EOSAEL 92
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NARROW BEAM MULTIPLE SCATTERING MODULE NBSCAT

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Chapter 1

Introduction

The module NBSCATof EOSAEL92 is a multiple scattering propagation model applicable to narrow light beams transmitted through aerosol clouds. The module calculates the transmitted and backscattered irradiance profiles as functions of the field of view, and the on-axis transmitted power and lidar returns for specified receiver geometries. The algorithm is based on the radiative transfer model described by Bissonnette (1988) and validated against laboratory data as reported in Bissonnette, Smith *et al.* (1988a, 1988b).

The constitutive equations are derived from a paraxial approximation of the radiative transfer equation in which the flux normal to the incident beam axis is modeled by a diffusion process. It is applicable to narrow light beams and for observation points not too far from the beam axis. It is not restricted to small-angle scattering but the scattering coefficient must be small enough to insure that the forward spreading occurs over distances much greater than the beam diameter to satisfy the paraxial approximation. The model allows for inhomogeneities along the beam axis and the calculations require only modest computer memory and time.

1.1 Availability

EOSAEL92 is available to U.S. Department of Defense, specified allied organizations, and their authorized contractors at no cost. DoD agencies needing EOSAEL92 should send a letter of request, signed by a branch chief or division director, to ASL. Contractors should have their DoD contract monitor send the letter of request. Allied organizations must request EOSAEL92 through their national representative.

Please include, within security restrictions, your intended use(s). Also, indicate what type of nine-track tape your computer can read. We can make "ASCII" tapes and UNIX "tar" format tapes in either 1600 or 6250 bpi. We can't supply EOSAEL92 on other media. Documentation for the modules is included.

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Chapter 2

Background

Light propagation in dense aerosol media is basically a multiple scattering problem in which photons undergo many scattering events before escaping the medium, reaching a target or entering a receiver aperture. These multiple scatterings can contribute significantly to the measured transmitted and backscattered radiation.

Monte Carlo calculations based on the summation of multiple independent single-photon paths have been applied with success, *e.g.* by Plass and Kattawar (1968), Bucher (1973) and O'Brien (1987). The method is very powerful but is calculation intensive and provides only case-by-case solutions. Another general framework is the theory of radiative transfer, a general description of which can be found in Ishimaru (1978). The radiative transfer equation is difficult to solve but it has given rise to various numerical and analytical approaches. The most direct numerical procedure is the discrete-ordinates method which is straightforward but rapidly overwhelms even the most powerful computer resources as discussed by Zardecki, Gerstl and Embury (1983). Simplifying approximations have therefore been worked out. For scattering particles with sharply forward-peaked phase functions, the small-angle approximation to the radiative transfer equation is applicable. This simplified equation has been solved by exact and approximate methods, *e.g.* Dolin (1966), Fante (1973), Tam and Zardecki (1979a, 1979b), and Zardecki and Deepak (1983). At the opposite limit of almost isotropic scattering, the transfer equation can be replaced by a diffusion equation which can be more tractable depending on the boundary conditions, as shown for example by Ishimaru (1978), Ishimaru *et al.* (1983), and Zardecki, Gerstl and DeKinder (1986). The solutions obtained from these models are in very good agreement with the experimental results in their respective range of validity. In a recent publication, Gerstl *et al.* (1987) combined the small-angle and diffusion approximations in an effort to connect the two domains of validity. Despite the need for empirical adjustments, their calculations correlate well with off-axis scattering data in a high-density hydrosol medium.

To calculate multiple scattering effects on transmission and backscatter, one must therefore either run large computer codes or use simplified models that have limited domains of validity, especially with respect to aerosol particle sizes. Here, we propose yet another approximate method based on the radiative transfer theory. It is limited to narrow incident light beams but is otherwise applicable to a broad spectrum of aerosol scattering properties. Excellent agreement with experimental data has been obtained for size parameters ($2\pi\times$ particle radius $\div$ wavelength) of order one and greater, which covers most atmospheric applications from the UV on up. The main advantages are that the model can handle inhomogeneities along the beam axis and that the solutions are easily calculable. NBSCATrequires only modest computer memory and time.

2.1 Model Overview

The model is based on the time-independent radiative transfer equation for the specific intensity $I(\mathbf{r}, \hat{\mathbf{s}})$ where $\mathbf{r}$ is the position vector and $\hat{\mathbf{s}}$ is the direction unit vector. The total $I(\mathbf{r}, \hat{\mathbf{s}})$ is written as the sum of the reduced and diffuse intensity components, $I_{ri}(\mathbf{r}, \hat{\mathbf{s}})$ and $I_d(\mathbf{r}, \hat{\mathbf{s}})$ respectively. The problem of interest here is that of a collimated beam illuminating a scattering aerosol medium. In this case, $I_{ri}(\mathbf{r}, \hat{\mathbf{s}})$ is given by

$$I_{ri}(\mathbf{r}, \hat{\mathbf{s}}) = I_0(z, \boldsymbol{\rho})\, e^{-\tau}\, \delta(\boldsymbol{\omega} - \boldsymbol{\omega}_\circ), \tag{2.1}$$

where $I_0(z, \boldsymbol{\rho})$ is the vacuum irradiance of the incident beam, $(z, \boldsymbol{\rho})$ are the coordinates parallel and normal to the beam axis, $\boldsymbol{\omega}$ and $\boldsymbol{\omega}_\circ$ are the solid angle vectors along $\hat{\mathbf{s}}$ and $\hat{\mathbf{s}}_0$, δ is the delta function such that $\int_{4\pi} d\omega\, \delta(\boldsymbol{\omega} - \boldsymbol{\omega}_\circ) = 1$, and τ is the optical depth defined by

$$\tau \;=\; \int (\alpha_m + \alpha_a + \alpha_s)\, dz, \tag{2.2}$$

where α_m is the molecular absorption coefficient of the medium, and α_a and α_s are respectively the aerosol absorption and scattering coefficients. The radiative transfer equation for the diffuse intensity is then given by

$$\nabla \cdot \hat{\mathbf{s}} I_d(\mathbf{r}, \hat{\mathbf{s}}) + (\alpha_m + \alpha_a + \alpha_s) I_d(\mathbf{r}, \hat{\mathbf{s}}) \;=\; \frac{\alpha_s}{4\pi} \int_{4\pi} p(\hat{\mathbf{s}}, \hat{\mathbf{s}}')\, I_d(\mathbf{r}, \hat{\mathbf{s}}')\, d\omega' + \frac{\alpha_s}{4\pi} p(\hat{\mathbf{s}}, \hat{\mathbf{s}}_0)\, I_0(z, \boldsymbol{\rho})\, e^{-\tau}, \tag{2.3}$$

where $p(\hat{\mathbf{s}}, \hat{\mathbf{s}}')$ is the single-scattering phase function normalized such that

$$\frac{1}{4\pi} \int_{4\pi} p(\hat{\mathbf{s}}, \hat{\mathbf{s}}')\, d\omega' \;=\; 1. \tag{2.4}$$

No general solution of the radiative transfer equation has yet been obtained. Here, we propose an approximation valid for narrow incident beams. First, the radiative transfer equation is integrated over the solid angle and the individual terms are divided into forward and backward components about the direction $\hat{\mathbf{s}}_0$ of the incident beam. The resulting equation is then separated into a forward and a backward equation. This is a valid transformation that conveniently applies to many practical situations. Because of the narrow beam geometry, the equations are further simplified by making the paraxial approximation. More specifically, the forward and backward flux densities F^+ and F^- are approximated as follows:

$$F^{\pm}(\mathbf{r}) \equiv \int_{(2\pi)^{\pm}} I_d(\mathbf{r}, \hat{\mathbf{s}})\, \hat{\mathbf{s}} \cdot (\pm \hat{\mathbf{s}}_0)\, d\omega \;\;\simeq\;\; \pm \int_{(2\pi)^{\pm}} I_d(\mathbf{r}, \hat{\mathbf{s}}) \cos \begin{pmatrix} 0 \\ \pi \end{pmatrix} d\omega. \tag{2.5}$$

The above approximation is justified because $I_d(\mathbf{r}, \hat{\mathbf{s}})$ is peaked in the directions $\hat{\mathbf{s}}_0$ and $-\hat{\mathbf{s}}_0$. This is a consequence of the narrow beam hypothesis. Indeed, because the incident beam is narrow, the highest radiation intensity even at large optical depths is still found in the unscattered or reduced intensity beam I_{ri} which thus constitutes the main source of scattered photons per unit volume. Hence, for observation points $\mathbf{r}$ close to the axis, the diffuse intensity I_d is greatest at angles $\arccos(\hat{\mathbf{s}}\cdot\hat{\mathbf{s}}_0)$ near 0 and π since it is at those angles that the length of the I_{ri} beam seen per unit solid angle is longest.

The resulting equations for $F^{\pm}$ contain additional unknowns: terms that represent the flux in the direction normal to $\hat{\mathbf{s}}_0$. Based on an analogy with turbulent transport, we model these terms by a diffusion process. This allows relating the unknown normal fluxes to $F^{\pm}$. More precisely, we write

$$\hat{\mathbf{t}}\int_{(2\pi)^{\pm}} I_d(\mathbf{r},\hat{\mathbf{s}})\,\hat{\mathbf{s}}\cdot\hat{\mathbf{t}}\,d\omega \;=\; -D^{\pm}\,\nabla_{\perp}F^{\pm}, \tag{2.6}$$

where $\hat{\mathbf{t}}$ is the unit radial vector in the plane transverve to $\hat{\mathbf{s}}_0$, and $D^{\pm}$ are diffusion coefficients given by

$$D^{+} = C^{+}\left\{(z-z') < \sin\theta^{+}(z') > \;+\; \int_{z'}^{z} dz \int_{\eta'}^{\eta} d\eta < \sin\theta^{+} > e^{\eta-\eta'}\right\}, \tag{2.7}$$

$$D^{-} = C^{-}\,(z'-z) < \sin\theta^{-}(z') > \;+ C^{+}\int_{z}^{z'} dz \int_{\eta}^{\eta'} d\eta < \sin\theta^{+} > e^{\eta'-\eta}. \tag{2.8}$$

$D^{\pm}(z,z')$ are the lateral diffusion coefficients at position z for radiation originally scattered at z'. In Eqs. 2.7 and 2.8, $< \sin\theta^{+} >$ and $< \sin\theta^{-} >$ are the average sines of the scattering angle in the forward and backward directions defined by

$$< \sin\theta^{+} > = \frac{\int_0^{\pi/2} p(\hat{\mathbf{s}},\hat{\mathbf{s}}_0)\,\sin\theta\,d\theta}{\int_0^{\pi/2} p(\hat{\mathbf{s}},\hat{\mathbf{s}}_0)\,d\theta};\quad < \sin\theta^{-} > = \frac{\int_{\pi/2}^{\pi} p(\hat{\mathbf{s}},\hat{\mathbf{s}}_0)\,\sin\theta\,d\theta}{\int_{\pi/2}^{\pi} p(\hat{\mathbf{s}},\hat{\mathbf{s}}_0)\,d\theta}, \tag{2.9}$$

and $C^{\pm}$ are constants given by

$$C^{+} = 0.080;\quad C^{-} = \int_{\pi/2}^{\pi} \frac{p(\hat{\mathbf{s}},\hat{\mathbf{s}}_0)}{p(-\hat{\mathbf{s}}_0,\hat{\mathbf{s}}_0)}d\theta. \tag{2.10}$$

The quantity η is the forward scattering optical depth,

$$\eta \;=\; \int \alpha_s^{+}\,dz, \tag{2.11}$$

where

$$\alpha_s^{\pm} \;=\; \frac{\alpha_s}{4\pi}\int_{(2\pi)^{\pm}} p(\hat{\mathbf{s}},\hat{\mathbf{s}}_0)d\omega, \tag{2.12}$$

are the forward and backward scattering coefficients and the scattering coefficient α_s is given by $\alpha_s = \alpha_s^{+} + \alpha_s^{-}$.

