

Dynamic geo-referenced scanning of aerial lidar systems

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ABSTRACT

Aerial lidar systems tend to have narrow instantaneous fields of view, with imagers ranging from a single pixel to many tens of thousands of pixels. To collect data over a large area, the narrow lidar field of view (FoV) must be scanned. We present a unique method of scanning a lidar FoV that provides significant flexibility and allows uniform ground coverage, concentrating the system capability only in areas of interest. This method uses a queue of convex polygons, specified in world coordinates. Pre-collection planning tools establish the polygon layout. In flight, the lidar system adaptively collects those polygons that are inside the sensor field of regard, rapidly switching among the polygons as the aircraft flies. This scanning method enables the lidar to accomplish repeated collections of a single target or collections that cover a long straight or meandering path. It also enables collection of corridors with irregular widths, such as power line corridors with bulges at municipal power sub-stations or rail or roadway intersections. In the case of mixed scene types, the system can concentrate more collection time on foliated regions relative to unfoliated regions. Angular diversity can be achieved by sequentially revisiting a single target polygon. Live target tasking is accomplished by adding new targets to the target queue without stopping an ongoing collection. We present scanning simulations and example lidar data collected in flight with this scanning strategy and show some examples of sampling uniformity under the finite bandwidth and acceleration of a real scanning system.

Keywords: Aerial Lidar Scanning, Beam Steering Control, Geiger Mode, Two-axis Scanning

1. INTRODUCTION

Airborne lidar mapping systems are employed to measure the 3D geometry and other properties of a region of interest. Lidar is an active imaging modality that employs a laser beam to illuminate a small region of the ground and simultaneously image it with one or more light detectors, perhaps arranged into a focal plane array. In order to image a region of interest (RoI) on the ground larger than the detector instantaneous field-of-view (FoV), the lidar system must be scanned across the scene. This paper describes a flexible and efficient method for scanning an intended area on the ground. In order to effectively collect the data required to construct a model of the RoI, the narrow FoV must be scanned across the RoI, at an appropriate speed, one or more times, as required by the scene content. Furthermore, the scanning methodology should operate robustly and predictably, should allow maximal flexibility to the operator of the lidar, should be cost effective, and should utilize aircraft flight time efficiently. We present a novel scanning method for an aerial lidar system and compare it to other scanning methods theoretically. We present an implementation of the scanning methodology in a Geiger-mode lidar system and evaluate the performance of the method using aerial data.

This work is especially adapted to Geiger-mode lidar systems, differentiated by their operating principle of digitizing the time of arrive of detected photons, one at a time. To realize the full efficiency advantage of Geiger-mode technology the system operator samples the scene with just enough laser pulses and corresponding pixel exposures to achieve the minimum required signal level, aggregated over many laser pulses. Geiger-mode systems benefit from more flexible scanning systems since the sampling density requirement (that is, the number of pixel exposures per unit area required to achieve the required number of detected photons) can vary substantially across a scene and from project to project.

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2. RELATED WORK

Some lidar detectors have a single detector element while others have arrays of detectors, but in all cases airborne lidar systems have a small angular field of view. Small angular FoV is associated with high angular resolution, but results in the need to scan the detector system over a scene to capture a wider target area. Scanning systems for lidar detectors are used to point the illuminator and detector around an intended target area. For aerial lidar systems, the target is a geo-located collection area on the ground that is of interest to a user or customer. Scanning for aerial lidar systems has historically been accomplished by means of a spinning polygon, Risley prisms or a gimbal mechanism.¹ Previous research at MIT Lincoln Laboratory² used a two-axis scan mirror to implement independent control of along-track and cross-track motion. The work presented here uses a two-axis scanner which allows for flexible scan patterns and can be used to yield uniform sampling and to perform dynamic scan patterns. Galvanometer scanner hardware was chosen in our implementation for its high acceleration capabilities.

Galvanometer scanners have been used with lidar systems in other projects. An early use of a galvanometer scan head coupled with a lidar system is presented by Hegna et. al.³ The authors paired the system with an Acuity Lidar Measurement System. Pairing galvanometers with lidar sensors has become more prevalent within the past 5 years. Shi⁴ reviewed three different lidar scanning methods including a spinning polygon, a rotating mirror and finally a galvanometer along with some benefits and deficiencies of each of these. The paper concludes that the galvanometer provides a low-cost effective option. Nguyen et. al.⁵ provide a model for a galvanometer along with an in-depth analysis of a raster scan mode that results in a mode similar to the spinning polygon scanner. The method presented here is different in that the scan pattern is relative to geolocated coordinates. Nguyen paired the galvanometer scanner with a custom lidar system made from a laser diode, raspberry pi, FPGA, time to digital converter, and programmable gain amplifier. In 2019 Choi⁶ studied a way to correct for differences in galvanometer speeds to improve image formation using a MicrorMax 677XX galvanometer coupled with a lidar system. The work presented here uses galvanometer scanners in an aerial mapping systems and develops a novel method for employing a two-axis scanning system to efficiently obtain lidar imagery.

3. OBJECTIVES FOR SCANNING LIDAR

Several objectives should be met simultaneously for the scanning system used in a lidar data collection project. The relative priority of the objectives depends on the project. These objectives include:

1. Achieve the required minimum sampling density across the scene;
2. Achieve uniformity of sampling across the scene;
3. Achieve the intended level of imaging angle diversity, typically with wide separation between interrogation angles; and
4. Minimize time spent pointing outside of the RoI.

