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EVALUATION OF DIFFERENT SCAN CONFIGURATIONS FOR AN EFFECTIVE FIELD PROCEDURE ON A TERRESTRIAL LIDAR SCANNER IN TROPICAL FOREST

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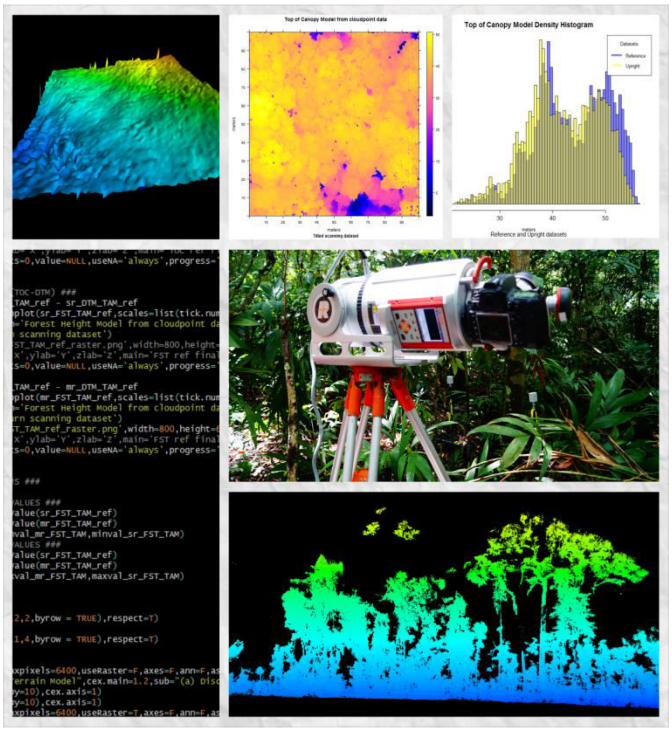
12th March 2014



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Evaluation of Different Scan Configuration for an Effective Field Procedure on a Terrestrial LiDAR Scanner in Tropical Forest

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Foreword

LiDAR has been developing for the last 20 years; however its main use was for civil engineering and architecture mostly. During the last years, researchers found out that this technology can be also applied for natural resource management, especially forestry. However, it is not completely understood the potential and its application; this is why I was really interested in this topic. My first insight in LiDAR was during the Advanced Earth Observation classes, in which we used a sample tree to extract parameters. This enable a spark on me, because I believe this technology was really new and I wanted to learn more about his. When I was looking for a thesis topic; an opportunity appeared; going back to my country, Peru, for a fieldwork scanning plots with a Terrestrial LiDAR. Without a doubt, I took the topic. During 6 weeks I learned, not only how to use the software, but also, how to use the LiDAR itself. Soon, I realized the advantages and limitations the LiDAR could have, and more important, there is no standard methodology for scanning in tropical forest. This is a unique opportunity for investigating the possibilities LiDAR can achieve in tropical forest.

I enjoyed working on this topic, this topic still under development, and I feel I can contribute a little bit with my research. This is why, my supervisor and me decided to publish this minor thesis as a scientific paper; in this case; in Remote Sensing Letters. For this reason, the format of this research is based on the Remote Sensing letters format template. We believed that this research should be known by the scientific community and be a start of LiDAR scanning procedures in tropical forest. This would be my first publication and will help to improve my academic skills.

Alvaro Lau,

Wageningen, March 12th 2014

Evaluation of different scan configurations for an effective field procedure on a Terrestrial LiDAR Scanner in Tropical Forest

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Despite the advances in forest measurements, characterizing parameters using a terrestrial laser scanner (TLS) still remains a challenge. This challenge is mostly due to the quality of the scan, technical constraints of the scanning system and adverse environmental conditions. A wide range of laser scan systems are commercially available today, and among those, partial hemispherical systems are the most common. These systems do not allow you to scan on a zenith angle and; therefore a second scan, on a tilted position, is necessary. A full hemispherical scan can be achieved by merging both scans. However, the use of a second scan increases project's budget. Knowing in advance the scan configuration needed for specific parameters, will benefit the fieldwork procedure. This study investigates the need of the second scan for three parameters, digital terrain model (DTM), forest height (FST) and top of canopy (TOC). In this study different setups (discrete-return and multiple-return) and different resolutions (0.5 m and 1.0 m) were analysed. First, RMSE residuals of up to 2.3 m proved that discrete-return scans could not achieve the same accuracy as multiple-return scans. Then, visual assessment of the rasters indicated the presence of outliers at 0.5 m, compared to 1 m resolution. This was confirmed by standard deviation; where 1 m resolution raster showed less dispersion than 0.5 m resolution raster (e.g. 9.23 % less dispersion for FST parameter). Finally, RMSE was calculated for the different parameters at 1 m resolution. For the DTM parameter, upright scans showed 78 % more accuracy than tilted ones, with a RMSE below 0.5m. However, for the FST parameter, upright scans Is only 6 % more accurate than tilted scans. For the TOC parameter the tilted scan is 12 % more accurate than the upright scan. Despite of the results, RMSE residuals are still too large (around 1 meter difference) to confirm the exclusive use of one scan (upright or tilted) to calculate these parameters. This study proved that using both scans, upright and tilted, for these parameters is the most effective way to have accurate forest measurements.