The diffusion model described by Eqs. 2.6-2.8 is the main hypothesis underlying the model. It determines how the forward and backward propagating beams spread out due to multiple scattering.

The resulting model equations for the forward and backward fluxes are

$$\frac{\partial F^{+}}{\partial z} - \nabla_{\perp}\cdot D^{+}\nabla_{\perp}F^{+} + (\alpha_m+\alpha_a+\alpha_s^{-})F^{+} = \alpha_s^{+}I_0(z,\boldsymbol{\rho})\,e^{-\tau} + \alpha_s^{-}F^{-}, \tag{2.13}$$

$$-\frac{\partial F^-}{\partial z} - \nabla_\perp \cdot D^- \nabla_\perp F^- + (\alpha_m + \alpha_a + \alpha_s^-)F^- = \alpha_s^- I_0(z, \boldsymbol{\rho})\, e^{-\tau} + \alpha_s^- F^+. \qquad (2.14)$$

Equations 2.13 and 2.14 are coupled parabolic partial differential equations. For most applications, we can neglect the backscatter-to-backscatter coupling, i.e. the last term in Eq. 2.13, and Eqs. 2.13 and 2.14 can be solved sequentially. The boundary conditions are $F^+(0,\rho) = F^-(Z,\rho) = F^{\pm}(z,\infty) = 0$ where Z is the depth of the aerosol cloud. Assuming a Gaussian profile for $I_0(z,\rho)$ and using the method of the Green's function, we can write the solutions in a general analytic integral form. The results are

$$F_{ri}^+(z,\rho) = \frac{P_0}{\pi w_0^2}\frac{T(z)}{W(z)} \exp\left[-\frac{\rho^2}{w_0^2 W(z)}\right], \qquad (2.15)$$

$$F^+(z,\rho) = \frac{P_0}{\pi w_0^2}\int_0^z dz'\, \frac{E(z,z')}{H(z,z')} \exp\left[-\frac{\rho^2}{w_0^2 H(z,z')}\right], \qquad (2.16)$$

$$\begin{aligned} F^-(Z,z,\rho) &= \frac{P_0}{\pi w_0^2}\int_z^Z dz'\, \frac{G(z,z')}{K(z,z')} \exp\left[-\frac{\rho^2}{w_0^2 K(z,z')}\right] \\ &\quad + \frac{P_0}{\pi w_0^2}\int_z^Z dz' \int_0^{z'} dz''\, \frac{L(z,z',z'')}{M(z,z',z'')} \exp\left[-\frac{\rho^2}{w_0^2 M(z,z',z'')}\right], \end{aligned} \qquad (2.17)$$

where P_0 and w_0 are respectively the power and the beam radius at $z = 0$ of the incident beam ($z = 0$ is chosen to coincide with the boundary of the medium). The functions T, E, G and L are transmittance functions and W, H, K and M, beam-spreading functions. They are given by integrals over the z coordinate of the propagation coefficients, as follows:

$$T(z) = \exp\left[-\int_0^z (\alpha_m + \alpha_t)\, dz\right], \qquad (2.18)$$

$$E(z,z') = \alpha_s^+(z')\, T(z') \exp\left[-\int_{z'}^z (\alpha_m + \alpha_a + \alpha_s^-) dz\right], \qquad (2.19)$$

$$G(z,z') = \alpha_s^-(z')\, T(z') \exp\left[-\int_z^{z'} (\alpha_m + \alpha_a + \alpha_s^-) dz\right], \qquad (2.20)$$

$$\begin{aligned} L(z,z',z'') &= \alpha_s^-(z')\, \alpha_s^+(z'')\, T(z'') \exp\left[-\int_{z''}^{z'} (\alpha_m + \alpha_a + \alpha_s^-) dz\right] \\ &\quad \times \exp\left[-\int_z^{z'} (\alpha_m + \alpha_a + \alpha_s^-) dz\right], \end{aligned} \qquad (2.21)$$

$$W(z) = 1 + \frac{\phi^2 z^2}{w_0^2}, \qquad (2.22)$$

$$H(z,z') = W(z') + \frac{4}{w_0^2}\int_{z'}^z D^+\, dz, \qquad (2.23)$$

$$K(z,z') = W(z') + \frac{4}{w_0^2}\int_z^{z'} D^-\, dz, \qquad (2.24)$$

$$M(z,z',z'') = W(z'') + \frac{4}{w_0^2}\int_{z''}^{z'} D^+\, dz + \frac{4}{w_0^2}\int_z^{z'} D^-\, dz, \qquad (2.25)$$

where ϕ is the divergence of the reduced intensity beam (including the diffraction divergence) and assumed given. It should be noted that ϕ must be small enough for the narrow-beam hypothesis to remain valid. These solutions are for an incident Gaussian beam. It is possible that more general profiles could also yield analytic solutions but NBSCATis strictly for Gaussian beams. However, we do not expect large errors in the multiple scattering results if NBSCATis applied to other profiles so long as the incident beam radius and divergence are small. In that case, one should input a Gaussian beam width w_0 and divergence ϕ that best approximate the actual beam parameters.

The solutions just derived are applicable to open receivers only. For detectors of limited fields of view, the angular distribution of the radiation flux must be taken into account. This cannot be done exactly since the radiative transfer equation was integrated over the solid angle to obtain the model equations leading to the solutions given by Eqs. 2.16 and 2.17. The dependence on the receiver field of view is reintroduced *a posteriori* by multiplying the differential contributions to the integral solutions of Eqs. 2.16 and 2.17 by factors U and V that take into account the field of view of the receiver and the angular distribution of the scattered photons. The modified solutions for the forward- and backscattered fluxes within a field of view Θ are

$$F^+(z,\rho,\Theta) = \frac{P_0}{\pi w_0^2}\int_0^z dz'\,U(z',z,\rho,\Theta)\,\frac{E(z,z')}{H(z,z')}\exp\left[-\frac{\rho^2}{w_0^2 H(z,z')}\right], \tag{2.26}$$

$$\begin{aligned} F^-(Z,z,\rho,\Theta) &= \frac{P_0}{\pi w_0^2}\int_z^Z dz'\,U(z',z,\rho,\Theta)\,\frac{G(z,z')}{K(z,z')}\exp\left[-\frac{\rho^2}{w_0^2 K(z,z')}\right] \\ &\quad + \frac{P_0}{\pi w_0^2}\int_z^Z dz'\,V(z',z,\rho,\Omega)\int_0^{z'} dz''\frac{L(z,z',z'')}{M(z,z',z'')}\exp\left[-\frac{\rho^2}{w_0^2 M(z,z',z'')}\right]. \end{aligned} \tag{2.27}$$

The function U and V are ratios (≤ 1) that measure the fraction of radiation scattered in plane z' from the reduced- and diffuse-intensity beams, respectively, and collected at position (z,ρ) within a field of view Θ to that collected by an open receiver in the same conditions. U and V are derived from a stochastic representations of the photon paths. The details are given in Bissonnette (1988) and Bissonnette, Smith *et al.* (1988b). The expressions used in NBSCATare

$$\begin{aligned} U(z',z,\rho,\Theta) &= \exp\left[-\int_{z'}^{z}\alpha_s^+\,dz\right]\mathcal{R}_{11}(z',z,\rho,\Theta) \\ &\quad + \left\{1-\exp\left[-\int_{z'}^{z}\alpha_s^+\,dz\right]\right\}\frac{1}{(z-z')}\int_{z'}^{z}dz_1\,\mathcal{R}_{12}(z_1,z',z,\rho,\Theta), \end{aligned} \tag{2.28}$$

$$\begin{aligned} V(z',z,\rho,\Theta) &= \exp\left[-\int_{z'}^{z}\alpha_s^+\,dz\right]\mathcal{R}_{21}(z',z,\rho,\Theta) \\ &\quad + \left\{1-\exp\left[-\int_{z'}^{z}\alpha_s^+\,dz\right]\right\}\frac{1}{(z-z')}\int_{z'}^{z}dz_1\,\mathcal{R}_{22}(z_1,z',z,\rho,\Theta), \end{aligned} \tag{2.29}$$

where

$$\mathcal{R}_{11}(z',z,\rho,\Theta) = \frac{\int d^2\boldsymbol{\rho}'\,F_{ri}^+(z',\boldsymbol{\rho}')p(z',\theta)R(\theta,\Theta)}{\int d^2\boldsymbol{\rho}'\,F_{ri}^+(z',\boldsymbol{\rho}')p(z',\theta)}, \tag{2.30}$$

$$\mathcal{R}_{21}(z',z,\rho,\Theta) = \frac{\int d^2\boldsymbol{\rho}'\,F^+(z',\boldsymbol{\rho}')p(z',\theta)R(\theta,\Theta)}{\int d^2\boldsymbol{\rho}'\,F^+(z',\boldsymbol{\rho}')p(z',\theta)}, \tag{2.31}$$

$$\mathcal{R}_{12}(z_1, z', z, \rho, \Theta) \simeq \frac{\int d^2\boldsymbol{\rho}' \int d^2\boldsymbol{\rho}_1 R(\theta_2, \Theta) F_{ri}^+(z', \boldsymbol{\rho}') p(z', \theta_0) p(z_1, \theta_1)}{\int d^2\boldsymbol{\rho}' \int d^2\boldsymbol{\rho}_1 F_{ri}^+(z', \boldsymbol{\rho}') p(z', \theta_0) p(z_1, \theta_1)}, \tag{2.32}$$

$$\mathcal{R}_{22}(z_1, z', z, \rho, \Theta) \simeq \frac{\int d^2\boldsymbol{\rho}' \int d^2\boldsymbol{\rho}_1 R(\theta_2, \Theta) F^+(z', \boldsymbol{\rho}') p(z', \theta_0) p(z_1, \theta_1)}{\int d^2\boldsymbol{\rho}' \int d^2\boldsymbol{\rho}_1 F^+(z', \boldsymbol{\rho}') p(z', \theta_0) p(z_1, \theta_1)}, \tag{2.33}$$

