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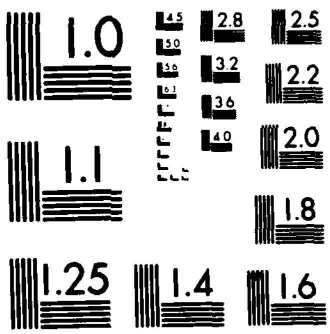

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Elltec Engineering Inc.

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MULTIPLE SCATTERING EFFECTS OF AN

ENSEMBLE OF IRREGULARLY SHAPED PARTICLES

FINAL REPORT

Cavour Yeh

Senior Research Engineer

July 12, 1984

U. S. Army Research Office

Contract No. DAAG 29-82-C-0008

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This report summarizes the result of the research carried out at EMtec Engineering, Inc., Los Angeles, under Contract DAAG29-82-C-0008 with the Army Research Office. This research dealt with the study of the propagation characteristics of wave passing through an ensemble of nonspherical particles for which the multiple scattering effects are important. Using the vector transport theory approach which includes the depolarization effects due to irregularly shaped particles, the incoherent specific intensities caused by the multiple scattering effects were computed. Also described are future research areas.

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Abstract

This report summarizes the result of the research carried out at EMtec Engineering, Inc., Los Angeles, under Contract DAAG29-82-C-0008 with the Army Research Office. This research dealt with the study of the propagation characteristics of wave passing through an ensemble of nonspherical particles for which the multiple scattering effects are important. Using the vector transport theory approach which includes the depolarization effects due to irregularly shaped particles, the incoherent specific intensities caused by the multiple scattering effects were computed. Also described in this report are several future research areas.

TABLE OF CONTENTS

I. Introduction

This is a final report on a study sponsored by the Army Research Office (DAAG 29-82-C-0008) from April 12, 1982 through April 11, 1984. The principal objective of this research was to learn the propagation behavior of wave passing through an ensemble of nonspherical particles for which the multiple scattering effects are important. Using the vector transport theory approach which includes the depolarization effects due to irregularly shaped particles, we were able to obtain the incoherent specific intensities caused by the multiple scattering effects. This final report gives a summary of our accomplishments during this phase of the research program.

II. Summary of Accomplishments

Results of our investigation are summarized in the following:

(1) Matrix representations of the vector radiative transfer theory for randomly distributed <u>nonspherical</u> particles.[2]

In recent years considerable attention has been paid to the problem of communication through various particles in the atmosphere such as fog, ice particles, snow, etc.[6] These particles are often nonspherical causing polarization dependent attenuation, depolarization, and cross polarization. These polarization effects are also evident in lidar and radar dectection and terrain scattering.[7-8]

In order to include complete polarization effects in the radiative transfer theory, the equation of transfer must be expressed in matrix form using the Stokes' vector. Even though the vector radiative transfer equation has been studied previously,[5-9] most of these studies are directed to spherical particles resuling in considerable simplification of the equation. For example, the extinction matrix becomes a scalar, and the Mueller matrix becomes a function of $\phi-\phi'$. For nonspherical particles, the coherent field becomes depolarized.[10] We have derived a compact matrix representation of the propagation of the coherent field in terms of the Stokes' vector as well as a compact representation of the extinction and Mueller matrices using the direct product. These formal matrix representations may facilitate calculation of the propagation and scattering characteristics of the Stokes' vector for nonspherical particles. Results of this investigation are given in a paper which has been submitted for publication in the Journal of the Optical Society of America.[2]

(2) First order multiple scattering theory for nonspherical particles.[3]

It is known that the atmosphere contaminated by smoke or hydrometeors (ice or rain) has profound effects on the propagation of high frequency electromagnetic energy, which in turn may degrade the performance of many modern communication or detection systems.[1] Smoke or hydrometeors may take on different shapes other than spheres and the close proximinity of these particles may enhance multiple scattering effects.[7,11,12] It is therefore important to assess the relative importance of nonspherical versus spherical particle effects in the multiple scattering of electromagnetic waves by an ensemble of particles.

Various studies of the multiple scattering effects of hydrometeors on microwave propagation have been conducted.[12-14] While earlier studies dealt with scalar fields and first-order solutions,[14] more recent ones have considered circularly or linearly polarized incident waves and exact solutions to the equation of transfer. In all of the previous studies only spherical particles were considered. The emphasis in this investigation is on the effects of nonspherical particles as compared with spherical particles on the coherent as well as incoherent intensities produced by multiple scattering.