For single photon-sensitive lidars in which the final data product is generated by analysis of an aggregation of photon detection events, a minimum desired sampling density is identified during the planning phase of the data collection. This is the desired number of times that a detector is exposed to a laser pulse illuminating the ground, per unit area. The sampling density required to meet the intended product point density depends on assumptions about the scene reflectivity and geometric complexity. If the sampling density is too low, there are not enough measurement attempts made to reliably detect the surfaces in the scene, and image quality and product utility suffers. The area collection rate of the system is inversely proportional to the sampling density, so if the system is operated at higher sampling density than necessary the area collection rate is compromised and the data collection process takes more time, often incurring extra costs. The image quality is often not appreciably improved by sampling densities higher than a threshold. To collect the desired image quality efficiently, the lidar system needs to be able to reliably achieve the sampling density desired for the projects' intended purpose.

In most cases the ground should be sampled at perfectly uniform density, meaning that each region of the ground would be interrogated the same number of times. In practice this is not possible, but scanning motions can be designed to achieve sampling uniformity that approaches the ideal case.

Angle diversity refers to the number of different viewing geometries that are used in the complete process of interrogating the scene. Angle diversity is critical in allowing a lidar system to make a more complete picture of a complex scene. For example, sides of a building that are shadowed when the building is viewed from one point may be observable when viewed from a different point on the other side of the building. Also, objects under forest canopy and other partial obscurants can be successfully imaged by probing the object through many different points in the canopy overhead, finding a hole at least one of the times the object is probed. In order to achieve interrogation angle diversity, the scene must be scanned from multiple different aircraft locations. Typically these different viewpoints should be far apart from each other. Survey measurements collected seconds, hours, or days apart can be combined into a single, coherent whole so long as the scene did not change over the course of the measurement process.

Rapid and efficient data collection is important due to the high cost of aircraft flight time, equipment rental, and labor. Reducing the time spent scanning outside the region of interest maximizes the value of the data that is collected.

4. GEO-REFERENCED LIDAR SCAN MODE

This section describes a method for scanning that scans geo-referenced collection areas and is designed to achieve the objectives outlined in Section 3. Geo-referenced scanning is the ability of a lidar sensor to aim at and scan locations and targets specified in a geo-reference coordinate frame e.g. latitude and longitude. This geo-referenced scanning is implemented such that it compensates for non-ideal aircraft position and orientation and follows a specific scanning pattern relative to the coordinates of the target. The Geo-referenced Scan Mode is comprised of 4 main parts:

1. Instantaneous mirror command computation, which computes the two mirror angular positions required to aim at a specific target location (Section 4.1),
2. Constant-speed scan lines which move the mirrors between desired mirror positions (Section 4.2),
3. Collection Zone coverage using a series of scan lines that ensure complete coverage (Section 4.3) and,
4. A Collection Zone Target Queue to enable advanced features and dynamic scanning (Section 4.4).

4.1 Instantaneous Mirror Command Computation

The ability to point the lidar system at a geo-referenced target is at the core of geo-referenced scanning. In order to aim at a three-dimensional, geo-referenced target, the lidar must be able to detect the sensor position and attitude and then compute two mirror positions that will cause the lidar to point at the desired location. The equation for the world line-of-sight vector, \mathbf{q} , corresponding to a detector line of sight, \mathbf{p} , for a given set of mirror angular positions, m_k , takes the form of the following matrix multiplication equation:

$$\mathbf{q} = \mathbf{T} \mathbf{W} \mathbf{H} \Theta \Omega \mathbf{E} \mathbf{N}_2(m_2) \mathbf{N}_1(m_1) \mathbf{M} \mathbf{p}. \quad (1)$$

In this equation, \mathbf{M} is a matrix representing the mounting angles of the receiver optical system, \mathbf{N}_k is a reflection matrix created from the mirror normal \mathbf{n}_k of the mirror k rotated by angle m_k , \mathbf{E} is a matrix representing the scanning unit mounting angles, Ω is the inertial navigation system mounting angles, Θ is a matrix representing the measured roll, pitch and yaw of the lidar system, \mathbf{W} is a matrix representing the rotations from local tangent plane to world coordinates and \mathbf{T} is a matrix that represents the translation from the lidar sensor origin to the world coordinates origin. The lidar position and attitude are measured with internal sensors. The target location is known. The mounting angles and detector line-of-sight are known through calibration. The unknowns in Equation 1 are the mirror positions (m_k), which are used to compute the mirror normals (\mathbf{n}_k) which are used to create the reflection matrices \mathbf{N}_1 and \mathbf{N}_2 , so this equation can be reduced to

$$\mathbf{w} = \mathbf{N}_2(m_2) \mathbf{N}_1(m_1) \mathbf{u} \quad (2)$$

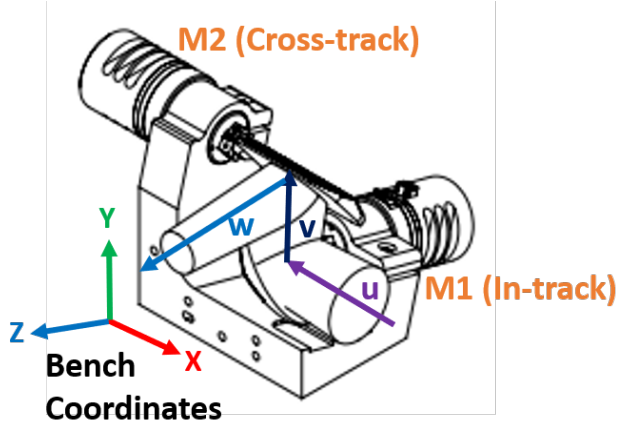


Figure 1. Diagram of the optical path through the two-axis scanning mirrors. The vector \mathbf{u} represents the light going into the mirror system, \mathbf{v} is the beam path between the two mirrors and \mathbf{w} is the beam path exiting the mirror system. The base image is courtesy of Thorlabs.

where \mathbf{u} is the beam path before the two mirrors and \mathbf{w} is the beam path after the two mirrors, expressed in a coordinate system attached to the optical bench. The vector \mathbf{v} is used to represent the beam path between the two mirrors as shown in Figure 1.

