

Airborne Lidar Observations of Canopy Structure at the BOREAS Tower Flux Sites

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INTRODUCTION

The Boreal Ecosystems Atmosphere Study (BOREAS) is a large-scale interdisciplinary experiment in the northern boreal forests of Canada focused on improving our understanding of the exchanges of radiative energy, sensible heat, water, CO₂ and trace gases between the boreal forest and the lower atmosphere [1]. The spatial organization of forest canopies is an important biophysical parameter affecting these exchange processes. As a part of the BOREAS experiment, airborne lidar observations were acquired that characterize the vertical structure of the boreal forest and the topography of the underlying ground surface. The Scanning Lidar Imager of Canopies by Echo Recovery (SLICER) was used to acquire surface lidar transects across tower flux sites established within areas of relatively homogenous vegetation cover in the BOREAS Southern and Northern Study Areas (SSA and NSA). SLICER was deployed on the NASA Wallops Flight Facility C-130 during the BOREAS Summer 1996 Intensive Field Campaign. Nadir lidar transects were acquired simultaneously with Advanced Solid-state Array Spectroradiometer (ASAS) multi-angle imaging of the SSA and NSA tower sites. The SLICER transects extend outward from the towers for a distance of 10 to 30 km (Fig. 1 and 2). The transects consist of narrow swaths nominally composed of contiguous, circular laser footprints each 8 m in diameter, with 5 footprints scanned cross-track.

SURFACE LIDAR MEASUREMENTS

SLICER provides geolocated measurements of canopy structure and topography by integrating surface lidar ranging data with aircraft position and attitude data, obtained by

differential kinematic Global Positioning System (GPS) and gyroscopic Inertial Navigation System (INS) measurements, respectively. Traditional laser altimetry provides a direct method for obtaining surface elevation measurements of very high accuracy. The basis for the method is ranging to the surface obtained by precise timing of the round-trip travel time of short-duration pulses of backscattered laser radiation. SLICER extends this technique to a surface lidar capability by digitizing the complete time-varying distribution of return pulse energy, or waveform, that results from the reflection of a single laser pulse from multiple targets occurring at varying heights within a large footprint. The waveform is a convolved measure of the vertical distribution of vegetation canopy components (foliage, twigs, branches) and the underlying ground's height distribution introduced by surface slope and roughness. The time-varying amplitude of the return signal is weighted by the nadir-projected area of intercepted surfaces, their reflectivity at the monochromatic near-infrared (NIR) laser wavelength (1064 nm), and the circular Gaussian spatial distribution of laser energy across the footprint. The height of the vegetation is readily extracted from the time delay between first and last returns, assumed to be reflections from the canopy top and ground. By using large diameter footprints, several times the typical crown widths, each waveform includes returns from the highest elements of the canopy and from the ground. Ground returns occur where there are sufficient intra- or inter-crown gaps of any size extending at nadir to the canopy floor, which is usually the case in all but the densest canopies.

In addition to vegetation height, the vertical distribution of vegetation structure can be derived from the varying strength of the return signal down through the canopy. The

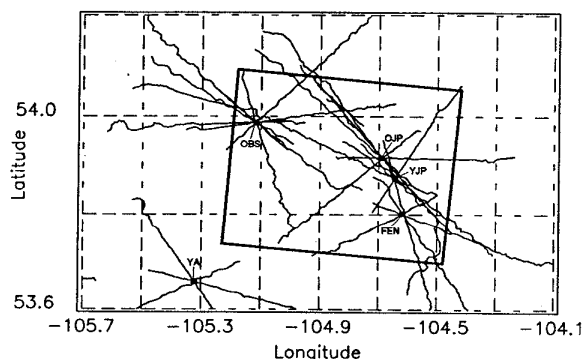


Fig. 1. SLICER transects (thin lines) and tower flux sites (filled squares) in the BOREAS Southern Study Area. The bold rectangle outlines the SSA modeling subarea.

