8

Characterization of Forests with LiDAR Technology

8.1. Introduction

Forest surfaces on a global scale represent one-third of the world land area [HAN 10]. Human civilizations have always interacted closely with these ecosystems, notably through the broad range of environmental services that they provide: protection of water resources, soil protection, mitigation of the excesses of local climate, reduction of impacts of gas emissions, and conservation of natural habitat and biodiversity [ALE 97]. Apart from these environmental services, forests are also of interest to the social life of these civilizations, especially through economic and recreational functioning, as well as their cultural dimension. This interest in forest ecosystems results, in particular, in a desire to monitor or even control them. In the 20th Century, the advent of aerial and satellite imagery revolutionized the traditional image of the forestry officer, patiently counting and measuring his trees on the ground.

Remote sensing technologies provide quick and repeated information about extensive areas, which cannot be matched by the scale of perception of an individual on the ground. The first applications of remote sensing to forestry were based largely on passive optical systems such as aerial or satellite imagery (*Landsat Thematic Mapper*, [GOW 97]) or, to a lesser

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extent, on active radar sensors, including ERS, ASAR/ENVISAT, ALOS and RADARSAT [KAS 97].

The lightning development of LiDAR technology during the past 15 years marks a real turning point in the potential of three-dimensional description of forest cover. This three-dimensional description has been valued mainly for the purpose of quantitative characterization of the forest, through the construction of models linking the LiDAR data with conventional dendrometric variables (stand height, basal area, number of stems, biomass, etc.). Within the context of biomass estimation, LiDAR data have enabled successful models of ecosystems with high levels of biomass to be constructed without the saturation phenomenon typically observed with traditional remote sensing data (optical and RADAR data) [KOC 10, ZOL 13].

8.2. The LiDAR technology

The applications of LiDAR technology in forestry can be gathered into two main approaches based on the management of the transmitted laser pulse: full waveform LiDAR and discrete return LiDAR. From a given laser impulse (Figure 8.1), the discrete return LiDAR sensors perform a synthesis of the return signal corresponding to the various surfaces encountered by the beam, this synthesis resulting in a series of points. Full waveform sensors are still less used in forestry [VAN 10]. They store the entire return signal without the loss of information relating to the point discretization stage that is inherent to the discrete return sensors. Full waveform LiDAR sensors detect and record the amount of energy reflected over time, represented in the form of a continuous curve (Figure 8.1).

In addition to the signal management method (discrete vs. full wave return), LiDAR applications are also differentiated by the size of the laser footprint on the ground. One can distinguish small footprints, of less than 1 m and generally corresponding to discrete return sensors, and large footprints, between 10 and 70 m, implemented in full wave sensors [MEA 99]. Given the less frequent use of the second category, the content of this chapter is mainly devoted to small footprint discrete return LiDAR. In order to simplify the reading of this chapter, if authors do not specifically mention the type of LiDAR survey, they refer to small footprint discrete return

LiDAR. For details relating to LiDAR technology itself, the reader should consult [CHA 16] and [MAL 16].

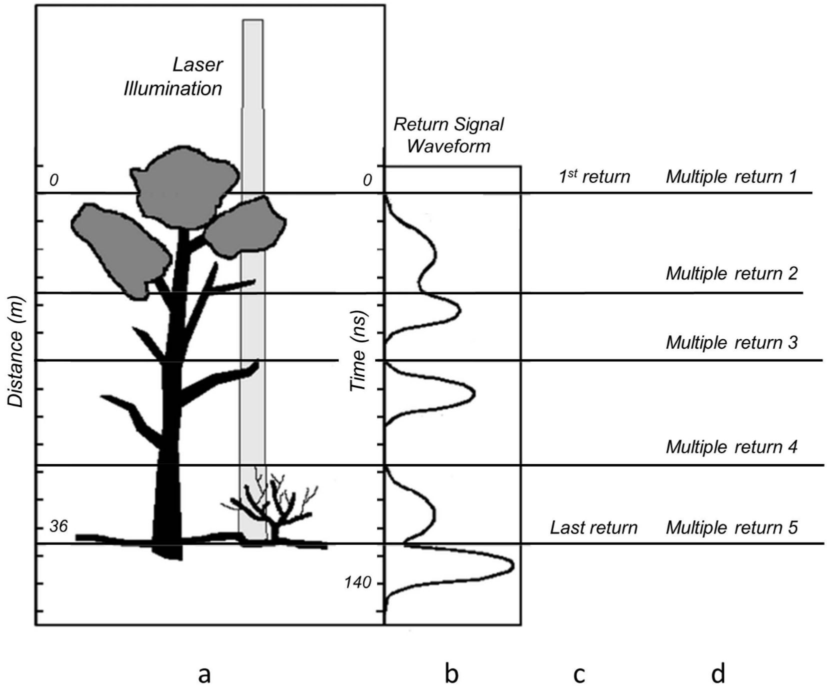

Figure 8.1. *a) Illustration (adapted from [LEF 02]) of various signal management methods for a hypothetical LiDAR impulse on a simplified tree; b) curve representing the return signal as recorded by a full waveform return LiDAR sensor. The succession of peaks and troughs of this curve enable the elements encountered by the laser beam to be identified; c) and d) the discrete return LiDAR sensors perform a simplification of the signal in the form of points corresponding to the main elements encountered by the beam. The systems known as "multi-echo" record not only the first and the last echo, but also the intermediate echoes*

8.3. LiDAR technology in forestry: platforms and applications

The first uses of airborne LiDAR sensors for environmental studies occurred in the 1960s, and involved non-forestry themes such as bathymetry [HIC 69] or the study of sea ice [HIB 75]. These early results mentioned the detection of forests and vegetation, but no special attention was devoted to them. The first forestry applications of LiDAR appeared in the 1980s [ALD 85, ARP 82, MAC 86, NEL 84].

This work was based on profiles captured by an airborne discrete return LiDAR Since these first studies, LiDAR technology was implemented on a wide variety of platforms (Figure 8.2): ground platform (in the case of the terrestrial LiDAR scanner), mobile terrestrial platform, aerial platform (with or without pilot), or on board a satellite. These different possibilities are presented in the following paragraphs and illustrated by four applications (Figure 8.2). These applications are representative of the use of LiDAR technology in forestry for the diffirent study objectives (mapping, resource inventory, ecological monitoring) in relation to platform and investigation scale (local < regional < global).

