State of the Art of Ground and Aerial Laser Scanning Technologies for High-Resolution Topography of the Earth Surface

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Abstract
Laser scanners have increased their efficiency exponentially when compared to state of the art ten years ago. More data can be acquired - and higher accuracy can be achieved - over longer ranges thanks to advancements in sensor technology. The goal of this review is to present state of the art of terrestrial and aerial laser scanner surveys with a critical discussion over quality, which is a very important aspect for high-resolution topography.

Keywords: Airborne/Terrestrial Laser Scanning, LiDAR, high resolution topography, error distribution, quality assessment

Introduction

Laser based geodetic measuring systems are improving constantly along with their potential for being applied in high-resolution topography, both from terrestrial sensors (TLS) and airborne/spaceborne sensors (ALS). This brings a positive trend to disciplines which require digital models of the ground (digital terrain models - DTMs) and of above ground objects (digital surface models - DSMs) on the earth surface.

This remarkable improvement in the past ten years has lead to an increased use of laser scanner data for high resolution topographic applications [Tarolli et al. 2009], and will very likely lead to an exponential increase of this technology for mapping and 3D modelling in the near future. The practical applications of state of the art laser scanning have been, and still are, thoroughly investigated by the scientific community. The potential fields of application for high-resolution information are numerous and still increasing. Archeology and cultural heritage use laser scanning for extracting shapes from terrain features under dense vegetation [Donneus and Briese, 2006]. High resolution digital terrain models are a critical component to modeling in geomorphology applications; channel network analysis [Vianello et al., 2009; Cavalli et al., 2012] and extraction [Pirotti and Tarolli, 2010; Sofia et al., 2011; Cazorzi et al., 2012] and landslide feature mapping [Cavalli and Tarolli, 2011; Tarolli et al., 2012] benefit from accurate surface models from laser surveys. Methods for the estimation of forestry parameters have been adopted since the early days of aerial laser scanning surveys [Pirotti et al., 2012b]. Since the laser beam can be affected by multiple reflections, often reaching the ground level, the acquisition of precious information both for terrain and canopy is allowed [Ackermann, 1999]. Point-clouds allow the extraction of metrics for the estimation of volume and biomass with a 3-20% error depending on forest structure and composition; tree-based [Popescu and Wynne, 2004] or area-based methods [Dubayah and Blair, 2000] can be used. A high point density (>20 points per m^2) also allows the discrimination of tree types (conifers vs. broadleaves) in certain study cases using ALS [Reitberger et al., 2009], as well as higher accuracy in terrain modeling under low and dense vegetation using TLS [Guarnieri et al., 2009].

Static terrestrial laser scanning, when confronted with ALS surveys, allows a more limited spatial coverage with irregularly distributed point density and often a certain degree of obstruction causing gaps [Pirotti et al., 2012a]. Nevertheless it provides high-quality and very high density information to be used for forest inventory [Maas et al., 2008], erosion risk assessment [Schmid et al., 2004] and applications where high density is an added value for prevention of natural hazards [De Agostino et al., 2012].

The first part of this work will report on the characteristics of high resolution surveys, especially regarding quality. The second part will analyse and discuss the methods to determine such quality in a laser scanner dataset.

High resolution laser scanning

A dataset originating from a laser scan survey is defined by resolution and accuracy of the elements in the point cloud. These two values are not constant in space, and vary to different degrees depending on several factors which will be discussed. In this note though, we correlate high resolution data with a point of one or more points per square meter. Point density depends on pulse repetition rate (PRR, which is usually reported in

thousand pulses per second, i.e. kHz), on the distance from the object and, in the case of a moving platform, on the speed of the vehicle. Table 1 and table 2 respectively report characteristics of recent TLS and ALS systems respectively. The performance of a sensor is tightly related to its ability to have high PRR keeping a high precision/accuracy standard. The limit to PRR depends mostly on the sensor, but an aspect which is even more a limiting factor in high resolution scans is the precision and accuracy of the points, which will be discussed in the following section.

Today sensors in the market have increased precision, accuracy and the range/PRR ratio (see table 1 and table 2 for references). The range is the maximum distance which can be reached by a pulse which can effectively provide a return signal. Range depends on PRR because the energy in a single emitted pulse decreases as PRR increases (figure 1). Sensors can provide very high PRR, but range limits have to be considered carefully in terms of the composition of the surface being hit (figure 1). This is especially true for high resolution surveys because often range limits are not taken into account due to the wrong conviction that a dataset with higher density is always better than a dataset with lower density. This can be true, but not in all cases.

