Simple 3-D codes for the exploration of inhomogeneity effects

Stefan Kinne   NASA-Goddard / UMBC-JCET

Abstract. The performance of approximate solutions to three-dimensional solar radiative transfer problems is investigated. Discrete Angle Radiative Transfer (DART) methods are useful tools to demonstrate 3-dimensional pattern for isotropic scattering media (e.g. infrared emission). However, for solar radiative transfer problems with anisotropic scattering (e.g. clouds) DART results are not very encouraging. Without modifications to subcell-initialization and to the speed of the solver, Monte-Carlo methods (with limited photons) are more than a competitive option.

Introduction:

Atmospheric radiative processes are commonly simulated with one-dimensional radiative transfer methods, assuming that radiative energy exchange is solely a function of height. This approximation is often accepted, in part due to tremendous additional computational requirements for multi-dimensional radiative transfer simulations. Common methods based on a statistical (Monte-Carlo) treatment are usually limited to case-studies (e.g. as to illustrate biases of the plane parallel assumption). However, these methods are too time-consuming for repetitive applications, as they are required in cloud-process studies. Thus, faster multi-dimensional methods are sought, even at the expense of accuracy.

One of the simplest concepts in multi-dimensional radiative transfer is the Discrete Angle Raditative Transfer (DART). Based on this concept, a standard method and an advanced method are introduced. Then, for a simple ‘step-cloud’ scenario, the (in-) accuracy of these methods is tested in comparisons to Monte-Carlo simulations.

Methods:

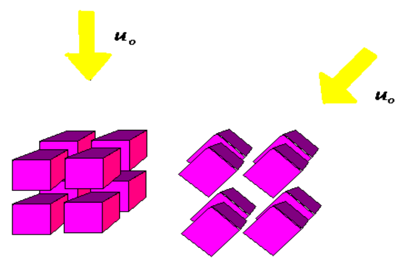
All three-dimensional methods discussed here, assume that atmospheric inhomogeneity can be approximated by an array of equal-sized homogeneous cells (in shapes of cubes or rectangular columns). Each cube (as we will call cell from now on) has its individual optical (single-scattering-) properties.

<u>MONTE-CARLO</u>: In Monte-Carlo methods, photons are repeatedly tracked, as they advance through the array of cubes. Processes within each cube are based on probabilities, which are given by the prescribed single scattering properties for each cube. Once a photon is absorbed within the medium or once a photon reaches a permitted exit, the next photon is processed. The final result (for absorption or the locations of exits) reflects a statistical probability. Thus, many photons are needed for accurate results. Monte-Carlo based results for transmission, reflection and absorption for the cases of the I3RC-comparison are summarized in the adjacent Table. Monte-Carlo results also provide the truth in accuracy test of approximate methods such as DART.

32000 ph	Tran.	Refl.	Abs.
Step-c 1	.673	.327	
Step-c 2	.418	.582	
Step-c 3	.597	.262	.141
Step-c 4	.325	.476	.199
64000 ph	Tran.	Refl.	Abs.
MMCR 1	.440	.560	
MMCR 2	.302	.698	
MMCR 3	.307	.402	.291
MMCR 4	.200	.553	.247
MMCR 5	.403	.758	
MMCR 6	.448	.552	
MMCR 7	.305	.695	
MMCR 8	.404	.758	
163840 p	Tran.	Refl.	Abs.
Landsat 1	.694	.306	
Landsat 2	.487	.513	
Landsat 3	.629	.243	.128
Landsat 4	.406	.422	.172

DART: The Dart-method (e.g. Lovejoy et al., 1990) describes a combination scheme, in which interactions among adjacent cubes are limited to a few directions. Prior to such combination, individual cube bulk-properties must be defined. This initial step is quite important. Results of Monte-Carlo simulations are preferred, because multi-dimensional adding or analytical functions (Gierens, 1993) are inaccurate (and such inaccuracy multiplies with the combination of many cubes). Here, Monte-Carlo based look-up tables define, how radiation reaching a cube is redistributed due to scattering, absorption and emission, with respect to the cube's permitted exit directions. The Dart-algorithm combines then properties of individual cells. Interactions among cubes occur at the center of each cube's surface. Here results of two Dart-methods are investigated. The simpler Dart-method allows interactions among cubes only in the one direction perpendicular to each of the six faces of a cube, thus '6-stream' Dart-method. The more advanced Dart-method permits five directions (four 45degree angles in addition to the normal direction) for each of the six faces of the cube, thus '30-stream' Dart-method. More permitted directions are expected to better accommodate anisotropic scattering. With a set of external boundary conditions in place, solutions with Dart-interactions are obtained iteratively until changes to scene-averaged reflection and transmission of consecutive loops become smaller than a pre-defined uncertainty.

