating the incoherent scattered intensity and RCS of random media. The proposed method was expressed as a simple formula, which can easily and quickly calculate the incoherent RCS and scattered intensity without multiple realization or complex calculation procedures. Therefore, it is expected that this method will be very useful in scattering analysis and RCS prediction of random media. To verify the proposed method, we compared our results to results obtained using a Monte-Carlo analysis with the MoM. The proposed method is in good agreement with the Monte-Carlo analysis. In addition, because both the coherent RCS and the incoherent RCS are directly estimated based on the effective permittivity of a random medium, the proposed method is efficient in comparison with conventional methods, such as the T-matrix and the radiative transfer method. The proposed method can also be applied to inclusions with not only a fiber shape but also various other shapes. Additionally, the proposed method can be also expanded to multi-environments in which the densities of scatterers are varying spatially, if the effective permittivity and analysis geometry are known.

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