Airborne laser scanning for forest applications - state of the art

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Airborne Laser Scanning for Forest Applications

State-of-the-Art

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1 A fast developing technique

1.1 History

Airborne laser scanning (ALS) is a remote sensing technique based on the measure of the flight time of laser pulses emitted from an aircraft and reflected by objects located on the ground. Its fast development during the two past decades has been made possible by the technological advances of global positioning system, inertial navigation, and lasers. At the beginning, LiDAR (Light Detection And Ranging) sensors boarded in aircrafts or satellites only operated on one-dimensional (1D) profiles along the platform path. Sensors are now equipped with orientating devices and are able to scan large swaths along the platform trajectory. By the end of the 1990's, the pulse repetition frequency of small footprint, commercial sensors was around 10 kHz [1], and service providers were only emerging. Now, leading sensors achieve a pulse repetition frequency of 300 kHz with the multipulse technology. Some countries have undergone a complete LiDAR coverage (Switzerland, Denmark) and wall-to-wall mapping is under way in some others (Finland, Sweden).

1.2 Principles

The main components boarded in the aircraft are:

- global positioning system (GPS),
- inertial measurement unit (IMU),
- laser emitter-receiver scanner,
- storage device.

A laser pulse is fired toward the Earth in a direction given by the orienting device (oscillating mirror, rotating prism). For vegetation and topographic mapping purposes, the laser wavelength is usually around 1000 nm, which assures correct reflectance values for a broad range of materials. Whenever the laser pulse is intercepted by an object, part of the energy is reflected toward the receiver and recorded. When the object is not solid or too dense (e.g. tree branches), a sufficient part of the laser beam may also continue its trajectory and be reflected by lower elements, eventually the ground surface (figure 1). This characteristic of laser scanning is of high importance as it allows to characterize the underlying 3D structure of the vegetation and to accurately detect the soil surface even in dense canopy areas.

The range to reflecting objects is computed as $R = c \times \frac{t}{2}$ where t is the fly-around time and c the pulse speed in the atmosphere, assumed to be equal to the speed of light. On analog scanners, t is determined in real-time by detecting the time when the leading edge of the reflected signal reaches a given threshold [2]. Such systems are able to store one to several echoes for each emitted pulse. They are called multi-echo laser scanners. In recent scanners, storage capacity has been greatly increased so that the full waveform of the reflected pulse is digitized. The post-processing of the data allows a finer detection (number and coordinates) and characterization of objects located within the footprint of the laser pulse [3, 4]. The footprint, which is the surface illuminated by the laser beam, depends on the divergence of the laser and on the range. Laser scanner with footprint size smaller than one meter are considered "small-footprint". Their range accuracy, which mainly depends on the width of the emitted pulse, is usually around 15 cm. The orienting device makes laser pulses sweep across the aircraft trajectory. Swath width is determined by the flying altitude and the scanning angle. LiDAR data are usually acquired in multiple, overlapping flying strips. A comprehensive description of relations and formulas for airborne laser scanning is available in [2].

Back in the office, objects coordinates are computed with the information from the on-board and ground-based components:

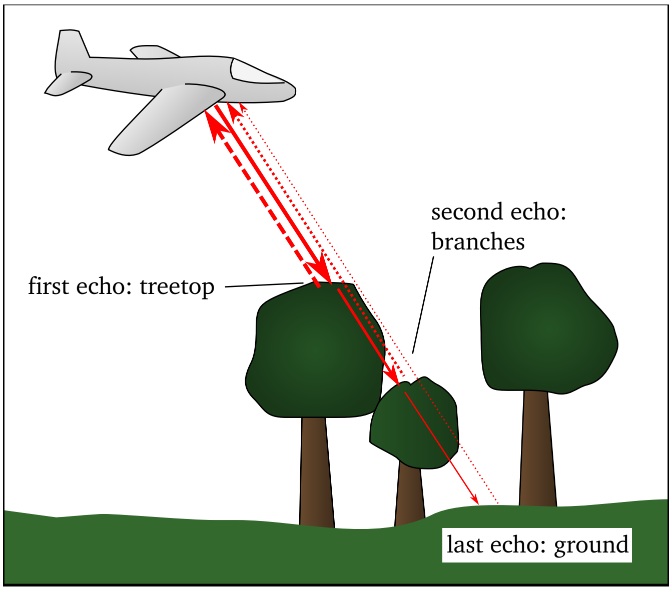


Figure 1: Principle of range measurement by airborne laser scanning.

