Remote Sensing of Environment 114 (2010) 1445–1461

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Effects of different sensors and leaf-on and leaf-off canopy conditions on echo distributions and individual tree properties derived from airborne laser scanning

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ARTICLE INFO

Article history:
Received 5 October 2009
Received in revised form 15 January 2010
Accepted 30 January 2010

Keywords:
Airborne laser scanning
Leaf-on canopy conditions
Leaf-off canopy conditions, Sensors
Individual trees
Intensity
Tree height
Stem diameter
Species classification

ABSTRACT

The objectives of this study were to quantify and analyze differences in laser height and laser intensity distributions of individual trees obtained from airborne laser scanner (ALS) data for different canopy conditions (leaf-on vs. leaf-off) and sensors. It was also assessed how estimated tree height, stem diameter, and tree species were influenced by these differences. The study was based on 412 trees from a boreal forest reserve in Norway. Three different ALS acquisitions were carried out. Leaf-on and leaf-off data were acquired with the Optech ALTM 3100 sensor, and an additional leaf-on dataset was acquired using the Optech ALTM 1233 sensor. Laser echoes located within the vertical projection of the tree crowns were attributed to different echo categories ("first echoes of many", "single echoes", "last echoes of many") and analyzed. The most pronounced changes in laser height distribution from leaf-on to leaf-off were found for the echo categories denoted as "single" and "last echoes of many" where the distributions were shifted towards the ground under leaf-off conditions. The most pronounced change in the intensity distribution was found for "first echoes of many" where the distribution was extremely skewed towards the lower values under leaf-off conditions compared to leaf-on. Furthermore, the echo height and intensity distributions obtained for the two different sensors also differed significantly. Individual tree properties were estimated fairly accurately in all acquisitions with RMSE ranging from 0.76 to 0.84 m for tree height and from 3.10 to 3.17 cm for stem diameter. It was revealed that tree species was an important model term in both and tree height and stem diameter models. A significantly higher overall accuracy of tree species classification was obtained using the leaf-off acquisition (90 vs. 98%) whereas classification accuracy did not differ much between sensors (90 vs. 93%).

1. Introduction

Over the past decade airborne laser scanning (ALS) has contributed significantly to improved efficiency of forest inventories (Eid et al., 2004; Næsset, 2007). Comparisons of ALS with other remote sensing methods like radar and optical sensors have shown that ALS is among the most promising remote sensing techniques in terms of accuracy of essential forest parameters such as height, volume, and biomass (Hyde et al., 2006; Hyde et al., 2007; Hyyppä & Hyyppä, 1999; Magnusson, 2006). Today, ALS is used operationally in stand based forest inventory where the products are biophysical characteristics like mean height and timber volume presented at the stand level (e.g. Næsset, 2007; Næsset et al., 2004). However, the first operational inventories in landscapes with a size of up to 2000 km^2 where individual trees derived from high-density ALS data are the primary units of interest, are now about to be completed. In both procedures, i.e., area-based methods and individual tree methods, biophysical parameters of interest such as canopy/tree height and volume are estimated from statistical measures derived from the laser echo distributions, in particular the laser height distribution, but also the laser intensity distribution is considered (e.g. Lim et al., 2003).

The echo distributions derived from ALS measurements are sensor dependent. Sensor and acquisition parameters like flying altitude, footprint size, pulse repetition frequency, beam divergence, and scan angle have been tested and found to influence the echo height distribution (Chasmer et al., 2006; Goodwin et al., 2006; Holmgren et al., 2003; Hopkinson, 2007; Næsset, 2004b; Næsset, 2009; Næsset et al., 2005; Yu et al., 2004). The sensor effects on echo distributions are of concern in several areas of application in forest inventory. First, the sensor effects are of interest when developing ALS methods for regional biomass-, carbon-, and forest health inventory and monitoring (Næsset & Nelson, 2007; Næsset et al., 2009; Solberg et al., 2006b). Examples of such inventories are the national forest inventory programs found in many countries. The inventory cycle in such programs is usually 5–10 years. The typical life time of commercial laser sensors is less than 4 years. Hence, the time period between repeated inventories is most likely longer than the life time of a sensor and two subsequent acquisitions will thus be conducted with different sensors. For regional and national systems for forest monitoring and carbon reporting compatibility between sensors over time is essential (Næsset et al.,

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doi:10.1016/j.rse.2010.01.024

2009; Nelson et al., 2003; Nelson et al., 2004). Systematical shifts in estimated properties caused by changing sensor properties could influence on conclusions inferred from multi-temporal observations by either overestimating the true changes or making changes undetectable. Second, sensor-specific effects are important in operational forest inventory at a more local scale. An expensive part of such inventories is the field survey conducted to collect local plot data for estimation of relationships between metrics derived from the ALS data and biophysical properties of interest. If estimated models of biophysical properties could be based on already existing field plots with associated ALS metrics derived from previous acquisitions in nearby areas the costs of the inventories could be reduced. It has been demonstrated that laser data from two different areas, acquired with the same sensor, can be handled together by common regression models without loss in accuracy of the estimated stand level biophysical properties (Næsset, 2007). Hence, stability in laser echo distributions, model parameters, and predicted values across different sensors are important when considering ALS and ground data to be combined across different areas (Næsset, 2007; Næsset et al., 2005).

