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A research program to develop and numerically test inverse methods for identifying the absence or presence of an object obscured within or behind a low visibility atmosphere or smoke cloud was completed. Time-dependent and time-independent methods were developed for simultaneously estimating the optical depth of an object and the albedo of its surface from backscattered irradiance measurements, and time-independent algorithms were also developed for estimating the optical depth of the atmosphere when the albedo of the hidden surface is known. The inverse transport methods are based on the radiative transfer equation for analyzing multiply-scattered radiation in a cloud.

The project consisted of four components: a) calculations of the effects on the lidar signal of a large flat object located at variable depths behind an obscuring cloud, b) calculations of the effects on the lidar signal of a small spherical object located at variable depths within an obscuring cloud, c) development of an analytically-based iterative method to estimate from the time-independent backscattered irradiance the albedo and optical depth of a large flat object located at variable depths behind an obscuring cloud, and d) development of approximate algorithms to estimate from the time-independent backscattered irradiance the albedo and optical depth of a large flat object located at variable depths behind an obscuring cloud.

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INVERSE TRANSPORT SOLUTIONS FOR IDENTIFYING HIDDEN OBJECTS

FINAL REPORT PREPARED BY

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INVERSE TRANSPORT SOLUTIONS FOR IDENTIFYING HIDDEN OBJECTS

Abstract

A research program to develop and numerically test inverse methods for identifying the absence or presence of an object obscured within or behind a low visibility atmosphere or smoke cloud was completed. Time-dependent and time-independent methods were developed for simultaneously estimating the optical depth of an object and the albedo of its surface from backscattered irradiance measurements, and time-independent algorithms were also developed for estimating the optical depth of the atmosphere when the albedo of the hidden surface is known. The inverse transport methods are based on the radiative transfer equation for analyzing multiply-scattered radiation in a cloud.

The project consisted of four components: a) calculations of the effects on the lidar signal of a large flat object located at variable depths behind an obscuring cloud, b) calculations of the effects on the lidar signal of a small spherical object located at variable depths within an obscuring cloud, c) development of an analytically-based iterative method to estimate from the time-independent backscattered irradiance the albedo and optical depth of a large flat object located at variable depths behind an obscuring cloud, and d) development of approximate algorithms to estimate from the time-independent backscattered irradiance the albedo and optical depth of a large flat object located at variable depths behind an obscuring cloud.

INVERSE TRANSPORT SOLUTIONS FOR IDENTIFYING HIDDEN OBJECTS

I. Introduction

There has been considerable research on developing remote sensing methods, but most of this earlier work relies on the cloud being optically thin and neglects multiple scattering effects, and much of it ignores the presence of an underlying surface or object imbedded in the cloud. The goal of this research program was to further the development of analytical and numerical inversion algorithms to estimate the effects of multiple scattering on the returned signal emerging from an optically-thick aerosol, such as battlefield smoke.

Both time-dependent and time-independent radiative transfer phenomena were considered. For the time-dependent portion of the research program, the detectability of large flat objects and spherical objects was studied as a function of the thickness of the obscuring cloud layer. For the time-independent portion of the research program, only the detectability of large flat objects was studied.

II. Lidar Measurements

A. A Large Flat Object

The objective of this portion of the project, reported in publications 1-3, was to examine the potential for characterizing an obscured surface (i.e., determining the albedo of the surface and its location) under the conceptualized situation of both the surface and the obscuring layer having plane-parallel geometry, with the justification that if the an object cannot be detected under such circumstances then it could not be detected in a nonplane-parallel geometry. As a further idealization consistent with this philosophy, the incident pulse of radiation was assumed to be uniform over the surface and infinitesimally short.

Under such conditions, it is possible to derive an analytical equation for the broadening of the backscattered pulse in time due solely to different geometrical path lengths for radiation traveling in a cloud that is a perfectly straight-ahead scatterer (which is equivalent to a vacuum if there is no absorption). For a cloud that is not a straight-ahead-scatterer, it is no longer possible to find an analytical solution so calculations were done with the TIMEX program, a general purposes time-dependent radiation transport program capable of performing one-dimensional discrete ordinate calculations.

