Korean Journal of Remote Sensing, Vol.28, No.3, 2012, pp.307~318

Maximum Canopy Height Estimation Using ICESat GLAS Laser Altimetry

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Abstract : To understand forest structures, the Geoscience Laser Altimeter System (GLAS) instrument have been employed to measure and monitor forest canopy with feasibility of acquiring three dimensional canopy structure information. This study tried to examine the potential of GLAS dataset in measuring forest canopy structures, particularly maximum canopy height estimation. To estimate maximum canopy height using feasible GLAS dataset, we simply used difference between signal start and ground peak derived from Gaussian decomposition method. After estimation procedure, maximum canopy height was derived from airborne Light Detection and Ranging (LiDAR) data and it was applied to evaluate the accuracy of that of GLAS estimation. In addition, several influences, such as topographical and biophysical factors, were analyzed and discussed to explain error sources of direct maximum canopy height estimation using GLAS data. In the result of estimation using direct method, a root mean square error (RMSE) was estimated at 8.15 m. The estimation tended to be overestimated when comparing to derivations of airborne LiDAR. According to the result of error occurrences analysis, we need to consider these error sources, particularly terrain slope within GLAS footprint, and to apply statistical regression approach based on various parameters from a Gaussian decomposition for accurate and reliable maximum canopy height estimation.

Key Words : Maximum canopy height, Geoscience Laser Altimeter System (GLAS), Airborne Light Detection and Ranging (LiDAR), Waveform analysis

1. Introduction

The canopy structure characterization has been considered as a major challenge in remote sensing, particularly for moderate- and high- density forest area. Since developed passive- and active sensors to measure and monitor forest canopy structure, the laser altimeter system, which can record the amplitude of backscattered laser energy reflectance from targeted objects, has been commonly employed due to feasibility of acquiring three dimensional canopy structure information (Harding *et al*., 2001).

The Geoscience Laser Altimeter System (GLAS) on board Ice, Cloud and land Elevation Satellite

Received May 10, 2012; Revised June 7, 2012, Revised June 21, 2012; Accepted June 22, 2012.

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(ICEsat) was employed to produce vertical vegetation canopy wavelength profile within its laser footprint. About global coverage of ±86° latitude is provided by ICEsat which launched in January 2003 and acquired during its 91-day repeat orbit cycle. The laser system produced 1,064 nm pulses, near-infrared wavelength might be sensitively reflected on vegetation, at an initial energy level of 75 mJ for the altimeter measurements (Duong *et al*., 2008). The footprints of GLAS are generated sequentially with 172 m and its receiver records the vertical canopy structure up to 81.6 m during the early laser campaigns (L1A and L2A periods). However, the later campaigns of GLAS changed from 81.6 m to 150 m to avoid truncation of signals from tall objects or steep slope (Harding and Carabajal, 2005). In the early laser campaigns, acquired waveform has a vertical resolution of 15 cm for a total of 544 bins while the waveforms of later campaigns have a vertical resolution of 15 cm for the lower 392 bins and 60 cm for the upper 152 bins. During the operation of GLAS (2003-2009), informative dataset in forest area was provided throughout the earth surface. Therefore, many researchers interested in forest have tried to explore the feasibility of the GLAS waveform for forest structure retrieval (Lefsky *et al*., 2005; Lefsky *et al*., 2007; Duong *et al*., 2008; Rosette *et al*., 2008; Sun *et al*., 2008).

According to previous studies, initial canopy height extraction methods from GLAS dataset were employed the direct method (Chen, 2010a). The direct method is a simple method to estimate canopy height through using vertical difference between signal start (maximum canopy top) and ground peak (Hofton *et al*., 2000; Neuenschwander *et al*., 2008). However, extracting accurate signal start and ground peak from general GLAS waveforms seriously suffered from severe fluctuation. In order to alleviate difficulties of extracting signal start and ground peak, Gaussian decomposition has been usually used to decompose uneven signal distribution (Hofton *et al*., 2000; Neuenschwander *et al*., 2008; Chen, 2010a and 2010b). That method is able to decompose a laser altimeter return waveform into a series of Gaussians so it is possible to determine the ground peak assuming the lowest peak among generated multiple Gaussian distribution.