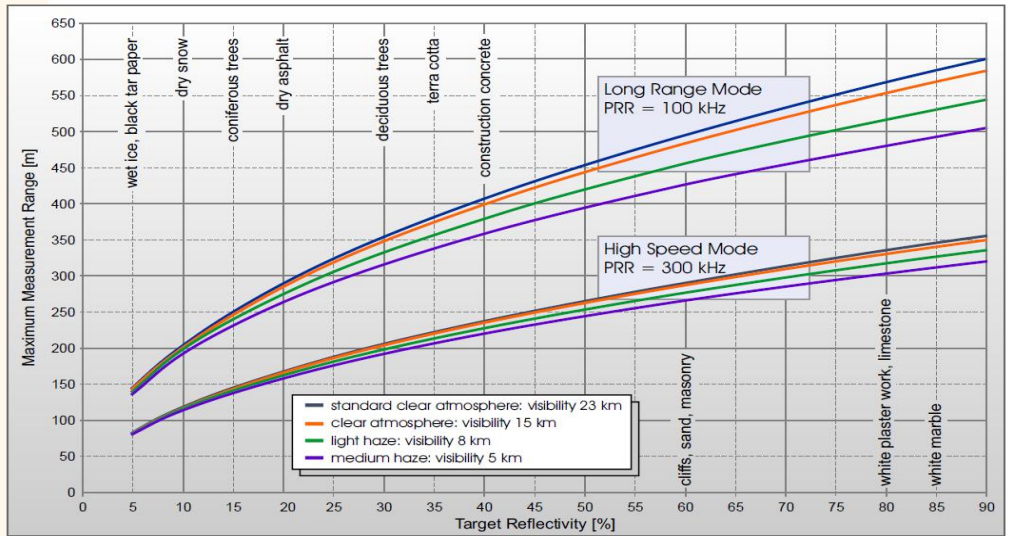


Figure 1 –Plot of maximum range as a function of object reflectivity and pulse energy on Riegl VZ-400 terrestrial laser scanner (from Data Sheet, RIEGL VZ-400, 03/04/2012 courtesy of Riegl ®).

Having determined that an increase in resolution means more points, but also requires higher accuracy and more overall quality, it is important to assess what components are significant for quality. Another important aspect is that a laser scanner dataset will not have a constant quality in the spatial domain, as point density, positional accuracy, scan geometry and surface morphology vary constantly during the survey.

Table 1 - Terrestrial Laser Scanning Systems with range greater than 100 m

Sensor Information				Laser Pulse Characteristics				Precision and Resolution		
Company and Model	Date of introduction	Weight [kg] (sensor)	Range measuring principle	Wavelength [nm]	Min. / max. range [m]	Beam diameter at exit [mm]	Beam divergence/spot (50 m distance) [mm]	Pulse frequency # (min-max) [kHz]	Range accuracy [mm] (σ)	Scan angle accuracy H/V [mD] (σ)	Range resolution [mm]
FARO Photon 120	2009	14.5	phase	785	0.6 / 120	3.3	3	122 - 976	2@10m		
FARO Photon 20	2009	14.5	phase	785	0.6 / 120	3.3	3	122 - 976	2@10m		
Leica Geosys. ScanStation C10	2009	13	pulse	532	0.1 / 300	6	6	50	4@50m	3.4	<1mm
Leica Geosys. ScanStation 2	2007	18.5	pulse	532	<1m / 300	6	6	50	4@50m	3.4	<1
Maptek I-Site 8800 LSS	2010	13.8	pulse	Near infrared	2.5 / 2000	8	12	8.8	10	10	1
Optech ILRIS-HD	2008	14	pulse	1535	3.0 / 2000	9.2	12	10	7	3	0.1
RIEGL VZ-400	2008	9.8	pulse	near infrared	1.5 / 600	7	18	300 (122)	5	0.5	1
RIEGL VZ-1000	2010	9.8	pulse	near infrared	1.5 / 1200	7	18	300 (122)	8	0.5	1
RIEGL LMS-Z620	2008	16	pulse	near infrared	2 / 2000	14	16	24 (11)	10	2.5	1
Trimble GX	2005	13	pulse	532	2 / 350	N/A	3	5	3	1.7	

(Information extracted and revisited from GIM International Magazine Product Survey, August 2010)

