A thorough accuracy estimation of DTM produced from airborne full-waveform laser scanning data of unmanaged Eucalypt plantations

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Abstract

A Digital Terrain Model (DTM) is needed to extract forest variables. Its accuracy affects that of these variables and thus it has to be known. Airborne Laser Scanning (ALS) is being increasingly used to produce DTM. The potential of full-waveform ALS (FWALS), however, for DTM-production in forest areas has not been thoroughly evaluated, especially under adverse conditions of heterogeneous forest stands, such as the typically extensively managed eucalypt plantations of north-central Portugal studied here. In the study area of 900 ha, an exhaustive assessment of FWALS-derived DTM accuracy was carried out based on the field survey of 43 plots. In each of these circular plots of roughly 400 m^2, the coordinates were measured for all trees and all prominent terrain points using GNSS receivers and total station. In addition, it was assessed the quality of the FWALS data by surveying $1m \times 1m$ grids of points on three bare areas. The accuracy assessment measures are computed by assuming normal and non-normal distributions of the differences between the h values of FWALS terrain points and those of control points at the same planimetric locations. Whilst the accuracy of the FWALS data is as expected, around 3 cm, that of the DTM of the forested area exceeds expectations. In fact, the DTM accuracy of 12 cm is higher than that obtained in prior ALS studies carried out in less adverse conditions than those studied here. Thus, the current FWALS-based methodology to derive DTM appears highly suitable to extracting forest variables.

EDICS Category: 3-BBND

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I. Introduction

One of the indispensable conditions for a sustainable development is a detailed and up-to-date knowledge of the available natural resources. In the case of Portugal, an important natural resource is that of its forests. Crucial information for foresters and land-use planners concerns, in particular, tree species, tree position, number of trees, mean height, volume and biomass per hectare. In relation to forest fires - which have attained dramatic proportions in Portugal in the last few years - the need for additional information on vegetation variables like shrub density and height, as well as on terrain topography must be stressed. Such information is fundamental for determining the risk of ignition and for predicting fire dynamics.

In Portugal, the technological delay has hampered the development of a suitable methodology for a fast and reliable survey of forestry data, adapted to new technologies and techniques. The majority of the forest inventories are done in situ by specialized teams. This makes them expensive and their quality is greatly correlated with the experience of the teams. The relief is modelled by the so-called Digital Terrain Models (DTM) produced by photogrammetric means. In forested areas, Photogrammetry is rarely adequate for DTM production because the trees hide the terrain underneath. Airborne Laser Scanning (ALS) , better known as LiDAR (Light Detection and Range), has shown itself to be an alternative/complementary technique to Photogrammetry for the production of high resolution DTM, especially in forested areas. Furthermore, it also allows the estimation of shrub density and height as well as tree variables such as height, localization, and mean tree crown and volume [1]. Hence, the errors in the DTM will propagate to the normalized Digital Surface Model (nDSM) and therefore, to the derivation of the forest inventory and fuel variables, like tree and shrub heights.

The vertical accuracy of a DTM produced with ALS data is influenced by the errors/inaccuracies originated from the [1]–[4]:

- ALS system (Global Positioning System (GPS), Inertial Navigation System (INS), and laser scanner);
- strategy for acquisition of ALS data (point density, first/last pulse, several pulses, flight height, scan angle);
- conversion of ALS data (full-waveform modelling, filtering and interpolation methods);
- characteristics of the target surface that is, topography and type(s), density and spatial distribution of vegetation.

While a general understanding of the accuracy of the ALS systems has been achieved, the accuracy of the derived DTM from ALS data in a forest environment has not been thoroughly evaluated [3], [5], mainly in unmanaged eucalypt forests. As far as we know, there are only few studies concerning eucalypt forest, like those of [6], [7], the later using even regular eucalypt plantations, in which the methods for quality assessment are not fully described. Furthermore, while in the recommendations of the article of [1] it is said that the extraction of DTM for forest areas is well established, this conclusion is based on a list of works using other forests than eucalypt forests. Moreover, by digitising and recording the complete echo waveform, the full-waveform ALS (FWALS) systems have, in comparison to the conventional real time processing multi-echo systems, the advantage of permitting echo detection in post processing. This makes the ranging determination process more robust. While this is expected to lead to higher accuracy of the derived distances and thus to a more accurate DTM [8], it remains to be proved in areas with the characteristics of the one here studied.

Table I lists some published accuracy values of DTM created by using ALS data of several forests/plantations ([3]–[7], [9]–[15]). A limitation of the studies is that they do not allow one to predict the DTM accuracy because they do not address all the four accuracy-influencing factors above listed.

In the context of a research project for estimating forest inventory parameters and fuel variables under eucalypt stands in Mediterranean climates, the vertical precision of the DTM obtained by automatic filtering of FWALS data had to be evaluated. In this paper it is thus assessed the vertical accuracy of a DTM obtained by automatic filtering of FWALS data of a eucalypt forest. In addition to the peculiar characteristics of the study area, which are often avoided in related

TABLE I

PUBLISHED ACCURACY VALUES OF DTM PRODUCED WITH ALS DATA (N.R = NOT REPORTED).

Authors	Area extent (ha)	ALS density (pts/m^2)	No. of check pts.	RMSE ; bias (cm)	Land cover
Kraus and Pfeifer (1998), [9]	9 100	0.1	466	57; 20	Beech.
Hyyppa et al. (2000), [10]	1.4	08-10	740	22 (Std)	Boreal forest. Norway spruce and Scots pine.
Reutebuch et al. (2003), [5]	500	4	347	32; 22	Coniferous forest (Douglas-fir in western Washington region).
Wack et al. (2003) [7]	0.48	5	602	19 (Std); 14	Eucalypt forest (Portugal)
Hodgson and Bresnahan (2004), [3]	200 000	0.25	654	21; n.r	Pavement, low grass, high grass, brush/low trees, evergreen and deciduous forests.
Takahashi et al. (2005), [11]	2 areas: 250 000 and 62 500	11.2	283	39; 14	Sugi plantations (*Cryptomeria japonica* D. Don)
Yu et al. (2005) [13]	8 areas of 100	10 5	1 474	9 (Std) 30 (Std)	Boreal forest (Kalkkinen) Norway spruce and Scots pine.
Gonçalves-Seco et al. (2006) [6]	281	7.8	2207	0.19 ; 0.16	Eucalypt forest (Spain)
Hollaus et al. (2006) [14]	12 800	1.8	2 200	10[1]; n.r 50[2]; n.r	ALS data along road sides.
Su and Bork (2006) [4]	2 700	0.75	256	59; 2	Riparian Meadows, Upland Grasslands, Shrublands and Aspen Forest.
Evans and Hudak (2007) [15]	2 areas of 85 000	0.3	165 39	70; -70 62; 60	Coniferous Forest

[1] For flat areas

[2] For slopped areas ($> 60°$)

studies, the accuracy estimation is carried out in a novel way. By novel way, its meant an exhaustive, well planned collection of reliable control data under a eucalypt forest comprising regular as well as irregular spacing plantations. The understory is heterogeneous and is mainly composed of whin, fern, heath, and gorse. Prior to the vertical accuracy assessment of the DTM, the quality of the delivered laser data was also evaluated. To this end, measurements on horizontal and inclined bare surfaces were used.

