ASSESSMENT OF LIDAR-DERIVED TREE HEIGHTS ESTIMATED FROM DIFFERENT FLIGHT ALTITUDE DATA IN MOUNTAINOUS FORESTS WITH POOR LASER PENETRATION RATES

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ABSTRACT:

In this study, the effects of different flight altitudes on tree height estimates with a small-footprint scanning lidar were investigated and assessed in mountainous forests with poor laser penetration rates. The study area was closed-canopy evergreen coniferous plantations dominated by Japanese cedar (*Cryptomeria japonica*) and hinoki cypress (*Chamaecyparis obtusa*) in Japan. The stand age ranged from 33 to 100 years and the area was undulating terrain with a variation in elevation ranging from 135 to 391 m above sea level. A total of 33 circular sample plots (0.04 ha) were established and predominant mean tree heights for each plot were calculated using individual tree heights within each sample plot. Data from three different flight altitudes (500 m, 1000 m, and 1500 m) were acquired with Optech ALTM3100 sensor in late summer 2006. The settings of lidar system were paid attention as the laser footprints should cover the targeted area without omission, i.e. the laser spot spacing should be close to footprint diameter in the resultant data. Owing to this idea, we were able to theoretically avoid missing treetops and passing through the canopy gaps just by chance for a given transmitted laser pulse. The results of this study demonstrate that the higher platform altitude would reduce both the penetration rates and the intensities of laser pulses, and affect not only the quality of digital surface model, but also the quality of digital terrain model more significantly in forests with undulating topographies, thus indicating the less accurate estimates of lidar-derived tree heights.

1. INTRODUCTION

Small-footprint scanning lidar systems have been often used for forest measurements because such systems have become widely available on a commercial basis (St-Onge et al. 2003). In the previous studies, especially the accuracy of lidar-derived tree height estimates was really high and comparable with the accuracy of field measured tree heights in some vegetation types of forests (e.g. Hyyppä et al., 2001; Holmgren et al., 2003; Magnussen and Boudewyn 1998; Maltamo et al., 2004; Næsset 1997, 2004; Persson et al., 2002; Popescu et al., 2002; Takahashi et al., 2005; Yu et al., 2004). Because it takes much time and energy to measure tree heights in the field, it seems that small-footprint scanning lidar has a good potential to become an operational technique for forest inventories if the costs of data acquisition can be reduced (Yu et al., 2004).

For the purpose of reducing costs of data acquisition and measuring wider areas, one way is to increase the flight altitude. When the flight altitude increases, laser-sampling density decreases if both the pulse-repetition frequency and scan angle are kept fixed. On this point, some researchers have focused on the effects of laser-sampling density on the estimation of forest parameters using small-footprint lidar (Næsset, 2004; Hirata, 2004; Yu et al., 2004). In general, when the sampling density decreases, not only does the number of detected trees decrease (Zimble et al., 2003), but also the accuracy of tree height estimates deteriorates because of missing treetops (Gaveau and Hill, 2003). Moreover, we also have to note that when the flight altitude increases, footprint size increases if the beam divergence is kept fixed. On this point, for example, Perrson et al. (2002) concluded that estimates of lidar-derived individual tree heights and crown diameters were not affected much by different footprint diameters of 0.26 m, 0.52 m, 1.04 m, and 2.08 m in a boreal coniferous forest dominated by Norway spruce (*Picea abies* L. Karst), Scots pine (*Pinus sylvestris* L.), and birch (*Betula spp*.) on flat terrain. Moreover, Nilsson (1996), Yu et al. (2004), and Goodwin et al. (2006) also showed similar results for the estimation of tree height or canopy height profile with varying footprint sizes in some vegetation types of forests on comparatively flat terrain. Now, there is an interesting consistent report in both Yu et al. (2004) and Goodwin et al. (2006). Yu et al. (2004) found that as a result of increasing flight altitude, no reflections received by laser from most of tree canopies were observed for data from 1500 m flight altitude when using a Toposys Falcon lidar system. They assumed this relates to the problem of insufficient laser-transmitted power (laser class I) or insufficient sensitivity of the receiver, as the received power strongly depends on the distance between the target and laser. Goodwin et al. (2006) found that the proportion of first/last return combinations were reduced by higher platform altitudes with more than 70 % of pulses recording a single return at 3000 m in some types of eucalyptus forests when using an Optech ALTM3025 sensor. They hypothesized that greater platform altitude and footprint size reduce the intensity of laser beam incident on a given surface

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area, thus decreasing the probability of recording a last return above the noise threshold.

