Three-Dimensional Analysis of Forest Structure and Terrain using LIDAR Technology[1]

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Abstract

Light Detection and Ranging (LIDAR) provides remotely sensed information on the vertical structure of forests that is very difficult to obtain either by optical or radar remote sensing techniques. Indeed, forest attributes such as tree height and biomass may be quantified more directly with LIDAR than with other remote sensing means. Recent developments in scanning laser altimetry and small footprint LIDAR systems can provide a very detailed picture of the forest canopy for management purposes or ecological studies.

This new GEOIDE research project (RES #50[2]) focuses on the evaluation of algorithms for estimating forest structural and biophysical variables as well as terrain characteristics. The project is organised into three research thrusts, each driven by specific application areas: measuring forest structural and biophysical variables, forest topography, and simulation of space-borne LIDAR data from airborne LIDAR. Here we present the objectives of our GEOIDE project and summarise selected results related to tree height estimation in previous studies undertaken by project team members.

Introduction

Recent technical developments in LIDAR have led to the concurrent use of scanning LIDARs, GPS, and inertial navigation systems, allowing for absolute altitude accuracies of 15 cm (Flood, 1999). Today's commercial airborne LIDAR systems have the capability of producing very small footprints with very high return densities (Baltsavias, 1999). Other LIDARs operating at higher altitudes produce much larger footprints for more extensive surveys, such as the LVIS designed to simulate the Vegetation Canopy LIDAR (VCL) 25

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m footprint mission planned for 2000 by NASA (Blair *et al*., 1999). The prediction of forest parameters is either direct or indirect. For direct measurement, a characteristic such as height is estimated by first minus last return of the raw data alone or by applying a linear transformation to the raw data. Indirect estimates are most often based on first estimating a fundamental parameter such as height that is then fed into a predictive model for biomass and volume. For this reason, the estimation of maximum or mean tree height often constitutes the key parameter of LIDAR forest studies. Other parameters, such as volume (Næsset, 1997), basal area, biomass (Lefsky, *et al*., 1999), and canopy cover (Weltz, *et al*., 1994) can also be estimated with high accuracy.

Problem Statement

Forests represent an important economic resource across Canada, accounting for $39.7 billion in export trade in 1998 alone (NRCan, 1999). Forests also account for significant exchanges of energy, sensible heat, water, CO_2 and trace gases with the lower atmosphere. For both economic and environmental reasons, it is critical to measure and understand the spatial organization of forest ecosystems. LIDAR provides remotely sensed information on forests that is very difficult to obtain either by optical or radar remote sensing techniques, or even by ground measures.

Optech, a Canadian owned private company is the world leader in designing and assembling scanning LIDARs holding the largest market share in the world. Additional emerging companies, such as Lasermap ImagePlus and Airborne 1, are providing terrestrial surveys with LIDAR systems and/or providing expertise in this area for business development or program management. Although Canada boasts a lead in LIDAR technology, the Canadian scientific community (related to LIDAR remote sensing of forests) is not large, nor sufficiently organized. Moreover, links with companies are only starting to emerge. Establishing a network of applied researchers to liaise with industry is necessary to maintain the Canadian competitive advantage in this field as applied to forestry and forest ecology.

Although scanning laser altimetry is very promising, few operational forest surveys rely on LIDAR. Beside the fact that the technology is fairly new and relatively unknown to the forest industry, some problems remain. In this GEOIDE project we intend to address outstanding issues limiting the use of LIDAR in the monitoring and measurement of forests.

Project Objectives

The results of this research will serve forestry, forest ecology and carbon budget objectives. The research activities revolve around:

- assessing forest structure and biophysical parameters;
- studying scale related questions (footprint and density of laser hits, scaling from small footprint to VCL);
- analysis of the LIDAR waveform;
- data fusion; and

- topographical “by-products” (generation of more accurate digital elevation models (DEMs), improved watershed delineation and modeling of water flows, etc.).

To enable investigation of these issues, we have organized this research into three key themes:

1) LIDAR for Measuring Forest Structural / Biophysical Variables and Terrain Elevation
This objective addresses the needs and aims of the forest industry, i.e., using LIDAR as an inventory, management and sampling tool. The airborne applications of LIDAR focus on accurate estimates of forest structure and terrain elevation.

2) Data Fusion
Great commercial potential exists not only for estimates of forest parameters from LIDAR alone, but expanded (and improved) data products derived from traditional optical remote sensing data and stereo data for forested areas. This would provide critical baseline data for forest management and planning. It is proposed that fusion of optical remote sensing data, and/or conventional/digital aerial photographs with LIDAR data for three-dimensional modeling be incorporated into this project. Further potential for coupling forest mensurational estimates with physiological estimates derived from hyperspectral remote sensing data will also be explored.