A mirror reflection matrix \mathbf{N} is derived from the standard reflection equation, $\mathbf{v} = \mathbf{u} - 2\mathbf{n}(\mathbf{u} \cdot \mathbf{n})$, converted into a form that can be used for matrix multiplication:

$$\mathbf{v} = (\mathbf{I} - 2\mathbf{n}\mathbf{n}^T) \mathbf{u} \quad (3)$$

so that

$$\mathbf{N} = \mathbf{I} - 2\mathbf{n}\mathbf{n}^T. \quad (4)$$

Equation 2 provides a set of three equations that can be solved for the mirror values, m_1 and m_2 , that cause the camera vector \mathbf{u} to be reflected into the desired line-of-sight vector, \mathbf{w} . Different systems with somewhat different geometries or system models can be set up and solved in a similar way.

In practice, the mirror faces are not exactly orthogonal to the rotation axis and the two rotation axes are not exactly orthogonal. These non-idealities introduce additional rotations as part of computing mirror normals and can have an impact on the accuracy of the pointing. Including these non-idealities in the above equations causes the equations to become significantly more complex and difficult to solve for m_1 and m_2 . An alternative to an exact treatment is to approximate these effects by applying a small rotational compensation matrix to the desired exiting beam path, \mathbf{w} , that approximates the effects of these small and constant manufacturing non-idealities. The derivation of the compensation matrix requires modeling of these effects and system calibration which is out of the scope of this paper. In practice, the compensation matrix allowed the scanning system to perform within engineering tolerances.

4.2 Constant Speed Mirror Control

Lidar scanning is often comprised of line segments called scan lines. Constant speed scanning is achieved by projecting a geo-referenced target location into angular mirror space (m_1, m_2) using the equations in Section 4.1 and then at each command update interval, continuously moving the mirror toward the desired mirror position at a constant speed. This end position is continually updated in mirror space as new lidar position data becomes available from the GPS/INS. When the line segment end position is achieved, a new geo-reference end point is projected into mirror coordinates and a new line is scanned. Moving the lidar detector in constant angular speed allows more uniform sampling on the target. Constant speed segments can be combined together to scan an area of interest.

Following straight lines in the scan mirror angle-angle space results in some curvature of the line traced out at the target location. This is not a significant detriment for this application because the curvature is minimal and adjacent lines have nearly identical curvature, resulting in uniform sampling density with no gaps. The effects can be reduced by segmenting the scan line into multiple pieces. The angular speed is limited by the acceleration capability of the two-axis scanning system at the turns. Management of the acceleration can be achieved by engineering the motion such that it does not require exceeding the acceleration capability.

4.3 Scanning a Geo-referenced Polygonal Collection Zone

The geo-referenced collection area is often provided by a customer as a general area with a boundary specified in latitude and longitude. Areas that are larger than the scanning field of regard are broken into smaller polygonal collection zones. The size of these polygons depends on the distance to the target. The optimal size will be different for different sensors and different altitudes. The scanning is more simple and more efficient if the polygons are required to be convex. If a concave polygon is desired, the area can be separated into multiple convex portions that can be used with the polygon target queue described in Section 4.4.

The polygon is divided into line segments and covered in a serpentine scan as described by Yang.⁷ This provides a simple and efficient way to ensure polygon coverage. Line segments oriented across the polygon use the specified desired constant speed that provides the desired sampling density. At the polygon border the line segments that transition to the next scan line use a higher speed, limited by the scanning system's acceleration capabilities. This minimizes time spent turning around at the edges of the polygon. The spacing of the line segments depends on the angular extent of the detector array. Detector arrays with larger angular extents (e.g. due to having a large number of pixels) allow for larger spacing between scan lines, which in turn allows for fewer scan lines and fewer turn-arounds, thereby lowering the dynamic performance requirements for the scanning system.

4.4 Target Queue

A queue of collection targets and the ability to switch between geo-referenced target polygons in real time enable some unique scanning capabilities. The Target Queue contains a set of collection units defined by geo-referenced polygonal boundaries and desired scanning parameters for that target. The Target Queue is a First In, First Out (FIFO) queue with some exceptions. In operation, the scanning control system steps sequentially through the queue evaluating each entry. First, if the current polygon is not within the sensor field of regard, it will be skipped and will remain in the queue. Second, if the assigned number of scans has not been completed the polygon will be scanned; this enables a polygon to be scanned multiple times in immediate succession. When the intended number of scans has been completed, the polygon is removed from the queue. If the polygon has been assigned the "sticky" attribute, instead of being removed from the queue it is reinserted at the end of the queue.

4.5 Geo-referenced Target Queue Scanning Use Cases

The first use case is a targeting mode. Areas of interest that fit within the scanner field of regard can be scanned as stand alone collection zones. The Target Queue would only have one polygon and the area is imaged repeatedly as long as it is in view. However, in some situations characteristics of the area of interest are known and indicate a higher or lower sampling density should be used in particular subregions of the area of interest. This might occur, for example, if a large field of grass (with high reflectivity) and a large black parking lot (low reflectivity) are both present, or if some of the scene is unoccluded while other parts have significant foliage. In these cases, areas that need more sampling can be added to the queue as independent polygon zones with their own sampling and scanning characteristics.

A second use case is a wide area mapping mode. If an area is much larger than the field of regard of the scanning system it can be divided into smaller polygons and which can be added to a queue. For performance reasons, it is better to group polygons into sets of polygons that can be imaged from single flight lines. Large map areas can be collected using these groups of polygons. It would be possible to divide the entire world into tessellating collection units to aid seamless data aggregation even when the data was not collected at the same time or by the same sensor.

