Airborne Laser Scanning to support forest resource management under alpine, temperate and Mediterranean environments in Italy

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Abstract
This paper aims to provide general considerations, in the form of a scientific review, with reference to selected experiences of ALS applications under alpine, temperate and Mediterranean environments in Italy as case studies. In Italy, the use of ALS data have been mainly focused on the stratification of forest stands and the estimation of their timber volume and biomass at local scale. Potential for ALS data exploitation concerns their integration in forest inventories on large territories, their usage for silvicultural systems detection and their use for the estimation of fuel load in forest and pre-forest stands. Multitemporal ALS may even be suitable to support the assessment of current annual volume increment and the harvesting rates.
Keywords: Airborne laser scanning, area-based approaches, individual tree crown approaches, forest management, timber volume estimation, multitemporal ALS surveys.

Introduction
Information about the state and changes to forest stands is important for environmental and timber assessment on various levels of forest ecosystem planning and management and for the global change science community [Corona and Marchetti, 2007]. Standing volume and above-ground tree biomass are key parameters in this respect. Actually, fine-scale studies have demonstrated the influence of structural characteristics on ecosystem functioning: characterization of forest attributes at fine scales is necessary to manage resources in a manner that replicates, as closely as possible, natural ecological conditions. To apply this knowledge at broad scales is problematical because information on broad-scale patterns of vertical canopy structure has been very difficult to be obtained. Passive remote sensing tools cannot help for detailed height, total biomass, or leaf biomass estimates beyond early stages of succession in forests with high leaf area or biomass [Means et al., 1999]. Over the last decades, survey methods and techniques for assessing such biophysical attributes have greatly advanced [Corona, 2010]. Among others, laser scanning techniques from space or

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airborne platforms have developed to the point where they can provide vertical profiles of forest vegetation.

The most widely used system is LiDAR (acronym for Light Detection And Ranging or Laser Imaging Detection And Ranging) based on a laser transmitting short infrared pulses, and a photodiode detecting the backscattered signals. The option mainly exploited to support forestry application is the Airborne Laser Scanning (ALS) based on a LiDAR system mounted on an airplane or an helicopter. On the ground the emitted ALS pulse have a dimension (footprint) generally between 0.2 and 2 meters in diameter while the density of pulses may vary from many returns per square meters to sparser densities [Hyyppä et al., 2008]. Several objects located along the emitted laser pulse path may create multiple reflected echoes. Laser scanner systems measure at least the round-trip time of the first and last pulse while new sensors are capable of recording the full waveform of the backscattered signal [Wagner et al., 2006]. As a result, ALS systems provide a three dimensional point cloud, where over vegetated terrain some of the signals are caused by reflections in the vegetation canopy and some by reflections at the ground surface [Hollaus et al., 2006].

Basic elaboration processes involves the elimination of LiDAR returns identified as below the nominal ground surface or above the expected canopy height, then the remaining LiDAR returns from the ground are separated from those from above ground targets [Donoghue et al., 2007].

The airborne LiIDAR back-scattered signals can be used as they are (i.e. point data or waveform) or they can be spatially interpolated to produce digital models. Signals from the ground are used to produce Digital Terrain Models (DTM) while above ground returns are used to produce Digital Surface Models (DSM). In areas covered by trees the algebraic subtraction of DTM from DSM corresponds to the Canopy Height Model (CHM), which provides a measure of the height of the upper canopy for each forest pixel in the surveyed area [Kraus and Pfeifer, 1998].

ALS data can convey a rich summary of forest features due to their ability to capture the forest heights: the accuracy of retrievable information is highly dependent on both the extrinsic specifications of the ALS survey as well as the intrinsic effects of the underlying forest structures. Most literature concerns applications under boreal environments [Maltamo et al., 2005; Næsset and Gobakken, 2008]. This paper aims to provide general considerations, in the form of a scientific review and commentary discussion, with special reference to selected experiences of ALS applications under alpine, temperate and Mediterranean environments in Italy as example case studies.

Data availability

ALS data most commonly used for forestry applications under alpine, temperate and Mediterranean environments are not produced by dedicated flights: forest technicians simply exploit the raster CHM available at low [Clementel et al., 2012] or even no cost from ALS surveys carried out for purposes other than forest applications. In Italy around 30% of the land has been covered so far for accurate hydraulic modeling. Laser-scanning data are the best information source for this kind of models, that are necessary to prevent damages by floods, as well to assure water resources for people and agriculture.

