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CHARACTERISTICS OF COHERENT AND INCOHERENT WAVES IN
SNOW AT MICROWAVE AND MILLIMETER WAVE FREQUENCIES(U)
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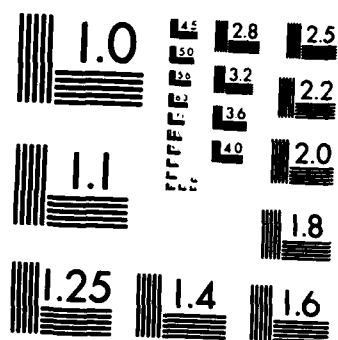
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) This final report summarizes our research findings in the study of the characteristics of coherent and incoherent waves in snow. We have conducted theoretical studies in dense media radiative transfer theory, backscattering enhancement, conventional transport theory and inverse scattering in random media.		

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CHARACTERISTICS OF COHERENT AND INCOHERENT WAVES IN SNOW
AT MICROWAVE AND MILLIMETER WAVE FREQUENCIES

FINAL REPORT

Period: October 15, 1985 to October 14, 1987

Leung Tsang

December 15, 1987

U.S. ARMY RESEARCH OFFICE

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I. STATEMENT OF THE PROBLEM

The propagation of electromagnetic waves in snow at microwave and millimeter wave frequencies is affected by volume scattering. Snow is a dense nontenuous medium. In a dense medium, the particles occupy an appreciable fractional volume. In a nontenuous medium, the permittivities of the particles are significantly different from that of the background medium. Our studies are directed towards basic theoretical investigations on effects of multiple scattering of waves in dense nontenuous media. We apply the theory to study the characteristics of coherent and incoherent waves in snow at microwave and millimeter wave frequencies.

II. SUMMARY OF IMPORTANT RESULTS

A. Dense Media Radiative Transfer Equation

Snow can be characterized as dense media. We have made progress in the study of active and passive microwave remote sensing of dense media. In a dense nontenuous medium, the classical radiative transfer theory, which is based on the assumption of independent scattering, is not valid. A set of transfer equations has been derived for dense nontenuous media. The derivation is based on field theory under the quasi-crystalline approximation with coherent potential on the first moment of the field and the modified ladder approximation on the second moment of the field. These equations are called radiative wave equations. They include a summation of all the ladder terms and assume a form that is identical to the classical transfer equations. However, the relations of the extinction coefficient, the scattering coefficient, the albedo, and the phase functions to the physical parameters of the medium are modified to include the effects of dense media. The new equations still preserve the advantages that (i) multiple scattering of the incoherent intensities are included, (ii) energy conservation and reciprocity are obeyed, and (iii) the form of the equations remains the same as the conventional transfer equations so that numerical solutions are calculated in the same manner. In addition, the dense media transfer equation takes into account (i) scattering by correlated scatterers, (ii) pair-distribution function of scatterer positions, and (iii) the effective propagation constant of a dense medium.

Numerical solutions of the dense-media radiative wave equations are illustrated as a function of incident angles, scattered angles, and physical parameters of the medium. We have derived the radiative wave equations for the scalar wave problem, for the vector electromagnetic propagation of the active remote sensing problem, and for the passive remote sensing problem. The results of passive remote sensing have found good agreement with measurements of snow.

Polarimetric signatures are also calculated. Presently, we are extending the model to study high frequency effects as well as media with multi-species of particles.

B. Backscattering Enhancement

Backscattering enhancement has been observed in laboratory controlled experiments of scattering from discrete particles. The effect is not contained in the ladder approximation nor in the radiative transfer theory because the cyclical diagrams which contribute significantly in the backscattering direction have been ignored. We have first examined backscattering enhancement by a second-order cyclical theory and have completed a study based on the resummation of all the cyclical diagrams. For the case of small scatterers or Rayleigh scatterers, the theory predicts a sharp peak in the backscattering direction of angular width of the order $2K''/K'$ where K' and K'' are the real and imaginary parts, respectively, of the effective propagation constant. A modified cyclical resummation, which includes the correlation of particle positions for dense media with small particles, has also been performed.

