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Improved discrete ordinate solutions in the presence of an anisotropically reflecting lower boundary: Upgrades of the DISORT computational tool

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ABSTRACT

A successor version 3 of DISORT (DISORT3) is presented with important upgrades that improve the accuracy, efficiency, and stability of the algorithm. Compared with version 2 (DISORT2 released in 2000) these upgrades include (a) a redesigned BRDF computation that improves both speed and accuracy, (b) a revised treatment of the single scattering correction, and (c) additional efficiency and stability upgrades for beam sources. In DISORT3 the BRDF computation is improved in the following three ways: (i) the Fourier decomposition is prepared "off-line", thus avoiding the repeated internal computations done in DISORT2; (ii) a large enough number of terms in the Fourier expansion of the BRDF is employed to guarantee accurate values of the expansion coefficients (default is 200 instead of 50 in DISORT2); (iii) in the post-processing step the reflection of the direct attenuated beam from the lower boundary is included resulting in a more accurate single scattering correction. These improvements in the treatment of the BRDF have led to improved accuracy and a several-fold increase in speed. In addition, the stability of beam sources has been improved by removing a singularity occurring when the cosine of the incident beam angle is too close to the reciprocal of any of the eigenvalues. The efficiency for beam sources has been further improved from reducing by a factor of 2 (compared to DISORT2) the dimension of the linear system of equations that must be solved to obtain the particular solutions, and by replacing the LINPAK routines used in DISORT2 by LAPACK 3.5 in DISORT3. These beam source stability and efficiency upgrades bring enhanced stability and an additional 5–7% improvement in speed. Numerical results are provided to demonstrate and quantify the improvements in accuracy and efficiency of DISORT3 compared to DISORT2.

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1. Introduction

The DISORT algorithm [1] solves the radiative transfer equation for monochromatic unpolarized radiation in a multi-layered, plane parallel medium. As part of its 50th anniversary celebration (http://www.opticsinfobase.org/ao/anniversary/), Applied Optics featured the DISORT paper [1] as its most cited article. As of 6 January 2012, this paper had been cited 1444 times. Thanks to NASA's distribution of the DISORT code since the 1990s, the use of the code by the international scientific community exceeds the 1444 citation count of the paper by an order of magnitude or more. DISORT has become a standard against which all other 1-D radiative transfer codes are compared, and it has been employed in many radiative transfer codes including Streamer [2], MODTRAN [3], SBDART [4] and libRadtran (see http://www.libradtran.org). Also, many university courses on radiative transfer use DISORT as a curriculum benchmark.

The first version of DISORT, released in 1988 [1], together with subsequent minor releases (referred to as DISORT 1.x), calculated intensities and fluxes for Lambertian and simplified non-Lambertian lower boundaries. This version was ideally suited for flux (irradiance) computations in a horizontal slab illuminated from the top, but produced less accurate intensities (especially in the forward scattering direction) when used together with the option for δ–M transformation [5]. In addition, the non-Lambertian lower boundary had limited applicability as it depended only on the angle between incident and reflected directions. The updated version (DISORT 2.0beta) released in 2000 [6] increased the accuracy of intensities by implementing the Nakajima–Tanaka intensity corrections [7] and included a more general (non-Lambertian) bidirectional reflection distribution function (BRDF) as the lower boundary. However, it has become apparent that this implementation (hereafter referred to as DISORT2) had some shortcomings mainly related to the treatment of the BRDF, which have previously been documented in some forms [8,9] but an upgraded computational code with adequate corrections has not been publicly released until now.

The purpose of the present paper is to remedy these shortcomings and provide an upgraded version of the code (hereafter referred to as DISORT3) that significantly enhances its reliability, accuracy, efficiency, and utility. In Section 2 we provide a basic description of the DISORT theory, while Section 3 is devoted to a discussion of the upgrades. In Section 4 we provide some examples, and in Section 5 we provide a summary.

2. Theory

2.1. Radiative transfer equation

The equation describing the transfer of diffuse monochromatic radiation through a plane parallel medium is given by [10,11]

$$\pm\mu\frac{dI(\tau,\pm\mu,\phi)}{d\tau}=I(\tau,\pm\mu,\phi)-S(\tau,\pm\mu,\phi) \tag{1}$$

where $I(\tau,\pm\mu,\phi)$ is the radiance, τ is the optical depth, $\mu=|\cos\theta|$, θ being the polar angle, and ϕ is the azimuth angle. We assume that the usual diffuse-direct splitting of the radiation field has been done, so that the source function $S(\tau,\pm\mu,\phi)$ consists of three terms

$$S(\tau,\pm\mu,\phi)=\frac{\varpi F_0}{4\pi}p(\pm\mu,\phi;-\mu_0,\phi_0)\,e^{-\tau/\mu_0}+(1-\varpi)B(T)$$
$$+\frac{\varpi}{4\pi}\int_0^{2\pi}\int_{-1}^{1}p(\pm\mu,\phi;\mu',\phi')\,I(\tau,\mu',\phi')\,d\mu'\,d\phi' \tag{2}$$

where the dependence of the single-scattering albedo ϖ, the scattering phase function $p(\pm\mu,\phi;\mu',\phi')$, and the Planck function $B(T)$ on the optical depth τ has been omitted for notational convenience. The first term on the right hand side of Eq. (2) is the single-scattering incident collimated beam pseudo-source resulting from the diffuse-direct splitting with $(-\mu_0,\ \phi_0)$ corresponding to the direction of the incident beam with irradiance $\mu_0 F_0$ normal to the slab. The second term is due to thermal emission, and the third term is due to multiple scattering.

2.2. δ–M transformation

For strongly forward-peaked scattering the radiative transfer equation is difficult to solve, and it has proven to be very useful to approximate the phase function p as a sum of a Dirac delta-function in the forward scattering direction and a remainder $\hat{p}$ as follows [5]:

$$p(\mu,\phi,\mu',\phi')\approx 2f\delta(\mu-\mu')\,\delta(\phi-\phi')+(1-f)\hat{p}(\mu,\phi,\mu',\phi') \tag{3}$$

where f is the separation fraction. Use of Eq. (3) in Eqs. (1) and (2) leads to identical equations except with $\hat{p}$, $\hat{\tau}$, and $\hat{\varpi}$, replacing p, τ, and ϖ where

$$d\hat{\tau}=(1-f\varpi)\,d\tau \qquad \hat{\varpi}=\frac{(1-f)\varpi}{1-f\varpi}. \tag{4}$$

The virtue of the δ–M transformation is to reduce significantly the computational burden. In general, for a phase function that is strongly forward-peaked due to light diffraction, a very fine angular resolution is required for accurate evaluation of the integral in the multiple scattering term in Eq. (2). By replacing the forward peak with a Dirac delta-function the forward peak is removed from the integral, which greatly decreases the number of terms needed to expand the remainder phase function $\hat{p}$ in a finite sum of Legendre polynomials.

2.3. Separation of the azimuth dependence

In slab geometry, an important simplification is obtained by making use of the addition theorem for spherical harmonics to write the phase function as a cosine series, and expand the radiance likewise

$$\hat{p}(\mu,\phi,\mu',\phi')=\sum_{m=0}^{M-1}(2-\delta_{0m})\hat{p}^m(\mu,\mu')\cos m(\phi-\phi') \tag{5}$$

$$I(\hat{\tau},\mu,\phi)=\sum_{m=0}^{M-1}I^m(\hat{\tau},\mu)\cos m(\phi-\phi_0). \tag{6}$$