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Assessment of terrain slope effects on GLAS waveform and canopy height retrieval using 3-D vegetation model

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Abstract. To assess the terrain effects on the Geoscience Laser Altimeter System (GLAS) waveform and canopy height retrieval, the 3-D lidar waveform model was used to simulate the GLAS waveform for the nine scenes with the slopes increasing from 0 to 30° in 1°. When slope increased from 0° to 10°, the magnitude of the canopy peak decreased by approximately 2/5 to 3/5, but the magnitude of the ground peak decreased by more than 4/5 for all the simulated scenes. The critical slope angle is in direct proportion to canopy height, and slightly decreases with the increased stand density. Further analysis showed that average error for the RH100 was 5.4 m when the slope was 10°, and reached 9.4 m when the slope was 15°. Meanwhile, the average error for the physical terrain correction method was –5.6 meters even for the slopes up to 30°. Thus, it is suitable to retrieve tree height for areas with up to 10° slopes using the direct method. However, a simple physical slope correction could be used in areas with greater slopes. This work enhances our understanding of the interactions between surface topography, forest structure and waveform shape.

Key words. Canopy height, surface topography, 3-D vegetation model, GLAS waveform.

1. Introduction

Forests are the largest carbon reservoirs in terrestrial ecosystems and play a critical role in the global carbon cycle and global warming mitigation. Forest canopy height is considered to be among most useful structural parameters for estimating forest biomass and productivity. It has been widely accepted that light detection and ranging (lidar) provides the most direct measurements of forest structure including canopy and forest biomass. The Geoscience Laser Altimeter System (GLAS)

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onboard NASA's Ice, Cloud and Land Elevation Satellite (ICESat) was the first space-borne lidar system to provide fast forest canopy height solutions. Successes have been reported in many studies, in which GLAS waveform data served as the core data for estimating the forest canopy height and above-ground biomass [1, 2].

The GLAS signal is very sensitive to surface topography due to its large footprint. The terrain effect makes it a big challenge to retrieve canopy heights over mountainous regions. Modeling work allows the explicit calculation of the effects of land slope. To data, several RTM models have been developed for simulating the lidar waveforms of forest canopies. For example, Sun and Ranson (2000) developed a 3-D forest canopy model for simulating lidar waveforms from forest stands of varying geometry and complexity [3]. North et al. (2010) presented a Monte Carlo radiative transfer model for simulating lidar waveforms within the framework of the FLIGHT model [4]. Yang et al. (2011) adopted the updated analytical GORT vegetation lidar model to simulate lidar waveforms with changes of vegetation, structure, surface topography, footprint size, off-nadir pointing, pulse width and surface roughness, and ratio of the canopy and background reflectivity [5]. Although terrain effects on the large footprint have been modeled in previous studies [6, 7], the efforts were usually based on relatively simple experiment designs. The diversity of forest structures was not accounted for in these study.

The 3-D lidar model developed by Sun and Ranson [3] is designed especially for the simulating return lidar waveforms from forest canopies. It is flexible in the experiment design. We extended the three-dimensional (3-D) lidar model developed by Sun and Ranson [3] to account for land slope and applied the extended model to assess the aforementioned impacts on vegetation lidar waveforms and height retrieval.

2. Modelling lidar waveform from vegetation canopies

2.1. The 3-D lidar waveform model of forest

The 3-D lidar waveform model was based on theory from geometric optics and radiative transfer (GORT). To model the lidar waveform, the 3-D scene was divided into cells according to the vertical resolution of the lidar (Fig. 1). The cell used in this study was a $0.15\,\text{m} \times 0.15\,\text{m} \times 0.15\,\text{m}$ cube that corresponded to the vertical resolution of GLAS. There were four different types of cells in the model: crown, trunk, air, and ground cells. Every cell was assigned to one type according to its position. The spectral reflectance and transmittance properties of the cells were also specified by type. The ground surface is described as a plane with a specified slope angle. The specific theory was shown in [3].

The assumptions in the following simulations were made:

1) Uniform tree crowns, i.e., the canopies within a waveform share the same structure, and are uniformly distributed.

