A Study on Factors Affecting Airborne LiDAR Penetration

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ABSTRACT

This study uses data from different periods, areas and parameters of airborne LiDAR (light detection and ranging) surveys to understand the factors that influence airborne LiDAR penetration rate. A discussion is presented on the relationships between these factors and LiDAR penetration rate. The results show that the flight height above ground level (AGL) does not have any relationship with the penetration rate. There are some factors that should have larger influence. For example, the laser is affected by a wet ground surface by reducing the number of return echoes. The field of view (FOV) has a slightly negative correlation with the penetration rate, which indicates that the laser incidence angle close to zero should achieve the best penetration. The vegetation cover rate also shows a negative correlation with the penetration rate, thus bare ground and reduced vegetation in the aftermath of a typhoon also cause high penetration rate. More return echoes could be extracted from the full-waveform system, thereby effectively improving the penetration rate. This study shows that full-waveform LiDAR is an effective method for increasing the number of surface reflected echoes. This study suggests avoiding LiDAR survey employment directly following precipitation to prevent laser echo reduction.

Key words: Airborne LiDAR, LiDAR penetration rate, Full-waveform LiDAR

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1. INTRODUCTION

Airborne Light Detection and Ranging (LiDAR) was first developed by NASA, 1970 - 1980. At this time airborne LiDAR was applied only for measuring a single point from an aircraft to the ground. This technology was unsuitable for collecting wide area topographic data. In the last decade, Global Positioning System (GPS) and Inertial Navigation System (INS) development enabled real-time Position and Orientation System (POS) development. Stuttgart University combined laser-scanning technology and POS from 1988 - 1993 (Ackermann 1999), with instruments implemented successfully only a few years later. Airborne LiDAR can be used to obtain a large point cloud dataset within a short time. The data include 3D ground surface and reflection intensity coordinate values (Farid et al. 2008; Akay et al. 2009). The data obtained from airborne LiDAR has been applied effectively in various practical applications, such as environmental surveys, ground-surface monitoring, disaster prevention, forest resource inventory, urban planning and management, flood simulations and power transmission line monitoring.

Airborne LiDAR instrumentation is currently being further advanced from discrete LiDAR to full-waveform LiDAR. Discrete LiDAR requires an echo extraction method, such as peak detection (maximum detection), leading edge detection or constant fraction detection and accordingly a threshold for the chosen method (Amann et al. 2001). If the shape of an echo is detected as complete and the intensity is greater than the threshold, the system records a discrete-echo. Conversely, if the echo shape overlaps or the intensity is weak, the system ignores the echo. The discrete LiDAR system typically records up to five echoes for each emitted laser beam, including the first and last, indicating that the discrete LiDAR system has a limit on the number of echoes it can detect and record (Lin 2009).

This discrete LiDAR system limitation (i.e., in detecting the returned number of echoes) can be overcome using a full-waveform LiDAR system, which has the ability to record the full-waveform of a laser beam, with a greater likelihood of
detecting the ground point gap at which the laser signals penetrate between the crown canopy surfaces. Users can apply their own waveform detection algorithms in full-waveform LiDAR dataset processing. They could therefore avoid the limitations of discrete LiDAR systems regarding waveform detection. A full-waveform LiDAR system could record multiple echoes within short intervals or weak return signals. This would create better opportunities for not losing any meaningful objects. The full-waveform recording method enhances the laser scan spatial resolution and also increases the number of ground points under a crown canopy.

In Digital Elevation Models (DEMs) with aerial photographs, the difficulty of revealing the ground under vegetation is great, thereby rendering the judgment of potential geological disaster areas difficult, resulting in errors when analyzing the geomorphology. The greatest advantage of using airborne LiDAR to produce DEMs is the complete removal of vegetation, adequately capturing ground surfaces (Hsu et al. 2009).

The LiDAR penetration rate is defined as the number of ground points divided by the total emission laser beams per unit area. Potential factors that could affect the penetration rate include the date, the altitude above ground level (AGL), the pulse mode, the terrain slope, the forest cover and plot variations (Hyyppä et al. 2005). Different opinions exist regarding penetration. For example, Morsdorf et al. (2008), Takahashi et al. (2008), and Næsset (2009) proposed AGL as a critical factor affecting penetration, whereas Huang and Shih (2008), Morsdorf et al. (2008), and Zhao and Popescu (2009) indicated that the relationship between the field of view (FOV) and penetration rate is crucial.