Isocline maps of the time-integrated signal for one and two layered media were obtained to show the obscuring nature of clouds of particles that scatter with Rayleigh scattering that is nearly isotropic and with a simulated atmosphere that scatters anisotropically. An "orthogonal" set of isoclines can be superimposed on these isoclines to give a grid for estimating the optical depth to the surface and its albedo.

Even if there is no obscuring cloud present, this inverse problem is complicated by the fact that the backscattered irradiance is broadened in time because of purely geometric effects, which are most pronounced in the plane geometry problem that was considered. As the thickness of a cloud (and its corresponding mean number of scatterings) is increased, this broadening is enhanced; the effect is increased if the cloud scatters in a more isotropic manner such as with Rayleigh scattering.

The effect on the backscattered irradiance of the surface albedo is mixed: the signal can be either increased or decreased, compared to the signal from an infinite cloud. Situations arise, for example, when a purely absorbing object, otherwise undetectable, becomes detectable when located behind the multiple scattering obscuration.

B. A Spherical Object

The objective of this portion of the project, reported in publication 4, was to assess the importance of multiple scattering for lidar detection of a spherical object obscured by an aerosol by using Monte Carlo radiative transfer calculations. Multiple scattering correction factors are significant and depend upon the location and size of the object, and the field of view and time resolution of the detector. The results obtained are directly applicable to noncoherent lidar detection, and for coherent lidar detection they indicate the increment in the noise level due to multiple scatterings.

The expected sharp peak in the returned signal caused by the presence of the object was seen, with some signal decrease and broadening for larger distances and detector field of views. Calculations were done both for time bins symmetrically located about the peak value of the time-dependent return signal and for fixed time bin locations defined by the equation

$$\Delta t_k = [(k-1)\Delta t,\, k\Delta t], \quad k \geq 1.$$

We found that it is important to distinguish between the use of a symmetric time bin located about the peak signal return and a fixed bin location in calculating the multiple scattering correction factor.

III. Time-Independent Measurements

A. Analytically-Based Iterative Method

The objective of this portion of the project was to obtain a method to simultaneously estimate the optical thickness τ_o of a homogeneous, plane-parallel cloud and the albedo ρ of an obscured surface using remote measurements of only the ingoing and outgoing radiance outside the cloud. An iterative approach was developed in publication 5 in which radiance moments I_{mn}, $n = 0, 1, 2, \ldots$, are to be obtained using the measured radiance at the surface of the cloud, and the corresponding moments I_{cn} are to come from direct radiative transfer calculations using the known optical properties of the cloud and assumed values of the unknown cloud thickness and surface albedo.

In this procedure one minimizes the sum $\sum_n w_n(I_{cn} - I_{mn})^2$ subject to variations in the two unknowns $u_1 = \rho$ and $u_2 = \tau_o$; the weights w_n should decrease with increasing values of n according to the decreasing accuracy of the higher angular moments of the radiance.

The difficulty in the iteration procedure comes in trying to obtain improved estimates. This requires the estimation of partial derivatives of I_{cn} with respect to each unknown since

$$I_{cn}(u_k + \Delta u_k) \approx I_{cn}(u_k) + \Delta u_k \partial_{u_k} I_{cn}, \quad k = 1, 2.$$

It follows that $\Delta\tau_o$ and $\Delta\rho$ must be estimated from

$$\min_{\Delta\tau_o, \Delta\rho} \sum_n (I_{cn} + \Delta\tau_o \partial_{\tau_o} I_{cn} + \Delta\rho \partial_\rho I_{cn} - I_{mn})^2.$$

In the usual iteration procedure one numerically evaluates the derivatives $\partial_{u_k} I_{cn}$ from two consecutive iterations and uses the results with the latest I_{cn}-values to estimate $\Delta\tau_o$ and $\Delta\rho$, but such evaluations are often very sensitive to inaccuracies in the calculations of the derivatives. A better approach is to develop an analytical procedure for computing the derivatives. In publication 5 the $\mathrm{F_N}$ method of transport theory has been advantageously used to do this and is especially well suited since it minimizes the required numerical calculations in the iteration scheme. This is because the matrix elements needed to calculate the derivatives depend only on the properties of the obscuring layer and are independent of the iterations, thus leaving only new source terms to be computed with each iteration.