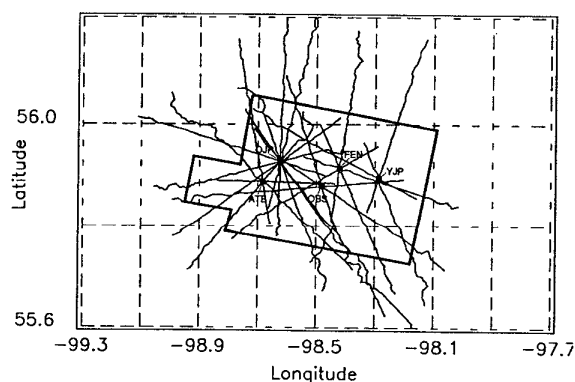


Fig. 2. SLICER transects (thin lines) and tower flux sites (filled squares) in the BOREAS Northern Study Area. The bold composite rectangles outline the NSA modeling subarea.

cumulative distribution of the canopy return signal, normalized by the total return, is a relative measure of the height distribution of canopy cover fraction. By accounting for the extinction of laser light with depth through the canopy, a height distribution of relative canopy surface area (canopy height profile, or CHP), can be derived from the cumulative distribution. Derivation of SLICER CHPs was developed and validated for United States eastern deciduous forests [2]. CHPs are relative, not absolute, measures of canopy distributions because the derivation of absolute canopy area depends on a priori knowledge usually not available (including ground versus canopy reflectivity at 1064 nm, proportion of woody versus leafy surfaces as a function of height, leaf angle distribution as a function of height, the extent of multiple scattering due to NIR transmission through foliage, and the degree of vertical correlation between canopy layers).

SLICER INSTRUMENTATION

SLICER is a scanning, airborne lidar that transmits short (ca. 60 cm) pulses of near infrared (1064 nm) laser light towards the ground using a laser transmitter specifically designed for surface lidar applications [3]. The instrument evolved from a profiling system [4] by incorporation of a galvanometer mechanism for scanning the transmitted laser beam perpendicular to the direction of the flight path. Laser pulses are typically emitted at a repetition rate of 80 Hz. As a pulse encounters the top of the vegetation photons intercepted by canopy surfaces are scattered; photons backscattered at nadir are collected by a receiving telescope in the aircraft. As the non-intercepted component of the pulse proceeds down through the canopy photons are backscattered at every level at which they encounter reflective surfaces, including the ground. Received photons collected by the telescope are focused on to a silicon avalanche photodiode detector which converts input optical energy into an output voltage signal. The round-trip travel time from transmission of the laser pulse to the first return of detector output voltage above a detection threshold is measured by a time interval unit (TIU). The TIU utilizes a high-frequency oscillator to achieve cm-level ranging accuracy. The travel time is converted to distance based on the speed of light. Upon reception of the first detected return signal, the time history of detector output voltage, which is sampled using an analog-to-digital digitizer, is stored as a return waveform. For BOREAS, the waveform stored 600 channels recording the detector output signal at a sampling rate of 0.72 nanosec per channel (i.e., 11 cm vertical sampling). Detailed documentation on the SLICER instrumentation and data processing procedures for BOREAS is available from the BOREAS Information System (<http://boreas.gsfc.nasa.gov>). The SLICER data sets for BOREAS are also available through this site. The data sets include the diameter of each laser footprint, the latitude, longitude and elevation of the first return, the azimuth and inclination of the laser pointing vector, the distance along the vector from the first return to the start, peak amplitude, and end of the ground return, and

the raw waveform. A browser is available, written in the Interactive Data Language (IDL), for display of these data.

SOUTHERN STUDY AREA RESULTS

Analysis of the SLICER data demonstrates that the surface lidar technique distinguishes canopy vertical structure at the SSA Old Aspen (OA), Old Jack Pine (OJP), Old Black Spruce (OBS), Young Jack Pine (YJP) and Young Aspen (YA) sites (Fig. 3). Average SLICER CHPs, derived using approximately 130 laser shots nominally from within 100 m of each tower, show distinct differences in total height, the height of maximum crown density, and the presence or absence of a separate upper and under story. Total height and maximum crown density height are 23 m and 17 m (OA), 14 m and 9 m (OJP), 13 m and 4 m (OBS), 5 m and 2 m (YJP), and 4 m and 1 m (YA), respectively. The crown depth of the upper story is similar (~ 10 m) at OA, OJP, and OBS, and distinct under story layers are present at OA and OJP.