Actually, GLAS data processing to understand and retrieval forest vertical structures (i.e. canopy height) is rarely applied to Korean forest area. With this point of view, this study introduces an application of GLAS waveform dataset on forest monitoring and mensuration. Particularly, this study tried to estimate maximum canopy height from sampled GLAS dataset based on direct method in Yangpyeong study site and evaluate the accuracy of maximum canopy height estimation using derivations from airborne LiDAR data.

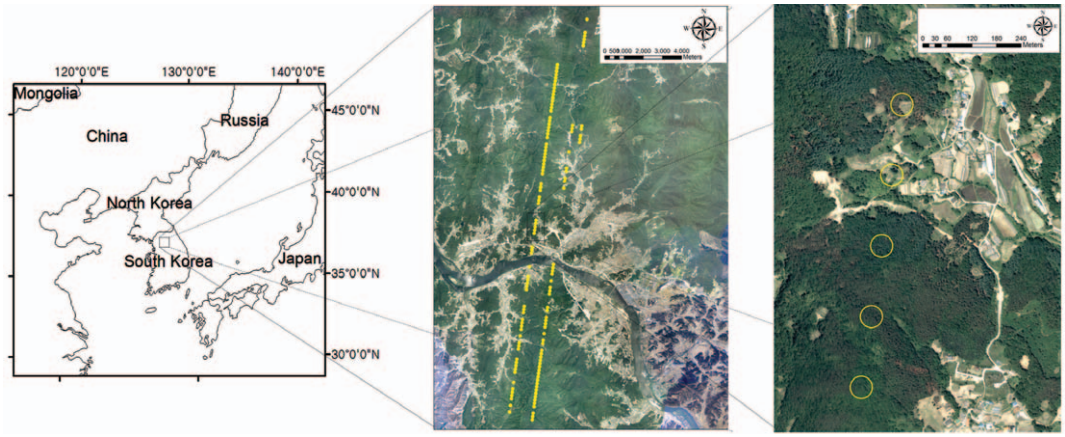
2. Material

1) Study area

The study area is located in Yangpyeong City of Kyeonggi Province (Datum: WGS1984, the upper left 127°18′ 12.7295″E, 37°40′ 17.6375″N and lower right 127°50′ 56.4683″E, 37°22′ 1.8228″N) central South Korea (Fig. 1). The area is approximately 878 km2 and situated from 160 to 1,157 m above sea level. The forest area in study site was dominated by steep hills, and composed to *Pinus koraiensis, Larix leptolepis, Pinus densiflora, Pinus rigida and Quercus spp*.

2) GLAS data

In this study, GLA01 (L1A Global Altimetry) and GLA14 (L2 Global Land Surface Altimetry) from Release-31 were used to estimate canopy maximum



(a) (b) (c)

Fig. 1. Geographical location of study area (a) and each GLAS shots (b, c).

Table 1. Information of ICESat campaigns, taken from NSIDC

Campaign	Laser 3B	Laser 3C	Laser 3D
Start date	2005-02-17	2005-05-20	2005-10-21
End date	2005-03-24	2005-06-23	2005-11-24
Days in operation	36	35	35
Orbit Reference ID (RefID)	2111	2111	2113
Near-infrared elliptical footprint major axis mean and standard deviation (m)	79.3 +- 11.6	55.4 +- 1.8	52.0 +- 1.1
Land waveform vertical extent (m)	150	150	150

height. Both GLAS dataset were acquired from L3B, L3C and L3D campaign and information of each campaign was listed in Table 1.

The records of GLA01 products include 40 shots received in 1 second and geographical locations of these shots were assigned only one estimated latitude and longitude. Using the record index (i_rec_ndx) and the transmit time of first shot (i_UTCTime) found in GLA14 data, the individual waveform was extracted from GLA01 data along with other parameters such as estimated noise level, noise standard deviation, and transmitted pulse waveform, which were used later in waveform processing. Prior to actual GLAS waveform analysis, filtering process might be required because GLAS waveforms might be contaminated by the atmospheric forward scattering or saturated signals. Therefore, only the cloud-free (the flag FRir_qaFlag=15 in the GLA14 products) and saturation-free (the saturation index satNdx=0 in the GLA14 products) shots were analyzed in this study (Chen, 2010a and 2010b; Duncanson *et al*., 2010). In the case of our study, 428 individual waveforms were excluded by filtering criteria among 540 waveforms under non-filtering process. Only 112 individual waveforms were employed to estimate maximum canopy height using direct method.