B. Approximate Analytical Method

In this part of the research program, approximate radiative transfer algorithms were developed to estimate the optical thickness of a cloud that is illuminated monodirectionally or diffusely; the albedo of the surface of a large flat object obscured behind the cloud was assumed known in this case. For measurements of the inward and outward irradiances above the clouds, one set of algorithms was derived from asymptotic radiative transfer theory and another set is derived from transport-corrected diffusion theory. The latter approach was also used to derive an algorithm for cloud thickness estimation from irradiance measurements deep within clouds.

The algorithms, reported in publication 6, have been developed for either monodirectional or diffuse incident illumination, and require measurement of only the inward and outward irradiances. Because the ratio of the outward to inward irradiances for a semi-infinite cloud is relatively insensitive to the higher-order Legendre expansion coefficients of the phase function, polynomial fits were developed for the ratio based on the Henyey-Greenstein phase function. These fitted results, combined with those developed by other researchers, eliminate the need for radiative transfer calculations unless very high accuracy is desired.

Radiative transfer calculations with the F_N method were used to numerically test the cloudtop detector algorithms for monodirectional illumination for the Haze-L and Fair Weather Cumulus cloud models. Both algorithms showed good agreement with the F_N results for optically thick clouds; the transport-corrected diffusion algorithm also agreed with the F_N method for optically thin clouds, but was less accurate for intermediate cloud thicknesses than the asymptotic algorithm. The algorithms tended to be better for non-normal incident illumination directions. An error analysis was done that confirmed the difficulty of estimating the optical thickness if the surface albedo value is close to the value of the irradiance ratio for a semi-infinite cloud.

It was demonstrated that the optical thickness cannot be estimated if the irradiance ratio for a semi-infinite cloud is approximately equal to the surface albedo or if the albedo of the underlying surface is nearly unity and the cloud absorption is weak.

List of Scientific Personnel Supported During The Grant

Norman J. McCormick, Professor and Principal Investigator (4.65 months at 100% time)

Tomasz Duracz, Research Assistant Professor (20 months at 100% time)

Hak C. Yi, graduate student (18 months at 50% time)

List Of Publications Completed During The Grant

1. T. Duracz and N.J. McCormick, "Radiative Transfer Calculations for Detecting a Target Behind Obscuring Atmospheres," Proceedings of the 1987 Chemical Reseearch, Development and Engineering Center Obscuration and Aerosol Research Conference (E.H. Engquist and K.A. Sistek, eds.), CRDEC-SP-88031, 581-589 (Oct. 1988).

2. T. Duracz and N.J. McCormick, "Radiative Transfer Calculations for Characterizing Obscured Surfaces Using Time-Dependent Backscattered Pulses," Applied Optics, **28**, 544-552 (1989).

3. N.J. McCormick, "Mathematical Inversion Algorithms for Optically-Thick Remote Sensing Applications," *RSRM '87: Advances in Remote Sensing Retrieval Methods,* (A. Deepak, H.E. Fleming, and J.S. Theon, eds.), A. Deepak Publishing (Hampton, VA), 135-142 (1989).

4. T. Duracz and N.J. McCormick, "Multiple scattering corrections for lidar detection of obscured objects," Applied Optics, submitted.

5. N.J. McCormick, "Optical Thickness Estimation Using the F_N Method Of Radiative Transfer," Transport Theory and Statistical Physics, submitted.

6. H.C. Yi and N.J. McCormick, "Cloud Optical Thickness Estimation From Irradiance Measurements," Journal of the Atmospheric Sciences, submitted.