Keywords: terrestrial laser scanning, forestry, tropical forest.

1. Introduction

Forest mensuration has been traditionally based on plot-scaled ground-based measurements combined with aerial photography. Ground-based measurements provide quantitative measurements, whereas aerial photography provides spatial patterns (Dassot et al. 2012; Donohue et al. 2007). However, ground-based measurements are often constrained by physical accessibility, efficient measurement techniques, trained personal and right equipment (Lovell et al. 2003). Moreover, measurements of individual trees are time consuming, labour-intensive and expensive to implement in large scale (Dassot et al. 2012). Some parameters, such as biomass, can only be measured by destructive sampling. This is why it is usually indirectly estimated based on other parameters, such as tree height and diameter (Kankare et al. 2013; Saatchi et al. 2011).

Due to the challenging limitations existing for traditional techniques (Lovell et al. 2003; Dassot et al. 2012; Keightley and Bawden 2010; Kankare et al. 2013; Saatchi et al. 2011), several innovative remote sensing methods have been developed to overcome these limitations (Rosell et al. 2009; T. Yao et al. 2011; Reitberger et al. 2009).Among others, LiDAR (Light Detection and Ranging) has the potential to provide detailed information about forest structure because it effectively adds a third dimension -range- to the data and intensity values at a specific wavelength (T. Yao et al. 2011; Reitberger et al. 2009; Hudak et al. 2009). Despite the new techniques, characterizing parameters using terrestrial laser scanners (TLS) in forest environments still remains a challenge, especially for tropical rainforest (Clark et al. 2011).

Before 2004, TLS market was dominated by discrete-return instruments. These systems can only record a few (n ≤ 5) individual ranges per pulse (Parrish and Jeong 2011). Nowadays, full waveform LiDAR or multiple-return LiDAR is widely used for forest parameter analysis. The waveforms are decomposed to produce a denser 3D point cloud density, providing more detailed information about the reflecting characteristics of trees than discrete-return LiDAR systems (Mallet and Bretar 2009; Hudak et al. 2009; W. Yao et al. 2012). This advantage is used to estimate and improve forest parameters on the waveform shape (Mallet and Bretar 2009).

The RIEGL VZ-400V-Line 3D is a full-waveform LiDAR with a scan configuration in the horizontal of 360 degrees and in the vertical of 100 degrees, from -40 degrees up to +60 degrees zenith (Riegl 2013; Béland et al. 2014). In other words, the RIEGL VZ-400 does not collect data above 30 degrees zenith per scan and therefore is not able to directly collect a full hemispherical scan. For parameters such as Diameter at Breast Height (DBH), Digital Terrain Model (DTM) or Digital Elevation Model (DEM), this might not be an issue; but for parameters such as canopy height, and crown diameter, the lack of data above the instrument may have a substantial effect on the measurements (Newnham et al. 2012).

This issue can be overcome by combining multiple scans to achieve a full hemispherical data acquisition. After the upright scan, in which the laser head is positioned in vertical position; a second scan (tilted scan), with the laser head tilted at 90 degrees, can be done in order to fulfil the existent gap. Then, both scans can be stitched into one tilted-upright scan using specialized software (Newnham et al. 2012; Hopkinson et al. 2004; J. G. Henning and Radtke 2008).

The inclusion of a second scan extends the measurement time. An average time-of-flight scanner generally requires between 5 to 25 minutes per scan (Kemeny and Turner 2008; Bienert et al. 2007; Olsen 2012), dependent on the point spacing. This means that only 5 to 10 scans can be performed per day (depending on terrain, weather conditions, scan area, vegetation density, travel time to each site, etc) (Kemeny and Turner 2008; Perroy et al. 2010) and the need for a second scan prolongs the time spent on scanning.