For airborne LiDAR in full-waveform recording mode, the echoes represent reflected signals from objects along the path to ground. By sampling the echo peaks users can record the distance using the LiDAR instrument by referring to the time that it takes for the signal to reach the ground object and return to the instrument. The analysis and fitting of waveforms are thus critical, for which the Gaussian distribution (Hofton et al. 2000; Wagner et al. 2006; Lin et al. 2008; Mallet et al. 2008), log normal distribution (Chauve et al. 2007), wavelet analysis (Molnar et al. 2011; Wang 2012) are frequently used. According to propositions from Hofton et al. (2000) and Jutzi and Stilla (2005), the Gaussian decomposition method can improve range measurement accuracy compared with algorithms using only single values. The following study will adopt the Gaussian decomposition method for extracting return laser echoes.

Waveforms are fitted by considering the waveform peak return time and identifying the travel time from objects on the ground. Full-waveform LiDAR produces data within a wide scanning range with a point cloud of approximately 10000 - 1000000. The automatic extraction of full-waveform LiDAR data is therefore critical.

A computer program based on the Gaussian decomposition method was designed for this study that can automatically extract ground points from full-waveform data to quickly complete data screening and processing. This study conducted an analysis of airborne LiDAR dataset collected from the Taichung calibration field; the middle reaches of the Lanyang River; and reservoir landslides in the Tseng Wen Reservoir catchment area. AGL, FOV, weather condition, and full-waveform recording scheme and other parameters are studied for how they most likely influence the penetration rate.

2. STUDY AREA

The first study was conducted in a forest area of the Taichung calibration field where the trees are approximately 10 m high. This site is covered with uniform forest vegetation with a height suitable for penetration research and analysis (Fig. 1a). The survey dates were 20 June 2011; 24 December 2011; 16 March 2012; and 16 September 2012. These dates span 2 years, with each date representing a different season. All four missions followed the same flight design, including three AGLs, 700, 1350, and 2300 m. The exceptions were the June 2011 mission without 700 m flights, and September 2012 survey without full-waveform. As shown in Table 1 it rained prior to both scanning dates in 2012.

The second study area spanned Sihi Village to Ying-shih Village near the Lanyang River (Fig. 1b). The survey dates were 20 June 2011; 24 December 2011; 16 March 2012; and 16 September 2012. These areas were suitable for use in a discussion on the relationship between the penetration rate and crown canopies affected by typhoons.

The third study area was located in the Tseng Wen Reservoir watershed (Fig. 1c), which is an important reservoir in southwestern Taiwan. The scan area spanned approximately 500 km². The survey dates were in January 2012. Twenty-five flight lines were flown with different combinations of altitude and FOV for accommodating the topographic and vegetation variations. Although this dataset was collected in a single season, the variation in flight parameters made it information rich for studying the penetration rate factors.

3. METHODS

This study focused on the relation between the penetration rate and the AGL, crown canopy, FOV of the study areas. Full-waveform LiDAR data were collected using a Leica ALS60 scanner in addition to discrete echo data. The penetration rate was measured using the ground point ratio over the emitted laser pulses in the area and calculated as follows:
Penetration rate = ground points / emitted laser pulses × 100%.
Four surveys were conducted in the Taichung calibration field with each survey date representing a different season. Other than the June survey which lacked AGL at 700 m, the flight line of each survey applied the same AGL. The recording formats included both discrete echo and full-waveform, except for the September survey (Table 1). The data obtained from this survey area were suitable for analyzing the penetration rate relation with the AGL, precipitation, relative humidity and full-waveform data.

