





# PythonicDISORT: A Python reimplementa- tion of the Discrete Ordinate Radiative Transfer package DISORT


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## Summary

The Radiative Transfer Equation (RTE) models the processes of absorption, scattering and emission as electromagnetic radiation propagates through a medium. Consider a plane-parallel, horizontally homogeneous atmosphere with vertical coordinate  $\tau$  (optical depth) increasing from top to bottom, directional coordinates  $\phi$  for the azimuthal angle (positive is counterclockwise), and  $\mu = \cos \theta$  for the polar direction ( $\theta$  is the polar angle measured from the surface normal) with  $\mu > 0$  pointing up following the convention of K. Stamnes et al. (1988). Given three possible sources, namely blackbody emission from the atmosphere  $s(\tau)$ , scattering from a collimated beam of starlight with intensity  $I_0$  as well as incident azimuthal and cosine polar angles  $\phi_0$  and  $\mu_0$ , respectively, and radiation from other atmospheric layers or the Earth's surface which is modeled by Dirichlet boundary conditions, the diffuse intensity  $u(\tau, \mu, \phi)$  propagating in direction  $(\mu, \phi)$  is described by the 1D RTE (Chandrasekhar, 1960; K. Stamnes et al., 1988)

$$\mu \frac{\partial u(\tau, \mu, \phi)}{\partial \tau} = u(\tau, \mu, \phi) - \frac{\omega}{4\pi} \int_{-1}^1 \int_0^{2\pi} p(\mu, \phi; \mu', \phi') u(\tau, \mu', \phi') d\phi' d\mu' - \frac{\omega I_0}{4\pi} p(\mu, \phi; -\mu_0, \phi_0) \exp(-\mu_0^{-1} \tau) - s(\tau) \quad (1)$$

Here  $\omega$  is the single-scattering albedo and  $p$  the scattering phase function. These are assumed to be independent of  $\tau$ , i.e. homogeneous in the atmospheric layer. An atmosphere with  $\tau$ -dependent  $\omega$  and  $p$  can be modeled by a multi-layer atmosphere with different  $\omega$  and  $p$  for each layer.

The RTE is important in many fields of science and engineering, for example, in the retrieval of optical properties of the medium from measurements (McGuire et al., 2008; Teng et al., 2020; Torricella et al., 1999). The gold standard for numerically solving the 1D RTE is the Discrete Ordinate Radiative Transfer package DISORT which was written in FORTRAN 77 and first released in 1988 (K. Stamnes et al., 1988; S. Stamnes, 1999). It has been widely used, for example by MODTRAN (Berk et al., 2014), Streamer (Key & Schweiger, 1998), and SBDART (Ricchiazzi et al., 1998), all of which are comprehensive radiative transfer models that are themselves widely used in atmospheric science, and by the three retrieval papers: Torricella et al. (1999), McGuire et al. (2008), and Teng et al. (2020). DISORT implements the Discrete Ordinates Method which has two key steps. First, the diffuse intensity function  $u$  and phase function  $p$  are expanded as the Fourier cosine series and Legendre series, respectively,

$$u(\tau, \mu, \phi) \approx \sum_{m=0} u^m(\tau, \mu) \cos(m(\phi_0 - \phi))$$

$$p(\mu, \phi; \mu', \phi') = p(\cos \gamma) \approx \sum_{\ell=0} (2\ell + 1) g_\ell P_\ell(\cos \gamma)$$

where  $\gamma$  is the scattering angle,  $g_\ell$  is the  $\ell$ th Legendre coefficient of the phase function  $p$ , and  $P_\ell$  is the Legendre polynomial of order  $\ell$ . These address the  $\phi'$  integral in (1) and decompose the problem into solving the equation

$$\mu \frac{\partial u^m(\tau, \mu)}{\partial \tau} = u^m(\tau, \mu) - \int_{-1}^1 D^m(\mu, \mu') u^m(\tau, \mu') d\mu' - Q^m(\tau, \mu) - \delta_{0m} s(\tau)$$

for each Fourier mode of  $u$ . The  $D^m$  terms are derived from  $p$  and are thus also independent of  $\tau$ . The  $Q^m$  terms are derived from the direct beam source. The second key step is to discretize the  $\mu'$  integral using a quadrature scheme. DISORT uses the double-Gauss quadrature scheme from Sykes (1951). This results in a system of ordinary differential equations that can be solved using standard methods, and post-hoc corrections are made to reduce the errors incurred by the truncation of the phase function Legendre series (Nakajima & Tanaka, 1988; Wiscombe, 1977).

My package PythonicDISORT is a Python 3 reimplementaion of DISORT that replicates most of its functionality while being easier to install, use and modify, though at the cost of computational speed. It has DISORT's main features: multi-layer solver, delta- $M$  scaling, Nakajima-Tanaka corrections, only flux option, direct beam source, isotropic internal source (blackbody emission), Dirichlet boundary conditions (diffuse flux boundary sources), Bi-Directional Reflectance Function for surface reflection, as well as additional features like actinic flux computation and integration of the solution functions with respect to optical depth. PythonicDISORT has been tested against DISORT on DISORT's own test problems. While packages that wrap DISORT in Python already exist (Connour & Wolff, 2020; Hu, 2017), PythonicDISORT is the first reimplementaion of DISORT from scratch in Python.

## Statement of need

PythonicDISORT is not meant to replace DISORT. Due to fundamental differences between Python and FORTRAN, PythonicDISORT, though quite optimized, remains slower than DISORT. Thus, projects that prioritize computational speed should still use DISORT. In addition, PythonicDISORT currently lacks DISORT's latest features, most notably its pseudo-spherical correction.

PythonicDISORT is instead designed with three goals in mind. First, it is meant to be a pedagogical and exploratory tool. PythonicDISORT's ease of installation and use makes it a low-barrier introduction to Radiative Transfer and Discrete Ordinates Solvers. Even researchers who are experienced in the field may find it useful to experiment with PythonicDISORT before upscaling with DISORT. Installation of PythonicDISORT through pip should be system agnostic as PythonicDISORT's core dependencies are only NumPy (Harris et al., 2020) and SciPy (Virtanen et al., 2020). In addition, using PythonicDISORT is as simple as calling the Python function `pydisort`. In contrast, DISORT requires FORTRAN compilers and manual memory allocation, has a lengthy and system-dependent installation, and each call requires a shell script for compilation and execution.

Second, PythonicDISORT is designed to be modified by users to suit their needs. Given that Python is a widely used high-level language, PythonicDISORT's code should be accessible to more people than DISORT's FORTRAN code. Moreover, PythonicDISORT comes with a Jupyter Notebook (Kluyver et al., 2016) – its [Comprehensive Documentation](#) – that breaks down both

the mathematics and code behind the solver. Users can in theory follow the Notebook to recode PythonicDISORT from scratch; it should at least help them make modifications.

Third, PythonicDISORT is intended to be a testbed. For the same reasons given above, it should be easier to implement and test experimental features in PythonicDISORT than in DISORT. This should expedite research and development for DISORT and similar algorithms.

PythonicDISORT was first released on [PyPI](#) and [GitHub](#) on May 30, 2023. It was used in Ho & Pincus (2024) and is being used in at least three ongoing projects: on the Two-Stream Approximations, on atmospheric photolysis, and on the topographic mapping of Mars through photoclinometry. I will continue to maintain and upgrade PythonicDISORT. The latest version: PythonicDISORT v0.9.3 was released on October 13, 2024.

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