3) Airborne LiDAR data

An Optech ALTM 3070 (a discrete LiDAR system) was used for acquisition of the LiDAR data, with the flight performance from 11th April to 28th May, 2009. The study area was measured at an altitude of 1,000m, with a sampling density of approximately 3~5 points per square meter, with radiometric resolution, scan frequency and scan width of 12bits, 70Hz and ±25°, respectively. For accurate

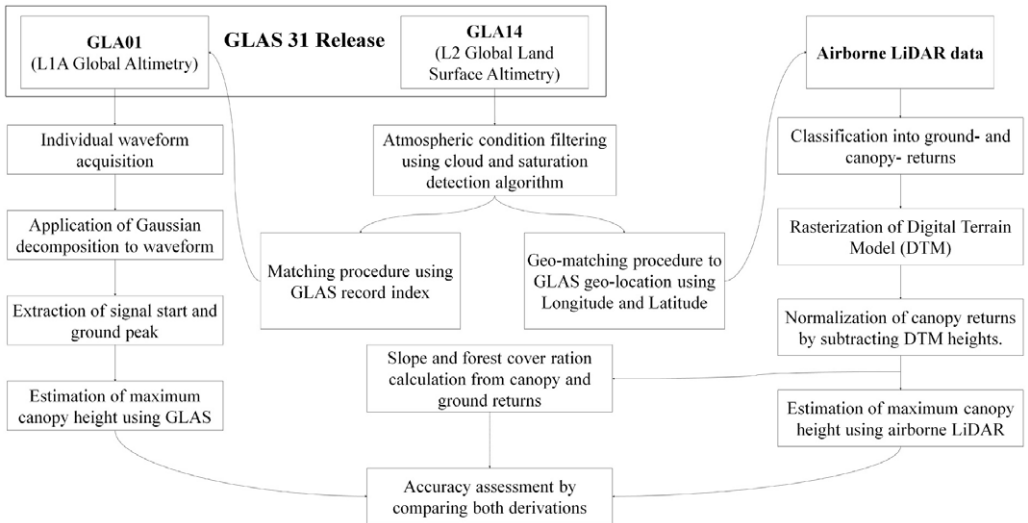


Fig. 2. Flowchart for maximum canopy height estimation using GLAS dataset.

analysis, we used LiDAR returns within $\pm 10^{\circ}$ scan angle as overlapped areas were eliminated by MicroStation and TerraSolid Program to reduce the scan angle affection to mean tree height and stem volume estimations (Næsset, 1997).

This study alternatively used maximum canopy height derived from airborne LiDAR data as reference data to evaluate employed GLAS estimation method. According to previous studies, airborne LiDAR data acquired with high resolution showed reliable performance to estimate canopy structures (Lefsky *et al*., 2002) and canopy structure estimation extracted from airborne LiDAR data also used to assess accuracy as a role of alternative reference data (Neuenschwander *et al*., 2008; Chen, 2010a; Duncanson *et al*., 2010). Therefore, this study performed the accuracy assessment procedure without any filed surveying.

3. Method

To estimate maximum canopy height using feasible GLAS dataset, we used direct method referred from several previous studies (Hofton *et al*., 2000; Neuenschwander *et al*., 2008; Chen, 2010b). After estimation procedure, maximum canopy height derived from airborne LiDAR data was applied to evaluate the accuracy of GLAS estimation based on direct method. In addition, several influences, such as topographical and biophysical factors, were analyzed and discussed to explain error sources of direct maximum canopy height estimation using GLAS data. Overall procedures were schematized in Fig. 2.

1) Maximum canopy height estimation using direct method of GLAS data

The individual waveform, which was recorded by the GLAS, represents the reflective energy magnitude as a function of time. To understand and extract parameters from GLAS waveform, this study employed a Gaussian decomposition method suggested by Hofton *et al*. (2000). Prior to suggestion of Gaussian decomposition method, existing waveform processing methods showed reliable parameterization results in a simple waveform,

