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Effects of backscattering enhancement considering multiple scattering in rain on MMW radar performance

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The theory of the second order backscattering enhancement in discrete random medium is discussed in this paper. The effects of rainfall on millimeter wave (MMW) radar performance are analysed based on Mie theory, Monte Carlo (MC) simulation and backscattering enhancement theory, at 35 and 95 GHz, respectively. The rain attenuation considering the raindrops multiple scattering is introduced into the estimation of the signal to clutter ratios (S/C) and the clutter to noise ratios (C/N) for MMW radar. The S/C and C/N are calculated by means of the backscattering enhancement, Mie theory and MC simulation method, respectively under the condition of rain environment. The results show that the S/C obtained by backscattering enhancement theory is smaller than the results by Mie and MC. The C/N by backscattering enhancement is greater than the results by other. The Mie and MC methods do not consider backscatter enhancement, underestimate the effect of raindrops scattering on radar performance. Hence, it is shown that the attenuation and backscattering enhancement induced by raindrops multiple scattering are necessarily taken into account for the performance estimation of MMW radar operating in heavy rainfall environment.

Keywords: Millimeter wave radar performance, Rainfall, Multiple scattering, Backscattering enhancement

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1 Introduction

The millimeter wave (MMW) radars have many advantages and are applied widely for target detection, control, remote sensing and so on, due to the fact that the range, angle and velocity resolution of MMW radar systems is better than the analogous centimeter systems. However, above 10 GHz microwave band, especially above 30 GHz millimeter wave band, the scattering and absorption induced by rainfall are severe. At higher frequency, the severer attenuation is induced by rainfall[1-3]. The rain attenuation and the volume clutter from raindrops scattering result in the MMW radar performance deterioration[4], especially in heavy rainfall region, such as tropical region.

The multiple scattering in rain may not be ignored for stronger rain at MMW band. Therefore, it is important to examine how the multiple scattering of raindrops is responsible for backscattering (BS) enhancement. There are many papers in which the influence of the propagation effects on radar operation is discussed[4-8], but the papers on the combination of rain attenuation with volume clutter considering the multiple scattering are comparatively sparse.

In MMW band, the multiple scattering in randomly distributed particles was studied by theoretical and experimental methods[9-12]. The backscattering enhancement, based on the theory of multiple scattering, was revealed and observed in laboratory controlled optical experiments and a sharp peak of small but finite angular width was exhibited in backscattering from a random distribution of discrete scatterers[9]. Kobayashia ***et al.*** pointed out the existence of backscattering enhancement in rainfall and studied a method to calculate the backscattering[13]. Backscattering enhancement has attracted attention because it is not predicted by conventional radiative transfer theory, which has applied extensively to propagation, scattering, radar remote sensing, condensed matter physics[14,15]. In the theoretical treatment of the backscattering enhancement from random discrete scatterers, a second-order theory in conjunction with a plane wave incidence is commonly used[9,16]. However, actual radar waves have a spherical wavefront and a finite beam width, hence, the theory was very recently extended to the case of finite beam width, and several interesting results have been obtained that includes the effect of foot print size on the magnitude of enhancement[13]. A computer simulation of enhanced backscattering from randomly distributed spherical scatterers at 30 GHz is presented[17]. The results correspond to the measurement.

In this paper, the attenuation considering raindrops multiple scattering is estimated by Monte Carlo (MC) simulation method. The rain volume clutter considering the backscattering enhancement induced by raindrops multiple scattering is studied based on multiple scattering and backscattering enhancement theory at MMW band. The influences of the rain clutter considering the raindrops multiple scattering on millimeter wave pulse radar performance are analyzed in the case of finite beam width and considering antenna non-uniform radiation. It leads to more accurate estimation of the target detectability and range resolution for MMW radar in application to rain weather.

2 Backscattering enhancement theory

Two main contributions of multiple scattering to reflective intensity in random discrete media were revealed: one is the conventional multiple scattering called ladder term, and the other called cross term, is the contribution from interference of two ray paths mutually satisfying the condition of time reversal paths.