However, surveys aimed to generate DTM or topographic measurements, to be used e.g. for land planning or hydrogeological purposes, are frequently characterized by a relatively low density of points per square meter and, above all, they are usually made in winter to minimize the noise by vegetation, since the aim is to achieve a high penetration rate through the vegetation canopy, i.e. to ensure that a high number of pulses reach the ground [Kraus and Pfeifer, 1998]. In summer, penetration rates less than 25-30% are normally obtained under forest stands [Kilian et al., 1996]. In the case of deciduous species (i.e. without green foliage during winter), which are those mostly frequent under temperate and Mediterranean forest environments, these rates can significantly be raised by winter surveys [Ackermann et al., 1994]: thus, commercial ALS flights for DTM production are almost always made between November and March under temperate and Mediterranean environments and even under alpine environments, at least in those areas not permanently covered by snow in that period. On the contrary the most favorable season to obtain ALS data specifically suitable for forestry applications under temperate and Mediterranean environments is summer, since in winter only the wooden part of the prevalently deciduous canopies generates LiDAR-significant returns [Clementel et al., 2012].

Summer and winter CHMs have been compared by Clementel et al. [2010] in an alpine site, showing strong correlation but with a systematic, significant stand height underestimation by the winter CHM. A tendency to slightly underestimate the real height is unavoidable with summer flights as well, because the pulse emitted by laser tends to penetrate into the canopy before a significant signal of return can be recorded and also, in the case of raster CHM, the point interpolation on regular cells determines a certain smoothing of tree height [Brandtberg et al., 2003]. However the stand height underestimation from summer ALS data is negligible for most operative forestry purposes. In general, the most accurate information on the height of the upper canopy in forest areas can be obtained by comparing summer and winter ALS data for canopy height and DTM, respectively.

Area-based and individual tree crown approaches

Experiences about exploitation of ALS data to support forestry are especially focused on: (i) qualitative and quantitative characterization of forest stands and description of their morphological and structural attributes; (ii) quantitative spatially explicit estimation of forest standing volume and biomass. Data sources and methods for this type of analysis is under evaluation at various scales: the value of LiDAR data derives from their ability to support the monitoring of ecosystem vertical structure which can be used to estimate aboveground ecosystem attributes. Other main current applications of ALS techniques in forestry are related to soil conservation and forest road planning [Pirotti et al., 2012]: these issues will not be addressed in this paper.

There are two broad categories of ALS data analysis approaches to support forest inventory and management: area-based approaches (AB), called also statistical canopy height distribution approaches, and individual tree crown approaches (ITC).

In the AB approaches, plot level data is related to ALS data aggregated at plot level to estimate stand biophysical attributes; AB approaches relates CHM raster pixels or point ALS data to measured plot characteristics to build parametric (e.g. regression) or non-parametric models to predict the forest attributes of interest. Collective biophysical variables are considered, referred to plots ranging from hundred up to thousand square meters; the established models have been shown to explain the majority of the variation in stand height, volume, and biomass [e.g. Næsset, 1997; Hudak et al., 2006; Hollaus et al., 2006; Garcia et al., 2010].

The ITC approaches include all the methods based on the detection of the individual trees (or at least of the distinguishable trees) in a given forest stand. ITC approaches may use both raster CHM and point ALS data to build individual crown polygons and/or 3-dimensional tree profiles; these individual tree records can then be aggregated to any scale required to create stand-level or ecosystem-level estimates [Akay et al., 2009].

AB and ITC approaches to estimating biophysical attributes are not mutually exclusive, and several authors demonstrated how they can be combined [e.g. Lindberg et al., 2010; Vastaranta et al., 2012].

ALS-assisted assessment of forest stand structure

The accuracy and coverage of ALS observations in forestry application is highly dependent on both the extrinsic specifications of the LiDAR survey as well as the intrinsic effects such as the underlying forest structure. Various AB approaches have been used to characterize and classify forest stands in terms of mean height. Floris et al. [2010] have observed a correlation coefficient of 0.90 between mean height data measured on the ground (plot size of 1256 m^2) and mean height measured on CHM in an alpine conifer forest. Barilotti et al. [2005] and Fusco et al. [2008] have obtained similar results in mixed conifers-broadleaves forests, and in mixed broadleaved coppices, respectively. Other features related to hypsometric variables detected by ALS have been proposed by Floris et al. [2009], like stand density and canopy roughness identifying the multi-layered or mono-layered structure of the stand: these descriptive features, appropriately combined, can be exploited to guide both the delineation of forest management units and to support forest stand stratification for inventory purposes.

