Assessment of Foliage Poke-Through Capabilities of an Airborne Geiger-Mode Lidar

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ABSTRACT

Lidar receivers with exquisitely sensitive Geiger-mode detectors are able to detect surfaces even when the line of sight from the lidar sensor to the surface is highly occluded by intervening forest canopy. Additionally, repeated scanning of a region of interest from a diversity of perspectives increases the likelihood of imaging any given surface through at least one substantially unoccluded line of sight. Together, these techniques allow airborne lidar collections to be tailored to achieve comprehensive human activity layer (HAL) data collection, even in areas with dense foliage. We present a study of the performance of a 3DEO lidar for foliage poke-through applications, exploiting both its Geiger-mode sensitivity and agile geo-referenced scanning system. We present two methods for estimating the utility of the resulting 3D point clouds in the HAL, near the ground, based on the spatial statistics of the point clouds. We apply those methods to airborne Geiger-mode lidar data of deciduous forests in Massachusetts and conifers in the US Pacific Northwest. We quantify the completeness of the point clouds as a function of the collection parameters. We then use this analysis to estimate the ideal collection parameters for a Geiger-mode lidar with georeferenced scanning to yield a high-utility data product.

Keywords: Geiger-mode lidar, foliage penetration

1. INTRODUCTION

Foliage poke-through or foliage-penetration (FOPEN) performance of an airborne lidar system is an important characteristic for users attempting to answer questions about an area that has moderate to heavy foliage cover. The following are a few of the potential tasks that are facilitated by this capability.

1. Determining ground elevation to create a digital terrain model (DTM)
2. Measuring tree and vegetation characteristics
3. Evaluating ease of human traversal and/or identifying human activity

Typically, FOPEN is achieved by repeatedly imaging a foliated target from different perspectives; each new viewpoint adds additional information that can be aggregated into a complete picture with limited occlusions. Different scenes, created by different varieties of trees, different seasons, etc., will have different requirements on how many scan are required and how spread out those scans need to be. These general considerations also apply to the imaging of urban scenes with tall buildings. In this work, we will present methods for quantitatively evaluating the performance of the collected data products, to better understand the utility of those data products for various tasks.

Geiger-mode focal plane arrays (GM cameras) have two main benefits with regards to FOPEN. The first benefit is data rate. A single GM camera with 4096 pixels running at 90 kHz is capable of capturing well over 100 million measurements per second. This allows collection of a scan with high data density in a few seconds, in turn allowing the time for many revisits to a particular target over a pass. The second benefit comes from recording individual photon detections. With those individual detections written down, data from multiple scans

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can contribute to a particular surface detection, which allows detection of faint signals through accumulation of signal over multiple scans and passes.

GM cameras have shown great potential as part of airborne lidar systems to deliver FOPEN capabilities, including systems such as AOSTB,[1] ALIRT,[2] and Zion.[3] There have also been several studies[4,5] that have demonstrated disappointing FOPEN results with GM and similar photon counting lidar systems. Given both positive and negative results of systems implementing the GM technology, one might reasonably assert that success is dependent on achieving proper system design, collection methods, and data processing for a particular class of scene.

In terms of system design, 3DEO builds and operates airborne lidar systems with agile, geo-referenced scanning systems[6] that allow efficient interrogation of targets throughout the sensor field of regard (FOR). Each geo-referenced target on the ground is scanned multiple times as the aircraft passes, as shown in Figure 1. This means that the mission planner can specify how many viewing angles a particular target will be imaged from per pass, and how many passes are required to achieve a desired total number of viewing angles.