The two-time survey conducted in the Lanyang River involved using the same parameters, with three typhoons hitting Yilan County during the survey period. Because the

![Image](image_url)

**Fig. 1.** Survey area of this study: (a) Lanyang River; (b) Taichung calibration field where in the red dashed rectangle; and (c) Tseng Wen Reservoir watershed.

| Date       | AGL (m)      | Precipitation     | Relative humidity (%) | Penetration (%) (discrete/full-waveform) |
|------------|--------------|-------------------|-----------------------|------------------------------------------|
| 2011/06/20 | 1350, 2300   | none              | 77                    | 26.36/42.70                              |
| 2011/12/24 | 700, 1350, 2300 | none             | 60                    | 22.33/36.80                              |
| 2012/03/16 | 700, 1350, 2300 | 3/10: 2.5 mm, 3/11: 2.0 mm, 3/12: 6.5 mm, 3/13: 6.5 mm, 3/14: 2.5 mm | 83                    | 15.59/29.55                              |
| 2012/09/16 | 700, 1350, 2300 | 9/14: 2.7 mm      | 70                    | 12.33/none                               |

**Table 1.** Flight parameters, weather factors, and penetration in the Taichung calibration field.

| Date       | Altitude (m) | Terrain (m) | Speed (knot) | FOV (degree) | Pulse Rate (Hz) | Scan Rate (Hz) |
|------------|--------------|-------------|--------------|--------------|-----------------|----------------|
| 2008/6/22  | 2590         | 800 - 1250  | 100          | 32           | 50000           | 25             |
| 2008/10/31 | 2590         | 800 - 1250  | 100          | 32           | 50000           | 25             |

**Table 2.** Flight parameters in Lanyang River.
same survey parameters were used, how the typhoon-affected penetration warrants discussion. Eleven regions were selected near the Lanyang River, with the penetration rate changes compared for the typhoons.

The survey parameters such as AGL and FOV differed in the Tseng Wen Reservoir watershed, and were suitable for discussing the relationship to the penetration rate. Four land-cover types were selected (i.e., bare ground, vegetation regions, woodlands and forested regions) for a discussion on changes in penetration rate over different vegetation coverage. The vegetation types were evaluated based on 10 m by 10 m ground area. Bare ground is defined as a vegetation coverage rate less than 25%, with vegetation regions rated at 25 - 50%, woodlands 50 - 75%. Higher than 75% would be forested regions.

4. RESULTS

Table 3 lists the Taichung calibration field penetration results. The discrete and full-waveform LiDAR data penetration rate was calculated at different AGL altitudes over three periods. The bold letters in Table 3 indicate the survey area located on the edge of the flight line, with a low penetration rate of approximately 5 - 10%. Figure 2 shows a point cloud profile with flight and flight edges that indicates that the point cloud volume in the swath edge is less than that of the center, which is consistent with Huang and Shih (2008). When calculating the average penetration rate the swath edge was not included to reduce the lower penetration rate influence at the swath edge.

The full-waveform LiDAR was 35.50%, whereas the discrete LiDAR was 21.10% (Table 3) for the average penetration rate of four surveys, indicating an increase of more than 15.39% for the full-waveform LiDAR. In addition, the full-waveform LiDAR data penetration rate was higher than the discrete LiDAR data by approximately 10% over all missions studied in the experiment. Figure 3 shows a top view and profile of the point cloud obtained from the full-waveform and discrete LiDAR data. The top view shows that the point cloud density of the full-waveform LiDAR is higher than that of the discrete LiDAR, and the full-waveform LiDAR profile shows more terrain points. Figure 4 displays a top view of the ground points, showing that the full-waveform LiDAR volume is higher and more evenly distributed compared to that of the discrete LiDAR.

As shown in Fig. 5 no clear correlation could be observed regarding the relation between the penetration rate and altitude, regardless whether full-waveform or discrete LiDAR system was used.

The penetration rate of either the full-waveform or discrete LiDAR data in 2012 was lower than that in 2011 (Fig. 5), and was probably influenced by precipitation before the survey was conducted in 2012. The precipitation resulted in water trapped under the ground surface, with the wet ground affecting the laser reflection, resulting in low penetration rate.

