LIDAR Flecks: Modeling the influence of canopy type on tactical foliage penetration by airborne, active sensor platforms

DOI: 10.1117/12.881509

CITATIONS: 9
READS: 417

6 authors, including:

Richard Massaro
George Mason University
14 PUBLICATIONS 65 CITATIONS
SEE PROFILE

Julie Zinnert
Virginia Commonwealth University
79 PUBLICATIONS 1,077 CITATIONS
SEE PROFILE

John E. Anderson
Engineer Research and Development Center - U.S. Army
67 PUBLICATIONS 872 CITATIONS
SEE PROFILE

Donald Young
Virginia Commonwealth University
145 PUBLICATIONS 3,210 CITATIONS
SEE PROFILE

Some of the authors of this publication are also working on these related projects:

- Global monitoring system for snow areas in Mediterranean regions: trends analysis implications for water resource management in Sierra Nevada (GMS-SNOWMED) View project
- organic fluorophores View project
LIDAR Flecks: Modeling the influence of canopy type on tactical foliage penetration by airborne, active sensor platforms

Richard Massaro\textsuperscript{a}, Julie Zinnert\textsuperscript{a,b}, John Anderson\textsuperscript{a,b}, Jarrod Edwards\textsuperscript{a,b}, Edward Crawford\textsuperscript{b}, and Donald Young\textsuperscript{b}

\textsuperscript{a}US Army Topographic Engineering Center, 7701 Telegraph Road, Alexandria, VA; \textsuperscript{b}Department of Biology, Virginia Commonwealth University, Richmond, VA

ABSTRACT

Our research focuses on the Army’s need for improved detection and characterization of targets beneath the forest canopy. By investigating the integration of canopy characteristics with emerging remote data collection methods, foliage penetration-based target detection can be greatly improved. The objective of our research was to empirically model the effect of pulse return frequency (PRF) and flight heading/orientation on the success of foliage penetration (FOPEN) from LIDAR airborne sensors. By quantifying canopy structure and understory light we were able to improve our predictions of the best possible airborne observation parameters (required sensing modalities and geometries) for foliage penetration. Variations in canopy openness profoundly influenced light patterns at the forest floor. Sunfleck patterns (brief periods of direct light) are analogous to potential “LIDAR flecks” that reach the forest floor, creating a heterogeneous environment in the understory. This research expounds on knowledge of canopy-specific characteristics to influence flight geometries for prediction of the most efficient foliage penetrating orientation and heading of an airborne sensor.

Keywords: LIDAR, foliage penetration, empirical modeling, airborne sensor

1. INTRODUCTION

The ability to “see” under a forest canopy from an airborne asset has been pursued since the dawn of aerial reconnaissance. While electro-optical (E-O) imagery can see the forest floor through canopy gaps, it is typically limited to two-dimensional data and therefore does not contain range information. Radar and synthetic aperture radar (SAR) systems have had limited success in FOPEN\textsuperscript{1} and are easily detectable by adversaries.

Airborne light detection and ranging systems (LIDARs) were developed to provide accurate digital elevation models (DEMs). LIDARs implement lasers which typically operate at near infrared (NIR) wavelengths such as 1.06 \( \mu \text{m} \) and 1.55 \( \mu \text{m} \). Integration of an onboard GPS unit and inertial measurement unit (IMU) with the range information yields highly accurate three-dimensional terrain data. The terrain data are typically first made into the form of a point cloud. DEMs can be made with further processing.

The presence of a forest canopy obviously hampers DEM creation and obscures ground-level targets of interest from an airborne LIDAR sensor. The amount of obscuration is dependent on many factors including, but not limited to, leaf area index (LAI), canopy height, species type, and percent canopy closure.\textsuperscript{2} The ability to penetrate the canopy with an airborne LIDAR is also dependent on beam divergence, pulse repetition frequency (PRF), flying altitude, aircraft heading, and off-look angle among other factors.\textsuperscript{3,4} In fact, recent attempts to correlate canopy-intercepted solar radiation with LIDAR data showed a strong dependence on divergence angle within an observer’s optical field of view.\textsuperscript{5} However, the extent to which FOPEN ability changes with respect to a combination of canopy characteristics, sensor settings, and flight orientation has not been studied in detail. The objective of this study was to empirically model the effect of PRF and flight heading/orientation on the success of FOPEN from a LIDAR airborne sensor. Specifically, we investigated the relationships between...
Figure 1. Three EMCCD images taken under the GTM canopy while the LIDAR operated overhead. (A) An image showing the LIDAR flecks partially in the vegetation and on the forest floor, (B) an image captured approximately 300 ms later without LIDAR flecks, and (C) an image captured approximately 15 s after (A) in the same scan demonstrating the gimbal’s staring capability.

return percentages from the canopy floor and sensor settings. Additionally, we investigated the relationships of LIDAR-derived forest characteristic variables to canopy structure and understory light.