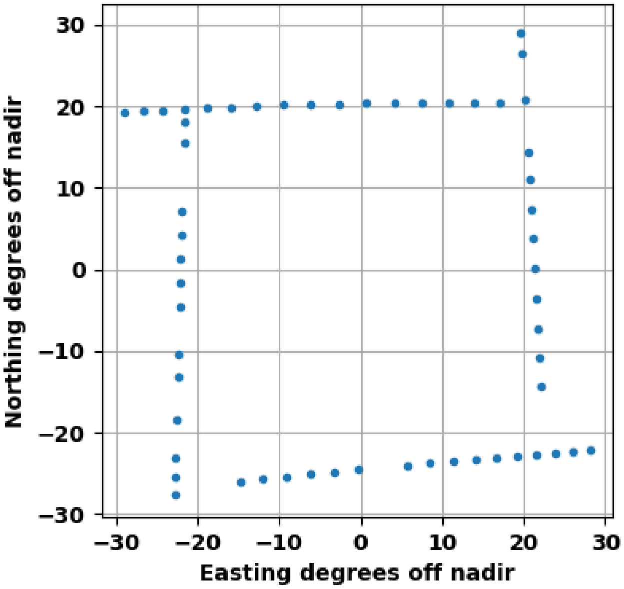

Figure 1. Angular displacement of aircraft for each scan of the PNW data set, relative to a nadir look on the target. Several scans were omitted from the set due to poor registration. Data was collected over four passes. Within each pass, the scans were separated by about 3 degrees.

In this paper, we present methods for evaluating a set of processed data to quantify the FOPEN performance. We then apply these methods and demonstrate a functional relationship between the number of scans and the FOPEN performance of the final data product for two separate airborne collections.

2. METHODS

This section describes methods of FOPEN characterization and the data that was evaluated using these methods. Subsets of scans are chosen from each of the data sets, with a minimum threshold angular separation between scans. For all comparisons, 20 unique sets of scans are aggregated to produce 20 aggregated point clouds; metrics are then calculated for each aggregate, then the average and standard deviation of those metrics are recorded. It is important to note that for simplicity, these scans are chosen such that the minimum angular separation between any two is 5 degrees. We expect that this is an overly-cautious threshold; we intend to dive deeper into the dependence of FOPEN performance on angular separation between scans in future work.

Figure 2. Upward-looking photograph showing typical occlusions in a deciduous forest. Taken in Dover, Massachusetts in September 2023.

2.1 Data

This work uses two data sets for evaluation. For both of these targets, more than 60 scans were collected. This represents a dramatic excess of scans to achieve even the highest quality of FOPEN performance. This allows us the freedom to create many sub-sets of scans to investigate FOPEN performance with statistical significance.

One data set was collected with a ZION-A lidar system over the University of Idaho Experimental Forest. We will refer to this as the Pacific Northwest (PNW) data set. This particular set of data includes scans from 4 passes, collected from a platform approximately 3,000 ft above ground level (AGL) at the end of June 2023. The target was a circle with a diameter of 150 meters, in an area densely populated with conifers. A total of 64 full scans were collected.

The other data set was collected with a ZION-B lidar system over a deciduous forest in Dover, Massachusetts during late September 2023. We will refer to this as the Massachusetts (MA) data set. This data set includes scans from 4 passes, collected from a platform at approximately 8,500 ft AGL. The target was a 300x700 m rectangle. A total 270 full scans were collected. Figure 2 shows an example of the foliage occlusion in the target area.

Data is processed with 3DEO's proprietary processing tools and workflow. Each scan (defined as the data collected from a single cycle of the scanning system interrogating a single target once) is processed into a Level 1 (L1) point cloud, which contains all reported photon detections from a scan (including multiple hits from single surfaces, dark events, and cross-talk events). These scans are denoised and pre-processed (Level 2) and then registered together. For each data set, the data from the registered scans were then aggregated and denoised, creating a Level 3 (L3) point cloud. That point cloud was used to create a digital terrain model (DTM) with 1 m resolution, using the SHR3D[7,8] algorithm developed at Johns Hopkins University Applied Physics Laboratory. The DTM is then interpolated and used to estimate a height above ground (HAG) value for each point in the L3 point cloud.

Scan-to-scan registration plays a very important role in the creation of accurate and useful aggregates. Including one or more poorly registered scans in the aggregate can lead to blurry imagery, lost low-level signals, and point clouds that can confuse ground finding algorithms. In our processing workflow, each registration is evaluated on several metrics; failed registrations are rejected and can be rerun if desired.

2.2 FOPEN Evaluation Method I: HAG Void Percentage

The first FOPEN evaluation method assesses the FOPEN performance of a point cloud by assessing the point density of the L3 product near the ground (as determined by SHR3D).