Considering these reports, it is considered that the penetration rates of laser pulses would decrease as increasing flight altitude in any type of forest. Thus, the accuracy of a digital terrain model (DTM) derived from higher altitude data would be less. In our previous study, we showed that the difference of the laser penetration rates in between closed canopy, middle-aged Japanese cedar (*Cryptomeria japonica*) and hinoki cypress (*Chamaecyparis obtusa*) plantations that had similar levels of canopy openness was significant ($P < 0.001$). (Takahashi et al., 2006). Although we acquired high laser-sampling density data (over 10 points/m^2) with footprint diameter of 0.15 m from approximately 300 m flight altitude, the penetration rate within each stand was 8.1 % and only 1.1 % in the Japanese cedar and hinoki cypress plantations, respectively. Therefore, we concluded that the generation of accurate DTMs in dense hinoki cypress stands with complex topographies is likely to be difficult when using such poor laser penetration data, although DTMs were not created and validated in the study. In Japan, many dense Japanese cedar and hinoki cypress plantations exist in mountainous areas. Many of the forests have not been adequately thinned and the canopy in such instances would be closed. Therefore, in order to evaluate the potential of airborne small-footprint lidar as an operational technique for forest inventories in Japan, we should investigate the effects of lidar data from different flight altitudes on the estimation of forest parameters in such forests.

Therefore in this study, we simply assessed lidar-derived tree heights estimated with data from different flight altitudes in closed-canopy Japanese cedar and hinoki cypress plantations with varying stand characteristics in mountainous areas. For the tree heights, we targeted predominant mean tree heights in this analysis because some previous researches have shown that lidar can usually give more information of predominant trees than that of lower trees in dense or closed-canopy coniferous forests (Persson et al., 2002; Takahashi et al., 2005).

2. MATERIALS AND METHODS

2.1 Study area and ground reference data

The study area was a national forest located in Ibaraki Prefecture in central Japan (lat. 36˚ 10’ N, long. 140˚ 10’ E). The size of the area was approximately 75.2 ha and over 80 % of this area was dominated by planted hinoki cypress and Japanese cedar which are evergreen coniferous tree species, and the rest of the area was dominated by some deciduous broadleaved tree species. The stand age ranged from 33 to 100 years in the coniferous area, and the area was essentially undulating terrain with a variation in elevation ranging from 135 to 391 m above sea level (Figure 1). During fall and winter of 2006, we established 33 circular sample plots (0.04 ha) within the coniferous plantations and differential global positioning system was used to determine the position of the center of each sample plot. Twelve plots consisted of purely planted Japanese cedar and the understorey vegetations consisting of *Aucuba japonica* and *Eurya japonica* which are evergreen shrubs with a height of less than approximately 3 m. Meanwhile, 19 plots consisted of purely young to middle-aged planted hinoki cypress and the understorey vegetations hardly existing except short shrubs or herbs with a height of less than approximately 1 m. Especially in Japan, closed-canopy unthinned hinoki cypress plantations have so low light intensity on the floor that there is scarcely understorey vegetations (Hattori et al., 1992). On the other hand, the forest floors of two plots in old and matured hinoki cypress stands consisted of *Aucuba japonica* and *Eurya japonica*, and some types of deciduous shrubs with a height of less than approximately 3 m. Moreover, there is an important information about the topographic locations of Japanese cedar stands and hinoki cypress stands in this study site. In Japan, applying the idea of right tree on right site, Japanese cedar is usually planted around mountain valleys, while hinoki cypress is usually planted around mountain ridges. In this site, the same thing can be found as seen in Figure 1.