Points emitted per second, also called Pulse Repetition Rate (PRR)

Table 2 - Airborne Laser Scanning Systems

Sensor Information			Laser Pulse Characteristics						Precision and Resolution		
Company and Model	Date of introduction or update	Wavelength [nm]	Pulse length [ns]	Beam divergence [mrad]	Scanning method *** Scan frequency [Hz]	Pulse frequency # (min-max) [kHz]	Max. scan angle (FOV) [deg]	Max. echoes/ pulse Waveform digitazation (Y/N)	Pulse sampling frequency	Pointing precision (roll / pitch / heading) [mdeg]	Elevation precision at 1km (σ) [cm]	Planimetric precision at 1km (σ) [cm]
IGI mbH LiteMapper 2400	2010	905	8	2.7	1 29	30	60 - 80	1 N	-	8/ 8 / 15	<7 *	<7 *
IGI mbH LiteMapper 5600	2010	1550	3	0.3	1 10 - 160	240	60	∞ Y	1 GHz	3 / 3 / 7	<7 *	<7 *
IGI mbH LiteMapper 6800	2010	1550	3	0.3	1 10 - 200	400	60	∞ Y	1 GHz	3 / 3 / 7	<7 *	<7 *
Optech ALTM Gemini	2006	1064	7 ns	0.8/0.25 I/e	2 70	167	50	4 Y(opt.)	<2.0 m	2.5 / 2.5 / 5	<10	35 **
Optech ALTM Orion M/C	2008	1064	<7 ns	0.25 I/e	2 70 / 90	200	50	4 Y(opt.)	<0.7 m	5 / 5 / 8	<10	15/25 **
Optech ALTM Pegasus HD500	2011	1064	<7 ns	0.25 I/e	2 140	500	65	4 Y(opt.)	<1.0 m	5 / 5 / 8	<10	20 **
RIEGL VQ-580	2010	1064	3 ns	0.2 mrad	1 10 - 100	50 - 300	60	∞ Y(online)			3 - 5 *	3 - 5 *
RIEGL LMS-Q680i	2010	1550	3 ns	<0.5 mrad	1 10 - 200	80 - 400	60	∞ Y(offline)	1 GHz		2 - 4 *	3 - 4 *

(Information extracted and revisited from GIM International Magazine Product Survey, February 2011)

Points emitted per second, also called Pulse Repetition Rate (PRR)

* Without GNSS/INS Error

** Accuracy σ (RMSE) (Ussyshkin & Theriault, 2010)

*** 1 = Rotating multi-facet mirror 2 = Oscillating mirror

Quality assessment of high resolution dataset

Quality is commonly intended as an indicator of how close a certain characteristic is to a defined reference value. A dataset from a laser scanner has a number of characteristics which define the overall quality of the scan dataset. This value defines a threshold for tolerance to decide suitability/acceptance of the final product for a certain end-user. The threshold values of quality indicators necessarily have to be more stringent if a high resolution product has to be derived from high resolution laser scanner data. Investigations on the topic have mostly regarded regularly-spaced grid representations of the terrain (i.e DTMs and DSMs). Minimum grid spacing, precision and tolerances related to scale, terrain morphology and type of land cover (e.g. covered by vegetation or not,

urban area or bare ground) have been defined in literature [Ackermann, 1980; Flotron and Kolbl, 2000; Cilloccu et al., 2009]. Robust methodologies have also been defined regarding the distribution of factors affecting quality over the survey area in relation to incidence angle between pulse and ground plane (or an estimate thereof), distance travelled by pulse, and point density [Skaloud, 1999; Karel et al. 2006].