For the case of moderate-size particles, the scattering is non-isotropic. We studied the backscattering enhancement of waves by nonisotropic scatterers. Multiple scattering effects are included by examining the summation of all the ladder terms and all the cyclical terms. If the observation angle is in the neighborhood of the backscattering direction, it is shown that both summations can be related to the unidirectional point source Green's function of the transport equation. For the case of small albedo or small optical thickness, the second-order theory is applied to calculate the Green's function. The angular width of backscattering enhancement in this case is of the order of the coherent wave attenuation rate divided by the wavenumber. For the case of large albedo and large optical thickness, the diffusion approximation is used to calculate the Green's function. For this case, the angular width is of the order of the transport rate divided by the wavenumber. The transport rate is equal to the product of the coherent wave attenuation rate and one minus the mean cosine of the scattering angle. Hence, the angular width is substantially smaller for particles with dominant forward scattering and is in good agreement with experimental observations. Presently, we are extending the diffusion approximation to the case of vector cyclical equations and also that of beam propagation. The effects of pair-distribution functions are also investigated.

C. Inverse Problems in Random Media

The inverse source problem of the scalar wave equation for a monochromatic source is generalized to the case of an inhomogeneous attenuative medium. The attenuative medium can be a lossless random medium or a lossy deterministic medium in which the coherent field attenuates. Two generalized holographic imaging equations are obtained based on the usage of two Green's function G_+^* and G_- . The kernel of the first equation with G_+^* is Hermitian and depends on the location and shape of the recording surface while the equation G_- has a non-Hermitian kernel that is independent of the recording surface. The solutions of the integral equations are investigated. The nonuniqueness of the solutions are also related to the nonradiating sources and to the minimum energy solution.

D. Conventional Transport Theory

We have investigated the small-angle approximation to discrete random media for the transport theory. Studies were performed for both plane wave and beam wave solutions. It is found that for particles with an index of refraction close to 1 and a size parameter larger than 10, the agreement is excellent. However, for optical propagation through fog, the difference between the radiative transfer and small-angle approximation can be more than 30%.

III. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSORSHIP DURING THIS PERIOD

1. L. Tsang and A. Ishimaru, "Radiative wave and cyclical transfer equations for dense nontenuous media," Journal of the Optical Society of America A, 2(12), 2187-2194, December 1985.
2. L. Tsang and A. Ishimaru, "Radiative wave equations for vector electromagnetic propagation in dense nontenuous media," Journal of Electromagnetic Waves and Applications, 1(1), 59-72, 1987.
3. L. Tsang, "Passive remote sensing of dense nontenuous media," Journal of Electromagnetic Waves and Applications, 1(2), 159-173, 1987.
4. L. Tsang, A. Ishimaru, R. P. Porter, and D. Rouseff, "Holography and the inverse source problem. III. Inhomogeneous attenuative media," Journal of the Optical Society of America A, 4(9), 1783-1787, September 1987.
5. S. L. Broschat, L. Tsang, A. Ishimaru, and E. I. Thorsos, "A numerical comparison of the phase perturbation, field perturbation, and Kirchhoff approximations for random rough surface scattering," in press, Journal of Electromagnetic Waves and Applications.
6. A. Ishimaru and L. Tsang, "Backscattering enhancement of random discrete scatterers of moderate sizes," in press, Journal of the Optical Society of America.

IV. PAPER PRESENTATIONS AT MEETINGS DURING THIS PERIOD

1. L. Tsang and A. Ishimaru, "Radiative Transfer Equations Modified for Application to Dense Nontenuous Media," International Union of Radio Science Meeting, Commissions B & F, Boulder, Colorado, January 1986.
2. L. Tsang, "Passive Remote Sensing of Terrain with a Dense Distribution of Particles," International Union of Radio Science Meeting, Commission F, Philadelphia, Pennsylvania, June 1986.
3. Y. Kuga, A. Ishimaru, H.-W. Chang, and L. Tsang, "Comparisons Between the Small-Angle Approximation and the Numerical Solution for Radiative Transfer Theory," Optical Society of America Annual Meeting, Seattle, Washington, October 1986.
4. S.-H. Lou, Y. Kuga, L. Tsang, and A. Ishimaru, "Laser Beam Propagation Through Turbid Media Using Small-Angle Approximation for Radiative Transfer Equations," Optical Society of America Annual Meeting, Seattle, Washington, October 1986.
5. L. Tsang and A. Ishimaru, "Backscattering Enhancement for Random Discrete Scatterers of Moderate Size," International Union of Radio Science Meeting, Boulder, Colorado, January 1987.