A gimbaled LIDAR system was developed by Johns Hopkins University Applied Physics Laboratory (JHUAPL) and the United States Department of Defense (DoD) to maximize the FOPEN ability of an airborne LIDAR. This system incorporates an Optech ALTM 3100 and a step-stare gimbal to provide multiple looks over an area of interest (AOI). This results in a very dense point cloud over the AOI. The average sample density is intended to exceed 80 points/m² on the forest floor from an altitude of 6000 ft AGL with horizontal precision of ±10 cm and a vertical precision of ±25 cm.

During several nighttime test flights, intensified imagery was concurrently collected on the forest floor with a Hamamatsu C9100-13 EMCCD camera. Several of these images are shown in Fig. 1. It was noted that the partial LIDAR pulses which reached the forest floor resembled daytime sunflecks. Hence, we coined the term “LIDAR flecks” for these LIDAR pulses which have been partially interfered with by the foliage overhead. It was also noted that the distribution of the LIDAR flecks on the forest floor would change with different PRFs, heading angle, aircraft altitude, and several other factors. In this manuscript, we address the dependence of LIDAR fleck distribution (or FOPEN) on these varying factors.

2. STUDY SITE AND DATA COLLECTION

The study focused on a region of the Guana Tolomato Matanzas (GTM) National Estuarine Research Reserve which is located approximately 10 miles north of St. Augustine, FL. The site is maritime forest dominated by evergreen canopy trees with a layer of saw palmetto in the understory.

Table 1. Canopy and light characteristics for plots at St. Augustine GTM. Values are means ± 1 SE.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Basal area (cm²)</td>
<td>6947 ± 1512</td>
</tr>
<tr>
<td>Density of trees (ha)</td>
<td>10.22 ± 2.26</td>
</tr>
<tr>
<td>% canopy cover</td>
<td>90.22 ± 1.12</td>
</tr>
<tr>
<td>LAI</td>
<td>3.33 ± 0.40</td>
</tr>
<tr>
<td>Average PPFD</td>
<td>217 ± 37</td>
</tr>
<tr>
<td>Min PPFD</td>
<td>26 ± 6</td>
</tr>
<tr>
<td>Max PPFD</td>
<td>1257 ± 135</td>
</tr>
</tbody>
</table>
Table 2. Tree species characteristics among plots at St. Augustine GTM. Values are means ± 1 SE.

<table>
<thead>
<tr>
<th>Species</th>
<th>Density (ha)</th>
<th>Frequency</th>
<th>Basal area (cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Juniperus virginiana</em></td>
<td>28 ± 6</td>
<td>0.9</td>
<td>1048 ± 335</td>
</tr>
<tr>
<td><em>Pinus elliottii</em></td>
<td>8 ± 3</td>
<td>0.6</td>
<td>3007 ± 1297</td>
</tr>
<tr>
<td><em>Quercus virginiana</em></td>
<td>3 ± 1</td>
<td>0.3</td>
<td>7956 ± 5018</td>
</tr>
<tr>
<td><em>Quercus laurifolia</em></td>
<td>3 ± 2</td>
<td>0.2</td>
<td>171 ± 55</td>
</tr>
<tr>
<td><em>Persea borbonia</em></td>
<td>9 ± 5</td>
<td>0.3</td>
<td>59 ± 13</td>
</tr>
</tbody>
</table>

2.1 Ground Data Collection

To test the foliage poke-through performance of the LIDAR system, a densely forested region of interest (ROI) within the GTM reserve was selected. The ROI was approximately 100 m x 100 m and located near the eastern bank of the Tolomato River (approximately 30.0151°N, 81.3455°W). Nine plots, each measuring 10 m x 10 m, were chosen to collect detailed canopy data. An aerial image of the region and plot layout is shown in Fig. 2. The GTM site was composed of a variety of tree species. The majority of trees were *Juniperus virginiana*, *Pinus elliottii*, and *Sabal palmetto*. A species list together with several chosen characteristics is found in Table 2. In all plots except 3, 4, and 6, *Vitis rotundifolia* was found within the canopy. The GTM site had a relatively sparse understory as can be seen in Fig. 2. Most of the understory small palms and dead underbrush. Ideally, a canopy of homogenous tree species would have been better suited for this study but we were limited by the flight and mission requirements of the sensor test.