Table 4 shows the flight parameters and penetration rate for 25 flight lines in the Tseng Wen Reservoir watershed. This study analyzed the penetration rate relationship with altitude AGL (Fig. 6) and FOV (Fig. 7). At first glance, Fig. 6 shows that a high altitude results in higher penetration rate, which seems to indicate a positive correlation. The linear regression shows a positive correlation with the slope of 0.001, indicating a low correlation. The altitude AGL has a gap between 1750 - 2500 m, and the mean penetration rate was calculated below 1750 m and above 2500 m, respectively. The results were 35.6 and 36.7%, respectively, indicating a rather insignificant difference. This is consistent with the result obtained from the Taichung calibration field. Based on these results the altitude and penetration rate may be concluded as not correlated. Figure 7 shows that the FOV and penetration rate are negatively correlated, with the linear regression line slope at -0.10, indicating that the penetration rate decrease caused by the incidence angle increase exists but is minor in this case.

Four types of vegetation regions were selected (i.e., bare ground, vegetation regions, woodlands, and forested regions) for penetration results comparison. Figure 8 shows the penetration rate changes according to the vegetation cover rate. The bare ground and forest regions have a higher and lower penetration rate, respectively, indicating that their penetration rates are negatively correlated.

Three typhoons landed in Yilan between the two surveys. The survey parameters for the two typhoon events were identical. Eleven woodlands with an area of approximately 10000 m² were selected for calculating and analyzing the penetration rates in different areas. Table 5 lists the penetration results for the 11 areas, showing the existence of more ground points and less laser scan points after the three typhoons. Excluding the closer penetration rate areas; the penetration rate after the typhoons was 15.10%, which is higher than 5.57% from before the typhoons. The penetration rate was nearly 3 times greater after the typhoons. This improvement is possibly due to the typhoons having reduced the vegetation cover rate. This result is consistent with the vegetation cover rates and penetration comparison obtained from the Tseng Wen Reservoir watershed.

Generally speaking, the precipitation before the airborne LiDAR survey or high vegetation cover rate in the survey areas had more influence on the penetration rate than AGL altitude. Moreover, if the airborne LiDAR survey adopts the full-waveform recording method, the penetration rate will be increased by about 15%.

If precipitation occurs before an airborne LiDAR survey and raises the vegetation cover rate, this typically results in lower penetration rate. If an airborne LiDAR survey is conducted using full-waveform, the penetration rate is increased by approximately 15%.
Table 3. Discrete and full-waveform LiDAR penetration rate (PR) with different AGLs in the Taichung calibration field.

| Date     | AGL (m)   | PR of discrete LiDAR (%) | Mean (%) | PR of full-waveform LiDAR (%) | Mean (%) |
|----------|-----------|--------------------------|----------|-------------------------------|----------|
|          |           |                          |          |                               |          |
| 2011/06/20 | 1336.74   | 24.82                    | 30.32    | 44.23                         | 43.67    |
|          | 1339.60*  | 18.96                    |          |                               |          |
|          | 1344.20*  | 18.75                    | 25.68    | 27.10                         | 43.67    |
|          | 1358.89   | 25.02                    |          |                               |          |
|          | 1356.09   | 27.20                    |          |                               |          |
|          | 2296.24   | 24.44                    |          |                               |          |
|          | 2296.54   | 26.79                    | 27.04    |                               | 41.74    |
|          | 2298.74   | 27.66                    |          |                               |          |
|          | 2306.86   | 29.28                    |          |                               |          |
|          | 691.52    | 21.60                    | 21.76    | 32.52                         | 32.75    |
|          | 705.22    | 21.92                    |          |                               |          |
| 2011/12/24 | 1324.35   | 26.70                    |          |                               | 39.06    |
|          | 1340.59   | 24.93                    |          |                               | 40.71    |
|          | 1332.37   | 23.40                    | 25.01    | 39.00                         | 39.59    |
|          | 1350.15*  | 13.36                    |          | 23.24                         |          |
|          | 1350.36*  | 14.60                    |          | 29.23                         |          |
|          | 2328.28   | 20.73                    |          |                               | 35.54    |
|          | 2300.98   | 19.70                    | 20.22    | 38.44                         | 38.08    |
|          | 2305.10   | 20.22                    |          |                               | 40.26    |
|          | 715.15    | 14.58                    | 15.70    | 27.77                         | 28.36    |
|          | 694.97    | 16.82                    |          |                               | 28.95    |
|          | 1331.34   | 15.35                    |          |                               | 32.14    |
|          | 1340.53   | 13.04                    |          |                               | 26.74    |
|          | 1336.91   | 12.30                    | 13.56    | 28.09                         | 29.44    |
| 2012/03/16 | 1332.22*  | 7.11                     |          | 13.89                         |          |
|          | 1356.21*  | 8.33                     |          | 19.19                         |          |
|          | 2283.56   | 15.52                    |          |                               | 31.26    |
|          | 2296.49   | 13.98                    | 17.50    | 30.46                         | 30.86    |
|          | 2269.62   | 18.44                    |          |                               | 35.93    |
|          | 2276.22   | 22.04                    |          |                               | 38.08    |
|          | 693.36    | 10.71                    | 10.51    | none                          | none     |
|          | 668.11    | 10.31                    |          |                               |          |
|          | 1362.56   | 14.85                    |          |                               |          |
|          | 1363.26   | 12.65                    |          |                               |          |
|          | 1342.93   | 13.63                    | 13.71    | none                          | none     |
|          | 1355.95*  | 7.96                     |          |                               |          |
| 2012/09/16 | 1405.03*  | 5.70                     |          |                               |          |
|          | 2295.66   | 12.34                    |          |                               |          |
|          | 2289.97   | 12.63                    |          |                               |          |
|          | 2317.66   | 12.25                    | 12.78    | none                          | none     |
|          | 2291.62   | 13.29                    |          |                               |          |
|          | 2289.67   | 11.93                    |          |                               |          |
|          | 2290.12   | 14.25                    |          |                               |          |