Quality of laser point position

The positional accuracy of each single point in the 3D scan space can be calculated from the following two types of reference frames: an absolute cartographic reference frame (*real world*) , and a relative reference frame represented by a reference "master" scan cloud (*scan world*). The quality assessment of position accuracy is carried out measuring the difference between corresponding point pairs (control points - CPs) in the point cloud and in a reference frame. CPs are measured with high precision topographic tools, e.g. DGPS, in the *real world* frame, or corresponding features in the *scan world* frame. The irregularly spaced points in the laser cloud do not allow to easily match CPs with corresponding objects, like it is the case with classic photogrammetry, where CPs can be defined with sub-pixel accuracy using chromatic contrast in targets [Mikhail et al., 1984; Ackermann, 1995]. The definition of CPs in point clouds needs to exploit the geometry of regular objects. To a lesser degree also return intensity can be used as support where specific elements allow to detect enough contrast (e.g. road pavement markings [Toth et al., 2007]). Registration of points clouds can be target-based which uses *ad hoc* positioned man-made targets, or surface-based, using directly the point cloud matching overlapping elements. Generally in both cases an iterative least-squares algorithm is used to minimize error metrics. The most common algorithm is the Iterative Closest Point (ICP) algorithm [Chen and Medioni, 1992]. Alignment methods use primitives which can be extracted keypoints (e.g. using SIFT or spin-images) [Huber and Hebert, 2003], segments, corners, local planes, or specific shapes like spheres or cubes. Surface-based methods use geometries derived from the scan itself, either directly using objects which have regular geometries (planes, building corners, roofs) or virtual geometries derived from intersections and other mathematical procedures [Theiler and Schindler, 2012]. Target-based registration is not commonly used in aerial surveys as it would require a significant expense in terms of time and money for distributing a suitable number of targets correctly in the area.

Precision and accuracy of positioning and orientation system

Precision and accuracy depend on sensor characteristics. In the case of sensors in moving platforms, they are also, and often to a greater degree, influenced by the accuracy of the inertial navigation system (INS) and of the differential global positioning system (DGPS) which together provide an estimate of orientation and position respectively of sensor center at the instant of laser pulse emission [Schaer et al., 2009]

Quality of estimated position in space

GPS positions, when using differential corrections from a permanent station (PS) at a distance (baseline) of 10 km between PS and GPS, have an estimated RMSE of 0.1 m (10 ppm of fixed GPS solution). Higher accuracy could be achieved by using a network-based solution, with multiple baselines instead of a single baseline; virtual reference

stations can also be included in the network to increase accuracy [Toth and Brzezinska, 2007].
The scan geometry, along with the morphology of the scanned surface and the scanner-to-target range, can increase the error as a function of the incidence angle of the pulse with the surface. Because data quality degradation, for the above-cited reasons, can potentially be estimated in real-time, a high-profile topic of investigation is the in-flight assessment of data quality [Skaloud, 2011], which would detect, a drop in quality. This would remove part of the quality control procedures necessary in post-processing.

Quality of estimated pulse direction
The three angles which define direction of the laser pulse in space are defined by vehicle orientation together with the internal moving parts of the sensor which make up the scanning mechanism such as the rotating or oscillating mirror. The vehicle orientation is measured by the INS sensors, therefore the magnitude of the errors depend solely on the quality of the INS and on its correct calibration. In table 1 and table 2 the precision of the angle measurements are reported. Static terrestrial laser scanners' positioning errors only depend on angle and distance errors intrinsic to the instrument, which can be limited by a sound calibration habit [Cuartero et al., 2010].

Precision and accuracy of range measuring system
It is true that most of the error in point positioning in mobile systems is due to the INS/GPS errors, nevertheless the time-of-flight (TOF) measurement adds a variable to the error equation. In this paper we report on TOF as opposed to other methods for measuring range because most aerial and long-range terrestrial laser scanners adopt this strategy. The return signal is processed internally to determine the range of the object which caused the reflection. The Constant Fraction Discriminator is a common method [Toth and Brzezinska, 2007] along with others, to determine the threshold above which to record the time-of-flight for calculating range [equation 1].
The range *R(t)* is calculated using the speed of the laser pulse:

$$R_{(t)} = T_n \frac{c}{2\left(1 + 78.7\frac{P}{273.15 + \vartheta}\cdot 10^{-6}\right)} \qquad [1]$$

where c is the speed of light (2.99792458×10^8 m/s), P is atmospheric pressure in mbar and ϑ is air temperature in degrees Celsius, T_n is the time interval between the maximum value of the outgoing pulse (*T0*, see figure 2) and the first sample over the baseline of the return waveform pulse segment. Pressure and temperature in the error budget are considered for the sake of comprehensiveness - a difference of 30° C and 200 mbar pressure brings a difference of about 3 mm which is not significant considering the magnitude of the other sources of error.
Quality of range measures also depends on the sampling interval and the complexity of the return signal, which, as can be seen in figure 2, can vary. The final precision, depicted in table 1 and table 2, of the sensor heavily depends on the precision of the above-

described range measurement and on the internal precision of the measures of angles of the scanning mechanism.