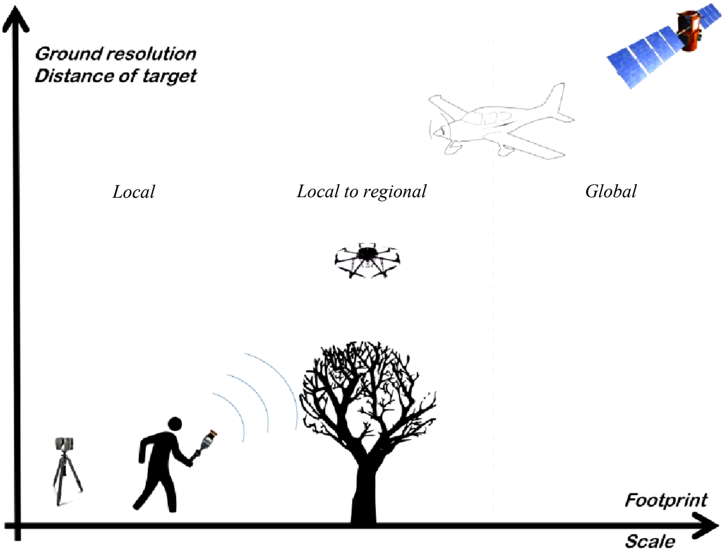

Figure 8.2. *The various platforms able to use LiDAR technology based on spatial resolution (ordinate axis) and scale of application (abscissa): from left to right, fixed and mobile terrestrial LiDAR scanners, aerial (drone and traditional aircraft) and satellite scanners*

8.3.1. *Satellite LiDAR : example of an ICESat project*

8.3.1.1. *State of the art*

The ICES at satellite (*Ice, Cloud and land Elevation Satellite*) was launched by the National Aeronautics and Space Administration of the United States (NASA) in 2003, and is currently the most important operational mission of a spatial LiDAR sensor. This satellite was equipped with a full waveform LiDAR and large footprint sensor (GLAS – *Geoscience Laser Altimeter System*). The GLAS sensor was operating discontinuously from 2003 to 2009. The main mission of the satellite involved mapping the thickness of the polar icecap, studying the altitude of the Earth's surface and observing the quantity of aerosols. Nevertheless, the sensor collected almost 250 million LiDAR beams relating to forest areas. These beams were acquired on the basis of rapid and occasional impulses (5 ns) covering the entire surface of the Earth discontinuously. The footprint of the GLAS LiDAR beam has a width of almost 70 m, the beams being spaced apart by a distance of around 170 m [LEF 10].

The data obtained from the ICESat project aroused enthusiasm amongst the forestry scientific community. It was valued in a number of studies mainly concerned with estimating the height of the forest cover, and the biomass contained within these ecosystems.

Lefsky *et al.* were the first to produce estimates of biomass with the aid of models based mainly on the maximum height, extracted from GLAS data, within temperate (United States) or tropical (Brazil) forests. The height and biomass estimation models constructed as part of this first study achieved a performance (R^2) ranging from 59 to 68%, with a biomass model whose R^2 was 73% in the case of Brazilian tropical forests. Using similar methods in temperate forests, the introduction of topographical indices into some of these models has significantly improved predictive performance [DUN 10, LEG 07, ROS 08].

The spatially discontinuous GLAS data were combined with other sources of data (ground-based and remote sensing) in order to obtain models enabling the modeling of height and forest biomass on a regional scale. Boudreau *et al.* [BOU 08], for example, combined the GLAS data with data obtained from airborne LiDAR sensors, satellite data (Landsat and SRTM – *Shuttle Radar Topography Mission*) together with thematic data aimed at establishing a biomass map on the scale of Quebec (1.3×10^6 km²). Similar methods were also carried out on more restricted areas by Simard *et al.* [SIM 08] and Nelson *et al.* [NEL 09] in Colombia (1.3×10^3 km²) and in Siberia (8.1×10^5 km²). The method developed by Simard *et al.* [SIMS 08] shows originality in basing its models exclusively on a combination of SRTM, GLAS data and reference biomass field measurements without the use of optical satellite data.

The “methodological leap” of making a world map of forests using ICESat data was realized by Lefsky [LEF 10] and Simard *et al.* [SIM 11], who produced a map of the height of the world’s forests at a resolution of 500 m. The results obtained by these two studies summarized in application no. 1 (section 8.3.1.2). More recently, these methods have been extended by Baccini *et al.* [BAC 12] and Saatchi *et al.* [SAA 11], who produced forest biomass maps on a pantropical scale. The models used were built on ICESat data and a network of biomass data collected in the field; 4079 plots; in the case of Saatchi *et al.* [SAA 11], and 283 for Baccini *et al.* [BAC 12]) mainly combined with MODIS (500 m) and SRTM (90 m) data. The accuracy of these global approaches on a regional scale is, however, called into question by the literature and still needs improvement [GUI 15, MAR 14, MIT 14].

The encouraging results obtained with the ICESat satellite have convinced NASA to get to work on an improved version of this: an ICESat 2 satellite should be launched in October 2017, for a period of 15 years. However, the purpose of quantification of biomass will again not be central to the mission, causing certain limitations to the applications in this field [GOE 11].

8.3.1.2. *Application 1: forest height on a global scale*

The work of Lefsky [LEF 10] and Simard *et al.* [SIM 11] led to the publication of a first comprehensive mapping of forest height using data obtained from the GLAS LiDAR sensor on board the American ICESat satellite. Over the course of seven years (2003-2009), the GLAS LiDAR mission (fullwave form sensor) collected almost 250 million LiDAR beams in forest areas. Lefsky’s study [LEF 10] is based on a forest height model combining spatially discontinuous LiDAR data with various spatially continuous worldwide databases (see Figure 8.3). Besides LiDAR data from the GLAS sensor, this study also relies MODIS data (resolution 500 m). Simard *et al.* [SIM 11] undertook a similar project, combining the same MODIS data with other sources of global and spatially continuous data including the *Worldclim* database (meteorological data), SRTM, protected areas maps, etc.

These studies have led to the first height maps forest environments on a global scale (500 m resolution), according to a method that is unified both in terms of input data and the way in which it is processed (Figure 8.3).

Lefsky [LEF 10] summarizes the extreme forest height values observed, while emphasizing the fact that the estimated height corresponds to the height of the 90th percentile of the heights of trees in the forest patch mapped. As expected, the tallest forest stands are located on the western coast of North America. They consist of conifers such as Sequoia (*Sequoiadendron giganteum*) and Douglas Fir (*Pseudotsuga menziesii*). The observed average heights often exceed 40 m, with some individuals reaching 70 m or higher. The boreal forests of northern Asia, with average heights consistently below 20 m, make up the forest formations of lowest height.

