Sampling and Mapping Forest Volume and Biomass Using Airborne LIDARs

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Abstract.—Since around 1995, extensive research efforts have been made in Scandinavia to develop airborne Light Detection and Ranging (LIDAR) as an operational tool for wall-to-wall mapping of forest stands for planning purposes. Scanning LIDAR has the ability to capture the entire three-dimensional structure of forest canopies and has therefore proved to be a very efficient technique to determine biophysical properties such as stand volume and biomass. In Norway and Sweden, airborne scanning LIDAR is now used operationally to estimate merchantable volume on forest stands remotely across areas from 50 km^2 to 2,000 km^2. Complete scanning LIDAR coverage over larger regions (e.g., counties, States, provinces, and countries) is not economically feasible at this time due to data acquisition and processing costs. Despite these challenges, it has been demonstrated that airborne profiling LIDARs can provide reliable estimates of forest volume and biomass when used in a sampling mode (i.e., a number of flight lines are flown as linear, parallel transects separated by many kilometers). Scanning systems can be similarly employed for regional forest inventory by considering the flight lines as part of a strip sampling design. In this article, we report on a joint research effort by the Norwegian University of Life Sciences, National Aeronautics and Space Administration, Norwegian national forest inventory (NFI), Yale University, Swedish University of Agricultural Sciences, and Swedish NFI to develop and test airborne LIDARs as regional forest sampling tools.

Background

Ever since the first public Norwegian national forest inventory (NFI)—the first NFI in the world—took place 1919 through 1932, the Norwegian NFI has provided vital information of the timber resources. During its 87-year history, the NFI has produced statistics at the national and regional levels and has thus been an important prerequisite for the formation of a national policy for the management of the resources and the control of the policy's implementation in various regions of the country. Even though the main focus of the NFI over all these years has been on the quantification of the timber resources, additional characteristics of the ecosystems have been incorporated as the society has focused on "new" aspects, such as, (e.g.,) the preservation of biodiversity, the effects of air pollution, and the forests' role as sinks and sources for greenhouse gases.

Over the years, the NFI has applied various designs of field-based strip and plot surveys as basic sampling models, and the sampling density has been adjusted from county to county to provide reliable estimates at national and regional (county) levels over time. Currently, the NFI is facing at least three major challenges: (1) to reduce costs by adopting remote-sensing techniques to some of the tasks in which remote sensing can provide reliable and cost-efficient estimates, (2) to provide statistical estimates of the timber resources at local scales (sub-county) to support the local public forest administration, and (3) to provide cost-efficient and reliable estimates of biomass or carbon stocks of forest and nonforest land to meet the Kyoto Protocol requirements. This third challenge includes biomass or carbon estimates of thousands of square kilometers of mountain forest above the official tree line, which is currently not part of the NFI or any other national monitoring systems. This ecotone

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is of special interest in the climate change and C sequestration debate because it is likely that a temperature-induced productivity increase could more easily be detected in the mountain forest due to the steep temperature-productivity gradients.

For purposes in which statistical estimates of forest resources of a certain region are sought, airborne Light Detection and Ranging (LIDAR) may be used as a sampling device to collect representative data for a region. For nearly two decades, airborne LIDAR has been used as a tool for research in forest inventory, but a few years ago it was demonstrated for the first time that LIDAR also can be a powerful tool in regional inventory. In 2000, the National Aeronautics and Space Administration (NASA) collected LIDAR data along 56 parallel flight lines across the entire State of Delaware. A so-called profiling LIDAR was used. Unlike a scanning LIDAR that collects data along a corridor of a width of, say, 100 to 1,000 m, a profiling system is only capable of collecting a narrow line of data underneath the aircraft. Along the flight lines, 142 ground samples based on 40-m segments using line intersect sampling were used to provide ground estimates of volume and biomass (Nelson *et al.* 2003; Nelson, Short, and Valenti 2004). These estimates were regressed against canopy structural properties derived from the LIDAR data using parametrically and nonparametrically fit, explicitly linear, and ln-ln models. Stratified and nonstratified versions of these models were considered and used to predict volume and biomass along all 56 flight lines over the State using a stratified sampling scheme accounting for the proportion of different land categories of the State. Year 2000 profiling LIDAR-based results based on 5,159 km of flight data were compared, by county and State, with 1999 U.S. Department of Agriculture, Forest Service, Forest Inventory and Analysis (FIA) data based on 225 FIA plots. Results indicate that nonparametrically fit linear models provided results that most closely agreed with FIA timberland estimates. LIDAR-based estimates of merchantable volume and biomass were within 23 percent of FIA estimates at the county level and within 18 percent of FIA estimates at the State level. In all cases, the LIDAR-based estimates were more precise than the comparable FIA estimates were.