2) Uniform ground surface.

3) Only single scattering was considered.

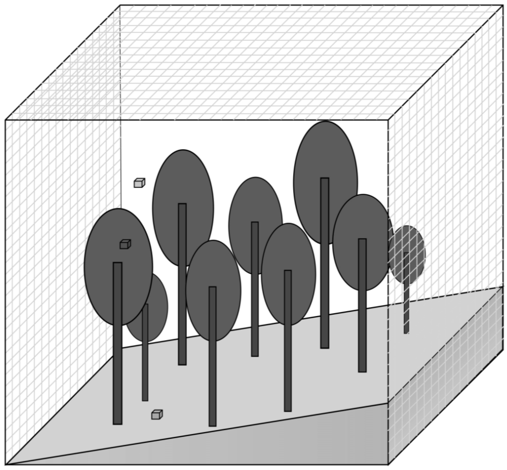

Fig. 1. The 3-D scene of a forest stand with certain slope (each cell in the model could be assigned to one type according to its position in the scene)

2.2. Tree structural model

As mentioned above, the 3-D model requires information about every tree in the laser footprint including DBH, height, crown geometry and species. In this study, tree crown shapes were modeled as ellipsoids. The structural parameters of trees were obtained from forest stand attributes. There were three tree models of different height used for the waveform simulation. The geometry parameters of every tree model are listed in Table 1.

Table 1. The parameters describing the simulated trees

Item	Tree model 1	Tree model 2	Tree model 3
DBH (Diameter at Breast Height)	15 cm	20 cm	25 cm
Tree height	10 m	15 m	20 m
Crown height	5.51 m	8.27 m	11.03 m
Crown width	2.90 m	4.35 m	5.81 m

Additional parameters used in the model were fixed to default: foliage area volume density is 1.25, $G_$factor is 0.5, leaf reflectance is 0.55, and ground reflectance is 0.2.

2.3. LiDAR sensor model

In this model, the set of parameters defining the lidar instrument were specified according to GLAS, approximating view and illumination geometry as nadir, which would produce a footprint diameter of 65 m. The angular divergence and temporal spread of the emitted pulse were assumed to be Gaussian. The width of the transmitted pulse used was 5 ns, and the vertical resolution of the lidar waveform was 0.15 m. The illuminating intensity decreased from 1.0 to e^{-2} from the center to the edge of the footprint.

2.4. Experiment setup

In this study, the size of the three-dimensional stand scene was 75 m $\times$ 75 m and the diameter of the laser footprint was 65 m. Three tree distribution scenes of different densities were designed. For each scheme, trees were distributed uniformly as the hexagonal rules in the footprint. The distances separating adjacent trees in the three scenes were 10 m for scheme A, 8 m for scheme B, and 6 m for scheme C. The three tree models described in subsection 2.3 were used for each scheme, and the slope increased from 0° to 30° by 1° steps. Nine groups of model simulations were, therefore, used in this study.

3. Simulation results and analysis

3.1. Terrain effect on vegetation lidar waveforms

Figure 2 shows the vegetation lidar waveforms at different slope angles and footprint sizes of 65 m for the simulated forest scenes. From the figure, one can see that terrain slope stretched the length of the waveform, and decreased the canopy, particularly the ground peaks. The heights of the canopy peak and ground peak also increased slightly with slope.

It is worth noting that the slope greatly impacted on the waveform extent. As expected, greater slopes tended to generate longer waveforms. With increased slope, the waveform was extended both in the signal-end and signal-start directions. Due to the rapid decline of the ground peaks, the stretch in the signal-start directions was more significant than in the signal-end direction. For a simulated scene with a thick stand density, this trend was more obvious because the ground return was weaker and disappeared more rapidly with increasing slope under that condition.