where p is the single-scattering phase function assumed axisymmetric and $R(\theta, \Theta)$ is the specified field of view profile with θ the variable and Θ the parameter. For example, a top hat profile is defined by $R(\theta, \Theta) = 1$ for $\theta \leq \Theta$ and 0 otherwise, and a Gaussian profile by $R(\theta, \Theta) = \exp(-\theta^2/\Theta^2)$. The current version of NBSCATuses a Gaussian profile. The angles θ's in Eqs. 2.30-2.33 are related to the integration variables as follows:

$$\cos(\theta) = \frac{|z - z'|}{\{|z - z'|^2 + |\boldsymbol{\rho} - \boldsymbol{\rho}'|^2\}^{1/2}}, \tag{2.34}$$

$$\cos(\theta_0) = \frac{|z_1 - z'|}{\{|z_1 - z'|^2 + |\boldsymbol{\rho}_1 - \boldsymbol{\rho}'|^2\}^{1/2}}, \tag{2.35}$$

$$\cos(\theta_1) = \frac{(z - z_1)(z_1 - z') + (\boldsymbol{\rho}_1 - \boldsymbol{\rho}') \cdot (\boldsymbol{\rho} - \boldsymbol{\rho}_1)}{\{|z_1 - z'|^2 + |\boldsymbol{\rho}_1 - \boldsymbol{\rho}'|^2\}^{1/2} \{|z - z_1|^2 + |\boldsymbol{\rho} - \boldsymbol{\rho}_1|^2\}^{1/2}}, \tag{2.36}$$

$$\cos(\theta_2) = \frac{|z - z_1|}{\{|z - z_1|^2 + |\boldsymbol{\rho} - \boldsymbol{\rho}_1|^2\}^{1/2}}. \tag{2.37}$$

Equations 2.15-2.33 constitute the model coded in NBSCAT. The calculation steps are as follows. The flux densities F_{ri}^+ and F^+ are first calculated through Eqs. 2.15 and 2.16. The field of view factors U and V are then obtained by substitution of the calculated F_{ri}^+ and F^+ into Eqs. 2.28-2.33. Finally, the forward and backward flux densities for the required receiver geometry are computed by carrying out the integrations of Eqs. 2.26 and 2.27. The necessary inputs are the incident beam power P_0, radius w_0 and divergence ϕ; the aerosol cloud depth Z; the positions of the source and receiver with respect to the cloud boundary; the receiver field of view Θ; the medium molecular absorption coefficient α_m; the aerosol absorption and scattering coefficients α_a and α_s; and the single-scattering phase function. The specialized parameters $\alpha_s^{\pm}$ and $D^{\pm}$ are calculated by NBSCAT. The medium properties are allowed to vary along the beam axis but are assumed constant transversely.

Chapter 3

Caveats

3.1 Grade of Software

The NBSCATmodel is a DEVELOPMENTAL code as defined in Table 3.1 reprinted from the EOSAEL92 Executive Summary, Volume 1. It has been extensively evaluated in laboratory tests but not in the field where only a limited number of comparisons have been carried out to date. NBSCAThas not yet been distributed to a wide community.

Table 3.1: Grades of Software

RESEARCH	
	Describes phenomena based on a physical or meteorological theory. Limited evaluations in the field or laboratory.
DEVELOPMENTAL	
	Tailored version of a research model. Limits of applicability have been defined. At least "several" evaluations have been made.
FIELDABLE	
	Applicability has been defined. Confidence has been established throughout the community. "Many" evaluations have been "passed". The model has been verified for its stated usage.

3.2 Model Failure

The model should not fail catastrophically except maybe for incompatible input parameters. The user is reminded that the model is applicable to narrow light beams and for observation points not too far from the beam axis, typically within 20 degrees of the source position in the forward direction and of the intersection point betwen the beam axis and the back of the cloud in the backward direction. It is not restricted to small-angle scattering. However, the scattering coefficient must be small enough to insure that the forward spreading occurs over distances much greater than the beam diameter to satisfy the paraxial approximation. This requires that the product of the scattering coefficient times the beam diameter be much less than one, say < 0.05, which is verified in most atmospheric applications. Warnings are issued if the input parameters fall outside the validity conditions but the program does not stop. Results in those cases should be discarded or, if used, used with extreme caution.

3.3 Verification Tests

3.3.1 Laboratory Tests

The most extensive validation tests were carried out in a laboratory experiment described by Bissonnette, Smith *et al.* (1988a, 1988b). In that experiment, the transmitted beam profile, the integrated backscatter and the range-resolved backscatter of 1.06 and 10.6 μm laser beams were measured in a 3.2 m long, 1 m wide and 0.75 m high closed chamber filled with water droplet clouds. The water droplets were produced with ultrasonic nebulizers and kept at adjustable concentrations with good precision. The chamber was divided in three sections to simulate cloud inhomogeneities. Very stable clouds of visible extinction ranging from 0.25 to 7 m^{-1} could be maintained independently in each section.

Very good agreement was observed with the profile measurements performed at optical depths varying between 0 and 9.7, at fields of view of 20, 140 and 350 mrad and for various cloud inhomogeneites determined by the relative cloud concentrations in the three sections. Point to point agreement for the 1.06 μm off-axis multiple scattering strength is better than 50%, which is of the order of the experimental uncertainties for these measurements. Similar measurements were done at 10.6 μm. In that case, the off-axis scattering remained below or obscured by the detector noise. The model calculations also agreed with these findings: the computed off-axis signal was of the order of or less than the measured noise level.

Cloud integrated backscatter measurements were performed at 1.06 and 10.6 μm for various cases of cloud configuration and for a receiver field of view of 10 mrad. The multiple scattering at 1.06 μm contributed up to more than 2/3 of the total signal. The agreement with NBSCATpredictions is better than 20%. At 10.6 μm, the multiple scattering contributions were not measurable for the conditions of the experiment in agreement with the NBSCATcalculations that predict differences much less than the experimental scatter.

Backscatter returns from three different sections of the cloud chamber were also measured at 1.06 μm for two fields of view, 3 and 15 mrad, and for two cloud configurations. Again, the agreement with NBSCATis better than 20% in all cases.

3.3.2 Field Tests

A field experiment was carried out to measure the point spread function, or the image of a point source, under low visibility haze, fog and rain conditions as described in Bissonnette (1991a, 1991b). The atmospheric conditions were simultaneously monitored by a transmissometer and a battery of fog particle and rain drop spectrometer probes. The image spread due to forward scattering was found to be negligible in haze and radiation fog but definitely measurable in advection fog and rain. The precision of the NBSCATcalculations is better than 25% except for one case of rain where, however, the experimental data appear questionable since incompatible with related measurements.

Another situation where multiple forward scatterings cause a significant effect is propagation in falling snow. It is found that the snow extinction coefficient measured with a transmissometer is a function of both the wavelength and the source/receiver geometry contrary to what is expected from single-scattering Mie theory. The reason is that the scattering is so highly peaked in the forward direction that it contributes significantly to the received signal, reducing in some cases the measured or apparent extinction coefficient by as much as 20-25%. The NBSCATmodel predicts that effect to an accuracy better than 5% for both visible and infrared (3-5 and 8-12 μm) wavelengths up to the maximum extinction encountered in the field trials, i.e. 12 km^{-1} at 0.63 μm. Results are published in Hutt *et al.* (1988) and Bissonnette, Hutt and St-Germain (1988).

3.3.3 Comparisons with Other Models

A comparative study of radiative transfer codes, including NBSCAT, was performed by Miller (1989). Using the EOSAEL92 module MSCATas a reference, he concluded that NBSCATyields consistent believable results for the transmission and lidar cases he ran. There are, however, some valid doubts about the accuracy of MSCATin some cases since MSCATallows only a limited number of scattering events.

Other MSCAT/NBSCATtransmission and backscatter comparisons are published in Bissonnette (1988). The RMS differences in the more than 100 comparisons carried out are less than 10%.

An intercomparison of multiple scattering lidar calculations by various groups in Canada, Germany, Israel, Italy, the United States and the USSR is under way, Cohen (1991). The models comprise Monte Carlo calculations, stochastic theories and radiative transfer approximations. For the lidar case studied to date, the models agree to within a factor of 2 and NBSCATis closest (better than 30%) to those predictions that include the greatest number of scattering orders. These results will be published in 1992.

3.3.4 Code Verification

The NBSCATcode was extensively verified by Echle and preliminary results are discussed in Wiegner and Echle (1991). The detailed study will be published in Echle's Master's thesis (1991), Meteorologisches Institut der Universität München.

3.3.5 Conclusion

In the experimental and theoretical tests performed to date, NBSCATgave results that on the average are well within 50% of the measurements or other model predictions. Considering the wide spectrum of experimental conditions under which the tests were performed, the difficulties of making accurate measurements of weak multiple scattering signals and the absence of a fully validated reference model, this is as good a performance as can be expected.

The 50% differences could be the result of any or all of these uncertainty sources combined, not only NBSCAT. No gross inconsistency has been found yet. All this, however, does not guarantee that NBSCATis free of bugs or systematic errors. Therefore, the user is reminded that NBSCATis still a DEVELOPMENTAL code that may not give accurate results in all situations. Any error or inconsistency should be reported to:

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Defence Research Establishment Valcartier
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Chapter 4

Operations Guide

4.1 Inputs

The necessary input data are read in from a number of cards or lines prefixed by an identifier. The order of the lines is irrelevant except for the lines belonging to the `AERP` identifier. Only the card, or cards, bearing changes need be repeated to start a new calculation within a same run. There are five different input cards plus a `GO` card to start the calculations and a `DONE` card to terminate the NBSCATrun. They are all read with the format `(2A4,2X,8F10.0)`. There can be multiple `GO` cards.

4.1.1 Run Parameters

This card defines what is to be calculated by NBSCAT. The identifier is `RUNP` and the variable definitions and units are given in Table 4.1. There are four input flags determining which quantities are to be calculated and two parameters specifying the width and resolution of the calculated profiles.

4.1.2 Source Parameters

This card specifies the parameters of the incident source beam. The identifier is `SORC` and the variable definitions and units are given in Table 4.2. The required information includes the position of the source and the width and divergence of the generated beam. The source power is assumed unity.

4.1.3 Receiver Parameters

This card specifies the receiver parameters. The identifier is `DETR` and the variable definitions and units are given in Table 4.3. The required data are the receiver position, aperture radius and field of view for both transmission and backscatter configurations.

4.1.4 Medium Parameters

This card specifies the molecular absorption coefficient of the medium in which the aerosol cloud is embedded. The identifier is MEDP and the variable definitions and units are given in Table 4.4.