II. Study area and data acquisition

A. Study area

The study area was selected nearby the city of Águeda, in the district of Aveiro, situated in the Northern part of Portugal. The selected area measures 900 ha (Figure 1-a). Its topography varies from gentle (2.5%) to steep slopes (34.2%), with altitudes varying from 27 to 162 m (Figure 1-b). The area is dominated by eucalypt plantations, but it also includes some pine stands and few built-up areas. The mean tree density is around 1 600 trees per hectare. The forest stands in the area have regular as well as irregular spaced plantations, both even and uneven-aged stands, and stands with and without extensive undergrowth (Figure 1-c).

B. Acquisition of the FWALS and image data

The FWALS data were acquired on the 14^{th} of July 2008. The laser system utilized was the Litmapper 5600. This system has, as main hardware components the high-resolution laser scanner from RIEGL, the LMS-Q560 with full-waveform processing, the AEROcontrol GPS/IMU system and the DigiCAM, a medium-format Airborne Digital Camera System operated simultaneously with the FWALS system. The AEROcontrol system is utilized for the precise determination of position and attitude with an Inertial Measurement Unit (IMU) of 256 Hz raw data rate and a differential GPS. The main system software relates to the AEROoffice - the GPS and the IMU data post processing software - the Riegl software, RiWorld for coordinate transformation and RiAnalyze for processing of the FWALS data, and the software bundle from TerraSolid. This comprises the software modules TerraScan, TerraModeler and TerraMatch. TerraScan is the dedicated software solution for manipulation, viewing, and classifying FWALS data. TerraModeler is a full-featured terrain modelling application for creating digital terrain/surface

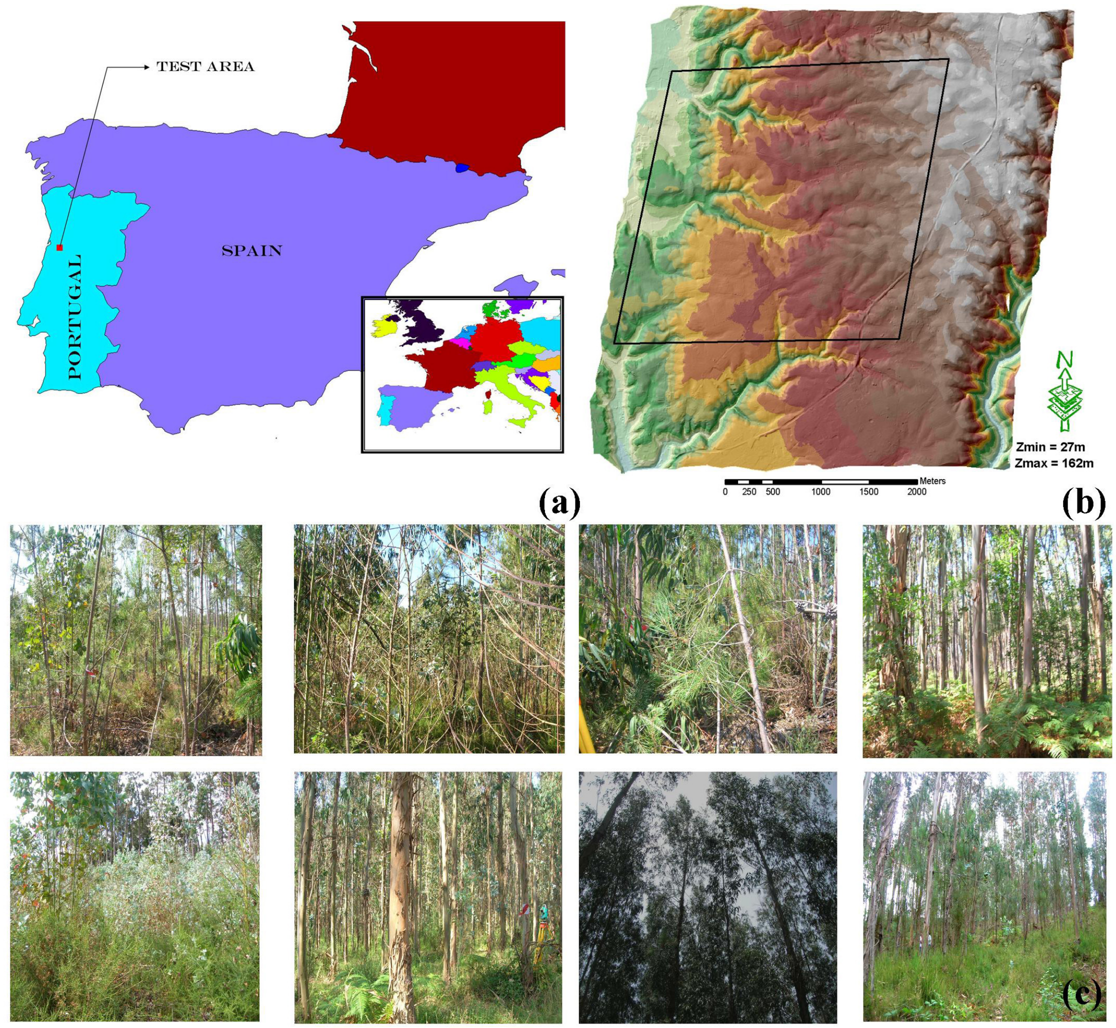

Fig. 1. (a) Localization of study area within Portugal and its delimitation; (b) DTM of the study area; (c) Examples of vegetation within study area.

models (DTM/DSM). TerraMatch is used for automated correction of ALS data (http://www.igi-systems.com/products/litemapper/components.htm, 19.01.2010).

Stereo-pairs of CIR images were acquired simultaneously with the FWALS data. The parameters selected for FWALS and image data acquisition are listed in Table II. The flight is constituted by thirty plus two flight lines, the latter in a direction perpendicular to the first and used for calibration purposes.

TABLE II

FWALS DATA AND IMAGE ACQUISITION PARAMETERS.