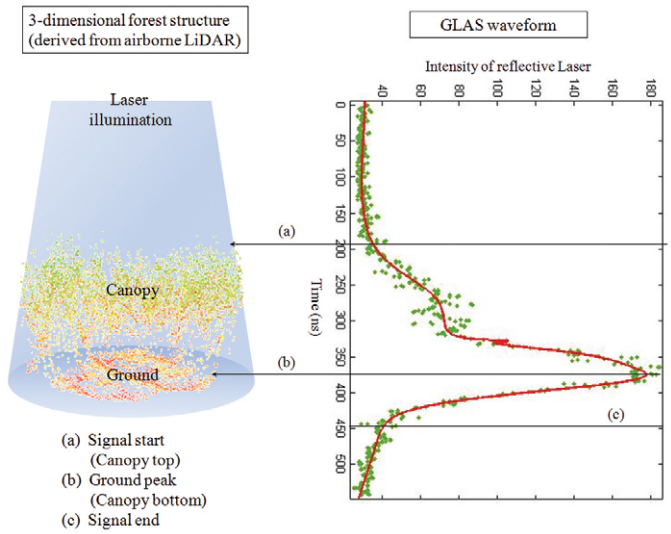


Fig. 3. Illustration of reflective waveform distribution corresponding 3-dimensional forest structure derived from airborne LiDAR data.

although these methods are suffered from complex waveform which contains several modes. Because existing methods do not provide a consistent ranging point to a reflecting surface. Therefore, many studies including Hofton *et al*. (2000), Neuenschwander *et al*. (2008) and Chen (2010b) used Gaussian decomposition to process complex waveform derived from GLAS instrument. A Gaussian decomposition is fundamentally assumed that a waveform can be defined by the sum of series of Gaussian curves (Duncanson *et al*., 2010). An individual Gaussian curve was parameterized amplitude (a, the height of the peak), position of the peak (u), and standard deviation (σ, controlling its width) as follows (Equation 1):

$$y = a \cdot \exp^{-(x-u)^2/2\sigma^2} \quad (1)$$

In the case of multiple Gaussian curve, the bias of the waveform (ε) fitting procedure is additionally employed to fit into waveform (Equation 2).

$$y = \varepsilon + a \cdot \sum_{i=1}^{i=n} \exp^{-(x-u)^2/2\sigma^2} \quad (2)$$

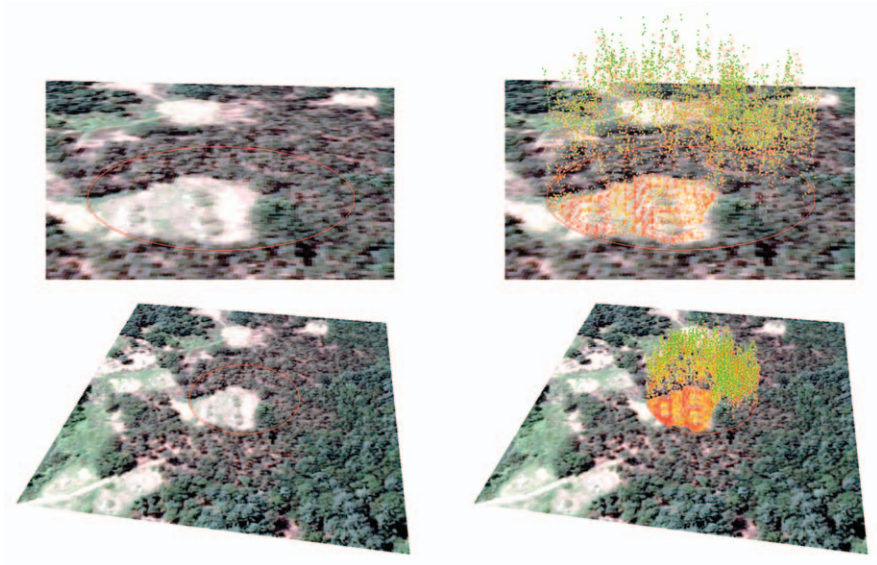
Through a Gaussian decomposition processing, simple or complex waveform were individually parameterized into each position of peak, widths and amplitudes. According to studies by Hofton *et al*. (2000), Neuenschwander *et al*. (2008) and Chen (2010b), the performance of direct method was processed by identifying the signal start (S_b) and ground peak (S_p) in individual waveform. Because signal start commonly explained as an approximate canopy top estimation and ground peak was used to canopy bottom estimation (Fig. 3).