4.1.5 Aerosol Parameters

The cloud configuration is specified by a series of cards headed by one card with the identifier AERP. The card order in that series can not be altered. NBSCATallows the cloud to be inhomogeneous along the propagation axis and to have a complex composition formed by mixing various aerosol types. The maximum number of aerosol types that can be mixed at any axial position is currently 5.

The user has two options.

In the first option, the aerosol angular scattering properties are read from the EOSAEL92 PHASEFN.DAT phase function file, or an equivalent user defined file, and the parameters specific to NBSCATare calculated by NBSCAT. The AERP card series for this option is defined in Table 4.5.

In the second option, the aerosol cloud parameters specific to NBSCATare read in directly from a file created by NBSCATin a previous run. Each time NBSCATis run, it creates a file AERP.DAT where all the aerosol parameters it needs to define a cloud configuration are copied. If in a subsequent run the user is interested in the same cloud configuration, his most efficient use of NBSCATwould be to use this option. The AERP card series for this case is defined in Table 4.6 and can be readily prepared from the AERP.DAT file.

The user is reminded that the current NBSCAT version assumes Gaussian profiles for the incident source beam and the field of view function. Since the model applies to narrow beams compared with the spread due to multiple scattering, we do not expect significant errors if the results are used with non-Gaussian beams except for points where the unscattered beam dominates, i.e. very close to the axis for the transmitted irradiance. However, some adjustments of the nominal values of FOVT and FOVL might be necessary for field of view functions different than Gaussian. These adjustments, or the values of the inputed FOVT and FOVL, should be estimated by comparing the actual field of view functions to a Gaussian.

4.2 Outputs

NBSCATcalculates the irradiance profile of the beam transmitted through the aerosol medium, the profile of the lidar return from a specific range inside the aerosol medium, the power transmitted to a receiver positioned on the beam axis, and the range-resolved lidar return for a given receiver geometry. The user can select any combination of these through his choice of the flag parameters defined in Table 4.1.

4.2.1 Transmitted Irradiance Profile

If the input flag ITRPRO is assigned a non-zero value, NBSCATcalculates the profile of the beam irradiance at position ZDTD and writes the results in the output file TRPRO.OUT. The

Table 4.1: The RUNP Card.

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
 RUNP         ITRANS    ILIDAR    ITRPRO    ILIPRO     LRMAX      RMAX
```

NAME	UNITS	Description
ITRANS		If = 0, the on-axis power is not calculated; if ≠ 0, the on-axis power is calculated at position ZDTD specified on the DETR card. There is no default; this information must be specified.
ILIDAR		If = 0, the lidar return is not calculated; if ≠ 0, the range-resolved lidar return is calculated at position ZDLD specified on the DETR card. There is no default; this information must be specified.
ITRPRO		If = 0, the transmitted irradiance profile is not calculated; if ≠ 0, the transmitted irradiance profile is calculated at position ZDTD specified on the DETR card. There is no default; this information must be specified.
ILIPRO		If = 0, the lidar irradiance profile is not calculated; if ≠ 0, the profile at position ZDLD of the lidar return from range ZDTD is calculated. ZDLD and ZDTD are specified on the DETR card. There is no default; this information must be specified.
LRMAX		Number of radial positions at which the transmission and/or lidar profiles are calculated, currently limited to a maximun of 31. There is no default; this information must be specified.
RMAX	cm	Maximum radial position at which the transmission and/or lidar profiles are calculated. There is no default; this information must be specified.

Table 4.2: The SORC Card.

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
 SORC             ZSD       WO      BEAMD     BEAMQ
```

NAME	UNITS	Description
ZSD	km	Position of the source measured from the front end of the cloud, must be ≤ 0. If the source is in the aerosol cloud, the front end of the cloud is taken as the position of the source and ZSD = 0 in this case. There is no default; this information must be specified.
W0	cm	Beam radius (1/e in irradiance) at the position of the source. There is no default; this information must be specified.
BEAMD	rad	Half angle beam divergence. There is no default; this information must be specified.
BEAMQ		Beam divergence expressed in number of times the diffraction limit. There is no default; this information must be specified.
Note:		The beam divergence can be specified in two different ways: either specify BEAMD and set BEAMQ = 0 or specify BEAMQ and set BEAMD = 0.

irradiance is defined here as the power received per unit area for a field of view FOVT. The units are watts/cm^2 for a nominal source strength of one watt. In terms of the functions F^+_{ri} and F^+ defined in Eqs. 2.15 and 2.26, the transmitted irradiance profile written in TRPRO.OUT is

$$\mathrm{I}_{tr}(\mathtt{ZDTD},\mathtt{R},\mathtt{FOVT}) \;=\; F^+_{ri}(\mathtt{ZDTD},\mathtt{R}) \;+\; F^+(\mathtt{ZDTD},\mathtt{R},\mathtt{FOVT}), \qquad (4.1)$$

as a function of the radius R expressed in cm and varying between 0 and RMAX. RMAX and the number LRMAX of radial positions are specified by the user on the RUNP input card. The output variables are clearly identified in the TRPRO.OUT image printed on the standard output as will be seen in the following chapter.

This is the most general NBSCAT output function for the determination of the multiple scattering effect on beam transmission through aerosols. To calculate the power $P_{tr}(\mathtt{ZDTD},\mathtt{FOVT},r,a)$ measured by a receiver of radius a and field of view FOVT located in the plane ZDTD at a radial distance r from the beam axis, one simply needs to integrate the NBSCAT output function I_{tr} with respect to the radial and azimuthal coordinates as follows:

$$P_{tr}(\mathtt{ZDTD},\mathtt{FOVT},r,a) \;=\; P_0 \int_0^{2\pi} d\psi \int_0^a \rho d\rho \, \mathrm{I}_{tr}(\mathtt{ZDTD}, \sqrt{r^2+2r\rho\cos\psi+\rho^2}, \mathtt{FOVT}), \qquad (4.2)$$

where P_0 is the source power, and r, ρ and a have dimensions of cm. The parameters ZDTD and FOVT can be varied through multiple runs of NBSCAT.

4.2.2 Lidar Profile

If the input flag ILIPRO is assigned a non-zero value, NBSCATcalculates the profile of the lidar irradiance backscattered from range ZDTD and measured at position ZDLD and writes

Table 4.3: The DETR Card.

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
DETR           ZDTD      ZDLD      DRTD      DRLD      FOVT     FOVL
```

NAME	UNITS	Description
ZDTD	km	Position where the transmitted irradiance profile and/or the on-axis received power are calculated, measured from the front end boundary of the cloud. Must be ≥ 0. ZDTD is also the maximum range for the range-resolved lidar return calculation and the range value of the calculated lidar irradiance profile. There is no default; this information must be specified.
ZDLD	km	Position where the lidar profile and/or the on-axis lidar return are calculated, measured from the front end boundary of the cloud. ZDLD $\leq$ ZSD, but if the source is in the cloud, ZDLD must be set equal to ZSD since the cloud is not defined for axial positions smaller than ZSD. There is no default; this information must be specified.
DRTD	cm	Radius of on-axis transmission receiver. There is no default; this information must be specified.
DRLD	cm	Radius of on-axis lidar receiver. There is no default; this information must be specified.
FOVT	rad	Half angle field of view of transmission receiver, used also for the transmitted irradiance profile. There is no default; this information must be specified.
FOVL	rad	Half angle field of view of lidar receiver, used also for the lidar profile. There is no default; this information must be specified.
Note:		The current version of NBSCATassumes Gaussian field of view profiles where FOVT and FOVL are the widths at 1/e. If lidar calculations are not made, ZDLD, DRLD and FOVL are irrelevant; if transmission calculations are not made, DRTD and FOVT are irrelevant.

Table 4.4: The MEDP Card.

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
MEDP           ALMD
```

NAME	UNITS	Description
ALMD	km^{-1}	Molecular absorption coefficient. There is no default; this information must be specified.

Table 4.5: The AERP Card for the case where the aerosol scattering properties are read from a phase function data file.

```
         1         2          3         4         5         6         7         8
12345678901234567890 123456789012345678901234567890123456789012345678901234567890
 AERP           NIH       ZCD
             NMIX(1)   ALPE(1)      ZD(1)
                      IDPF(1,1)  WGT(1,1)
                      IDPF(1,2)  WGT(1,2)
                      .........  ........
             NMIX(2)   ALPE(2)      ZD(2)
                      IDPF(2,1)  WGT(2,1)
                      IDPF(2,2)  WGT(2,2)
                      .........  ........
             .......  .........  ........
```

NAME	UNITS	Description
NIH		Number of range positions where the aerosol parameters are specified. If = 1, the aerosol cloud is homogeneous; if > 1, the aerosol cloud is inhomogeneous. There is no default; this information must be specified.
ZCD	km	Cloud depth. If the cloud depth is greater than ZDTD, ZCD should be set equal to ZDTD. There is no default; this information must be specified.
NMIX		Number of different aerosol types to be mixed to form the required aerosol composition at position ZD. $1 \leq$ NMIX ≤ 5. There is no default; this information must be specified.
ALPE	km^{-1}	Cloud extinction coefficient at position ZD. If = 0.0, the value stored in the phase function data file is used. There is no default; this information must be specified.
ZD	km	Position where the aerosol parameters ALPE, IDPF and WGT are assigned. Must be ≥ 0. If NIH = 1, this input is irrelevant.
IDPF		Phase function identifier for the phase function data file. There is no default; this information must be specified.
WGT		Weight given to the aerosol type defined by IDPF. The sum of the WGTs for $k = 1$ to $k =$ NMIX must equal unity. There is no default; this information must be specified.
Note:		The program interpolates linearly between the positions ZD to form a continously varying aerosol cloud.

Table 4.6: The AERP Card for the case where the aerosol parameters specific to NBSCATare directly read in from a file previously created by NBSCAT.