2.2 Airborne Data Collection

On April 30, 2010, the NIWC was used as the base of operations for a test and evaluation of the gimbaled LIDAR system. During the early afternoon, 24 “target” mode scan lines were flown over the GTM ROI. After sunset, 35 scan lines were flown in “target” mode over the GTM ROI. The scan lines were flown in varying combinations of aircraft heading, laser PRF (33, 50, and 100 kHz), and altitude (640 m to 1900 m AGL). All 100 kHz scans were flown at a nominal altitude of 640 m and all 33 kHz and 50 kHz scans were flown at a nominal altitude of 1900 m. The laser’s beam divergence was kept constant.
3. METHODS

3.1 LIDAR Data Processing

All LIDAR data were processed into ASPRS LAS 1.2 format (UTM Zone 17, WGS 84). The day and night scans were processed separately to create two DEMs of the ROI each having a 1-meter raster grid. Separate day and night DEMs were created to rule out potential changes in the sensor alignment and diurnal effects between the sorties. The DEMs were created using a nearest neighbors recursive interpolation algorithm which filled in areas of limited ground returns due to dense foliage coverage. The night DEM is shown in Fig. 3.

Ground returns were then tabulated using these DEMs. A simple ground return percentage (GRP) was calculated using the relationship

\[ GRP = \frac{N_{\text{ground}}}{N_{\text{total}}} \]  

where \( N_{\text{ground}} \) is the number of ground returns per square meter and \( N_{\text{total}} \) is the total number of returns per square meter. A return was considered to be a ground return if it was within a 0.5 m buffer from the calculated ground. In the derivation of the relationships presented in the following sections, we only considered regions where \( N_{\text{total}} > 50 \) and where the calculated GRP \( \leq 0.2 \). This is because we desired a high sample rate and regions where the overstory was considerably dense. These constraints omit regions with sparse vegetation; we were not interested in these regions.
3.2 Plot Measurements

Species, canopy depth (D), tree density (d_s), tree basal area, leaf area index (LAI), percent canopy, and light (PPFD) were quantified for nine 10 X 10 m plots. Canopy height was estimated from LIDAR data and height to the bottom of the canopy was measured using a telescoping pole marked in 0.1 m increments. Mean canopy depth (D) for each plot was measured as the mean difference between canopy height and height to the bottommost point in the canopy in each plot. Stem density and basal area were measured at 1.25 m height for all species. LAI was measured at 5 points in each plot using the LAI-2000 (Licor Biosciences, Lincoln, NE). Percent canopy was measured using a spherical densiometer.

Understory photosynthetic photon flux density (PPFD) was sampled at 3 points in each plot using the Li-Cor 190S quantum sensors attached to an LI-1400 data logger (Licor Biosciences, Lincoln, NE). Sensors were placed at ground level and spaced 4.2 m apart along the diagonal axis of each plot. For each sensor, PPFD was measured and logged every 1 s for 1 h during midday (± 1 h solar noon) on a cloudless day. Total, mean, max, min and coefficient of variation (CV) of PPFD were calculated for each plot.

3.3 Statistical Analyses

For each flight line, total LIDAR points per plot were related to field plot measurements using linear regression analysis. In order to further characterize forest structure using the LIDAR point cloud, data from each flight line were extracted from each return (1-4) into 4 vertical layers; ground, low vegetation (0.5 - 1.5 m from the ground), medium vegetation (1.51 - 5 m from the ground), and high vegetation (> 5 m) using QT Modeler. From these classifications, multiple forest characterization equations were calculated from Miura and Jones. These equations represent the presence of understory vegetation (V_L), canopy cover (CC), and presence of mid-story vegetation (V_M). For each flight line, the LIDAR forest characterization values were related to field measurements using linear regression analysis.