Based on these definitions of parameters, we can easily calculated signal extent between signal start and ground peak and this extent was used to estimate maximum canopy height (H_{mc}) with laser velocity (Vlas : the speed of light : 300,000 km/s) (Equation 3).

$$H_{mc} = (S_b - S_p) \cdot V_{las} \quad (3)$$

2) Comparison of maximum canopy height derivations from GLAS- and Airborne LiDAR data

In order to evaluate the accuracies of direct method for estimating maximum canopy height, maximum canopy height derived from airborne LiDAR data was used to compare with derivation from GLAS



(a) Geo-location of GLAS laser shot (b) Geo-matched airborne LiDAR data

Fig. 4. Example of GLAS geo-location and geo-matched airborne LiDAR data.

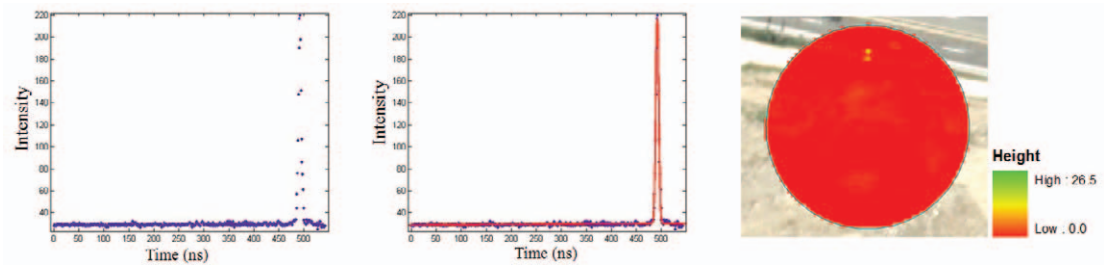
data. For geo-matching between GLAS and airborne LiDAR data, coordinate (datum) were equally projected as TM (GRS80) and each GLAS footprint size by campaigns was considered when extracting LiDAR discrete points within footprint (Fig. 4).

Prior to estimate maximum canopy height from airborne LiDAR data, every airborne LiDAR returns were classified by the automatic procedure within the TerraScam Program. The LiDAR returns classified into two groups including ground and above ground returns. Ground returns are determined to be reflected on the ground within the plots, and canopy returns include every return except ground returns. The LiDAR data should be normalized for each return to retain the real height information related to the return hierarchy (van Aardt *et al*., 2006). To normalize all returns, a Digital Terrain Model (DTM) with 1m spatial resolution using only ground returns was firstly generated. Thereafter, the heights of all returns upon canopy were subtracted from the DTM heights. Maximum canopy height within GLAS laser footprint was estimated by ordering every returned point. Thereafter, comparative analysis between maximum canopy height derivations from GLAS- and Airborne LiDAR data was performed.

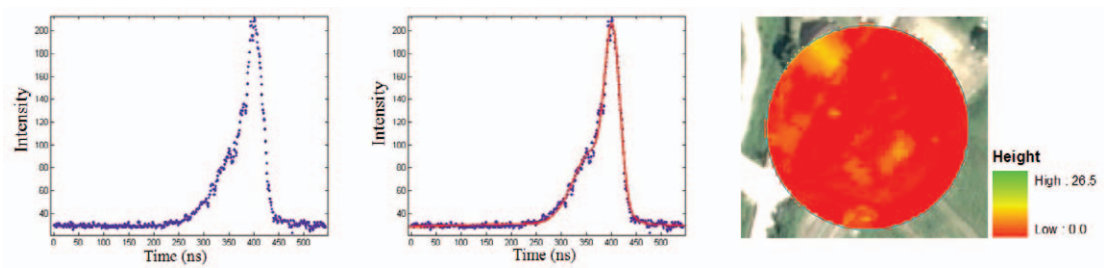
4. Result and discussion

In the 112 individual waveforms generated from GLAS instrument, each individual waveform was fitted through adopting the Gaussian decomposition method. Each individual waveform was parameterized into signal off and ground peak respectively. Then the maximum canopy height was estimated through calculating the time extent between signal off and ground peak and multiplying vertical length of each nanosecond considering each campaign.