The purchase cost of a TLS instrument is no less than ~ €29,000 euros (Eitel et al. 2013)and the commercial rate (in 2008) of the scanner per day is around €970 – €3,000 euros; the lower end just for the equipment rent and the higher end for the equipment rent, trained operator and spatial pre-processing (Grayson et al. 2012). Knowing beforehand which kind of scanning configuration is needed for each tree parameter, a more efficient allocation of resources (time and money) can be done in order to use them, minimizing costs and maximizing the sampling (Pueschel 2013). Even though, no optimal scan configuration has been established (Hopkinson et al. 2004), knowing beforehand the factors which influence scan collection, allows the adjustment of the measurement set-up to maximize the quality of the data collected (Van der Zande et al. 2006). Hence, the general objective of this research is to evaluate the need for a full hemispherical scan setup. This study will focus on three parameters, Digital Terrain Model (DTM), Forest Height (FST) and Top of Canopy (TOC). In order to accomplish the general objective, the following research issues will be investigated; a) confirm if discrete-return can achieve the same accuracy as multiple-return scan setup, b) determine which raster resolution (0.5 m or 1 m) has to be used for accurate parameter estimates and c) to evaluate the need for a full hemispherical setup.

2. Study area and data acquisition

We chose four plots, located in tropical forest; two of them placed in the West African forest (Gabon) and the other two in the Peruvian Amazon. The selected plots are managed by the Global Ecosystem Monitoring network (GEM), from the School of Geography and the Environment, University of Oxford, United Kingdom. Each plot comprises an area of 100m by 100m, with a regular square sample pattern of 20m by 20m. TLS scans of the GEM plots were collected between August and October 2013.

The plots in Gabon, Mondah1 and Mondah2, are located in the Akanda National Park, a wet evergreen forest, with an average altitude of 70 m.a.s.l. Mondah1 is a monodominant forest (Aucumea forest), and Mondah2 is an old growth mixed forest. The plots in Peru, Esperanza and Tambopata, are located in the Manu National Park and Tambopata National Reserve respectively. The Esperanza plot is located in the amazon cloud forest at 2,500 m.a.s.l., with a 30° slope; while the Tambopata plot is located in the amazon basin, at 700 m.a.s.l.

The data was acquired using the RIEGL VZ-400V-Line 3D© TLS [RIEGL Laser Measurement Systems GmbH, Horn, Austria, www.riegl.com], mounted on a survey tripod about 1.5m above the ground. The scanning process covered 360° azimuth and -40° to +60° zenith range; with an angular resolution of 0.06. For each plot, measurements on each scan positions were done, following the 20 m by 20 m sample pattern. In each scan position, two scan configurations were acquired: an upright scan and a tilted scan. In the Esperanza plot the upright scans were done at 30 degrees (perpendicular the slope) and two extra scans, on the first and last position, were acquired with a tilt of 0 degrees in order to level the point cloud.

Figure 1. Study area and data acquisition. (a) shows Mondah1 and Mondah2 plots, located in Gabon, Africa; while (b) shows Tambopata and Esperanza plots in Peru, South America. RIEGL VZ-400V-Line 3D© TLS in tilted scan configuration can be seen in (c).

Each scan produces a point cloud, which origin refers to a fixed scan position of the scanner. In order to co-register each point cloud, cylindrical reflectors (tie-points) were located throughout each plot, in a way that the tie-points can be detected from multiple scan positions. Besides the scan, GPS measurements, tripod height, scan orientation and hemispherical pictures were taken on each scan position.

3. Methods

3.1 Pre-processing point clouds

Co-registration of the point cloud was done using RiScan Pro$^{©}$ software [RIEGL Laser Measurement Systems GmbH, Horn, Austria, www.riegl.com]. Standard deviations of co-registered tie-points were smaller than 0.005 m. Since discrete-return instruments are more common and cheaper, and due to the multi-return characteristic of the TLS used in this study; a simulated discrete-return setup was also created by filtering only first and single return point cloud per scan. Our study assumed that multi-return point cloud has the maximum achievable accuracy. Because of this, our study aims to see if discrete-return point cloud can achieve the same accuracy as multi-return scans. Three scenarios were set; an upright scenario: generated from the upright scans; a tilted scenario: generated from the tilted scans; and finally, our reference scenario; which is the merged upright and tilted scans.