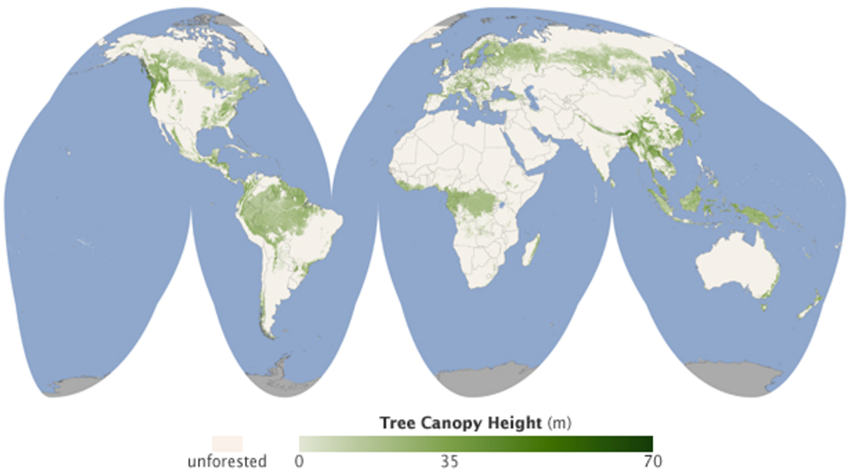

Figure 8.3. *Heights of world forests – the first global map of the heights of the world's forests (0–70 m), derived from the work of Lefsky [LEF 10]. Source: http://www.nasa.gov/topics/earth/features/forest-height-map.html. For a color version of this figure, see www.iste.co.uk/baghdadi/3.zip*

8.3.2. *Airborne LiDAR*

8.3.2.1. *State of the art*

The first forest applications of airborne LiDAR focusing on forest structure description and quantification were developed by Arp *et al.* [ARP 82] in Latin America (Venezuela), by NASA in Pennsylvania [NEL 84] and by the forest services of Canada [ALD 85, MAC 86]. These first studies were limited to a local level, centered on an individual flight line along which vertical profiles were extracted. The emergence of kinematic GPS positioning systems coupled with inertial stations led to the development of scanning sensors (scanning LiDAR), the referencing and merging of different frames of acquisition [WEH 99], as well as the acquisition of spatially continuous LiDAR surveys. In addition to the constantly decreasing costs, the improvement in the referencing of LiDAR acquisitions, coupled with various technological advances (accuracy of GPS, quality of inertial stations, increase in transmission frequency, storage capacities and in-flight processing) has led to the expansion and commercial success of LiDAR technology over the last twenty years [LIM 03, MAS 14].

Since the earliest studies, researchers have tried to enhance the information obtained about the canopy surface and the ground, but also about all the elements of the various vegetation layers in between the ground and the top of the canopy. The purpose was generally to test the link between the variables derived from LiDAR data and the height, biomass or marketable timber volume [ARP 82, MAC 86, NEL 88]. These pioneering studies formed the basis of many others which, during the 1990s, confirmed LiDAR as a source of input data for numerous characterization and quantification models on a tree or plot scale. In addition to the general LiDAR derived mapping products (Figure 8.4), which are digital terrain models (DTMs), digital surface models (DSMs) and canopy height models (CHMs), most of these studies synthesize LiDAR data in the form of different point cloud parameters (Figure 8.5). These parameters are extracted at different scales (individual tree < plots (several trees) < entire area studied). These applications involve, for example, elements related to the vertical distribution of points (such as the standard deviation of heights) or the value of the intensity of the returns (as an average). The models produced by these studies have been mainly related to the height of the canopy (as the individual height and the maximum height), the biomass, or any other variable describing the supply of stock of standing timber (such as the basal area and the number of trees per hectare) [LIM 03]. These modeling approaches reached an operational stage thanks to National Forest Inventory data.

Thanks to the data collected in the field at plot level, in national or regional forest inventories, dendrometric models can be calibrated and validated for large areas. Application no. 2 (section 8.3.2.2) describes a regional mapping project of forest structure variables related to the height of the stands (dominant height). This project makes use of an extensive "field" database obtained from a regional forest inventory. It provides a fine example of a forestry application recognizing the importance of LiDAR data as part of a decision support instrument functioning on the scale of a region of 17, 000 km² (see [DED 15] for further details).

In addition to the dendrometric information, LiDAR data makes it possible to evaluate forest ecological parameters, such as the species composition [DON 07]. In this context, the intensity value of the return signal can be interesting if a normalization is performed between the various lines of flight [KOR 10]. Due to the information that it contains in relation to the vertical structure of the forest cover, LiDAR data present valuable input data for the detailed modeling of forest species habitat [GOE 10, NEL 05, VIE 08]. It is also used in the evaluation of the ecological integrity of forest ecosystems [JOH 10, MIC 13]. Application no. 3 (section 8.3.2.3) summarizes a case study carried out on the characterization of the ecological integrity of riparian forests on the basis of an airborne LiDAR dataset.

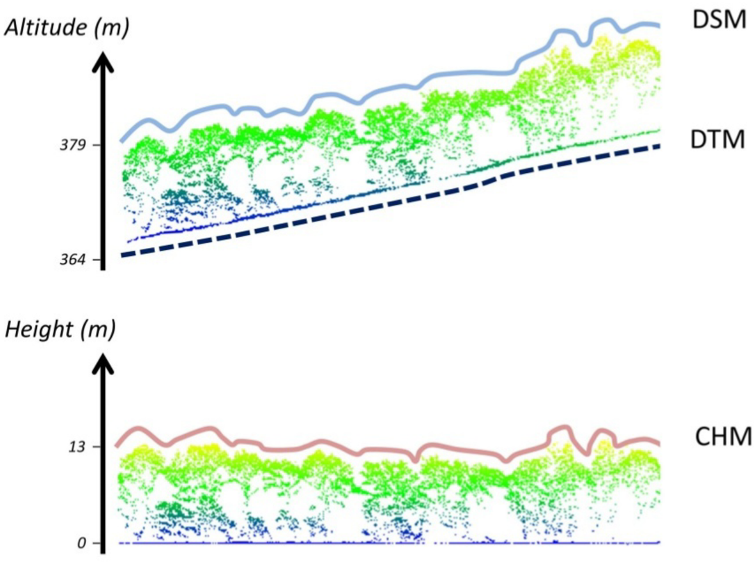

Figure 8.4. *Examples of LiDAR products used in forestry: digital terrain model (DTM), digital surface model (DSM) and canopy height model (CHM). The CHM is the nomalization of the point cloud by means of the DTM. The illustration is based on a discrete LiDAR dataacquired from an airborne. For a color version of this figure, see www.iste.co.uk/baghdadi/3.zip*