3) Methods and Estimates of Vertically Distributed Forest Attributes from Multiple Scales of LIDAR Data
This objective addresses the needs of the forest industry, research, and reporting communities. National and international reporting commitments, related to sustainability of forest practices (Montreal Process: Criteria and Indicators) and more specifically carbon stores (Kyoto Process: Reforestation, Afforestation, and Deforestation (RADs)), require forest biomass as a reportable or a model input. The estimation of biomass with LIDAR data is viewed as sufficiently reliable and mature, that, as mentioned above, the VCL satellite is scheduled for launch later this year (Dubayah *et al.*, 1997). The data available from the satellite platform may provide an independent means for the forest industry to acquire data relating the structure and condition of their holdings.

Project preliminary research: LIDAR estimation of canopy heights

Surface LIDAR Stability of Canopy Height Estimates

It is recognised that tree height is an important attribute required by the forest industry and reporting agencies. Surface LIDAR has been applied as a tool for characterising the vertical structure of forests. The Scanning LIDAR Imager of Canopies by Echo Recovery (SLICER) records data on canopy height, vertical structure, and ground elevation. The vertical resolution of the SLICER is approximately 1m, with a horizontal resolution of approximately 10 m, with the five hits resulting in an approximate 50 m wide swath.

Prior to applying remote estimates of height in an inventory context, the consistency of the estimates at locations and over areas is assessed. Locations which have more than one LIDAR hit from differing flight over-passes allow for an assessment of the stability of point height estimates. To assess the stability of area estimates, the height estimates from multiple flight lines through individual polygons are assessed.

Recording and evaluating multiple LIDAR hits at the same location indicates that variability in LIDAR heights is likely due to surface cover variability and/or geolocating of the sensor. The small differences noted in LIDAR heights, on a point basis, are largely related to the canopy structure. Slight shifts in canopy footprint position are evident more readily for conifer than deciduous cover-types; which is likely due to the conifer forest allowing for greater light penetration than the deciduous cover type. The mixed forest canopy height stability results are, as expected, intermediate between the conifer and deciduous results.

Investigation of multiple LIDAR flight lines through the same polygon allows for an analysis of the variance of the within-line and among-line canopy height variability within polygons. Through stratification of the data we are able to investigate the observed height variability as a function of the number of lines characterising an individual polygon. The LIDAR flight lines collect data representing differing areas within polygons. Our results indicate, for example, that when 2 flight lines are flown over a polygon, the canopy height estimates from the lines are within 1 meter of agreement 50% of the time and within 2 metres 75% of the time. Our study area is in Saskatchewan, where height is often operationally measured to 5 meter classes within which our estimates fall. Our results, on a point and polygon basis, indicate the utility of LIDAR data as a sampling tool in a forest inventory context (Wulder, *et al*., 2000).

Scanning LIDAR Estimation of Tree Height

In this study, small footprint LIDAR data are used to estimate individual tree height. However, estimating the height on an individual tree requires that the laser hit fall on the point of maximum height, an event that cannot normally be verified unless ancillary data is available. Two distinct aerial surveys of an 8 km^2 area of the boreal forest in Québec, Canada, yielded respectively 50 cm resolution multispectral imagery and a laser altimetry coverage (the average distance between to hits being approximately 1.5 m). Subtracting the interpolated terrain altitudes from the interpolated canopy altitudes yielded a 50 cm resolution canopy height model (CHM). The multispectral imagery was overlaid onto the CHM after rectification to help locate trees and provide information on species. The height of individual trees read from the CHM at the center of the tree crowns visible on the overlaid multispectral imagery were compared with field observations consisting of the mean of two height measurements for each GPS-positioned tree. A linear regression model between actual and laser-predicted heights yielded an R^2 of 0.90 for 36 trees (hardwood and softwood). The mean difference between actual tree height and laser-predicted tree height is 1.4 m, while the mean difference between the two ground measurements for the same trees is 1.5 m, suggesting that the accuracy of height prediction based on laser altimetry is comparable to that of ground measures. The correlation between crown radius and laser-predicted height error is -0.76, confirming that smaller trees have a lower chance of being properly hit by the laser beam (St-Onge, 1999). Current research is directed toward improvement of the predictions and automation of the process. (St-Onge, 1999).

Conclusion

This GEOIDE project will enable development and testing of methods and algorithms appropriate for the use of LIDAR in the characterisation of forests. The creation and facilitation of research and applications networks is also a key objective of this project.

As illustrated from the two research examples, LIDAR is a powerful data collection tool, with great potential for operational forest management and ecosystem characterisation.

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