Airborne LiDAR System Optimisation for Foliage Penetration

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1. Introduction

There is a significant history of using LiDAR point cloud data for determining various forest parameters. Although there are some general rules-of-thumb for parameters such as off-nadir angle and laser footprint size when trying to maximize penetration through tree cover, there are more variables that can contribute to effective foliage penetration. This study will evaluate the use of several flight and system parameters that can now be varied with the introduction of newer megahertz-pulse-rate LiDAR systems.

As a precursor to developing conclusions from the tests, several metrics for analyzing foliage penetration are compared, and one metric chosen for the remaining analysis.

The operation variables that can be manipulated in the system allow trade-offs between such things as pulse energy and pulse rate in an effort to maximize the number of "hits" one the forest floor and thus obtain more detailed DEMs from which to evaluate forest parameters such as tree height. Results based on recent testing by PASCO using Leica TerrainMapper will be compared to results from earlier-generation systems to reveal if the "conventional wisdom" still applies, or whether operational parameters should indeed be adjusted to further maximize foliage penetration.

Although the study is performed on a specific type of LiDAR system, the results can be applied to other system types in the current generation of high-pulse-rate linear-mode LiDAR systems. Furthermore, a discussion of the parallels to, and implications for further development of, single-photon LiDAR systems will be made.

2. Data and Methods

Airborne data were collected from two sites. A comparison of the two sites is given in Table 1 below:

Table 1. Test Flight comparison.

Parameter	Flight 1	Flight 2
Area	10 km^2	
Terrain Relief	100 m	
Dates	Mid October 2018	Late January 2019
Variables tested	Pulse energy (low, med, high) Off-nadir angle (10, 20 degrees)	Pulse energy (low, med, high) Scan pattern (planar sine, circle) Detector threshold (two steps below default)

The initial flight seeks to verify the conclusions from the 2004 study by Roth and Marsh, in particular the relationship between off-nadir angle and relative penetration.

The second flight seeks to expand on the test to include a comparison of planar scanning (similar to that used in the 2004 test) and the circular scan pattern normally used in the test system. It should be noted that the planar scanning tests perform in 2004 were performed at maximum off-nadir angles of 27.5 degrees, where the more recent tests were limited to a maximum 40-degree FOV. One difference

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between planar and circular scan patterns is that the circular pattern results in a constant off-nadir angle, whereas off-nadir angle varies across the planar-canned FOV.

In addition to varying the scan pattern, the second flight provided variations in both pulse energy and detector threshold.

3. Results and Discussion

As expected, increasing laser pulse energy (and thus SNR), increases the probability that any given laser pulse will result in one or more valid returns. While multiple returns are beneficial, many types of classification algorithms used to derive tree height depend on a significantly dense bare earth DEM.

Three metrics were compared for evaluation of the propensity of the laser pulse to result in valid returns below the top of the canopy:

(1) Forest Penetration Factor (FPF) = total returns/total laser shots
(2) Ground Return Factor (GRF) = total ground returns/total laser shots
(3) Ground Fill Factor (GFF) = total cells with at least one ground return/total cell in AOI

The first two metrics provide some indication of the ability to characterize the quality of forest capture, and the portion of laser shots resulting in successful ground detection. However, GFF provides a better picture of the "completeness" of the forest floor capture and was therefore used for to judge the effect of varying different acquisition parameters. In addition to getting additional returns from the edges of larger (i.e., already detected) canopy openings, an increase in GFF indicates that returns are also received from smaller canopy opening is different locations that were not previously detected. For the purposes of the study, a 1m grid size was used.

In the first flight, increases in SNR were beneficial, providing a roughly 10% increase in GFF when measured with a 1m grid size. Reducing the FOV from 40 to 20 degrees provided an average 8% increase in GFF. Changing both variable together produced a compounding effect.

In addition to varying SNR, variations in the second flight allowed measurement of the effect of scan pattern (sine versus circular) as well as detection threshold. This second flight confirmed the trends of the first flight, with a roughly 10% increase in GFF over the range of SNRs tested.

Data from sine and circular scan patterns at the same FOV of 40 degrees showed that GFF was approximately 5% better for the particular cypress forest sample plot. This may not be entirely conclusive and may vary by vegetation type.

The effect of reducing detection threshold predictably produced some benefit, with approximately 7% increase in GFF by lowering the detection threshold slightly from the default setting. Further reductions, while likely producing additional forest floor measurements, predictably increased the occurrence of noise points (false returns). These noise points will require additional processing time both in the generation of the raw point cloud and in subsequent filtering steps. Therefore, users would be advised to take care when considering changing the detection threshold value, as there was no detectable increase in GFF between the two lower threshold settings.

A comparison between a typical linear-mode LiDAR design and that of a single-photon LiDAR system (Leica SPL100) shows some potential in this alternative technology. The very small laser divergence (<0.1 mr) of each "beamlet" in the SPL100 potentially provides a better concentration of laser energy through small canopy openings. Furthermore, the current SPL100 scanner design produces the same circular pattern that showed advantages on the linear-mode test system. Some study of foliage penetration of single-photon LiDAR in comparison to linear-mode has been undertaken previously by Sinclair, but the results are based on GRF as opposed to GFF. Therefore, further study is needed.

4. Conclusions

Evaluation of sample data from the linear-mode LiDAR system shows that, of the three metrics proposed as a measure of foliage penetration, Ground Fill Factor is the most informative.

Conventional wisdom of limiting the maximum off-nadir angle to approximately 20 degrees (i.e., 40 degree FOV) appears to hold, as some increase in GFF has been seen in data even between 20- and 10-degree off-nadir angles.

From the flight data, it is clear that increasing SNR setting as a flight planning or design parameter has significant benefit. However, from a commercial standpoint, it is preferable that this increase in SNR not be at the expense of lower effective pulse rate, an effect which would be typical and expected. Therefore, other methods for increasing the amount of laser energy making it through upper levels of the canopy are required.

From the tests performed using linear-mode LiDAR, the implication is that minimizing laser output divergence is one key to obtaining higher SNR, given limited size "holes" in the forest canopy. This has the greatest benefit in "closed canopy" situations, where the openings in the canopy are limited both in number and in size. In more open canopy situations (e.g., lodgepole pine forest in the western US), the benefit would not be so pronounced.

Another possibility for increasing SNR lies in a reduction in laser pulse width. Provided adequate detector response times, reducing laser pulse width (within the limits of the particular laser type used) proportionally increases the peak power in each laser pulse. It should be noted that the optoelectronic design of the receiver is critical in this respect, as excessive reduction of laser pulse width can result in a reduction in the effective response of the detector. When optimized, a reduced pulse width presents a good balance between increased peak pulse power and detector/electronic roll-off. This can allow both increases in GFF as well as increased detail in forest canopy.

An additional benefit to shorter pulse widths is the potential for reductions in minimum pulse separation. As with reduced divergence, reducing minimum pulse separation can allow return reflections to be differentiated in vertical layers of canopy that are closer together. In addition to hardware design, this minimum return separation is also affected by the processing software, particularly that used for separation of random noise from legitimate target returns.

While providing some benefit, reducing detection threshold should not be taken to an extreme, as the result will be additional noise points being processed and then having to be filtered out.

Single-photon LiDAR holds the promise of an enabling technology, with high efficiency at any given point density, and can potentially make nation-wide forest inventory at individual tree levels practical. Current single-photon systems have the low beam divergence mentioned above, giving great potential for forest applications as well as the preferred circular scan pattern. The main areas of further development of the single-photon technique lie more on the software side with improvements to reduce the aggressiveness of noise filters so that legitimate points are not removed.

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