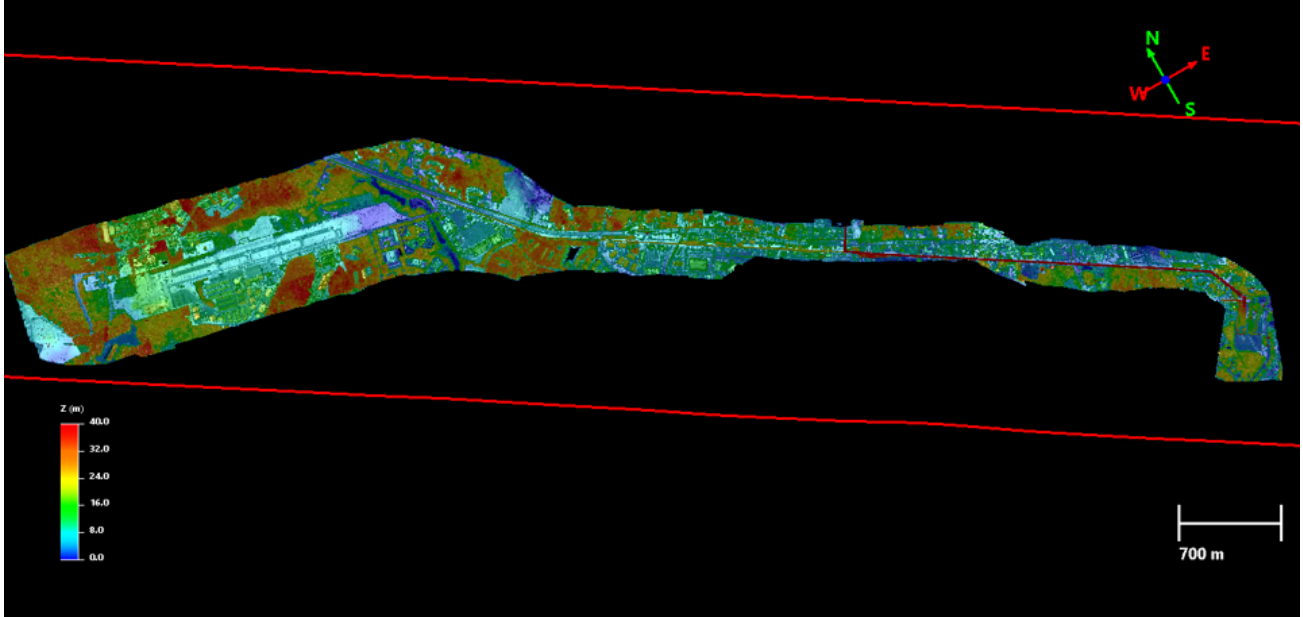


Figure 2. Top-down view of lidar imagery collected using straight flight lines, while scanning a set of geo-referenced ground targets of varying sizes. The imagery is colored by height. The scanning follows a wide swath around an airport runway, then follows a narrower region around a road, transitions to a power line and then makes a corner and scans a power sub-station. This imagery shows all of the data that was collected; no data cropping was performed. The straight red lines indicate the flight lines used to collect this imagery.

A third use case is for target areas that are long and thin and possibly meandering, such as coast lines, mountain crests, canyons, rivers, paths, power lines, train tracks, roads or trails. In these cases, an area of a desired width around the path is divided into polygons and added to the target queue. This enables the airplane to fly in a straight line while the scanner does the work of following the target line. This results in the highest possible sampling density on the area of interest because no time is spent imaging areas that are not of interest. This also enables the ability to scan wider in some places and narrower in others. This may be useful when following a power distribution line into a power plant where it could be advantageous to scan wider to capture the entire facility, or using a wide scan to capture a town while using a narrow width for the roads connecting towns.

5. RESULTS

5.1 Theoretical Sampling Uniformity

This section will present a theoretical comparison of four different scan methods, evaluating them for sampling uniformity. Then, some examples of actual sampling uniformity achieved using the geo-referenced scan mode with two-axis scan hardware and a Geiger-mode camera are presented.

Sampling uniformity of four different scan methods is compared using a simulation which allows scanning and collection parameters to be held constant. In this simulation, the flight speed, flight altitude, swath width, detector count, field of view and laser pulse rate were held constant. This scanning simulation counts interrogations, not range measurements, so laser power, detector efficiency and scene reflectivity are irrelevant. The scan parameters were chosen to ensure a 50% array overlap between adjacent scan lines. This overlap was chosen because the lemniscate scan will have large gaps and sampling non-uniformity at the edges when the overlap in the middle is less than 50%. Figure 3 shows four lidar scanning methods used to scan a 500 m wide area while the simulated aircraft carrying the simulated lidar sensor was traveling along a straight path. The blue line in each figure represents the path of the center of the detector array for each type of scan method. All scanning systems are simulated assuming actual hardware physical realities. For the Constant Speed mode, this includes angular acceleration limits representative of real galvanometer hardware.