Our formulation for the incoherent intensities is based on the equation of transfer for the Stokes' parameters, while the formulation for the coherent intensities is based on the classical approach of van de Hulst. A linearly polarized wave is assumed to be obliquely incident upon a plane-parallel medium containing the ensemble of particles. In principle, the equation of transfer can be solved exactly using the eigenvalue-eigenvector technique with the scattering characteristics of the particles being calculated using the extended boundary condition method[15] and a given drop size and orientation distribution. Numerical computation based on this technique is being carried out and results will be presented. The main purpose of the present investigation is to present the first-order solution to this problem dealing with non-spherical particles. It is believed that providing the first order expressions for the incoherent intensities represents the necessary initial step towards the complete solution of the multiple scattering problem.

As specific examples, numerical results based on the first-order solution are obtained for the co-polarized and cross-polarized intensities as functions of observation angle and optical depth for two types of particles: those with high loss tangent (i.e., high absorbent) and those with low loss tangent (i.e., low absorbent). As expected, we found that multiple scattering effects are more pronounced for ensemble of low absorbent particles than for ensemble of high absorbent particles.

Results of this investigation are given in a paper which has been submitted to Applied Optics for publication.[3]

(3) Vector radiative transfer equation for nonspherical particles.

It is important to distinguish the vector radiative transfer equation which is capable of including the polarization effects, from the scalar radiative transfer equation. In the following we shall delineate the formulation of the vector transfer equation for an ensemble of nonspherical particles. Let us now consider a specific geometry in order to obtain the multiple scattering effects. The geometry consists of a layer of uniformly distributed nonspherical particles of thickness d. (See Fig. 1) A linearly polarized

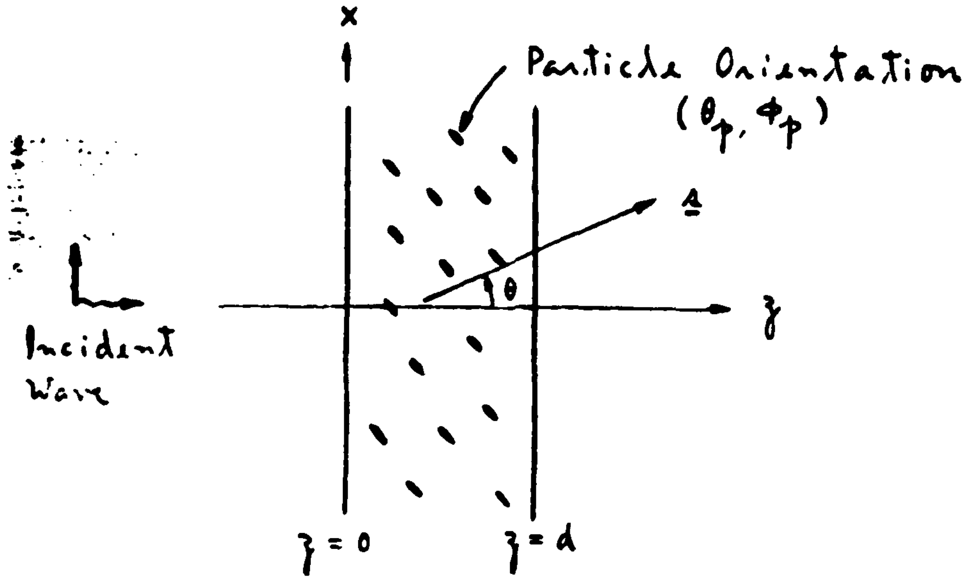

Fig. 1(a) Geometrical Configuration of the Problem.