Note: * The bold letters indicate the survey area located on the edge of the flight line.
Fig. 2. Top view of airborne LiDAR point cloud in the Taichung calibration field (a) and the point cloud profile of in-flight edge (b) and non-flight edge (c). Green points: last or only one return echoes; white points: unclassified points; orange points: ground points; white rectangle in (a) show the profile location.

Fig. 3. Top view and profile of point clouds by discrete and full-waveform LiDAR in the Taichung calibration field. (a) Top view of discrete LiDAR; (b) profile of discrete LiDAR; (c) top view of full-waveform LiDAR; and (d) profile of full-waveform LiDAR. Green points: least or only one return echoes; white points: unclassified points; orange points: ground points; white rectangle in (a), (c) show the profile location.
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Fig. 4. Top view of ground points in the Taichung calibration field. (a) Discrete LiDAR data; and (b) full-waveform LiDAR data. Green points: least or only one echoes; white points: unclassified points; orange points: ground points.

Fig. 5. Relation between AGL and penetration rate by discrete and full-waveform LiDAR in the Taichung calibration field. (a) Discrete and full-waveform LiDAR surveyed in 2011; (b) discrete and full-waveform LiDAR surveyed in 2012. The label in lower left of (a) and upper left of (b) represent the surveyed date and record method (D: discrete LiDAR, F: full-waveform LiDAR). The results show the linear regression (dashed line) some are positive and some are negative, and the penetration rate in 2011 are higher than 2012.

Table 4. Flight parameters and penetration rate in the Tseng Wen Reservoir watershed.

| Flight Line Label | AGL (m) | FOV (degree) | Emitted points | Ground points | Penetration rate (%) |
|-------------------|---------|--------------|----------------|---------------|---------------------|
| 1                 | 1727.03 | 40           | 17735          | 6669          | 37.60               |
| 2                 | 1365.98 | 45           | 66260          | 25470         | 38.44               |
| 3                 | 2831.16 | 31           | 63644          | 28257         | 44.40               |
| 4                 | 2809.23 | 32           | 43788          | 16732         | 38.21               |
| 5                 | 2761.22 | 30           | 73362          | 23452         | 31.97               |
| 6                 | 2962.82 | 28           | 61644          | 24124         | 39.13               |
| 7                 | 3125.06 | 26           | 47379          | 14722         | 31.07               |
| 8                 | 3227    | 23           | 28245          | 6677          | 23.64               |
| 11                | 3660.32 | 26           | 18176          | 5098          | 28.05               |
| 12                | 3728.25 | 25           | 70784          | 32601         | 46.06               |
| 13                | 3535.92 | 26           | 63432          | 30779         | 48.52               |
| 16                | 3498.61 | 28           | 6062           | 2283          | 37.66               |
| 17                | 3125.12 | 32           | 44072          | 13862         | 31.45               |
| 18                | 3220.68 | 32           | 71021          | 24665         | 34.73               |
Table 4. (Continued)

