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Effect of slope on treetop detection using a LiDAR Canopy Height Model

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ABSTRACT

Canopy Height Models (CHMs) or normalized Digital Surface Models (nDSM) derived from LiDAR data have been applied to extract relevant forest inventory information. However, generating a CHM by height normalizing the raw LiDAR points is challenging if trees are located on complex terrain. On steep slopes, the raw elevation values located on either the downhill or the uphill part of a tree crown are height-normalized with parts of the digital terrain model that may be much lower or higher than the tree stem base, respectively. In treetop detection, a highest crown return located in the downhill part may prove to be a "false" local maximum that is distant from the true treetop. Based on this observation, we theoretically and experimentally quantify the effect of slope on the accuracy of treetop detection. The theoretical model presented a systematic horizontal displacement of treetops that causes tree height to be systematically displaced as a function of terrain slope and tree crown radius. Interestingly, our experimental results showed that the effect of CHM distortion on treetop displacement depends not only on the steepness of the slope but more importantly on the crown shape, which is species-dependent. The influence of the systematic error was significant for Scots pine, which has an irregular crown pattern and weak apical dominance, but not for mountain pine, which has a narrow conical crown with a distinct apex. Based on our findings, we suggest that in order to minimize the negative effect of steep slopes on the CHM, especially in heterogeneous forest with multiple species or species which change their morphological characteristics as they mature, it is best to use raw elevation values (i.e., use the un-normalized DSM) and compute the height after treetop detection.

1. Introduction

Information on individual trees is critical for a variety of forest activities and for environmental modeling at the local and regional scales (Lichstein et al., 2010). In the last decade, airborne Light Detection and Ranging (LiDAR) has become a reliable remote sensing technique for estimating individual tree parameters, due to its capability to generate detailed and very precise three-dimensional tree information (Hyyppä et al., 2008; Lim et al., 2003).

As an initial and important step in any analysis of LiDAR data on individual trees, treetop detection has attracted much attention and research (Hosoi et al., 2012; Hyyppä et al., 2012; Jing et al., 2012; Kaartinen et al., 2012; Popescu and Wynne, 2004; Vastaranta et al., 2011). Identifying the correct treetop can provide accurate information on crown characteristics and the tree height information, which in turn are useful inputs for growth and volume estimation models (Gebreslasie et al., 2011; Vastaranta et al., 2011; Wulder et al., 2000). A widespread approach is to identify local maxima, which generally correspond to the location and height of individual trees, and then to construct crown segments (Falkowski et al., 2006; Næsset and Økland, 2002; Solberg et al., 2006; Véga and Durrieu, 2011).

The local maxima are typically obtained from the height variation of a LiDAR-derived Canopy Height Model (CHM), also known as a normalized Digital Surface Model (nDSM) (Forzieri et al., 2009; Li et al., 2012; Persson et al., 2002; Yu et al., 2011). There are two ways to create a CHM: with rasters or with point clouds (Li et al., 2012; Persson et al., 2002). When working with rasters, the LiDAR ground returns are used to create a raster DTM (Digital Terrain Model), and the highest or first LiDAR returns are used to create a raster DSM (Digital Surface Model). Then the raster DTM is subtracted from the raster DSM to create the final raster CHM (Lim et al., 2003). When working with point clouds, the

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classified LiDAR is height-normalized by replacing the raw elevation of each return (i.e. its z coordinate) with its height above the DTM (Khosravipour et al., 2014; Van Leeuwen et al., 2010). Either way, the end result is the absolute canopy height above the bare-earth terrain surface.

Although the procedure of computing local maxima from a CHM is conceptually simple, the accuracy of its result largely depends on the quality of the acquired LiDAR data, its processing and/or post-processing, and the forest conditions (Kaartinen et al., 2012). For example, the use of a higher density of laser pulse footprints improves the chance of the laser hitting the treetops (Hyyppä et al., 2008; Lefsky et al., 2002), and the use of an efficient local maxima technique enhances treetop identification by reducing commission and omission errors (Chen et al., 2006; Kaartinen et al., 2012; Vauhkonen et al., 2012). A new study suggests that the accuracy of treetop detection can be improved further by removing height irregularities in the CHM (Khosravipour et al., 2014). Moreover, a number of studies indicate that the various forest conditions (e.g., crown sizes, ages, site types, tree species and forest density) can significantly influence intermediate LiDAR derivatives and thereby the performance of tree detection algorithms (Falkowski et al., 2008; Pitkänen et al., 2004; Popescu and Wynne, 2004; Vauhkonen et al., 2012; Yu et al., 2011).

