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Simulation of satellite, airborne and terrestrial LiDAR with DART (I): Waveform simulation with quasi-Monte Carlo ray tracing

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ABSTRACT

LIght Detection And Ranging (LiDAR) provides unique data on the 3-D structure of atmosphere constituents and the Earth's surface. Simulating LiDAR returns for different laser technologies and Earth scenes is fundamental for evaluating and interpreting signal and noise in LiDAR data. Different types of models are capable of simulating LiDAR waveforms of Earth surfaces. Semi-empirical and geometric models can be imprecise because they rely on simplified simulations of Earth surfaces and light interaction mechanisms. On the other hand, Monte Carlo ray tracing (MCRT) models are potentially accurate but require long computational time. Here, we present a new LiDAR waveform simulation tool that is based on the introduction of a quasi-Monte Carlo ray tracing approach in the Discrete Anisotropic Radiative Transfer (DART) model. Two new approaches, the so-called "box method" and "Ray Carlo method", are implemented to provide robust and accurate simulations of LiDAR waveforms for any landscape, atmosphere and LiDAR sensor configuration (view direction, footprint size, pulse characteristics, etc.). The box method accelerates the selection of the scattering direction of a photon in the presence of scatterers with non-invertible phase function. The Ray Carlo method brings traditional ray-tracking into MCRT simulation, which makes computational time independent of LiDAR field of view (FOV) and reception solid angle. Both methods are fast enough for simulating multi-pulse acquisition. Sensitivity studies with various landscapes and atmosphere constituents are presented, and the simulated LiDAR signals compare favorably with their associated reflectance images and Laser Vegetation Imaging Sensor (LVIS) waveforms. The LiDAR module is fully integrated into DART, enabling more detailed simulations of LiDAR sensitivity to specific scene elements (e.g., atmospheric aerosols, leaf area, branches, or topography) and sensor configuration for airborne or satellite LiDAR sensors.

1. Introduction

Sampling the Earth's atmosphere and surface features with LiDAR sensors provides detailed data on topography, vegetation architecture, aboveground biomass, and novel approaches for change detection in vegetated and urban areas (Vosselman and Maas, 2010). Waveform LiDAR sensors (wLiDAR) provide ranging information based on the return energy in the backscattered signal which is discretized into short sampling intervals. In addition to the distance from the vegetation canopy and ground surface, wLiDAR data captures energy returned from the diffuse media (e.g., the atmospheric column and vegetation profile). Thus, the inversion of waveform signal can infer the distribution of subcanopy elements, and distribution of atmospheric constituents. wLiDAR sensors are usually categorized according to the platform, the beam divergence (footprint), the sampling method, the laser wavelength, the pulse width, and the method of detection and digitization. Airborne wLiDAR systems typically utilize a small footprint (<1 m diameter) infrared or green laser beam, and a scanning or multi-faceted mirror for distributing laser pulses in the cross-track direction (Asner et al., 2007, 2012). Space-based wLiDAR devices have been profiling systems with large footprints: the Geoscience Laser Altimeter System (GLAS) LiDAR had a 50–60 m diameter footprint (Zwally et al., 2002) and a 25 m diameter footprint is planned for the Global Ecosystem Dynamics Investigation (GEDI) waveform LiDAR (Krainak et al., 2012, Dubayah et al., 2014).

A general-purpose simulation tool of wLiDAR can help to evaluate the influences of instrument characteristics and environmental conditions on LiDAR waveforms, including the development of inversion algorithms for specific systems. Several models have been developed to simulate wLiDAR from medium to large footprints. Semi-empirical models (Blair and Hofton, 1999, Chauve et al., 2007) consider waveform as a sum of Gaussian or Lognormal profiles computed by convolving the target objects' reflectance and pulse energy spatial distribution (2-D

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Gaussian profile). The analytical model of Sun and Ranson (2000) simulates waveforms of heterogeneous vegetation landscapes made of the turbid medium. Ni-Meister et al. (2001) used a geometric optical and radiative transfer (GORT) model to estimate waveform in the solar hot spot configuration (Kuusk, 1991). These analytical models provide computationally efficient estimations of waveforms. However, the modeling approaches provide less accurate waveform data because they consider only first-order scattering returns. Simulation of multiple scattering mechanisms that occur in the LiDAR FOV is particularly important for near infrared (NIR) LiDAR systems over vegetation, given the high reflectance and transmittance of foliage in typical LiDAR wavelengths (1064 nm). Furthermore, previous models also work with simplified simulations of Earth surfaces.