FWALS	Image
FWALS sensor: Riegl LMS-Q560	Camera sensor: Digicam H39 + 50 mm focal length
Wavelength: 1550 nm	Wavelengths in CIR mode (nm): B=500−620; G=580−800; R=800−1000
Scan angle: 45°	
Pulse rate: 150 kHz	Image repetition rate: 1.9 sec
Effective Measurement rate: 75 kHz	
Beam divergence: 0.5 mrad	
Ground speed: 46.26 m/s	
Flying height above terrain: 600 m	Flying height above terrain: 600 m
Swath: 497 m	Overlap: 60%
Sidelap: 70%	Sidelap: 30%
Single run density of laser shots: 3.3 pts/m^2	Nr. of pixels forward: 7 216
Expected final density: 9.9 pts/m^2	Nr. of pixels sideward: 5 412
Distance between lines: 150 m	
Spot diameter: 30 cm	Ground sampling distance (GSD): 8.2 cm

III. Methods

A. *Procedures for acquisition and quality assessment of reference data*

Reference data are needed to verify, in terms of precision and reliability, the DTM produced by means of the laser data and a filtering algorithm (III-B2). The strategy for the reference data collection was not straightforward. In forest areas, the collection of these data is time consuming, mainly in plots with a high density of shrubs and trees. Furthermore, because the data were georeferenced, geodetic Global Navigation Satellite Systems (GNSS) receivers had to be used.

The planning of the topographic survey was based on that of the forest inventory, which started by selecting 43 plots, with a radius of 11.28 m, within the study area (dots in Figure 2-a). The DTM was represented by the coordinates of terrain points located aside trees, which give also the locations of the trees, and by the coordinates of prominent terrain points, like those on breaklines (Figure 2-b). The characterization of each plot in the study area, in terms of mean slope (III-C), shrubbery (height varying between 10 cm and 2 m) and high vegetation (height

>2 m) is shown in Figure 3.

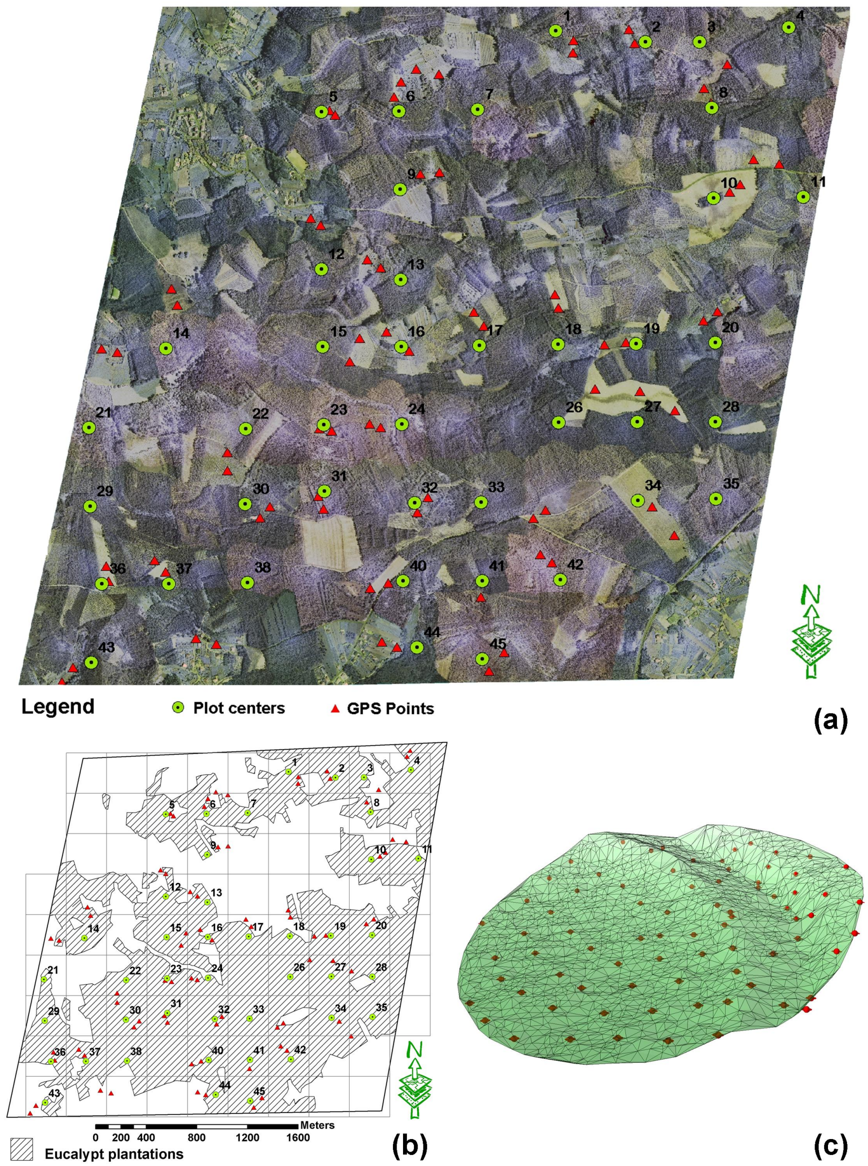

Fig. 2. Planning of the topographical survey: (a) and (b) location of the 43 forest plots; (c) DTM of plot no. 43 with breaklines, produced with the FWALS points classified as terrain. The small circles represent the points measured by topographic means.

In addition to the DTM quality assessment, it was also decided to assess the quality of the delivered FWALS data. To this end, it were measured points, in a grid format of approximately 1×1 m^2, on bare surfaces (roads and fields; Figures 4-a, 4-b and 4-c).

This information was collected by means of a topographic survey using the radial method [16].