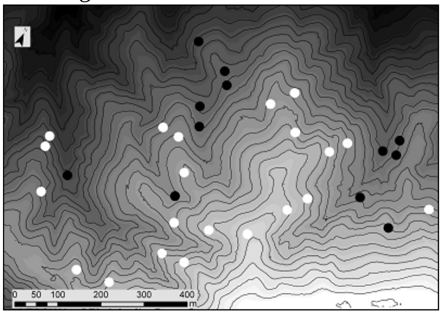

Figure. 1. The topographic map created by a digital terrain model (500 m-altitude data) within the study area. The gray-scale color represents the elevation ranging from 135 to 391 m a.s.l. (black to white). Black lines, black circles, and white circles denote the contour (10 m interval) and the field sample plots in Japanese cedar and hinoki cypress stands, respectively.

	Japanese cedar			Hinoki cypress		
	Min	Max	Mean	Min	Max	Mean
Stand age	38	100	59	33	99	44
Density (per 1 ha)	475	2800	1575	475	2575	1899
No. of trees	19	112	63	19	103	76
No. of predominant trees[a]	9	58	33	11	63	43
Mean DBH (cm)	14	37	24	15	37	20
Basal area (m^2/ha)	37.6	76.8	59.1	42.1	66.5	53.4
Mean tree height (m)	10.8	24.8	18.8	9.6	22.2	14.7
Predominant mean tree height[a] (m)	11.5	26.8	20.2	11.1	22.8	15.5

[a]For trees whose heights were greater than the mean tree height within each plot

Table 1. Summary statistics of field data for 33 sample plots

Within each sample plot, all trees with diameter at breast height (DBH) > 4 cm were callipered. Tree heights were measured on sample trees within plots for young and middle-aged forests and all trees within plots for old and matured forests with Vertex hypsometer. For the young and middle-aged forests, sample trees were selected with equal probability and over 50 % of the number of trees within each plot. Next, height-diameter curve was produced for each plot and unmeasured tree heights were estimated from each model. Then the arithmetic mean tree height (*H*) was calculated with all individual tree heights within each plot. Finally, the trees whose heights were greater than *H* within each plot were targeted and the arithmetic mean value was regarded as field measured predominant mean tree height (H_{dom}) in this study. A summary statistics for 33 field sample plots is shown in Table 1.

2.2 Lidar data collection

Lidar data acquisition was performed on 31st August 2006 using a helicopter-airborne laser scanner (Optech ALTM 3100) operated by Aero Asahi Co., Ltd., Japan. The study site was flown at three flight altitudes, namely, 500 m, 1000 m, and 1500 m (a.g.l.), providing data with different point densities and footprint sizes. In this study, these data were referred to as 500 m-, 1000 m-, and 1500 m-altitude data, respectively. Assuming that laser footprints should cover the targeted area without omission, i.e. the laser spot spacing should be close to footprint diameter in the resultant data, we changed flight speed, scan frequency, and pulse-repetition frequency at each flight altitude. At each flight altitude, several parallel flight lines were recorded to cover the entire area with average overlapping of 64 % between adjacent flight lines. Maximum scan angle was 11˚ and pulses transmitted at scan angles that exceeded 8˚ were excluded from the final data in order to avoid the low quality data at the edge of strips (Lovell et al., 2005) and be average overlapping of 50 % between adjacent flight lines. The beam divergence of 0.31 mrad produced footprint diameters of 0.16 m, 0.31 m, and 0.47 m for 500 m-, 1000 m-, and 1500 m-altitude data, respectively. The resultant laser-sampling densities within the study area were approximately 57, 25, and 9 points/m^2, respectively. Both first and last returns and also intermediate returns were recorded as well as the intensity of all returns for each flight altitude data.