A first possible pair is constituted of a field E_A and its self-complex-conjugate field E^*_A in the case of second order scattering (Fig. 1). It can be represented by the second order ladder term, which corresponds to the conventional second-order scattering derived by the radiative transfer theory. The first-order ladder term corresponds to the conventional single scattering intensity.

Another possible pair, as shown in Fig. 2, in the case of second order scattering, the field E_A travels in the same path as first case, while the conjugate field E_B travels the time reversal path of the E_A. It is represented by the second order cross term[13]. The second-order theory can be considered to be sufficient for a dilute system, such as rain[17,18].

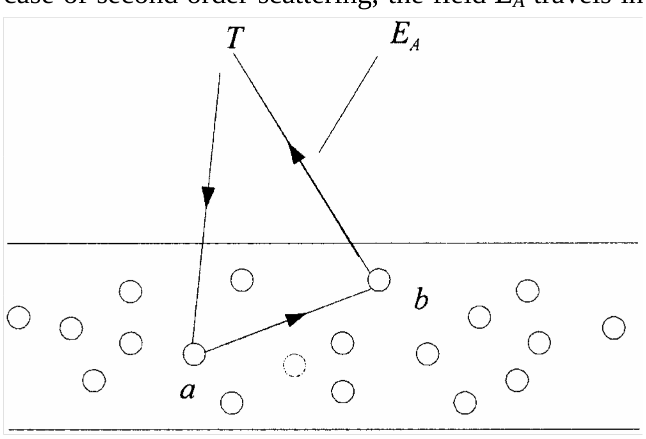

Fig. 1 — Second-order ladder scattering

Consider a beam wave incident upon a half-space for including discrete scatterers in the direction θ_i (Fig. 3). The effective wave number K in Region 1 is given by:

$$K = k + 2\pi N_0 F / k = K' + iK'' \qquad \dots (1)$$

where, k, is the wave number of free space in Region 0; N_0, the number density of particles; and F, the complex scattering amplitude. It is assumed that the concentration of particles is low so that K' is close to k. The imaginary part of F contributes to the attenuation K'' (Ref 19). According to the Foldy-Twersky-Oguchi formula, K'' can be shown as:

$$K'' = \mathrm{Im}[2\pi N_0 k^{-1} F(\hat{k}_i, \hat{k}_i)] \qquad \dots (2)$$

The effective incident and scattered wave number in rain can be represented, respectively as:

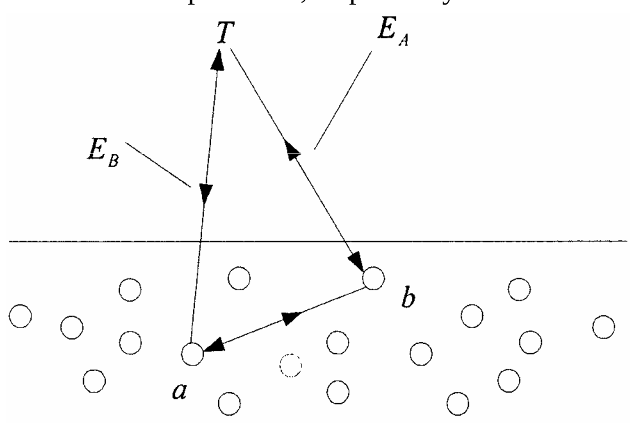

Fig. 2 — Second-order cross scattering

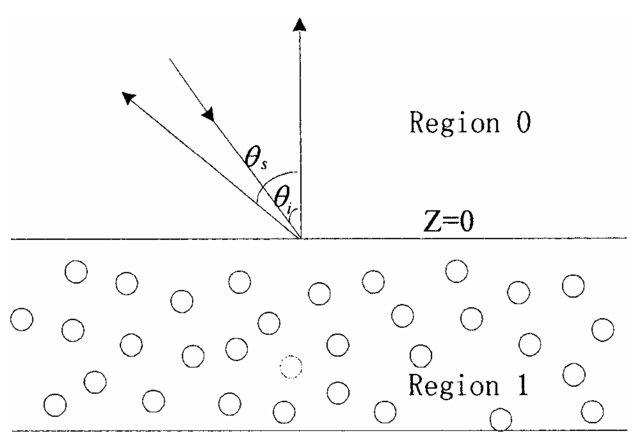

Fig. 3 — Scattering sketch by a slab of scatterers

$$\vec{K}_i = k\sin\theta_i\cos\phi_i\hat{x} + k\sin\theta_i\sin\phi_i\hat{y} - K_{iz}\hat{z} \quad \dots (3)$$

$$\vec{K}_s = k\sin\theta_s\cos\phi_s\hat{x} + k\sin\theta_s\sin\phi_s\hat{y} + K_{sz}\hat{z} \quad \dots (4)$$

where, $K_{iz} \approx k\cos\theta_i + iK''/u_i$; $u_i = \cos\theta_i$;

$K_{sz} \approx k\cos\theta_s + iK''/u_s$; $u_s = \cos\theta_s$,

in which the base vector $\hat{z}$ in the Cartesian system is taken in the zenith and the direction of $\hat{x}$ and $\hat{y}$ are arbitrary in the orthogonal plane to $\hat{z}$. The $F(\hat{k}_s, \hat{k}_i)$ is scattering amplitude matrix scattered from the direction $\hat{k}_i$ to $\hat{k}_s$. The $F(\hat{k}_i, \hat{k}_i)$ is the forward scattering amplitude matrix.

Based on the above analysis and the work of Kobayashi *et al.*[13], the first-order ladder term backscattering power can be write in the form of:

$$I_L^{(1)} \approx P_t G_0^2 \lambda^2 \theta_d^2 (2^7 \ln 2\pi r_s^2)^{-1} N_0 \{2(k''_{iz} + k''_{sz})\}^{-1} \cdot \sum_{\hat{\alpha}} \left| \left\langle \hat{\alpha} \middle| F(-\hat{k}_i, \hat{k}_i) \middle| \psi_0 \right\rangle \right|^2 \{1 - \exp[-2(k''_{iz} + k''_{sz})d]\} \quad \dots (5)$$

The second-order ladder term and second-order cross term power can be written, respectively in the forms of:

$$\begin{aligned} I_L^{(2)} = {} & P_t G_0^2 \lambda^2 \theta_d^2 (2^7 \ln 2\pi r_s^2)^{-1} N_0 \{2(k''_{iz} + k''_{sz})\}^{-1} \\ & \cdot \int_0^\infty d\eta \int_0^{2\pi} d\varphi \int_0^d d\varsigma \frac{\eta}{1+\eta^2} \\ & \cdot \exp[-k_e\sqrt{1+\eta^2}\varsigma] \exp[-\varsigma^2\eta^2 / 4\sigma_r^2] \\ & \cdot \sum_{\hat{\alpha}} \{ \left| \left\langle \hat{\alpha} \middle| F(\hat{k}_s, \hat{r}) F(\hat{r}, \hat{k}_i) \middle| \psi_0 \right\rangle \right|^2 \\ & \cdot [\exp\{-2k''_{iz}\varsigma\} - \exp\{2k''_{sz}\varsigma - 2(k''_{iz} + k''_{sz})d\}] \\ & + \left| \left\langle \hat{\alpha} \middle| F(\hat{k}_s, -\hat{r}) F(-\hat{r}, \hat{k}_i) \middle| \psi_0 \right\rangle \right|^2 \\ & \cdot [\exp\{-2k''_{sz}\varsigma\} - \exp\{2k''_{iz}\varsigma - 2(k''_{iz} + k''_{sz})d\}]\} \end{aligned} \quad \dots (6)$$