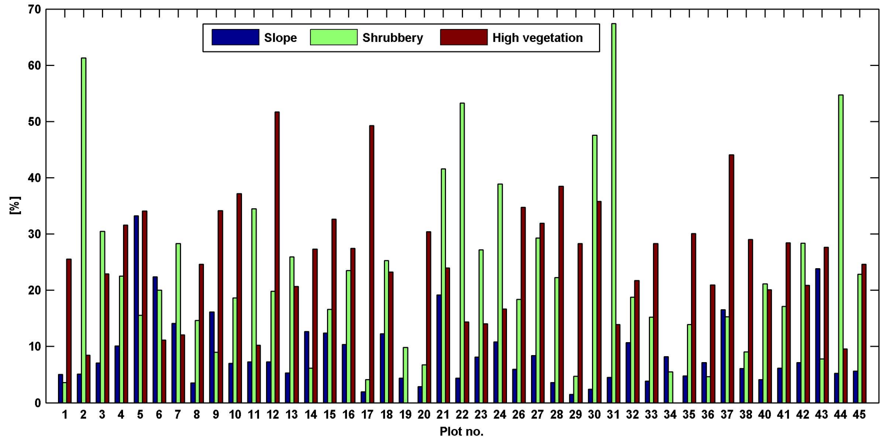

Fig. 3. Characterization of each plot in the study area

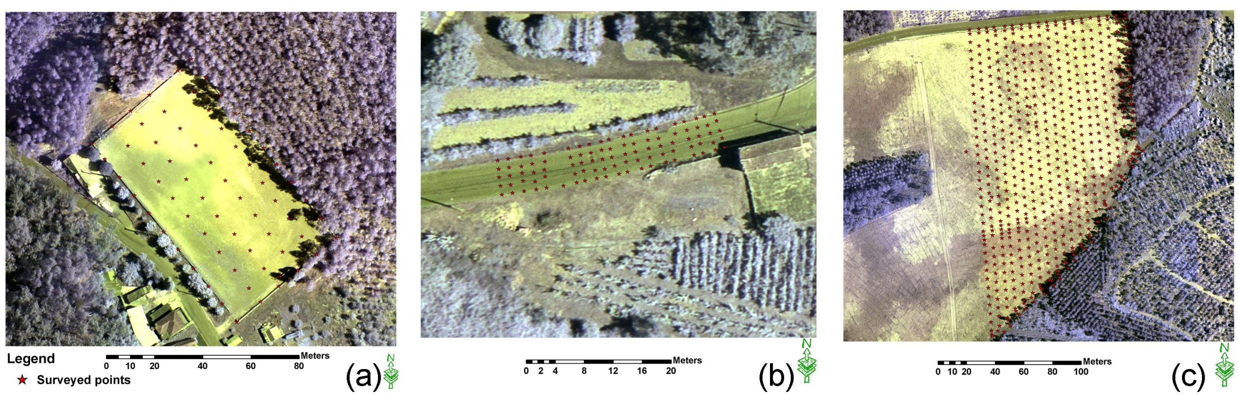

Fig. 4. Reference data for FWALS quality assessment: (a), (b) and (c) surveyed points on bare surfaces (paved road, football field and arable field, respectively).

The coordinate system in which the FWALS and image data were collected ($WGS84 - UTM29$) uses the reference ellipsoid of the World Geodetic System (WGS 84) and the cartographic projection Universal Transverse Mercator (UTM) zone 29, for X and Y coordinates. For the Z coordinate it is used the WGS84 elipsoidal height. These coordinates will be from now on referred to as absolute coordinates X, Y and h. Because this is not a local system, the geographic information collected in the field had to be converted to that system by using the GPS. To this end, it was decided to attach to each plot two GPS-derived points, named *GPS base* (triangles in Figure 2-a), whose coordinates were measured with two GNSS receivers. They allow coordinating the surveyed points directly in the referred coordinate system. There are needed two points to orient the total station. These two points are placed as close as possible to the plot and as much as possible in an opened space (Figure 5). This criterion turned out to be difficult to fulfil in the study area.

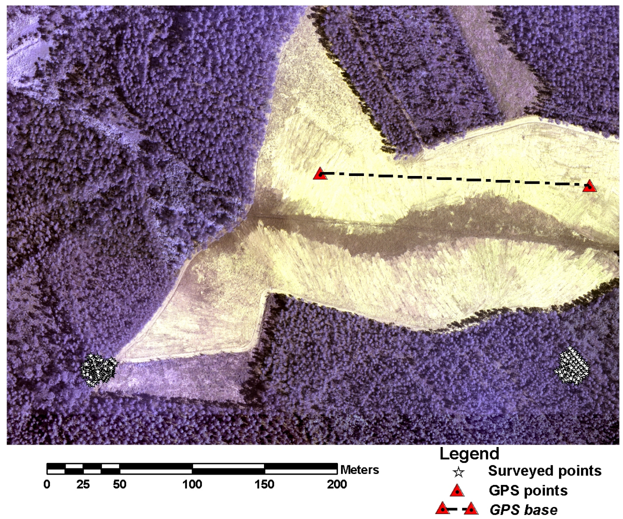

Fig. 5. An example of a *GPS base* used to georeference the measurements on two plots.

The method used to measure the coordinates of the two GPS-derived points was the relative positioning by using a fixed receiver on a geodetic pillar with known coordinates on the $WGS84 - UTM29$. This method, in post processing, is the most precise and may reach levels of precision in the order of the cm [17].

The GPS observations were collected according to a previous planning dictated by the following specifications: minimum time of observation of 60 minutes, depending on the point surroundings (normally it took 120 minutes), minimum number of 7 satellites and value of the Position Dilution of Precision (PDOP) less than 3. In total, the coordinates of 82 points, i.e., 41 *GPS bases* were measured. The number of *GPS bases* does not coincide with that of plots because two *GPS bases* were assigned to two plots each.

As some of the GPS-derived points of the *GPS bases* had nearby some trees that might degraded the GPS signal, we developed a strategy to control the quality of their coordinates. This strategy is based on the distances and height differences between the two points of the *GPS* *bases* computed in two coordinate systems. One is a local system and the other the absolute system ($WGS84-UTM29$). Those variables are compared to each other. It is assumed that the variables obtained by topographic methods, using a total station, are error free. It was decided that if the differences in the distance values and in the height differences were bigger than 6 cm, the coordinates of the GPS-derived points had to be re-measured by stationing once again the GPS on the points. The mean error and RMSE of the differences in distance are 1.7 cm and 2.5 cm, respectively, whilst the mean error and RMSE of the differences in height differences have the values of 1.9 mm and 2.6 cm, respectively.

B. FWALS data processing

1) Full-waveform data preparation: The full-waveform laser data were purchased already processed by the company that acquired the data. The processing was done with the RiAnalyze software from Riegl. The basic processing is based on a Gauss Pulse Estimation technique. This aims to combine the execution time of a simple centre of gravity approach ([18]) with the accuracy of Gaussian Pulse Fitting technique and provides multiple returns ([19]). A maximum of 5 returns were obtained for all the FWALS echoes.

The strips of FWALS data were also adjusted and georeferenced by the referred company using the TerraMatch and the RiWorld softwares and were stored in the form of LAS blocks. TerraMatch compares overlapping laser strips with each other and corrects their orientation to obtain the best fit and improved accuracy of the laser data. The adjustment is based on measured differences between the xyz shape or the intensity of laser points from different strips (http://www.terrasolid.fi/system/files/TerraMatch.pdf, 23.12.2010). With the TerraMatch software the misalignment between the navigation and the laser systems is estimated with calibration strips. The misalignment is then corrected when georeferencing the cloud of points with the RiWorld software. The TerraMatch software is once again used to adjust the height values between points in overlapping strips by smoothing GPS fluctuations. Finally, the data are verified for systematic errors by comparing the h values of ground control points with those of laser points.

2) Point cloud filtering: The point cloud obtained by processing the full-waveform data contains both laser returns from objects located on the ground (buildings, trees, understory vegetation) as the ground itself. Moreover, in vegetated areas the laser pulse can penetrate the canopy, travelling between the branches and leaves and be reflected by the understory (e.g.

sub-canopy trees and shrubs) and by the ground.

Since we are interested in the reconstruction of the terrain surface it is necessary to remove the non-ground returns from the point cloud. Removing non-ground measurements from the point cloud is here referred to as filtering. In order to find the most probable ground returns from the initial point cloud the filtering process uses the last return of each pulse.