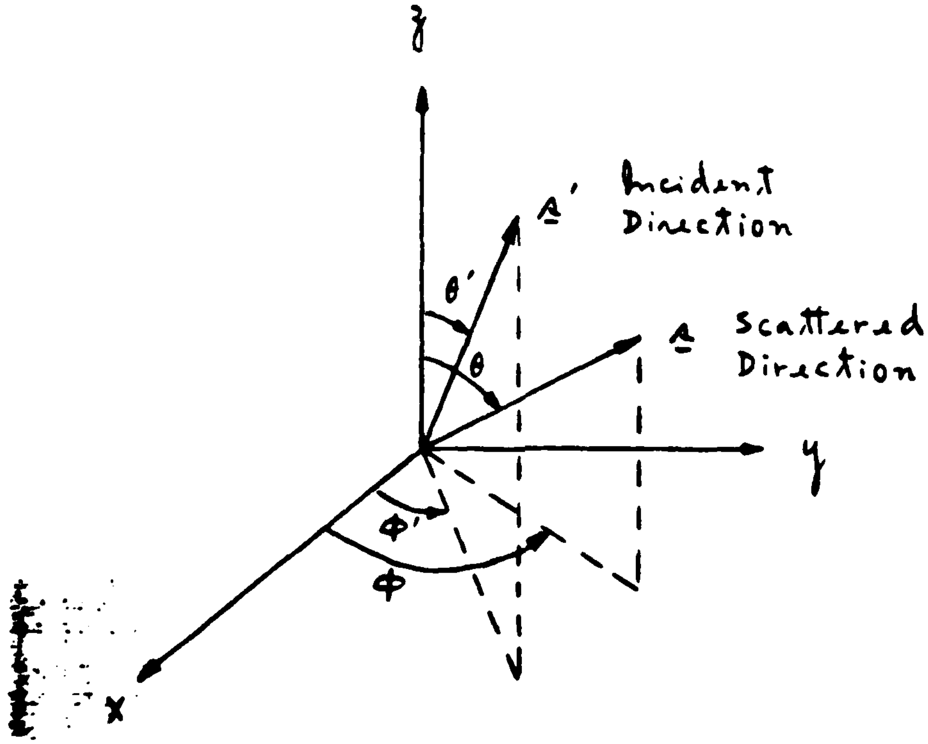

Fig. 1(b) Orientation of the Directions of the Incident and the Scattered Waves.

coherent plane wave is incident upon this layer of particles. We are interested in the transmitted co-polarized coherent intensities as well as the transmitted co-polarized and cross-polarized incoherent intensities. Consider the modified Stokes' parameters (I_1, I_2, U, V)[5]:

$$I_1 = \langle E_1 E_1^* \rangle, \; I_2 = \langle E_2 E_2^* \rangle$$
$$U = 2\mathrm{Re}\langle E_1 E_2^* \rangle, \; V = 2\,\mathrm{Im}\langle E_1 E_2^* \rangle \qquad (1)$$

where E_1 and E_2 are the electric field components in the θ and ϕ directions, respectively (Fig. 1), Re and Im denote the real part and the imaginary part, and the asterisk means the complex conjugate. The equation of transfer for arbitrarily shaped particles is given by

$$\mu \frac{d}{dz} [I] = [T][I] + \int [S][I']d\omega' + [I_i] \qquad (2)$$

where

$$[I] = \begin{bmatrix} I_1 \\ I_2 \\ U \\ V \end{bmatrix}$$

which is a 4x1 incoherent specific intensity matrix, and where

$[I_i]$ = 4x1 incident specific intensity matrix

$\rho[\ ]$ = integration over the size distribution $N(D)$, and so

$$\rho|f_{11}|^2 = \int_0^\infty |f_{11}(D)|^2 N(D)dD;$$

$[I]$ = incoherent specific intensity at z in the direction of (μ, ϕ), $I(z, \mu, \phi)$;

$[I']$ = incoherent specific intensity at z in the direction of (μ', ϕ'), $I(z, \mu', \phi')$;

$d\omega'$ = $d\mu' d\phi'$ = differential solid angle;

μ = $\cos\theta$;

μ' = $\cos\theta'$.

The scattering matrix [S] and the extinction matrix [T] are expressed in terms of the scattering amplitudes f_{11}, f_{12}, f_{21} and f_{22} as follows:

(f_{ij} are functions of $(\mu, \phi; \mu', \phi')$)

$$[S] = \begin{bmatrix} \rho|f_{11}|^2 & \rho|f_{12}|^2 & \rho\mathrm{Re}(f_{11}f_{12}^*) & -\rho\mathrm{Im}(f_{11}f_{12}^*) \\ \rho|f_{21}|^2 & \rho|f_{22}|^2 & \rho\mathrm{Re}(f_{21}f_{22}^*) & -\rho\mathrm{Im}(f_{21}f_{22}^*) \\ \rho 2\mathrm{Re}(f_{11}f_{21}^*) & \rho 2\mathrm{Re}(f_{12}f_{22}^*) & \rho\mathrm{Re}(f_{11}f_{22}^*+f_{12}f_{21}^*) & -\rho\mathrm{Im}(f_{11}f_{22}^*-f_{12}f_{21}^*) \\ \rho 2\mathrm{Im}(f_{11}f_{21}^*) & \rho 2\mathrm{Im}(f_{12}f_{22}^*) & \rho\mathrm{Im}(f_{11}f_{22}^*+f_{12}f_{21}^*) & \rho\mathrm{Re}(f_{11}f_{22}^*-f_{12}f_{21}^*) \end{bmatrix} \tag{3}$$

and

$$[T] = \begin{bmatrix} 2\mathrm{Re}M_{11} & 0 & \mathrm{Re}M_{12} & \mathrm{Im}M_{12} \\ 0 & 2\mathrm{Re}M_{22} & \mathrm{Re}M_{21} & -\mathrm{Im}M_{21} \\ 2\mathrm{Re}M_{21} & 2\mathrm{Re}M_{12} & \mathrm{Re}(M_{11}+M_{22}) & -\mathrm{Im}(M_{11}-M_{22}) \\ -2\mathrm{Im}M_{21} & 2\mathrm{Im}M_{12} & \mathrm{Im}(M_{11}-M_{22}) & \mathrm{Re}(M_{11}+M_{22}) \end{bmatrix} \tag{4}$$

with

$$M_{mp} = i\frac{2\pi}{k}\ \rho\ f_{mp}(\mu,\phi;\mu,\phi) \quad (m = 1, 2;\ p = 1, 2) \tag{5}$$

Here, the forward scattering amplitudes $f_{mp}(\mu,\phi;\mu,\phi)$ are obtained from the solution for the scattering by a single arbitrarily shaped particle For an incident wave whose electric field components E'_ℓ and E'_r are polarized along two mutually perpendicular directions $\underline{\ell}'$ and $\underline{r}'$ with $\underline{r}' = \dfrac{\underline{z} \times \underline{s}'}{|\underline{z} \times \underline{s}'|}$

$\underline{\ell}' = \underline{r}' \times \underline{s}'$, s' = direction of the incident wave, the scattered electric field components E_ℓ and E_r which are polarized along two mutually perpendicular directions $\underline{\ell}$ and $\underline{r}$ with $\underline{r} = \dfrac{\underline{z} \times \underline{s}}{|\underline{z} \times \underline{s}|}$, $\underline{\ell} = \underline{r} \times \underline{s}$, $\underline{s}$ = direction of the scattered wave, are

$$\begin{bmatrix} E_\ell(\underline{s}) \\ E_r(\underline{s}) \end{bmatrix} = \frac{e^{ikR}}{R} \begin{bmatrix} A'_{\ell\ell} & A'_{\ell r} \\ A'_{r\ell} & A'_{rr} \end{bmatrix} \begin{bmatrix} E'_\ell(\underline{s}') \\ E'_r(\underline{s}') \end{bmatrix} \qquad (6)$$

The f_{mp_1} ($m = 1, 2$; $p = 1, 2$) functions are related to $A'_{\ell\ell}$, $A'_{\ell r}$, $A'_{r\ell}$, A'_{rr} as follows:

$$\begin{bmatrix} f_{11} \\ f_{12} \\ f_{21} \\ f_{22} \end{bmatrix} = [Q] \begin{bmatrix} A'_{\ell\ell} \\ A'_{\ell r} \\ A'_{r\ell} \\ A'_{rr} \end{bmatrix} \qquad (7)$$

$$[Q] = \begin{bmatrix} -(c,c) & +(s,c) & -(c,s) & (s,s) \\ -(s,c) & -(c,c) & -(s,s) & -(c,s) \\ (c,s) & -(s,s) & -(c,c) & (s,c) \\ (s,s) & +(c,s) & -(s,c) & -(c,c) \end{bmatrix} \qquad (8)$$