6. L. Tsang and B. Wen, "Conventional and New Radiative Transfer Equations for Volume Scattering in Geophysical Media," 1987 International Geoscience and Remote Sensing Symposium and International Union of Radio Science Commission F Meeting, University of Michigan, Ann Arbor, Michigan, May 1987.
7. D. P. Winebrenner, L. Tsang, and B. Wen, "Polarimetric Signatures and Incoherent Geophysical Information in Remote Sensing of Natural Media," 1987 International Geoscience and Remote Sensing Symposium and International Union of Radio Science Commission F Meeting, University of Michigan, Ann Arbor, Michigan, May 1987.

V. PARTICIPATING SCIENTIFIC PERSONNEL

Leung Tsang	Principal Investigator
Yasuo Kuga	Research Assistant Professor, Investigator
Boheng Wen	Research Assistant (Ph.D. expected June 1988)
Kung-Hau Ding	Research Assistant (Ph.D. expected December 1988)
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Radiative wave and cyclical transfer equations for dense nontenuous media

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In a dense medium, the discrete scatterers occupy an appreciable fractional volume. In a nontenuous medium, the index of refraction of the scatterers is significantly different from that of the background medium. In a dense nontenuous medium, the classical radiative-transfer theory, which is based on the assumption of independent scattering, is not valid. In this paper, a set of transfer equations has been derived for dense nontenuous media. The derivation is based on field theory under the quasi-crystalline approximation with coherent potential on the first moment of the field and the modified ladder approximation on the second moment of the field. These equations are called radiative wave equations. They include a summation of all the ladder terms and assume a form that is identical to the classical transfer equations. However, the relations of the extinction coefficient, the scattering coefficient, the albedo, and the phase functions to the physical parameters of the medium are modified to include the effects of dense media. Numerical solutions of the dense-media radiative wave equations are illustrated as a function of incident angles, scattered angles, and physical parameters of the medium. The backscattering-enhancement phenomenon is accounted for by a summation of the cyclical scattering terms into a cyclical transfer equation for dense nontenuous media. Numerical solutions of the cyclical transfer equation are also illustrated.

Radiative Wave Equations for Vector Electromagnetic Propagation in Dense Nontenuous Media

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Abstract— A set of radiative wave equations including all four Stokes parameters is derived for vector electromagnetic wave propagation in dense nontenuous media. The derivation is based on the quasi-crystalline approximation with coherent potential on the first moment of the field, and the modified ladder approximation on the second moment of the field. These two approximations are shown to be energetically consistent for dense nontenuous media. To simplify the derivation of the radiative wave equations, the model of small spherical scatterers is used. The derived radiative wave equations assume the same form as the classical radiative transfer equations. However, the relations of the extinction rate, the albedo and the phase matrix to the physical parameters of the media include the effects of dense media and can be different from the classical relations of independent scattering.

INTRODUCTION

In a dense medium, the particles occupy an appreciable fractional volume. In a nontenuous medium, the dielectric properties of the particles are significantly different from that of the background medium. In recent years, studies have been made in the propagation and scattering of waves in dense nontenuous media with applications to geophysical terrain such as snow, ice-covered land, soil and vegetation [1-9]. In a dense nontenuous medium, the assumption of independent scattering, that is often used in radiative transfer theory [10], is not valid. The model of a continuous random medium, that has been applied to turbulent media with a small refractive index fluctuation [11] is not appropriate and the discrete scatterer model is to be preferred. Differences between continuous medium theory and discrete scatterer theory have also been discussed [12].

