COMBINING STEREO-PHOTOGRAMMETRY AND LIDAR TO MAP FOREST CANOPY HEIGHT

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ABSTRACT

Lidar and digital stereo-photogrammetry techniques are being developed to improve on current methods used to map forest canopy height. Contrary to lidar, the latter technique is limited in that is does not have the capacity to automatically produce dense and accurate information on the ground elevations needed to calculate height. We propose a new canopy height mapping approach that combines both techniques. First, the photogrammetric digital surface model of the canopy and the lidar ground elevations are coregistered. Then the elevation differences between the two models are computed to produce a composite canopy height model (CHM). We demonstrate that the composite CHM constitute a smoothed version of the corresponding lidar CHM. The correlation between composite heights and lidar-only heights are of 0.79 and 0.96 respectively for point wise and plot wise comparisons.

1. INTRODUCTION

In recent years, numerous studies have demonstrated the capacity of small footprint scanning lidar for mapping forest canopy structural attributes such as height and volume (Hyyppä et al., 2001; Næsset 2002b, Næsset and Økland 2002, Dubaya and Drake 2002, Lim et al. 2003). The accuracy of estimates of various attributes of individual tree, plot, and stand are in most cases higher than those achieved by other means of remote sensing. Lidar-based estimates are in some cases as accurate as field measurements themselves (Næsset 2002b). This level of accuracy can be achieved because lidars have the capability of measuring the elevation of both the canopy surface and the underlying terrain. In comparison, photogrammetric measurements of closed canopies only give information on canopy surface altitude. Despite its advantages, lidar-based forest mapping may remain an experimental tool for a number of years due to its high acquisition costs. Low flying heights and narrow viewing angles translate into a high number of flight lines compared to that of aerial photo surveys (Baltsavias, 1999). The cost of recurrent lidar surveys over large areas for forest monitoring purposes will likely remain prohibitive. Moreover, research on forest dynamics currently cannot benefit from scanning lidars as multi-date datasets are still extremely rare, and long term retrospective studies are today not possible.

Both the high costs of lidar and the limitations of photogrammetry may be alleviated by combining these two types of remote sensing techniques to produce composite canopy height models (CHMs). Because it is theoretically possible to co-register a lidar bare earth digital terrain model (DTM) and a photogrammetric stereo-model, it should be possible to subtract lidar terrain elevations from photogrammetric canopy elevations to produce canopy heights. There are several advantages to this compositing technique. Assuming ground elevation is stable over time, bare earth lidar DTMs availability would allow forest monitoring to be performed using recurrent aerial photo surveys or stereo acquisition of high resolution satellite images (e.g. Ikonos and QuickBird). Retrospective studies that would consist in mapping forest attributes from archived stereo photos combined to recent lidar DTMs would become possible.

The principal question this paper addresses is the capability of automated stereo matching algorithms to correctly reconstruct the canopy DSM. Commercial softcopy photogrammetry programs were essentially developed for terrain mapping, and may lack the ability to reliably match stereo images of the forest due to tree leaning, complex canopy geometry, and occlusion patterns that vary between the left and right photos. Results from previous studies disagree on the level of accuracy that can be achieved through stereo-matching. Some studies report that height estimate errors may be large (Gong et al. 2000, Naesset 2002a), while others report accurate results (Miller et al. 2000).

We first present the study site and give the data characteristics. We then explain how the photogrammetric DSM was generated and registered to the lidar data, and how the composite CHM was compared to the corresponding lidar-only CHM.

2. STUDY SITE AND DATA

The data used for this study was acquired over the Green River locality, about 60 km northeast of Edmundston, New-Brunswick, Canada (long. 68°09'00" W; lat. 47°44'10" N). The study region is underlaid by a sedimentary bedrock covered by a well-drained glacial till. In the studied sector, the elevations range from approximately 400 m to 550 m. The study site lies within the Balsam fir (*Abies balsamea L. [Mill.]*) ecoregion (Loucks, 1962). Balsam firs represents more than 80% of all trees and are accompanied by a significant number of white birch (*Betula papyrifera* Marsh.). The site is under intensive forest management and bears numerous young stands and regeneration areas.