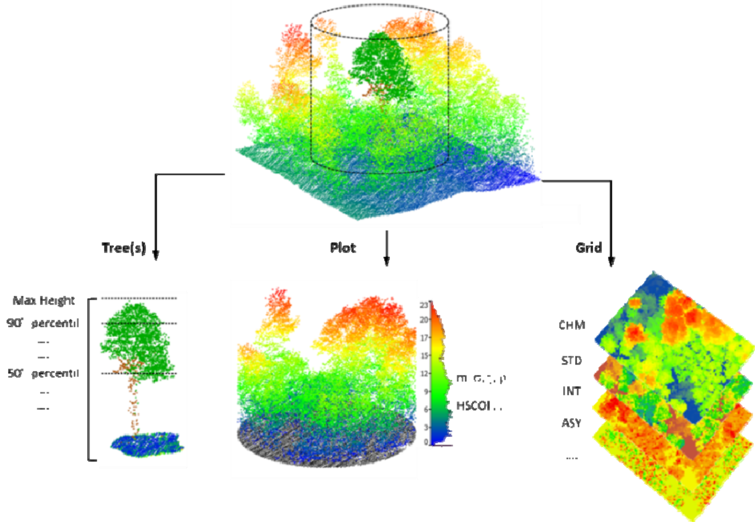

Figure 8.5. *The extraction of variables derived from a LiDAR point cloud can be perfomed at three levels: single tree, tree plot (e.g. circular one) and continuous grid (raster data). These variables, also known as metrics, are mainly statistical parameters calculated on the basis of the distribution of the height of the points: maximum height, height percentile (90th, 50th…), mean (m), standard deviation (STD or σ), kurtosis (γ), skewness (ASY or ρ). The signal intensity (INT), or the number of returns, can also be used in addition to the height. More complex parameters, such as Height-Scaled Crown Openness Index (HSCOI) [LEE 07], can also be implemented. The HSCOI is based on the concept of voxels, and represents a measure of the porosity of the canopy. In the case of a tree or a plot, these variables are calculated for the entire point cloud under consideration. In the case of a raster, these same variables are computed at the level of the pixel. For a color version of this figure, see www.iste.co.uk/baghdadi/3.zip*

8.3.2.2. *Application 2: regional characterization of forests, a case of dominant height in Wallonia, Belgium*

Sampling field inventory still the main source of information for the characterization and monitoring of forest resources.

They generally involve taking dendrometric measurements (diameter at breast height, total height, etc.) of trees within a set number of plots of several acres. These measurements provide variables to describe standing volume stocks, the stand structure, the health condition... The repeating of some measurements over time also makes it possible to calculate indicators of evolution of the timber resource and estimate its production.

The capacity of LiDAR to capture the three-dimensional structure of vegetation has opened up the way for extensive research into the description and quantification of forest environments. In particular, the exploitation of airborne LiDAR data has been an answer to the significant costs of data field acquisition by an individual. The accuracy of dendrometric variables derived from LiDAR data (mainly height) can be considered as equal to, if not better in the case of height, those obtained from field inventory methods [NAE 04, MAL 09].

The Wallonia public services (southern Belgium) have a complete coverage of the area (≈17,000 km²) with airborne LiDAR data of a density of the order of 1 ground classified point/m². On the basis of the raw LiDAR point cloud, two models have been produced with a spatial resolution of 1 m: a DTM describing the elevation of the ground in each pixel, and a DSM describing the altitude of elements present on the ground surface. Subtraction of these two layers enables the production of a CHM. The CHM obtained from LiDAR data represents the maximum height reached by the vegetation in each pixel (Figure 8.4), offering a height measurement of the canopy.

The dominant height is an indicator widely used by forest managers, mainly in forest stands with uniform structure. It is defined as the average height of the 100 largest trees per hectare [RON 93]. Combined with the stand age, it provides a very good indication of the productivity (site index). It can also be involved in the estimation of standing timber volume.

On the basis of the CHM produced on the scale of Wallonia, the dominant trees were identified by the detection of local maxima [POP 04], which assumes that a local maximum of the CHM corresponds to the apex of a tree (Figure 8.6).

An estimation model of the dominant height was produced using the height values of these local maxima, linking them to field height estimations. These total height measurements were conducted on a sub-sample of the plots of the Walloon Regional Forest inventory. The dominant “field” height is consequently based on the average of the 100 highest local maxima per hectare, to which a constant is added. This may be considered as a correction of the underestimation of the dominant height. This underestimation is explained by the fact that the laser impulse rarely reaches the exact position of the apex of the dominant trees, but a part of the crown located on average 1 m lower in the case of spruce, and 1.3 m in the case of Douglas firs. Further analysis of the models failed to show any effects of the slope of the ground or the stand age.

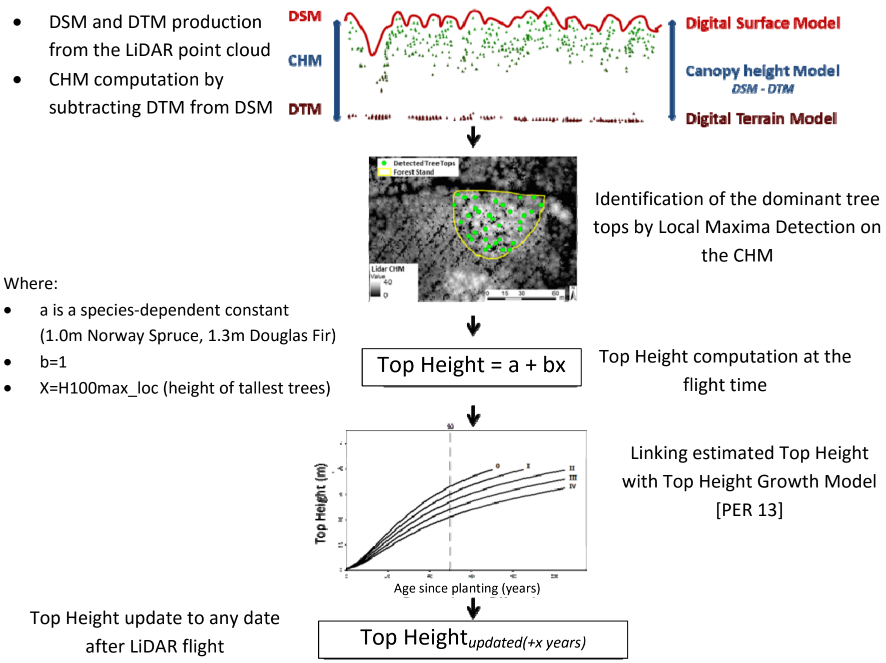

Figure 8.6. *Modeling of the dominant height of Walloon coniferous forests (≈17,000 km²). The dominant height at the time of the LiDAR acquisition is extracted from the point cloud by means of the CHM. The dominant height is then updated by using height growth model. See Dedry et al. [DED 15] for further details*

In order to facilitate the use of this model, it was integrated into the open source environment QGIS (GIS software) throughout a plug-in which dominant height estimation was combined with a growth prediction model to update dominant height [PER 13]. On the basis of information linked to the nature and age of the stand, the plug-in also provides an estimation of productivity in the form of a *Site Index*, corresponding to the dominant height reached at 50 years old.