Three-dimensional (3-D) radiative transfer models (RTM) rely on radiative transfer equations to simulate local absorption, scattering, and thermal emission. Many RTMs can work with detailed scenes with realistic geometry and optical properties. Some 3-D RTMs use an MCRT approach for solving the radiative transfer equation. MCRT models are powerful tools because they simulate multiple scattering processes as a succession of exactly modeled single scattering processes (Disney et al., 2000). There are many MCRT models that can simulate LiDAR waveform, e.g. FLIGHT (North, 1996), RAYTRAN (Govaerts and Verstraete, 1998, Disney et al., 2009), and FLIES (Kobayashi and Iwabuchi, 2008), etc. The LiDAR signal simulated by the FLIGHT model has been validated with the reflectance and waveforms from GLAS measurements (North et al., 2010). Since MCRTs simulate rays in terms of multiple simulated photons, an inherent trade-off exists between the simulation accuracy and the number of simulated photons. Computational time is the major constraint with MCRTs, especially if the scene element phase functions cannot be inverted, a typical case because common scattering elements have anisotropic and complex phase functions. The processing time of one second for a single pulse waveform could be limiting, as many actual wLiDAR systems have a pulse repetition frequency up to hundreds of kHz.

In this paper, we present a new quasi-MCRT model that simulates wLiDAR in an accurate and computationally efficient manner. It is implemented in the Discrete Anisotropic Radiative Transfer (DART) model (Gastellu-Etchegorry et al., 1996, 2004, 2012, 2015). It is a general-purpose model for any LiDAR configuration (footprint size, pulse energy, spatial and temporal pulse distribution, view direction, etc.), for any urban or vegetation landscape, including topography. MCRT within the atmosphere is also implemented and coupled, which does not exist in most Earth surface RTMs. Section 2 of this paper summarizes DART theory that is useful for clearer understanding of further sections. Section 3 presents a new approach, called box method, for fast selection of photon scattering direction for any scattering event, which is the fundamental method for the quasi-MCRT model in DART. Section 4 explains the implementation of the quasi-MCRT model in a LiDAR simulation, with the introduction of a new approach called Ray Carlo method. For each scattering event, this method tracks a fraction of the radiation returned towards the direction of the sensor to reduce the total number of simulated photons, greatly improving simulation accuracy and processing speed. Section 4 also presents sensitivity studies for different landscape and atmosphere conditions, including a comparison with Laser Vegetation Imaging Sensor (LVIS) waveforms for a temperate forest. Section 5 highlights atmosphere tracking, with specific accelerating techniques that reduce MCRT noise. A companion paper presents DART-LiDAR applications for simulating multiple pulse acquisitions, terrestrial LiDAR, and photon counting LiDAR systems (Yin et al., in press). Nomenclature of this paper is shown in Appendix A.

2. DART model theory

DART is a 3-D RTM that has been under development since 1992. It simulates 3-D radiative budget and airborne and satellite images of urban and natural landscapes from visible to thermal infrared domains (Gastellu-Etchegorry et al., 1996, 2004, 2008, 2015), for any 3-D experimental landscape configuration (forest stand, agricultural crop, atmosphere, topography, sun direction or date) and instrument specification (e.g., spatial and spectral resolutions, sensor viewing direction, platform altitude).