In order to create the Digital Terrain Model (DTM) and Top of Canopy Model (TOC) for each scenario, the 2.5D raster function in RiScan Pro was used. For the DTM and TOC rasters, “true minimum” and “true maximum” option was selected respectively. This option uses the true horizontal coordinates of the points within a single raster cell to produce points which are not evenly distributed, by not placing them in the centre of the 2D raster cells. Finally, these scenarios are created at 0.5 m resolution and 1 m resolution raster. Finally, we exported the rasters to ASCII files for further analysis.

3.2 Statistical analysis

The statistical analysis of this research is done in R$^{©}$ (R Core Team 2013). The packages “sp” (Pebesma and Bivand 2005), “raster” (Hijmans 2013), “HydroGOF (Zambrano-Bigiarini 2013) and “scales” (Wickham 2012) are used for the analysis. The input ASCII files were imported and converted to a raster. NA values were eliminated using the focal function and the outer 10 m border was cropped in order to eliminate external influences. The following parameters were generated from these rasters:

- Top of Canopy Model(TOC)
- Digital Terrain Model (DTM)
- Forest Height (FST)

The Forest Height raster was computed by subtracting the DTM from the TOC (Edson and Wing 2011), as seen in equation (1).

$$FST = TOC - DTM \tag{1}$$

The estimation parameters of error based solely on observed error at test points can be calculated by the Root mean square error (RMSE) (Heuvelink 1999). RMSE shows the difference between values predicted and values observed. This difference is called residual, which ranges from 0 to infinite, with 0 being a perfect forecast to the observed scenario. Because it is a square quantity, RMSE is influenced more strongly by large error than small errors and is defined mathematically as seen in equation (2):

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2} \tag{2}$$

where y_i denotes our assessed value; $\hat{y}_i$ denotes our reference value; and n denotes the number of verifying points. First, we used the RMSE (in meters) to compare discrete-return rasters (y_i) with multiple-return rasters ($\hat{y}_i$). This aims to confirm if discrete-return data can achieve the same accuracy as multiple-return data. After that, visual assessment and standard deviation was calculated for 0.5 m and 1.0 m raster resolution in order to determine which resolution has less dispersion around the mean. Data with outliers had greater standard deviation than the data with no outliers. Outliers denoted the presence of misplaced points and evidenced the accuracy of the resolution. Finally, our study compared the tilted and upright scenarios (y_i) against our reference value ($\hat{y}_i$). RMSE of tilted and upright scenario were compared in order to evaluate the need of a full hemispherical scan setup

4. Results and discussion

4.1 Discrete versus multiple-return scan setup

Figure 2 shows the reference TOC scenario for Tambopata plot. While Figure 2a shows the discrete-return raster, Figure 2b shows the multiple return raster at 1.0 m resolution. Even though only little difference can be visually appreciated between the rasters; the density histogram; Figure 2c shows the difference between discrete-return (yellow) and multiple-return (blue). Statistical analyses for Tambopata plot revealed that the standard deviation for the discrete-return scan was 6.1 m, while for the multiple-return scan was 6.09 m. Deeper analyses, using RMSE denoted that the deviation of discrete-return scans from multiple-return scans could extend from 10 cm up to 2.3 m (Table 1).

At 0.5 m resolution, DTM showed a residual of 0.367 m. This stated that discrete-return rasters had a residual of 0.367 cm against multiple-return rasters. These residuals were higher for FST and TOC, with 2.2 m and 2.3 m respectively. In other words, the discrete-return FST raster differs in 2.2 m from multiple-return FST raster. At 1 m resolution, RMSE decreased; for DTM, the difference between discrete-return and multiple-return point cloud was 0.177 m. Nevertheless, residuals for FST and TOC were 1.33 and 1.38 m respectively. Our results evidenced the idea that discrete-return scans cannot achieve the same accuracy as multiple-return scans.