$$\begin{aligned} I_C^{(2)} = {} & P_t G_0^2 \lambda^2 \theta_d^2 (2^7 \ln 2\pi r_s^2)^{-1} N_0^2 (k''_{iz} + k''_{sz})^{-1} \\ & \cdot \int_0^\infty d\eta \int_0^{2\pi} d\varphi \int_0^d d\varsigma \frac{\eta}{1+\eta^2} \\ & \cdot \exp[-\{k_e\sqrt{1+\eta^2} + k''_{iz} + k''\}\varsigma] \\ & \cdot \exp[-\varsigma^2\eta^2 / 4\sigma_r^2]\{1 - \exp[-2(k''_{iz} + k'') \\ & \cdot (d - \varsigma)]\} \mathrm{Re}[\{\sum_{\hat{\alpha}} \left\langle \hat{\alpha} \middle| F(\hat{k}_s, \hat{r}) F(\hat{r}, \hat{k}_i) \middle| \psi_0 \right\rangle^* \\ & \cdot \left\langle \hat{\alpha} \middle| F(\hat{k}_s, -\hat{r}) F(-\hat{r}, \hat{k}_i) \middle| \psi_0 \right\rangle \} \exp[i(k_{dz} - t)\varsigma]] \end{aligned} \quad \dots (7)$$

In which P_t, is the transmitted power of radar system; G_0, the radar antenna gain; λ, wavelength; θ_d, beam divergence angle; r_s, propagating distance; and σ_y, footprint radius, which is defined by $\sigma_r^2 = r_s^2\theta_d^2 / 2^3 \ln 2$.

3 Effect of rain on MMW radar

3.1 Mie single scattering

Rainfall causes MMW radar signal attenuation, debases the signal-noise-ratio of radar system, decreases beam propagating distance, and so on. In order to calculate the attenuation, backscattering, multiple scattering, and backscattering enhancement caused by rainfall, the extinction cross section, scattering cross section, absorption cross section, and backscattering cross section of a raindrop are calculated by means of Mie theory[10], these are expressed as:

$$\sigma_t(D) = \frac{2\pi}{k^2} \sum_{n=1}^{\infty} (2n+1)\,\mathrm{Re}(a_n + b_n) \quad \dots (8)$$

$$\sigma_b(D) = \frac{\pi}{k^2} \left| \sum_{n=1}^{\infty} (2n+1)(-1)^n (a_n - b_n) \right|^2 \quad \dots (9)$$

$$\sigma_s(D) = \frac{2\pi}{k^2} \sum_{n=1}^{\infty} (2n+1)(|a_n|^2 + |b_n|^2) \quad \dots (10)$$

$$\sigma_a = \sigma_t - \sigma_s \quad \dots (11)$$

Here, a_n and b_n, are coefficients determined by complex spherical Bessel and Hankel function.

3.2 MC simulation multiple scattering

The rain attenuation considering multiple scattering is simulated by Monte Carlo method[10,12]. In heavy rainfall, the raindrops multiple scattering should be included in attenuation and backscattering.

A Monte Carlo model is a purely stochastic construction of an ensemble of photons trajectories through a random discrete medium. The length and direction of each trajectory segment are governed by the probability density function derived from the basis scattering and absorption properties of medium.

In discrete random medium, suppose that an incident wave beam is considered as a flux of photons, which contains N photons. For a photon in collision with a particle, either the photon is absorbed or scattered. The direction of photon motion may be altered to a new direction. Let $s(\tau_0, \mu)$ be a phase space point, where, τ_0 is optical distance; and $\mu = \cos\alpha$, α is the angle between the scattering direction and z-axis. Each photon encounters possibly with particle many times. Every scattering relates only with the proximate one time, that is, the phonon-particle collision process is described as Markov process. When a phonon is scattered repeatedly for m times, each time may be described as a random phase point (state) of a Markov chain. The state series is denoted by $\{s_l\}$ where $(l = 1,\ldots,m)$. Then, when a phonon scattered by mth order, it arrives at s, this process is expressed as m independent events. The total probability that the photon is not absorbed at s point is expressed as:

$$P(s) = \sum_{m=0}^{\infty} P_m(s) \quad \ldots (12)$$

Since, the photon motion in rain is a Markov process, well then, there is

$$P_m(s) = P(s_1 / s_0) \cdots P(s / s_{m-1}) \quad \ldots (13)$$

where, conditional probability, $P(s_l / s_{l-1})$ (l=1,...,m), is the probability of a photon scattered from phase space point s_{l-1} to s_l. The function of estimation total probability is given as:

$$P_t = \sum_{m=0}^{\infty} P_m = \sum_{m=0}^{\infty} W_m \exp\left[-C_t \frac{h - z_m}{\cos\alpha_m}\right] \cdot \eta(\cos\alpha_m) \cdot \prod_{l=1}^{m} \eta(h - z_l)\eta(z_l) \quad \ldots (14)$$

Here, $C_t = N<\sigma_t>$; and $\eta(x) = 1$ （$x > 0$） $\eta(x) = 0$ ($x \le 0$). The weight function:

$$W_m = W_{m-1} \exp\left[-C_a \left|\frac{z_m - z_{m-1}}{\cos\alpha_m}\right|\right] \quad \ldots (15)$$

where, $C_a = N < \sigma_a >$; and σ_a, is absorption cross section of a raindrop. The α_m is the angle between the mth scattering direction and wave propagation direction, z-axis. The initial weight value is $W_0 = 1$.

Let total number of photons is N, by tracking photons scattering direction and trace, the mean transmission T is shown as:

$$T = \frac{1}{N} \sum^{N} P_t \quad \ldots (16)$$

3.3 MMW radar signal to clutter ratio and signal to noise ratio

When a pulse radar is designed to detect the target in medium, such as rain, the scattering clutter of raindrops produces the effect on the target echo. The clutter induced by raindrops scattering in radar detective signal is called rain clutter. The volumetric rain clutter is the scattering clutter induced by the volumetric rain medium.

For monostatic radar, considering backscattering enhancement induced by multiple scattering, the rain clutter power is represented by[13]:

$$P_{rain} = (I_L^{(1)} + I_L^{(2)} + I_C^{2}) e^{-0.46A} \quad \ldots (17)$$

where, $e^{-0.46A}$, denotes the rain attenuation factor, in which A is the specific attenuation considering multiple scattering. Without considering the multiple scattering and the backscattering enhancement of rain, the rain clutter power is represented by:

$$P'_{rain} = I_L^{(1)} e^{-0.46A_1} \quad \ldots (18)$$

Here, A_1, is the specific attenuation of single scattering by Mie theory. Marshall-Palmer raindrops size distribution is adopted in the calculation of the rain attenuation and backscattering under different rain rates.

The target radar equation[19] considering the attenuation of raindrops multiple scattering under the condition of rainfall environment is written as:

$$P_r = P_t G^2 \lambda^2 \sigma e^{-0.46A} / (4\pi)^3 R^4 L_s \quad \ldots (19)$$

The radar equation considering the attenuation of raindrops multiple scattering for rain medium is given by analogy with the target radar equation, as follows:

$$P''_{rain} = P_t G^2 \lambda^2 e^{-0.46A} / \left((4\pi)^3 2\ln 2 R^4 L_s\right) \sum_{i=1}^{N} \sigma_i \quad \ldots (20)$$

So, the ratio of signal to rain clutter (S/C) is:

$$S/C = P_r / P_{rain} \quad \ldots (21)$$

The signal to noise ratio[4] (S/N) is:

$$S/N = P_t G^2 \lambda^2 \sigma e^{-0.46A} / (4\pi)^3 R^4 k_0 T_e B_n F_n L_s \quad \ldots (22)$$

In Eqs (13) and (15), σ, is the radar cross section (RCS) of target; k_0, the Boltzmann constant; and other parameters[4] are given in Table 1.