This example describes how a low density LiDAR dataset, acquired on a regional scale, can be used to characterize the productivity of even-aged coniferous stands. The importance of airborne LiDAR in this application resides in its capacity to deliver useful indicators on a scale adapted to stand management. This kind of application is becoming an accepted addition to the inventories obtained by traditional sampling carried out in the field; in some countries, LiDAR is already used in operational terms for forest inventories [WHI 13, NAE 07, MAL 11, WOO 11].

8.3.2.3. *Application 3: ecological integrity of riparian forest in Wallonia*

As well as locating and describing forest vegetation as a timber resource (height, volume, biomass...), LiDAR data can also provide information relating to the functioning of the ecosystem, such as the ecological integrity.

The concept of ecological integrity can be described as the degree of integrity of a given environment in relation to its capacity to assume all the ecological functionalities associated with it. This application describes how, based solely on indicators derived from LiDAR datasets with a high point density (>40 points/m²), the ecological integrity of riparian forests may be characterized on a scale that corresponds to a river system of almost 30 km (Table 8.1). The indicators are constructed from spatial analysis of various parameters directly extracted from the LiDAR point cloud: (e.g. CHM and DTM) in order to characterize riparian forests as well as various variables relating to the morphology of the watercourse, such as the water surface and the width of the valley bottom. As an example, Figure 8.7 represents the evolution of the density of the forest cover dominated by exotic conifer stands in the Houille Valley (Namur Province, Belgium). It highlights the presence of coniferous stands at a distance less than the statutory distance of 12 m (*Natura 2000* protection status) on virtually all the study area. Furthermore, the most important rise of density in coniferous stand is recorded within an area of great biological interest.

Riparian forest parameter	Indicator of ecological function
Longitudinal continuity	Dispersion corridor for plants, habitat and migration area for birds and mammals
Overhanging riparian forest	Effect of shade, regulation of temperature, habitat creation and nutrient supply
Density of coniferous stands	Reduction in the stability of riverbanks and biodiversity
Floodplain height above water level	Frequency of flooding, proximity of the water, directly related to the specificity and diversity of riparian area
Riparian forest height (average, variation coefficient)	Location of mature stands (average height); spatial diversity (high variation coefficient) in relation to species diversity

Table 8.1. *Indicators of ecological integrity of riverside forests derived from a LiDAR point cloud (adapted from Michez et al. [MIC 13])*

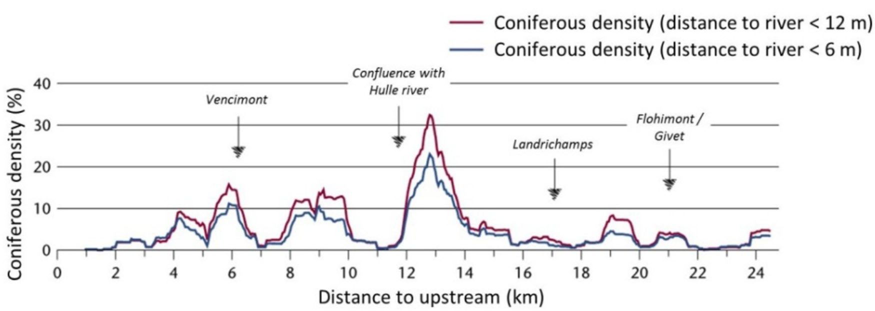

Figure 8.7. *Density of the forest cover dominated by exotic conifer stands (mobile average over 1 km) in the Houille Valley (50°N 4°58E, Namur Province, Belgium) in February 2011 – adapted from Michez et al. [MIC 13]. Abscissa: density of conifers. Ordinate: distance in relation to the upstream point of the study (Gedinne). In italics, particular points along the watercourse studied. For a color version of this figure, see www.iste.co.uk/baghdadi/3.zip*

LiDAR data also make it possible to obtain valuable information about the "topographical proximity" of riparian forests. Such information, in relation to the watercourse and thereby the riparian character, enables us to distinguish the riparian forest from the neighboring stands. The floodplain height above water level (Figure 8.8) was developed in order to express, for a specified part of the riparian forest, its proximity with respect to the base of the riverbank. As well as being an indicator of the typical characteristics of riparian forests, this parameter also provides information on the physical condition of the riverbank and the modified character arising from this. The two cases shown in Figure 8.8 represent contrasting scenarios along the study site. The first scenario (Figure 8.8(a)) corresponds to a section with a higher mean height above water level, following an artificial reshaping of the watercourse and its banks. The second scenario (Figure 8.8(b)) corresponds to a more natural situation, with a lower mean height above water level, and thus a riparian forest in much closer contact with the watercourse.

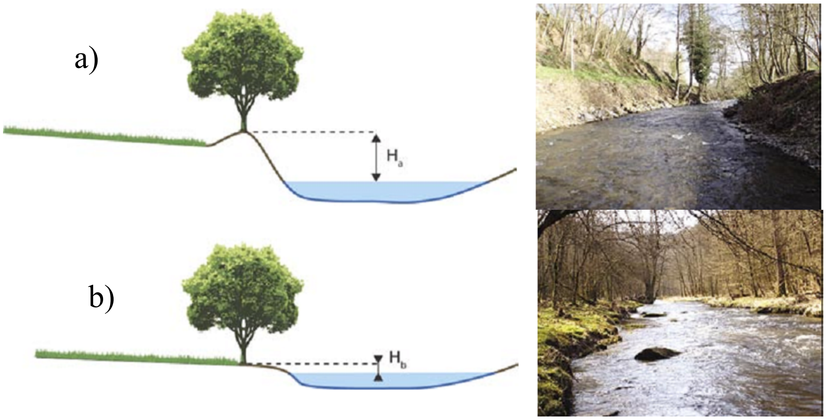

Figure 8.8. *Two contrasting scenarios of height above water level: Ha > Hb*

8.3.3. *Terrestrial LiDAR*

8.3.3.1. *State of the art*

The use of the terrestrial LiDAR scanner (TLS) in forests follows the introduction onto the market of portable LiDAR scanners with a range exceeding 10 meters [DAS 11]. The difference of TLS compare to other LiDAR systems are its static configuration (system attached to a tripod), the absence of an inertial unit and its capacity to measure the surrounding areas in 3D with millimeter accuracy. There are two categories of TLS, which differ in their measurement methods of the distance traveled by the LiDAR laser: the time of flight (*tof*) TLS and the phase-shift TLS. These two systems differ mainly in the time required to acquire a given resolution (higher for phase-shift TLS), signal range (higher for the *tof* TLS), as well as the type and accuracy of the information collected. Both record the position where the laser is reflected, but some tof TLS may record several returns of one emitted signal or even the full waveform of it, whereas phase-shift TLS record only one return. Moreover, phase-shift TLS suffer from the mixed pixels (ghost points) and range/intensity cross talk effects which may limit the accuracy of the points at the edge of objects. These two systems are explained in more details in Petrie and Toth [PET 09].

