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Airborne small-footprint discrete-return LiDAR data in the assessment of boreal mire surface patterns, vegetation, and habitats

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ABSTRACT

Boreal mires encompass high diversity in species and habitats, many of which are endangered. In Finland, extensive use of peatlands has resulted in habitat fragmentation. A need for accurate and cost-efficient vegetation mapping and monitoring of habitat changes exists in mire conservation, restoration and peatland forestry. LiDAR is an emerging and excellent tool for probing the geometry of vegetation and terrain. Modern systems measure the backscattered signal accurately and also provide radiometric information. Experiments were carried out in a complex minerotrophic–ombrotrophic eccentric raised bog in southern Finland (61°47′N, 24.18′E). First, we tested discrete-return LiDAR for the modeling of mire surface patterns and the detection of hummocks and hollows, as well as the effect of mire plants on the Z accuracy of the surface echoes. Secondly, the response of different mire vegetation samples in LiDAR intensity was examined. Thirdly, we tested area-based geometric and radiometric features in supervised classification of mire habitats to discover the meaningful variables. The vertical accuracy of LiDAR in mire surface modeling was high: 0.05–0.10 m. A binary hummock-hollow model that was estimated from a LiDAR-based elevation model matched flawlessly in aerial images and had moderate explanatory power in habitat classification trials. The intensity of LiDAR in open-mire vegetation was mainly influenced by the surface moisture, and separation of vegetation classes spanning from ombrotrophic to mesotrophic vegetation proved to be difficult. Area-based features that characterize the height distribution of LiDAR points in the canopy were the strongest explanatory variables in the classification of 21 diverse mire site types. Actual qualifying differences in the ground flora were unattainable in the LiDAR data, which resulted in inferior accuracy in the characterization of ecohydrological conditions and nutrient level of open mires and sparsely forested wet sites. Mire habitat classification accuracy with LiDAR surpassed earlier results with optical data. The results suggested that LiDAR constitutes an efficient aid for monitoring applications. We propose the co-use of images and LiDAR for enhanced mapping of open mires and tree species. *In situ* calibration and validation procedures are required until invariant geometric and radiometric features are discovered.

1. Introduction

Airborne LiDAR is an active remote sensing technique that measures the properties of scattered light to determine the range and other information of a distant target (Wehr and Lohr, 1999). LiDAR is an efficient tool for probing vegetation geometry and topographic features. In the last 4–8 yrs, it has revolutionized photogrammetry and environmental 3D data acquisition. LiDAR is particularly suitable in forests, because it enables coincident measurement of the vegetation and terrain, which cannot be done reliably in passive images. LiDAR is less dependent on weather conditions than optical sensing. Prevalent method is the use of laser pulses, with frequencies in excess of 150 kHz. LiDAR provides both geometric and radiometric data. Discrete-return LiDAR sensors extract 1–4 returns per pulse, 3D points, and intensity values that correspond to backscatter amplitude. Full-waveform LiDAR samples at GHz rate the entire reflected waveform for computer-intensive postprocessing and extraction of points and elaborate waveform features (Wagner et al., 2006). LiDAR provides discrete point sampling, whereas images have a continuous 2D coverage. LiDAR is less affected by shadows and occlusions, which constitutes an advantage over optical images. The XY accuracy of the pulse center is typically 0.1–0.5 m, depending on the flying height. The accuracy in Z is usually better than 0.2 m. The footprint, i.e. the illuminated area on the ground, is determined by the beam divergence. Values range from 0.2 m to 1.0 m for flying heights of 1–5 km.

Arborne LiDAR is a powerful technique to use in terrain modeling even under leaf-on conditions (Kraus and Pfeifer, 1998; Korpela and Välimäki, 2007). The canopy returns can be used to

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characterize forest vegetation height, type and density (Næsset, 2004). Co-use of images improves species estimation accuracy, which in turn enhances the accuracy of the biomass estimates (Packalén and Maltamo, 2007; Korpela et al., 2008). For monitoring applications, the repeatable and high absolute XYZ accuracy is advantageous, since changes can be detected at submeter scales (Yu et al., 2006, 2008) and the same measurement units, e.g. trees, plots or 3D voxels, can be monitored over time. This reduces the effect of sampling error in the change estimates.

Using LiDAR to obtain 3D data of objects is simple and cost-effective and explains why LiDAR is replacing photogrammetry in many tasks, although 3D reconstruction and object classification still remain a challenge regardless of the method by which the 3D point data were obtained. In discrete-return LiDAR, the intensity carries radiometric information to support object classification. A disadvantage for users is that the intensity is not affected only by the target backscatter reflectance. Factors that influence intensity also include the intentional and random power variation of the transmitted pulse, the speckle effect of the laser, electronic noise in the receiver and the background noise, changes in the receiver sensitivity, the wavelength used, surface geometry, pulse width, scanning distance and angle, and two-way transmission losses in the path of the signal (Wehr and Lohr, 1999; Ahokas et al., 2006; Kaasalainen et al., 2007a; Morsdorf et al., 2007). The size of the footprint influences the XYZ and intensity distributions in vegetation canopies (Hopkinson, 2007). However, it should be stressed here that LiDAR intensity cannot be used for deriving the reflectance of shoots, leaves and needles that are normally smaller than the illuminated area (Wagner et al., 2008). In practice, the intensity variation caused by the varying LiDAR-to-target range is the most important factor to be accounted for in a LiDAR campaign (Hopkinson, 2007; Kaasalainen et al., 2007a; Höfle and Pfeifer, 2007; Korpela, 2008). This reduces noise in the intensity data. However, the normalization for range is ambiguous for targets such as the forest canopy, because the normalization coefficient depends on the size of the scatterers (Ahokas et al., 2006; Korpela, 2008; Wagner et al., 2008). Work on developing methods for absolute calibration and retrieval of surface albedo from calibrated LiDAR observations is also ongoing (Kaasalainen et al., 2005, 2007a; Ahokas et al., 2006; Wagner et al., 2008). Even in calibrated data, retrieval of the reflectance of objects smaller than the footprint remains ill-posed. This constitutes a challenge for the use of LiDAR radiometry in vegetation classification and explains why the co-use of images is sought in many cases (Koetz et al., 2008; Korpela et al., 2008). Currently, topographic sensors are used in forest applications. These operate on a single wavelength, typically in the near-infrared band, and are optimized for terrain modeling. Future sensors are anticipated to be multispectral, which may increase the range of applications (Kaasalainen et al., 2007b).