4. RESULTS

4.1 GRP, PRF, and Trajectory Relationships

We compared GRP values with various sensor and aircraft variables. An intriguing inverse relationship was found between PRF and GRP. The mean GRP was calculated for each PRF setting (33, 50, and 100 kHz) used during the nighttime target-mode scans. The values are reported in Table 3. The GRP-PRF relationship is non-linear and tends to flatten out at higher PRFs. This relationship is observed even though the 33 kHz and 50 kHz scans were flown at a higher altitude (1900 m) than the 100 kHz scans (640 m).

<table>
<thead>
<tr>
<th>PRF (kHz)</th>
<th>GRP</th>
</tr>
</thead>
<tbody>
<tr>
<td>33</td>
<td>0.126 ± 0.057</td>
</tr>
<tr>
<td>50</td>
<td>0.112 ± 0.052</td>
</tr>
<tr>
<td>100</td>
<td>0.108 ± 0.048</td>
</tr>
</tbody>
</table>

The GRP values for all of the target-mode scans at a PRF of 100 kHz were compared to the aircraft heading angle at which they were collected. The day and night scans were separated due to possible diurnal effects. The plots of mean ground return percentage (GRP) versus heading angle for the day and night scans are shown in Figure 4. The upper and lower error bars show ± 1-σ deviation of the distribution of GRP values from GRP at the corresponding heading angle.

It is apparent from the plots in Figure 4 that there is a dependence of GRP on aircraft heading angle. Even though the dependence may be small, there is a rather clear decrease in the GRP at heading angles of 0° and 180°. A daytime scan at a heading angle of 180° was not collected, but the GRP trend towards 180° in the top plot of Figure 4 is noticeably decreasing. Meanwhile, scans with heading angles from approximately 45° to 135°
Figure 4. Aircraft heading angle (in degrees) versus GRP for daytime flights (top) and nighttime flights (bottom). Error bars represent ± 1σ deviation from mean.
Figure 5. Model fits of GRP versus aircraft heading angle for day (solid line) and night scans (dashed line). The measured GRP are also plotted for day (o) and night scans (+).

and 210° to 315° consistently resulted in higher GRP values. Aircraft altitude plays a large role in determining GRP given a certain LIDAR PRF. In this study, however, aircraft altitude changed only slightly from line to line at a given PRF. Therefore, GRP dependence on altitude at constant PRF could not be sufficiently studied.

Next, empirical results from the PRF and heading angle relationships were combined to derive a general model for GRP over a similar sub-tropical, maritime forest given a known heading angle and PRF setting on a gimbaled LIDAR system. The GRP is approximated by,

$$\text{GRP} \approx \text{GRP}_{cont}(\text{PRF}) - A \left[ \cos^3(2\alpha) + \sin^{12}(\alpha) \right]$$

where $\alpha$ is the aircraft heading angle (0° = north, 90° = east), $\text{GRP}_{cont}(\text{PRF})$ is the mean continuum GRP at a given PRF, and $A$ is a scaling parameter which has been fitted using least squares error analysis. A $\text{GRP}_{cont}(\text{PRF})$ of 0.118 and values of 0.021 (day) and 0.043 (night) were fitted for $A$. Day and night coefficients of determination ($R^2$) were calculated to be 0.519 and 0.525, respectively. A series of inverse Lorentzian-type functions could have been used, but they would fail to naturally account for the sinusoidal repetition of the heading angle dependency. It is believed that the discrepancy between the day and night models would likely be reduced if a day scan at a heading of 180° had been performed.

4.2 Plot Measurements

Site canopy and light characteristics are given in Table 1. While LAI was relatively low, canopy closure was high (90% cover; Table 1). This indicates that structural complexity was minimal, but upper canopy trees provided a good amount of cover. Understory PPFD was variable, with majority of values collected falling in lower PPFD classes (Figure 6). However, higher PPFD values were obtained in all plots indicating sunfleck contribution (Table 1; Figure 6). The study site was dominated by $J. \text{virginiana}$, which occurred in 90% of the plots and had an average basal area of 1048 cm$^2$. 
4.3 LIDAR Forest Characterization

LIDAR derived forest characterization variables were showed many significant relationships to multiple ground collected canopy structure and light values (Table 4). The best and most significant relationships were obtained from LIDAR points representing mid-level vegetation (1.51 - 5 m). There was little overall effect of PRF on the vegetation characterization. However, accuracy of quantifying vegetation characteristics varied with flight line orientation. LIDAR derived variables were best predictors of ground sampled canopy structure and understory light at 180° flight orientation. PRF of 100 kHz showed the best relationships between LIDAR variables and ground measurements (Table 4). However, PRF of 33 kHz best predicted openings above the ground.