2.3 Processing lidar data and estimating predominant mean tree heights

Firstly, the unevenly distributed laser reflection point data were converted into one raster layer with a pixel size of 0.5 m. The raster layer, referred to as DSM_{raw}, was assigned the height value of the highest laser reflection point within each pixel using only first pulse data. To create a continuous surface model, the values of the no-data pixels in DSM_{raw} were interpolated by an inverse distance weighting (IDW) method that does not change the original value (Popescu et al., 2002). The interpolated DSM_{raw} was defined as DSM.

Next, in the noise (i.e. lidar vegetation point) filtering processes for DTM creation, we firstly applied an automatic method used in Holmgren et al. (2003) and Takahashi et al. (2005). Parameter settings were not changed during the processing for all data within the study area in order to evaluate objectively the quality of the resultant DTM for all data. Firstly, the unevenly distributed laser reflection point data were converted into one raster layer with a pixel size of 0.5 m. The raster layer, referred to as DTM_{raw}, was assigned the lowest laser reflection point within each pixel using only last pulse data which had a distance between the first and the last pulse in the same laser beam was more than 2.0 m in this study. Each center pixel of DTM_{raw} was compared with the other pixels within a 6 m horizontal distance, and if the vertical angle of the neighbouring pixels from the center pixel exceeded 45°, the center pixel was classified as ground laser data and the neighbouring pixels were removed. Then, the remaining pixels were referred to as ground laser data. Finally, DTM was created with the remaining pixels by spline interpolation (Magnussen and Boudewyn, 1998).

Then we also applied a semi-automatic method which requires human edits by the contractor (Aero Asahi Co., Japan) in the noise filtering processes for DTM creation. In this study, this semi-automatic method is denoted as a processing which requires a human operator to not only determine the input parameters for the noise removal algorithms (e.g. the parameters of 6 m and 45° as used in the automatic method), but also edit data manually with intensive visual checks. Normally, such methods seem to be often applied for DTM products by any contractor. Although such semi-automatic methods are nonobjective and largely depend on the operator’s experience and technical intuition, it is considered that the method can produce much better quality of DTM than that of automatic method when the ground laser data exist enough to discriminate high or low vegetation laser data and ground laser data visually (Raber et al., 2002). On the other hand, it seems to be difficult to distinguish objectively high or low vegetation laser data from ground laser data when the ground laser data is poor. In this study, we found that both 1000 m- and 1500 m-altitude data had really poor ground laser data especially in some young and middle-aged hinoki cypress stands, conversely 500 m-altitude data had little more than many ground laser data in the stands. Therefore in this study, firstly the semi-automatic method in the noise filtering processes was applied for 500 m-altitude data by the contractor intensively, and a DTM was created with the remaining pixels by spline interpolation as mentioned above. Hereafter, the DTM was regarded as a reference terrain data and referred to as DTM_{ref}. Because the DTM_{ref} was created by similar noise filtering processes as mentioned above but a little bit different process by the contractor (Yokota et al., 2006), so we created DTM uniformly for three flight altitude data using the DTM_{ref} as follows. If a given pixel value of DTM_{raw} of each flight altitude data is greater than that of corresponding pixel of DTM_{ref}, the pixel is ideally regarded as noise and removed. But in order to avoid the effect of the interpolation error (e.g. overestimation of elevation) within the DTM_{ref} on excessive removing pixels, if the difference between DTM_{raw} and the DTM_{ref} is greater than 1 m, such pixel of DTM_{raw} is regarded as noise and removed for all data. Finally, DTM for each data was created with the remaining pixels by spline interpolation as mentioned above.

To estimate lidar-derived predominant mean tree heights (H_{dom_L}), firstly a canopy height model (CHM) was calculated by subtracting DTM from DSM for each flight altitude data. Previous researches have shown that the raster-based CHM can usually give more information of predominant trees than that of lower trees in dense or closed-canopy forests (Persson et al., 2002; Takahashi et al., 2005). We then smoothed the DSM with a low-pass filter (3 by 3 pixels) used in the previous researchers (Hyyppä et al., 2001; Maltamo et al., 2004) and applied a 3 by 3 local maximum filtering (Wulder et al., 2000) to detect predominant treetops for each data. Then individual tree heights were derived from the CHM at the horizontal location of the local maxima of the smoothed DSM. Finally, the arithmetic mean value of the lidar-derived individual tree heights within each sample plot was calculated and regarded as H_{dom_L}.