TLS technology has quickly established itself as an additional remote sensing tool besides aerial or satellite remote sensing systems the use of TLS in forests can provide a relatively accurate three-dimensional description of the surrounding ecosystem from the ground (Figure 8.9). The forestry sector is starting to be more and more interested by this technique since it makes it possible to acquire non-destructive three-dimensional data on trees or groups of trees with unprecedented precision. The parameters collected or derived from data obtained from TLS can be dendrometric (position, diameter, height, crown radius, volume and biomass of trees) or ecological (leaf area index, distribution of gaps, foliar distribution, distribution of micro-habitats), or even ecophysiological (interaction between the light and the canopy). Some of these parameters are difficult or even impossible to collect by traditional inventory or measurement methods.

The use of TLS as a tool for forest inventory is detailed in the following section. For more information on other uses of this technology in forest environments, we recommend the synthesis work of Dassot *et al.* [DAS 11] and Van Leeuwen and Nieuwenhuis [VAN 10].

8.3.3.2. *TLS as a tool for forest inventory*

The estimation and spatialization of parameters such as timber volume or biomass using aerial or spatial remote sensing data first require a calibration and validation phase. The calibration stage consists of developing models relating attributes acquired or generated by remote sensing to forest parameters deduced from measurements carried out in the field (basal area, volume and biomass).

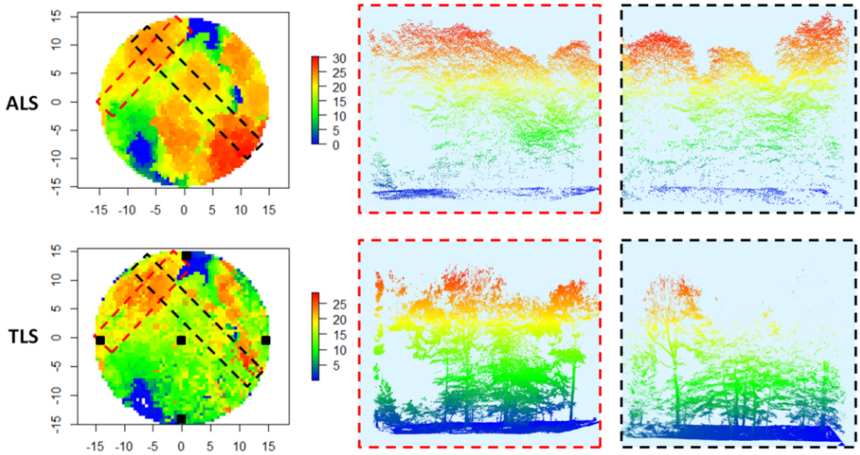

Figure 8.9. *Canopy height models (CHMs) (in m) of an uneven deciduous forest extracted from airborne LiDAR scanning (ALS) and terrestrial LiDAR scanning (TLS). Above, illustrations are derived from CHM and point cloud profiles of high density ALS data (≈45 points/m²). Below, the illustrations are based on data from five TLS scans of a FARO Focus 3D 120 (black squares). For a color version of this figure, see www.iste.co.uk/baghdadi/3.zip*

The samples used in the calibration of models are taken from plots in which various measurements have been carried out on the trees. The most commonly recorded measurements in a conventional field inventory are species, diameter at breast height (DBH) and height. These measurements are then used, by means of allometric equations [8.1], [8.2], to estimate parameters such as timber volume or above-ground biomass. The biomass of a standing tree is then estimated indirectly by means of an equation. This equation is defined either (1) for one species, by relating biomass to one or two parameter(s) measured in the field, such as the DBH (equation [8.1] illustrates the type of equation commonly used in temperate forests [ZIA 05]), or (2) for multiple species integrating other parameters such as tree height and basic wood density (an example of equation [8.2] which is generally used in tropical forests [CHA 14, CHA 05]).

$$AGB = a\ DBH^b \qquad [8.1]$$

$$AGB = a\ (DBH\ \rho H)^b \qquad [8.2]$$

with AGB, which represents the above-ground biomass (kg), DBH is the diameter at breast height (cm), ρ is the basic wood density (g/cm³), H

is the total height of the tree (m), *a* and *b* are statistically adjusted parameters.

TLS offer the possibility of conducting most of these measurements in the field (DBH, height and location of trees) in a way that is objective, accurate and repeatable. It also opens up the possibility of improving the timber volume estimates by a direct estimate of the volume through adjustment of cylinders along the trunk [RAU 13] instead of the indirect estimates with allometric equation. The improvements may also arise from a number of additional parameters that can be measured on each tree making of the plot (diameter at various heights, taper, volume of a section of trunk...). These parameters could ultimately serve as additional input for allometric equations.

The three-dimensional scan of a plot using TLS is carried out according to one of the following three acquisition methods: single-scan, multi-scan and multi-single-scan.

Single-scan involves acquiring one scan of the plot by placing the scanner at its center. The acquisition time is thus minimal (a few minutes). On the other hand, with only one point of view, it does not provide a complete observation of the plot, since some trees or parts of trees are out of the scanner's field of view: this is the occlusion effect. Multi-scans reduce the occlusion by carrying out scans at various places within the plot. However, this approach requires artificial references in the plot (reflective targets or simple geometrical elements: cylinders or spheres) in order to combine the scans. Setting up these reference elements is time-consuming because they must be placed so as to be visible from several positions of the scanner. Finally, the third method, multi-single-scan, involves making several scans of the plot and combining these scans without the use of artificial references, but by using the position of the trees detected on each individual scan [LIA 13]. This method assumes that the base of the trunks have circular cross-sections, with an assumption that is not encountered in all kinds of forests (for example: temperate and tropical deciduous forests).