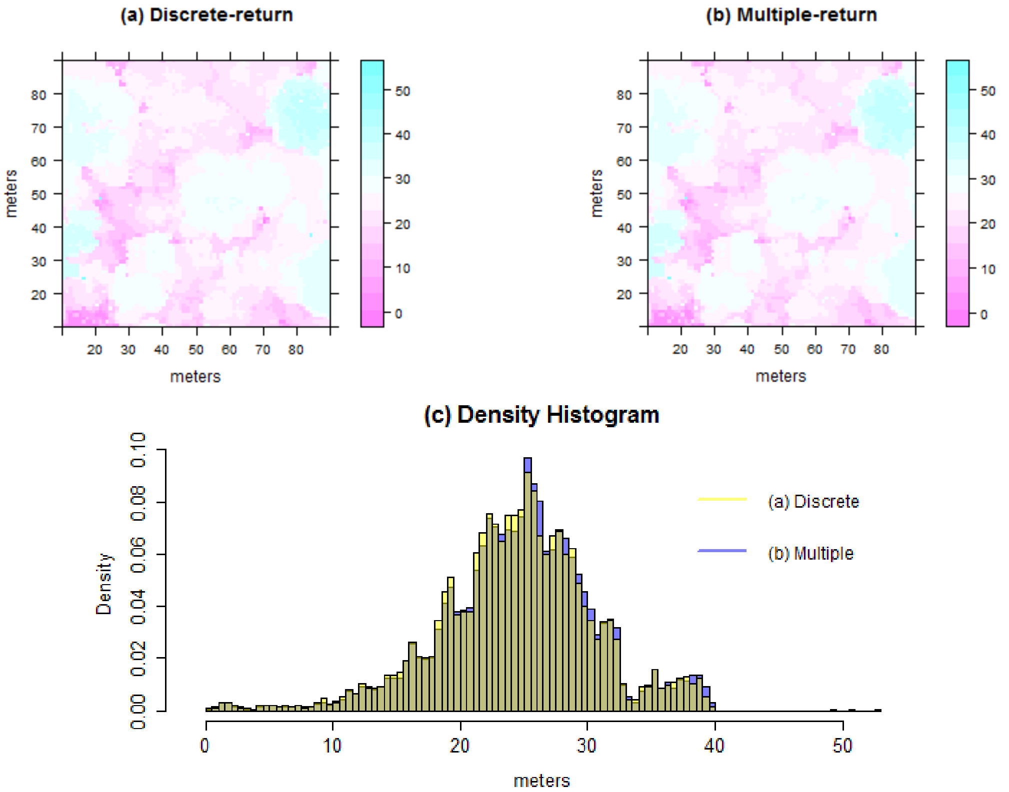

Figure 2. Tambopata reference plot at 1.0 m resolution. (a) shows discrete-return Top of canopy model, (b) shows multiple-return Top of canopy model, and (c) shows the difference between discrete-return and multiple return.

Similar findings were reported by Mallet (2009), Pirotti (2011), Clark (2011), and Fieber (2013). For example, Mallet (2009) stated that waveform processing (from multiple-return data) can improve object range determination. In forested areas, as stated, with improvements in canopy and ground heights, depending on the type of survey and landscape. Pirotti (2011) evidenced that DTM from multiple-return instrument produced a more homogeneously cover of the area of interest, and potentially providing a more detailed DTM, even with presence of dense vegetation. For this reason, Clark (2011) stated that dense canopy and vegetation, especially in tropical forest, made retrieval LiDAR returns from discrete-return difficult. Another study, conducted by Fieber (2013), showed the relevance of full-waveform against the performance of discrete-return parameters. These studies support the fact that multiple-return would improve the accuracy of measurements in tropical forest and strength the estimation models by reducing RMSE.

Table 1. RSME (in m) between discrete-return and multiple-return scans.

	0.5 m resolution	1 m resolution
Digital terrain model (DTM)	0.367	0.177
Forest tree height (FST)	2.208	1.336
Top of canopy (TOC)	2.306	1.381

Note: Only reference datasets were used to calculate RMSE.

4.2. Raster resolution

Visual assessment at different resolutions revealed the presence of outliers, seen as anomalous peaks in the rasters. Figure 3 shows the DTM (Figure 3a and 3b) and TOC (Figure 3c and 3d) rasters of Mondah1 plot, at 0.5 m resolution (Figure 3a and 3c) and 1 m resolution (Figure 3b and 3d). The 0.5 m resolution rasters showed more peaks and rougher surface than 1 m resolution rasters. This presence might be caused by the existence of objects that are wider than the cell resolution, for example trees or bushes. Those objects occluded more area than the cell resolution, therefore giving an outlier value, e.g.; the height of the object. Ozdemir and Donoghue (2013) reported that objects larger than the selected grid cell could create gaps in the raster, or outliers, like in the present study.

