Progress In Electromagnetics Research, PIER 55, 241–248, 2005

OPTIMAL SCATTERING POLARIZATION CHARACTERISTIC FOR CYLINDER TARGET IN RAIN AT MILLIMETER WAVE BAND

J.-Y. Huang, S.-H. Gong, and F. Wang

School of Science, Xi'dian University
Box 273, Xi'an 710071, China

Abstract—Scattering characteristic of target in rain is studied in this paper, which calculates scattering matrix of rain area and that of cylinder target in rain, taking the effect from rain into account by substituting rain media for random media with equivalent complex permittivity. SCR (ratio of scattering signal induced by target in rain to clutter from rain) is computed, and the relation between SCR and polarization status of transmitting and receiving antennas is deduced. By optimizing the SCR, optimal polarization status of transmitting and receiving antennas are found. And, the results found in this paper are serviceable for communication system design [2, 4].

1 Introduction

2 Scattering Matrix of Rain Area

3 Scattering Matrix of Finite Length Cylinder in Rain Media

4 SCR of Cylinder in Rain Media

5 Conclusion

References

1. INTRODUCTION

In general, targets exit in random media, such as turbulent air, rain, cloud, snow and dust etc. Therefore, it is important to study the scattering peculiarity of targets in those media [2, 3]. Currently, investigation about electromagnetic scattering of targets and clutter is in time, space and frequency domain. In the mean time, application of polarization information is believed to be promising to detect and identify targets and restrain clutter. Effects induced by raindrop on testing targets are severest in millimeter wave band. The paper studies cylinder target in rain media in polarization field. Matrix of rain area is given too. In order to consider the effect of rain, equivalent complex permittivity of rain area is used when scattering matrix of cylinder target in rain media is computed. Then, the matrix is got combining boundary condition of cylinder target with electromagnetic wave propagation theory. Based on that, relationship between SCR (ratio of signal scattered by cylinder target to clutter from rain) and the parameter of polarization status of transmitting and receiving antennas is deduced. From above work, the polarization parameter corresponding to optimal SCR can be found.

2. SCATTERING MATRIX OF RAIN AREA

As a linear polarization wave incident on rain area, the scattered field at a distance r from rain area is related to the incident field by

$$\begin{bmatrix} E_v^s \\ E_h^s \end{bmatrix} = \frac{j\exp(jk_0 r)}{k_0 r} \begin{bmatrix} E_v^i \\ E_h^i \end{bmatrix} \tag{1}$$

where E_h^i and E_v^i are the horizontal and vertical polarization components of incident field, E_h^s and E_v^s are those of scattered field. And, $S_0 = \begin{bmatrix} S_{vv} & S_{vh} \\ S_{hv} & S_{hh} \end{bmatrix}$ is Sinclare scattering matrix of rain area. In Eq. (1), $k_0 = 2\pi/\lambda$ is the wave number in free space. The clutter coming from rain is the statistical sum of the echoes from every raindrop confined within the beam, so the elements of Sinclare scattering matrix S_0 of rain area can be written as [1, 6]:

$$\begin{aligned} S_{vv} =& \int_{D_{\min}}^{D_{\max}} \left\{ \sum_{m=0}^{\infty} \sum_{n=m}^{\infty} (j)^n \left[\left(j a^s_{omn} \frac{m P_n^m(\cos\theta)}{\sin\theta} + b^s_{emn} \frac{\partial P_n^m(\cos\theta)}{\partial\theta} \right) \right.\right. \\ & \cos m\phi \cos\zeta + \left(-j a^s_{omn} \frac{m P_n^m(\cos\theta)}{\sin\theta} + b^s_{emn} \frac{\partial P_n^m(\cos\theta)}{\sin\theta} \right) \\ & \left.\left. \sin m\phi \sin\zeta \right] \right\} N(R, D) dD \end{aligned} \tag{2}$$

$$\begin{aligned} S_{hh} =& \int_{D_{\min}}^{D_{\max}} \left\{ \sum_{m=0}^{\infty} \sum_{n=m}^{\infty} (j)^n \left[\left(-j a^s_{omn} \frac{\partial P_n^m(\cos\theta)}{\partial\theta} - b^s_{emn} \frac{m P_n^m(\cos\theta)}{\sin\theta} \right) \right.\right. \\ & \sin m\phi \cos\zeta + \left(-j a^s_{omn} \frac{\partial P_n^m(\cos\theta)}{\partial\theta} + b^s_{emn} \frac{m P_n^m(\cos\theta)}{\sin\theta} \right) \end{aligned}$$