To reconcile the radiative transfer theory and the analytic wave theory, it is possible to derive radiative transfer type equations from the second moment equation of the analytic wave theory [8,12]. These types of equations are similar in form to the classical transfer equation. We call them radiative wave equations to distinguish them from the classical radiative transfer equations because (1) they are derived from wave theory and not heuristic and (2) they often correct the deficiencies of the classical transfer equation when the latter is not valid. In such cases, major differences exist between the radiative wave equations and the clas-

Passive Remote Sensing of Dense Nontenuous Media

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Abstract— The thermal microwave emission of media with dense distribution of particles is studied. A general relation, that holds for media with nonuniform as well as uniform temperature distribution, is first derived between active and passive remote sensing. The brightness temperature of passive sensing is proportional to the integration of the product of the temperature distribution and the divergence of the Poynting's vector of active sensing. The governing radiative transfer equations for passive remote sensing of dense media are then derived by reference to the corresponding radiative wave equations for active sensing. The radiative wave equations are based on quasicrystalline approximation with coherent potential for the first moment of the field and a modified ladder approximation for the second moment of the field. The numerical results for classical radiative transfer theory and the dense media transfer theory are compared. The theory is also used to compare with brightness temperature measurements over a snow field.

I. INTRODUCTION

In recent years, studies have been made in the propagation and scattering of waves in dense nontenuous media with applications to geophysical terrain such as snow, ice-covered land, soil and vegetation [1-10]. In a dense nontenuous medium, the assumption of independent scattering, that is often used in classical radiative transfer theory, [11] is not valid. To reconcile the radiative transfer theory and the analytic wave theory, it is possible to derive radiative transfer type equations from the second moment equation of the analytic wave theory [9, 12]. We call them radiative wave equations to distinguish them from the classical radiative transfer equations because (1) they are derived from wave theory and not heuristically, and (2) they often correct the deficiencies of the classical transfer equation when the latter is not valid.

In this paper, a set of radiative wave equations is derived for passive remote sensing of media with a dense distribution of particles. A general relation is first derived between active and passive remote sensing, that holds for media with nonuniform as well as uniform temperature distribution. By using the fluctuation-dissipation theorem [9] and the symmetry relation of Green's functions, it is shown that the brightness temperature of passive sensing is proportional to the integration of the product of the temperature distribution and the divergence of the Poynting's vector of active sensing. The governing radiative wave equations for passive sensing are next derived by reference to the corresponding equations that were derived for active sensing in a previous paper [13]. The radiative wave equa-

Holography and the inverse source problem.

III. Inhomogeneous attenuative media

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Received November 5, 1986; accepted April 21, 1987

The inverse source problem of the scalar wave equation for a monochromatic source is generalized to the case of an inhomogeneous attenuative medium. The attenuative medium can be a lossy deterministic medium or a lossless random medium in which the coherent field attenuates. Two generalized holographic imaging equations are obtained that are based on the use of two Green's functions, G_+ and G_- . The kernel for the first equation with G_+ is Hermitian and depends on the location and the shape of the recording surface, whereas the equation with G_- has a non-Hermitian kernel that is independent of the recording surface. The solutions of the integral equations are investigated. The nonuniqueness of the solutions are also related to the nonradiating sources and to the minimum energy solution.

INTRODUCTION

A problem that arises in optics and acoustics is the inverse source problem,¹⁻⁴ the solution of which consists of deducing the source from measurements of the radiated field performed outside the volume containing the source. The inverse source problem is usually formulated in terms of integral equations relating the source to some quantity calculated from the measured fields. Such equations are sometimes called *generalized holographic-imaging equations*. Studies have also been made on the uniqueness of the solution of the integral equation, which has been related to the possible existence of nonradiating sources.³⁻⁶ Previous treatment of the inverse source problem has assumed the medium to be homogeneous and lossless. Recently, an extension has been made to the case in which the medium is inhomogeneous and nonabsorbing.⁷

In many practical situations, the background medium is lossy. Absorption effects are often important in optics, microwaves, and acoustics. For the case of wave propagation in random media,^{8,9} the coherent wave propagates in an effective medium and attenuates with distance. In this paper we generalize the results of the inverse source problem of Refs. 4 and 7 to an inhomogeneous attenuative medium. Two integral equations are obtained that are based on the use of two Green's functions. In the first case, the backpropagated wave attenuates back to the source region. The kernel is complex Hermitian. However, it is dependent on the location and the shape of the recording surface. The mathematical development in this case is similar to that of Ref. 7. In the second case the backpropagated wave grows back to the source region. The kernel is independent of the location and the shape of the recording surface, which has to lie outside the source region. However, the kernel is complex non-Hermitian. The solutions of the two integral equations are investigated. The nonuniqueness of the solutions is also related to the nonradiating sources and to the minimum energy sources.