Barilotti et al. [2005] have observed that the capability of the laser pulses to reach the ground in forest areas (laser penetration index, LPI) is inversely proportional to tree height and density of the stands; additionally, LPI proves to be closely and inversely proportional to the Leaf Area Index (LAI) measured on the ground, evidencing the potential of ALS data to feed ecological process models that rely on LAI assessment.

ALS data can be used for forest canopy gaps detection, which is relevant both for the ecological studies of stand dynamics and even to exclude the gaps from the sampling process for inventory purposes so to increase the sampling efficiency. Barbati et al. [2009] have applied the hot-spot analysis based on the calculation of the local statistic variable Gi* of Getis-Ord [Getis and Ord, 1992] in a coastal Mediterranean pine forest.

Bottalico et al. [2009] did a comparison between the hot-spot analysis and the morphological functions proposed by Koukoulas and Blackburn [2004] to extract gap boundaries.

Floris et al. [2009] have adopted a rule of spatial contiguity on a minimum surface under alpine conditions.

Barilotti et al. [2007a] have developed automated extraction of individual trees from CHM: they have been detected through a sequence of morphological transformations by a *Top Hat* algorithm implemented under open-source GrassGIS environment [Neteler and Mitašova, 2004]. *Top Hat* is a mathematical function of image processing that allows to highlight the relief structures [Schmidt and Hewitt, 2004], which in the case of forest stands are constituted by the tree apexes. Barilotti et al. [2007b] have also developed the automatic delineation of tree crowns by the subsequent use of a segmentation algorithm able to classify the laser points in subsets belonging to the individual crowns. The technique has proved to detect less than 80% of the trees in the examined alpine conifer stands, and even less in stands mainly composed by broadleaved trees. In the latter case, the delineation of individual tree crown contours is generally difficult, due to the frequent high geometric irregularity of crown shapes, high local variation of foliage and branch density and the more pronounced tendency of tree crowns to interpenetrate each other than in conifer stands [Heurich, 2008].

Abramo et al. [2007] have applied the methods developed by Barilotti et al. [2007a,b] in various types of spruce, beech-spruce-fir, spruce-fir, spruce and beech forests, detecting 71% of the trees with a stem diameter at breast height (dbh) greater than 5 cm, 89% of the trees with dbh greater than 17.5 cm and about 94% of the dominant trees. ITC approaches based on segmentation algorithms was also used by Dalponte et al. [2011a], exploiting the algorithm developed by Hyyppä et al. [2001a,b], and by Forzieri et al. [2009], who have obtained acceptable results for stands where the ratio between the mean tree interdistance and the mean tree crown diameter is greater than 0.6.

ALS-assisted assessment of forest standing volume and biomass

Under alpine, temperate and Mediterranean environments the assessment of the forest standing volume and biomass has been mainly carried out by AB approaches. The strategy is to establish models predicting the stand attributes of interest on the basis of ALS-derived metrics. Such metrics are computed by the raw (point or waveform) ALS data, that allow to calculate plot metrics like number of returns, above ground elevation of highest return, height percentiles, coefficient of variation of return height, skewness and kurtosis of returns height, non-ground percent of total returns, etc., or simply by the raster CHM values, that allow to calculate plot metrics like mean height per pixel, coefficient of variation of the