Lidar data was acquired by LaserMap Image Plus (Boisbriand, Canada) on 26 August 2000 using Optech's ALTM1225 placed onboard a Piper Navajo airplane flying at 700 m AGL at a speed of 60 m/s. The lidar produced 20,000 pulses per second and recorded for each pulse the first and the last return, and the return intensity. A 50% overlap between adjacent flight lines ensured that no gaps appeared in the coverage and that most areas received pulses from two flight lines, thus doubling the return density. The maximum angle from nadir was 15 degrees, which produced a swath width of 375 m. The average post spacing is of 0.75 m for vegetation returns, and 3.60 m for ground returns. True color 1:12,500 aerial photograph diapositives were purchased from the New Brunswick Natural Resource Ministry. These were acquired on 20 August 1996 using a Wild RC-20 camera with a focal length of 153 mm flown at 2350 m AGL. Sun elevation at the time of acquisition was of 47 degrees. The photos were digitised using a Epson Expression 836XL scanner at a resolution of 1600 x 1600 dpi. Considering the photographs' scale, the average ground pixel size is 19.8 cm.

3. METHODS

The implementation and accuracy assessment of the compositing method requires that a lidar DTM, DSM, and CHM be first generated. This necessitates that the lidar returns be separated into ground and non-ground lidar subsets, a task that was performed by the lidar survey provider using the ALTM 2.27 program from Optech Inc. (Toronto, Canada). First and last returns where all pooled before classification. The DTM was created by performing a TIN interpolation on the ground-classified last returns. Using the same method, the DSM was produced using all first returns (unclassified). Both TINs were gridded to a 0.5 m resolution. This pixel size was chosen so as to be slightly smaller than the post spacing of the lidar first returns (0.75 m) in order to preserve as much canopy topography details as possible. The lidar-only CHM was created by subtracting the DTM from the DSM in grid form. The interpolation, gridding, and grid arithmetics were carried out using ArcInfo and ArcGrid from ESRI Inc.

The compositing method is implemented by calculating the absolute orientation of the aerial photographs based on X,Y,Z control points data taken on the lidar DTM. This theoretically ensures that the photogrammetric stereo-model will be correctly registered to the lidar DTM. In forested regions, only stable bare areas, such as roads, rock outcrops, and the like, qualify as reliable control points. Trees should not be used due to growth between photograph and lidar acquisitions. Height well spread control points were selected on bare areas visible on both the lidar data and the aerial photos based on visual correspondence.

The photogrammetric processing was carried out using Virtuozo 3.2 from Supresoft Inc. (Beijing, PRC). The image matching was performed on the central parts of the photos using a 5x5 pixel stereo-matching window. Virtuozo employs global image matching, bridge-mode correlation, and uses area and feature-based matching (Zhang et al., 1992). Stereoscopic parallax was sampled every five (photo) pixels in the X and Y directions, i.e. approximately every 1 m, and interpolated to a 0.5 m DSM.

The composite CHM was generated in grid form by subtracting the lidar DTM from the photogrammetric DSM. The resulting composite CHM was assessed by measuring the difference and correlation between the lidar-only heights, used as reference, and the composite-based heights. The accuracy assessment of the composite CHM involved three experiments: 1) checking the accuracy of composite CHM spot canopy heights, 2) assessing the degree of smoothing introduced by stereo-matching and its impact on the accuracy of the composite CHM, and 3) assessing the accuracy of plot wise quantile-based height estimates calculated on the composite CHM. Figure 1 shows the relationships between the lidar DTM, and the various DSMs and CHMs used in this study.

The point-wise accuracy of spot canopy heights was assessed by calculating the mean, minimum, maximum and SD of elevation differences between the lidar and the composite CHMs, and by calculating the correlation (r), R^2 and standard error of estimate (SE) between the two models. Lidar spot heights (lidar point CHM) were obtained by calculating the difference between the Z value of lidar first returns (lidar point DSM) and the lidar interpolated DTM elevations directly underneath. The composite CHM spot heights were obtained by reading the composite CHM pixel values directly at the lidar return X,Y locations. We verified if a relationship existed between the composite height errors and the lidar heights by computing the r and R^2 of these two variables.