Another concern in forest inventory is the time of data acquisition. Appropriate acquisition periods are commonly separated into two distinct times of the year, i.e., (1) when the deciduous trees have leaves (leaf-on) and (2) the dormant period of deciduous trees (leaf-off). It is common practice to acquire ALS data for operational forest inventories under leaf-on conditions, but in some areas leaf-off conditions are preferred. One reason for avoiding the leaf-off period is the much more narrow time window of having leaf-off conditions and bare ground (without snow) at northern latitudes combined with the risk of snowfall. However, there may be several reasons why leaf-off acquisitions may be considered as an alternative season for forest inventory ALS acquisitions. First, under leaf-off conditions a larger amount of pulses will be capable of penetrating through the canopy and be reflected off the ground in deciduous forest. Higher proportions of ground echoes will give more accurate digital terrain models (DTM). ALS acquisitions for regions or even for entire nations are sometimes performed under leaf-off conditions to optimize the accuracy of the DTMs (Liang et al., 2007). Hence, forest inventories may take advantage of laser data collected for DTM generation to reduce the overall inventory costs. Second, leaf-off data may help in reducing the influence of the so-called “hardwood problem” in ALS assisted forest inventories (Nelson et al., 2007). The “hardwood problem” refers to the poorer laser based estimates of biomass sometimes found in mixed (Næsset, 2005) and deciduous (Nelson et al., 2004) forests as compared to pure coniferous forest. Næsset (2005) studied this problem in an area-based inventory of a mixed forest under leaf-on and leaf-off conditions. It was revealed that utilizing the leaf-off laser data slightly improved estimates of mean height, basal area, and timber volume compared to utilization of the leaf-on data. Furthermore, at the individual tree level, species classification have been tested and found to be promising under leaf-off conditions. In a comparative classification study of coniferous and deciduous trees using waveform data the overall accuracy was 85% under leaf-on condition and 96% under leaf-off condition (Reitberger et al., 2008). Species classification can be a strategy for reducing the impact of the “hardwood problem”. Thus, there are multiple reasons why leaf-off acquisitions may be considered as an alternative to leaf-on acquisitions; (1) cost sharing of leaf-off ALS data acquired for DTM production, (2) the slightly more accurate results likely to be obtained in area-based forest inventory of certain forest types, and (3) the promising results of tree species classification obtained for individual trees. Hence, knowledge and understanding of the differences between echo distributions obtained under leaf-on and leaf-off canopy conditions are needed.

In the current study, we compared the differences in echo distributions (height and intensity) of individual trees obtained under different canopy conditions and with different sensors. Analyses of individual trees will give us better understanding of echo distributions derived from ALS data. A specific advantage of studying individual trees is that the different tree species can be analyzed independent of each other. Tree species produce different echo distributions which may provide significant differences in derived metrics (Ørka et al., 2009). Tree species is clearly an important factor in the analysis of effects of canopy conditions where only deciduous trees will be affected by the changes form leaf-off to leaf-on conditions. Likewise, the emitted pulses from different sensors may interact differently with different tree species creating a species specific sensor effect. In the current study, we addressed the species specific effects of different sensors and canopy conditions by analyzing the echo distributions of individual trees.

To the very best of our knowledge, studies of the effects of sensor and canopy conditions on echo distributions and biophysical properties have until now focused on the area-based approach and have mostly been conducted at the plot level (Hopkinson, 2007; Næsset, 2005; Næsset, 2009). As individual tree inventory now becomes operational, effects of different sensors and canopy conditions on prediction of biophysical properties of individual trees will be important as well. A proposed advantage with individual tree inventory is that a smaller amount of reference data will be needed for model calibration (Hyyppä et al., 2008). Stability of model parameters and predictions using different sensors will support the idea of using a small number of reference trees in individual tree inventory. It will also support the idea of reusing models across nearby areas flown with different sensors and contribute to lower inventory costs. Higher accuracy obtained with data acquired under leaf-off conditions would favor this time period for acquisition of ALS data for forest inventory. Therefore it is important to assess how different canopy conditions and sensors affect model parameters and predicted values of important individual tree properties likely to be a part of such inventories. In this study, we considered tree height, stem diameter, and tree species as the most important properties to be derived using the individual tree method (c.f. Holmgren & Persson, 2004; Hyyppä et al., 2001; Ørka et al., 2009; Persson et al., 2002).

The objectives of the present study were to quantify and analyze differences of (1) leaf-off vs. leaf-on conditions and (2) acquisitions with two different sensors on (a) the laser height echo distributions and (b) the laser intensity echo distributions of ALS point cloud data. The differences were analyzed for separate echo categories and tree species. Furthermore, (3) we assessed how these changes in canopy conditions and change of sensors influenced on the accuracy and model parameters for three individual tree properties derived from ALS data, i.e., (a) tree height, (b) stem diameter, and (c) tree species.

2. Material and methods

2.1. Study area

The study area is located in Østmarka forest reserve (59°50′N, 11°02′E, 14 190–370 masl) in southeastern Norway. The forest reserve is about 1800 ha in size. This forest has developed without logging and silvicultural treatments since the 1940s. Today, the forest in the reserve is size diverse and it is partly multilayered. The dominating tree species are Norway spruce (*Picea abies* (L.) Karst.) and Scots pine (*Pinus silvestris* L.). Deciduous trees are found scattered in the landscape. Birch (*Betula* ssp.) and aspen (*Poplus tremula*) are the most commonly occurring deciduous species. Data from an adjacent area outside the reserve was also used to include younger forest in the study. This particular forest area is actively managed.

2.2. Field data

Field data collection was carried out on 28 field plots of 0.1 ha size during summer 2003. The 20 plots inside the reserve were laid out subjectively to comprise spruce dominated sites (Bollandsås &