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
 AERP             NIH      ZCD
             NMIX(1)  ALPE(1)      ZD(1)
               ALSPD     ALSMD      ALAD     DIFPD     DIFMD      SAPD
                SAMD     BETAD
             NMIX(2)  ALPE(2)      ZD(2)
               ALSPD     ALSMD      ALAD     DIFPD     DIFMD      SAPD
                SAMD     BETAD
               .....     .....     .....     .....     .....     .....
```

NAME	UNITS	Description
NIH		Number of range positions where the aerosol parameters are specified. If $= 1$, the aerosol cloud is homogeneous; if > 1, the aerosol cloud is inhomogeneous. There is no default; this information must be specified.
ZCD	km	Cloud depth. If the cloud depth is greater than ZDTD, ZCD should be set equal to ZDTD. There is no default; this information must be specified.
NMIX		Any **negative** value. It is NMIX < 0 that makes NBSCATbranch to this option of reading directly the parameters ALSPD, etc. There is no default; this information must be specified.
ALPE	km^{-1}	Cloud extinction coefficient at position ZD. There is no default; this information must be specified.
ZD	km	Position where the aerosol parameters ALPE, IDPF and WGT are assigned. Must be ≥ 0. If NIH $= 1$, this input is irrelevant.
ALSPD	km^{-1}	Aerosol forward scattering coefficient α_s^+, see Eq. 2.12.
ALSMD	km^{-1}	Aerosol backscattering coefficient α_s^-, see Eq. 2.12.
ALAD	km^{-1}	Aerosol absorption coefficient α_a.
DIFP		The product $C^+ < \sin\theta^+ >$, see Eqs. 2.9 and 2.10.
DIFM		The product $C^- < \sin\theta^- >$, see Eqs. 2.9 and 2.10.
SAPD	rad	Average scattering angle over the forward hemisphere.
SAMD	rad	Average scattering angle over the backward hemisphere.
BETAD	$\mathrm{km}^{-1}/\mathrm{sr}$	Backscattering coefficient at exactly 180 degrees, used to calculate the conventional lidar return.
Note:		The ALSPD, etc. have of course no default values. The program interpolates between the positions ZD to form a continously varying aerosol cloud.

the results in the output file LIPRO.OUT. The lidar irradiance is defined as the backscattered power received per unit area and unit length for the specified field of view FOVL. The units are watts/cm^2/km for a nominal source strength of one watt. In terms of the function F^- defined in Eq. 2.27, the lidar irradiance profile written in LIPRO.OUT is

$$\mathtt{I}_{li}(\mathtt{ZDTD,ZDLD,R,FOVL}) = \left(\frac{\partial}{\partial \mathtt{Z}} F^-(\mathtt{Z,ZDLD,R,FOVL}) \right)_{\mathtt{Z=ZDTD}}, \tag{4.3}$$

as a function of the radius R expressed in cm and varying between 0 and RMAX. RMAX and the number LRMAX of radial positions are specified by the user in the RUNP input card. The output variables are clearly identified in the LIPRO.OUT image printed on the standard output.

To transform the results into engineering units for a laser pulse of energy E and duration T, one has to multiply the NBSCAT output function $\mathtt{I}_{li}$ by $Ec/2$ and integrate over the receiver aperture, where E is expressed in joules and the speed of light c in km/s. More specifically, for a receiver of radius a and field of view FOVL located in the plane ZDLD at a radial distance r, the power received from range ZDTD can be calculated as follows:

$$P_{li}(\mathtt{ZDTD,ZDLD,FOVL}, r, a) = \frac{Ec}{2} \int_0^{2\pi} d\psi \int_0^a \rho d\rho\, \mathtt{I}_{li}(\mathtt{ZDTD,ZDLD}, \sqrt{r^2 + 2r\rho\cos\psi + \rho^2}, \mathtt{FOVL}), \tag{4.4}$$

where r, a and ρ have dimensions of cm. The pulse duration T drops out of the formula because the average pulse power is taken as E/T and the range resolution as $cT/2$. The parameters ZDLD,ZDTD and FOVL can be varied through multiple runs of NBSCAT.

4.2.3 Transmitted On-Axis Power

If the input flag ITRANS is assigned a non-zero value, NBSCATcalculates the transmitted power measured by a receiver of radius DRTD and field of view FOVT positioned on the beam axis at a range position ZDTD and writes the results in the output file TRANS.OUT. The units are watts for a nominal source strength of one watt. In terms of the function F^+_{ri} anf F^+ defined in Eqs. 2.15 and 2.26, the transmitted on-axis power $\mathtt{P}_{tr}$ written in TRANS.OUT is

$$\mathtt{P}_{tr}(\mathtt{ZDTD,DRTD,FOVT}) = 2\pi \int_0^{\mathtt{DRTD}} \left\{ F^+_{ri}(\mathtt{ZDTD,R}) + F^+(\mathtt{ZDTD,R,FOVT}) \right\} \mathtt{R}\, d\mathtt{R}. \tag{4.5}$$

For a specific application, one needs only multiply $\mathtt{P}_{tr}$ by the source power P_0. The variables ZDTD and FOVT can be changed through multiple runs of NBSCAT. In addition to the quantity $\mathtt{P}_{tr}$, the output file TRANS.OUT also provides the single scattering and multiple scattering components of $\mathtt{P}_{tr}$, i.e.

$$\mathtt{P}^{ss}_{tr}(\mathtt{ZDTD,DRTD,FOVT}) = 2\pi \int_0^{\mathtt{DRTD}} F^+_{ri}(\mathtt{ZDTD,R})\mathtt{R}\, d\mathtt{R}, \tag{4.6}$$

$$\mathtt{P}^{ms}_{tr}(\mathtt{ZDTD,DRTD,FOVT}) = 2\pi \int_0^{\mathtt{DRTD}} F^+(\mathtt{ZDTD,R,FOVT})\mathtt{R}\, d\mathtt{R}. \tag{4.7}$$

Each quantity is unambiguously identified in the TRANS.OUT image printed on the standard output.

The calculated power $\mathtt{P}_{tr}$ written in TRANS.OUT could have been derived from the transmitted irradiance profile of Section 4.2.1. The expressions given by Eqs. 4.5-4.7 were purposely coded in NBSCATbecause they have applications in many practical situations.

4.2.4 Lidar Return

If the input flag ILIDAR is assigned a non-zero value, NBSCATcalculates the range-resolved lidar backscatter for a receiver of radius DRLD and field of view FOVL positioned on or very close to the beam axis at ZDLD and writes the results in the output file LIDAR.OUT. The units are watts/km for a nominal source strength of one watt. In terms of the function F^- defined in Eq. 2.27, the lidar return written in LIDAR.OUT is

$$\mathtt{P}_{li}(\mathtt{Z,DRLD,FOVL}) = 2\pi \int_0^{\mathtt{DRLD}} \frac{\partial}{\partial \mathtt{Z}} F^-(\mathtt{Z,ZDLD,R,FOVL})\mathtt{R}\, d\mathtt{R}, \tag{4.8}$$

as a function of Z varying between 0 and ZDTD. To calculate the lidar return in watts for a laser pulse of energy E in joules and duration T, one needs only multiply $\mathtt{P}_{li}$ by $Ec/2$ where c is the speed of light in km/s. The pulse duration T drops out of the lidar return power calculation because the average pulse power is taken as E/T and the range resolution as $cT/2$. Separate columns are printed out in the LIDAR.OUT file for (a) the conventional single scattering lidar return,

$$\mathtt{P}_{ss}(\mathtt{Z,DRLD}) = \frac{\pi\, \mathtt{DRLD}^2}{(\mathtt{Z - ZDLD})^2} \mathtt{BETAD} \exp\left\{-2\int_0^{\mathtt{Z}} \mathrm{ALPE}\, dz\right\}, \tag{4.9}$$

where the backscatter coefficient BETAD defined in Table 4.6 is either read from the phase function data file or from the AERP input data cards; (b) the contribution to $\mathtt{P}_{li}$ from the reduced intensity beam, i.e. from the first term in Eq. 2.27; (c) the contribution to $\mathtt{P}_{li}$ from the forward scattered beam, i.e. from the second term in Eq. 2.27; and (d) the total $\mathtt{P}_{li}$, i.e. the sum of the last two columns. Each quantity is unambiguously identified in the LIDAR.OUT image printed on the standard output. All of these output functions, including $\mathtt{P}_{ss}$, must be multiplied by $Ec/2$ for application to a specific lidar experiment.

The lidar output $\mathtt{P}_{li}$ of LIDAR.OUT could have been derived from the lidar irradiance profile of Section 4.2.2. It was coded separately in NBSCATbecause it is of considerable practical importance.

4.2.5 Calculated Aerosol Parameters

The aerosol parameters calculated by NBSCATare written in the output file AERP.DAT. The variables and their units are clearly identified. As explained in Section 4.1.5, these data can be used to construct the AERP input data cards if the same aerosol cloud configuration is used in a subsequent run.

Chapter 5

Sample Runs

5.1 Overview

Three sample runs are discussed below. In the first one, we calculate the transmitted power through a homogeneous aerosol medium as a function of the receiver field of view. The results illustrate the effect of forward scattering on transmittance measurements. This case corresponds to a simple set of input data cards and shows how multiple runs can be used to study the dependence of the quantity of interest on a given parameter, in this case the field of view. The second example shows the user how to construct a complex inhomogeneous aerosol medium. In the first two examples, NBSCATreads the full angular scattering properties of the chosen aerosols from a phase function data file such as PHASEFN.DAT of EOSAEL92 and calculates the macroscopic parameters required by the model. In the third example, we use the option of recalling the parameters calculated in a previous run as inputs to a new run. This is particularly interesting if the same cloud configuration is to be used several times. In this case, NBSCATdoes not need to redo the integrations for the macroscopic parameters and saves computation and I/O time, especially if a large phase function file needs to be scanned through.

5.2 Sample Run 1

The objective of the calculations is to determine the effect of forward scattering on transmittance measurements. We assume a visible source ($\lambda = 0.55\mu$m) collimated by a 15 cm diameter collimator to a divergence of 10 mrad, a transmission range of 1 km, and a 15 cm diameter receiver aperture. The aerosol medium is a homogeneous fog of extinction coefficient equal to 5 km^{-1}. We want to calculate only the transmitted power and to study the dependence of the received power on the field of view. The input data file for this example is given in Table 5.1.

5.2.1 Input data for Sample Run 1.