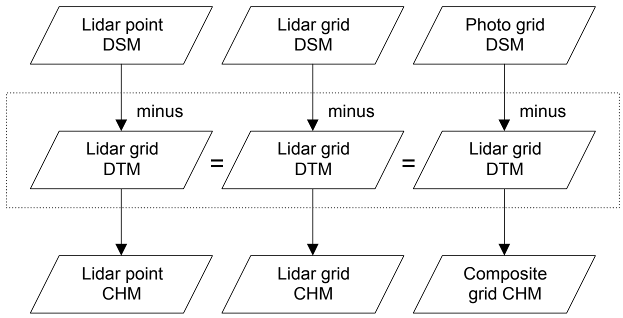

Figure 1: Relationships between digital surface models (DSM), digital terrain model (DTM), and canopy height models (CHM).

Both theory (Kasser and Egels, 2001, p. 207) and empirical evidence in forest related studies (Gong et al., 1999; Halbritter, 2000; St-Onge and Achaichia, 2001; Naesset, 2002a) suggest that digital surface models reconstructed using stereo-matching are smoother than the true topography they represent. Preliminary tests revealed that the composite CHM appears smoother than the corresponding gridded lidar-only CHM. We assessed this smoothing effect by calculating the correlation between the composite CHM and filtered versions of the lidar CHM. This was performed by applying a mean filter in a moving window over the lidar CHM. The size of the mean filter was varied from 3x3 to 21x21 pixels with a two-pixel step, thus progressively smoothing the CHMs. Correlation was also evaluated for filter sizes of 31x31 and 41x41. The correlation coefficient between the smoothed lidar CHM and unfiltered composite CHM was plotted against the size of the filtering window. For this experiment, the grid version of the lidar CHM was used to facilitate computations. To verify that changes in the correlation coefficient do not result from an attenuation of height differences attributable to planimetric shifts, we also performed the reverse experiment, i.e. we compared the unfiltered lidar CHM to filtered versions of the composite CHM using the same window sizes.

The plot wise quantile-based height estimation experiment consisted in calculating, for the lidar and the composite CHMs, the maximum height, and the 99th and 95th percentile heights within thirty 100 x 100 m windows evenly spread in the studied sector. Again, mean, minimum, maximum and SD of elevation differences were calculated as well as the correlation and R^2 between the lidar and composite CHM quantile-based height estimates. Statistical computations were performed with Statistica 6.0 from StatSoft Inc.