2.4 Assessment of lidar-derived tree heights

Data assessments were made separately in Japanese cedar and hinoki cypress stands basically. Firstly, the relationships between lidar-derived and field measured predominant mean tree heights were investigated by regression analysis. Next, systematic error (i.e. bias) and root mean square error (RMSE) for the tree height estimates were computed as follows:

$$RMSE = \sqrt{\frac{\sum (H_{dom\_L} - H_{dom})^2}{n}} \qquad (1)$$

where H_{dom_L} and H_{dom} are lidar-derived and field measured predominant mean tree heights, respectively and n is the number of sample plots. Then, in order to understand the errors of the tree height estimates, DTMs for different flight altitude data derived from both the automatic and the semi-automatic methods were compared with a reference DTM, i.e. DTM_{ref}, and the systematic errors were evaluated for each DTM. Also the laser penetration rates of last pulses within each sample plot were calculated for each data. Additionally, the arithmetic mean laser-intensity of first pulses within each sample plot was also calculated. Then we assessed the statistical significant differences for each factor (i.e. penetration rate and intensity) among three flight altitude data. In this study, Friedman test and the Scheffe procedure as a multiple comparison post hoc test were applied in the statistical tests. Moreover, these two factors were tested in between Japanese cedar and hinoki cypress stands for each flight altitude data by Mann-Whitney U test.

3. RESULTS

	Japanese cedar			Hinoki cypress		
	500 m	1000 m	1500 m	500 m	1000 m	1500 m
All trees	756	756	756	1595	1595	1595
Predominant trees[a]	393	393	393	902	902	902
Local maxima[b]	399	409	344	760	724	606

[a]The trees whose heights were greater than the mean tree height within each plot

[b]Local maxima derived from lidar data with 3 by 3 local maximum filtering were denoted as the number of predominant trees in this study

Table 2. The number of trees in the field and lidar-detected trees within all (33) sample plots for each flight altitude data

	Altitude	Automatic		Semi-automatic	
		Bias (m)	RMSE (m)	Bias (m)	RMSE (m)
Japanese cedar	500 m	-0.16	1.12	-0.46	1.11
	1000 m	-0.81	1.46	-0.74	1.28
	1500 m	-2.54	6.12	-1.15	1.63
Hinoki cypress	500 m	0.18	0.98	0.00	0.84
	1000 m	1.50	3.78	0.39	1.23
	1500 m	2.18	5.91	0.88	2.29

Table 3. Bias and root mean square error (RMSE) for predominant mean tree height estimates when using DTMs created by an automatic and a semi-automatic method

The number of detected predominant treetops, i.e. local maxima, for each altitude data is shown in Table 2. Although the number of local maxima within the DSM of 1000 m-altitude data was higher than that of 500 m-altitude data in Japanese cedar stands, there seems that greater platform altitude and footprint size reduced the number of local maxima. The magnitudes of the differences between the number of predominant trees in the field and lidar-detected trees were greater in hinoki cypress stands than in Japanese cedar stands.

The relationships between field measured and lidar-derived predominant mean tree heights are shown in Figure 2. The results show that the number of the outliers increased as the flight altitude increased in both two methods. Bias and RMSE for predominant mean tree height estimates are shown in Table 3. Japanese cedar stands had underestimates of height, conversely hinoki cypress stands had overestimates of height in both methods. Figure 3 shows that the cause of under and over-estimations of predominant mean tree heights in Japanese cedar and hinoki cypress stands, respectively. That is, the underestimations of DTM would produce the overestimations of tree heights in hinoki cypress stands, in contrast, the overestimations of DTM would produce the underestimations of tree heights in Japanese cedar stands. In the semi-automatic method, the magnitude of the difference between maximum and minimum RMSEs in hinoki cypress stands was greater than that of Japanese cedar stands.

