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# Discrete Return Lidar in Natural Resources: Recommendations for Project Planning, Data Processing, and Deliverables

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**Abstract:** Recent years have seen the progression of light detection and ranging (lidar) from the realm of research to operational use in natural resource management. Numerous government agencies, private industries, and public/private stakeholder consortiums are planning or have recently acquired large-scale acquisitions, and a national U.S. lidar acquisition is likely before 2020. Before it is feasible for land managers to integrate lidar into decision making, resource assessment, or monitoring across the gambit of natural resource applications, consistent standards in project planning, data processing, and user-driven products are required. This paper introduces principal lidar acquisition parameters, and makes recommendations for project planning, processing, and product standards to better serve natural resource managers across multiple disciplines.

**Keywords:** lidar; remote sensing; standards, processing; natural resources; forestry

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## 1. Introduction

Discrete return Light Detection And Ranging (lidar) is quickly gaining prominence in natural resource research and management due to an inherent ability to represent complex vertical structures and ground surfaces with very high precision [1-3]. Lidar is now moving out of the research arena into operational use in natural resource management applications, leading to the need for standards in acquisition parameters to leverage data across disciplines [4]. Federal agencies, private organizations, and several U.S. states are actively planning and acquiring large-scale acquisitions. Planning is underway for a national lidar acquisition (http://lidar.cr.usgs.gov/) that would improve the National Elevation Dataset (NED) and provide other lidar-derived products for multiple users. Such a large and expensive endeavor underscores the need for accepted and consistent lidar data acquisition, processing, and product standards.

Lidar, in contrast to passive optical remote sensing data which rely on inference using some radiance measurement or reflectance index, provides direct measurements of elevation, from which vegetation height and cover density can easily be derived. This has been highlighted in recent years by the combination of high point density scanning laser altimetry data with high precision global positioning system (GPS) data, to provide very detailed three-dimensional information [5,6]. Lidar derived biophysical properties more directly inform us about the structure of the vegetation being observed (e.g., height/diameter relationships, biomass, and carbon allocation). The accuracy and resolution of forest structure and ground features that lidar provides makes it a very attractive tool in many natural resource applications including: ground surface mapping, geology [7], habitat assessment [8], timber resource planning [3], post disturbance assessment, fire and fuels [9], slope stability [10], hydrology [11], fisheries [12], and coastal change [13].

Lidar operates on the fundamental principle that the time taken for a laser pulse to travel from the sensor to a target and back again to the sensor enables calculation of the distance between the instrument and the scattering object(s). A critical step before the lidar can be used in applications is the conversion of these relative elevations to above ground heights [14,15]. Once this is accomplished a variety of information can then be extracted. For example, statistical distributions of canopy height, density, and intensity have provided a multitude of information regarding forest structure [16,17].

In 2002 the American Society of Photogrammetry and Remote Sensing (ASPRS) introduced the LAS (http://www.lasformat.org) binary data format [18], which has been widely adopted by lidar vendors as an industry standard. However, to enable non-lidar experts to use lidar data of consistent quality and to ensure that data are applicable across multiple disciplines, standards are still needed in acquisition parameters, processing, and subsequent data products. To meet this need, this paper provides a definition of parameters, provides recommendations for project planning, and introduces data processing. A set of proposed deliverable products is then presented, following processing level guidelines, which will make lidar data immediately usable by analysts with no lidar experience. In this paper, the primary focus will be on discrete return lidar operating in near-infrared wavelengths, the predominant form in which lidar data currently may be obtained.

## 2. Project Planning

Project planning is critical in ensuring that the resulting data are applicable to a variety of disciplines. Differences in acquisition parameters can have a significant effect on the lidar data. In the following section, a discussion of the elements needed in project planning and a definition of critical parameters is presented.