Figure 5 shows the variation in magnitude of the ground and canopy peaks with slope. It was discovered that the decreasing tendency of the ground peaks for all the simulated senses was the same. The magnitude of the ground peak from a flat to a 10° slope decreased by more than 4/5. However, the decreasing rate of the canopy peak was related to canopy height. The lower the canopy height was and the faster the canopy peak decreased. The magnitude of the canopy peak from a flat to 10° slope decreased by approximately 2/5 to 3/5. From that, the ground returns were more distorted than the canopy returns. At a 10° slope, the ground peak was still noticeable for all the simulated senses except for the last one. As the slope continued to increase, the ground and canopy peaks gradually merge; at a specific slope or steeper, the ground peak disappeared.

3.1.1. The critical angle for ground peak identifying. To better address the slope effect, the concept of critical angle was introduced in this study. It is defined as the

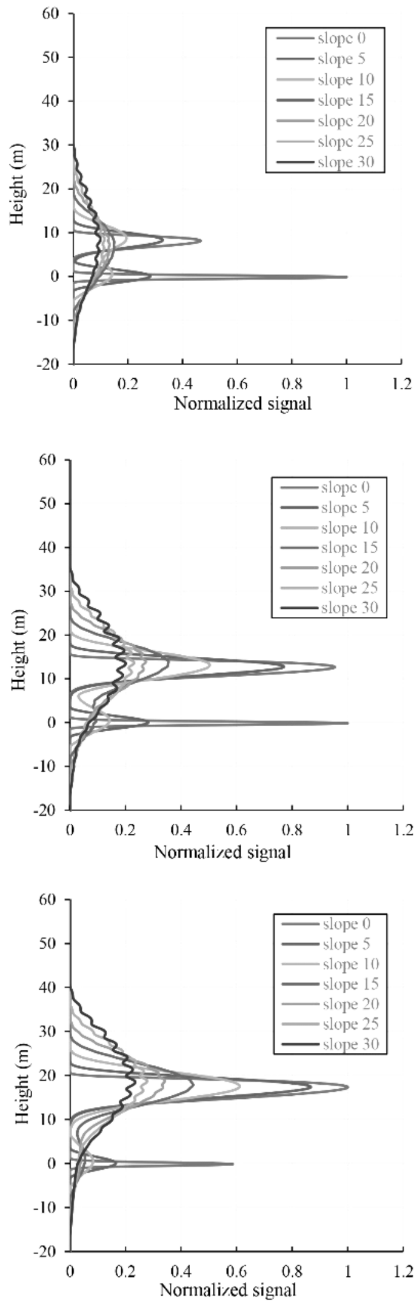

Fig. 2. The simulated waveforms over different terrain slope: from top to bottom, trees are distributed according to the scheme A in subsection 2.4 with the heights of 10 m, 15 m, and 20 m, from top to bottom, respectively

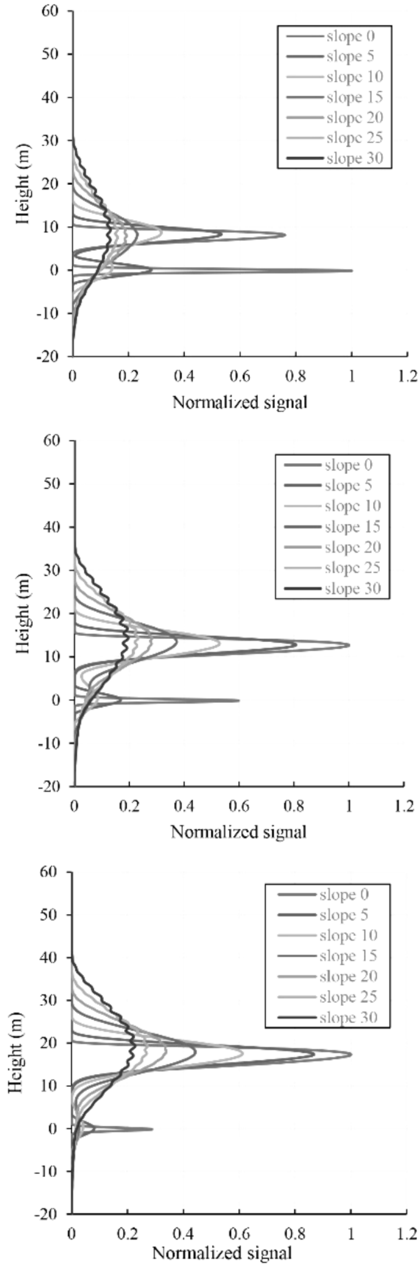

Fig. 3. The simulated waveforms over different terrain slope: from top to bottom, trees are distributed according to the scheme B in subsection 2.4 with the heights of 10 m, 15 m, and 20 m, from top to bottom, respectively