```
WAVL      1.06
   NBSCAT
   RUNP      1.         1.         1.         1.         31.        500.
```

```
SORC      0.0       0.5       0.000     1.0
MEDP      0.0
AERP      7.0       1.0
          1.0       0.5       0.0
                    24.0      1.0
          1.0       0.5       0.24
                    24.0      1.0
          2.0       10.0      0.25
                    24.0      0.05
                    26.0      0.95
          2.0       15.0      0.5
                    24.0      0.03
                    26.0      0.97
          2.0       10.0      0.74
                    24.0      0.05
                    26.0      0.95
          1.0       0.5       0.75
                    24.0      1.0
          1.0       0.5       1.00
                    24.0      1.0
DETR      1.000     0.0       0.50      5.0       .1        .0025
DONE
END
STOP
# THE FOLLOWING IS EOSAEL SOURCE CONTROL INFORMATION YOU CAN SAFELY REMOVE IT
# SCCS  @(#) NBSCAT01.DAT 1.1 04/22/91
```

The RUNP card activates only the ITRANS flag since we are not interested in profile and lidar calculations. LRMAX and RMAX are respectively set at 31 and 500 cm but these numbers are irrelevant in this case.

From the description given above, the source position ZSD of the SORC card is set equal to 0 and its radius W0, equal to 7.5 cm. Since the problem is one of an incoherent collimated source, the beam divergence is better defined by BEAMD. Hence, we choose the half angle beam divergence BEAMD = 0.005 rad and set BEAMQ = 0. The diffraction limit BEAMQ option is generally more suitable for laser applications.

The medium is assumed to have a zero molecular absorption and ALMD is set equal to 0 on the MEDP card.

The AERP card series is the simplest possible since the aerosol medium is homogeneous. The first of the AERP cards sets NIH = 1 (homogeneous aerosol) and the cloud depth ZCD = 1 km. In the homogeneous case, the cloud depth has no significance, but for NBSCATit is necessary to choose ZCD at least as large as ZDTD, the distance to the receiver and/or the maximum range for lidar and profile calculations, here equal to 1 km. The following two AERP cards specify the aerosol properties. We are not mixing different types of aerosols so NMIX = 1 and we set the extinction coefficient ALPE = 5 km^{-1} as required for this application. The aerosol type is IDPF = 25, the heavy fog option of PHASEFN.DAT, and the weight WGT is necessarily 1.

Table 5.1: Standard output image of the TRANS.OUT file for Sample Run 1.

.1000E+01	.6475E+01	.6475E+01	.1000E+00	.3277E-04	.1648E-07	.3279E-04

We want to study the dependence of the transmitted on-axis power on the receiver field of view. To do this, we choose the multiple run option inserting new DETR cards between GO cards as shown in Table 4.1. On the DETR cards, ZDTD and DRTD are fixed at respectively 1 km and 7.5 cm but FOVT is varied between 0.0001 and 1.0 rad. The other DETR parameters related to the lidar configuration, i.e. ZDLD, DRLD and FOVL, are fixed and equal to 0, 1 and 1.8 respectively. Since no lidar calculations are performed, these values are irrelevant.

The image of the resulting NBSCAToutput file TRANS.OUT printed on the standard output is shown in Table 5.2. All output functions are clearly identified in the header. We see that the single scattering detected power remains a constant equal to 0.1516 $\times 10^{-5}$ for all values of the field of view as expected since the unscattered beam is collimated. Actually, there is a slight divergence equal to 15 cm/1 km = 0.00015 rad but NBSCATdoes not take that into account. The single scattering power is obviously what would be measured if none of the scattered radiation would reach the receiver. The single scattering theory predicts that the detected power for the present application is given by

$$P_{ss} \;=\; \frac{P_0 r_0^2 \exp\left(-\tau\right)}{\left(w_0^2 + \phi^2 z^2\right)}, \tag{5.1}$$

where $\tau = 5$ is the optical depth, $r_0 = 7.5$ cm is the radius of the receiver aperture, $w_0 = 7.5$ cm is the radius of the collimator aperture, $\phi = 0.005$ rad is the half angle beam divergence, and $z = 1$ km is the range. Substituting these numbers in Eq. 5.1, we obtain $P_{ss} = 0.1516 \times 10^{-5}$ for $P_0 = 1$ in exact agreement with the results of Table 5.2.

The multiple scattering detected power increases with the field of view from a value negligible compared with P_{ss} at 0.1 mrad but equal to approximately twice P_{ss} at 1 rad. Therefore, for the assumed geometry, NBSCATpredicts that the measured transmittance is a strong function of the field of view. For example, at a receiver half angle field of view of 1 mrad, the apparent extinction coefficient α_{app} determined from the total detected power would be

$$\alpha_{app} \;=\; \alpha_e \;-\; \frac{1}{z}\ln\left(\frac{0.1582}{0.1516}\right) \;=\; 4.957\text{km}^{-1}, \tag{5.2}$$

i.e. less than 1% off the true extinction coefficient α_e of 5 km^{-1}, but at a half angle field of view of 0.1 rad, the error on the extinction coefficient would be greater than 10%.

Upon running NBSCAT, the input data and corresponding calculated results are echoed to the standard output. The output file listings given in this chapter are reproduced from the standard output printouts.

5.3 Sample Run 2

The second example illustrates how a complex inhomogeneous aerosol cloud can be defined in NBSCAT. The set of input data cards for this case is shown in Table 5.3.

5.3.1 Input data file for Sample Run 2.

```
WAVL      0.55
   NBSCAT
   RUNP      1.        0.        0.        0.        31.       500.
   SORC      0.0       0.5       0.000     1.0
   MEDP      0.0
   AERP      1.0       1.0
             1.0       5.0
                       25.0      1.0
   DETR      1.000     0.0       0.500     1.0       .000100   1.8
   GO
   DETR      1.000     0.0       0.500     1.0       .000300   1.8
   GO
   DETR      1.000     0.0       0.500     1.0       .000500   1.8
   GO
   DETR      1.000     0.0       0.500     1.0       .001000   1.8
   GO
   DETR      1.000     0.0       0.500     1.0       .002000   1.8
   GO
   DETR      1.000     0.0       0.500     1.0       .003000   1.8
   GO
   DETR      1.000     0.0       0.500     1.0       .004000   1.8
   GO
   DETR      1.000     0.0       0.500     1.0       .005000   1.8
   GO
   DETR      1.000     0.0       0.500     1.0       .007000   1.8
   GO
   DETR      1.000     0.0       0.500     1.0       .010000   1.8
   GO
   DETR      1.000     0.0       0.500     1.0       .015000   1.8
   GO
   DETR      1.000     0.0       0.500     1.0       .020000   1.8
   GO
   DETR      1.000     0.0       0.500     1.0       .025000   1.8
   GO
   DETR      1.000     0.0       0.500     1.0       .030000   1.8
   GO
   DETR      1.000     0.0       0.500     1.0       .035000   1.8
   GO
   DETR      1.000     0.0       0.500     1.0       .040000   1.8
   GO
   DETR      1.000     0.0       0.500     1.0       .050000   1.8
   GO
   DETR      1.000     0.0       0.500     1.0       .060000   1.8
   GO
   DETR      1.000     0.0       0.500     1.0       .070000   1.8
   GO
   DETR      1.000     0.0       0.500     1.0       .080000   1.8
   GO
   DETR      1.000     0.0       0.500     1.0       .100000   1.8
   GO
   DETR      1.000     0.0       0.500     1.0       .200000   1.8
   GO
```

```
DETR      1.000     0.0       0.500     1.0       .300000   1.8
GO
DETR      1.000     0.0       0.500     1.0       .400000   1.8
GO
DETR      1.000     0.0       0.500     1.0       .500000   1.8
GO
DETR      1.000     0.0       0.500     1.0       .600000   1.8
GO
DETR      1.000     0.0       0.500     1.0       .700000   1.8
GO
DETR      1.000     0.0       0.500     1.0       .800000   1.8
GO
DETR      1.000     0.0       0.500     1.0       .900000   1.8
GO
DETR      1.000     0.0       0.500     1.0       1.00000   1.8
GO
DETR      1.000     0.0       0.500     1.0       1.20000   1.8
GO
DETR      1.000     0.0       0.500     1.0       1.40000   1.8
GO
DETR      1.000     0.0       0.500     1.0       1.60000   1.8
DONE
END
STOP
# THE FOLLOWING IS EOSAEL SOURCE CONTROL INFORMATION YOU CAN SAFELY REMOVE IT
# SCCS  @(#) NBSCAT02.DAT 1.1 04/22/91
```

All the NBSCAToptions are triggered in the RUNP card. LRMAX is set to its maximum value of 31 and the profiles are to be computed up to a distance of 500 cm from the beam axis. The 31 radial positions between 0 and 500 cm are calculated in NBSCATand follow a quadratic law to give a greater resolution near the beam axis where the gradients are strongest.

The incident beam here is a diffraction limited, 0.5 cm radius, 1.06 μm Nd:YAG laser beam and there is no molecular absorption. The resulting SORC and MEDP cards are self-explanatory.

Since all calculation options are turned on in the RUNP card, the parameters of the DETR card have a slightly different interpretion depending on which quantity is considered. More specifically, the transmitted irradiance profile is to be calculated for a range ZDTD $= 1$ km and a field of view FOVT $= 0.1$ rad; the lidar irradiance profile at ZDLD $= 0$ is to be calculated for a range value ZDTD $= 1$ km and field of view FOVL $= 0.0025$ rad; the on-axis transmitted power is to be calculated for a receiver of radius DRTD $= 0.5$ cm and field of view FOVT $= 0.1$ rad positioned at ZDTD $=$ 1km; and the lidar return at ZDLD $= 0$ from 100 equally spaced range values between 0 and ZDTD $= 1$ km is to be calculated for an on-axis receiver of radius DRLD $= 5$ cm and field of view FOVL $= 0.0025$ rad.

The emphasis for this example is the AERP card series. We define an inhomogeneous aerosol medium made up of a 500 m deep fog layer immersed in a uniform 99% relative humidity rural aerosol background. The leading edge of the fog layer is located 250 m from the laser source. We specify the aerosol properties at seven axial positions. The first card specifies NIH = 7 and the overall cloud depth ZCD = 1 km. At the first step ZD = 0, we have a pure rural aerosol (NMIX = 1, IDPF = 24, WGT = 1) of extinction ALPE = 0.5 km^{-1}. These conditions remain unchanged up to ZD = 0.24 km. Hence, the two cards for the second step are exactly the same as for the first step except for ZD = 0.24 km. Next, at ZD = 0.25 km, we mix (NMIX = 2) the rural aerosol (IDPF = 24) with fog (IDPF = 26) in the proportion 0.05 and 0.95, specified by the WGT values, for a total ALPE = 10 km^{-1}. At the following two steps, we have the same rural aerosol/fog mixture with varying proportions to make ALPE = 15 km^{-1} at ZD = 0.5 km and 10 km^{-1} at 0.75 km. The tail end of the aerosol cloud, from 0.76 to 1 km, is the same as the front end. Hence, the last two steps are identical to the first two except for the ZD values. NBSCATcalculates the macroscopic aerosol parameters for the specified mixture at each of the seven steps and linearly interpolates between the different ZDs to form a smoothly varying cloud. The number of permissible steps is currently limited to 101. It is up to the user to determine the number of steps needed to resolve his required cloud structure.

The calculation results are stored in the output files TRANS.OUT, TRPRO.OUT, LIDAR.OUT and LIPRO.OUT for the transmitted on-axis power, the transmitted irradiance profile, the range-resolved lidar return and the lidar irradiance profile, respectively. The images of these files printed on the standard output are reproduced in Tables 5.4-5.7. The file structures are self explanatory. In the LIDAR.OUT file, the single scattering column gives the lidar return calculated with the conventional single scattering lidar equation; the reduced intensity beam column gives the contribution to the multiple scattering return from the unscattered beam, i.e. the first term of Eq. 2.27; the forward scattering column gives the contribution to the multiple scattering return from the forward scattered radiation beam, i.e. the second term of Eq. 2.27; and the total lidar return is the multiple scattering return, i.e. the sum of the preceding two columns.

5.3.2 Standard output image of the TRANS.OUT file for Sample Run 2.