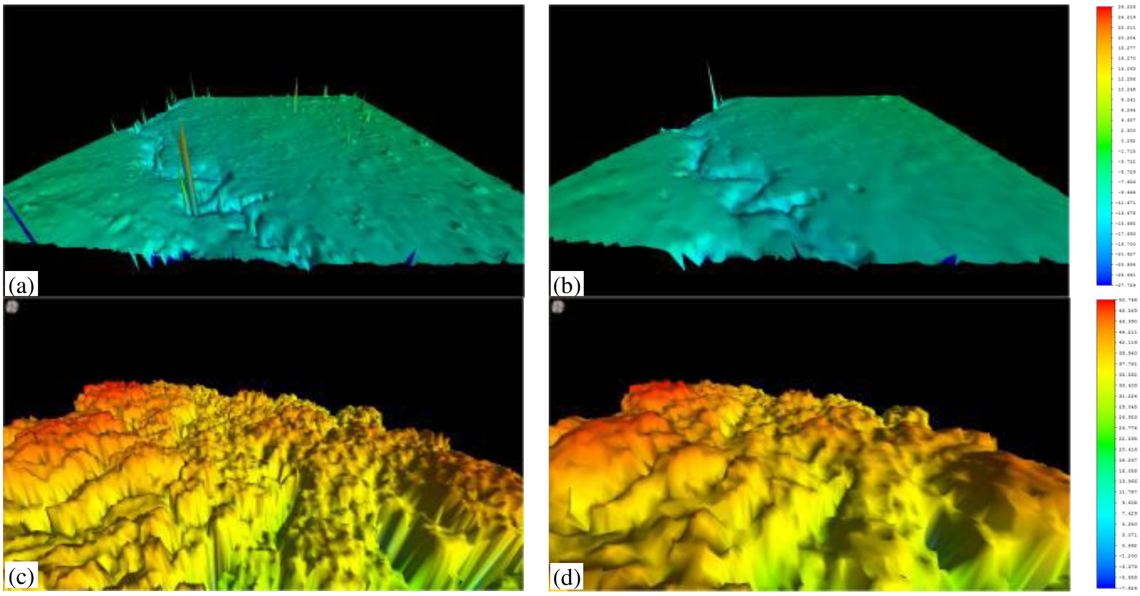

Figure 3. Resolution visual assessment. (a) and (b) show Mondah1 DTM raster, (a) at 0.5 m resolution and, (b) at 1.0 m resolution. (c) and (d) show Mondah1 TOC raster, (c) at 0.5 m resolution and (d) at 1.0 m resolution. Comparison was done for multiple-return raster

Standard deviations of the rasters confirmed what the visual assessment stated before. Table 2 shows the standard deviation of the rasters for different resolutions. For DTM parameter, the dispersion between 0.5 m and 1 m is just 1.1 cm (0.24 %) in favour of 0.5 m resolution. However, for FST and TOC parameters, the dispersion is greater between them, in favour of 1 m resolution. Dispersion decreased 9.23 % (from 5.826 m to 5.334 m) for FST and 5.49 % (from 7.051 m to 6.684 m) for TOC parameters when you passed from 0.5 m to 1 m resolution. These results reaffirmed that 1 m raster resolution produce less disperse parameter estimates.

Table 2. Standard deviation (in m) between different resolutions.

	0.5 m resolution	1 m resolution
Digital terrain model (DTM)	4.492	4.503
Forest tree height (FST)	5.862	5.334
Top of canopy (TOC)	7.051	6.684

Note: Only reference datasets from multiple-return scans were used.

Similar results had been observed as well by Ozdemir (2013), who reported that small grid cell sizes of 1x1 or 2x2 m seemed to work well to represent tree crowns and diameter at breast height (DBH) for airborne LiDAR. Also, Gaulton (2010) and Chauve (2007) reported a raster cell size of 1 m for their models. Another similar study, conducted by Parker (2009) showed that 0.2 m raster size can be used, however, a 1 m filter is needed to remove small peaks in the surface caused by small trees, maximizing smoothing function. Similar finding were reported by Allouis (2012), who used 0.5 m resolution of DTM, but due to a lower density of points, the DTM was finally interpolated on a 1 m grid. Our study focused in tropical forest, where trees and dense vegetation can easily create occlusion bigger than half meter, creating gaps in the raster or outliers. Hence, these studies and our results supported 1 m resolution for these parameters.

4.3 Tilted or upright scan configuration

Table 3 shows the RMSE residuals at 1 m resolution raster of multiple-return scans. The results for DTM parameter reported that upright raster could achieve the same accuracy as our reference raster or merged tilted-upright raster. Upright raster had a RMSE of 0.114 m; 78% more accurate than tilted raster (0.514 m). This also means that upright rasters differed only 0.114 m from merged tilted-upright rasters, while tilted rasters differed in 0.514 m from merged tilted-upright rasters. The Esperanza plot has a higher RMSE than the other plots due to its steep slope (< 30%) and environmental constraints (high humidity for being a cloud forest).