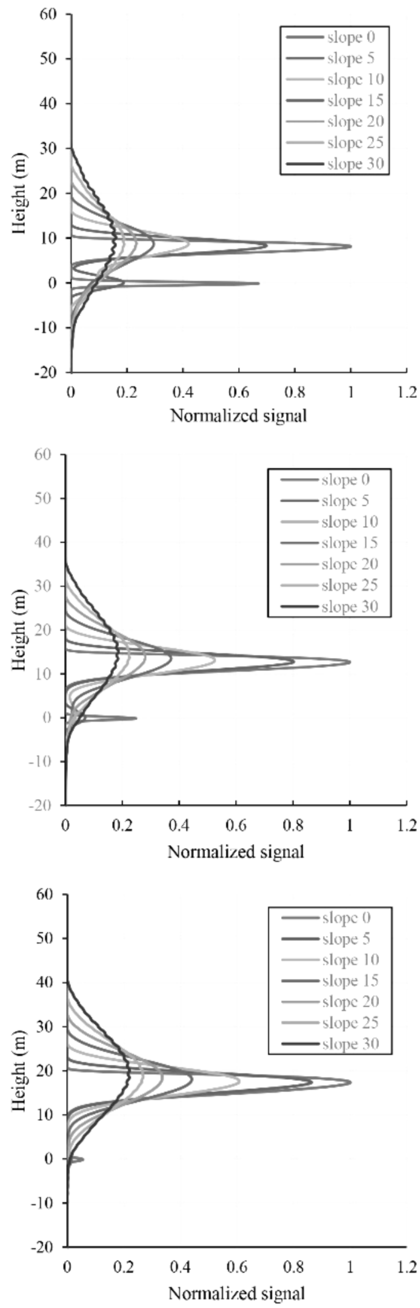

Fig. 4. The simulated waveforms over different terrain slope: from top to bottom, trees are distributed according to the scheme C in subsection 2.4 with the heights of 10 m, 15 m, and 20 m, from top to bottom, respectively