Scanning LIDAR is typically used to collect wall-to-wall data of ground topography and forest canopy elevations. Such systems are now being used operationally in forest stand inventory in Scandinavia (Næsset *et al.* 2004), and the procedures used to estimate biophysical stand properties are very similar to those used for data collected by profiling systems (i.e., field training data are related to LIDAR-derived metrics for a number of conventional ground plots distributed throughout the area in question, and estimated regression equations are used to predict biophysical properties of every stand in the target area based on the wall-to-wall coverage of LIDAR data [Næsset 2002, Næsset and Bjerknes 2001]). Extensive testing has indicated that the accuracy of LIDAR-based stand inventory is superior to that of conventional inventories based on fieldwork and/or stereo photogrammetry (Holmgren 2004; Maltamo *et al.* 2006; Næsset 2002, 2004a, 2004b).

Like profilers, however, scanning LIDARs, which capture data along wide corridors, can be used as sampling tools as well. The overall scientific aim of the ongoing study is to develop airborne scanning LIDAR as a strip sampling tool to inventory timber volume and biomass in large areas and compare the accuracy and costs of such an application with what can be obtained by a profiling system. This article presents the project plans and expected output of the work.

Methodology

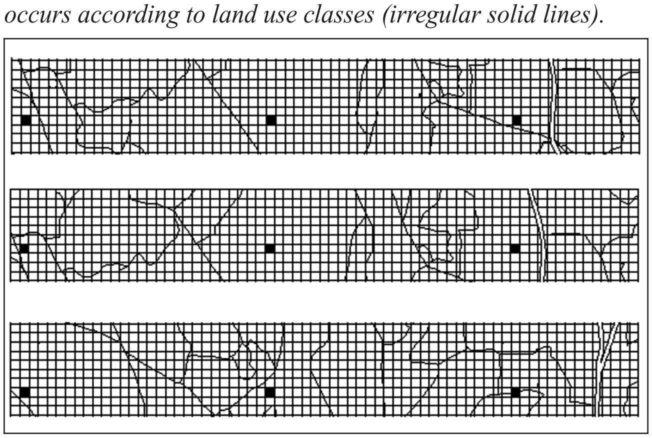
The profiling LIDAR to be tested in this project is the Portable Airborne Laser System (PALS) assembled at NASA/Goddard Space Flight Center (Nelson, Parker, and Hom 2003). PALS has previously been flown over Delaware, where the target variables were merchantable volume and aboveground biomass (Nelson *et al.* 2003). Later, it was flown over parts of U.S. States such as Texas and New Jersey, over Quebec in Canada, and over Japan. In the present project, PALS profiles are flown over NFI permanent forest inventory ground plots to develop parametric (regression) and nonparametric models that will tie the LIDAR measurements to ground-measured volume and biomass. These models will, in a subsequent step, be used to predict timber volume and biomass along all the flight lines. The forest area in question will be stratified according to forest types defined by criteria such as tree species and site productivity. The stratification will be based on existing Geographic

Information System databases of site productivity and land use status while Landsat multispectral image data and nonparametric estimation techniques using the NFI permanent sample plots as training data will guide the classification of the forest into different tree species categories. Thus, the entire inventory area will be assigned to one of several mutually exclusive classes and the classes will be used to correct the stratified estimates of timber volume and biomass derived along the PALS flight lines (ratio estimation).

A number of commercial scanning LIDAR systems are available in the market (Baltsavias 1999), but a disadvantage of these systems, as compared with simple profiling systems, is the high costs for data acquisition. Despite this disadvantage, in regional applications to provide volume and biomass estimates at subcounty, county, or national levels that conform to NFI requirements, even a scanning system can be used as a sampling tool by simply collecting laser scanner data along strips that may be separated by many kilometers.

The concept for a sampling-based method for timber and biomass inventory using airborne scanning LIDAR will, to a large extent, follow the procedure for wall-to-wall mapping of forest stands outlined previously (Næsset 2002, Næsset and Bjerknes 2001). NFI ground plots underneath the scanner flight lines will be used to derive stratified parametric and nonparametric models that tie ground measurements to the LIDAR data. Similar to the application based on profiling, these models will be used to predict volume and biomass along all flight lines. In contrast to profiling LIDAR, where the units used in prediction are short segments of LIDAR data with a length of, say, 40 m, the prediction units for scanner data are grid cells with a size equal to the ground plot size (see fig. 1). As with the profiling-LIDAR–based sampling approach, the scanner-based stratified volume and biomass estimates along the flight-line corridors will be adjusted according to the distribution of the entire area in question on different strata.

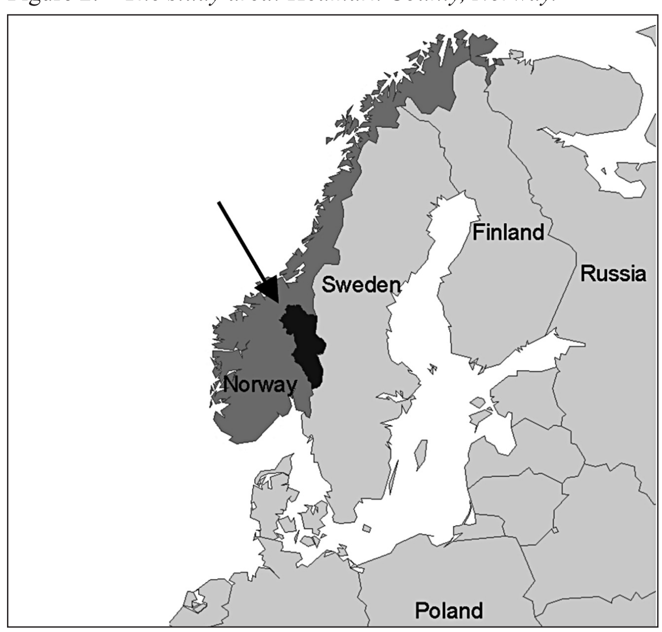
Figure 1.—*An illustration of a scanning Light Detection and Ranging (LIDAR) strip sampling scheme. The three strips of LIDAR data are divided into regular grid cells—the primary unit of the estimations. The black cells indicate systematically distributed field sample plots used as training data. Stratification occurs according to land use classes (irregular solid lines).*