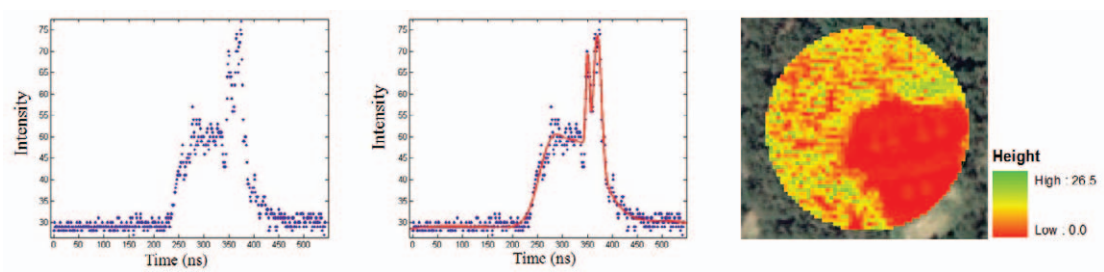
Fig. 5 showed resulted laser reflectance altimetry, fitted Gaussian curve and surface height distribution within several sampled footprints. A GLAS waveform is typically characterized by multiple energy peaks contributed by the reflectance from ground and its above objects, particularly trees in



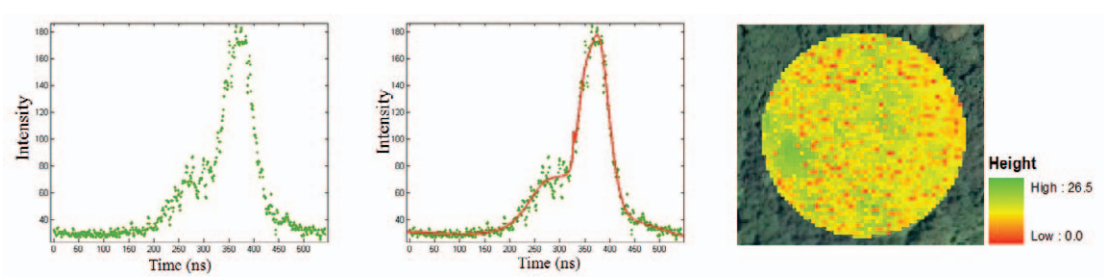
(a) Laser reflectance altimetry (left), fitted Gaussian curve (medium) and surface height distribution (right) in flat area



(b) Laser reflectance altimetry (left), fitted Gaussian curve (medium) and surface height distribution (right) in slope area



(c) Laser reflectance altimetry (left), fitted Gaussian curve (medium) and surface height distribution (right) in flat forest area



(d) Laser reflectance altimetry (left), fitted Gaussian curve (medium) and surface height distribution (right) in slope forest area

Fig. 5. Laser reflectance altimetry, fitted Gaussian curve and surface height distribution within several sampled footprints.

forest area. According to our results, a narrow Gaussian curve just fitted by decomposition method over flat area (Fig. 5a). The lowest peak of this waveform corresponded to the ground surface. In the case of Fig. 5(b), the lowest peak in slope area showed broader width of Gaussian curve than flat area. Because reflectance energy from steep and non-forest area was dispersedly returned to GLAS instrument (Chen, 2010b). Trees in forest area or complex terrain also influenced to Gaussian curves represented at Fig. 5(c) and 5(d). These complexities from surface objects and terrestrial features

Table 2. Descriptive statistics of results in GLAS and airborne LiDAR processing

	Maximum canopy height from GLAS	Maximum canopy height from airborne LiDAR	Error	Absolute error
Max	41.47	29.58	25.25	25.25
Min	11.93	13.10	-14.12	0.14
Ave	24.64	21.69	2.95	6.16
Std	7.00	3.29	7.63	5.36

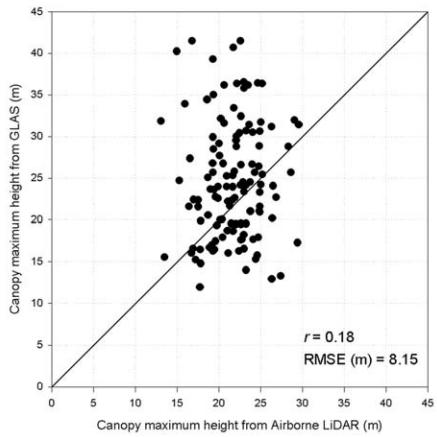


Fig. 6. Accuracy assessment result (based on LiDAR derivation) of maximum canopy height estimation using GLAS data.

complicated the shapes and parameters of relevant waveform.