Intensity has not been used extensively for vegetation mapping. One reason may be that intensity measurements have been noisy until recently, since sensor manufacturers first focused on improving range determination accuracy. Intensity metrics were used for the classification of tree species (Holmgren and Persson, 2004; Donoghue et al., 2007; Brandtberg, 2007; Ørka et al., 2007), for modeling of canopy gap fraction (Hopkinson and Chasmer, 2007), and for land-cover classification (Brennan and Webster, 2006; Yoon et al., 2008). Korpela (2008) examined range-normalized intensity data for the mapping of ground lichens. Normalization improved the precision of the classifications.

Mire habitats occupy significant proportions of the Boreal Zone, in Fennoscandia, Canada, and Russia. In Finland, drained and pristine mires constitute 28% of the land cover (Korhonen et al., 2008). In southern Finland, 75% of mires have been drained for forestry and agriculture (Virkkala et al., 2000). Mires are also utilized for peat harvesting for energy and horticultural purposes. In Finland, restoration of drained mires was begun in the 1990s (Aapala et al., 2008). Boreal mire ecosystems are sensitive to climate changes and changes in the vegetation and canopy structure due to atmospheric nutrient fallout (Strack, 2008). Efficient monitoring tools for change detection and the appraisal of restoration success are needed. Currently, mire habitats are mainly mapped using field surveying, in which aerial images are a stratification aid, but the work is laborious and expensive.

The use of LiDAR or other 3D remote-sensing methods in mire vegetation appraisal is largely unexplored. Waser et al. (2008) used a method that combines advanced image matching of large-scale aerial images with sparse leaf-off LiDAR for the detection of changes in forested area and shrub encroachment in prealpine mire environment. Reliable 3D reconstruction of canopies by stereo matching proved imprecise, due to occlusions. Large image overlaps are required, which leads to multi-image matching (e.g. Hirschmugl et al., 2007). Underestimation of tree heights and imprecision of canopy surface models acquired by means of stereo image matching were also reported (Næsset, 2002; Korpela and Anttila, 2004). The use of interest operators for finding corresponding treetops in multiple images for 3D treetop positioning leads to accurate height determination (Korpela, 2007), but this approach has not been tested in mire environments, where crowns are often seen in low contrast and trees exhibit considerable height variation. In view of the difficulties of image matching, LiDAR is a very attractive option for the reconstruction of canopies under the conditions found in mires. Vehmas et al. (2008, 2009) used airborne LiDAR in site-type mapping of mineral soil forests in eastern Finland, especially for the detection of lush herb-rich sites. The detection was based on the characteristics of point-height distributions in the canopy. The site types correlated with the height growth rate of trees; however, the site types were defined by the understory vegetation: the occurrence of certain herbs, ferns, and bushes. Gatziolis (2007) estimated site indices in the coastal Pacific Northwest of the USA, using LiDAR measurements of dominant height.

Images and their monoscopic interpretation are often the only options in retrospective vegetation analysis, since commercial LiDAR has been available only since 2002–2004. Historical and up-to-date aerial photographs and hyperspectral data were used in peatland habitat mapping in Finland by Holopainen (1998). The habitat classes that were sought were defined according to drainage conditions, main tree species, degree of stocking, and site fertility—features that would be measurable in optical images but still relevant for ecological decision-making. Holopainen (1998) generalized 21 pristine mire site types into nine habitats. The most fertile mineral soil classes were difficult to detect, while treeless mire habitats were successfully separated in optical data.

Our hypotheses are that airborne LiDAR data, through their proven ability to probe the geometric and radiometric properties of all vegetation layers, could be used for retrieving the key taxonomic features of pristine mire site types in Finland. It would be suited for the long-term monitoring of changes in mire surface structure and vegetation. More precisely, we see the potential for (a) accurate digital elevation modeling (DEM) and retrieval of the hummock-hollow mire surface patterns and (b) for measurement and characterization of the density, vertical distribution, and species mixture of ground, shrub layer, and tree vegetation.

- We carried out experiments on two nearby mires and tested,
- the geometric accuracy of LiDAR in retrieving the mire surface elevation,
- the response of LiDAR intensity to different mire vegetation surfaces, and
- LiDAR- and DEM-based features in the classification of pristine mire site types, mire habitats, dominant tree species, and the nutrient status of the site types.