| Flight Line Label | AGL (m) | FOV (degree) | Emitted points | Ground points | Penetration rate (%) |
|-------------------|---------|--------------|----------------|---------------|---------------------|
| 19                | 3084.69 | 32           | 27758          | 10607         | 38.21               |
| 20                | 3166.38 | 30           | 29089          | 12065         | 41.48               |
| 21                | 2890.9  | 32           | 52072          | 19599         | 37.64               |
| 22                | 3004.1  | 32           | 20536          | 9475          | 46.14               |
| 23                | 2827.6  | 36           | 16624          | 7848          | 47.21               |
| 25                | 1112.47 | 45           | 19504          | 5562          | 28.52               |
| 26                | 1137.23 | 45           | 9381           | 4166          | 44.41               |
| 27                | 1360.51 | 40           | 83306          | 24001         | 28.81               |
| 28                | 2641.11 | 40           | 17987          | 4561          | 25.36               |
| 29                | 2529.88 | 40           | 26913          | 8660          | 32.18               |
| 30                | 2615.86 | 38           | 48994          | 14873         | 30.36               |

Fig. 6. Relation between AGL and penetration rate in the Tseng Wen Reservoir watershed. The linear regression (dashed line) shows a positive correlation with the slope of 0.001, and the mean penetration rate below 1750 m and above 2500 m were 35.6 and 36.7%, respectively, indicating the positive trend is insignificant.

Fig. 7. Relation between FOV and penetration rate in the Tseng Wen Reservoir watershed. The result shows negatively correlation. The slope of the linear regression (dashed line) is -0.10.

Fig. 8. Relation between different vegetation cover rate and penetration rate in Tseng Wen Reservoir watershed. The penetration rate calculated in bare ground (a), vegetation region (b), woodland (c) and forested region (d).
5. DISCUSSION

Based on the penetration analysis for the Taichung calibration field and the Tseng Wen Reservoir watershed, this study observed that the AGL does not have a strong correlation with the penetration rate, for the same vegetation cover. If a user attempts to adjust the altitude for higher penetration rate, the result is unreliable because it may show either an increase or a decrease in terms of the average penetration rate. In addition, the FOV has only a minor negative correlation with penetration rate.

Because of advancements in LiDAR recording methods, the limitation of discrete LiDAR that records only a few echoes which exceed the threshold was improved. At present, full-waveform LiDAR is frequently applied for extracting more ground point echoes to increase the penetration rate. According to observations in this study, the full-waveform recording method can increase the penetration rate by approximately 15%.

The results show that the penetration rates were lower in the Taichung calibration field if it rained before the survey. Both discrete and full-waveform LiDAR have a lower penetration rate of approximately 9.60 - 9.98%, with an equal drop degree. Current airborne LiDAR uses a near-infrared wavelength of approximately 1000 - 1500 nm. According to the spectral optical bands response, if the wavelength is longer than 0.8 μm, the water response is close to zero, which is the reason that the laser does not penetrate the cloud and water body. Therefore, this study recommends avoiding laser survey missions when the ground is wet. If the ground surface contains water, this may result in reduced spectral response, thereby weakening the strength of laser echo signals.

Precipitation occurred before the two surveys were conducted in 2012, but it did not rain on the day of the survey, and thus, data regarding relative humidity were collected from the Wuci weather station to analyze its relation to the

Table 5. Penetration rate in the Lanyang River.