Points in a point cloud are classified as either ground or non-ground returns using a progressive Triangular Irregular Network (TIN) densification algorithm implemented in the TerraScan software v4.006 (www.terrasolid.fi/en, 11.05.2010) and based on the algorithm published in [20], [21]. This algorithm begins by constructing a sparse TIN with the lowest point inside a square neighbourhood of a certain size. The TIN is densified by adding points of the set of unclassified points that satisfy certain criteria. The densifying of the TIN stops when no more unclassified points satisfy the criteria or if a certain ground point density is achieved. An additional threshold may be used to control the maximum terrain slope allowed at each triangle of the TIN surface. In this work, the parameters used for filtering the laser point cloud were tuned empirically and happen to coincide with the default values ([22]) with exception of the neighbourhood size parameter that has the value of 10 m (the default is 60 m and therefore too big when compared to each plot size).

C. *DTM accuracy assessment*

In addition to the accuracy assessment of the DTM produced by the filtering process of the laser data, the contribution of the quality of the FWALS data alone into that assessment was verified. To this end, three DTM were produced, by using topographic means, on flat bare surfaces (a paved road, a football field and an arable field; see III-A). The accuracy assessment of these DTM as well as the DTM produced after the filtering process of the laser data relates to the estimation of the mean and RMSE of the differences (dh) between the h values of FWALS terrain points and those of the reference points (III-A) at the same planimetric locations. These FWALS terrain points are interpolated from a TIN computed with the filtered FWALS terrain points (III-B2). The TIN was created from the filtered FWALS data instead of from the reference data because the density of FWALS terrain points is higher than that of reference points (3.8 versus 0.2 pts/m^2). This means that many points on the terrain presented in the FWALS filtered data are not present in the reference data. Therefore, it is more appropriate to interpolate the laser data to the planimetric positions of the reference data. The TIN format is also chosen, instead of the grid format, to handle the breaklines. Futhermore, the interpolation methods associated to this format are computationally simpler when compared, for example, with the kriging method, at expenses of being more sensitive to measurements errors.

The deviation of the distribution of the residuals dh from the normal distribution implies the use of other accuracy estimators than the mean and RMSE ([23], [24]). Therefore, that deviation has to be evaluated. This is done using two different methods. One method superimposes on the histogram of the residuals a curve for a normal distribution obtained by ordinary estimation of mean error and variance. If the Gaussian curve does not fit the data very well it means that the residuals are not originating from a normal distribution, e.g. because the distribution is not symmetric around its mean or because the distribution is more peaked around its mean than the normal distribution while having heavier tails ([24]). These effects are measured by the skewness and kurtosis of the distribution. The analysis of the so-called quantile–quantile (Q–Q) plot is another method for verifying a deviation from the normal distribution. The quantiles of the empirical distribution function are plotted against the theoretical quantiles of the normal distribution. If the distribution is normal the Q–Q plot should yield a straight line. As a robust and distribution free approach handling outliers and non-normal distribution, [24] suggest as accuracy measures the median m_{dh} of residuals, the normalized median absolute deviation ($NMAD = 1.4826 \cdot median_j(|dh_j - m_{dh}|)$, and the 68.3% and 95% quantiles of the absolute value of residuals.

It was also verified if the quality of the DTM has a relation with the vertical structure of the vegetation and with the terrain slope. Therefore, a linear regression analysis between the quality of the DTM produced by filtering the laser data and the vertical structure of the vegetation was computed. Linear regression was carried out between the values estimated for the mean and the RMSE of residuals per plot and respectively, the percentages of the number of points classified by the filtering process as terrain, as shrubbery with height varying from 10 cm until 2 m and as higher vegetation cover.

The linear regression analysis between the quality of the referred DTM and the mean slope of the terrain within plots was also performed. Linear regression was carried out between the values estimated for the RMSE of residuals per plot and the mean slope within each plot. The mean slope was estimated by fitting a plane to the reference terrain points. The plane is in fact the geometric shape that represents best the geometry of all the terrain surfaces within the plots. A relation between the RMSE values and the spatial distribution of the plots as well as the spatial point density was also studied by means of visual inspection. The spatial point density was computed for 1×1 m^2 cell using only the last returns [25]. For those plots on the same flight line, the associated RMSE values were also inspected for a relation.

The developed methodology is summarized in the form of a flow-diagram in Figure 6.

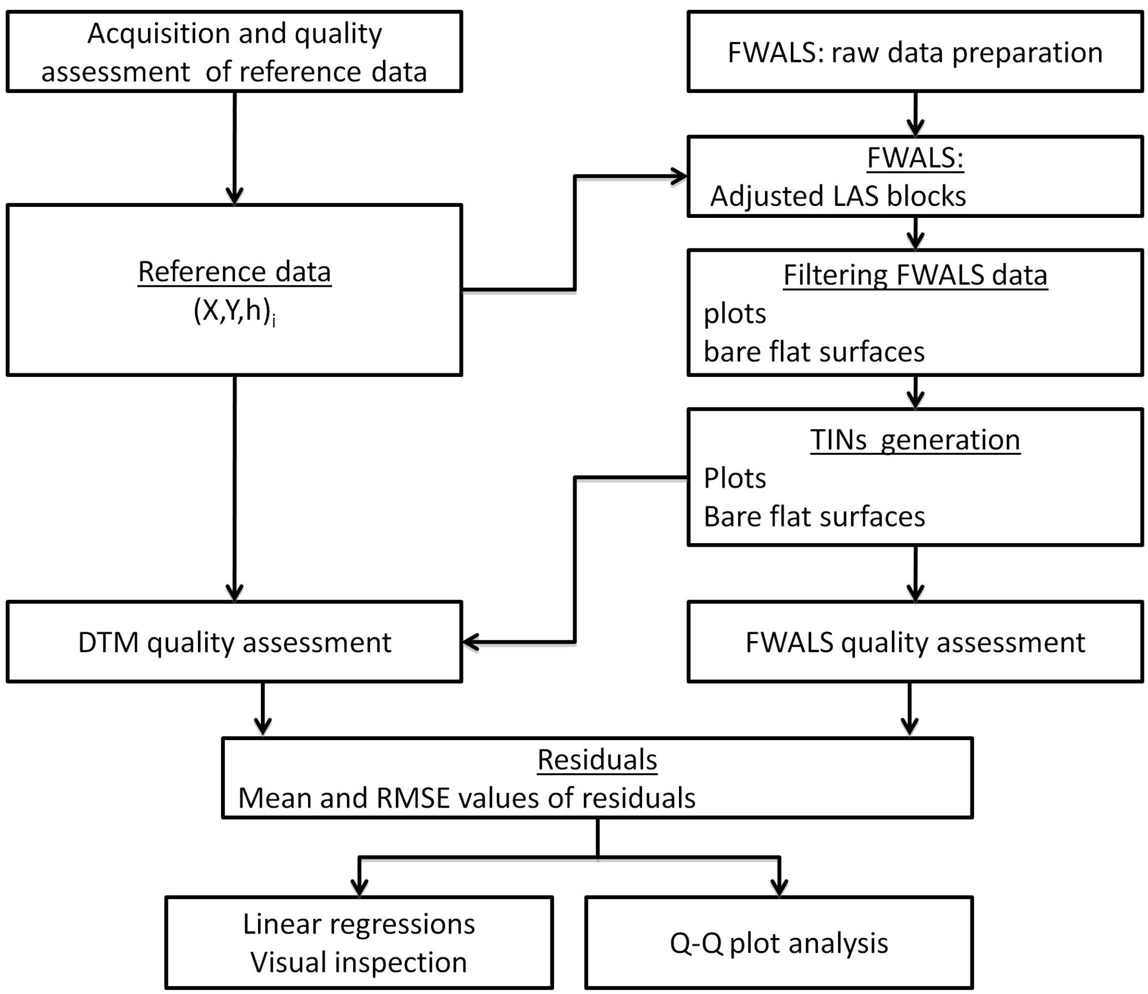

Fig. 6. A concise presentation of the developed methodology.