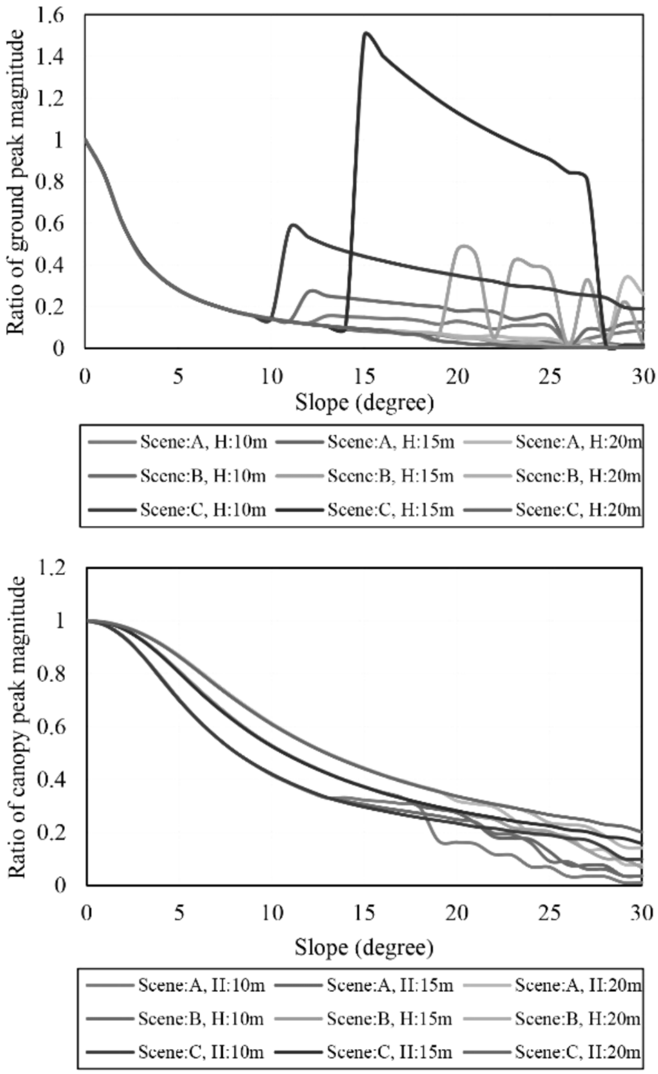

Fig. 5. The variation of magnitude of the ground (top) and canopy peak (bottom) with the slope (the oscillates of magnitude is because that ground peak mix with the vegetation peak with the increasing slope)

slope angle where the ground and vegetation returns are completely mixed [5]. When a slope exceeds the critical angle, it is quite challenging to estimate vegetation height by identifying the ground peak.

The canopy height is a major factor that influences the critical angle for the GLAS waveform. Table 2 shows the critical angle of the different simulated scenes. From the table, one can see that the critical angle was directly proportional to vegetation height. As discussed above, terrain slope leads to a mixture of the lower part of the canopy return and the higher part of the ground return. Taller trees mean larger departures of the canopy bottom from the ground. Therefore, a larger critical angle is needed to mix the vegetation return with the ground return. As shown in Table 3, for scene A, the 20 m canopy has a critical angle of 20 °, whereas the critical angles were 15 ° and 11 ° for the 15 m and 10 m canopies, respectively. The simulated results of scenes B and C tell nearly the same story. A different case is that of C with a canopy height of 20 m. The canopy cover for that case reached 84.68 %. Under that condition, the ground return was very small on a flat terrain. With the increasing slope, the ground peak is declined rapidly, and the ground peak thus could not be identified from the waveform at a small slope angle.

Another factor that affects critical angle is canopy cover. The increase in canopy cover led to a greater laser return from the canopy or a decrease in the ground return. Table 3 shows that critical angle slightly decreased with increased canopy cover. An exception was scene C, which had a canopy of height 20 m, for the reason discussed above.

Table 2. The critical angles of the simulated scenes

Trees distribution	Canopy height (m)	Canopy coverage (%)	Critical angle (°)
Scene A	10 m	7.59	11
Scene A	15 m	17.02	15
Scene A	20 m	29.96	20
Scene B	10 m	11.89	10
Scene B	15 m	26.73	14
Scene B	20 m	47.62	19
Scene C	10 m	21.34	9
Scene C	15 m	47.44	13
Scene C	20 m	84.68	10

3.2. Canopy height error due to terrain slope

As discussed above, the topographic slope greatly affects the GLAS waveform shape and relative parameters. Therefore, the slope is expected to affect the estimation of canopy height. With the direct method, RH100 was considered as the maximum canopy height over flat terrain. Yang et al. (2011) developed an analytical equation that could be used to estimate the canopy height [5]. In this section, the estimation errors of the canopy heights calculated by the two methods are analyzed.

RH100 is the distance between the signal start and the ground return. Therefore, precise detection of the ground peak is important because it is used as a reference for calculating the quartiles. The identification of the ground peak in this study was based on the Gaussian decomposition of the waveform. The last fitted Gaussian peak was assumed to be the ground peak. In Fig. 6, top part, the canopy height error is calculated as the difference in the RH100 values and the input canopy height values of the 3-D lidar waveform model of the forest. As shown in the picture, height error was a function of terrain slope angle when the slope was less than 15 °. As the slope exceeded the critical angle, the RH100 values contained large errors from the misidentification of the ground return, and the height errors were irregular with regard to slope. The average error for the RH100 was approximately 5.4 m when the slope was 10 °, and reached 9.4 m when the slope increased to 15 °.

In Fig. 6, bottom part, the canopy heights were estimated using the analytical equation developed by Yang et al. (2011).