According to the statistical tests, the penetration rates of last pulses in 500 m-altitude data were significantly greater than that of other altitudes in both stands (Table 4). Moreover, there were statistically significant differences among the intensities of first pulses of all three flight altitude data in both stands.

	Altitude	Penetration rate (%)	Intensity
Japanese cedar	500 m	14.1	74.3
	1000 m	3.2	16.9
	1500 m	2.1	11.2
Hinoki cypress	500 m	2.3	99.0
	1000 m	0.6	23.6
	1500 m	0.4	16.3

Table 4. Mean values of laser penetration rates of last pulses and laser-intensity of first pulses

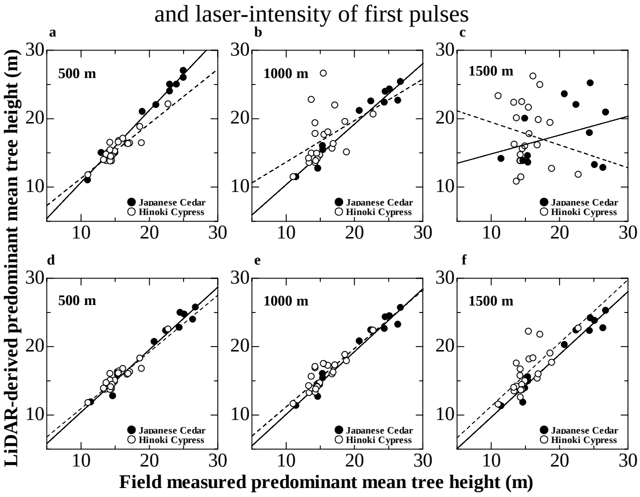

Figure 2. The relationships between field measured and lidar-derived predominant mean tree heights (H_{dom_L}) of three flight

altitude data. Solid and dashed lines denote regression lines of Japanese cedar and hinoki cypress data, respectively. H_{dom_L} in above three graphs (a, b, and c) and below three graphs (d, e, and f) are the estimates when using DTMs created by an automatic and a semi-automatic method, respectively.

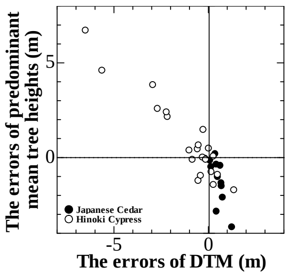

Figure 3. The relationship between the errors of DTM of 1500m-altitude data derived from a semi-automatic method and the errors of predominant mean tree height estimates for all sample plots. The errors of the DTM denote as the difference between the mean elevation within each plot of the DTM and that of a reference DTM (DTM_{ref}) created by a contractor.

4. DISCISSIONS AND CONCLUSIONS

In order to investigate the effects of different flight altitudes on the estimation of tree heights in forests with poor laser penetration rates, we used lidar-derived predominant mean tree heights derived from the information of local maxima in DSM and heights in CHM in this study. The validity of this approach seems to be ensured by the results of regression analysis and the errors of the tree height estimates as shown in Figure 2 (d) and Table 3. In this study, the settings of lidar system were paid attention as the laser footprints should cover the targeted area without omission, i.e. the laser spot spacing should be close to footprint diameter in the resultant data. Owing to this idea, we were able to avoid theoretically missing treetops and passing through the canopy gaps just by chance for a given transmitted laser pulse. But in fact, the no-data pixels of DSM_{raw} (50 cm resolution) were found for all flight altitude data even though the mean laser-sampling density is high (at least over 9 points/m^2). This problem is considered to be inevitable for any scanning lidar system as long as using airborne platform and targeting uneven surface, especially in mountainous forest areas.