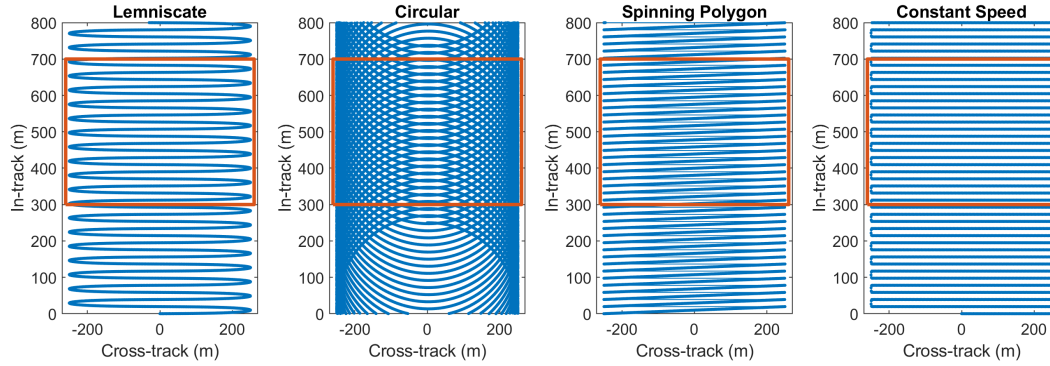


Figure 3. A representation of four different methods used to scan an aerial lidar system as described in the text. The blue line in each figure represents the path of the detector array. The Lemniscate scan is a side-to-side pattern based on sine waves. The Circular scan mode continually moves the sensor line of sight around in a circle repeating forward, left, backward and right looks. The Spinning Polygon scan mode results in a raster scan. The Constant Speed method uses the two-axis mirror system to create a serpentine scan pattern over a target of interest. The highlighted regions are used for sampling density analysis.

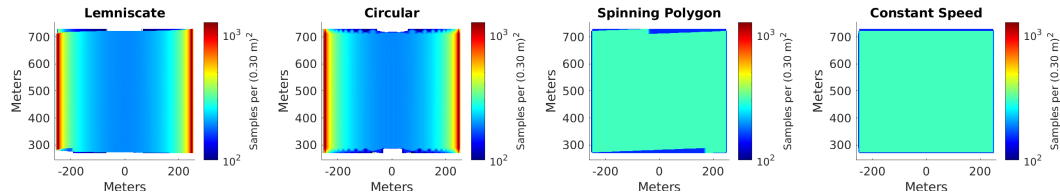


Figure 4. Theoretical sampling density achievable by four different scan methods. Lemniscate and Circular density have lower sampling uniformity while Spinning Polygon and Constant Speed scanning have more uniform sampling. The color bar is logarithmic to better show the magnitude of sampling non-uniformity.

The Lemniscate scan is a side to side pattern based on sine waves. This type of pattern is used by the AOSTB Geiger-mode System.² This pattern is sinusoidal in both axes; the along-track motion is at twice the frequency of the across-track motion and with the along-track amplitude chosen to maximize uniformity of overlap between successive scan lines. The across track frequency is chosen to ensure a desired spacing between the scan lines and depends on the forward speed and the lidar detector array FoV.

The Circular scan is employed by the Harris/Veridaas System and Woolpert Bulldog lidar systems.⁸ This mode continually moves the sensor line-of-sight around in a circle and never images nadir. Instead, it repeats forward, left, backward and right looks. The across-track and along-track sinusoids are at identical frequency.

The Spinning Polygon scan is used by Reigl⁹ and many other traditional or linear-mode lidar systems. This scanning method results in a raster scan.

The Constant Speed scan is used by the Zion System¹⁰ and is the pattern used for the scanning method described in this paper. This method uses the two-axis mirror system to create a serpentine scan pattern over a target of interest.

The sampling density for each scan mode was calculated by projecting an array of detectors onto the ground and counting the number of samples within each element of a 2D grid pattern. The sample count is shown in Figure 4 and histogrammed in Figure 5. The histogram calculation was limited to the highlighted region of Figure 3 to avoid end affects. Figure 4 shows the sampling density map for each scan mode. The density map resolution is matched to the size of one detector pixel at the target location to reduce aliasing affects. These maps use a logarithmic color scale to better show the magnitude of sampling non-uniformity. The Lemniscate and Circular scans show higher sampling densities on the edges of the scanning area. Both utilize sinusoidal cross-track motion and the similar behavior is therefore expected. The Spinning Polygon shows near perfect uniformity since it doesn't have a mechanical turn around. The Constant Speed scan shows uniformity similar to the Spinning Polygon due to the very rapid turn-arounds enabled by high mirror accelerations.

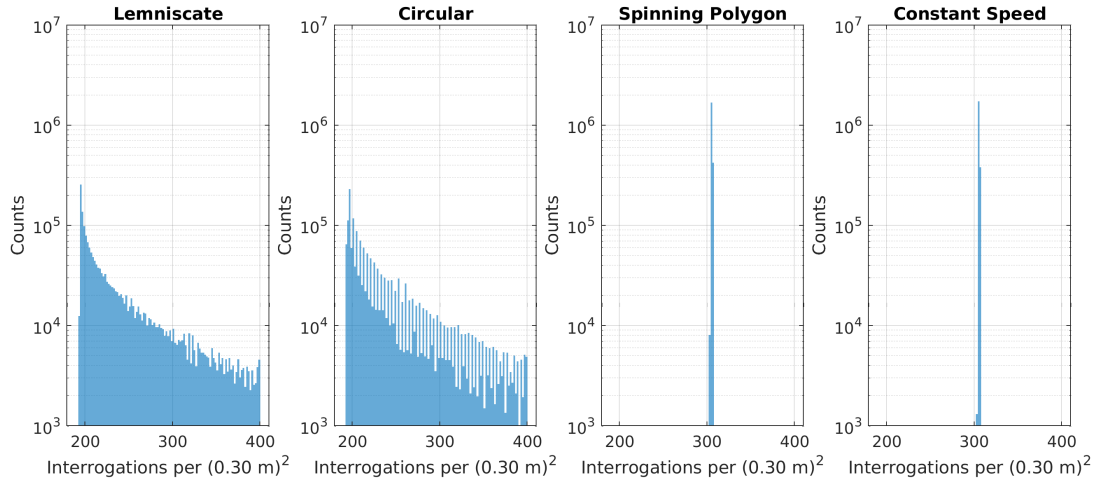


Figure 5. Theoretical sampling density histograms of four different scanning methods for aerial lidar systems. The ideal histogram would be a large spike in a single bin. The Spinning Polygon and the Constant Speed scan modes show more uniform sampling density due to less time spent turning around and employing constant cross-track angular rates.