PROBLEM STATEMENT

We consider the inverse source problem for a localized monochromatic source $\rho(\mathbf{r})$ embedded in an inhomogeneous attenuative medium. The wave equation is

$$(\nabla^2 + k_0^2 n^2(\mathbf{r}))\psi(\mathbf{r}) = -\rho(\mathbf{r}), \quad (1)$$

where k_0 is the free-space wave number. The index of refraction is a complex quantity and is a function of position:

$$n(\mathbf{r}) = n'(\mathbf{r}) + in''(\mathbf{r}), \quad (2)$$

with $n'(\mathbf{r}) > 0$ and $n''(\mathbf{r}) \geq 0$. Superscript primes and double primes are used to denote the real and imaginary parts, respectively. The source region is τ , and the recording surface Σ is outside the source region. The wave function ψ and its normal derivative are known on the recording surface.

There are two Green's functions $G_+(\mathbf{r}, \mathbf{r}')$ and $G_-(\mathbf{r}, \mathbf{r}')$ associated with the medium. The Green's function G_+ denotes an outgoing attenuative wave from a point source, and the Green's function G_- represents an incoming growing wave:

$$(\nabla^2 + k_0^2 n^2(\mathbf{r}))G_+(\mathbf{r}, \mathbf{r}') = -\delta(\mathbf{r} - \mathbf{r}'), \quad (3)$$

$$(\nabla^2 + k_0^2 n^2(\mathbf{r}))G_-(\mathbf{r}, \mathbf{r}') = -\delta(\mathbf{r} - \mathbf{r}'). \quad (4)$$

It then follows that the wave function ψ is

$$\psi(\mathbf{r}) = \int_{\tau} d\mathbf{r}' G_+(\mathbf{r}, \mathbf{r}') \rho(\mathbf{r}'). \quad (5)$$

For the case in which the medium is homogeneous with $n(\mathbf{r}) = n_0$, the Green's functions G_{0+} and G_{0-} are, respectively,

$$G_{0+}(\mathbf{r}, \mathbf{r}') = \frac{\exp(ik|\mathbf{r} - \mathbf{r}'|)}{4\pi|\mathbf{r} - \mathbf{r}'|}, \quad (6)$$

$$G_{0-}(\mathbf{r}, \mathbf{r}') = \frac{\exp(-ik|\mathbf{r} - \mathbf{r}'|)}{4\pi|\mathbf{r} - \mathbf{r}'|}. \quad (7)$$

with

**A Numerical Comparison of the Phase Perturbation,
Field Perturbation, and Kirchhoff Approximations
for Random Rough Surface Scattering**

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Running head: Numerical comparison of rough surface scattering methods

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ABSTRACT — The phase perturbation technique is a method for treating wave scattering from rough surfaces. Winebrenner and Ishimaru showed that the phase perturbation expressions for the reflection and backscattering coefficients reduce to those of classical field perturbation theory for small surface roughness. Their analysis also indicated that the reflection coefficient reduces exactly and the backscattering coefficient approximately to those of the Kirchhoff approximation for gently undulating surfaces. We numerically verify these results for a one-dimensional surface with Gaussian surface spectrum satisfying Dirichlet boundary conditions. We find that the phase perturbation backscattering coefficient reduces numerically to that of Kirchhoff over a large range of parameter values when the Kirchhoff approximation is considered to be valid. In addition, the phase perturbation results differ from the field perturbation and Kirchhoff results when neither classical method is expected to give accurate results. Energy conservation is also considered.

perturbation methods

Kirchhoff approximation

rough surface scattering

wave scattering

random Gaussian surfaces

BACKSCATTERING ENHANCEMENT OF RANDOM DISCRETE
SCATTERERS OF MODERATE SIZES

by

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Abstract:

The scattering of waves by particles of moderate size is nonisotropic. In this paper, the backscattering enhancement of scattering of waves by nonisotropic scatterers is studied. Multiple scattering effects are included by examining the summation of all the ladder terms and all the cyclical terms. If the observation angle is in the neighborhood of the backscattering direction, it is shown that both summations can be related to the unidirectional point source Green's function of the transport equation. For the case of small albedo or small optical thickness, the second order theory is applied to calculate the Green's function. The angular width of backscattering enhancement in this case is of the order of the coherent wave attenuation rate divided by the wavenumber. For the case of large albedo and large optical thickness, the diffusion approximation is used to calculate the Green's function. For this case, the angular width is of the order of the transport rate divided by the wavenumber. The transport rate is equal to the product of the coherent wave attenuation rate and one minus the mean cosine of the scattering angle. Hence, the angular width is substantially smaller for particles with dominant forward scattering and is in good agreement with experimental observations.