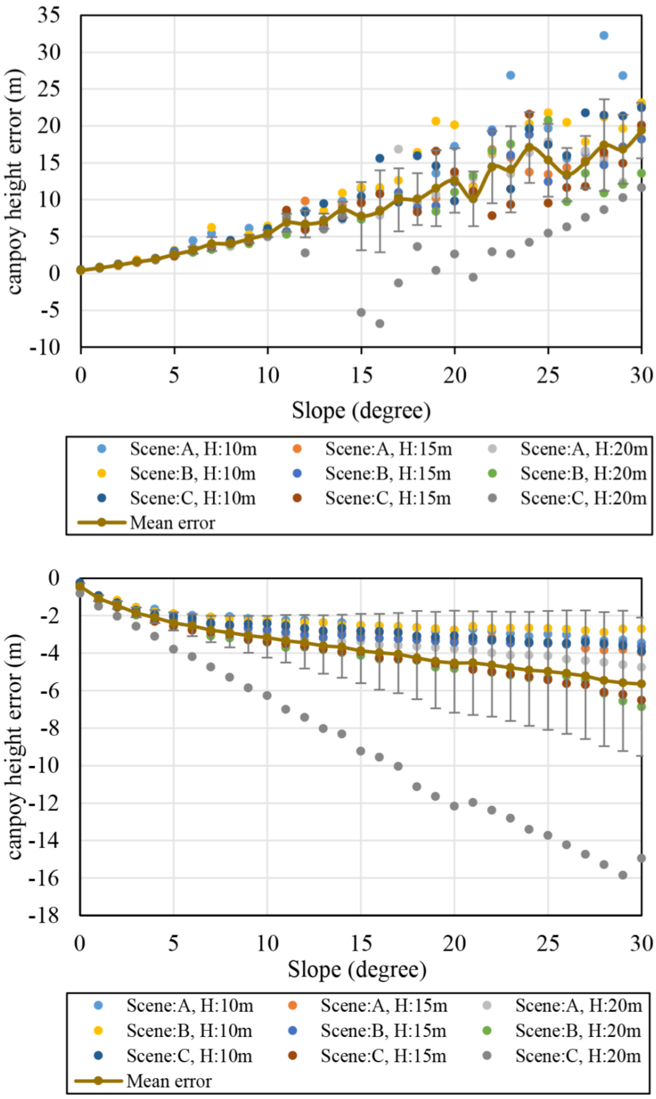

Fig. 6. Relation between maximum canopy height estimation error and slope using (top) direct method, (bottom) slope-correction model developed by Yang et al. [5], error bars represent the standard error of each mean

Due to the underestimation of waveform extents in areas with high topographic relief, this method could be expected to result in lower height estimates. Higher slopes and stand densities would lead to more increased underestimations of forest canopy heights. For scene C with a canopy height of 20 m, the absolute errors in canopy height increased rapidly with increasing slope. The canopy height was underestimated by 6.3 m when the slope was 10 °. As the slope increased to 30 °, this value reached to almost 16 m. For other simulated scenes, the variation in the estimation errors with slope was relatively small. When the slope increased from 0 ° to 30 °, the absolute errors of canopy height increased by only a few meters. Our results have demonstrated that the GLAS height estimating approach described by Yang et al. (2011) can be used in areas with slopes up to 30 °, but there may be lager underestimations for high stand density forests.

4. Discussion

The work in this paper enhances our knowledge regarding the impact of terrain slope on GLAS waveforms. The simulation results have shown that terrain slope broadens and decreases canopy and ground peaks. This finding is in agreement with pervious simulation results [1, 5, 7]. Our study has further revealed that although the waveform extends both in the signal-end and signal-start directions, the stretch in the signal-start direction is more significant than that in the signal-end direction, especially for simulated scenes with thick stand densities. Moreover, compared with the canopy peak, the magnitude of the ground peak decreased more rapidly. The magnitude of the canopy peak from a flat to a 10 ° slope decreased by approximately 2/5 to 3/5. However, the magnitude of the ground peak from a flat to a 10 ° slope decreased by more than 4/5 for all the simulated scenes.