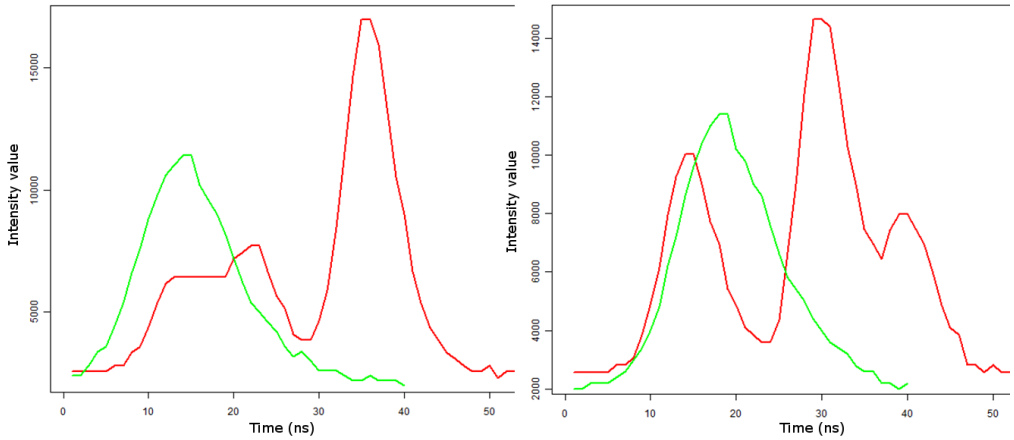


Figure 2 – Two examples of segments of return signal, each with two segments (green and red).

Spatial resolution and point density

The number of points in the 3D space which sample the object being scanned is typically the first characteristic that is referred to in a survey, even more so when oriented to high-resolution products. It can be expressed as pulse density or as point density; the former being the number of pulses which intersect a unit area, the latter the number of returns actually present in a unit area. Both depend on sensor settings (i.e. PRR, scan rate), survey mode (speed of vehicle) and on the geometry of the objects which are being scanned. The point density should be equal to or greater than the pulse density, unless the signal is dropped because the object distance is out of range. Most sensors today provide at least first and last return, usually four returns, and at most the full waveform of the return pulse which allows in principle an infinite number of returns to be detected. The laser beam can be compared to a conical shape whose summit is at the sensor center and base towards the earth surface [Mallet and Bretar, 2009]; its projection towards the earth surface can be partly occluded by vegetation, building edges and anything which does not cause complete occlusion thus causing partial loss of the pulse energy. Point density is therefore not a constant value due not only to the above cited causes, but also due to variation in sensor orientation during movement (figure 3D) , overlapping survey strips (figure 4 - top), and scan geometry. The distance map can be used as a reference to infer areas where the scan geometry caused very low point density, thus where a potential lower accuracy might be expected.

The density of the points is directly correlated with quality of the final digital elevation models because areas sampled with less points will degrade the interpolation accuracy due to lack of information. An important measure of quality can be expressed by the distance map [Karel et al., 2006] which reports the distance between the cell center and the points which are used to calculate the cell value (figure 3).

Point density alone is not enough to discriminate quality among laser scanner surveys, as accuracy plays a critical role, especially among high density surveys. A very high resolution survey lacking accuracy only leads to low-quality products which are prone to

misinterpretation. In the previous section we described the most significant factors which contribute to the error budget related to measurement. Other characteristics of laser scanning technology which are related to spatial resolution of the sampling is the angular resolution and the spot size. A typical laser scanner can have an angular sampling step of 0.001° and a beam width of 0.2 mrad (see table 2 and 3). This would correspond, at a distance of 100 m, to a distance between consecutive points of ~1.8 mm and a footprint diameter of ~20 mm. [Lichti and Jamtsho, 2006; Pesci et al., 2011] well outline the importance of spot size related to the spot spacing and to the size of the elements which have to be modeled, concluding that each instrument has an optimal sampling step (angular resolution) required to achieve a certain object separation.