The distribution of the sampling density for each of the four scan methods is shown in Figure 5. The ideal histogram showing perfect sampling uniformity would be a single peak at the desired sampling density, and zero for all other sampling densities. The histograms for the Lemniscate and Circular scans show nearly identical performance with a relatively low number of interrogations for most of the area. These correspond to the center of the scan which is often the location of most interest to users and customers. These scan modes also have long tails of significantly higher sampling in the turn-around regions. The Spinning Polygon and the Constant Speed modes both show performance that approaches the ideal sampling uniformity with nearly all bins getting sampled the same number of times. The two-axis scanner has high enough acceleration that the time spent turning the mirror around is negligible.

The cumulative distribution functions of the sampling density of the four scan modes are shown in Figure 6 on a single plot to aide comparison. This figure shows more clearly that the time spent turning around reduces the amount of time available to interrogate the center of the scanning area. This results in a lower overall sampling density in the majority of the target area. A system with regions of lower sampling density must reduce the ground speed in order to achieve the required sampling density everywhere, and therefore such a system has a lower area collection rate in operation.

5.2 Aerial Lidar Sampling Uniformity

We have implemented the scanning methodology described above in 3DEO's Zion Geiger-mode lidar system. It uses a two-axis scanner and the Constant Speed, geo-referenced scan mode. Figure 7 shows the density map of a scan over a target site collected with the Zion lidar system. This scan was collected from 3,000 ft AGL and used 60% scan line overlap. The 5% of bins that were interrogated 20 or less times occurred in the North-east region of the collection and were caused by slightly larger gaps between the scan lines in this area that was further off-nadir than the rest of the collection. This is a deficiency of the scanning implementation that will be remedied in future versions. The intended interrogation rate of 20-35 interrogations per bin was achieved for about 60% of the bins and higher interrogation rates were achieved for the remaining 35% of the bins.

5.3 Angular Diversity

The ability to collect from different viewing geometries provides the aerial lidar system with the ability to reduce the effects of shadowing, fill in voids, capture more data on a given target and better penetrate through partial obscurants such as foliage. The scanning approach presented in this paper enables the operator to configure the system to utilize an amount of angular diversity that is appropriate to the imaging task. Ullrich et. al.¹¹ show diagrams of angular diversity for polygon scanners and for circular scanners. In the format used by Ullrich, the

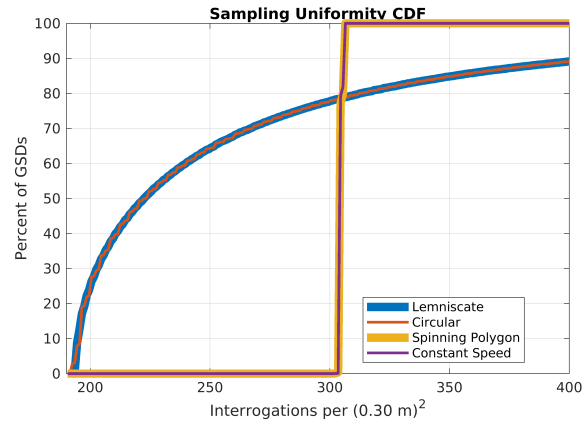


Figure 6. This plot shows the cumulative distribution function of the sampling density histogram for four different scan methods. Scan methods that take more time to turn around at the edges (Lemniscate and Circular) have less time to interrogate the center of the scan and have less uniform sampling density. These show significantly lower sampling density on 70-80% of the collection zone and those interrogations instead occur in the turn-around area.

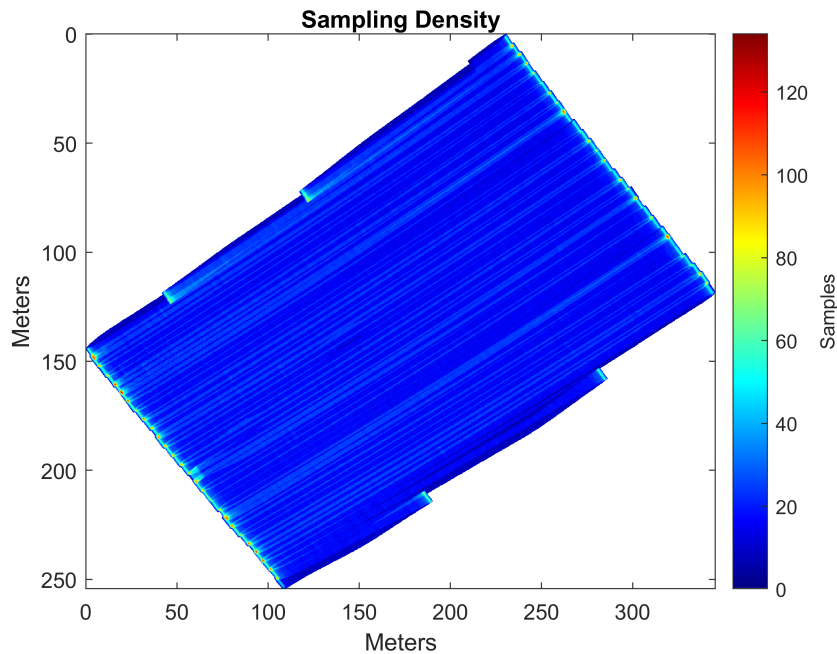


Figure 7. Sampling density map for a collection with ID 070009 from the Zion lidar system. This shows some higher sampling density in the turn-around areas, but overall very uniform sampling. The area in the center of the target has two tones because the scan mode used 60% overlap which caused some areas to get imaged more than others.