```
.1000E+01  .5000E+01  .5000E+01  .1000E-03  .4895E-03  .3998E-08  .4895E-03
   .1000E+01  .5000E+01  .5000E+01  .3000E-03  .4895E-03  .1671E-07  .4895E-03
   .1000E+01  .5000E+01  .5000E+01  .5000E-03  .4895E-03  .3306E-07  .4895E-03
   .1000E+01  .5000E+01  .5000E+01  .1000E-02  .4895E-03  .8810E-07  .4895E-03
   .1000E+01  .5000E+01  .5000E+01  .2000E-02  .4895E-03  .2560E-06  .4897E-03
   .1000E+01  .5000E+01  .5000E+01  .3000E-02  .4895E-03  .4992E-06  .4900E-03
   .1000E+01  .5000E+01  .5000E+01  .4000E-02  .4895E-03  .8133E-06  .4903E-03
   .1000E+01  .5000E+01  .5000E+01  .5000E-02  .4895E-03  .1189E-05  .4906E-03
   .1000E+01  .5000E+01  .5000E+01  .7000E-02  .4895E-03  .2072E-05  .4915E-03
   .1000E+01  .5000E+01  .5000E+01  .1000E-01  .4895E-03  .3535E-05  .4930E-03
   .1000E+01  .5000E+01  .5000E+01  .1500E-01  .4895E-03  .5774E-05  .4952E-03
   .1000E+01  .5000E+01  .5000E+01  .2000E-01  .4895E-03  .7447E-05  .4969E-03
   .1000E+01  .5000E+01  .5000E+01  .2500E-01  .4895E-03  .8608E-05  .4981E-03
   .1000E+01  .5000E+01  .5000E+01  .3000E-01  .4895E-03  .9407E-05  .4989E-03
   .1000E+01  .5000E+01  .5000E+01  .3500E-01  .4895E-03  .9965E-05  .4994E-03
   .1000E+01  .5000E+01  .5000E+01  .4000E-01  .4895E-03  .1037E-04  .4998E-03
   .1000E+01  .5000E+01  .5000E+01  .5000E-01  .4895E-03  .1088E-04  .5003E-03
   .1000E+01  .5000E+01  .5000E+01  .6000E-01  .4895E-03  .1118E-04  .5006E-03
   .1000E+01  .5000E+01  .5000E+01  .7000E-01  .4895E-03  .1137E-04  .5008E-03
   .1000E+01  .5000E+01  .5000E+01  .8000E-01  .4895E-03  .1150E-04  .5010E-03
   .1000E+01  .5000E+01  .5000E+01  .1000E+00  .4895E-03  .1165E-04  .5011E-03
```

.1000E+01	.5000E+01	.5000E+01	.2000E+00	.4895E-03	.1186E-04	.5013E-03
.1000E+01	.5000E+01	.5000E+01	.3000E+00	.4895E-03	.1190E-04	.5014E-03
.1000E+01	.5000E+01	.5000E+01	.4000E+00	.4895E-03	.1191E-04	.5014E-03
.1000E+01	.5000E+01	.5000E+01	.5000E+00	.4895E-03	.1192E-04	.5014E-03
.1000E+01	.5000E+01	.5000E+01	.6000E+00	.4895E-03	.1192E-04	.5014E-03
.1000E+01	.5000E+01	.5000E+01	.7000E+00	.4895E-03	.1193E-04	.5014E-03
.1000E+01	.5000E+01	.5000E+01	.8000E+00	.4895E-03	.1193E-04	.5014E-03
.1000E+01	.5000E+01	.5000E+01	.9000E+00	.4895E-03	.1193E-04	.5014E-03
.1000E+01	.5000E+01	.5000E+01	.1000E+01	.4895E-03	.1193E-04	.5014E-03
.1000E+01	.5000E+01	.5000E+01	.1200E+01	.4895E-03	.1193E-04	.5014E-03
.1000E+01	.5000E+01	.5000E+01	.1400E+01	.4895E-03	.1193E-04	.5014E-03
.1000E+01	.5000E+01	.5000E+01	.1600E+01	.4895E-03	.1193E-04	.5014E-03

5.3.3 Standard output image of the TRPRO.OUT file for Sample Run 2.

5.3.4 Standard output image of the LIDAR.OUT file for Sample Run 2.

5.3.5 Standard output image of the LIPRO.OUT file for Sample Run 2.

The example was primarily chosen to illustrate the capabilities of NBSCATbut a few observations on the resulting multiple scattering effects are worth mentioning. For the lidar problem considered here, the transmitted power measured with the on-axis 1 cm diameter, 0.1 rad field of view receiver is negligibly affected by forward scattering. The irradiance profile has the characteristic off-axis aureole due to forward scattering. The range-resolved lidar return is definitely affected by multiple scattering as soon as we get into the fog layer. Finally, the lidar profile shows a signal drop of $\sim 40\%$ from the beam axis to a position 5 m off-axis.

5.4 Sample Run 3

This example shows how the parameters of a previously used cloud configuration can be directly inputed instead of recalculated from detailed phase function data. To do this, we rerun Sample Case 2 using the second option of the AERP card series described in Table 4.6. The aerosol parameters calculated by NBSCATin Sample Run 2 and stored in the file AERP.DAT are copied in the AERP input card series. The new input file for this example is reproduced in Table 5.8.

5.4.1 Input data file for Sample Run 3.

```
WAVL      1.06
   NBSCAT
```

```
RUNP      1.        1.        1.        1.        31.       500.
SORC      0.0       0.5       0.000     1.0
MEDP      0.0
AERP      7.0       1.0
          -1.0      0.5       0.0
          .4541E+00 .3178E-01 .1415E-01 .8270E-02 .5377E+00 .1110E+00
          .7172E+00 .9408E-02
          -1.0      0.5       0.24
          .4541E+00 .3178E-01 .1415E-01 .8270E-02 .5377E+00 .1110E+00
          .7172E+00 .9408E-02
          -1.0      10.0      0.25
          .9316E+01 .6679E+00 .1581E-01 .7795E-02 .1877E+00 .1021E+00
          .5007E+00 .5662E+00
          -1.0      15.0      0.50
          .1398E+02 .1003E+01 .1528E-01 .7786E-02 .1853E+00 .1019E+00
          .4975E+00 .8613E+00
          -1.0      10.0      0.74
          .9316E+01 .6679E+00 .1581E-01 .7795E-02 .1877E+00 .1021E+00
          .5007E+00 .5662E+00
          -1.0      0.5       0.75
          .4541E+00 .3178E-01 .1415E-01 .8270E-02 .5377E+00 .1110E+00
          .7172E+00 .9408E-02
          -1.0      0.5       1.00
          .4541E+00 .3178E-01 .1415E-01 .8270E-02 .5377E+00 .1110E+00
          .7172E+00 .9408E-02
DETR      1.000     0.0       0.50      5.0       .1        .0025
DONE
END
STOP
# THE FOLLOWING IS EOSAEL SOURCE CONTROL INFORMATION YOU CAN SAFELY REMOVE IT
# SCCS  @(#) NBSCAT03.DAT 1.1 04/22/91
```

The AERP card series is made up of the same seven steps as in the previous example but, this time, the NMIX variable is given a negative value triggering NBSCATto read the macroscopic aerosol parameters directly instead of reading first a phase function and then calculating the parameters. The list, description and units of the parameters are given in Table 4.6.

The parameters ALPE and ZD at each step are the same as they were in Sample Run 2 but they need not be. What the series of eight parameters actually defines is a local cloud structure, i.e. a relative distribution of particle types and sizes applied to a given wavelength. The absolute concentration can vary. NBSCATadjusts those eight parameters according to the specified ALPE value at each step. Different ZD positions could also have been assigned. Similarly, all the other run, source and receiver parameters, **except the wavelength**, could have been modified. They were chosen the same here to demonstrate that the two separate AERP options of specifying the aerosol properties produce the same end results as indicated by comparing Tables 5.4–5.7 to 5.9–5.12. The last digit differences in some values are the result of the truncation to four digits of the calculated parameters when copied into the AERP.DAT file.

The AERP option used in this example is particularly useful and efficient if the same relative aerosol cloud structure is to be used in many subsequent runs with many different receiver and source (except the wavelength) parameters.

5.4.2 Standard output image of the TRANS.OUT file for Sample Run 3.

```
.1000E+01  .6475E+01  .6475E+01  .1000E+00  .3277E-04  .1648E-07  .3279E-04
```

5.4.3 Standard output image of the TRPRO.OUT file for Sample Run 3.

```
 31  .50000E+00  .00000E+00  .10000E+01  .00000E+00  .10000E+00
   .0000E+00  .6797E-01  .9239E-01  .1256E+00  .1707E+00  .2321E+00  .3155E+00
   .4288E+00  .5830E+00  .7924E+00  .1077E+01  .1464E+01  .1991E+01  .2706E+01
   .3678E+01  .5000E+01  .6797E+01  .9239E+01  .1256E+02  .1707E+02  .2321E+02
   .3155E+02  .4288E+02  .5830E+02  .7924E+02  .1077E+03  .1464E+03  .1991E+03
   .2706E+03  .3678E+03  .5000E+03
   .0000E+00
   .1621E+01  .1591E+01  .1567E+01  .1522E+01  .1443E+01  .1307E+01  .1089E+01
   .7768E+00  .4164E+00  .1315E+00  .1563E-01  .3054E-03  .2122E-06  .3096E-12
   .1273E-20  .1273E-20  .1273E-20  .1273E-20  .1273E-20  .1273E-20  .1273E-20
   .1273E-20  .1273E-20  .1273E-20  .1273E-20  .1273E-20  .1273E-20  .1273E-20
   .1273E-20  .1273E-20  .1273E-20
   .1000E+01
   .5372E-04  .5370E-04  .5369E-04  .5365E-04  .5359E-04  .5348E-04  .5327E-04
   .5288E-04  .5218E-04  .5090E-04  .4862E-04  .4468E-04  .3822E-04  .2863E-04
   .1679E-04  .6266E-05  .1014E-05  .3537E-07  .4705E-09  .3972E-09  .3904E-09
   .3784E-09  .3584E-09  .3272E-09  .2852E-09  .2403E-09  .2058E-09  .1843E-09
   .1683E-09  .1558E-09  .1460E-09
```

5.4.4 Standard output image of the LIDAR.OUT file for Sample Run 3.