B11/F4-5 RADIATIVE TRANSFER EQUATIONS MODIFIED FOR
1020 APPLICATION TO DENSE NONTENUOUS MEDIA
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B11/
1040

The classical radiative transfer equation has been used extensively in studying volume scattering in remote sensing problems. The advantages of using the radiative transfer theory are that (i) multiple scattering of the incoherent intensities are included in the theory, (ii) energy conservation is satisfied, and (iii) numerical solutions are tractable. However, the transfer equation, in its classical form, is not applicable for dense nontenuous media.

In a dense medium, the particles occupy an appreciable fractional volume. In a nontenuous medium, the permittivity of the particles is significantly different from that of the background medium. In a dense nontenuous medium, the assumption of independent scattering of the particles no longer holds so that the classical transfer equation is not valid. In this paper, we derive a set of "new" transfer equations from analytic wave theory. The approximations made on the analytic wave theory are (i) quasi-crystalline approximation with coherent potential on the first moment of the field and (ii) a modified ladder approximation for the second moment of the field. These two approximations are shown to satisfy energy conservation. The differences between the "new" set of transfer equations and the classical ones will be discussed. Both the scalar wave equations and the vector electromagnetic propagation will be studied.

PASSIVE REMOTE SENSING OF TERRAIN WITH A
DENSE DISTRIBUTION OF PARTICLES

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Passive remote sensing has been applied to terrain media where particles are densely distributed. The radiative transfer equation, in its classical form, has been commonly used to study the volume scattering effects of these problems. However, it has been demonstrated, both experimentally and theoretically, that independent scattering is not true in media with a dense distribution of particles, and the classical radiative transfer equation is not valid.

Recently, a set of "new" transfer equations has been derived from analytic wave theory for dense media. The differences between the "new" set of transfer equations and the classical ones will be discussed. The new equations still preserve the advantages that (i) multiple scattering of the incoherent intensities are included, (ii) energy conservation is satisfied, and (iii) numerical solutions are tractable. Numerical results of the brightness temperatures based on the theory will be illustrated using the physical parameters of the terrain media.

Commission F: Remote Sensing Theory

Presented at the National Radio Science Meeting, Philadelphia, Pennsylvania, June 1986.

Friday

AFTERNOON

24 October 1986

FL

RAINIER ROOM

1:00 PM Atmospheric Optics

James H. Charnick, NOAA EPL Wave Propagation Laboratory, Presider

FL1 Atmospheric isoplanatic angle measurements

DONALD L. WALTERS, KURT S. STEVENS, Naval Postgraduate School, Physics Department, Monterey, CA 93943.

Four generations of atmospheric isoplanatic angle sensors have recently evolved. An apodized 20-cm aperture lightweight low-cost instrument has been developed that achieves accurately weighted isoplanatic angle measurements with 1-s time resolution. Comparing data from four different locations in the northern hemisphere, at least three general isoplanatic angle categories are evident. Frequently we observe rapid, 10 s to several minutes, 200-400% variations in the atmospheric isoplanatic angle. The location of the atmospheric jet stream is the most significant forcing function. (12 min)

FL2 Photoacoustic measurements of atmospheric aerosol absorption coefficients in the ultraviolet, visible, and infrared

DEBBY C. RAMSEY-BELL, DONALD R. HUFFMAN, U. Arizona, Atmospheric Sciences Department, Tucson, AZ 85721.

Atmospheric particles affect the global climate by absorbing and scattering electromagnetic radiation. Knowledge of their optical properties at solar wavelengths (0.3-4 μm) and terrestrial wavelengths (8-20 μm) is needed. Photoacoustic measurements using broadband visible light have been previously made, resulting in values for the atmospheric aerosol absorption coefficient of $1 \times 10^{-7} \text{ m}^{-1}$. The photoacoustic instrument has been modified for narrowband measurements in the ultraviolet through infrared regions. Absorption coefficient spectra have been obtained for atmospheric particulates collected at mountain altitudes and in Tucson, Arizona. This information has been used for identification of the absorbing material.

