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MULTIPLE SCATTERING OF POLARIZED PULSE WAVES IN RANDOM MEDIA

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Abstract: We extend the study of polarized continuous waves to polarized pulse waves propagating through a random media defined by discrete scatterers. We develop the time-dependent vector radiative transfer equation and solve it using Mie scattering and the discrete ordinates method in both linear and circular polarization. In addition, we investigate the off-axis scattered waves, also called snake waves. Degree of polarization (DOP) and cross-polarization discrimination (XPD) are calculated. The results suggest that the circular polarization waves maintain greater DOP and XPD over those of the linear polarization.

INTRODUCTION

In recent years, there has been an increasing interest in the imaging and detection of objects in random clutter environment. Examples are optical and ultrasound imaging of biological media, and the detection of buried objects such as land mines in clutter surroundings. One of the important questions is the effect of the scattering environment on the spatial and temporal resolution of the image. To study this question, we discuss the following problems:

(1) What is the generalized time-dependent vector radiative transfer formulation which is numerically stable.
(2) The advantages of circular polarization over linear polarization in imaging, showing the difference in the specific intensities and the degree of polarization.
(3) The near axis scattering, called the "snake wave", shows the increased co-polarized components and the decreased cross-polarized components for circular polarization compared with linear polarization.

MODIFIED PULSE VECTOR RADIATIVE TRANSFER EQUATION

For a narrow band and plane-parallel medium case, the time-dependent vector radiative transfer equation is Fourier transformed to obtain the following modified frequency domain vector radiative transfer equation:

$$\mu \frac{\partial}{\partial \tau}[\mathbf{I}_d] + \left(1-(\mu-1)i\frac{\omega}{\tau_o}\right)[\mathbf{I}_d] = \int_0^{2\pi}\int_{-1}^{1}\mathbf{S}(\mu,\phi,\mu',\phi')][\mathbf{I}_d]d\mu' d\phi' + \mathbf{F_0}(\tau,\mu,\phi)\exp(-\tau) \text{ for } 0\le\tau\le\tau_o \tag{1}$$

where ω is the normalized frequency, the optical distance τ defined by $\tau = \rho\sigma_t z$ where ρ is the number density, σ_t is the total-cross section of a single particle, and z is the actual distance. Note that τ_o is the optical depth defined by $\tau_o = \rho\sigma_t L$ where L is length of the slab of the random medium, the scattering matrix [**S**] is calculated from Mie scattering explained by Cheung[2]. The time-domain diffuse Stokes vector [$\mathbf{I}_d$] is then given by

$$[\mathbf{I}_d(t,\tau)] = \begin{bmatrix} I_1 & I_2 & U & V \end{bmatrix}^T = \frac{1}{2\pi}\int[\mathbf{I}_d(\omega,\tau)]\exp\left(i\frac{\omega}{\tau_o}\tau - i\omega t\right)d\omega \tag{2}$$

where t is normalized with respect to the propagation time. It is important to note that equation (1) is modified from the vector radiative transfer to obtain stable frequency-domain solutions. Equation (1) is numerically solved using the discrete ordinate method and Fourier series decomposition in the azimuthal direction. For linear polarization, two Fourier components are needed while for circular polarization, one Fourier component with two separate equations is needed. The degree of polarization (DOP) and the cross-polarization discrimination (XPD) are defined by Equation (3).

$$DOP = \frac{\sqrt{(I_1-I_2)^2+U^2+V^2}}{I_1+I_2} \quad , \quad XPD = 10\log\left[\frac{I_{co-pol}}{I_{x-pol}}\right] \tag{3}$$

In the continuous waves (CW) investigation, we solve Equation (1) at $\omega = 0$. For the pulse wave calculation, we use 1000 number of frequencies to resolve a time-domain pulse.

CIRCULAR VS. LINEAR POLARIZATION

It has been noted that circularly polarized waves can maintain coherence over a longer distance than in a linear polarization. Figure 1 shows the CW solution for circular and linear polarizations and their co-polarized and cross- polarized characteristics as a function of optical depth. It shows that, in the forward and off-axis direction, the circular polarization has more co-polarized components and less cross-polarized components than those of the linear polarization. This is also shown in Figure 2 where the DOP and XPD for circular polarization is higher than those for linear polarization. Figure 3 shows the pulse characteristics at the optical depth of 10. The pulse for circular polarization clearly has much less cross-polarized components than the linear polarization indicating its possible use for imaging.

SNAKE WAVE AND NEAR-AXIS SCATTERING

It has been proposed and experimentally verified that the near-axis scattering called the "snake wave" can be used to produce an image with improved resolution. In Figure 1, we show that the near-axis ($\theta = 1.7°$) has higher co-polarized and lower cross-polarized components than the off-axis ($\theta = 44°$) scattering, especially when optical depth is small. Pulse snake waves for optical depths of 1 and 10 are shown in Figure 4. This confirms the stronger presence of the snake waves in smaller optical depth.