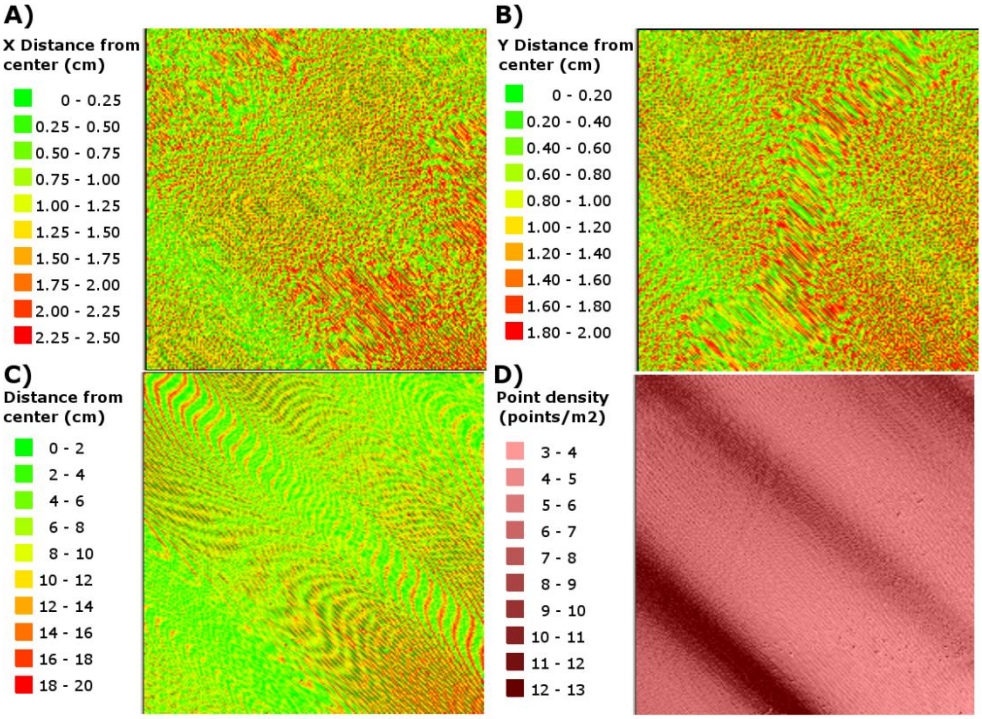


Figure 3 – A)-C) are distance maps respectively in the X, Y and absolute distance. D) represents pulse density (pulses/m^2).

Figure 4 shows on top the variability in point density due to orientation variation along flight (pitch angle), and on the bottom the density of only points classified as ground with Axelsson's [1999] progressive triangulation algorithm. The density is sensibly lower in the part covered by vegetation (top left), and is distributed more homogenously due to the method which is applied.

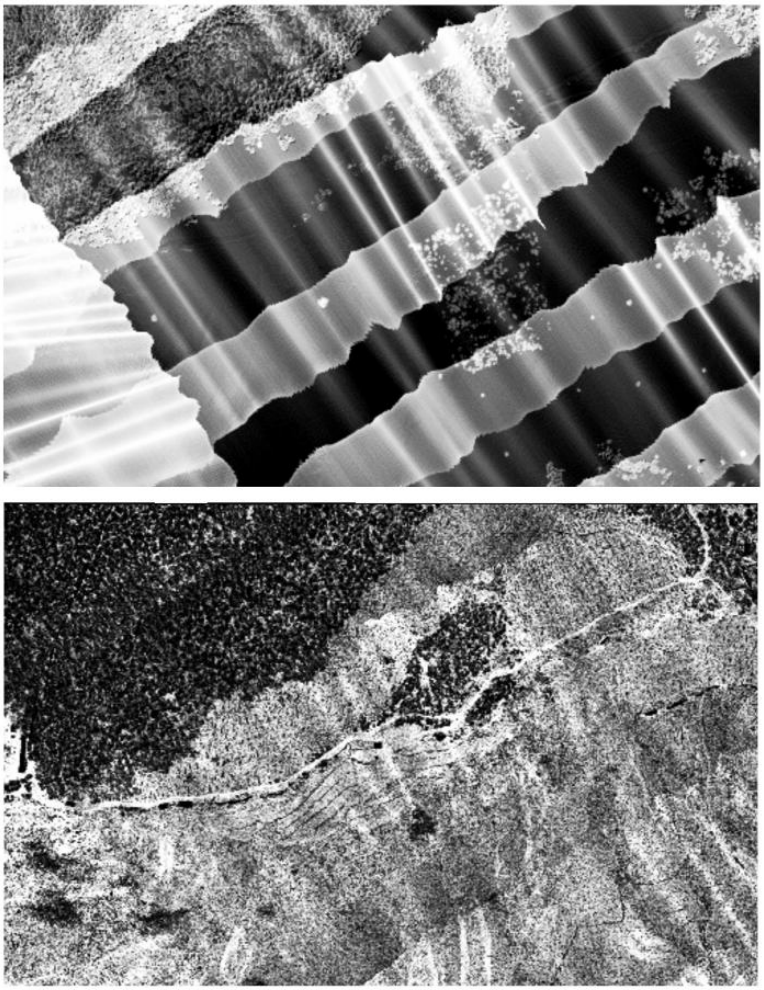


Figure 4 – Point density distribution (lighter colors for higher density); the top image includes all points, the bottom image represents ground only.