The point cloud obtained from (x) scans of the plots is then processed automatically or semi-automatically in order to extract the desired dendrometric parameters. An example of the required processing stages for the extraction of these parameters is shown in Figure 8.10. It should be noted that the volume and the biomass of a plot remain difficult to estimate automatically, since the detection of trees, the mitigation of occlusions and the species determination still need improvement, especially in tropical forests. The case study (application 4) shown below illustrates one possible solution to the mitigation of the occlusion effect by using mobile LiDAR scanning.

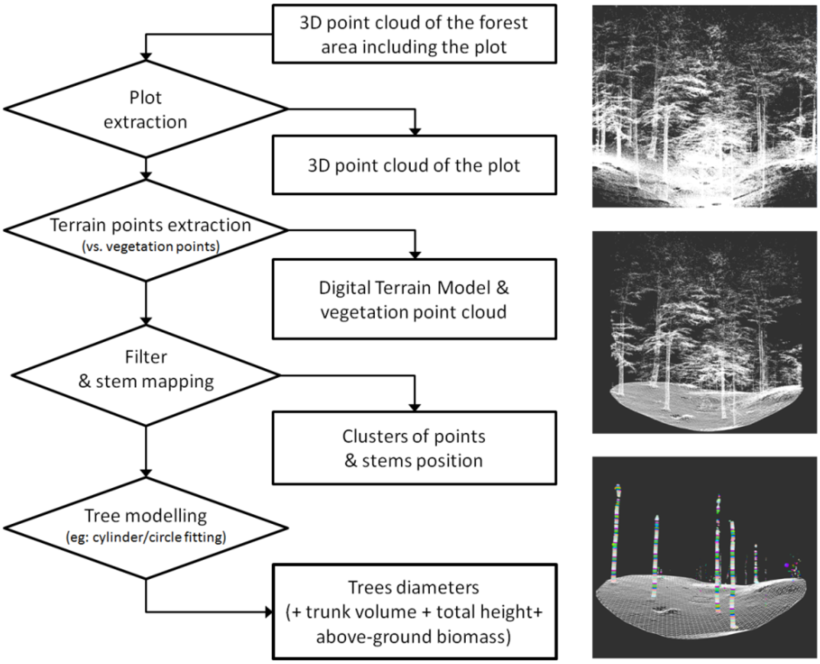

Figure 8.10. *TLS processing stages for the extraction of dendrometric parameters. (1) Extraction of plot within the point cloud, (2) separation of "ground" points from "vegetation" points (generation of DTM), (3) filtering vegetation points (cluster of points and stems positions), (4) tree modeling (cylinder/circle fitting) of clusters identified as one tree for the extractions of diameters as the DBH (+ total height + trunk volume) and, by means of allometric equations, the estimation of above-ground tree volume or biomass*

8.3.3.3. *Application 4: ground-based LiDAR scanner in forest inventories, comparison of acquisition methods*

In recent years, the use of a mobile terrestrial platform has gradually emerged as an alternative to the TLS for forest plots scanning [LIA 14a, LIA 14b, RYD 15]. In fact, the mobile character of the scanner has the advantage of minimizing the occlusion phenomenon and covering a wider area in a given time. The study presented in this section aims to evaluate the potential of the portable MLS as an alternative to the traditional acquisition methods of single-scan and multi-scan. The three acquisition methods tested are thus the single-scan (FARO1 method), multi-scans with five scanner positions, including a central one (FARO5 method) and the mobile scan (ZEB1 method). The names of the methods refer to the scanners used: the FARO Focus 3D 120 for the TLS and the ZEB1 of Geoslam for the MLS. The scans were carried out on 10 circular plots (15 m radius), which differ in terms of forest type (deciduous, coniferous or mixed), stand structure (coppice, even-aged or uneven-aged forest) and topography (flat or sloping ground). The processing was carried out using the Computree open-source sofware (plug-in ONF/ENSAM).

The occlusion effect, which results in partial three-dimensional information of the scanned trees, is more or less an issue according to the acquisition method. In order to evaluate the importance of this occlusion in three scanning methods, a slice 10 cm thickness at a height of 1.3 m above ground level was carried out on the point cloud for each trees of the plots (DBH >10 cm). The trees were then classified regarding the proportion of the scanned section (Figure 8.12).

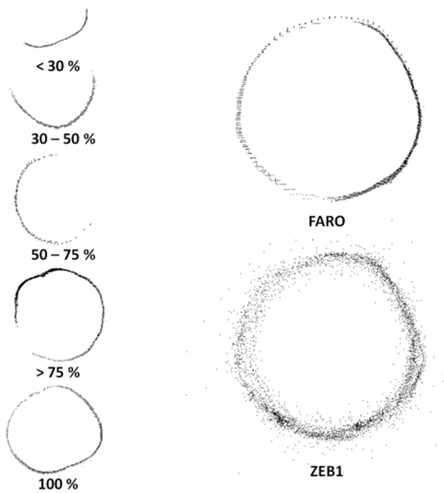

Figure 8.11. *Cross-sections of the scanned trees at a height of 1.3 m above ground-level. On the left, percentage of the cross-section closure. On the right, the precision of positioning of the scanning points for the two technologies used in the study (terrestrial LiDAR scanner: FARO Focus 3D 120; portable mobile LiDAR scanner: ZEB1) is presented*

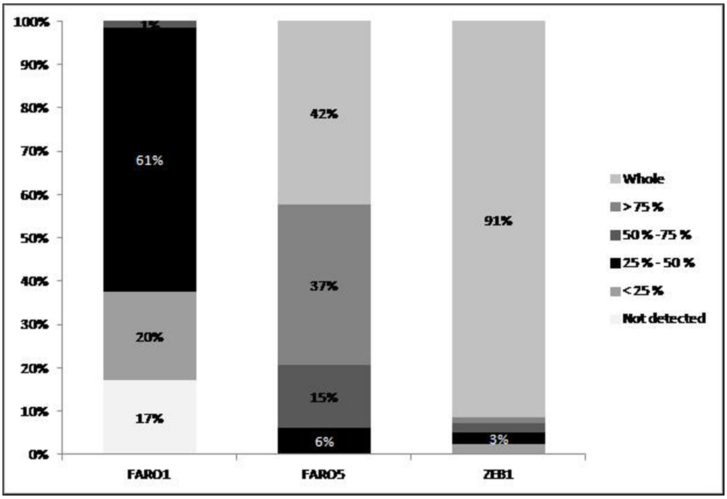

Figure 8.12. *Percentage of the cross-section closure between the three different scanning methods according to the visual interpretation of the point cloud slices at 1.3 m height (thickness of 10 cm) of the eight plots, according to the three acquisition methods: single-scan (FARO1), multi-scans (FARO5) and mobile LiDAR scanner (ZEB1). For a color version of this figure, see www.iste.co.uk/ baghdadi/3.zip*