```
.0000E+00  .2500E-02  .0000E+00  .4449E-06  .0000E+00  .4449E-06
   .1000E-01  .2500E-02  .7315E-06  .7048E-06  .1911E-11  .7048E-06
   .2000E-01  .2500E-02  .1811E-06  .1796E-06  .8956E-11  .1796E-06
   .3000E-01  .2500E-02  .7967E-07  .7947E-07  .5770E-11  .7947E-07
   .4000E-01  .2500E-02  .4437E-07  .4434E-07  .4286E-11  .4434E-07
   .5000E-01  .2500E-02  .2811E-07  .2812E-07  .3410E-11  .2812E-07
   .6000E-01  .2500E-02  .1933E-07  .1934E-07  .2829E-11  .1935E-07
   .7000E-01  .2500E-02  .1406E-07  .1407E-07  .2413E-11  .1408E-07
   .8000E-01  .2500E-02  .1066E-07  .1067E-07  .2101E-11  .1067E-07
   .9000E-01  .2500E-02  .8337E-08  .8348E-08  .1856E-11  .8350E-08
   .1000E+00  .2500E-02  .6685E-08  .6695E-08  .1660E-11  .6697E-08
   .1100E+00  .2500E-02  .5470E-08  .5479E-08  .1498E-11  .5480E-08
   .1200E+00  .2500E-02  .4551E-08  .4558E-08  .1363E-11  .4559E-08
   .1300E+00  .2500E-02  .3839E-08  .3845E-08  .1248E-11  .3847E-08
   .1400E+00  .2500E-02  .3277E-08  .3283E-08  .1150E-11  .3284E-08
   .1500E+00  .2500E-02  .2826E-08  .2831E-08  .1064E-11  .2832E-08
   .1600E+00  .2500E-02  .2459E-08  .2464E-08  .9888E-12  .2465E-08
   .1700E+00  .2500E-02  .2157E-08  .2161E-08  .9224E-12  .2162E-08
```

.1800E+00	.2500E-02	.1905E-08	.1908E-08	.8632E-12	.1909E-08
.1900E+00	.2500E-02	.1693E-08	.1696E-08	.8103E-12	.1697E-08
.2000E+00	.2500E-02	.1512E-08	.1515E-08	.7626E-12	.1516E-08
.2100E+00	.2500E-02	.1358E-08	.1361E-08	.7195E-12	.1361E-08
.2200E+00	.2500E-02	.1225E-08	.1228E-08	.6803E-12	.1228E-08
.2300E+00	.2500E-02	.1110E-08	.1112E-08	.6445E-12	.1113E-08
.2400E+00	.2500E-02	.1009E-08	.1011E-08	.6118E-12	.1012E-08
.2500E+00	.2500E-02	.5039E-07	.5043E-07	.5435E-10	.5048E-07
.2600E+00	.2500E-02	.3886E-07	.3883E-07	.7155E-10	.3890E-07
.2700E+00	.2500E-02	.2993E-07	.2986E-07	.8140E-10	.2994E-07
.2800E+00	.2500E-02	.2301E-07	.2292E-07	.8600E-10	.2301E-07
.2900E+00	.2500E-02	.1766E-07	.1757E-07	.8689E-10	.1765E-07
.3000E+00	.2500E-02	.1352E-07	.1344E-07	.8524E-10	.1352E-07
.3100E+00	.2500E-02	.1033E-07	.1026E-07	.8189E-10	.1034E-07
.3200E+00	.2500E-02	.7880E-08	.7812E-08	.7747E-10	.7890E-08
.3300E+00	.2500E-02	.5995E-08	.5937E-08	.7245E-10	.6009E-08
.3400E+00	.2500E-02	.4549E-08	.4501E-08	.6714E-10	.4568E-08
.3500E+00	.2500E-02	.3443E-08	.3404E-08	.6178E-10	.3466E-08
.3600E+00	.2500E-02	.2599E-08	.2568E-08	.5652E-10	.2624E-08
.3700E+00	.2500E-02	.1956E-08	.1932E-08	.5146E-10	.1984E-08
.3800E+00	.2500E-02	.1469E-08	.1450E-08	.4665E-10	.1497E-08
.3900E+00	.2500E-02	.1099E-08	.1086E-08	.4214E-10	.1128E-08
.4000E+00	.2500E-02	.8204E-09	.8105E-09	.3794E-10	.8485E-09
.4100E+00	.2500E-02	.6104E-09	.6036E-09	.3407E-10	.6376E-09
.4200E+00	.2500E-02	.4528E-09	.4483E-09	.3052E-10	.4788E-09
.4300E+00	.2500E-02	.3348E-09	.3321E-09	.2729E-10	.3594E-09
.4400E+00	.2500E-02	.2468E-09	.2454E-09	.2436E-10	.2697E-09
.4500E+00	.2500E-02	.1814E-09	.1808E-09	.2170E-10	.2025E-09
.4600E+00	.2500E-02	.1329E-09	.1330E-09	.1929E-10	.1523E-09
.4700E+00	.2500E-02	.9699E-10	.9752E-10	.1712E-10	.1146E-09
.4800E+00	.2500E-02	.7058E-10	.7137E-10	.1515E-10	.8651E-10
.4900E+00	.2500E-02	.5119E-10	.5211E-10	.1336E-10	.6547E-10
.5000E+00	.2500E-02	.3700E-10	.3796E-10	.1175E-10	.4971E-10
.5100E+00	.2500E-02	.2602E-10	.2695E-10	.1000E-10	.3695E-10
.5200E+00	.2500E-02	.1839E-10	.1924E-10	.8501E-11	.2774E-10
.5300E+00	.2500E-02	.1306E-10	.1383E-10	.7207E-11	.2104E-10
.5400E+00	.2500E-02	.9314E-11	.9997E-11	.6096E-11	.1609E-10
.5500E+00	.2500E-02	.6674E-11	.7270E-11	.5143E-11	.1241E-10
.5600E+00	.2500E-02	.4805E-11	.5319E-11	.4328E-11	.9646E-11
.5700E+00	.2500E-02	.3475E-11	.3913E-11	.3633E-11	.7546E-11
.5800E+00	.2500E-02	.2525E-11	.2896E-11	.3042E-11	.5938E-11
.5900E+00	.2500E-02	.1842E-11	.2155E-11	.2541E-11	.4696E-11
.6000E+00	.2500E-02	.1351E-11	.1612E-11	.2118E-11	.3730E-11
.6100E+00	.2500E-02	.9944E-12	.1212E-11	.1762E-11	.2974E-11
.6200E+00	.2500E-02	.7354E-12	.9163E-12	.1463E-11	.2379E-11
.6300E+00	.2500E-02	.5463E-12	.6960E-12	.1213E-11	.1909E-11
.6400E+00	.2500E-02	.4076E-12	.5313E-12	.1004E-11	.1535E-11
.6500E+00	.2500E-02	.3054E-12	.4074E-12	.8296E-12	.1237E-11
.6600E+00	.2500E-02	.2298E-12	.3139E-12	.6851E-12	.9990E-12
.6700E+00	.2500E-02	.1737E-12	.2429E-12	.5653E-12	.8082E-12
.6800E+00	.2500E-02	.1318E-12	.1888E-12	.4662E-12	.6550E-12
.6900E+00	.2500E-02	.1005E-12	.1474E-12	.3843E-12	.5317E-12
.7000E+00	.2500E-02	.7692E-13	.1155E-12	.3167E-12	.4323E-12
.7100E+00	.2500E-02	.5912E-13	.9094E-13	.2611E-12	.3520E-12

```
 .7200E+00  .2500E-02  .4563E-13  .7187E-13  .2152E-12  .2871E-12
 .7300E+00  .2500E-02  .3537E-13  .5703E-13  .1775E-12  .2345E-12
 .7400E+00  .2500E-02  .2752E-13  .4543E-13  .1465E-12  .1919E-12
 .7500E+00  .2500E-02  .4009E-15  .1428E-14  .3723E-14  .5151E-14
 .7600E+00  .2500E-02  .3864E-15  .1369E-14  .3430E-14  .4800E-14
 .7700E+00  .2500E-02  .3727E-15  .1323E-14  .3167E-14  .4490E-14
 .7800E+00  .2500E-02  .3596E-15  .1287E-14  .2927E-14  .4214E-14
 .7900E+00  .2500E-02  .3471E-15  .1255E-14  .2710E-14  .3966E-14
 .8000E+00  .2500E-02  .3351E-15  .1227E-14  .2514E-14  .3740E-14
 .8100E+00  .2500E-02  .3236E-15  .1200E-14  .2336E-14  .3536E-14
 .8200E+00  .2500E-02  .3126E-15  .1174E-14  .2175E-14  .3349E-14
 .8300E+00  .2500E-02  .3021E-15  .1150E-14  .2028E-14  .3179E-14
 .8400E+00  .2500E-02  .2920E-15  .1127E-14  .1895E-14  .3022E-14
 .8500E+00  .2500E-02  .2823E-15  .1104E-14  .1774E-14  .2879E-14
 .8600E+00  .2500E-02  .2731E-15  .1082E-14  .1664E-14  .2746E-14
 .8700E+00  .2500E-02  .2642E-15  .1061E-14  .1563E-14  .2624E-14
 .8800E+00  .2500E-02  .2556E-15  .1040E-14  .1471E-14  .2511E-14
 .8900E+00  .2500E-02  .2474E-15  .1020E-14  .1386E-14  .2407E-14
 .9000E+00  .2500E-02  .2395E-15  .1000E-14  .1309E-14  .2309E-14
 .9100E+00  .2500E-02  .2320E-15  .9812E-15  .1237E-14  .2218E-14
 .9200E+00  .2500E-02  .2247E-15  .9624E-15  .1171E-14  .2133E-14
 .9300E+00  .2500E-02  .2177E-15  .9441E-15  .1110E-14  .2054E-14
 .9400E+00  .2500E-02  .2110E-15  .9262E-15  .1053E-14  .1980E-14
 .9500E+00  .2500E-02  .2045E-15  .9087E-15  .1001E-14  .1910E-14
 .9600E+00  .2500E-02  .1983E-15  .8916E-15  .9521E-15  .1844E-14
 .9700E+00  .2500E-02  .1923E-15  .8749E-15  .9067E-15  .1782E-14
 .9800E+00  .2500E-02  .1865E-15  .8585E-15  .8644E-15  .1723E-14
 .9900E+00  .2500E-02  .1809E-15  .8426E-15  .8249E-15  .1667E-14
 .1000E+01  .2500E-02  .1756E-15  .8269E-15  .7880E-15  .1615E-14
```

5.4.5 Standard output image of the LIPRO.OUT file for Sample Run 3.

```
31  .50000E+00  .00000E+00  .10000E+01  .00000E+00  .10000E+00
 .0000E+00  .6797E-01  .9239E-01  .1256E+00  .1707E+00  .2321E+00  .3155E+00
 .4288E+00  .5830E+00  .7924E+00  .1077E+01  .1464E+01  .1991E+01  .2706E+01
 .3678E+01  .5000E+01  .6797E+01  .9239E+01  .1256E+02  .1707E+02  .2321E+02
 .3155E+02  .4288E+02  .5830E+02  .7924E+02  .1077E+03  .1464E+03  .1991E+03
 .2706E+03  .3678E+03  .5000E+03
 .1000E+01
 .2618E-16  .2586E-16  .2561E-16  .2521E-16  .2464E-16  .2398E-16  .2346E-16
 .2325E-16  .2322E-16  .2322E-16  .2322E-16  .2322E-16  .2322E-16  .2322E-16
 .2322E-16  .2322E-16  .2322E-16  .2322E-16  .2321E-16  .2320E-16  .2318E-16
 .2315E-16  .2309E-16  .2298E-16  .2278E-16  .2243E-16  .2184E-16  .2088E-16
 .1952E-16  .1790E-16  .1639E-16
```

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