For processes with highly directional radiation, such as direct sunlight, it is advantageous to make this particular direction one of the permitted interaction directions among the cubes of the Dart-methods. For solar radiative transfer simulations (with solar zenith angles other than zero) this required a turning of the cubes, so that a cube's surface faced the sun. This comes at some at the cost of some flexibility:



Only a few solar zenith angles α ($uo=\cos\alpha$) permitted, as to permit a smooth transition from cube center to cube center ($\tan \alpha = 1/n$ or $\tan \alpha = n/1$, with n being an integer divider of cubes in the horizontal). For example, a 2*2 cube-pattern (as shown to the right) only permits zenith angles of 0 and 45 deg, whereas a 4*4 cube arrangement already can accommodate four zenith angles (0, 27, 45 and 63 deg). An artifact from the cube-tilting are empty spaces in the turned cube arrangements. These holes are most numerous for at 45degree. Empty spaces are 'jumped' in cube interactions. With the tilting of the cubes, also each cube's optical depth increases, to a maximum of 1.414-times at 45degree. For solar zenith angles larger then 45 degree symmetry relationships are used, such that the necessary virtual grid array never need to exceed 2n+2 (with n being the number cubes in the vertical and horizontal, and '2' for the boundary conditions, which wrap the entire array of cubes).

Results:

Simulations with the Dart-methods were conducted for interactions of sun-light with a 250m thick cloud layer composed of alternating 250m wide sections of optical depths of 2 and 18 (I3RC step-cloud case). In order provide radiation fields each 250m section needed to be subdivided into 16 sub-sections. This required two adjacent 16*16 arrays of cubes to simulate the repeating cloud-pattern in the Dart-methods. The combination of (1) highly forward scattering (g = 0.85) cases with little ($\omega0$=.99) or negligible absorption ($\omega0$=.99999) and (2) the many necessary cubes, which quickly multiple anisotropy scattering errors, demonstrate the limitation of the method. Transmission- / Reflection- / Absorption-comparisons to Monte-Carlo simulations (with different frequency in photon counts) are given for solar zenith angles of 0.0 and 63.43 degree (*u0*=1.0 and *u0*=0.4472) in a Table below (a 60 degree angle, as requested for I3RC comparisons, is not possible for the turned 32*16 cube arrangement).

T / R / A –table Method	μo=1, ωo=.99999	μo=.4472 ωo=.99999	μo=1 ωo=.99	μo=.4472 ωo=.99
MC (32000)	.673 / .327 / .0	.395 / .605 / .0	.597 / .262 / .141	.302 / .502 / .196
MC (9600)	.675 / .325 / .0	.392 / .608 / .0	.604 / .259 / .136	.311 / .494 / .193
MC (320)	.666 / .334 / .0	.381 / .619 / .0	.600 / .265 / .134	.341 / .500 / .159
6-stream DART	.547 / .453 / .0	.324 / .676 / .0	.477 / .328 / .195	.257 / .554 / .189
30-stream DART	.617 / .379 / .0	.348 / .654 / .0	.541 / .298 / .161	.269 / .554 / .177