On the assumption that the targeted area was fully covered with laser shots for all flight altitude data, the results of this study indicate that the higher platform altitude would deteriorate the quality or accuracy of lidar-derived variables such as the number of detectable local maxima in DSM, penetration rates and intensities of laser pulses, the elevation of DTM, and tree height estimates. These findings are partly similar to those previously reported in Yu et al. (2004) and Goodwin et al. (2006), even though the vegetation species and topographies were different from that of this study area. But there were some dissimilar points in this study. The most crucial failing at higher flight altitude seems to be less penetration rates of laser pulses, thus indicating the less accuracy of the resultant DTM in mountainous forests with undulating topographies. Judging from the low penetration rates in Table 4 and the outliers in Figure 2 (e and f) in hinoki cypress stands, lidar ground laser data did not seem to exist enough to recover the shape of the field topographies. Therefore, the results in Figure 2 (b and c) indicate that it is difficult to remove lidar vegetation points properly and correctly in such forests by using fixed input parameters for the noise removal algorithms, i.e. automatic methods when the laser penetration rates are poor. Although we could use a good reference DTM (DTM_{ref}) in this study, whether another semi-automatic method which depends on human edits manually and visually without using such reference DTM can produce an equivalent to the quality of the DTMs created in this study for 1000 m- and 1500 m-altitude data remains unknown. However, judging from the results in Figure 2, it would be necessary semi-automatic noise filtering methods to acquire better DTM of such forests even if the resultant DTM is not objective product.

Figure 3 shows the positive and negative errors of tree height estimates would be mainly caused by the negative and positive errors of the DTM, respectively. Moreover, the tendencies that many hinoki cypress stands had lager negative errors of the DTM while many Japanese cedar stands had lager positive errors of the DTM can be understood by the topographic locations of each stand as seen in Figure 1. That is to say, because most hinoki cypress stands located around the mountain ridges, poorly penetrated laser pulses would be missing the top of the ridges, thus resulting in the lower elevation of the DTM and the greater estimates of tree heights. Meanwhile, although Japanese cedar stands in this study area might have the opposite effect from hinoki cypress stands, it is also considered that the existence of understorey bushes might be involved in the overestimations of the DTM. As indicated in Goodwin et al. (2006) and Hyyppä et al. (2005), the all results of this study are highly site dependent as lidar-derived relationships will be influenced by its structural complexities. But the relationships between the topographic locations and the penetration rate of laser pulses would effect significantly on the resultant DTM in any type of forest.

Although lidar data was acquired in late summer (growing season) in evergreen Japanese cedar and hinoki cypress stands in this study, the assessment of different flight altitude data acquired in winter (leaf-off season) for the estimation of tree heights should be performed because the leaf biomass of evergreen forests differs between summer and winter (Tsutsumi 1989). Therefore, if such low laser penetration rates were improved in hinoki cypress stands in winter, the acquisition of lidar data should be performed in winter. Anyhow, the results of this study demonstrate that the higher platform altitude would reduce both the penetration rates and the intensities of laser pulses, and affect not only the quality of DSM, but also the quality of DTM more significantly in forests with undulating topographies, thus indicating the less accuracy of lidar-derived tree height estimates. In fact, the errors of tree height estimates increase with increasing flight altitude as shown in Table 2, and there are some hinoki cypress stands whose tree height errors are over 4 or 5 m in 1500 m-altitude data (Figure 2 (f)). Although the accuracy of tree height estimates in Japanese cedar stands was high in all flight altitude data, the penetration rates of laser pulses are not enough magnitude of 1500 m-altitude data (Table 4). Considering these results, if we ensure the accurate lidar-derived tree height estimates (the error is 1 m or so) in summer in both Japanese cedar and hinoki cypress plantations with varying stand characteristics, the flight altitude should be set lower than at least 1000 m.

Further work should be performed to investigate the effect of laser-sampling density on the accuracy and quality of DTM and tree height estimates in this study site, especially in closed-canopy hinoki cypress plantations, to establish optimal settings of lidar system for an operational technique for forest inventories in mountainous forests in Japan.

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