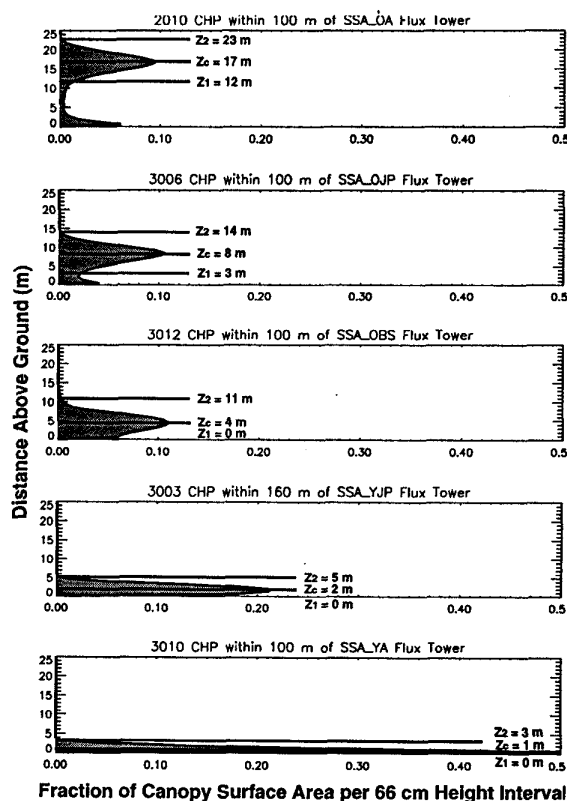


Fig. 3. Canopy Height Profiles for five SSA flux sites (shaded) derived by averaging laser footprints within specified distance of the tower. Four digit code refers to transect flight day and number. Canopy top height, z_2 , leaf-area density inflection height, z_c , and canopy base height, z_1 , are shown.

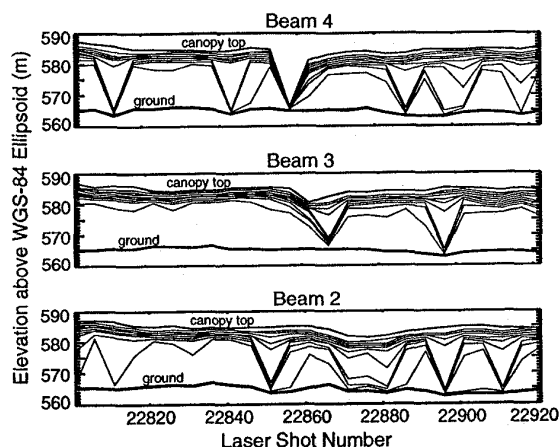


Fig. 4. Elevation profiles for the three center beams of a SLICER transect through SSA OA site showing canopy top, ground, and 10% CHP contours. See text for explanation.

CHP profiles can be used to visualize the spatial variability of canopy structure at the tower sites. Fig. 4 illustrates CHP profiles from a SLICER transect at the SSA OA tower site, portrayed as 10% contours of canopy surface area accumulating downward from the canopy top to the ground. Each of the 3 center cross-track beam positions is displayed as a separate profile. Parallel, closely-spaced contours near the top of the canopy indicate a single, well defined upper story. Downward deflections of some of the contours indicate laser footprint locations where a significant component of the canopy surface area occurs in the understory. Downward deflection of all the contours and the canopy top near the midpoint of the beam 4 profile indicates a canopy gap at the scale of, or larger than, the laser footprint.

DERIVATION OF AERODYNAMIC RESISTANCE

Surface lidar observations of canopy height profiles, such as that provided by SLICER, provide a means to measure canopy aerodynamic resistance, a land cover boundary condition incorporated in Global Circulation Models (GCMs). The Simple Biosphere Model 2 [5] provides one means to model key land cover parameter inputs to GCMs, including aerodynamic resistance of vegetation canopies. The SiB2 model describes the canopy in terms of average regional values for canopy top height, z_2 , leaf-area density inflection height, z_c , and canopy base height, z_1 . The SLICER CHPs readily quantify these three diagnostic canopy heights at the BOREAS tower sites (Fig. 3), and demonstrate the spatial variability of these heights over short length scales.

ORBITAL SURFACE LIDAR MISSIONS

SLICER has demonstrated a strong potential for unique and important characterization of canopies by surface lidar in selected North American study areas (SLICER acquisitions are

cataloged at <http://denali.gsfc.nasa.gov/lapf>). Satellite surface lidar observations, such as the experimental results provided to date by the Shuttle Laser Altimeter (SLA) [6] and the comprehensive global characterization to be achieved by the Vegetation Canopy Lidar (VCL) beginning in 2000 [7], will make it possible to extend these observations on a global basis. These missions will achieve an accurate global inventory of canopy structural characteristics for the first time. Initial results from the first two flights of SLA can be viewed at <http://denali.gsfc.nasa.gov/lapf>.

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