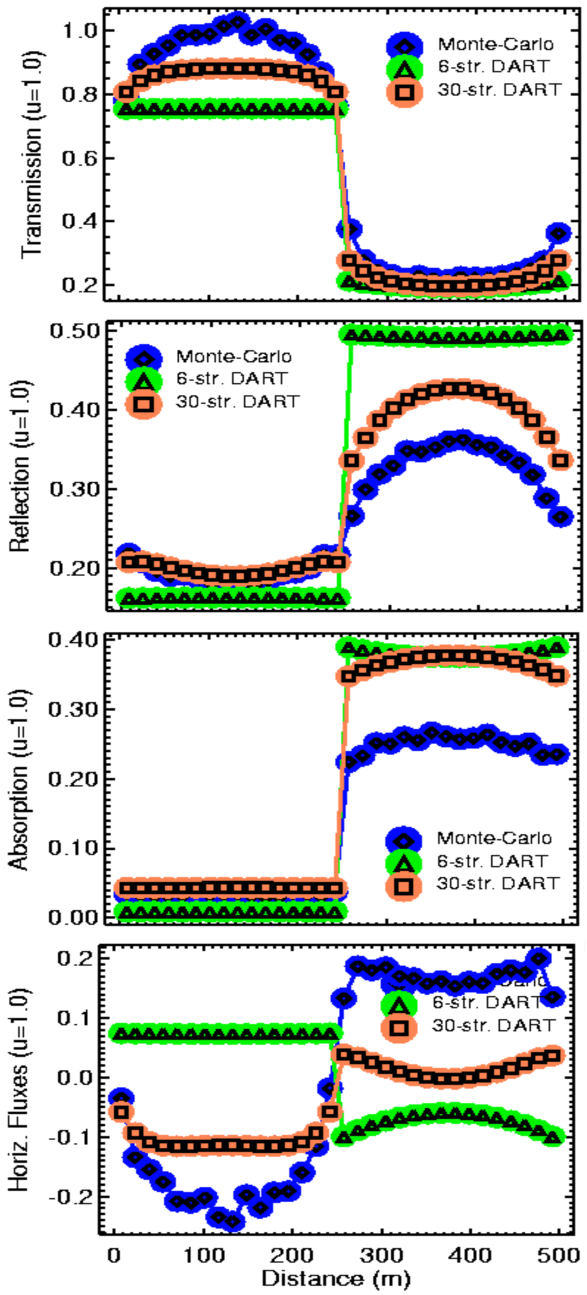
Comparisons of these averages for the entire cloud-field demonstrate that the DART-methods - unable to simulate the strong forward scattering with its limited number of permitted scattering directions - underestimate transmission and overestimate reflection. Side-scattering, which exits through the sides of a cube, is highly forward scattering, but it is (more so in the 6-stream Dart-method) forced into a normal direction. Related errors, which may be small for a few cubes, quickly increase as many cubes (here 512) are combined. The 30-stream Dart-method, with the option of four additional 45degree directions, performs better, however, strong deviations to the Monte-Carlo (MC) results remain.

More revealing is a comparison of the radiation fields, which are illustrated for transmission, reflection, absorption and horizontal fluxes. Results are presented for the two step-cloud cases with absorption (ωo=0.99). Results for an overhead sun (and strong forward scattering conditions) are given in Figures to the right.

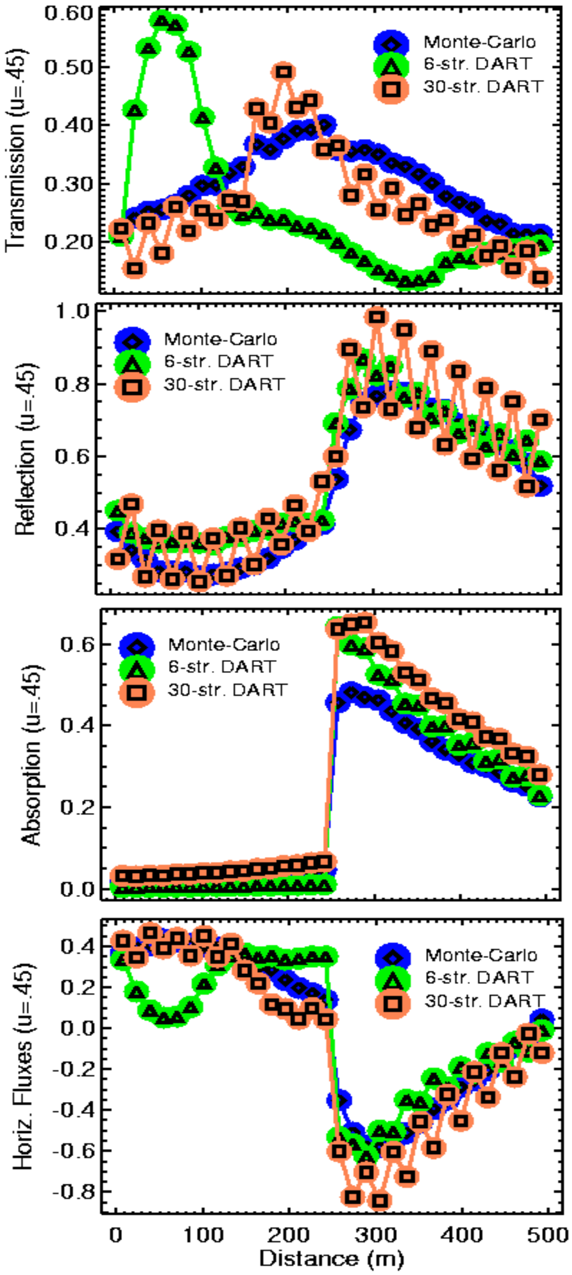
The 6-stream Dart-method acts at overhead sun-positions (u=1.0) almost as separate plane-parallel solutions at each grid point (Independent Pixel Approx):
- No enhanced transmission below the section of lower optical depths from reflections off optically thick clouds
- No reduced reflection over the edges of the optically thicker section of the step-cloud.
- No significant (and even inverse) horizontal fluxes.
Absorption is overestimated, because the tendency to less forward scattering in Dart-methods in this case.

