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Bias of cylinder diameter estimation from ground-based laser scanners with different beam widths: A simulation study

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ABSTRACT

In this study we have investigated why diameters of tree stems, which are approximately cylindrical, are often overestimated by mobile laser scanning. This paper analyzes the physical processes when using ground-based laser scanning that may contribute to a bias when estimating cylinder diameters using circle-fit methods. A laser scanner simulator was implemented and used to evaluate various properties, such as distance, cylinder diameter, and beam width of a laser scanner-cylinder system to find critical conditions. The simulation results suggest that a positive bias of the diameter estimation is expected. Furthermore, the bias follows a quadratic function of one parameter – the relative footprint, i.e., the fraction of the cylinder width illuminated by the laser beam. The quadratic signature opens up a possibility to construct a compensation model for the bias.

1. Introduction

Terrestrial Laser Scanning (TLS) and Mobile Laser Scanning (MLS) are promising methods for efficient collection of forest data such as stem diameters, positions, and stem profiles (Liang et al., 2016). These types of forest data can be used to calculate the economical value of the stock and used for planning purposes. Methods currently being developed for precision forestry require accurate information about individual trees (Holopainen et al., 2014). Furthermore, information about biomass and carbon storage can be used for environmental monitoring.

Research on MLS for forestry applications is currently a topic of interest, while earlier research in MLS has come from fields such as robotics and mobile mapping (Fentanes et al., 2011; Rodr´iguez-Cuenca et al., 2015). A common approach to MLS is to use a line-laser scanner (2D laser scanner), where knowledge of the scanner movement is used to combine sequential 2D scans into a 3D point cloud. The line scanner can be handheld (Bauwens et al., 2016), car-mounted (Forsman et al., 2016), or mounted to a forest harvester (Jutila et al., 2007; Hellström et al., 2012). Such systems can provide data cheaply, either by covering large forest areas in a short time or by providing results as a by-product of forest operations (e.g., during harvesting or thinning). However, many studies of MLS report systematic overestimations of tree stem diameter values ranging from a few percent to almost ninety percent e.g., (Jutila et al., 2007; Öhman et al., 2008; Hellström et al., 2012; Ringdahl et al., 2013; Kelbe et al., 2015; Kong et al., 2015), using either circle fit or angular stem width methods. The systematic overestimation can be due to multiple error sources, such as problems with delineation of stems from branches in the point cloud (Olofsson et al., 2014); partial stem visibility (Bu and Wang, 2016); unsuitable methods for diameter estimation from the stem points (Pueschel et al., 2013); or errors in the point measurements by the laser scanner.

The effect of point measurement errors has been investigated with respect to slopes in terrain models from aerial laser scanning (Schaer et al., 2007; Toth, 2009) and long range TLS (Fey and Wichmann, 2017), sloped or stepped surfaces giving a temporal spread of the pulse (Jutzi and Stilla, 2003), and with respect to limitations in detail resolution for brick walls from terrestrial laser scanning (Pesci et al., 2011). Soudarissanane (2016) have studied how the errors in laser scanning are influenced by the scanning geometry, such as the distance and the angle of incidence to the reflecting surface. To our knowledge, the effect of point

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measurement errors on the estimation of parameters for cylindrical surfaces such as tree stems has not been previously published.

The purpose of this study is twofold: (1) To characterize the error in a point measurement made by a laser scanner on a cylindrical surface and (2) to quantify the effect of the errors on the estimated cylinder diameters.

2. Materials and methods

2.1. Terminology

The terminology used in this paper is defined in Table 1 and Fig. 1.

2.2. Point measurements by a laser scanner

A point measurement by a time-of-flight (ToF) laser scanner is performed by measuring the time needed for a pulse to travel from the emitter of the laser scanner to the reflecting object and back to the detector. The distance is computed from the measured time, and the position of the point relative to the scanner is calculated from the distance together with the direction of the center of the beam.

The exact timing of the echo detection depends on the shape of the echo and the echo detection method. Common detection methods are either based on intensity thresholds, leading edge slopes, constant fraction of amplitude, or intensity maxima (Jutzi and Stilla, 2003; Wagner et al., 2004; Shan and Toth, 2009). If the emitted pulse is square and the incidence angle at the target is perpendicular, the echo signal will be close to square. In that case, the different detection methods will give almost the same results. However, if the laser pulse hits a slanted or curved surface, where the measured distance varies within the footprint, the echo will be distorted (see Fig. 2; Jutzi and Stilla, 2003; Shan and Toth, 2009). The distortion is affected by the angle of incidence and the size of the footprint, which in turn depends on the beam width and the distance to the target. The distortion will be especially pronounced if part of the beam falls outside the target, the likelihood of which additionally depends on the angular separation (Pesci et al., 2011). Finally, variation in target reflectivity can further influence the shape of the echo signal. The echo distortion and its effect on the timing is discussed in detail in Section 2.4.