$$\cos m\phi \sin\zeta \Big]\Big]\Big\} N(R, D)dD \tag{3}$$

$$S_{vh} = 0,\ S_{hv} = 0 \tag{4}$$

where S_{vv} and S_{hh} are the same polarization components of scattering matrix, S_{vh} and S_{hv} are cross polarization components of scattering matrix which are zero under the assumption raindrop being sphere and multiple scattering being leaved out of account. In Eq. (2) and Eq. (3), a_{omn} and b_{emn} are expansion coefficients of scattered field, ζ is angle between electric field vector and incidence plane, θ is scattering angle, and it is 180 degree if back scattering is considered. D is diameter of raindrop, and $D_{\max}$ is maximum value and $D_{\min}$ is minimum value. Rain rate is denoted by R and raindrop size distribution spectrum by $N(R,\ D)$, which is in Weibull distribution here. $P_n^m(\cos\theta)$ is associated Legendre function.

3. SCATTERING MATRIX OF FINITE LENGTH CYLINDER IN RAIN MEDIA

We consider a finite length cylinder in rain media whose axis is along z axis as shown in Fig. 1, in which the right side of $y = -L$ is rain area. Taking rain area as random media with equivalent complex permittivity ε_1 [5] , the effect of rain on scattering field is considered. When a plane wave incident on rain area as shown in Fig. 1, the

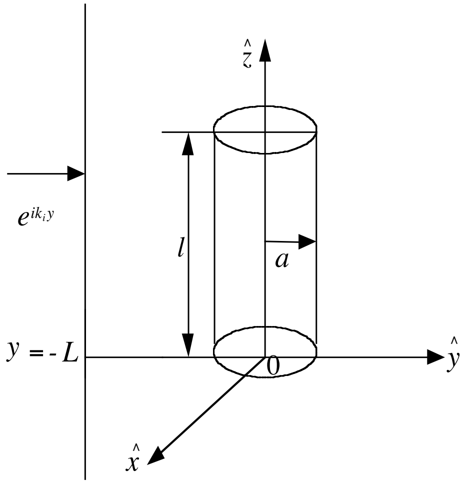

Figure 1. A finite length cylinder in rain media.

incident wave on finite length cylinder in rain media is the transmitted wave.

The field scattered by a finite length cylinder in rain media can be deduced based on boundary condition on the surface of cylinder and the large argument expression of Bessel function [7], which is written as

$$\begin{bmatrix} E_v^s \\ E_h^s \end{bmatrix} = \frac{je^{jk_0 r}}{k_0 r} \begin{bmatrix} S_{vv} & S_{vh} \\ S_{hv} & S_{hh} \end{bmatrix} \begin{bmatrix} E_v^i \\ E_h^i \end{bmatrix} \tag{5}$$

The cross polarization components can be neglected, because it is much smaller than the polarization components, so

$$S_{vh} = S_{hv} = 0 \tag{6}$$

$$S_{vv} = 2\sqrt{\frac{2}{\pi}} \frac{2\eta_2 k_0}{\eta_2 + \eta_1} e^{-jk_v(y+L)} \times \sin(-kl/2)(1-\varepsilon_r) \sum_{n=-\infty}^{\infty} e_{nv} Z_n \tag{7}$$

$$S_{hh} = 2\sqrt{\frac{2}{\pi}} \frac{2\eta_2 k_0}{\eta_2 + \eta_1} e^{-jk_h(y+L)} \times \sin(-kl/2)(1-\varepsilon_r) \sum_{n=-\infty}^{\infty} \frac{k}{2\lambda_i} \left[\eta h_{nh} z_{n+1} e^{j\phi_s} + \eta h_{nh} z_{n-1} e^{-j\phi_s}\right] \tag{8}$$

where

$$k_v = k_0 + \frac{2\pi}{k_0} \int_{D_{\min}}^{D_{\max}} f_v(i,i) N(R,D) dD \tag{9a}$$

$$k_h = k_0 + \frac{2\pi}{k_0} \int_{D_{\min}}^{D_{\max}} f_h(i,i) N(R,D) dD \tag{9b}$$

$$e_{nv} = \frac{j}{R_n J_n(u)} \left\{ \frac{H_n'^2(v_i)}{v_i H_n^{(2)}(v_i)} - \frac{J_n'(u)}{u J_n(u)} \right\} \tag{10}$$