The L3 point cloud is cropped on the HAG channel to the region defined by 1 meter below to 2 meters above the ground. A map of the data density is created using a 2D histogram of the cropped point cloud in 0.6 meter square bins. The map is masked with a chosen threshold (3 points per bin) to separate into void and non-void regions. This binary map is then used to estimate the total area of voids within the area of the target, using OpenCV, which is divided by the total void plus non-void area.

For a given scene we expect adding new scans from unique perspectives will cause the fractional area of the target that is void to decrease. While this method is moderately dependent on a generated DTM to inform the HAG values, it can tolerate a modest amount of error (±1 meter) before the resulting fraction is impacted. This method is however impacted by voids that are created by low or nonexistent ground-level returns due to e.g. water or buildings.

2.3 FOPEN Evaluation Method II: Generated DTM Evaluation

The second FOPEN evaluation specifically assesses the "test" DTM against a "truth" DTM. In this case, the truth DTM is created using an aggregate of all available scans. This could also be gathered from ground surveys or other outside information. An option for evaluation if other sources of data don't exist is to randomly remove scans from an aggregate to create variations.

The truth DTM is loaded and used to create a rectangular grid interpolator. For each point in the test DTM, the interpolator is sampled and the difference squared, then the values are averaged, the result of which is then raised to the 1/2 power (RMSE).

As the test DTM approaches the truth DTM, this value should go to zero. Comparing the size of variations introduced by adding or removing one or more scans can indicate the stability of the DTM solution. This method is strongly dependent on the approach for generating a DTM, and thus a bit less reliable in the general sense.

3. DISCUSSION

In Figure 3 and 4, we show the two metrics and uncertainty for various sets of scans. There are several interesting effects worth exploring.

In both figures, we see that the HAG void percent keeps decreasing as more scans are added, but the DTM RMSE stops improving around 15 scans.

We surmise that there are several contributing effects:

1. The accuracy of the DTM should improve as the void fraction decreases. When the remaining voids become smaller than the DTM resolution, the impact of further reducing the void fraction should drop off, eventually reaching zero .

2. SHR3D includes a command-line argument for vertical uncertainty, but does not include outlier rejection. In that sense a single false alarm that is classified as a last return can result in an error of one or more meter in the output DTM. As the number of scans increases, the chance of coincident noise points increases; without outlier rejection, those noise points can distort the DTM, as seen in the error bars on the DTMRSE at high scan numbers in Figure 4.

3. We chose to produce GeoTIFF DTMs with a resolution of 1 m. For the purposes of comparison, the "truth" DTM is loaded and used to create a rectangular grid interpolator using linear interpolation. The test DTM is then compared to the truth at points that are interpolated based on the sample locations in the test DTM.