height per pixel or the sum of the heights of all the pixels in the plot.
Corona et al. [2008] have examined the correlation between volume measured in circular plots of 314 m^2 and the sum of the CHM heights (raised to a power) within plots in a temperate broadleaved forest. The relationship has proved to be heteroschedastic and linear through the origin, with correlation coefficient equal to 0.78. Starting from this finding, Corona and Fattorini [2008] have subsequently proposed a design-based approach for the AB ALS-assisted estimation of forest standing volume: adopting the height of the upper canopy at pixel level as auxiliary information, a ratio estimator of the total volume is derived, together with the unbiased estimator of its sampling variance and the corresponding confidence interval. With reference to the same above mentioned broadleaved forest, these authors have shown that the use of ALS data as auxiliary information can give rise to a confidence interval of the estimation approximately between half and two-thirds smaller than that obtained by field sampling plots only. Barbati et al. [2009] have tested the same estimation approach in a coastal Mediterranean pine forest, finding a correlation coefficient between the volume measured in circular plots of 1256 m^2 and the sum of the CHM heights within the plots equal to 0.88. A study of Fusco et al. [2008] on mesophillous coppice stands confirms the relationship between the woody biomass and the sum of CHM heights, with a correlation coefficient equal to 0.87. Extensive AB experimentations for assessing forest standing volume under alpine environments have been carried out by Floris et al. [2010]: these authors developed regression models between CHM metrics and standing volume measured in sample plots in spruce forests and found that the CHM mean height (excluding those pixels with height less than 2 m) can reliably predict the volume, with a correlation coefficient equal to 0.94. Under alpine conditions, Tonolli et al. [2011] have also analyzed the relationship between the standing volume measured on plots with size ranging from 400 m^2 to 3600 m^2 and metrics obtained from point ALS data: the most explicative metrics resulted the mean height of the first return and, with much less importance, the median of the heights of the second return. These authors also found that the relationship is significantly influenced by the plot size, with correlation coefficient increasing from 0.7 to 0.8 in the considered plot size range.
For professional application purposes and, distinctively, for forest planning, it is interesting to assess the accuracy of the ALS-assisted estimation over forest areas of a certain size (e.g., an entire forest compartment). In this case, if the estimates of standing volume by ALS metrics are unbiased, a compensation of positive and negative errors can be assumed, and good overall accuracy is presumed. Floris et al. [2010] have examined this topic for a compartment of 10 ha in an alpine spruce forest where a full callipering was available, observing a difference of the estimate of the total volume less than 3% with respect to the true value. Moreover, ALS-assisted models allow to map the variability of the volume at sub-compartment level: this is an important and innovative issue for forest planning aims (e.g. harvesting planning), not achievable with the traditional forest inventory practices based on field plots only. Overall, the presented results demonstrate that AB approaches have now reached the maturity to be used for mapping forest canopy heights and stand volume and biomass under complex environments throughout large areas.
ITC approaches to predict forest standing volume or biomass comprise various steps: (i) single tree detection, (ii) ALS measurement of the height of each detected tree, (iii) prediction of dbh of each detected tree by inversion of the height-dbh relationship established in the field, (iv) estimation of the volume of each detected trees through double-entry (height, dbh) volume equations. Beyond the mentioned difficulties to pinpoint single trees (even if this issue is relatively less relevant for stand volume estimation since most volume is due to the bigger trees, which are those normally more reliably detected), this approach significantly involves error propagation across the considered steps. The results by Dalponte et al. [2011a] in alpine spruce forests shows

that the capability of the ITC approach to assess tree dbh is relatively low (about 6 cm of absolute bias on trees with dbh equal to 45 cm), with overestimation for dbh up to 40 cm and underestimation for larger dbh, and standard errors of volume estimates around 0.7-0.8 m^3 for trees with average volume around 2.3 m^3. However, for the whole 481 examined trees, the bias of the volume estimation is only -5%. A study by Abramo et al. [2007] shows that the differences between the volume assessed by field plots and that predicted by the ITC approach is equal to 5-6% for spruce stands (except for a case in which the difference was 11%), 10% for beech high forests and around 19% for beech coppices. On the other hand, it is difficult to infer from the above results the reliability of the prediction over large areas, since in this case species identification of each detected tree is required (distinctive height-dbh and volume models are valid for the different species), making mandatory the tree species reconnaissance, e.g. by fusion of ALS data with multi- or hyper-spectral optical data [Dalponte et al. 2008; Tonolli et al., 2011].

Perspectives

In the last years the interest of ALS applications is remarkably increased, because of ALS data ability to capture dimensional information of the Earth's surface. The development of methodologies for ALS data processing has led to an increase of the number of applications also in forestry. Distinctively, in many boreal countries ALS techniques are already under operative use for obtaining information on forest standing volume, biomass and stand structural attributes. The overview presented in this paper highlights the relative suitability of ALS-assisted inventory procedures also with respect to alpine, temperate and Mediterranean environmental and operative conditions in Italy.

Under such conditions AB approaches have been much more applied than the ITC ones. However, these latter may have distinctive relevance when the interest is not only the assessment of forest standing volume or biomass but also the 3-D representation of forest stands, as required e.g. for ecological studies (e.g. habitat suitability studies) or for studies and simulations related to aesthetic preferences.