Metrics of accuracy and precision

Quality is assessed by providing indicators of positional accuracy and precision by measuring the difference between laser points (P_L) and ground control points (P_{GCP}) which have been positioned with higher accuracy methods (usually one order of magnitude); $e = P_L - P_{GCP}$. Accounting for the three directions in the 3D space it is:

$$e_m = \sqrt{\Delta x^2 + \Delta y^2 + \Delta z^2} \qquad [2]$$

where x, y and z are the coordinates of corresponding points in 3D space. The error metrics are usually basic statistics of the error distribution; the minimum and maximum value (i.e. range), the mean (μ), the standard deviation (SD) and the root mean squared of

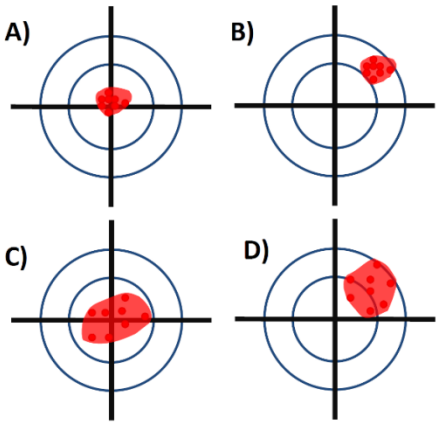
errors (RMSE). The last two metrics describe dispersion (precision, i.e. random errors) and accuracy (i.e. systematic errors). They are respectively:

$$\mu = \frac{1}{n}\sum_{i=1}^{n}\Delta x + \frac{1}{n}\sum_{i=1}^{n}\Delta y + \frac{1}{n}\sum_{i=1}^{n}\Delta z \quad [3]$$

$$SD = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(e_i - \mu)^2} \quad [4]$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}e_i^{\,2}} \quad [5]$$

where n is the number of observations (points).
Maximizing accuracy can in some part be related to an operational phase which takes good care of planning of the survey. Considering a joint use of TLS and ALS and a educated choice of sensors can decrease survey times, processing time and overall costs. Pfeifer and Briese [2007] have discussed the geometrical aspects of both technologies, highlighting the need for exploiting the use of ground control and/or more reference stations for DGPS.



A) High precision ~1, high accuracy ~1
bias (μ) ~0

B) High precision ~1, very low accuracy ~15
bias (μ) ~15

C) Low precision ~4, low accuracy ~4
bias (μ) = 0

D) Low precision ~4, very low accuracy ~16
bias (μ) ~15

Figure 5 – Schematic representation of measure quality; the two concentric circles represent a nominal distance from the center of 10 and 20.

Conclusions

In this paper certain aspects of high resolutions surveys have been considered and discussed. The importance of accuracy for earth surface, high resolution, surveys has been analysed in terms of the factors that influence positional accuracy, range, point density and quality of the final product. It is possible to conclude with a few considerations. First

of all the "more point density is better" is not necessarily true, but depends on the complexity of the surface and its composition. What must be carefully considered is the use and the end-product of those points. In Pirotti and Tarolli (2010) it is clearly reported how channel extraction does not always improve with an increase in point density. This can be the case with other applications. A more important aspect than point density is the accuracy in the absolute positioning of the points. Less, but more accurate, points are a much better deal than more but less accurate points. It is therefore crucial to assess the quality of a laser scanner dataset. Ideally ground control points for RMSE calculation should be distributed considering areas which are likely to have lower accuracy, but low accessibility does not always allow easy measurement (e.g. in mountain areas). For this reason, a planning phase which considers factors affecting quality as described in this paper can be useful. It might be the case that a lower scanning resolution might decrease survey time without affecting the final product. A combined TLS and ALS survey might be a winning strategy to cover the respective limitations due to scan geometry (e.g. occlusions due to complex morphology in mountain areas). Minimizing errors can be done operationally by a deeper understanding of sensors characteristics and of their implications.

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