4 Results and Discussion

Based on Marshall-Palmer raindrops size distribution model, the rain attenuation of single and multiple scattering are calculated by means of Mie theory and MC simulation at 35 and 95 GHz. According to the MMW radar parameters given in Table 1, the rain backscattering calculated by the backscattering enhancement theory and Mie theory are shown in Fig. 4 and Fig. 5, respectively. Here, the thickness of rain slab decided by pulse width is $d = c\tau/2$. Marshall-Palmer raindrops size distribution model[20] is shown as:

$$n(D, R_a) = n_0 \exp(-\Lambda D) \quad \text{... (23)}$$

where, $n_0 = 0.8\times10^4$; $\Lambda = 4.1R_a^{-0.21}$; $D = 2a$; and R_a (mm h^{-1}) is rainfall rate.

In Figs (4 and 5), the phenomena of backscattering enhancement in rain are presented by the curves of the power of rain backscattering as a function of scattering angel at 35 and 95 GHz. It is shown that the power of rain backscattering exhibit a small peak in the backscattering direction. They also show rapid reduction in the region about $|\theta_s| < 0.0005$ degree. The phenomena of backscattering enhancement, however, are not observed for the single scattering by means of Mie theory. So, the backscattering enhancement considering the raindrops multiple scattering and the contribution from interference of two ray paths mutually satisfying the condition of time reversal paths could increase the power of rain backscattering.

The signal to clutter ratios are analysed at various rainfall rate: 5, 20 and 50 mm h^{-1}, for the 35 and 95 GHz monostatic radar in rain environment, respectively based on backscattering enhancement (En), Mie theory and MC simulation, respectively. The relations between the S/C and propagation distance are presented with En (solid-line), MC (dot-line) and Mie (symbol), respectively, and shown in Fig. 6 and Fig. 7, respectively. The results show that the S/C results simulated by means of MC are slightly lower than the S/C by Mie as rainfall rate is larger than 20 mmh^{-1}. As rainfall rate is smaller, the multiple scattering of rain is also smaller, the results by MC is approximate to the one by Mie. The S/C results obtained by En theory are smaller than the results by MC and Mie at 35 and 95 GHz. When the rainfall is heavy, the S/C is less. The backscattering enhancement considering the multiple scattering and backscattering coherence from raindrops scattering could cause the serious decrease of signal to clutter

Table 1 — Millimeter wave radar parameters

Parameter	Sign	35 GHz	95 GHz
Peak power, W	P_t	20	20
Pulse width, ns	τ	50	50
Repeat frequency, KHz	f_P	10	10
Antenna aperture, m	D	0.6	0.2
Beam divergence angle, deg	θ_d	1	1
Equivalent noise temperature, K	T_e	1166	1468
Noise bandwidth, MHz	B_n	20	20
Noise coefficient, dB	F_n	6	7
System loss, dB	L_s	9.2	12.9
Target RCS, m^2	σ	0.202	0.202