Table 4. Linear regression analysis ($r^2$, P) for canopy/light characteristics and LIDAR derived forest characterization variables at different pulse return frequencies (PRF). Both PRFs represent 180° flight orientation. Only significant relationships are reported.

<table>
<thead>
<tr>
<th></th>
<th>33 kHz</th>
<th>100 kHz</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>VL</td>
<td>CC</td>
</tr>
<tr>
<td>% canopy</td>
<td>0.94, 0.0064</td>
<td>0.88, 0.0184</td>
</tr>
<tr>
<td>Density (m²)</td>
<td>0.89, 0.0143</td>
<td></td>
</tr>
<tr>
<td>Maximum PPFD</td>
<td>0.89, 0.0157</td>
<td></td>
</tr>
<tr>
<td>CV PPFD</td>
<td>0.81, 0.0361</td>
<td></td>
</tr>
</tbody>
</table>

Figure 6. Frequency histogram for understory PPFD [0 - 1600 μmol/(m² · s)]
5. CONCLUSION

We have confirmed previous assertions of an inverse relationship between increased LIDAR pulse repetition frequency and decreased foliage penetration in closed canopies. The relationship is easier to observe at lower PRFs but may flatten out at high PRF settings. We believe an explanation for this relationship may involve the change in energy per pulse with PRF. Our explanation assumes there are partial openings in the canopy to the ground. In this case, lower PRFs have higher energies per pulse thus allotting more energy from the LIDAR flecks to impinge the canopy floor and return back through the canopy to the sensor. At higher PRFs, the energy per pulse is insufficient and therefore dissipates through the canopy to the point where the canopy floor return is undetectable by the sensor. Higher PRF is more sensitive to vegetative structure, which is seen in the higher relationships between LIDAR derived variables and ground measured canopy/light characteristics. This would become especially important in canopies with complex structure (i.e. high LAI, multiple layers of leaves oriented at various angles and azimuths), influencing light penetration and return. In comparison to other deciduous systems, the understory canopy at St. Augustine was relatively simple in terms of structure and species composition. One would expect the PRF-GRP relationship to be even more apparent if the lower PRF scans were flown at the same lower altitude as the high PRF scans. The altitude restraints for this test were imposed due to eye safety concerns. We intend to continue to investigate this PRF-GRP conjecture with state-of-the-art, high-PRF LIDARs.

Analysis of the heading angle effects on GRP has determined a loose but credible relationship. At northward or southward aircraft headings, there were considerably less returns from the forest floor. An aircraft heading of 180° provided optimal relationships with ground measurements, independent of GRP. This may coincide with optimal leaf orientation relative to the solar path in late spring at this latitude. The results compare well with previous studies. Future studies will include comparisons of numerous canopy types to further evaluate these empirical relationships. It is thought that leaf orientation may be the culprit for the lower GRP values at northward and southward headings. Leaves will be oriented generally towards the south to capture the most sunlight. Thus, gimbaled LIDAR pulses will be intercepted more often when the sensor is on a north or southbound trajectory since the leaves will have a larger projected cross-section. The most returns from the forest floor coincided with heading angles in the range of 45° to 135° and 210° to 315°. The reason for this is not as clear but is likely a canopy-specific result. A generalized model was developed for this particular maritime forest type to estimate the mean ground return percentage given an aircraft heading angle. The model only considered PRFs of 100 kHz with a constant sensor altitude of 640 m, nominally. We expect that the scaling parameter \( A \) in the model changes with (i) different PRFs and (ii) different sensor altitudes. We expect that the shape of the model will change with (i) the absence of a gimbal, (ii) different forest types, and (iii) seasonal changes. We expected the strong relationships seen with understory light patterns as these are due to direct beam sunlight penetration to the forest floor and analogous to direct beam LIDAR. We consider these results an important step in predicting the likelihood of forest floor returns to an airborne active sensor platform when attributes of the obstructing canopy are known.

ACKNOWLEDGMENTS

This work was funded through the US Army Corps of Engineers ERDC basic research program. We would like to thank our DoD collaborators for collecting and providing the LIDAR data over the GTM site. We are very grateful to Mr. Forrest Penny and Florida’s Department of Environmental Protection for their invaluable assistance and allowing us to have prolonged access to the GTM site.

REFERENCES