CONCLUSIONS

We have developed a numerically stable, modified vector radiative transfer formulation for polarized pulse scattering in random media. The solutions are used to show the difference between circular and linear polarization and the near-axis and the off-axis scattering. In general, circular polarization has higher co-polarized and lower cross-polarized components than linear polarization, and these characteristics may be used to improve the imaging in clutter environment. It is also shown that the near-axis intensities are considerably higher than off-axis intensities, indicating the "snake wave" phenomena.

ACKNOWLEDGEMENT

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REFERENCES

[1] A.D. Kim and A. Ishimaru, "*Comparisons between linearly and circularly polarized light scattering in discrete random media*," submitted to Applied Optics.

[2] R. L-T Cheung and A. Ishimaru, "*Transmission backscattering and depolarization of waves in randomly distributed spherical particles*," Applied Optics. Vol. 21, pp-3792-2798, 1982.

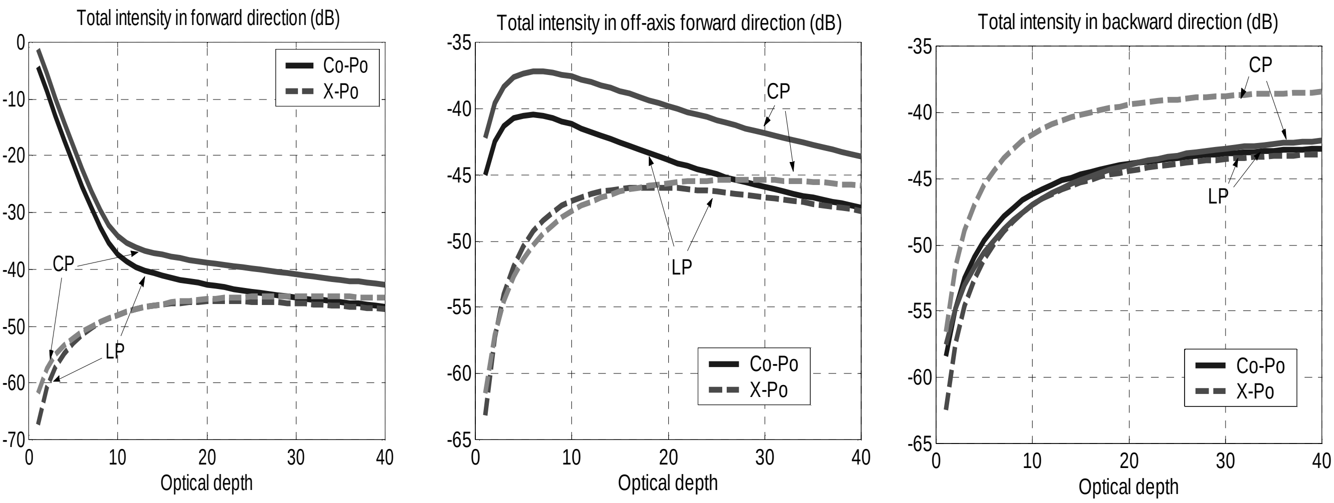

Figure 1. CW specific intensity

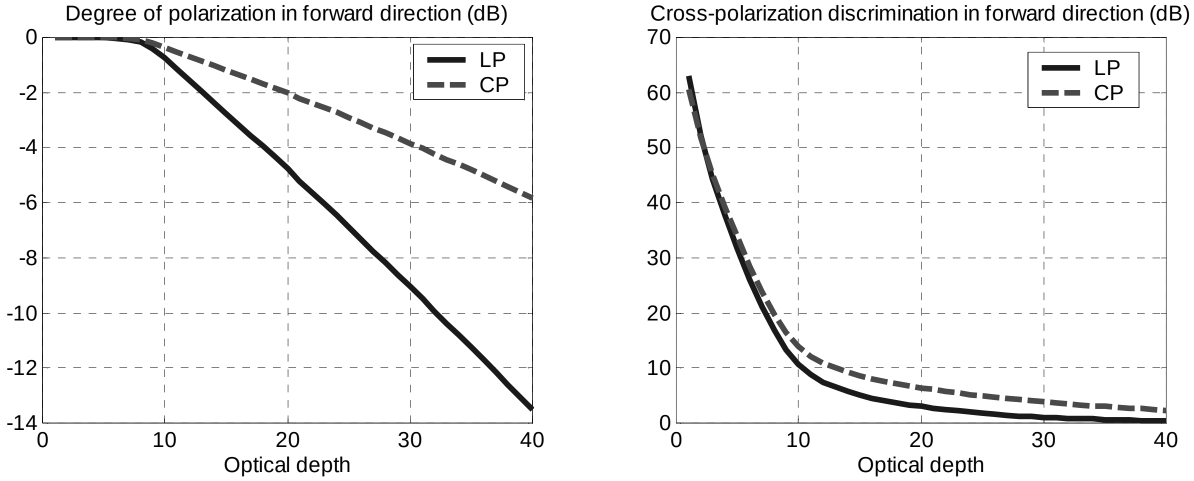

Figure 2. Continuous waves DOP and XPD in forward direction

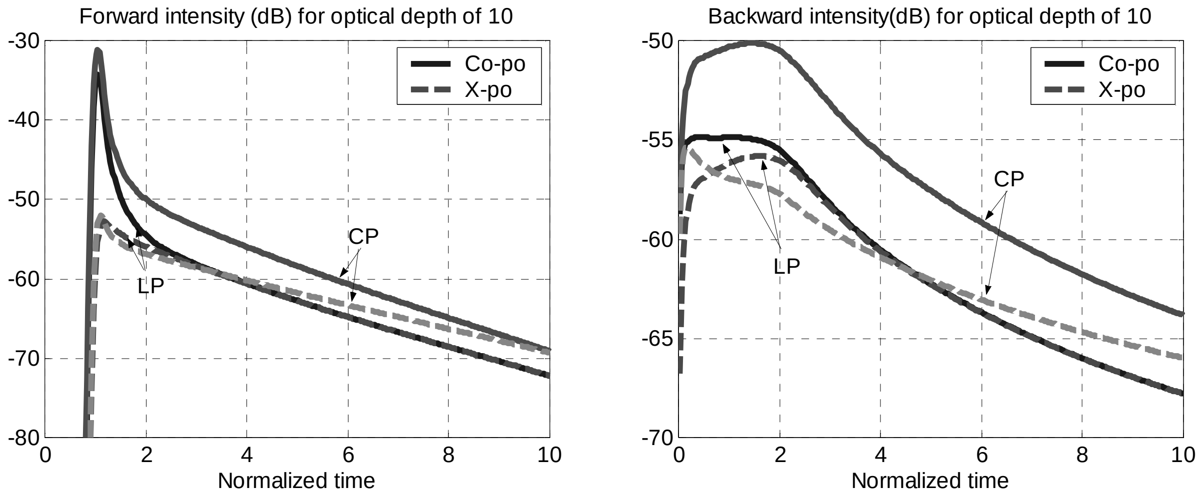

Figure 3. Pulse specific intensity for optical depth of 10

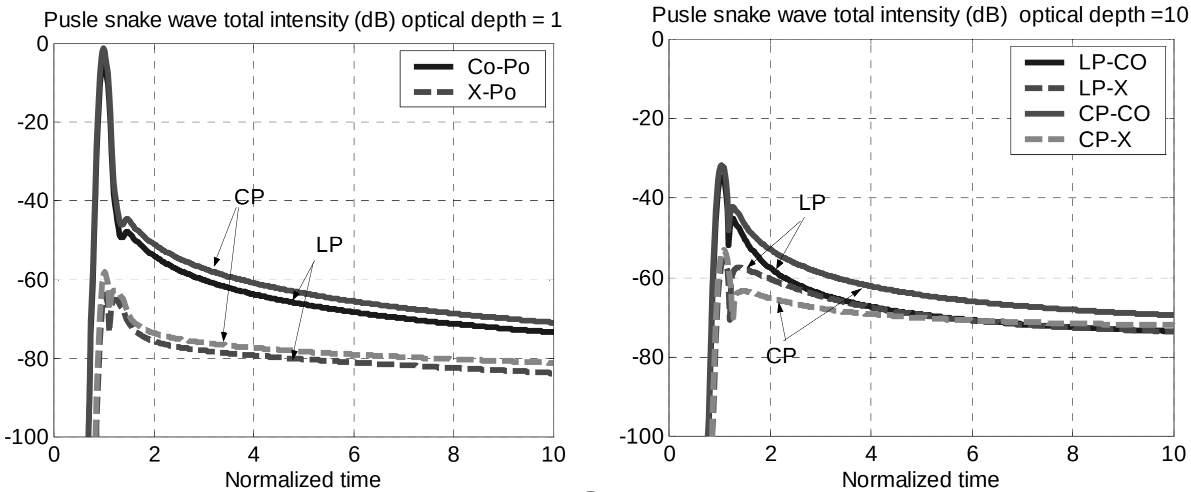

Figure 4. Pulse snake waves intensity: left: optical depth of 1; right: optical depth of 10