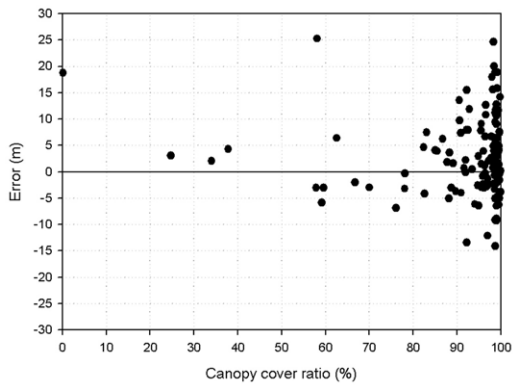
Directly estimated maximum canopy height of each individual waveform averaged at 24.64 m, while average of derivations from airborne LiDAR data was estimated at 21.69 m. The GLAS-based maximum canopy height tended to be higher than that from airborne LiDAR data and difference between GLAS- and LiDAR-based maximum canopy heights was approximately at 2.95 m. In other words, the maximum canopy height estimation by GLAS dataset was overestimated. When looked into the standard deviation of each maximum canopy height, GLAS estimation was more widely distributed and dispersed than airborne LiDAR.

In the result of plotting estimations of each dataset in Fig. 6 and seeing the average error in Table 2, estimations from GLAS tended to be overestimated. The root mean square error (RMSE) was approximately calculated at 8.15 m and the correlation coefficient was at 0.18.

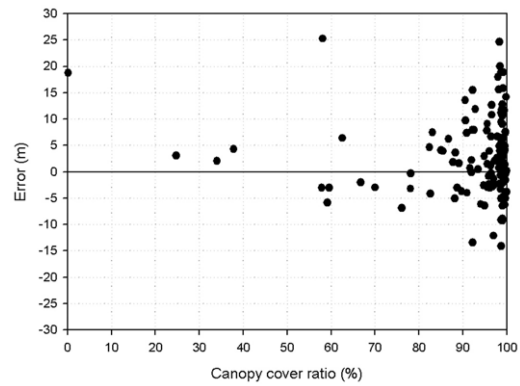
Actually, these errors' extents in terms of RMSE might be acceptable when compared with related study by Chen (2010b). Chen (2010b) tried to estimate maximum canopy height using direct and statistical methods. According to the results of his study, RMSE between maximum canopy height estimation by GLAS and airborne LiDAR data was averagely evaluated at 8.87 m. However, his study had a correlation coefficient of 0.55 and it was much higher than that of this study.

As Chen's study, the performance of direct estimation method using GLAS dataset could be influenced by slope and canopy cover ratio. To examine the error sources of study, this study attempted to identify relationship between these factors and error occurrences, slope factor was closely related with error occurrence, while relationship between canopy cover ratio and error occurrence was not apparently shown in this study (Fig. 7a and 7b). When we plotted both factors with absolute errors, the 112 GLAS laser footprints were dominantly distributed at near high slope and canopy cover ratio area (Fig. 7c), the error sources of maximum canopy height estimation from slope and canopy cover ratio was not easily explained. However, many studies relevant with this study reported that over mountainous areas with complex terrain and canopy structure could make a difficulty for the identification of ground elevation and complication of fitting the Gaussian peaks to ground and surface objects (Zwally *et al*., 2002; Harding and Carabajal, 2005; Lefsky *et al*., 2005; Chen, 2010a).

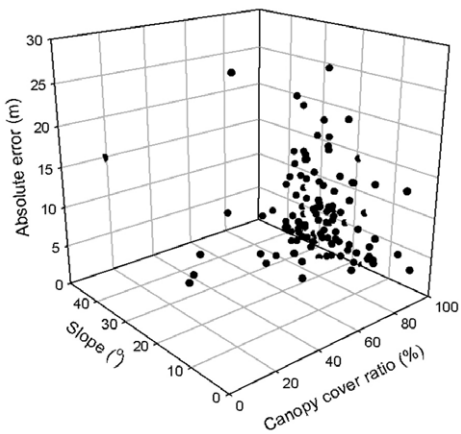
The error sources in our study, these might be classified into wrongly extracted signal start and