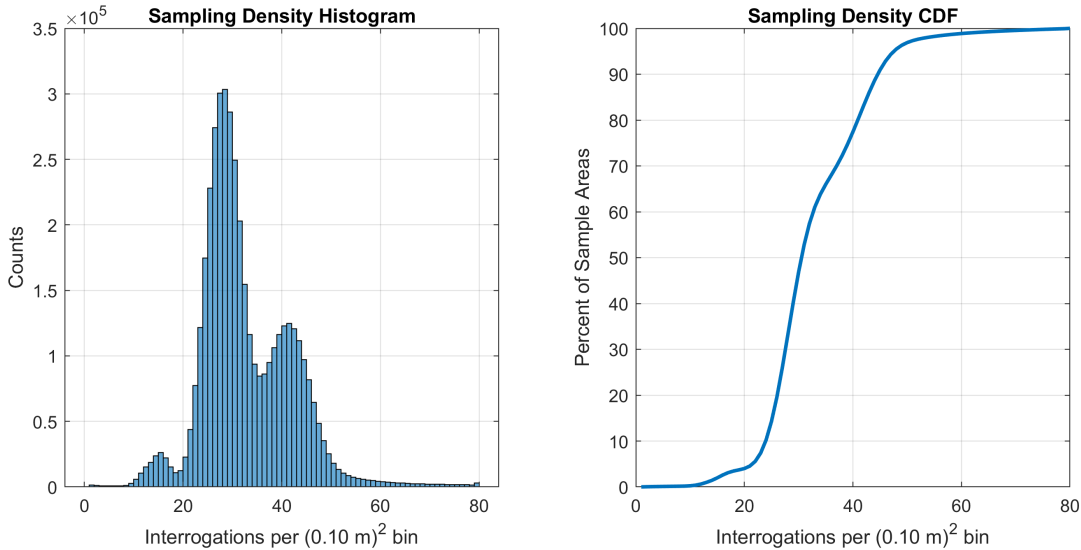


Figure 8. Sampling density histogram for a collection with ID 070009 from the Zion lidar system. The multi-peak nature of the histogram is due to using a 60% scan line overlap causing some areas to be interrogated more than others.

solid color represents the viewable area on the ground, the dark lines represent an example scan pattern that covers the entire FoR, the circles represent viewing geometries and are placed in a few representative points in the field of regard. The red lines in the circles represent angles from which the area can be viewed. The length of the line or the distance from center represents the elevation angle and heading represents the azimuth angle. Figure 9 shows a comparable angular diversity diagram for the Geo-referenced Scan Mode in the same format used by Ullrich. The two-axis scanner’s dynamic ability to perform nearly random access of the field of regard and the use of the target polygon queue allows this scan method to revisit target areas from many different geometries. Pre-flight planning tools can be used to ensure scan parameters are chosen to enable three or more scans of each ground location per scan. As Ullrich points out, a Circular scan mode never images nadir even with 50% overlap, however the Geo-referenced Scan Mode can and does point near nadir during the collection. The nadir view is often important for urban scenes with deep canyons or similar complex geometries.

Additionally, Geiger-mode systems have the ability to aggregate raw range measurements from different swaths to refine range estimates in the final data product. Therefore it is common practice for Geiger-mode systems to fly 2x faster with 50% swath overlap. Figure 10 shows how the angular diversity improves for two different types of swath overlap. This provides another three or more views per target area from different viewing geometries. On the left, two flight lines are offset from each other and are flown at opposite headings. The scanning system scans the same collection area on the ground. Objects in the center of the swath get very well sampled with uniform angular diversity. Objects on the edges of the swath are viewed from many different angles, but not all sides of each object are viewed. On the right, two flight lines are offset by 50%. This collection pattern results in the edges of the swath being viewed from all sides while the center of the swath is viewed primarily from one side. For foliage penetration, having different angles is sufficient, however for urban or suburban scenes, viewing from all four sides better captures the scene. In this case, swaths can be made narrower than the entire field of regard using the center of the FoR that enables views from all sides. Other flight lines and headings are possible, enabling the the angular diversity to be tailed to the task.

6. CONCLUSION

We have developed a scanning methodology for active aerial imaging systems, such as lidar, that enables efficient data collection. The method accomplishes key objectives of a) geo-referenced scanning of desired target areas; b) sampling uniformity; c) configurable angular diversity; and d) configurable, spatially-dependent sampling density. The methodology has been implemented in an operational Geiger-mode lidar system using a two-axis

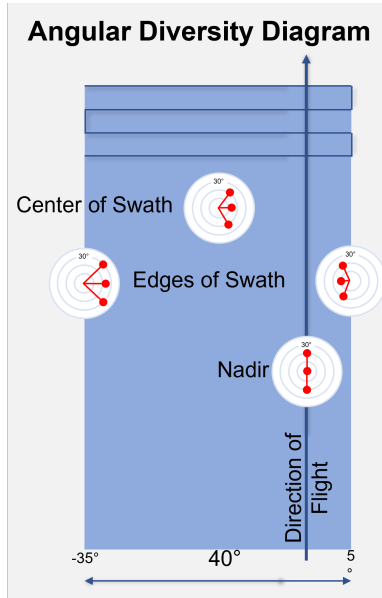


Figure 9. An illustration of the angular diversity diagram for the scanning method described in this paper presented in the same format used by Ullrich.¹¹ In this representation, the solid color represents the swath width on the ground, the dark lines suggest a typical the scan pattern, the circles are placed in a few representative locations within the viewing geometry. The red lines represent angles from which the target can or will be viewed. The length of the line or the distance from center represents the elevation angle and the heading of the line represents the azimuth angle. These diagrams show the viewing geometries achievable in one pass. Note that the Zion lidar system field-of-regard is centered about 15 degrees to the left and extends ± 20 degrees along-track.