The estimation of diameter at 1.3 m is, on average, good for multi-scan and MLS acquisitions (bias lower than −0.2 cm and RMSE lower than 1.5 cm in the case of this study) and acceptable for single-scan acquisitions (bias of −1.2 and RMSE of 3.8 cm) for trees detected automatically. However, for the single-scan method, a significant number of the trees are missed (17% in this study; see Figure 8.12). The estimation of forest parameters thus remains limited for this acquisition method. Despite its lower scanning accuracy (Figure 8.11), MLS seems to be a good alternative for the scanning of forest plots, since it leads to diameter estimations similar to those of the multi-scans method, while being more efficient in the field (average acquisition time of 25 min as opposed to 1h 15 min for the multi-scans method). Moreover, the higher coverage of the plots by MLS (better completeness of sections at a height of 1.3 m, Figure 8.12) should provide a better adjustment of the cylinders for trunk volume estimation. Portable MLS should therefore rapidly become a future technology for three-dimensional data acquisition of the forest from the ground.

8.4. Future of LiDAR technology in forestry?

The contribution of LiDAR technology towards the characterization of forest ecosystems is now very widely documented in the literature. The use of LiDAR data have made it possible to obtain estimates of tropical forest biomass with a greater accuracy than ever before [KOC 10]. In the field of forestry, several prospects are worth highlighting, as much for their technological evolution as their method of implementation.

8.4.1. *Technological evolution*

The constant miniaturization of LiDAR sensors is especially encouraging. Several business solutions are now available, involving LiDAR sensors of less than 1 kg in weight and with an operating range of a 100 m (for example, the Velodyne HDL32E and VLP16 LiDAR). Some slightly heavier sensors, but whose mass does not prohibit mounting on an Unmanned Aerial Vehicle (<4 kg) are also being marketed (for example, the Riegl VUX-1). This has a more suitable operating range for forestry applications (flight altitude of 300 m), notably in the case of resource inventories. However, few studies that highlight these newly commercialized LiDAR solutions are currently available [PFE 14, TUL 14]. On a trial basis, some projects have been developed with LiDAR scanners embedded within a UAV (multirotor type), particularly for scanning trees: Lin *et al.* [LIN 11] as well as Wallace *et al.* [WAL 12]. These projects are still very experimental, however, and function over restricted areas (several trees, or perhaps a stand) and further research is required to integrate this technology on a more operational basis.

Furthermore, the recent coming of “flash LiDAR”, also known as *Photon Counting Lidar,* could further improve the implementation of LiDAR in a UAV. Functioning in a similar way to a camera (instant recording of photons returning from a LiDAR beam split into different directions by a lens), these sensors have a lower weight and energy consumption than that of traditional LiDAR scanners. This type of system will equip the future satellite ICESAT 2 [MOU 14]. It could potentially be installed on UAV platforms, or on mobile terrestrial LiDAR scanners. Several general pilot studies have already been undertaken [DUO 12, ZHO 12].

8.4.2. *Multispectral LiDAR and combination of ALS LiDAR data with optical data*

The late 2000s saw the emergence of several projects combining the simultaneous acquisition of airborne LiDAR data with other data types, especially from spectrometers. Among these, the results obtained by the Carnegie Airborne Observatory of Stanford University (United States) [ASN 12, ASN 07] proved to be very promising in terms of detailed characterization of complex ecosystems, such as the species composition in tropical rain forests [SOM 15] or the study of ecological traits of forest species on a regional scale [ASN 14].

Multispectral LiDAR systems also constitute an interesting prospect. Given that bathymetric LiDAR sensors have already been using two spectral bands (one green LiDAR sensor and one near-infrared LiDAR sensor) for many years, the multispectral character is not an innovation in itself. The acquisition of a "colored" point cloud on the basis of the information recorded by a combination of LiDAR sensors with different emission frequencies provides a convincing three-dimensional and colored view of the forests observed. The whole colored point cloud could thus provide spectral information about all vertical layers of forest ecosystems (dominant and dominated vegetation), comparable with that obtained using passive remote sensing methods on the canopy, but not limited by the light conditions. This development prospect would facilitate numerous applications, especially regarding a more detailed characterization of the forest vegetation structure (wood vs. leaves, species composition etc.), even for the vegetation beneath the forest cover. Pioneering studies have modeled and tested experimental prototypes with encouraging results. [MOR 09, WAL 14]. The first systems are now available on the market (Optech Titan) and cover three spectral bands, one in the visible region (532 nm) and two in the infrared (1064 and 1550 nm).

8.4.3. *Towards a global mapping of world forests using LiDAR data?*

Whether aerial or satellite, the importance of LiDAR data for the characterization of forest biomass is widely documented in the literature. Comprehensive studies of forest biomass (notably [BAC 12, SAA 11]) have thus far been confined to the spatial extrapolation of LiDAR data obtained from the ICESat satellite. Since ICESat satellites are not operational anymore, any improvement in these results will involve an intensifying of the information on the vertical structure of forests. The ICESat 2 satellite (http://icesat.gsfc.nasa.gov/icesat2/) will make it possible to obtain a new spatially discontinuous coverage of the world's forests by 2017. However, this project, still hypothetical and not specifically dedicated to the study of forests, would only provide a limited improvement on these first models [GOE 10, GOE 11]. The GEDI mission (http://science.nasa.gov/missions/gedi/) of NASA could also offer data in addition to the ICESat 2 satellite, with its main objective being the mapping of biomass by 2018.

Another emerging issue in the scientific community is the coverage of tropical forests using airborne LiDAR data. This application, especially promoted and evaluated by Mascaro *et al.* [MAS 14], would make it possible, in four years, to obtain a global coverage of tropical forests using high resolution airborne LiDAR data, with a budget that represents barely 5% of the United Nations REDD program budget (*Reducing Emissions from Deforestation and Forest Degradation*).

8.5. Key points

LiDAR is an active remote sensing technology that makes possible the characterization of the forest vertical structure on scales ranging from an individual tree to the world's forests.

The first technological developments took place in the early 1980s, but its use on an operational basis has only been going on since the 2000s, particularly in support of national forest inventory projects (in Canada, Finland, etc.).

In forestry, LiDAR technology is generally used for the estimation of dendrometric variables (heights, basal areas, timber volume, biomass...) but also for more qualitative characterizations (species composition, ecological integrity of forest ecosystems, health condition...).

LiDAR makes it possible to estimate the biomass in tropical forests, where there are significant standing stocks, without the saturation phenomenon typically observed using traditional remote sensing data.

The costs of acquisition represent the main limitation to the development of the large-scale use of LiDAR in forestry.

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