For FST parameter, RMSE for both rasters showed more than 1 meter deviation from the merged tilted-upright raster; 1.12 m and 1.285 m for the upright and tilted raster respectively. Even though upright raster was only 6 % more accurate than tilted raster, both were far from achieving independently the same accuracy as a merged tilted-upright raster. The same pattern could be observed for the TOC parameter, where RMSE ranged from 0.86 m to 1.295 m. Although the tilted rasters were 12 % more accurate than upright rasters, RMSE was still large enough to prove that tilted raster could not achieve the same accuracy as a merged tilted-upright raster.

Table 3. RMSE (in m) for multiple-return scan setup, at 1.0 m resolution raster resolution.

	Esperanza	Mondah2	Mondah1	Tambopata	Mean RMSE
Digital Terrain Model (DTM)					
Upright scenario	0.288	0.065	0.072	0.029	0.114
Tilted scenario	1.092	0.191	0.175	0.598	0.514
Forest Height (FST)					
Upright scenario	1.156	1.298	0.863	1.161	1.120
Tilted scenario	1.550	1.126	0.908	1.157	1.185
Top of Canopy Model (TOC)					
Upright scenario	1.112	1.295	0.860	1.159	1.106
Tilted scenario	0.972	1.092	0.875	0.971	0.978

Our study supports the need of a merged tilted-upright scan for FST and TOC parameters while only upright scans for DTM parameter. Results for FST and TOC parameters showed that single scans, tilted or upright scans, did not achieve the same accuracy as our reference data, a merged tilted-upright scan. For DTM parameter, a residual of 0.114 m can be expected only by using upright scans. Literature regarding tilted or upright scan accuracy is scarce. Nevertheless, few authors had evidenced the advantages of simulating full-hemispherical scans. For example, Huang (2011) stated that combining vertical (upright) and tilted 90° scans could obtain a complete vertical information of the forest. Similar findings were reported by Henning (2006), where he found loss of accuracy at points higher than 10 m, due to reduction of surface points for single scans.

The errors do show spatial patterns, which directly relate to the scan configuration (tilted or upright), type of parameter (DTM, FST or TOC) and position of the scans in the plot. In Figure 4 these patterns are shown for the Tambopata plot DTM raster at 0.5 m resolution (Figure 4a and Figure 4b) and at 1 m resolution (Figure 4c and Figure 4d) for tilted scans. Since tilted scan configuration only scans 90° on the zenith, sparse cloud points at ground level are expected. Moreover, the dense understory, typical of tropical forest, created more occlusion for the scanner at ground level. Furthermore, these patterns were not present in any of the upright rasters. For these reasons, these patterns were evident in DTM rasters mostly. Data from tilted scan are not enough to create an accurate DTM raster. These patterns could be seen in Figure 4a; and it was more evident in Figure 4b, which is the residual raster (reference raster minus tilted raster).