IV. RESULTS

The quality of the DTM obtained with the laser data was computed for each plot individually, by using the strategy described above. The estimated values for the mean, standard deviation and RMSE are plotted in Figure 7. As it may be seen in that figure, the values of the mean of residuals vary, in absolute value, between 5 and 28 cm, whilst the RMSE varies between 4 and 29 cm. When considering all the plots together, i.e., 3 174 points, the value of the mean of residuals is 8 cm whilst the RMSE is 15 cm. These are very good values considering the cover characteristic within the plots. Furthermore, there has been no manual editing, i.e, manual removal of gross errors.

The bias of 8 cm, shows that the FWALS filtered points are above the terrain surface. This may result from the vegetation cover within the plots. Nonetheless, this value is quite low considering the characteristics of the plots (Figure 3), which proves that the strategy for laser data acquisition and processing is effective.

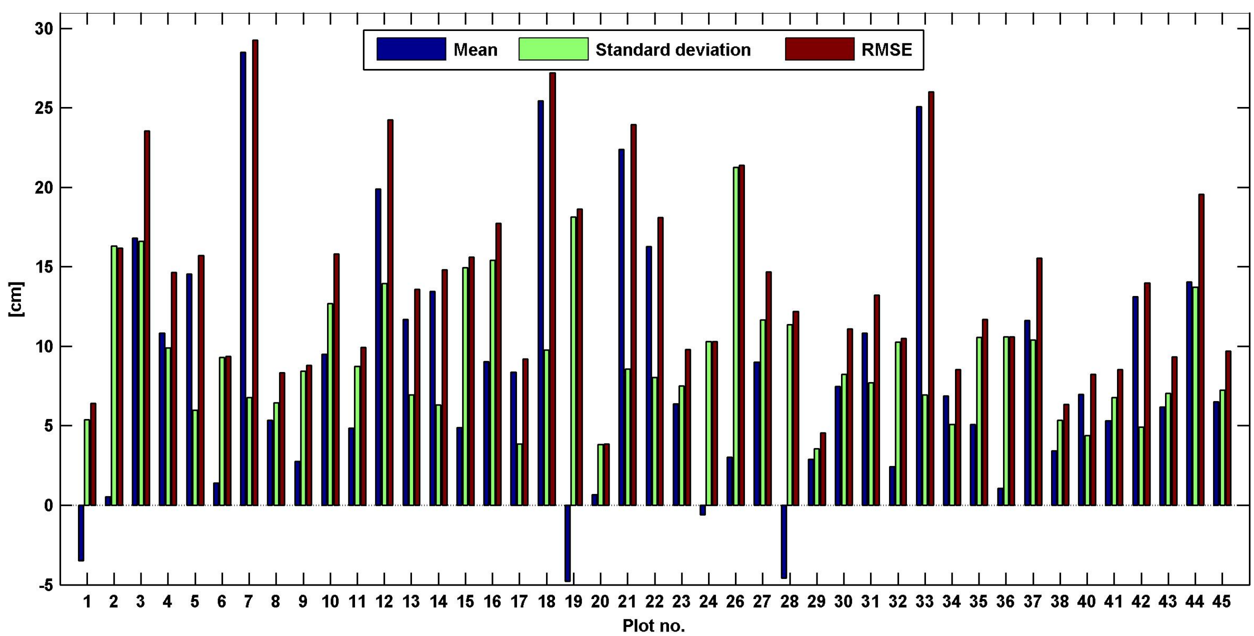

Fig. 7. Values of the mean, standard deviation and RMSE of residuals per plot. The plots 19 and 34 are the only ones in open areas. They have young eucalypt plantations with mean heights smaller than 30 and 20 cm, respectively. Although situated in an open area, plot 19 has a bigger RMSE because of the terrain relief (it contains a breakline).

The gross errors present in the results (min= -79 cm; max= 72 cm) deviate the distribution of the residuals from a normal distribution. Figure 8 shows the histogram of the residuals on which is superimposed a curve for a normal distribution obtained by ordinary estimation of mean error and variance. As mentioned in III-C, the deviation from normality is measured by the skewness and kurtosis of the distribution which, in this case, have the values of -0.177 (std. error = 0.043) and of 3.979 (std. error = 0.087), respectively.

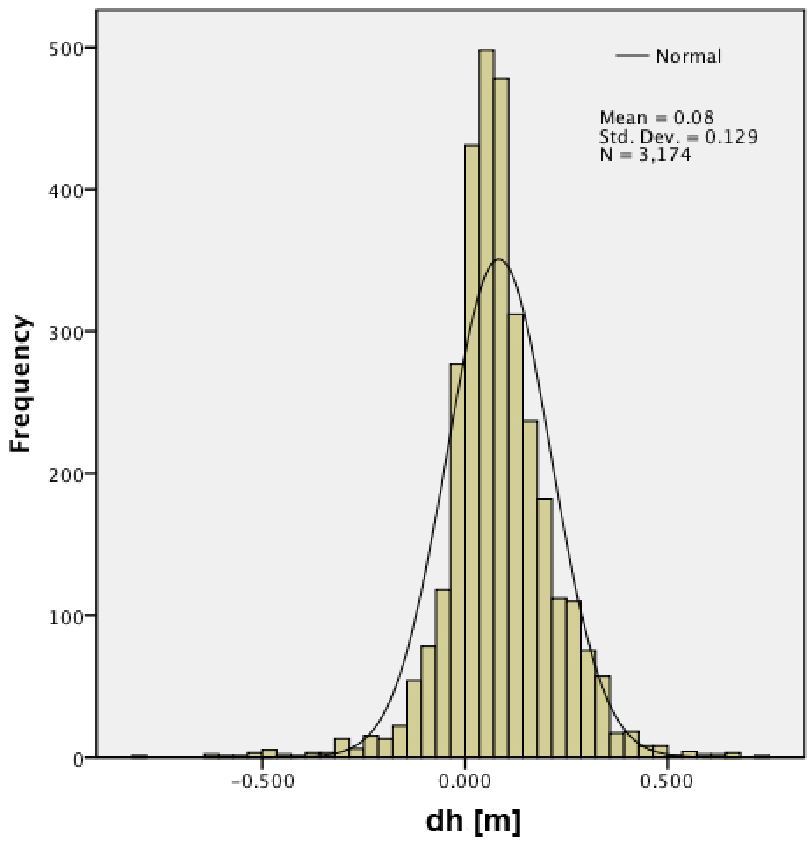

Fig. 8. Histogram of the residuals. Superimposed on the histogram are the expected counts from a normal distribution with mean and standard deviation estimated from the data.