Spectral differences are found for samples collected in urban and remote locations. Differences are also seen in spectra for small particles (<0.4 μm) and large particles (>0.4 μm). (12 min)

1. D. C. Ramsey-Bell and G. Couture, Appl. Opt. 24, 2397 (1985).

FL3 Comparisons between the small-angle approximation and the numerical solution for radiative transfer theory

YASUO KUGA, AKIRA ISHIMARU, HUNG-WEN CHANG, LEUNG TSANG, U. Washington, Department of Electrical Engineering, Seattle, WA 98195.

The small-angle approximation for the radiative transfer theory is based on the assumption that the scattered wave is confined within a small angle in the forward direction. This assumption is generally valid for the turbulence case in which the turbulence size is much greater than the wavelength and the index of refraction is close to 1. However, the validity of this assumption for a discrete random

medium with an index of refraction much greater than the surrounding medium is not well known. In spite of this, the small-angle approximation has sometimes been used for discrete random media because of its mathematical simplicity.

We first investigate the validity of the assumption using the Mie solution. We then present the numerical results of the plane wave case for different values of size parameter, index of refraction, and optical distance. The agreement between the small-angle approximation and the radiative transfer theory is excellent when the index of refraction is close to 1 and the size parameter is larger than 10. However, for optical wave propagation through fog, the difference between radiative transfer and small-angle approximation is more than 30%. (12 min)

FL4 Laser beam propagation through turbid media using small-angle approximation for radiative transfer equations

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Laser beam propagation through fog or cloud is a problem of considerable interest. Although numerical solutions of the radiative transfer equation are available for the case of plane wave incidence, only very few numerical solutions are calculated for the beam wave case because of the formidable amount of computation time required. The small-angle approximation has been shown to be useful for light wave propagation in turbulent media where the variance of index of refraction fluctuations is small. However, its applicability to turbid media with discrete scatterers is not clear because of the much larger contrast in the index of refraction. The small-angle approximation is used to calculate the beam wave solution through foggy atmospheres at visible wavelengths. The Henyey-Greenstein phase function is used to describe the scattering characteristics of the particles. The mutual coherence function is first calculated and then the intensity and the specific intensities are calculated. Numerical results are illustrated as a function of optical thickness and the mean cosine of scattering angles. They are compared with available exact numerical solutions of the transport equations and are also used to explain the results observed in laboratory experimental data. (12 min)

FL5 Power spectra of turbulence-induced wavefront aberrations and optical path difference

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When a point source radiates wavefronts which traverse a turbulent atmosphere, the received wavefronts will contain aberrations which vary in time. In addition, if several point sources radiate in an array configuration, the resulting wavefronts will contain optical path differences. As a result, the phase profiles incident on an unobscured collecting aperture will be distorted in a time-varying pattern.

We have expanded the phase profile in a basis set of Zernike polynomials and computed the power spectrum appropriate to each polynomial coefficient. The technique used incorporates Parseval's identity to allow evaluation of certain inner products in the frequency domain. This allows us to simplify the analysis considerably and to extend it to arbitrary orders of basis set polynomials.

We have written a computer program to quickly evaluate the spectra for relatively low-order aberrations in various conditions, and we present some of those results. (12 min)

FL6 Fundamental two-scale solution for a wave propagating in a random medium

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The fundamental solution is a result of several different analytical methods. To date, only a comparison of the scintillation index and the spectrum of intensity fluctuations (or equivalently the correlation function) has been made, with numerical simulation and experimental data. We extend the comparison of the two-scale results to the full spatial behavior of the fourth moment. We compared our results with numerical solutions obtained by the finite-difference method and found that the typical scales of the fourth moment's evolution are present.

Properties such as symmetry/asymmetry and decorrelation are also clearly displayed. (12 min)

FL7 Complex angular momentum angular distributions for Mie scattering in the metallic limit

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The full angular distributions for scattering of a monochromatic plane wave by a perfectly conducting sphere, obtained by numerical summation of the exact partial wave expansion, are compared with the predictions of complex angular momentum (CAM) theory. The size parameter $x = ka$ (where k = wavenumber, a = sphere radius) ranges from large values down to values of order unity, to determine the limits of applicability of CAM theory. A complete set of scattering data, i.e., the polarized intensities and the phase difference between the two polarizations, is plotted.