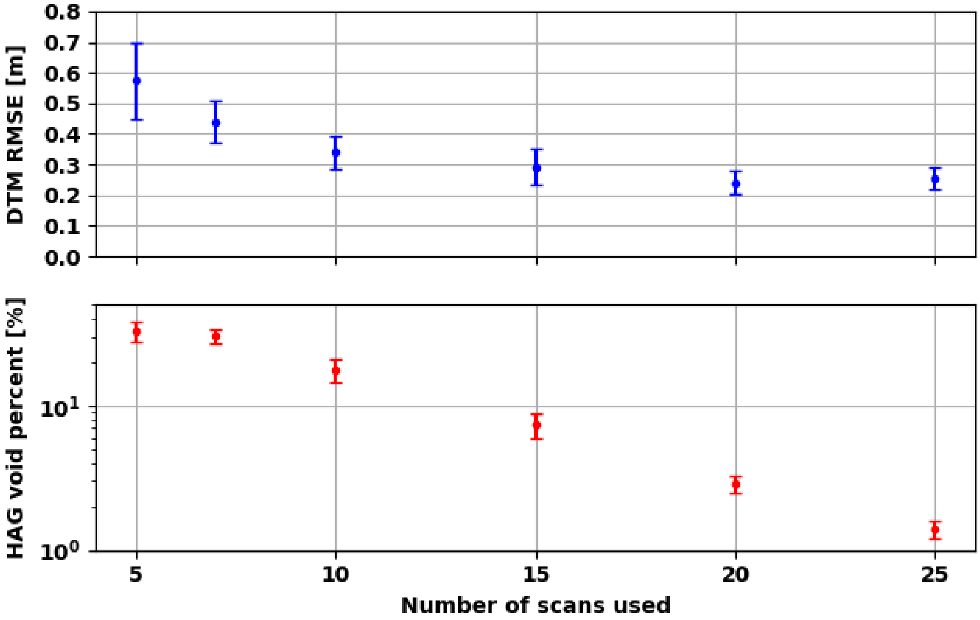

Figure 3. FOPEN performance metrics for different sets of data from the PNW collection. Each point represents the average statistic of 20 sets, with error bars given by the standard deviation of the set.

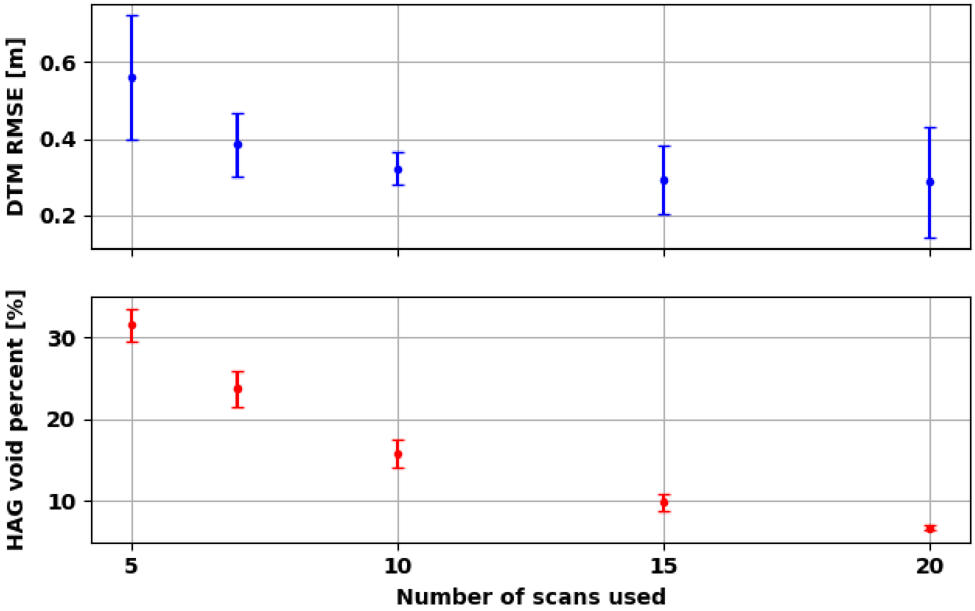

Figure 4. FOPEN performance metrics for different sets of data from the MA collection. Each point represents the average statistic of 20 sets, with error bars given by the standard deviation of the set.