- range and pulse angle (laser emitter-receiver),
- plane trajectory (on-board GPS and ground reference stations),
- plane attitude: yaw, pitch and roll (IMU).

Further processing includes laser strip adjustment to correct for hardware calibration errors, and detection of erroneous points: high points due to atmospheric noise and low points due to multiple reflections. For a small-footprint laser scanner, accuracy of the final 3D point cloud is typically 25 cm (planimetric) and 15 cm (altimetric). Point density varies greatly depending on acquisition parameters and desired applications, from one to more than one hundred points per square meter. For small footprint lasers, the 3D point cloud contains precise geometric information related to the objects which constitute the canopy cover. For large footprint lasers, the coarser planimetric resolution is generally compensated by the full waveform digitization (e.g. LVIS [5], SLICER [6, 7] and spaceborne GLAS/ICESAT).

2 Airborne laser scanning in forestry

2.1 First steps

The ability of LiDAR sensors to detect ground surface even in forested areas was first used for topographic purposes, mainly to derive accurate digital terrain models (DTM). However, the accuracy of the geometric information about the vegetation structure quickly sparked interest among the foresters. Following the development pace of the technology, forest stand parameters were first estimated with LiDAR profiling altimeters [8], and then with laser scanners [9]. Height variables [8–11] and stand volume [9, 12] were the first forest parameters investigated but laser data also proved efficient for other stand parameters, such as leaf area index, diameter and number of stems [6] or basal area [13].

At this time, large footprint LiDARs were mainly operated by NASA for research purposes, but commercial small-footprint were becoming widely available thanks to topographic acquisitions [14]. These first works showed the great potential for forestry applications, from stand parameters estimation to land cover classification, wildlife management and habitat mapping [15]. Soon, pre-operational studies for large-scale stand attributes mapping were undertaken [16, 17].

2.2 Fast development

In the early 2000's, research on forest applications of airborne LiDAR developed considerably. The existing methods, that had been principally tested on coniferous forests, were validated in other contexts: with SLICER data over broadleaved forest [7], temperate deciduous, temperate coniferous and boreal forest [18], with LVIS data on tropical rain forest [19, 20], with small footprint LiDAR on young forests [21] or northern hardwood forests [22].

The area-based method, which consists in the calibration of models linking quantiles of the point cloud vertical distribution to forest variables, proved very convenient for the retrieval of stand parameters such as height, mean diameter, stem density, basal area and volume [23, 24], or above ground biomass [25]. The method turned out to be efficient in various forest contexts [21] and quite robust to the laser point density [26]. It was quickly implemented at operational scale [24]. It was also successful in estimating tree properties e.g. total and crown height [27], and also more complex stand patterns such as the Weibull parameters of the diameter distribution [28].

Even tough this pragmatic approach adopted to predict forest parameters from laser-derived quantiles proved efficient, further investigation of the waveform signal and its interaction with the canopy was undertaken:

- simulation of LiDAR waveforms reflected by the canopy [29],
- decomposition of waveforms as sums of Gaussian components [3],
- modelling of waveforms with a time-dependent stochastic radiative transfer model [30].

Meanwhile, technological improvements in pulse repetition frequency soon allowed point cloud densities sufficient for single tree delineation from small footprint LiDARs [31]. Most of the studies relied on image processing techniques applied to canopy height models (CHM) [32–36] but some also tested point cloud processing [37, 38] (figure 2). The methods were rapidly improved in order to extract as much information as possible from the geometric features of the delineated trees, e.g. crown diameter [39], length or volume. Researchers soon faced the problem that suppressed trees were not easily detectable, hence the impossibility to predict height or diameter distributions with this sole method. As a result, deriving stand-level attributes from the aggregation of tree-level information remained problematic [40].

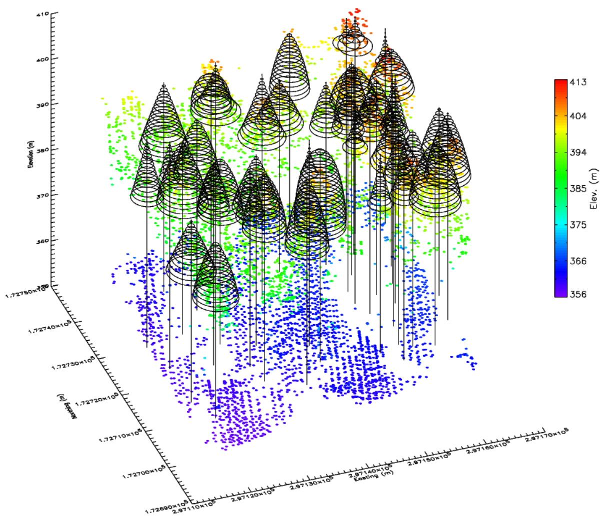


Figure 2: Single tree reconstruction from Bayesian object recognition in the point cloud, image from [37].