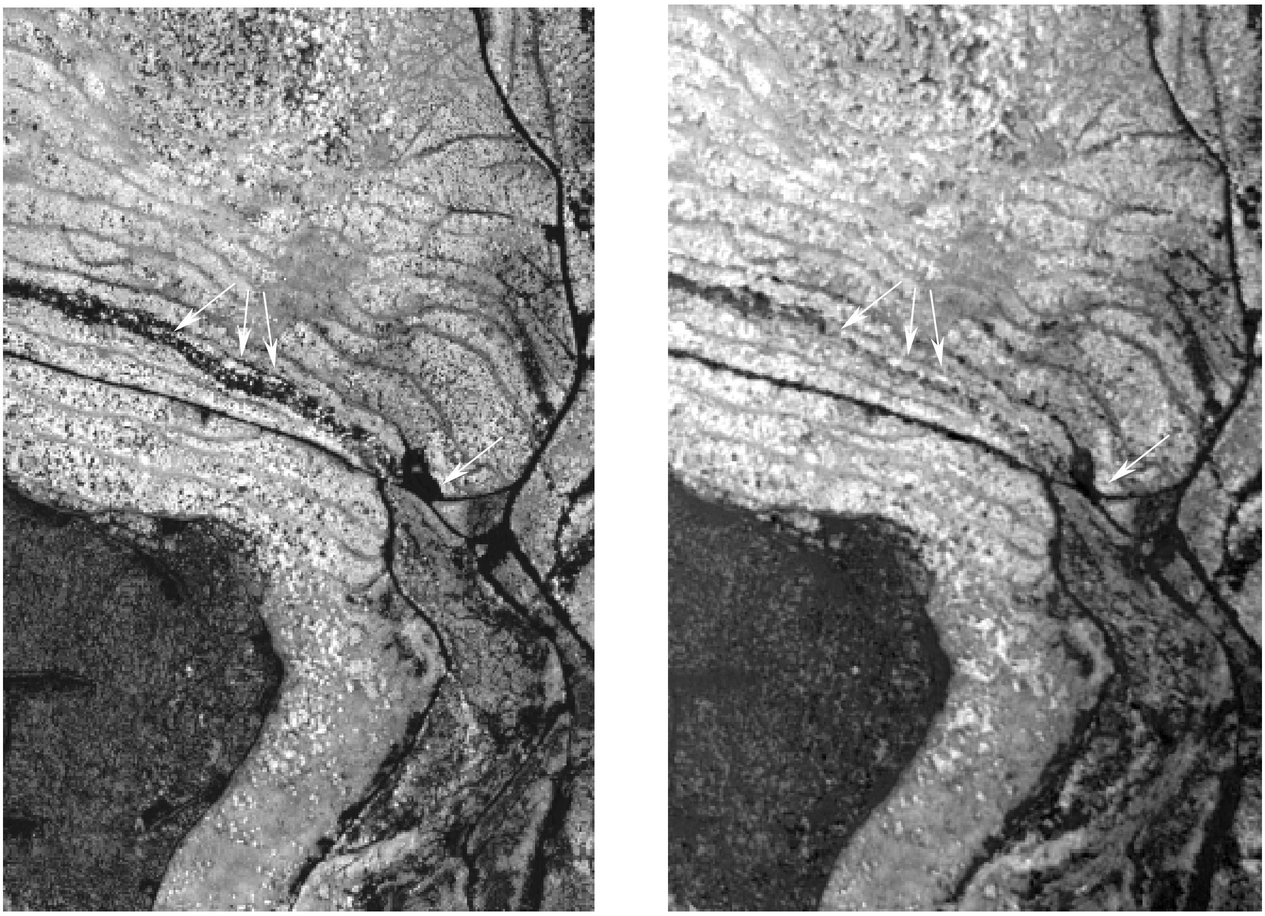

Figure 2: Lidar CHM (left) derived from laser data acquired in 2000, and composite CHM (right) produced using aerial photographs acquired in 1996. Each image represents 1100 m by 1670 m. Arrows show conspicuous changes between the two years.

	mean	**min**	**max**	**SD**	**r**	**R^2**	**SE**
lidar CHM	6.42	-4.09	24.84	4.19	-	-	-
composite CHM	5.98	-8.37	21.76	4.41	0.78	0.61	2.60
lidar - composite	0.44	-22.03	19.46	2.84	0.26	0.07	4.05
| lidar – composite |	2.13	0.00	22.03	1.93	*0.07*	*0.00*	4.18

Table 1: Point wise canopy height comparison between the compositing method and lidar. Mean, minimum, maximum, and standard deviation (SD) of lidar CHM and composite CHM heights or height differences. The correlation (r), coefficient of determination (R2), and standard error of estimate (SE) involve lidar-only CHM heights as the independent variable. Statistics were computed with n = 2,450,509. All relationships are statistically significant at $p < 0.01$.

4. RESULTS

The lidar and composite CHMs are shown in figure 2. Canopy height variations are very similar in both CHMs but the composite CHM appears smoother. Overlaying both CHMs on the a video screen did not reveal visible shifts in the two models. A close examination of both CHMs however revealed that a few small areas showed strong disagreement (see arrows on figure 2). Visual inspection of the air photographs and of the lidar CHM revealed that some mature trees present in the 1996 photographs had entirely disappeared from the lidar data acquired in 2000. These trees had obviously been cut or had fallen in the 4 year interval between photo and lidar acquisition. The results of the accuracy of spot height estimations are shown in table 1. For the 2,450,509 lidar first returns comprised in the study sector, the average height difference between the CHMs is of 0.44 m with an SD of 2.84 with minimum of and maximum of – 2.03 and 19.46 respectively. The correlation between the composite and lidar canopy heights is 0.78. Note that negative heights appear in both CHMs, reaching –4.09 m in the lidar CHM and –8.37 m in the composite CHM, due to classification and DTM interpolation artefacts. The correlation coefficient between composite height errors and lidar heights was very low but significant: 0.26 in the case of signed differences, and of 0.07 for absolute differences. The fact that these two low valued coefficients were found significant appears to be caused by the very high number of