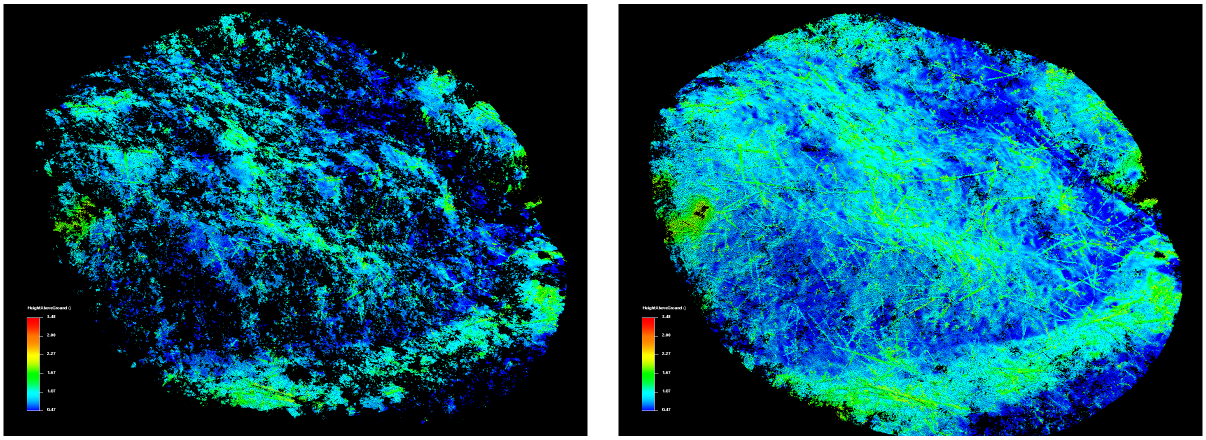

Figure 5. Comparison of the aggregate of 5 (left) and 25 (right) scans. Both point clouds have been cropped to show only points with HAG values between -1 and 2 meters, and colored by HAG. The 5-scan aggregate shows a significant number of voids.

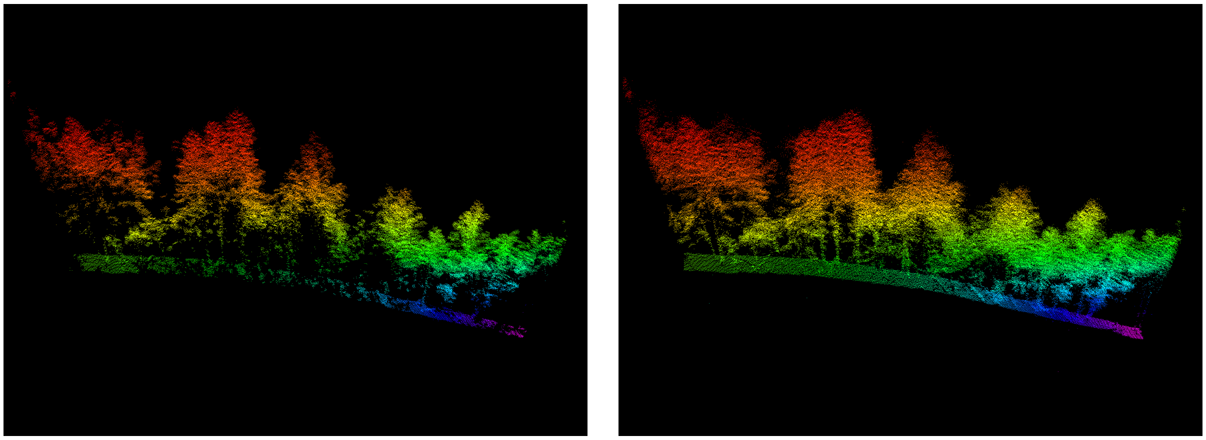

Figure 6. Comparison of the aggregate of 5 (left) and 25 (right) scans. Transect width is 2 meters. Points are colored by z; the tallest trees are about 25 meters tall. The 25-scan aggregate shows very good ground coverage, while the 5-scan aggregate has significant voids.

In other words, we may surmise that the error associated with data voids falls below other, fixed error sources. Improving DTM generation methods will likely reduce those other error sources in the future.

In Figure 4, we see that the HAG void percent does not approach zero in the same way as in Figure 3. This is likely due to voids that are mostly independent of occlusions, such as bodies of water. Future refinement of this metric could include identification and rejection of such voids from the metric.

Figures 5 and 6 show the impact of low (5) and high (25) quantity of diverse scans on image quality and voids. While some information may be gleaned about broad scene characteristics from the 5-scan aggregates, the 25-scan aggregates provide detailed and comprehensive information.

4. CONCLUSIONS

We have demonstrated a functional relationship between the number of suitably-spaced scans and the FOPEN performance of the aggregate of those scans for two collection scenarios. We expect that this relationship will vary based on the foliage type, tree density, and collection conditions. Application of this relationship to sensor design, mission planning, and collection should enable efficient, reliable, collection of high-quality FOPEN data. For the two data sets considered, 15-20 scans per target delivered a consistent DTM and relatively low void percentage.

There is more work to be done in understanding the impact of imaging angle on FOPEN performance; this includes quantifying the impact of off-nadir angle of each scan and the impact of scan-to-scan angular separation for different classes of scene.

There is also more work to be done in reliable DTM creation for Geiger-mode lidar data.

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