Whatever the approach, single-tree or area-based, concerns arouse about the sensitivity of the algorithms to both the LiDAR acquisition parameters and the forest structure. Indeed the increasing number of different scanners and the various possibilities for planning a LiDAR acquisition, altogether with the cost of LiDAR data, raised the issue of the optimization of surveys. Some studies relied on real data to assess the influence of acquisition parameters on estimated forest attributes, e.g. with LVIS data in tropical environments [41], or with small footprint LiDAR (effect of sampling on height underestimation [42], effect of flying altitude [43]). Simulations were also used as a convenient way to test several parameter combinations [44, 45] which would have been unaffordable in real-size experiments.

While some studies focused on the potential of LiDAR data alone for the retrieval of various forest parameters, e.g. geometric information [46, 47] or intensity information [22, 48] for species classification, others tried to take advantage of the synergy with optical sensors. Indeed the spectral information is more relevant than ALS data for tree species identification [17, 31, 49]. Besides, the large-scale availability of optical spaceborne data is useful for wall-to-wall mapping of forest attributes such as canopy height [17, 50, 51]. Indeed, LiDAR can be used as a calibration or validation tool for the structural analysis of vegetated ecosystems with spaceborne optical sensors [52]. Moreover, the combination of LiDAR and spectral data proved to be superior to the use of any of them alone, e.g. for tree crown delineation [53].

The potential of LiDAR data for a broad range of ecological applications was quickly identified [54], including its use in carbon content [55, 56] or gross primary production [57] studies.

2.3 Diversification

At this stage a great part of exploratory analysis of LiDAR potential for forest applications was done and basic methods had been tested on numerous datasets. Then LiDAR research expanded to a wide range of applications and tackled large-scale related issues.

Investigations on waveform modelling [58–61], calibration [4, 62, 63] and on the forest/signal interaction [64–66] increased as more and more full waveform small footprint scanners were commercially available. These methods allow a finer detection of echoes and the extraction of calibrated attributes. Such information proved useful for species classification [67, 68]. Reversely, pseudo-waveforms can be reconstructed from multi-echo sensors data [69].

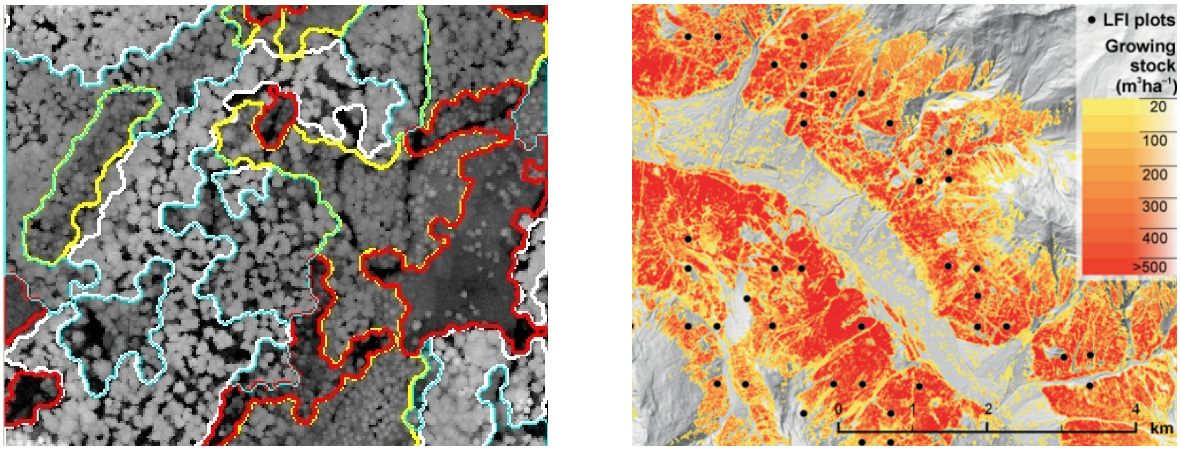
The issue of tree species classification indeed turned out to be an important pre-requisite for stand classification or species-specific attributes estimations. Some interesting results were obtained with LiDAR data alone [47, 70–75], by taking advantage of points attributes, such as intensity [76, 77], backscatter coefficient [67, 68] or directly from the full waveform data [78, 79]. Species classification was also facilitated by the synergy with spectral data. The issue of deriving species-specific estimates received considerable attention [80], e.g. for volume [81, 82], stem number and diameter [83], or diameter distribution [84].