The analysis of the so-called quantile–quantile (Q–Q) plot provides another way of verifying a deviation from the normal distribution. Figure 9 shows the Q–Q plot for the distribution of the residuals. A deviation from a straight line may be seen at both extremes, which indicates that the distribution of the residuals is not normal. The obtained robust accuracy measures (III-C) are tabulated in Table III. Although the distribution of the residuals deviate from the normal distribution, the differences between the robust accuracy measures and those estimated by assuming a normal distribution of the residuals are not significant. The difference between the values of the standard deviation of residuals and of the $NMAD$ is only about 3 cm. If one takes the robust measures m_{dh} and $NMAD$ as values representative for the mean and standard deviation of residuals, a robust estimator for the RMSE value (RRMSE), estimated as $\sqrt{m_{dh} + NMAD^2}$, is 12 cm (Table III).

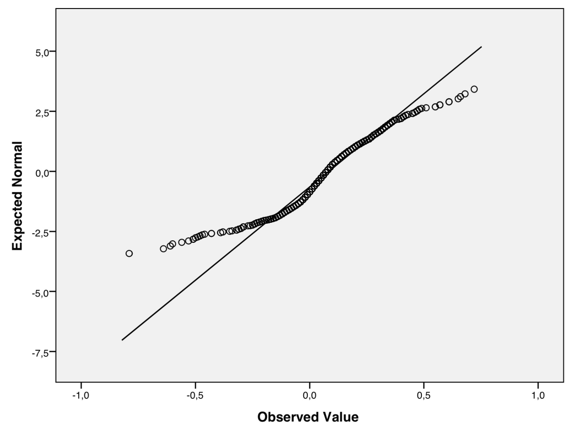

Fig. 9. Quantile-Quantile (Q-Q) plot of the distribution of residuals computed to assess the DTM accuracy.

TABLE III
ROBUST ACCURACY ESTIMATORS.

Accuracy estimator	Value (cm)
m_{dh}	7
NMAD	10
68.3% Quantile	13
95% Quantile	32
RRMSE	12

The existence of a linear relation between the quality of the DTM and the vertical structure of the vegetation and the mean slope of the terrain in each plot was studied by means of linear regression. It is expected that this relation exists. Figures 10-a,10-b and 10-c show the linear regression between the values estimated for the RMSE per plot and respectively, the percentages of the number of points classified by the filtering process as terrain, as shrubbery with height varying from 10 cm until 2 m and as high vegetation cover (i.e. with height $>$ 2m).

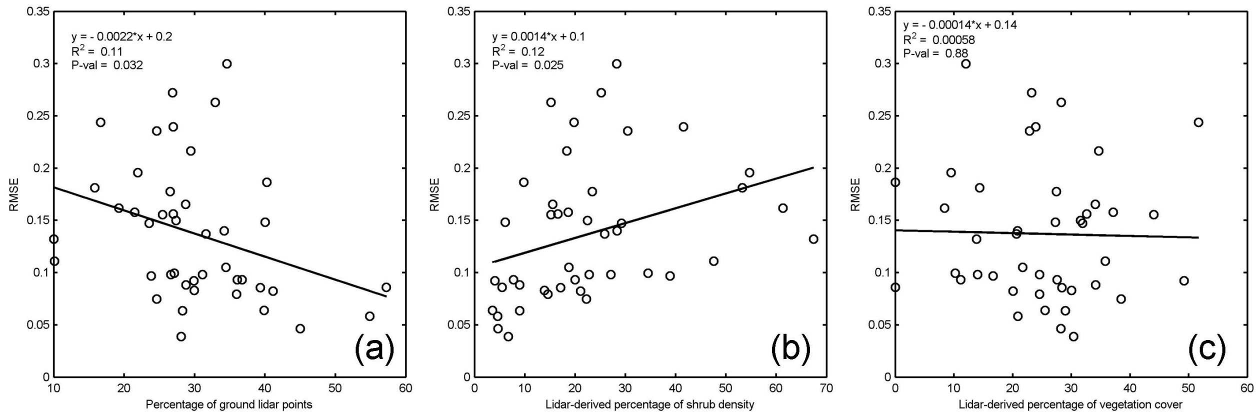

Fig. 10. Linear regression between the value of RMSE and the process-derived percentage of: a) terrain points, b) shrubbery and c) higher (≥ 2 m) vegetation cover per plot.

Figure 11 shows linear regression between the values estimated for the RMSE per plot and the mean terrain slope within each plot.

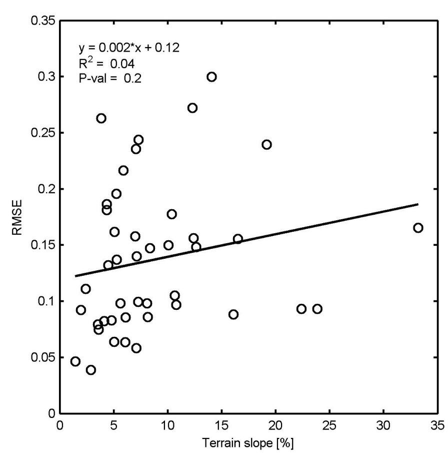

Fig. 11. Linear regression between the values of RMSE and the mean terrain slope per plot.

Contrary to what was expected, the low values obtained for the coefficient of determination ($R^2_{\text{(a)}} = 0.08$; $R^2_{\text{(b)}} = 0.13$; $R^2_{\text{(c)}} = 0.10$) indicate that there is no linear relation between the quality of the DTM and the vertical structure of vegetation. In fact, there is no relation judging by the point dispersion characteristics shown in Figure 10. The same tests and results were obtained when using the mean of the residuals per plot instead of the RMSE. In relation to the characteristics of plots in terms of vegetation cover, this means that the algorithm published in [21], together with the high density of the laser points per m^2 (in mean 10), is quite robust and insensitive to the obstacles on the terrain. In relation to the terrain slope, the results show that there is no relation between the slope and the RMSE of residuals, which contradict those found in other studies [12] but also support results from others [5].

The spatial distribution of the RMSE values per plot, the spatial point density and the flight lines, within the study area are illustrated in Figure 12. As in previous studies [5], there seems to be no relation between the RMSE values and the spatial distribution of the plots. It appears to be also no relation between the RMSE values and the spatial point density. This is not surprising once the mean point density is high. In Figure 12, it may be also seen that the RMSE values for plots situated along the same strip have no relation among them. Because the strips have been adjusted, and thus systematic errors removed, it may be stated that there is as well no relation between the RMSE values and bias strip differences.