$$(c,c) = \frac{-(r,r) + \chi\,(\ell,\ell)}{1 - \chi^2} \qquad (9)$$

$$(c,s) = \frac{(r,\ell) + (\ell,r)}{1 - \chi^2} \qquad (10)$$

$$(s,c) = \frac{-(\ell,r) - \chi\,(r,\ell)}{1 - \chi^2} \qquad (11)$$

$$(s,s) = \frac{(\ell,\ell) - \chi\,(r,r)}{1 - \chi^2} \qquad (12)$$

with

$$\begin{aligned}
(\ell,\ell) &= [(1-\mu^2)\,(1-\mu'^2)]^{1/2} + \mu\mu' \cos(\phi'-\phi) \\
(\ell,r) &= -\mu' \sin(\phi'-\phi) \\
(r,\ell) &= \mu \sin(\phi'-\phi) \qquad (13) \\
(r,r) &= \cos(\phi'-\phi) \\
\chi &= \cos(\Theta) = [(1-\mu^2)\,(1-\mu'^2)]^{1/2} \cos(\phi'-\phi) + \mu\mu' \\
\mu &= \cos\theta \\
\mu' &= \cos\theta'.
\end{aligned}$$

(θ',ϕ') and (θ,ϕ) correspond to the incident and scattered wave directions, respectively and Θ is the angle between the incident and scattered waves. The scattering functions $A'_{\ell\ell}$, $A'_{\ell r}$, $A'_{r\ell}$, and A'_{rr} from a single arbitrarily shaped scatterer can be calculated according to the extended boundary condition approach (the T-matrix approach).[15]

The incident specific intensity matrix $[I_i]$ is the source function generated by the scattering of the reduced incident specific intensity $[I_{ri}]$ propagating in the direction of $\mu_i = \cos\theta_i$ and $\phi_i = 0$, and is given by

$$[I_i] = \int [S][I_{ri}]d\omega' \tag{14}$$

where $[I_{ri}]$ is given by the incident Stokes vector $[I_o]$

$$[I_{ri}] = [Q][I_o] \tag{15}$$

and $[Q]$ is the 4x4 matrix. We can also express $[I_{ri}]$ using the field representation.

If the incident wave with the total intensity of unity is polarized parallel to the x-z plane (vertical polarization), $[I_0]$ is given by

$$[I_0] = \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix} \tag{16}$$

Similarly, if the incident wave is polarized perpendicular to the x-z plane (horizontal polarization), we have

$$[I_0] = \begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \end{bmatrix} \tag{17}$$

The boundary condition for the incoherent specific intensity $[I]$ is

$$\begin{aligned} [I] &= 0 \quad \cos\theta > 0 (0 \le \mu \le 1) \text{ at } z = 0 \\ [I] &= 0 \quad \cos\theta < 0 (0 \ge \mu \ge -1) \text{ at } z = d \end{aligned} \tag{18}$$

The equation of transfer (Eq.(2)) and the boundary condition (18) constitute the complete mathematical formulation of the problem. This is an integro-differential equation with five variables (z, μ, μ', ϕ, and ϕ').

(4) Multiple scattering calculations for nonspherical particles based on the vector radiative transfer theory.[4]

In this investigation we shall consider the multiple scattering of a linearly polarized plane wave incident upon a plene-parallel slab consisting of uniformly distributed identical particles. It is assumed that every particle is a spheroid whose symmetry axis is normal to the slab. We aim at computing the incoherent field that is generated within the slab, in terms of its Stokes' vector. Our starting-point is the integro-differential equation of radiative transfer.[5,9] This formulation provides the incoherent Stokes' vector for a given normal or oblique illumination as a function of the scattering amplitudes of a single particle. Both attenuation and multiple scattering are taken into account. The analysis is based upon the Fourier expansion of this equation of transfer. Because of the specific symmetry and orientation of the particles, the Fourier components of the Stokes' vector are independent of one another. Such a decoupling enables us to determine a given component by solving the separate equation of transfer that it will satisfy. After an estimate of the integral terms by Gauss' quadrature, the component's values on a net of discrete backward and forward directions are solutions of a system of first-order differential equations with constant coefficients and are computed by an eigenvalues-eigenvector technique. A partial sum of the Fourier series composed of such components represents the incoherent Stokes' vector; in the case of normal incidence, only tow such components are different from zero (order 0 and 2).