In the penumbra region, beyond the forward diffraction peak (Airy pattern) and up to scattering angles θ of order $x^{-1/2}$, CAM theory leads to a new and improved version of Fock's theory of diffraction, the uniform Fock approximation. Beyond this region, scattering is dominated by the WKB approximation, but surface-wave contributions also play an important role, especially in the lower range of values of x and θ .

The asymptotic predictions of CAM theory are in excellent agreement with the exact angular scattering patterns. (12 min)

FL8 Loss of image resolution in haze and dust

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Scattering of light by particulate matter in the atmosphere generates a glow or aureol around pointlike sources, such as street lights seen from a distance. A scene can be thought of as an ensemble of pointlike sources or pixels, each having an aureol associated with it. This phenomena causes images of the scene to be smeared; hence, the presence of the scatterers in the path of propagation causes loss of image resolution. A computational method was previously reported¹ whereby a Monte-Carlo code coupled with an optics design program was used to generate aureols at the image plane of a detector. This procedure now includes a Gaussian MTF for the camera, so that the optics of a camera operating in a scattering environment can be completely simulated.

Aureols generated by this method are compared with those by an analytical method proposed by Lutomiński.² It is determined in what conditions of optical depth and peakedness of phase function the two methods give the same results. In a 1981 paper Kopelka et al.³ observed enhanced propagation with increasing wavelengths in the near to mid

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0940 BACKSCATTERING ENHANCEMENT FOR RANDOM DISCRETE
SCATTERERS OF MODERATE SIZE
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Backscattering enhancement for random discrete scatterers was previously studied by calculating the contributions of cyclical scattering terms in multiple scattering processes. The method was applied to the case of small particles, where it was shown that the cyclical scattering processes exhibit a peak in the backscattering direction with angular width $2K''/K'$ with K' and K'' being the real and imaginary parts of the effective propagation constant. In this paper, the method is extended to the case of scatterers comparable to or larger than a wavelength. The problem of a plane wave normally incident on a half space of dielectric spheres is considered. The problem is of particular interest because besides the peak due to cyclical scattering, there can also be a peak due to single scattering in the Mie phase function. Numerical results are illustrated as a function of particle size and concentration. The relative importance of the two peaks will be discussed.

CONVENTIONAL AND NEW RADIATIVE TRANSFER EQUATIONS FOR
VOLUME SCATTERING IN GEOPHYSICAL MEDIA

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Recently, a set of new radiative transfer equations has been derived from wave theory for electromagnetic wave propagation in dense geophysical media. The motivation is that conventional transfer equations assume independent scattering which is not valid in dense media. The differences between the conventional and new transfer equations will be discussed. The new equations still preserve the advantages that (i) multiple scattering of the incoherent intensities are included, (ii) energy conservation and reciprocity are obeyed, and (iii) the form of the equations remains the same as the conventional transfer equations so that numerical solutions are calculated in the same manner. In addition, the dense media transfer equation takes into account (i) scattering by correlated scatterers, (ii) pair-distribution function of scatterer positions, and (iii) the effective propagation constant of a dense medium. In this paper, we also show numerical results based on the new transport equations using the physical parameters of the terrain media and compare them with that of the conventional theory and experimental data in both active and passive remote sensing.

**Polarimetric Signatures and Inherent Geophysical
Information in Remote Sensing of Natural Media**

by

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Abstract

We investigate the polarization properties of the scattered field according to a discrete scatterer model. This model can apply to a number of natural media: in particular, we use it to represent first- and multi-year sea ice at L- and C-band. We discuss potential ways to infer geophysical properties of the scattering medium model using complete information about the polarization of the scattered field (e.g., position of polarization nulls and degree of polarization), especially in cases where like- and cross-polarized backscatter cross sections alone do not provide much geophysical information. Although the scattering model used in this initial investigation may be somewhat too simple to predict detailed, quantitative polarization properties of sea ice, it does provide considerable insight and guidance in choosing polarimetric quantities to examine as data of this kind become available.

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