	mean	min	max	SD	r	R^2	SE
lidar$_{max}$	17.09	8.95	21.26	3.58	-	-	-
composite$_{max}$	13.21	5.00	19.54	4.54	0.93	0.86	1.35
lidar$_{99}$	13.54	7.11	17,79	3.35	-	-	-
composite$_{99}$	11.19	3.89	17,33	4.28	0.95	0.90	1.09
lidar$_{95}$	11.53	5,77	15.99	3.25	-	-	-
composite$_{95}$	9.75	2,89	15.84	4.09	0.96	0.93	0.87
lidar$_{max}$ - composite$_{max}$	3.88	0,52	8,96	1,80	-	-	-
lidar$_{99}$ – composite$_{99}$	2,36	-0,85	5,81	1,53	-	-	-
lidar$_{95}$ – composite$_{95}$	1.78	-1,35	4,40	1,28	-	-	-
| lidar$_{max}$ - composite$_{max}$ |	3.88	0,52	8,96	1,80	-	-	-
| lidar$_{99}$ – composite$_{99}$|	2,46	0,62	5,81	1,37	-	-	-
| lidar$_{95}$ – composite$_{95}$|	1.92	0,10	4,40	1,04	-	-	-

Table 2: Plot wise quantile-based mean, minimum, maximum, and standard deviation (SD) of lidar CHM, and composite CHM heights, and of height differences. The correlation (r), coefficient of determination (R2), and standard error of estimate (SE) involve quantile-based lidar-only CHM heights as the independent variable (for equal CLIPE and lidar quantiles). All statistics were computed with n = 30. All relationships are statistically significant at $p < 0.01$.

cases ($n > 2,000,000$). The F statistic from which p is calculated will have a large value, thus signalling a significant relationship, even for weak relationships when n is very large, as it is the case here. To get a better understanding of the relationship between composite height errors and lidar heights, we artificially reduced n to an arbitrary low number by randomly selecting 100 cases over the more than two million points. This increased p to 0,001 in the case of the signed differences, and to 0.390 in the case of absolute differences. The latter relationship is thus not significant at the $p < 0.05$ level.

Figure 3 shows the effect of spatial filtering on the correlation between the lidar and composite CHMs. Filtering the lidar CHM significantly increases the correlation (up to 0.90) while filtering the composite CHM lowers it. The correlation of the unfiltered gridded lidar CHM with the composite CHM is already of 0.81, i.e. 0.3 higher than its point-based equivalent, due to the smoothing effect of gridding itself. The effect of augmenting filter size on the lidar CHM gives rise to an initial sharp correlation increase that progressively stabilizes. The correlation was found to decrease at larger filter sizes of 31x31 and 41x41 pixels (not shown).

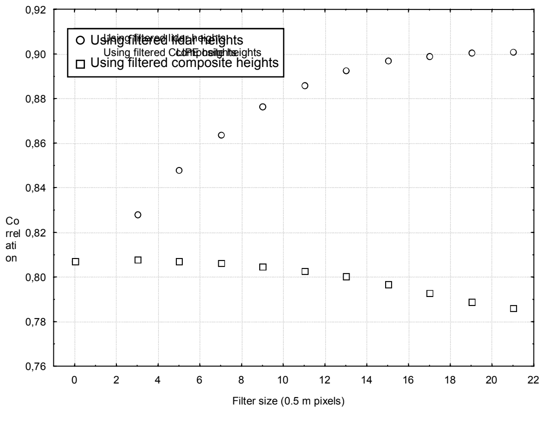

Figure 3: Variations of the correlation coefficient between the lidar-only and composite CHMs as a function of filter size. The correlation between filtered lidar and unfiltered composite CHMs, and the reverse, are shown.

Table 2 shows the result of the quantile-based height estimation differences and the correlations between lidar and composite CHMs for the 30 100 x 100 m windows. Differences in maximum height are all positive, indicating that lidar heights are always higher than composite CHM heights in the top part of the canopy. Differences are highest for maximum height, and decrease progressively for the 99th and 95th percentiles. In the latter case, the absolute differences are of only 1.92 m. Moreover, the plot wise quantile correlations are notably higher than the point wise or pixel-based correlations. Observe that again, the best results are obtained for the 95th percentile. Note that the lidar-only 95th percentile plot height can be predicted using the composite CHM equivalent with a coefficient of determination of 0.93 and a standard error of the estimate of 0.87 m.