| NO | Ground points | Emitted point | Penetration rate (%) | Ground points | Emitted point | Penetration rate (%) |
|----|---------------|---------------|----------------------|---------------|---------------|----------------------|
| 1  | 996           | 30125         | 3.31                 | 1577          | 15297         | 10.31                |
| 2  | 876           | 47314         | 1.85                 | 1711          | 95420         | 1.79                 |
| 3  | 330           | 20146         | 1.64                 | 941           | 9805          | 9.60                 |
| 4  | 1362          | 16204         | 8.41                 | 1178          | 12311         | 9.57                 |
| 5  | 524           | 21406         | 2.45                 | 2095          | 10110         | 20.72                |
| 6  | 1457          | 14788         | 9.85                 | 3606          | 13726         | 26.27                |
| 7  | 1028          | 14179         | 7.25                 | 792           | 8472          | 9.35                 |
| 8  | 1341          | 20425         | 6.57                 | 873           | 6959          | 12.54                |
| 9  | 531           | 17073         | 3.11                 | 308           | 11626         | 2.65                 |
| 10 | 2535          | 20584         | 12.32                | 2514          | 19669         | 12.78                |
| 11 | 888           | 10330         | 8.60                 | 1625          | 9649          | 16.84                |
| average | 1107.36 | 21710.91 | 5.88                      | 1565.45      | 19367.64      | 12.04                |
penetration rate, with the objective of obtaining evidence to support the premise of this study. The Wuci weather station is located approximately 2 km from the Taichung calibration field. The weather data is therefore representative of the Taichung calibration field. Table 1 shows the relative humidity of the Taichung calibration field on the day of the survey, indicating that the relative humidity does not correlate to the penetration rate. Therefore, precipitation has a greater influence on LiDAR penetration rate compared to relative humidity.

A Digital Surface Model (DSM) was also produced for this study, depicting the Lanyang River before and after the typhoons. The DSM was then subtracted from the DEM to obtain the volume above the ground surface. Changes in the volume were compared. Because the study area was located in a mountainous region, the volumes of artificial objects were assumed to undergo few or no changes, which occurred in the crown canopy affected by the typhoons. The DSM volumes before and after the typhoons were approximately 0.85 and 0.79 km$^3$, respectively, and therefore, the typhoons may have been responsible for reducing the volume of the crown canopy, resulting in improved penetration rate.

Evidence on the relation between the vegetation cover type and penetration rate was obtained by analyzing different vegetation covers and their penetration rate in the Tseng Wen Reservoir watershed, followed by a comparison of changes in the DSM volume in the Lanyang River. Penetration rate and the vegetation cover percentage are negatively correlated when more vegetation cover types are considered. This results in a reduced penetration rate, showing that with the same vegetation cover type, even if the altitude is lowered, the penetration rate could not be improved significantly.

6. CONCLUSION

This study analyzes datasets collected at various periods of time with different airborne LiDAR survey and flight parameters. The correlations between penetration rate and different flight parameter combinations are discussed. The results show that the AGL and penetration rate do not have a strong correlation for the same vegetation cover type. Changing altitude does not improve the penetration rate.

The land-cover types of the Tseng Wen Reservoir are grouped into four categories on the basis of the type of vegetation coverage, namely bare ground, vegetation regions, woodlands, and forested regions. The results show that the penetration rate of the bare ground is the highest and that of the forested regions is the lowest. Land-cover type or canopy feature of vegetation cover is obviously also an important factor in determining penetration rate. This observation is further supported by the Lanyang River study data. The same flight parameters were used before and after the typhoons for the Lanyang River. Nevertheless, a higher penetration rate is obtained after the typhoon. This is due to a lower vegetation cover rate that resulted from the typhoon. In addition, ground surface moisture may reduce laser reflection or absorb laser energy thereby resulting in reduced/smaller echoes.

In addition, full-waveform provides obvious improvement in extraction of ground points when compared with the traditional discrete LiDAR.

As this study is solely based on datasets collected with a Leica ALS60 and an Optech ALTM3070, further studies should be conducted for other sensors. In order to improve airborne LiDAR penetration rate, it is suggested that flight missions directly following rainfall be avoided and the full-waveform approach be adopted.

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REFERENCES

Ackermann, F., 1999: Airborne laser scanning-present status and future expectations. ISPRS J. Photogramm., 54, 64-67, doi: 10.1016/S0924-2716(99)00009-X. [Link]

Akay, A. E., H. Oğuz, I. R. Karas, and K. Aruga, 2009: Using LiDAR technology in forestry activities. Environ. Monit. Assess., 151, 117-125, doi: 10.1007/s10661-008-0254-1. [Link]

Aman, M. C., T. Bosch, M. Leschure, R. Myllylä, and M. Rioux, 2001: Laser ranging: A critical review of usual techniques for distance measurement. Opt. Eng., 40, 10-19, doi: 10.1117/1.1330700. [Link]

Chauve, A., C. Mallet, F. Bretar, S. Durrieu, M. P. Deseilligny, and W. Puech, 2007: Processing full-waveform LiDAR data: Modelling raw signals. ISPRS Workshop on Laser Scanning 2007 and SilviLaser 2007, Espoo, Finland, 102-107.