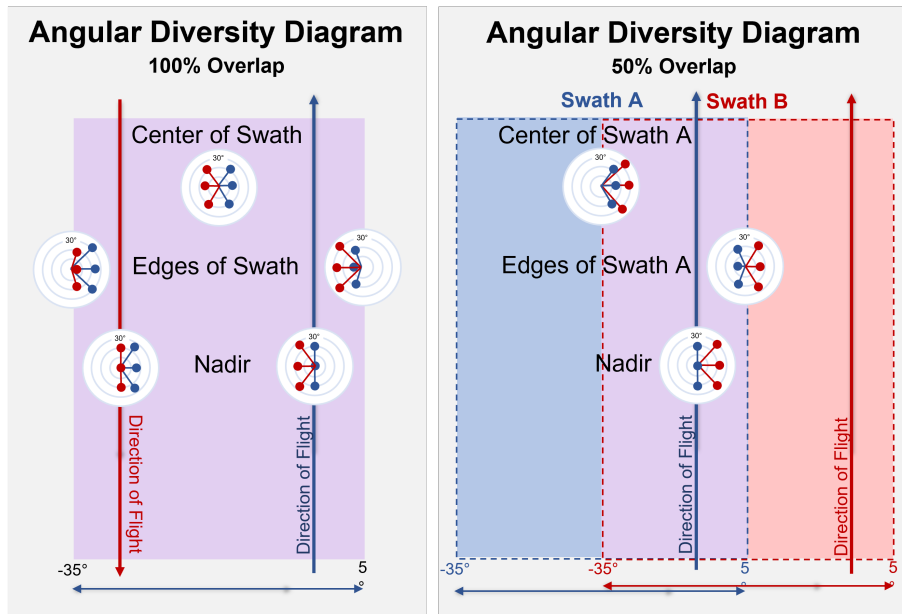


Figure 10. Angular diversity achieved in two different swath overlap scenarios. The solid blue represents one swath, red a second swath and violet represents the overlap region of the swaths. On the left, two flight lines are offset from each other and are flown at opposite headings. The scanning system scans the same collection area on the ground. Objects in the center of the swath get very well sampled with uniform angular diversity. Objects on the edges of the swath are viewed from many different angles, but not all sides of each object are viewed. On the right, two flight lines with identical heading are offset by 50%. This collection pattern results in the edges of the swath being viewed from all sides while the center of the swath is viewed primarily from one side.

scanner. The system is able to efficiently concentrate the lidar system capability on just those areas on the ground that the operator desires to map, such as meandering corridors of varying width or polygons outlining specific regions of interest. The flexibility of the system enables Geiger-mode lidar efficiency to be achieved in operation.

REFERENCES

- [1] Raj, T., Hashim, F. H., Huddin, A. B., Ibrahim, M. F., and Hussain, A., “A survey on lidar scanning mechanisms,” *Electronics* **9**(5) (2020).
- [2] Albota, M. A., Gurjar, R., Mangogna, A., Dumanis, D., and Edwards, B., “Contributed review: Advanced three-dimensional laser radar imaging with the airborne optical systems testbed,” *Review of Scientific Instruments* **89**(10), 101502 (2018).
- [3] Hegna, T., Pettersson, H., Grujić, K., and Teknova, “Inexpensive 3-d laser scanner system based on a galvanometer scan head,” (2010).
- [4] Shi, S., Wang, L., Johnston, M., Rahman, A. U., Singh, G., Wang, Y., and Chiang, P. Y., “Pathway to a compact, fast, and low-cost lidar,” in [*2018 4th International Conference on Control, Automation and Robotics (ICCAR)*], 232–236 (April 2018).
- [5] Nguyen, X. T., Dinh, V. L., Lee, H.-J., and Kim, H., “A high-definition lidar system based on two-mirror deflection scanners,” *IEEE Sensors Journal* **18**, 559–568 (Jan 2018).
- [6] Choi, G., Han, M., Seo, H., and Mheen, B., “A method for reducing scanning error rate of LIDAR using a galvanometer,” in [*Image and Signal Processing for Remote Sensing XXV*], Bruzzone, L. and Bovolo, F., eds., **11155**, 651 – 659, International Society for Optics and Photonics, SPIE (2019).
- [7] Yang, Z., Lu, Y., Yeung, H., and Krishnamurty, S., “From scan strategy to melt pool prediction: A neighboring-effect modeling method,” *Journal of Computing and Information Science in Engineering* **20**, 1–31 (02 2020).
- [8] Hopper, N., “Next generation topo-bathy sensor,” *Geo Week* (2022).
- [9] Ullrich, A., Pfennigbauer, M., and Rieger, P., “How to read your lidar spec—a comparison of single-laser-output and multi-laser-output lidar instruments,” *Riegl laser measurement systems GmbH* (2013).
- [10] Fried, D., Call, B., Kelley, D., Reichel-Vischi, K., Reichert, C., and Eldredge, A., “Low swap, commercially-available geiger-mode lidar system,” International Society for Optics and Photonics, SPIE (2022).
- [11] Ullrich, A. and Pfennigbauer, M., “Linear LIDAR versus Geiger-mode LIDAR: impact on data properties and data quality,” in [*Laser Radar Technology and Applications XXI*], Turner, M. D. and Kamerman, G. W., eds., **9832**, 29 – 45, International Society for Optics and Photonics, SPIE (2016).