Synergies with other remote sensing data were also investigated. LiDAR was compared [85–87] or used with radar data [88–91]. Comparison were also made with multispectral data [53, 92, 93] and combined used of the data was tested [91, 94, 95], even at the single tree level [36, 96, 97], or with the underlying idea to combine LiDAR accuracy with optical wall-to-wall cover [98–101].

Indeed, the methods were increasingly used at operational scale, e.g. in Scandinavia [102, 103], England [104], Alaska [105], Denmark [106]. This raised the issue of the validity of models developed at smaller scales [107–112]. Several studies proposed or compared various prediction methods [83, 113, 114]. At operational scale, the problem of the aggregation of stand parameters from single tree attributes remained unsolved. The estimation of tree distribution [115] or the calibration of tree lists [116] have been tested as possible solutions, and alternative methods were proposed for the imputation of single tree attributes [117]. Some of them may be seen as a convergence between the single-tree and the area-based approaches, the considered areas being previously delineated single tree segments [118, 119].

2.4 Applications

The range of LiDAR applications kept broadening, applying to several scientific fields and different scale levels. Regarding land cover classification [120, 121], LiDAR proved efficient for stand delineation and forest classification [122, 123] (figure 3a). Some studies focused on particular ecosystems, such as riparian forests [124], or cottonwood [125–127]. LiDAR is generally a well-suited tool to qualify the structure of forest stands [128–138], but also of the understory [139–141] or ground vegetation, e.g. with herb-rich forests [142]. Particular or general features of the forest can be detected or assessed with laser data, e.g. canopy gaps [143–146], canopy fractional cover [147–149], forest maturity [150].



(a) Automatic stand delineation in the Black Forest (Germany, image from [122])

(b) Stem volume map of Vorarlberg (Austria, image from [151])

Figure 3: Examples of operational applications of LiDAR remote sensing

Such information is then useful for ecological applications such as dead standing biomass assessment [152], habitat mapping [153–157], particularly related to avian species [158–160], or ecosystem studies (light interception [161], leaf area index [162–167], forest pigment mapping [168], pest control [169, 170]).

Georeferenced data is of great interest for forest management. This includes risk management, e.g. with forest fire modelling [171], and estimation of fuelwood [172–176] and past damages [177–179]. Predicted stand parameters are also useful to quantify the forest protection effect against rockfalls [180, 181]. Silvicultors are of course interested in all stand parameters introduced in the previous paragraphs (height, diameter, basal area, stem number, volume...). Economical analyses showed that the investment in LiDAR-based inventory procedures are justified by better resource management [182–184]. At single tree level, the geometric information (e.g. crown base [185, 186], 3D surface reconstruction [187], stem volume [188]) allows a better allocation by the forest practitioner, and can be used as input for virtual training environments [189]. LiDAR data is also useful for short and long-term forest change detection. Growth or harvesting operations [190–192], tree migration [193], pest infestation [170], disturbance dynamics [194, 195] can be precisely monitored. Studies also showed the possibility of retrospective analysis of optical data [196–198].

Today's context of global warming and all its implications in global carbon cycle and stocks assessment have also oriented LiDAR investigations. Several studies have addressed the issue of biomass mapping [199–204].

2.5 Main achievements in mountainous or complex environments

After the first experiments on coniferous forests, a broader range of forest conditions was investigated. Single tree methods were tested on temperate deciduous trees, including coppice individuals [35], heterogeneous mixed stands in boreal forest [205], uneven-aged broadleaved stands [97] or mixed stands [206]. Area-based methods were also tested in various conditions, e.g. broadleaved [207], mixed [208, 209], mixed multilayered forest [210]. In complex stands, such as mixed deciduous ones, the forest structure was more difficult to characterize [211]. Additional LiDAR-derived attributes were proposed to address this issue in multilayered forests [212].

Alpine environments were also investigated. The effect of footprint size and sampling density [213], topographic factors [214] on individual tree delineation were evaluated. Major works include the retrieval of canopy structure from LVIS data in montane forests [154], estimation of tree heights in sugi (*Cryptomerica japonica*) plantations [215]. Single tree [206] and area-based [209] methods were tested on forests stands located in Germany. Studies also tried to define simple indices able to predict stand parameters at operational scale [151, 204, 216–218] (figure 3b).

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