The critical slope angle range was 9 °–20 ° at a 65 m footprint size in this study. The model simulations showed that the critical slope angle changed depending on vegetation height and stand density. The critical angle was proportional to canopy height, and slightly decreased with increasing stand density. This means that a high and not too dense forest with a single one-layer canopy can generate a waveform from which the ground peak could be identified, even if the terrain is steep and rough. However, the critical angle can also be very small when the stand density is too large regardless of whether the canopy height is high or low. The study by Yang et al. [5] showed that the critical angles were 10.5 ° for a one-layer canopy and 12.5 ° for a two-layer canopy at a 70 m footprint size and noted out that the critical angle decision could be much more complicated. In addition, Hilbert et al. [13] found that slopes between 10 ° and 15 ° appeared to be a critical limit for the usefulness of the waveforms. The results in this paper are essentially in agreement with the predecessor conclusions and further found the critical angle could change in a wider range depending on vegetation height and stand density.

The results from the simulation aid our understanding of the overall height error caused by surface topography. The results from this study showed that average error of RH100 for the nine groups of simulation results was about 5.4 m when the slope was 10 °, and reached 9.4 m when the slope was 15 °. As the slope exceeded the critical angle, the ground peak merged with the canopy peak, making it difficult to extract tree height using the direct method. Therefore, a conclusion was reached that it is suitable for retrieving tree heights for areas with up to a 10 ° slopes using the direct method. Some adjustment could be made according to the local conditions of study sites in the actual operational process of tree height retrieval. These results are consistent with previous studies [6, 8]. The simple physical slope correction developed by Yang et al. [5] could be used in areas with slopes up to 30 °, but may yield lager underestimation for forests with high stand densities. Previous studies have shown that large-footprint lidar estimates of maximum canopy height can be significantly improved using the simple physical slope correction [6, 9].

Modeling topographic effects on large-footprint lidar waveforms is an area of ongoing research. A simplifying assumption in the 3-D lidar waveform model was that only single scattering contributes to the returned signal. Blair and Hofton [10] demonstrated that multiple scattering was not a significant contributor to waveforms. However, North et al. explicitly modeled multiple scattering within the canopy using a Monte Carlo radiative transfer model, and found that it would cause a 'tail' beneath the ground peak in both simulated and GLAS waveforms [4]. Under this condition, the ground elevation may be underestimated due to increased path length, and such uncertainties would be reflected in calculations of waveform metrics and canopy height estimation. Some studies have suggested the presence of litter on forest floors possibly contribute to multiple scattering [11]. Further studies are needed to quantify the effects of multiple scattering in the canopies and understories on lidar pulse waveforms.

To model the impacts of surface topography on the GLAS waveforms under different forest conditions, the topography was described as a horizontal plane with specified slope angles. This method cannot model all topographic effects, but at the scale of the GLAS footprint a sloped plane will suffice. Moreover, some settings are simple and ideal in this model, such as the same vegetation structure, the uniform distribution in the footprint and ellipsoidal crown, which also affect the lidar waveform [7, 12]. The model performance need to be validated by using an actual dataset of field measurements and airborne lidar data.

5. Conclusion

In this paper, the 3-D lidar waveform model developed by Sun and Ranson [3] was used to simulate the terrain effects on a large footprint lidar waveform and on canopy height retrieval. Model simulations showed that terrain slope broadens and decreases canopy and ground peaks. Although the terrain slope stretched the waveform both in the signal-end and signal-start directions, the stretch in the signal-start direction was more significant due to the rapid decline of the ground return. The critical slope angle, where the ground and vegetation returns are completely mixed, ranged from 9 ° to 20 ° in this study. It was in direct proportion to canopy height, and slightly decreased with the increasing stand density.

The direct method and slope-correction model was employed to estimate canopy height based on the simulation results. An error analysis showed that the direct method could be used to retrieve tree height in areas with slopes up to 10 °. However, the simple physical slope correction could be used to could be used in areas with slopes up to 30 °, but there may be increased underestimation for high stand density forests. The present study clearly demonstrates the relationship between GLAS waveform and topography. Therefore, it can help improve the accuracy of canopy height estimation using GLAS or future spaceborne lidar data.

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