$$\eta h_{nh} = \frac{j}{R_n J_n(u)} \left\{ \frac{H_n'^2(v_i)}{v_i H_n^{(2)}(v_i)} - \frac{\varepsilon_r J_n'(u)}{u J_n(u)} \right\} \tag{11}$$

$$R_n = \frac{\pi v_i^2 H_n^{(2)}(v_i)}{2} \left\{ \left(\frac{H_n'^2(v_i)}{v_i H_n^{(2)}(v_i)} - \frac{J_n'(u)}{u J_n(u)} \right) \cdot \left(\frac{H_n'^2(v_i)}{v_i H_n^{(2)}(v_i)} - \frac{\varepsilon_r J_n'(u)}{u J_n(u)} \right) \right\} \tag{12}$$

$$z_n = \frac{a^2}{u^2 - v_s^2} \left[u J_n(v_s) J_{n+1}(u) - v_s J_n(u) \cdot J_{n+1}(v_s) \right] \tag{13}$$

$$u = ka\sqrt{\varepsilon_r} \qquad v_i = ka \qquad v_s = ka\sin\theta \tag{14}$$

$$k_0 = 2\pi/\lambda \qquad \eta_1 = \sqrt{\mu_0/\varepsilon_0} \qquad \eta_2 = \sqrt{\mu_0/\varepsilon_1} \tag{15}$$

where k is wave number in cylinder, θ is scattering angle, ε_r is complex relative permittivity of cylinder, and $f_{v,h}(i,i)$ is forward-scattering amplitude function.

4. SCR OF CYLINDER IN RAIN MEDIA

Stokes vector τ can express polarization status of electromagnetic wave, which can be defined as:

$$g_0 = |E_v|^2 + |E_h|^2 = C^2 \tag{16a}$$

$$g_1 = |E_v|^2 - |E_h|^2 = C^2\cos 2\varepsilon\cos 2\tau \tag{16b}$$

$$g_2 = 2|E_v||E_h|\cos\phi = C^2\cos 2\varepsilon c\sin 2\tau \tag{16c}$$

$$g_3 = 2|E_v||E_h|\sin\phi = C^2\sin 2\varepsilon \tag{16d}$$

$$J = [g_0, g_1, g_2, g_3]^T \tag{17}$$

ε and τ are geometry description factors on Poincare polarization sphere. ϕ is phase difference between E_v and E_h. We consider transmitting and receiving antennas are the same polarization, so $J = J_t = J_r$, and let $C^2 = 1$ for convenience.

Muller matrix is introduced to describe polarization status of electromagnetic wave with vector $\mathbf{J}$, which can be related to Sinelair matrix by [8]

$$[M] = [A]\left([S]\times[S^*]\right)\left[A^{-1}\right] \tag{18}$$

where A is a full order matrix [8].

Then, the received power from rain clutter induced by back scattering of rain area and that of signal scattered from cylinder target are denoted as P, P_c, respectively,

$$P = J^T MJ \qquad P_c = J^T M_c J \tag{19}$$

In Eq. (19), M and M_c are Muller matrix of signal scattered by cylinder and rain clutter. Then, the SCR is written as

$$SCR = \frac{J^T MJ}{J^T M_C J} \tag{20}$$

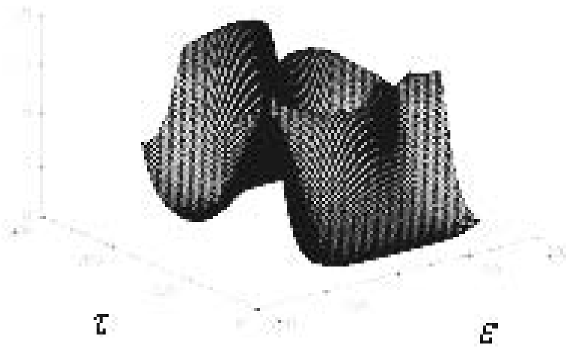

Figure 2. SCR changing with polarization status (R = 10 mm/h f = 35 GHz).

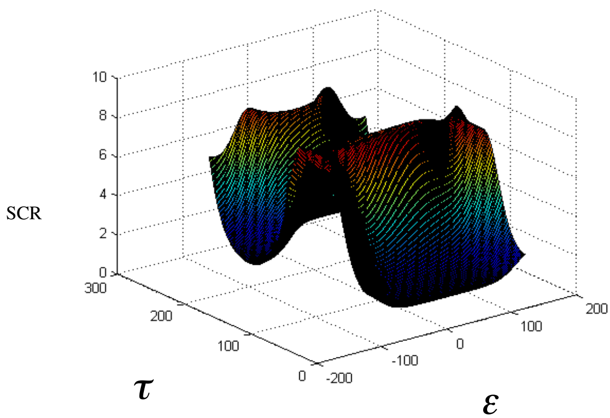

Figure 3. SCR changing with polarization status (R = 50 mm/h f = 35 GHz).