Complex forest terrain presents a challenging problem, as it affects the performance of the height normalization step by distorting the CHM, which can reduce the accuracy of extracted tree biophysical parameters (Vega et al., 2014). On steep slopes, the raw elevation values located, for example, on either the downhill or the uphill part of a tree crown are height-normalized with parts of the DTM that may be much lower or higher than the tree stem base, respectively (Breidenbach et al., 2008). Therefore, in the CHM, the downhill part of the crown will "rise" while the uphill part will "sink", causing the entire tree crown to be systematically distorted. In treetop detection, the "rising" branch overhanging lower terrain in the downhill part can turn into a "false" local maximum that is distant from the true treetop. This problem was posed in Isenburg's keynote speech at Silvilaser 2012 (Isenburg, 2012). He found a CHM that overestimated true tree height by more than double: eucalyptus trees on steep and eroded slopes in the Canary Island of Tenerife were estimated as being 51 m tall whereas their true height was 25 m. Takahashi et al. (2005) and Véga and Durrieu (2011) also reported that one of the sources of tree height overestimation from LiDAR-derived CHM is a horizontal offset error between field and LiDAR treetop detection, particularly on steeper slopes. They concluded the difference may be due to the LiDAR-derived treetop simply being identified as the maximum value of CHM within the crown area on steeper slopes. Heurich et al. (2003) pointed out that this error increases for leaning trees and/or steeper terrain slopes. Breidenbach et al. (2008) reported an increasing underestimation of the CHM-derived height with steeper upward slopes and vice versa for downward slope, which can cause tree height – one of the most important stand characteristics determined in forest inventory – to be misinterpreted, thereby affecting estimates of subsequent biophysical parameters such as biomass, volume and carbon sequestration. The recent study of Vega et al. (2014) suggested using un-normalized elevation values (i.e. using the DSM), and computing the height after a tree crown segmentation step, to avoid the undesirable effect of steep slopes on the CHM. However, until now, the influence of the normalization process on treetop detection and height estimation has neither been studied nor quantified.

The aim of this study was to quantify the effects of slope gradient on the accuracy of treetop detection when using a LiDAR-derived CHM. We first present a simplified theoretical model to illustrate how normalization causes a systematic error in CHM-based treetop detection when an individual tree is located on a slope. We then assess the accuracy of treetop detection by using both the CHM (i.e. the normalized elevations) and the DSM (i.e. un-normalized elevations). Next, we compute the positional difference between the same tree detected in both the CHM and the DSM, in order to investigate the influence of the slope on the horizontal displacement of CHM-detected trees and its effect on subsequent height estimation.

2. Theoretical model

The systematic error in CHM-based treetop identification can be quantified by using a conceptual model that is based on field measurement of tree heights. In the field, the original tree height is determined as a vertical distance from tree apex to the upslope root crown (Husch et al., 1982). According to the model (illustrated graphically in Fig. 1), the height of a tree is calculated as the magnitude (length) of a vector h originating at the base of the tree and ending at the treetop. Without loss of generality, we can assume that the tree height is formulated as:

$$h = b + 2r \tag{1}$$

where b is the crown base height and r is the radius of the hypothetical tree crown.

When computing the tree height from the height-normalized model (i.e., CHM) the distance from the highest crown return to its projection on the DTM is used, which introduces a systematic error when the terrain is sloping (Takahashi et al., 2005; Véga and Durrieu, 2011; Vega et al., 2014). We assume a tree on a terrain of constant slope with an idealized spherical crown is always hit at the highest point across the canopy by the laser pulses (i.e. no

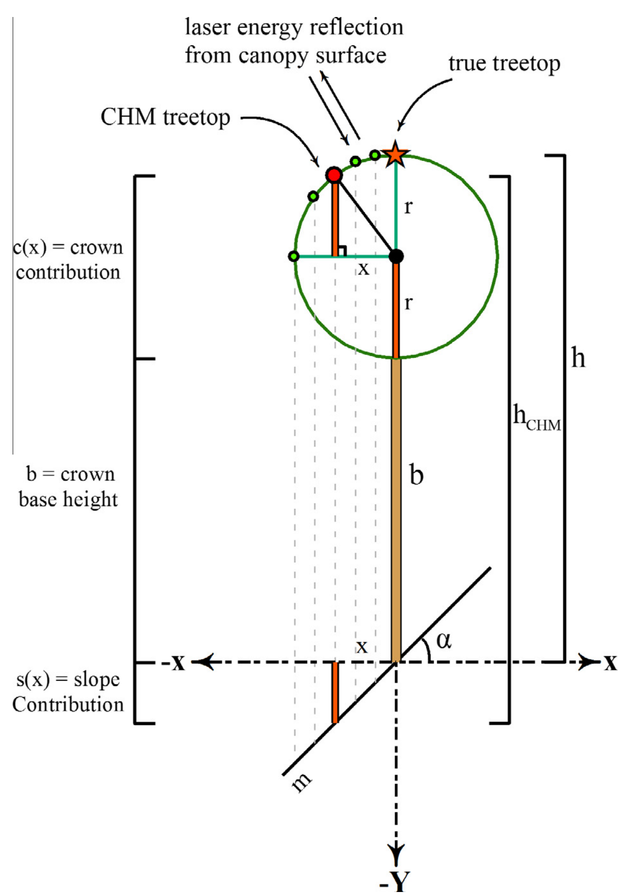

Fig. 1. Schematic diagram of the geometry involved in the treetop detection based on the effect of slope gradient on a LiDAR-derived CHM.