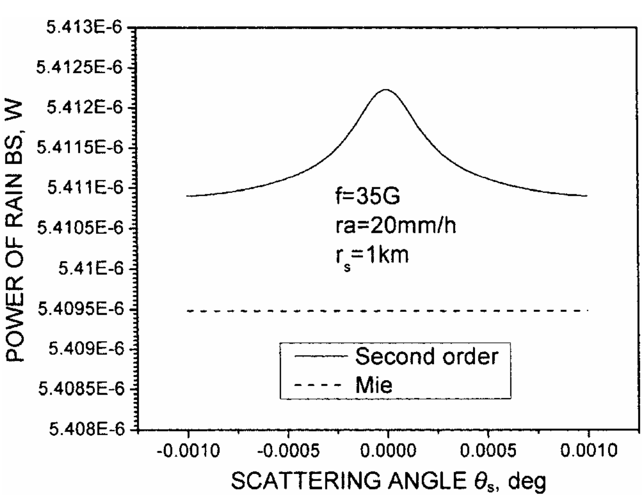

Fig. 4 — Power of rain backscattering with scattering angle at 35 GHz

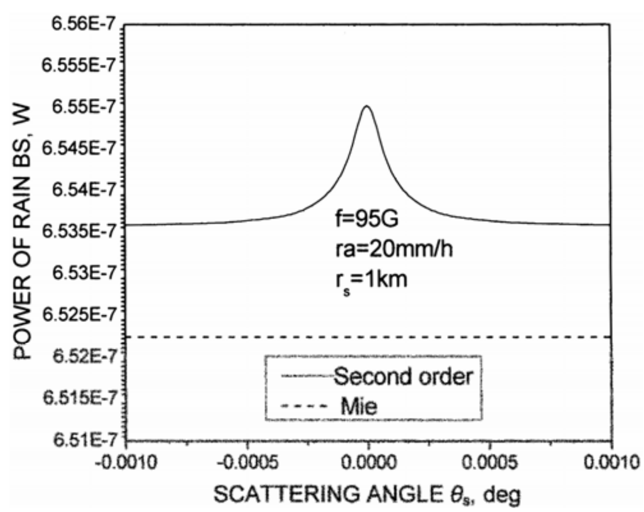

Fig. 5 — Power of rain backscattering with scattering angle at 95 GHz

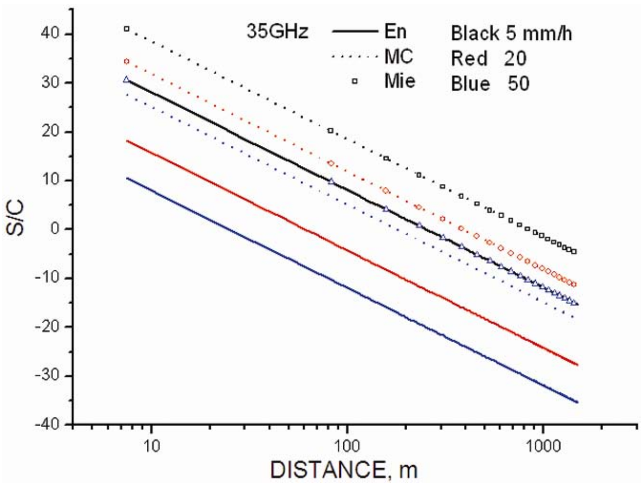

Fig. 6 — Ratios of signal to rain clutter with distance at 35 GHz

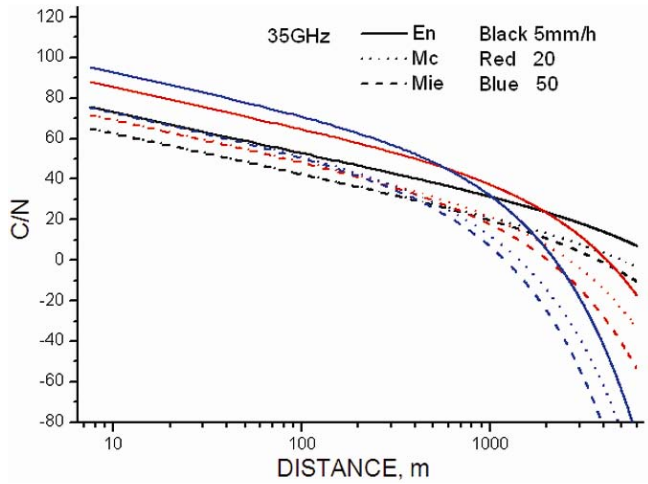

Fig. 8 — Ratio of rain clutter to noise with distance at 35 GHz

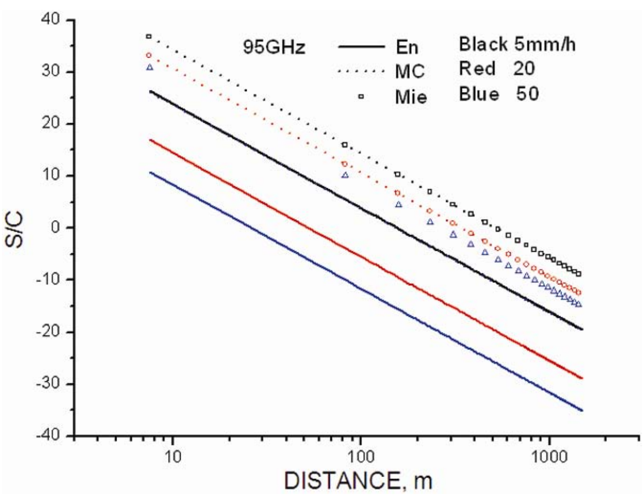

Fig. 7 — Ratios of signal to rain clutter with distance at 95 GHz

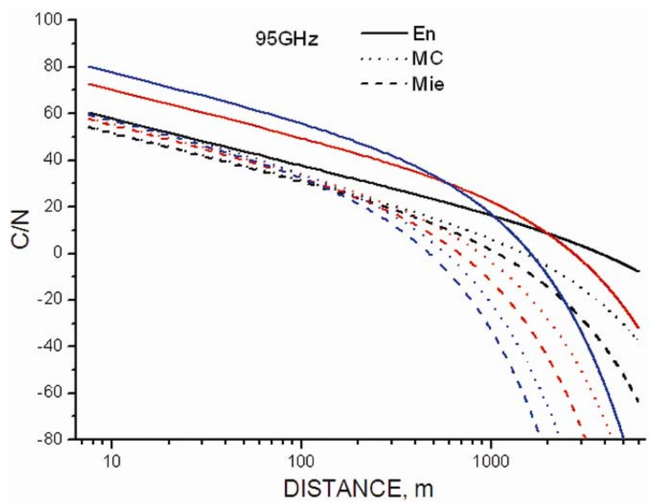

Fig. 9 — Ratio of rain clutter to noise with distance at 95 GHz

ratios, especially in heavy rainfall. It is shown that the results calculated by means of Mie theory and MC simulation underestimate the rain clutter power and overestimate the rain S/C due to not considering of backscattering enhancement effect.

The relationships of clutter to noise ratios (C/N) with path length are presented, by the En (solid-line), MC (dot-line) and Mie (dash-line) methods, in Fig. 8 and Fig. 9. The C/N results obtained by En method are greater than the results by MC and Mie under the condition of various rain rates at 35 and 95 GHz. At heavy rainfall, the C/N by MC simulation is slightly greater than the one by Mie, but is less than the results by En, because the rain multiple scattering is only considered by MC simulation, and by En calculation, the backscattering enhancement is taken into account. Hence, the C/N is underestimated by means of the Mie and MC, in which the backscatter enhancement is not included.

As path length is small, when the rainfall is heavy, the C/N is more. However, as path length is about greater than a kilometer, the C/N is less when the rainfall is heavy, which is because rain attenuation increase. It is noted that calculated values by second-order backscattering theory are larger than values by MC and Mie theory. It is shown that backscattering enhancement can cause the increase in clutter to noise ratio.

5 Conclusions

The second-order backscattering enhancement induced by rainfall and Monte Carlo simulation method are discussed. Based on Marshall-Palmer raindrops size distribution, the rain attenuation of single and multiple scattering are calculated by Mie theory and MC simulation, and introduced into the estimation of MMW radar performance. The influence of rainfall on radar S/C and C/N are analysed based on Mie, Monte Carlo simulation and backscattering enhancement theory at 35 and 95 GHz, respectively. The relations of the signal to clutter ratios and the clutter to noise ratios with path lengths are obtained by En, Mie theory and MC simulation method. The Mie and MC methods do not consider backscattering enhancement, underestimate the effects of raindrops scattering on radar performance. Hence, it is shown that the attenuation and backscattering enhancement induced by raindrops multiple scattering are necessarily taken into account for millimeter wave radar operating in rainfall environment, especially in heavier tropical region.

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