Results of the 30-stream Dart-method better resemble Mont-Carlo results. Expected 3-dimensional radiation field patterns are reproduced, however, effects are underestimated in magnitude.

The comparisons clearly indicate the limited use of Dart-methods to anisotropic scattering media. Better cube-initializations, which account for the way the incoming radiation exits a cube are certainly a key to better Dart-simulation under these conditions.

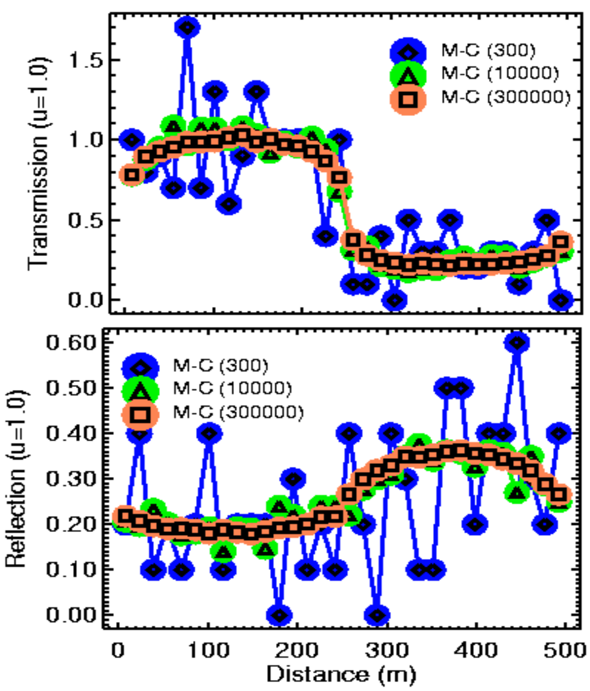


An additional complication for Dart-methods with few permitted directions is the treatment of direct sun-light for other than overhead sun-positions. Both Dart-methods discussed here turn cubes (which represent cloud sub-cells) towards the sun. This creates not only artificial holes in the cube arrangement, but it also causes ragged cloud boundaries. Both artifacts are the reason for 'ripples' in the radiation fields of the Dart-methods. Results for a solar zenith angle of about 63degree are presented in the Figures to the right.
The 6-stream Dart-method displays quite different fields for transmission and horizontal fluxes, largely related to the holes in the cube arrangements. The same fields for the 30-stream Dart-method better resemble those from Monte-Carlo simulation. Both Dart-methods reproduce reflection and absorptions patterns, except for variation 'ripples', which are especially large for the 30-stream Dart-method.



Discussion:

Results with Dart-methods for highly anisotropic scattering media and results involving turned cubes are not encouraging. Although improvements (e.g. better cube-initialization, separate treatment of direct and diffuse contributions, better flux-evaluation at rugged surfaces) are possible, there is still the issue of slow convergence of the iterative solution for these anisotropic conditions (e.g ca 200 for the 6-stream of 100 for the 30-stream method).



Unless faster solutions processes are applied, Monte-Carlo solutions based with fewer (well positioned) photons are at least comparable in speed - with better accuracy. Demonstrations for the overhead step-cloud case are given in the Figures to the left. 300 photons already can provide good field averages (see Table) and 1000 photons may be sufficient for the radiation fields.

REFERENCES:

Gierens,K. 1993 : A fast six-flux radiative transfer method for application in finite cloud models. Inst.fuer.Phy.Atmos, Report2, DLR, Germany.
Lovejoy,S., A.Davies, P.Gabriel, D.Schertzer and G.L.Austin, 1990 : Discrete angle transfer. Scaling, similarity, universality and diffusion. J.G.R. 95, 11699-11715.