A 3-D scene (Fig. 1) is the superposition of three rectangular volumes: the high atmosphere (HA), the mid atmosphere (MA), and the Earth scene, with topography. Scene simulation is independent of the RT modeling, which allows one to simulate several sensors with the same landscape. Major DART simulated scene elements include: trees, grass and crop canopies, urban features, and water bodies. Additionally, DART can import scene elements from external sources (e.g., http://tf3dm.com/3d-models/plants) to simulate Earth scenes of varying complexity. Atmosphere cells are defined by their gas and aerosols contents and spectral properties (i.e., scattering phase functions, vertical profiles, extinction coefficients, spherical albedos, etc.) that are user defined, or imported from internal or external databases such as AERONET (http://aeronet.gsfc.nasa.gov/). Atmospheric RT modeling includes the Earth-atmosphere radiative coupling.

An Earth scene is an array of 3-D cells (Δx, Δy, Δz) where any scene element is created with a dual approach as a set of cells that contain turbid media or a set of geometric primitives (triangles) called "facets". Turbid medium is a statistical representation of matter that is used to simulate fluids (air, soot, water, etc.) and vegetation foliage. A fluid turbid medium is a volume of homogeneously distributed particles defined by their density (particles/m^3), cross section (m^2/particle), single scattering albedo, and scattering phase function. Turbid vegetation medium is a volume of leaf elements simulated as infinitely small flat surfaces defined by their orientation, i.e. leaf angle distribution $\frac{g(\Omega_f)}{2\pi}$ (LAD; sr^{-1}), volume density u_f (m^2/m^3), and isotropic transmittance and reflectance, with a specular component.

A facet is a surface element defined by its orientation Ω_n in space, area, and optical properties: direct transmittance t_{dir}, diffuse transmittance t_{diff} and reflectance ρ, with $t_{diff}+\rho\leq 1$. A ray of light incident on a facet interacts with the front side, which is defined by a normal vector, but it does not interact with the facet's backside. Thus, depending on the type of object, any surface can be simulated using only 1 facet or 2 facets with opposite normal vectors, and optionally different optical properties. For an energy flux W along Ω_s, the direct transmittance along Ω_s is $t_{dir}^{1/|\Omega_s\cdot\Omega_n|}$; the scattered flux is $W\cdot(1-t_{dir})\cdot\rho$; and the transmitted diffuse flux is $W\cdot(1-t_{dir}^{1/|\Omega_s\cdot\Omega_n|})\cdot t_{diff}$. Reflectance ρ can be Lambertian, Hapke (1981), RPV (Rahman et al., 1993), etc., with a specular component that is defined by the facet refraction index, an angular width and a multiplicative factor. Facets are used to build virtual houses, plant leaves, tree trunks, and branches, etc. Vegetation canopies are therefore simulated as assemblies of turbid medium voxels or facets or combinations of both.

Rays $W(r,\Omega)$ are tracked with the so-called ray-tracking method: they propagate in space r along discrete directions, with each one being characterized by its vector Ω and solid angle $\Delta\Omega$ (sr). They are iteratively tracked until the scene exitance difference between 2 consecutive iterations is smaller than a defined threshold (considered as convergence). In each iteration, rays intercepted in the previous iteration are scattered and tracked towards all relevant N_{dir} discrete directions in the current iteration, which corresponds to multiple scattering. Three types of discrete directions are used:

- $N_{dir,nv}$ pre-defined directions. They cover the 4π space: $\sum_{i=1}^{N_{dir,nv}}\Delta\Omega_i=4\pi$, with user-defined propagation vector and solid angles. They can oversample angular sectors such as the solar hot spot (Kuusk, 1991) and penumbra (Dare, 2005) configurations. They are used for precise simulations of 3-D radiative budget and radiance images with orthographic projection towards these directions (Yin et al., 2013b).

- $N_{dir,vd}$ pre-defined virtual directions. Their properties are set to "virtual" because rays along these directions are not actual fluxes contributing to the energy balance in the 4π space and cannot be scattered