Study Area

The target area of this investigation is Hedmark County, Norway. The total area is approximately 27,000 km^2 (fig. 2). The productive forest area is 13,420 km^2 (Tomter *et al.* 2001). The total standing volume is 134.7 million m^3. The forest is dominated by Scotch pine (48 percent) and Norway spruce (42 percent). Birch is the dominant deciduous tree species (8 percent). No precise estimates of the area covered by mountain forest exist, and, in the ongoing research, we will estimate the area, timber volume, and biomass or carbon stocks of this biome.

Figure 2.—*The study area: Hedmark County, Norway.*



Field Data

NFI circular ground plots will be used to calibrate equations that will relate ground-measured timber volume and biomass to the LIDAR data. Hedmark County is covered by 2,207 permanent NFI sample plots. The 250-m^2 plots, with a plot radius of 8.9 m, are distributed on a 3-x-3-km grid. Twenty percent of the permanent plots are remeasured every year, and the plots are selected within a 45-x-45-km block of plots according to a Latin square design. The NFI ground plots measured in 2005 through 2008 will be used in the calculations.

The NFI comprises all types of land below the coniferous forest limit (i.e., from approximately 120 m above sea level up to 900 m above sea level), but a comprehensive description is made only for forest land. Because it is also an objective to demonstrate that airborne LIDAR can provide data required for reporting on the United Nations Framework Convention on Climate Change and the Kyoto Protocol, approximately 100 additional ground plots will be measured on land other than forest land during the summers of 2006 and 2007.

About 100 additional field plots in the mountain forest above the official tree line, which is currently not a part of the NFI or any other national monitoring systems, will also be measured in 2006 and 2007.

On each plot, all trees with diameter at breast height of more than 4 cm are callipered, and the tree heights of an average of 10 sample trees per plots are measured. The coordinates (x, y) of each plot center are determined with an average accuracy of less than 0.5 m using differential Global Positioning System and Global Navigation Satellite System measurements, according to the procedures suggested by Næsset (2001). Timber volume will be estimated according to standard volume equations for individual trees (see Næsset 2002 for further details) and biomass will be estimated according to allometric equations (Marklund 1988). Estimates of standing carbon will be derived from the dry biomass estimates based on the 0.5 conversion factor from dry biomass to mass of carbon suggested by Gower *et al.* (1997) and Houghton *et al.* (2000).

LIDAR Data

During the summer of 2006, the PALS profiling LIDAR and an Optech ALTM 3100C scanning LIDAR were flown along parallel flight lines over the ground plots. Approximately 9,000 km of flight lines were flown with the PALS LIDAR profiler, whereas scanning LIDAR data were acquired along 4,500 km of flight lines. The spacing between flight lines was 3 and 6 km for the profiler and scanner, respectively, which means that the profiler was flown over all ground plots while the scanner was flown over 50 percent of the plots. The average pulse density for the scanner was 2.5 to 3 m^{-2}. The first and last echoes were recorded by the profiler, while the scanner recorded up to four echoes per laser pulse. The scanner data cover as much as 8 percent of the entire land surface in the county and thus this data set represents a very large sample of the forest in the area.

Discussion

The estimates of timber volume for Hedmark County derived by scanning and profiling LIDAR will be compared with the official statistics based on the NFI for the 1995-to-1999 period. Because the NFI only provides county-level estimates, only totals for the entire county will be compared. The standard error of the official estimate of total standing volume is estimated to 3.0 percent (Tomter *et al.* 2001). Despite these limitations, we hope to be able to compare subcounty estimates derived from the scanning and profiling LIDAR data acquisitions with corresponding estimates from a complete wall-to-wall inventory by scanning LIDAR planned to take place in a 2,000 km^2 area in the county. This inventory is part of an operational project to provide improved digital terrain models and data for forest management planning undertaken by the local mapping authorities and the local forest owners, respectively.

Many sources of errors will be associated with the estimates of volume and biomass at county and subcounty levels derived from the scanning as well as the profiling systems. Some of the major sources of variance are sampling errors, regression errors inherent in the LIDAR data/field data relationships, and errors in allometric and other equations. These sources probably have different effects on the estimates derived by profiling and scanning LIDAR.

The efforts to improve laser-based inventories will—if the results confirm the hypothesis—reduce the costs and improve the accuracy and applicability of airborne LIDAR in future NFI programs.

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