One of the main outcomes from the ALS area-based literature here considered is that mean height or median height or sum of the heights provides enough information for reliable estimation of forest standing volume, making even the simple auxiliary information provided by CHM very cost-effective to support forest inventories in many situations. This information is often available at low or even no cost from ALS surveys carried out for purposes other than forest inventories, while it is usually much harder or more expensive to get the whole original dataset of backscattered signal returns, as is required to compute metrics from ALS point or waveform data.

The possibility to integrate ALS data in forest inventory over large areas using probability sampling schemes is an aspect to be further developed. In this perspective, the availability of ALS data can range between full coverage over a given territory, where ALS data can be exploited as ancillary data known for the entire population so to adopt e.g. a ratio estimation approach like that proposed by Corona and Fattorini [2008], to a sample of the territory based on transects below the flight lines to spot samples within transects, so to adopt e.g. a multiphase/multistage estimation approach like those proposed by Gregoire et al. [2011] and Ståhl et al. [2011]. Maselli et al. [2011] investigated the application of parametric and non parametric methods to Landsat satellite imagery in order to extend stem volume estimation from LiDAR data taken over few strips to the entire forest area.

A critical aspect of all the ALS-assisted procedures is the need for georeferencing and coregistration of both LiDAR measurements and ground truth locations. Ground reference data collection represents an important element in the prediction of ALS-assisted estimation of dendrometrical attributes, and at present it is the most expensive part of such analyses. However, an experiment by Dalponte et al. [2011b] in an alpine site, where the presence of a complex landscape increases the uncertainty of the Global Positioning System (GPS) accuracy, has shown that the GPS error did not significantly influence the volume prediction

accuracy of AB approaches. These results, obtained in a complex mountainous area, allow to infer that similar (or better) results could also be obtained within non mountainous areas.
A poorly investigated topic is the ALS detection of silvicultural systems under temperate and Mediterranean conditions, i.e. the discrimination between high forest and coppice stands. So far, no published paper covers such an issue, that has been long remained unresolved by optical remote sensing: conversely, since ALS can pinpoint the vertical structural properties of a forest stand, it should provide effective support information to such an end. Moreover, it would be likely possible to detect understory in forest or new forest and other wooded lands in rural abandoned spaces rapidly growing. Preliminary evidences seem to indicate that ALS data can distinguish sparsely-distributed individual trees and shrubs on forest-pasture and forest-field ecotones [Sankey, 2011].
Another relatively poorly investigated topic is linked to the attributes associated to the forest structure: for example, to what extent ALS information can be used in forest fuel models mapping, which is currently usually based on expensive field surveys. Few studies on this aspect [e.g. Seielstad and Queen, 2003; Mutlu et al., 2008] suggest the processing of ALS-derived metrics able to distinguish some fuel models used as input data in fire behavior models, as it improves the forest fuel parameters estimation either by using information processed from ALS point data, when ALS metrics are significant predictors of canopy bulk density and canopy base height for generating maps of canopy fuels for input into fire behavior models, such as in FARSITE [Peterson et al., 2007], or combining multispectral passive imagery [e.g. Riaño et al., 2003; Mutlu et al., 2008; Erdody and Moskal, 2010].
As mentioned, ALS paired with other optical remote sensing data is a well-established approach to spatially estimating forest attributes [Ioki et al., 2009; Straub et al., 2010; Breidenbach et al., 2010]. The use of optical remote sensing data in conjunction with ALS data is helpful in both delineating crown boundaries and in differentiating between species. The ability to make species level distinctions is especially important when estimating merchantable timber volumes and biomass, as these attributes differ between species in trees that are the same size.
ALS technology is evolving very quickly and the forestry sector can directly benefit from it, as shown by the selected literature here presented and discussed. It is important to match processing methods with the appropriate scale and scope: some processing methods are valid at the plot scale, whereas other procedures perform well at the regional scale; to be effective, certain ALS data analyses require a minimum point density, whereas other methods perform well using large-footprint sensors [Pirotti, 2011].
Due to the expected technical innovations of ALS systems (e.g., see Koch, 2010), it can be assumed that ALS data will play a even more prominent role in estimation of forest standing volume and biomass in the next years. Multitemporal ALS survey will even be potentially effective to support the assessment of current annual volume increment and the detection of harvesting rates and stand structural degradation. However, it is still particularly important to relatively lower data acquisition costs, so to make ALS data even more accessible for dedicated professional application.

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