Farid, A., D. C. Goodrich, R. Bryant, and S. Sorooshian, 2008: Using airborne lidar to predict Leaf Area Index in cottonwood trees and refine riparian water-use estimates. J. Arid Environ., 72, 1-15, doi: 10.1016/j.jaridenv.2007.04.010. [Link]

Hofron, M. A., J. B. Minster, and J. B. Blair, 2000: Decomposition of laser altimeter waveforms. IEEE Trans. Geosci. Remote Sensing, 38, 1989-1996, doi: 10.1109/36.851780. [Link]

Huang, C. M. and T. Y. Shih, 2008: On the laser incidence angle and airborne LiDAR penetration rate. J. Photogramm. Remote Sens., 13, 67-73. (in Chinese)

Hyyppä, H., X. Yu, J. Hyyppä, H. Kaartinanen, S. Kaasalainen, E. Honkavaara, and P. Rönnholm, 2005: Factors
affecting the quality of DTM generation in forested areas. ISPRS WG III/3, III/4, V/3 Workshop “Laser scanning 2005”, Enschede, the Netherlands, 85-90.

Jutzi, B. and U. Stilla, 2005: Measuring and processing the waveform of laser pulses. Proceedings of the 7th Conference on Optical 3-D Measurement Techniques, 194-203.

Lin, Y. C., 2009: Digital terrain modelling from small-footprint, full-waveform airborne laser scanning data. Ph.D. Thesis, Newcastle University, United Kingdom.

Lin, Y. C., J. Mills, and S. Smith-Voysey, 2008: Detection of weak and overlapping pulses from waveform airborne laser scanning data. 8th international conference on LiDAR applications in forest assessment and inventory, Edinburgh, UK, 478-487.

Mallet, C., U. Soergel, and F. Bretar, 2008: Analysis of full-waveform LiDAR data for classification of urban areas. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Vol. XXXVII, Part B3a, Beijing, 85-92.

Molnar, B., S. Laky, and C. Toth, 2011: Using full waveform data in urban areas. Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci., XXXVIII-3/W22, 203-208, doi: 10.5194/isprsarchives-XXXVIII-3-W22-203-2011. [Link]

Morsdorf, F., O. Frey, E. Meier, K. I. Itten, and B. Allgöwe, 2008: Assessment of the influence of flying altitude and scan angle on biophysical vegetation products derived from airborne laser scanning. Int. J. Remote Sens., 29, 1387-1406, doi: 10.1080/01431160701736349. [Link]

Næsset, E., 2009: Effects of different sensors, flying altitudes, and pulse repetition frequencies on forest canopy metrics and biophysical stand properties derived from small-footprint airborne laser data. Remote Sens. Environ., 113, 148-159, doi: 10.1016/j.rse.2008.09.001. [Link]

Takahashi, T., Y. Awaya, Y. Hirata, N. Furuya, T. Sakai, and A. Sakai, 2008: Effects of flight altitude on LiDAR-derived tree heights in mountainous forests with poor laser penetration rates. Photogramm. J. Finland, 21, 86-96.

Wagner, W., A. Ullrich, V. Ducic, T. Melzer, and N. Studnicka, 2006: Gaussian decomposition and calibration of a novel small-footprint full-waveform digitising airborne laser scanner. ISPRS J. Photogramm., 60, 100-112, doi: 10.1016/j.isprsjprs.2005.12.001. [Link]

Wang, C. K., 2012: Exploring Weak and overlapped returns of a LiDAR waveform with a wavelet-based echo detector. Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci., XXXIX-B7, 529-534, doi: 10.5194/isprsarchives-XXXIX-B7-529-2012. [Link]

Zhao, K. and S. Popescu, 2009: Lidar-based mapping of leaf area index and its use for validating GLOBCARBON satellite LAI product in a temperate forest of the southern USA. Remote Sens. Environ., 113, 1628-1645, doi: 10.1016/j.rse.2009.03.006. [Link]