(a) Relationship between absolute error and slope

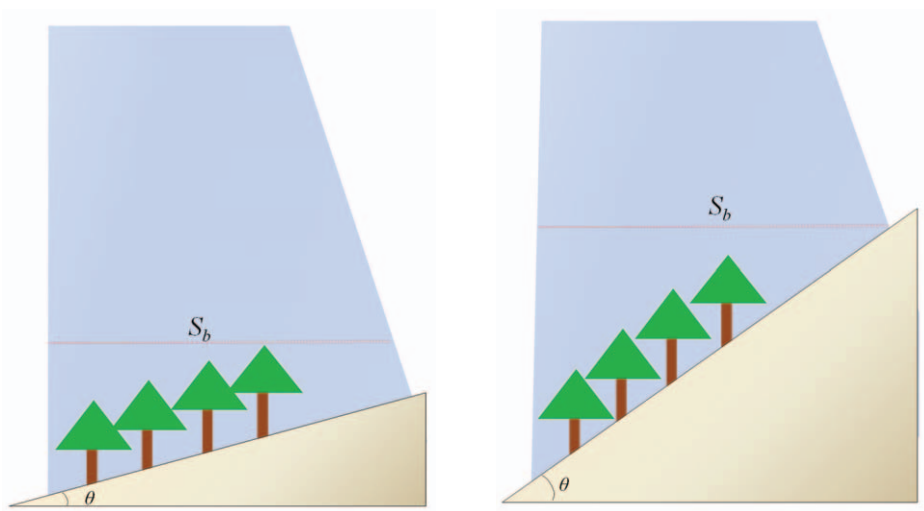


(b) Relationship between error and canopy cover ratio



(c) Absolute error distribution by slope and canopy cover ratio

Fig. 7. Relationships between several factors (slope and canopy cover ratio) and error occurrences.



(a) S_b: reflected from canopy with lower θ

(b) S_b: reflected from ground with lower θ

Fig. 8. Visual explanations of misinterpretation in signal start and ground peak estimation in mountainous area.

ground peak. In the case of signal start error source, complex terrain or higher slope in actual over mountainous area might cause the errors when laser pulse collides on the highest objects within a footprint. Although GLAS data can depict vertical structures of flat surface without any difficulty (Fig. 8a), measuring the height of canopy in high slope area (Fig. 8b) could be overestimated due to upper ground and object. In the case of ground peak error source, slope (θ) effect on the extent and shape of the lowest Gaussian curve considered as ground peak. If θ is higher and signal start can be estimated well, laser footprint cover the larger area with larger vertical extent, so extent and shape of the Gaussian curve was generated with complexity. That also can cause misinterpretation in estimating ground peak.

Although this study limited to alleviate mentioned error sources, further study will be required to improve an accuracy of estimation via developing and adopting fresh approaches. According to the advance researches, some researchers developed statistical regression approach with waveform metrics to remedy limitations of direct method in mountainous forest area (Zwally *et al*., 2002; Harding and Carabajal, 2005; Lefsky *et al*., 2005; Chen, 2010a). In general regression model, it typically include waveform extent (Lefsky *et al*., 2005; Rosette *et al*., 2008, Chen, 2010a), which means the vertical distance between the signal start and end of a waveform in GLAS waveform. The waveform extent tends to be increase with terrain slope even if the canopy distribution is the same. When looked into previous studies, error occurrences related to terrain slope could be reduces by including metrics related to terrain slope. The results of these studies reported higher performance of maximum canopy height estimation in mountainous area with high slope. Therefore, further study will adopt a statistical regression model approach and metrics related to terrain slope are essentially included in the regression models to remove terrain slope's effects.

5. Conclusion

To understand forest structures, the GLAS instrument have been employed to measure and monitor forest canopy with feasibility for acquiring three dimensional canopy structure information. This study tried to exam the potential of GLAS dataset in forest canopy mesuration field of South Korea, particularly maximum canopy height estimation. As the result of estimation using direct method, RMSE was estimated at 8.15 m and estimation tended to be overestimated when comparing to derivations of airborne LiDAR data. This performance might be acceptable in direct method application over mountainous area due to complex terrain and surface objects according to previous relevant studies. However, the performance of GLAS-based maximum canopy height was not reasonable when consider the correlation coefficient between estimation from GLAS and airborne LiDAR. In analysis about error occurrences, terrain slope tend to be distributed near higher slope and it might be a negative factor in estimation process. Therefore, further study will adopt a statistical regression model approach and metrics related to terrain slope are essentially included in the regression models to remove terrain slope's effects.

Acknowledgement

This study was carried out with the support of 'Forest Science & Technology Projects (Project No. S210912L010100)' provided by Korea Forest Service and National Research Foundation research

project "Korea-specific climate change research under the satellite-ecological approach (2011-0020227)".

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