2.3. Laser scanner specifications

The information about the technical parameters and the precision of a particular laser scanner is typically found in the data sheet

Table 1
Terminology used in this paper.

Term		Description
Point		A 3D position calculated from a laser measurement
Pulse		Unit of emitted light
Echo		Reflection of a pulse
Signal		Temporal properties of a pulse or an echo
Beam		Spatial properties of a pulse or an echo
Ray		Spatial discretization unit of a beam
Beam width (Beam divergence)	α	The width of $\pm 2\sigma$ of the gaussian distributed intensity, also called second moment or D4σ (ISO, 2016)
Angular separation (Angular resolution)	β	The difference in the outgoing angle of neighboring beams
Footprint		The area on the target illuminated by the beam
Relative footprint		The ratio of the beam diameter at intersection with the cylinder divided by the cylinder diameter, in percent

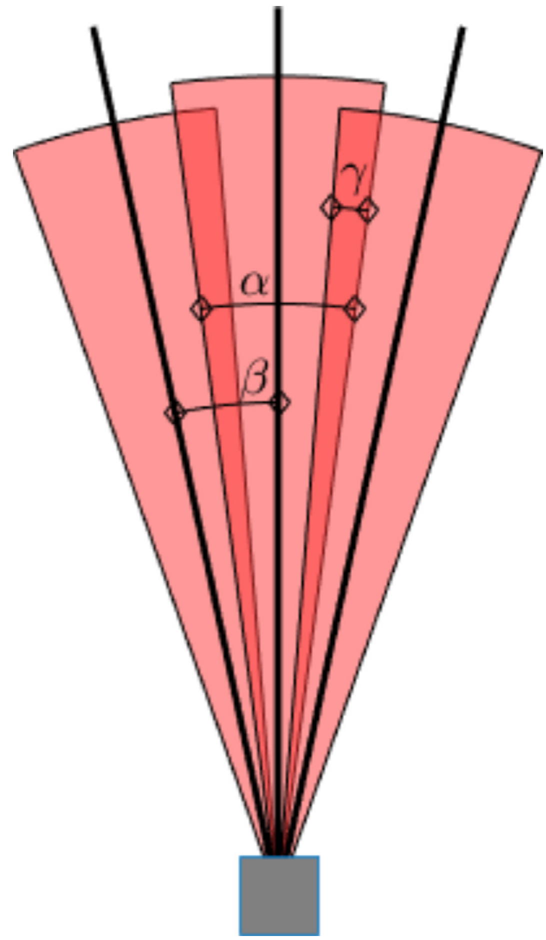

Fig. 1. Top view. The angular separation is the angle β between the centers of the laser beams (black lines). The beam width, also called beam divergence, is marked with α. The beam width is defined using the $D4\sigma$ definition, which means that the width corresponds to $\pm 2\sigma$ of the normally distributed beam intensity. If $\beta < \alpha$, there is an overlap between the beams, indicated by γ. Often, real world laser scanners have a positive overlap to ensure that objects cannot go undetected between the laser beams. Note that the angles are exaggerated here for visibility.

published by the manufacturer. In Table 2, we list the parameters of four laser scanners that have been used for tree stem diameter measurements (Hellström et al., 2012; Ringdahl et al., 2013; Olofsson et al., 2014; Forsman et al., 2016; Jaakkola et al., 2017 and others). Three scanners were mobile line ("2D") laser scanners (SICK LMS 511, SICK LMS 221, Velodyne VLP16) and one was a stationary ("3D") scanner (Trimble TX8). Comparing data sheets from different manufacturers can be non-trivial since the listed parameters generally do not follow the same standard. We thus emphasize that some tabulated numbers have been deduced to the best of our knowledge from the actual numbers in the data sheets and other technical documentation. Comparing error levels is equally non-trivial, as the specified errors are a mix of random errors and/or systematic errors at different ranges or range intervals. We observe that, in the cases where such information was available, the declared errors were specified for a flat, white, diffuse surface at a perpendicular angle of incidence.

2.4. Simulation

A simulation of a horizontal scanning by a line laser scanner of a tree, represented by a vertical cylinder, was implemented in MATLAB (www.mathworks.com). The laser beam was modelled as a cone with a fixed opening angle with its tip at the laser