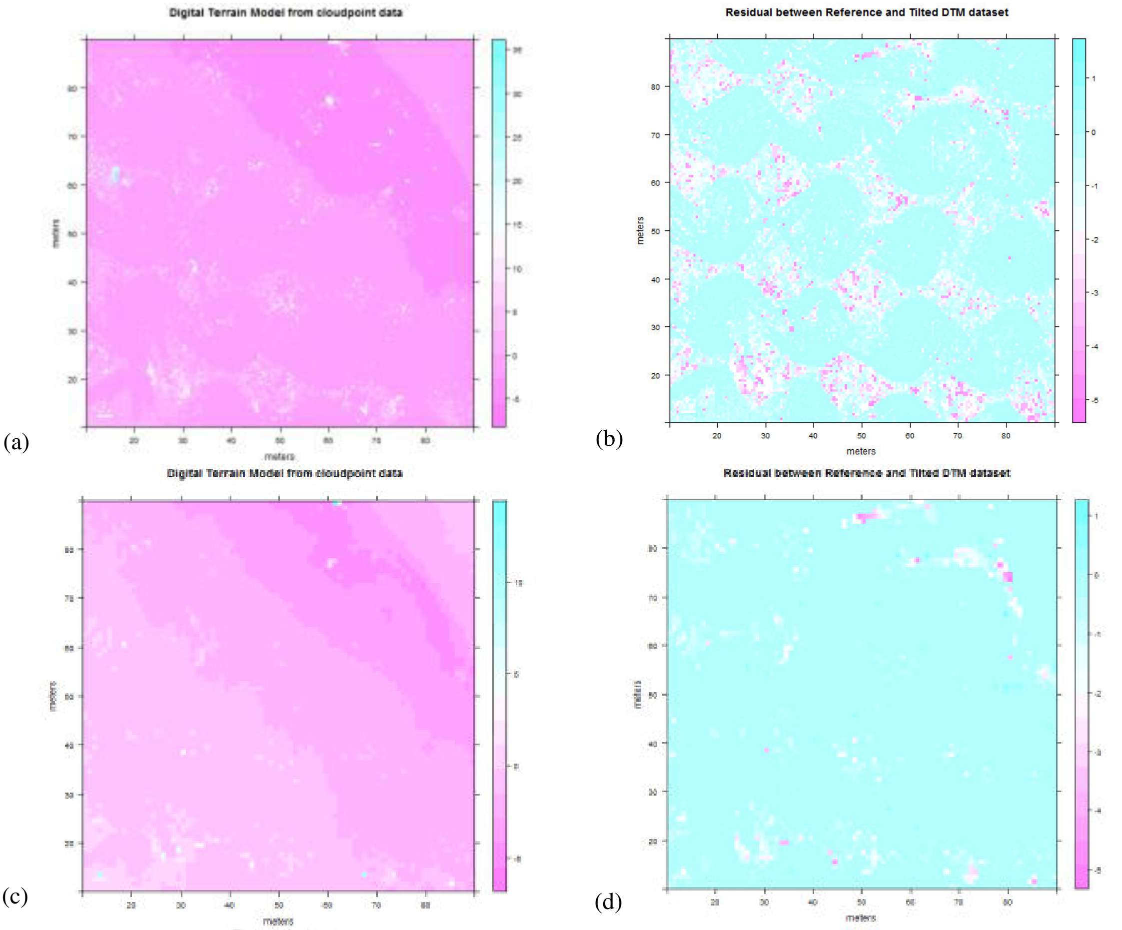

Figure 4. Spatial pattern present in tilted scan configuration for Tambopata plot. (a) DTM raster from discrete-return at 0.5 m resolution. (b) Shows residual raster from tilted and reference scans. Spatial patterns are more evident in residual rasters. (c) Same plot DTM raster but multiple-return at 1.0 m resolution. (d) Residual raster from tilted and reference raster. Spatial pattern are not present.

This might explain why no spatial patterns were found in TOC rasters, since tilted scans have enough points for modelling TOC rasters. FST raster also evidenced these patterns. FST rasters are related to DTM rasters, so, these patterns were also expected to show up. Our study found that these patterns were presented in 81 % of the tilted DTM rasters; however, it was presented only in 31 % of the tilted FST rasters. None of the TOC rasters presented these patterns. Also, circular patterns, around each scan position in the plot, might denote more point density with more homogenous data; and in the surrounding areas, less point density, with more heterogeneous data. The dense understory, typical of tropical forest, created more occlusion for the scanner. This limited the scanning radius from 10 to 20 m from each scan position. This explains the presence of heterogeneous data outside the circular pattern for DTM rasters, were there is less data to create an accurate raster.

Since this study is focused on tropical forest, the density of the understory plays a major role in the scanning range. This had to be taken into account in the scanning grid, since scanning points with more than 20 meters between them can create gaps in the cloud point. All these evidences support the idea that merged tilted-upright rasters from multiple-return scans and at 1 m resolution provide the most accurate data. Figure 4c and 4d shows the same plot, but in multiple-return and 1.0 m resolution. These images did not show any of the spatial patterns, due to its different characteristics.

5. Conclusions

This research was done in tropical forest plots; this is why it is crucial to delineate the scope for each parameter before fieldwork, since it cannot be generalized. This article addressed the need of full-hemispherical scan for three parameters, digital terrain model, forest height and top of canopy model. Our results supported the use of a merged tilted-upright scan to achieve the best accuracy for these parameters. In order to achieve this, we proved that multiple-return scans were more accurate than discrete-return scans. Multiple-return scans improved the accuracy of measurements in this study, creating a denser cloud point, with more data available to estimate parameters. Our results also stated that 1 m resolution is more accurate than 0.5 m resolution. This research was done in tropical forest plots, where trees can have more than 50 cm diameter at DBH. Thus, creating spikes in the raster processing, because the minimum value was actually the height of the tree. It is up to the final user to decide which raster resolution fit the best. Finally, this study proved that single scans (tilted or upright) cannot achieve the same accuracy as a merged tilted-upright scan. We tested for three parameters, and residuals ranged up to 1.1 m difference for single scans. In brief, this study proved that using both scans, upright and tilted, for these parameters is the most effective way to have accurate forest measurements.

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