The behavior of the incoherent field is thereby investigated for low-loss particles (ice) and high-loss particles (smoke) illuminated by x-polarized waves under typical incidences. Patterns of the x-polarized (co-polarized) and y-polarized (cross-polarized) incoherent intensities versus the direction of observation are computed. These results enable us to examine the convergence of the process and the influence of the particles' geometry and distribution. The consequences of the low- or high-losses are emphasized. Comparisions with results obtained by a first-order scattering theory are also carried out. Initial indication is that excellent qualitative as well as quantitative agreement was found for low particle density - small optical depth medium and good qualitative (but not so good quantitative) agreement was also apparent for higher particle density - larger optical depth medium.

Results of this investivation will be given in a paper which will be submitted to Radio Science for publication.[4]

Let us now discuss further the two ways of solving the vector radiative transfer equation as discussed in sections (2)-(4) above. The first way, the exact way, starts with the expansion of the vector radiative transfer equation in Fourier series in ϕ. The integral with respect to μ' is converted to a series representation by the Gauss' quadrature formula. The resultant set of coupled linear first-order equations are then solved by the eigenvalue-eigenfunction technique with the given boundary conditions. The second way, the approximate way, uses a perturbation technique on the transfer equation. The result, called the first-order solution, is a set of analytic expressions for the incoherent intensities. We have progressed in both of these directions: The attractiveness of the first-order approach is in its simplicity and clarity and the ease of obtaining numerical results while the exact approach, although very complicated, provides accurate results which can be used as reference or check points for the first-order or other approximate approaches. The exact results may also provide regions of validity for the approximate first order expressions. It is noted that because of complexity of the exact approach and the many resultant numerical difficulties associated with large, ill-conditioned matrices, extreme care must be taken in performing the calculations. We have successfully treated the problem of a slab of uniformly distributed identical oblate or prolate spheroidal particles with their symmetry axis aligned along the normal direction of the slab. Different sizes, shapes, and densities of the particles as well as different incident angles for the plane wave were considered. This is the first time that such a calculation taking into consideration the complete polarization effects has been carried out for an ensemble of the nonspherical particles.

It can be seen from the above summary of accomplishments that starting with the vector radiative transfer theory including the depolarization effects, we have been able to

- obtain the first-order expression for the coherent and incoherent intensities for waves propagating through an ensemble of spherical or nonspherical particles,
- expand the vector radiative transfer equation for nonspherical particles in Fourier series. (In general, all Fourier components are coupled to each other. We have investigated the special case for which the Fourier components are decoupled),
- obtain specific numerical solution to the vector radiative transfer equation for certain orientation and symmetry of the nonspherical particles,

- **discuss the limitation of the radiative transfer theory based on experimental evidence (In general, the radiative transfer theory is applicable when the particle density is approximately less than 1% in volume.).[16]**

III. Future Research Areas

Having developed our capability in solving the vector transport equation for nonspherical particles, we are now in a position to expand our horizon to perform research in the following areas:

- Further development of general numerical codes of vector radiative transfer solutions.
- Beam propagation in an ensemble of spherical or nonspherical particles where multiple scattering effects are important.
- Wave propagation in a medium with non-uniform density distribution of particles.
- Pulse propagation in a random distribution of discrete spherical or nonspherical scatterers.

IV. Listings of Papers and Presentations

The following is a list of papers and presentations by our group during the current ARO research program.

(a) "Matrix representations of the vector radiative transfer theory for randomly distributed nonspherical particles" JOSA A, 1, pp. 359-364 (1984).

(b) "First order multiple scattering theory for nonspherical particles", to appear in Appl. Opt. (1984)

(c) "Multiple scattering calculations for nonspherical particles" based on the vector radiative transfer theory" to appear in Radio Science (1984).

(d) "Multiple scattering by nonspherical particles" presented at the 1982, 1983 and 1984 CLS Scientific Conference on Obscuration and Aerosol Research, Aberdeen Proving Group (U. S. Army), Maryland.

(e) "Vector radiative transfer theory" presented at the 1984 URSI - International AP-S Meeting, Boston, Mass.

V. Personnel

Principal Investigator:

Cavour Yeh (Senior Engineer)

Other Research Personnel

Akira Ishimaru (Senior Engineer)

D. Lesselier (Engineer)

E. Tong (Programmer)

F. Manshadi (Programmer)

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3. A. Ishimaru, C. Yeh and D. Lesselier, "First order multiple scattering theory for nonspherical particles", Submitted to Applied Optics (1983)

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