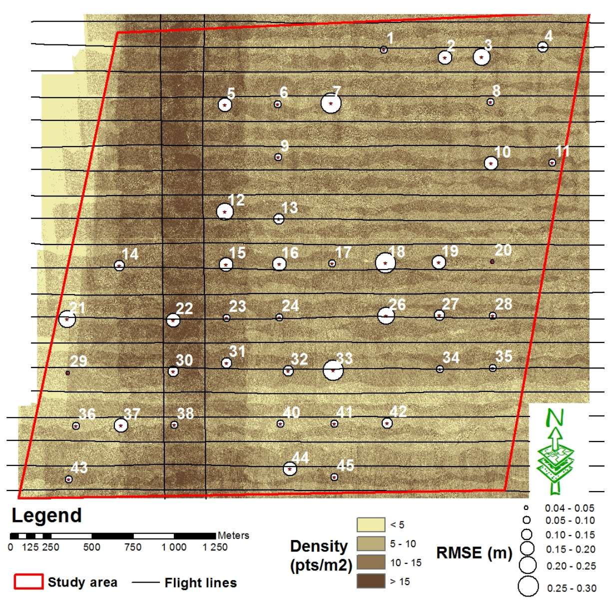

Fig. 12. Spatial distribution of the RMSE value per plot.

In order to verify the contribution of the quality of the FWALS data alone into the assessment of the quality of the DTM, the quality of the laser data was verified, as described in III-C. The accuracy measures, i.e., the mean and the RMSE of residuals are used instead of the robust estimators above mentioned because the distribution of residuals is considered normal (skweness and kurtosis equal to 0.067 and 0.268, respectively. See Figure 13 representing the Q-Q plot). The computed mean and RMSE are listed in Table IV. These values are quite good and similar to those obtained in previous studies ([26]). The worst is obtained for the arable land and results from the fact that the pole used for measuring sunk into the fresh soil for a few centimeters. This pole is used to transport the prism needed to measure the coordinates of the DTM points by topographic means. There is a bias that shows that the FWALS filtered points are above the terrain surface. Nonetheless, this bias value is insignificant for the majority of applications.

TABLE IV

MEAN AND RMSE VALUES OF RESIDUALS, PER SURFACE.

	Mean (cm)	RMSE (cm)
Paved road	2.8	3.2
Football field	1.8	3.4
Arable field	6.8	8.4

In addition to this evaluation of the accuracy of the FWALS data, the mean and standard deviation of the residuals between the h values of the *GPS bases* and those derived from the laser data at the same location were computed. A mean of 0.3 cm and a RMSE of 6.8 cm were obtained. This mean value of residuals is quite different from those computed in flat surfaces because whilst the *GPS bases* are spread all over the study area, and thus involving all the 30 laser strips, the other use only 7 laser strips, 5 of which are common.

V. DISCUSSION AND CONCLUSIONS

A study as the one here presented, carried out in an area of 900 ha with unmanaged eucalypt forest with great amount of high shrubbery, chaotic tree distribution and high tree density, is quite demanding. It requires an exhaustive and well-planned collection of reliable control data to properly assess the quality of FWALS data and of a derived DTM. The georeferencing of these data makes use of GNSS techniques, which are very time consuming in environments where a high density of high vegetation predominates. This is because under high vegetation, the GNSS receiver has to be stationed on the GPS-derived points for long periods of time

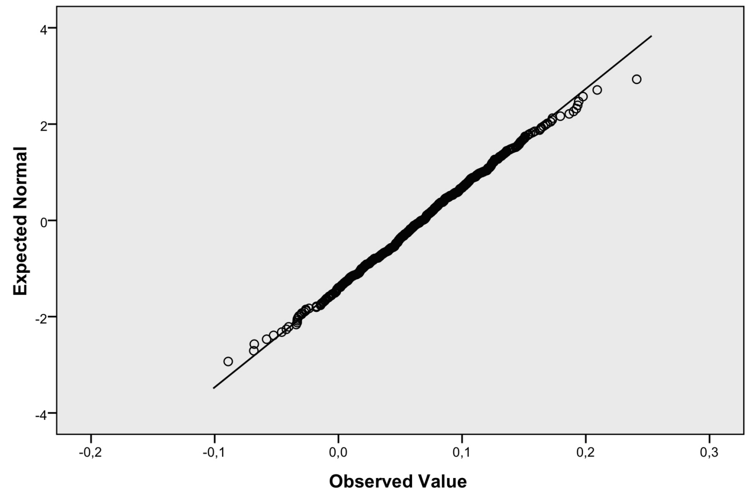

Fig. 13. Quantile-Quantile (Q-Q) plot of the distribution of residuals computed to assess the accuracy of the delivered laser data.

(the georeferencing of the GPS-derived points took approximately 170 hours). Furthermore, topographic measurements in plots covered with high shrubs are also difficult to execute.

The accuracy of the produced DTM is very good and suitable for a great number of applications. The value of 12 cm in RMSE is smaller than that published in several studies carried out in less chaotic forests (Table I; [1]). It also compares to the RMSE value claimed 12 years ago in [2], but for flat surfaces, and still referred in several studies. For similar surfaces, a value of 3 cm in RMSE was instead obtained. Although such a high DTM accuracy is not needed per se for this type of applications, such as forest inventory, acquiring very dense point clouds is recommended to describe the crown characteristics accurately, including total tree height ([1]).

Considering that the outgoing pulse width is 4 ns, the expected echo separation is 60 cm. Nonetheless, the full-waveform data processing algorithm detected 93 pairs of consecutive echoes with a separation smaller than 60 cm, among the 40 523 recorded pairs of consecutive echoes. It may be said that there is a slight improvement in echo separation, due to the post-processing wave analysis but it remains to be verified if all of the 93 pairs of echoes really relate to reflections.

The filtering algorithm based on the filter of [21] also proved to be very robust to terrain with the aforesaid characteristics. The low values obtained for the coefficients of determination R^2 between the RMSE values per plot and the percentages of the number of points classified by the filtering process as terrain, as shrubbery with height varying from 10 cm until 2 m and as higher vegetation cover indicate that there is not a relation between the quality of the DTM and the vertical structure of vegetation. This means that the Axelsson algorithm, together with a high density of the laser points per m^2 (in mean 10), is quite robust and insensitive to the obstacles on the terrain. The spatial distribution of the RMSE values per plot shows also no relation between the RMSE values and the spatial distribution of the plots as well as the spatial point density. The same conclusion was attained for the relation between the RMSE values and the mean terrain slope. Because this is not what was expected further studies are needed.

To conclude, the FWALS system proved to be adequate, in terms of data accuracy, for the production of DTM in areas of unmanaged high-density eucalypt forest. The accuracy figure of 12 cm for the DTM produced in such areas, using the data acquisition parameters listed in Table II and the Axelsson filtering algorithm [21], is also acceptable to derive forest canopy structure metrics.

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