5. DISCUSSION

The correlation between the lidar CHM and the composite CHM (0.78) may be affected by 1) misregistration, 2) changes (cuts, new gaps, differential growth, defoliation, death, etc.) between 1996 and 2000, 3) errors and approximations in the photogrammetric DSM caused by stereo-matching, occlusions, and shadows, 4) inner crown returns due to the high penetration capacity of lidar pulses. A visual appraisal revealed that the contribution of coregistration errors to the composite CHM errors is low, ruling out misregistration as the main cause. However, it is possible that even a slight misregistration (1 m or less) may decrease correlations. As most trees are balsam firs characterized by a very acute apex, even a small shift will create a situation where many crown apices of one CHM would be aligned to lower tree sides on the other CHM. The filtering experiment however presents clear evidence that the planimetric shift, if it exists, is not the main cause of error. If the two CHMs were identical but simply shifted one relatively to the other, the filtering of the composite CHM should have modified the inter-CHM correlation as much as filtering the lidar CHM. However, filtering the lidar CHM markedly improved correlation while filtering the composite CHM decreased it, indicating that the smoothing effect due to stereo-matching is much more important than that of the planimetric shift. This is also supported by the visual appearance of both CHMs in figure 2. The smoothing effect may be explained by a number of factors.

The photogrammetric DSM results from the interpolation of homologous point pairs having a post spacing of approximately 1 m. Some minute canopy topographic details will obviously be missed. The stereo-matching procedure itself also smoothes the elevations because it matches image patches, not individual pixels. Sharp elevation changes are for this reason filtered out (Kasser and Egels, 2001). Furthermore, contrast, and thus texture, are poor in the shadow regions between tree crowns because of the low radiometric resolution of argentic photographs. Because the stereo-matching process does not perform well in low texture areas, it is likely that the topography of shadowed canopy parts is not well reconstructed. Also, there is considerably more tree occlusion in the photos than in the lidar data because photographic view angles far exceed the 15^o maximum of lidar (view angles reach 30^o in our case). Furthermore, the two different viewpoints of the cameras produce two different occlusion patterns and consequently, two significantly different images. The parts of the canopy that are visible only on one photograph can't be matched with their homologous counterpart. Moreover, lidar pulses may penetrate a tree crown between branches and produce inner crown returns lower than the crown's apparent surface visible on the photographs. There returns will give a height that is lower than the corresponding photogrammetric height. Filtering of the lidar CHM should here again reduce the differences between lidar and composite heights. Finally, changes in the 4 year interval between the photography and lidar acquisition would normally decrease inter-CHM correlation compared to a situation where two synchronous datasets would have been examined.

The plot wise quantile-based height differences and correlations agree again with the hypothesis that stereo-matching truncates tree apices due to its smoothing effect. Indeed, differences decrease with the percentile height in the canopy, indicating that with the composite method, the heights of points located some distance below the maximum height of conifer trees are better estimated than that of points close to the maximum height. The results also show that lidar heights are most often greater than composite heights. The heights at the 95th percentile are in close agreement between the two CHMs (1.78 m difference). Considering that trees have grown in the interval between the photographic and lidar acquisition, we speculate that the true plot-wise 95th percentile height difference (i.e. for synchronous datasets) may be lower than 1 m. For these reasons, it is reasonable to think that composite CHMs could be used instead of lidar-only CHMs to estimate mean stand height.

6. CONCLUSIONS

We have demonstrated how a photogrammetric-lidar CHM may be created, and evaluated to what degree it reproduces the height variations observed in a lidar-only CHM. It was found that, despites changes between 1996 and 2000, point wise canopy height variations can be predicted by the composite method with a SE of 2.5 m or less, and 3) that plot wise composite predictions are markedly better (SE = 0.87 m) than point wise predictions. It was also found that the agreement between the composite and lidar-only CHMs is increased when the latter is filtered, suggesting that the photogrammetric DSM is smoother than its lidar equivalent. We conclude that the compositing method allows the creation of CHMs that constitute close approximations of lidar-only CHMs. It should therefore be possible to map canopy height and mean stand height using the compositing method with good accuracy.

Future developments of the compositing method include the improvement of the coregistration of lidar and photogrammetric DSMs, as well as the improvement of the generation of photogrammetric DSMs. Adaptation of digital stereo-photogrammetry algorithms to the particular topographic features of forest canopies will undoubtedly benefit canopy height mapping using the compositing method.

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