5. CONCLUSION

Assume a cylinder with relative permittivity of $9.6+j4.0$, being 35.0 cm long and its radius is 0.42 cm. The scattering matrix and Mueller matrix of the cylinder can be computed from Eq. (8) and Eq. (18), and those of rain area can be calculated using Eq. (2), Eq. (3) and Eq. (18). Then, the SCR is obtained from Eq. (20), under the condition that rain-rate ranges between 4 mm/h and 100 mm/h, and the frequency is in millimeter wave band. Fig. 2 and Fig. 3 show part results of above computation, in which the relation of ε and τ changing with polarization parameter is illuminated. Gopt (the polarization parameter corresponding to optimized SCR) can be found from Eq. (20) combining iterative method and extreme principle.

The results indicate that the effect from rain clutter can be restrained by employing circular polarization antenna to obtain optimal SCR, under the condition of small or middle rain rate. However, when rain rate is large, for instance, $R = 50\,\mathrm{mm/h}$, Gopt is $[1, -0.6844, -0.0144, 0.729]^T$. Poincare polarization sphere denotes that optimal polarization status of transmitting and receiving antennas are left elliptical polarization.

The conclusion is that, in case of large rain rate, it is necessary to predict gopt at different rain rate. Then, the SCR can be improved by adopting self-adaptive method to maintain optimized polarization status of transmitting and receiving antennas.

The method used in the paper is effective for other targets and for other background clutters, such as fog, snow, dust and so on.

REFERENCES

1. Hamid, A.-K., "Electromagnetic scattering from a dielectric coated conducting elliptic cylinder loading a semi-elliptic channel in a ground plane," *Journal of Electromagnetic Waves and Applications,* Vol. 19, No. 2, 257–270, 2005.
2. Crane, R., *Propagation Handbook for Wireless Communication System Design,* CRC Press, 2003.
3. Huang, J. Y. and Y. P. Wang, "A study of effects induced by rain for 3 mm wave band," *Inter'1. J.IR and mm Wave,* Vol. 13, No. 3, 341–349, 1992.
4. Panagopoulos, A. D., P. D. Arapoglou, and P. G. Cottis, "Satellite Communications at Ku, Ka, and V bands: Propagation impairments and mitigation techniques," *IEEE Communication Surveys and Tutorials,* Vol. 6, No. 3, 2–14, 2004.
5. Li, Y. L., J. Y. Huang, and T. W. Yang, "Equivalent permittivity model of rain media," *Journal of Optics,* Vol. 32, No. 3, 378–381, 2003 (in Chinese).
6. Ajewole, M. O., L. B. Kolawole, and G. O. Ajayi, "Theoretical study of the effect of different types of tropical rainfall on microwave and millimeter-wave propagation," *Radio Science,* Vol. 34, No. 5, 1103–1105, 1999.
7. Karam, M. A., A. K. Fung, and Y. M. M. Antar, "Electromagnetic wave scattering from some vegetation sample," *IEEE Trans. on Geoscience and Remote Sensing,* Vol. 26, No. 6, 799–808, 1988.
8. Zhuang, Z. W., S. P. Xiao, and X. S. Wang, *Radar Polarization*

Information Processing and Application, Publishing House of National Defense Industry, 1999 (in Chinese).

Ji-Ying Huang was born in Nanchang, in 1939. She graduated from the Physics Department, from Wuhan University, China, in 1962. Since Sept. 1962 she has been with the School of Science, Xidian University, where she is now a professor and the adviser of doctor degree graduate student. Her research interests include millimeter waves propagation in random medium and applications.

Shu-Hong Gong was born in Shanxi, in 1978. He received the M.Sc. degree in radio physics from Xidian University, China, in 2004. Since Sept. 2003 he has been with the School of Science, Xidian University, where he is now a assistant. He is currently working toward his Ph.D. degree in radio physics, Xidian University and his area of special interest includes millimeter waves scattering and propagation in random medium.

Fang Wang was born in Jiangsu, in 1978. She received the M.Sc. degree in radio physics from Xidian University, China, in 2004. Her research interests include millimeter waves propagation.