### *2.1. Lidar Sensors*

Terrestrial lidar sensors can be categorized into three types: profiling, discrete return, and waveform. Early in the application of lidar for vegetation classification, profiling sensors effectively measured canopy height and predicted timber volume [19]. Profiling sensors are the simplest design of laser altimetry systems, where the sensor is recording only one return at fairly course sample densities along a narrow swath. With the addition of a scanning component, discrete-return lidar technology has improved to the degree that it is now possible to use lidar for large scale applications in remote sensing [20].

Discrete return lidar are small footprint (typically 20–80 cm diameter) systems that record one to several returns through the canopy, in a vertically non-systematic manner. The criterion for collecting multiple returns is based on the intensity of the laser energy returned to the sensor, with three to five return systems being most common. Waveform sensors digitize the total amount of energy returned to the sensor in fixed distance intervals, providing a continuous distribution of laser energy for each laser pulse.

Each lidar sensor technology (e.g., waveform, discrete return) has distinct advantages and disadvantages, making sensor choice both application (i.e., terrestrial, aquatic, bare-earth, vegetation) and scale dependent (resolution). Although small footprint waveform sensors are becoming commercially available they are much less mature for high-resolution natural resource applications and provide an overwhelming quantity of data. Previous waveform sensors have been large footprint instruments (3–8 m) that can exhibit low signal to noise rations compared to discrete return sensors. The larger footprint size of these waveform sensors increases the probability of the top of the tree being sampled, thus reducing height bias [2]. Discrete return systems, while commonly underestimating height, provide extremely high point densities and currently provide broader and more resolute representation of ground and canopy surfaces in the horizontal plane, making them advantageous for mapping. The ratio of ground to non-ground point volumes directly indicates light penetration through the canopy and has been shown to correlate strongly with forest structure [21,22].

Terrestrial lidar sensors for vegetation assessment operate in near-infrared wavelengths, typically 0.9–1.5 μm, with the most common being 1.064 μm. The main reasons for this are: 1) vegetation, soil, rock, etc. reflects strongly in these wavelengths, ensuring a relatively strong signal; 2) atmospheric transmittance is high at these wavelengths, ensuring minimal loss of signal from atmospheric scattering and absorption. Development of sensors such as the Experiential Advanced Airborne Research lidar (EAARL) small-footprint waveform sensor [23] operating in the blue-green wavelength range (532 nm) allows for lidar collection in a range of environments. In contrast to near-infrared wavelengths, blue-green enables sub-surface information, such as stream morphology, to be collected in aquatic environments [12]. This sensor is still experimental and remains untested for the assessment of terrestrial vegetation or ground surface mapping. Considerations such as scattering, bias, signal-to-noise ratios, and atmospheric transmittance need further research before such blue-green sensors are widely applied to characterize non-aquatic ecosystems. Large strides have been made in the development of small footprint waveform sensors as well as other technologies (i.e., single-photon lidar, flash lidar). A comparison of discrete return and these developing technologies is out of the scope of this paper. Although, it should be noted that these are potentially important technologies and should be investigated as they become more widely available.

### *2.2. Acquisition Parameters*

1) Pulse repetition frequency (PRF)

Pulse repetition frequency (PRF) is the number of pulses per second (i.e., 50,000 KHz = 50,000 pulses per second) generated from the lidar system. The PRF is a primary factor in determining the pulse density that can be achieved on a single flight swath. Commercially available systems are currently capable of PRFs exceeding 150 KHz (e.g., Leica ALS50; Optech Gemini), which allow for increase pulse densities. However, the use of a high PRF requires a lower flight altitude above ground level which can be a limiting factor in extreme mountainous terrain. An experienced lidar provider can be very helpful in choosing a PRF that is suitable for the goals of the project.

2) Number of returns

Discrete return lidar can record multiple measurements within a single laser pulse. If the reflected signal strength exceeds a given threshold, then the sensor will record another measurement, up to the maximum number allowed by the sensor (laser pulses reflected where there is no canopy will result in a single ground return per laser pulse). Lidar sensors use variable gain to compensate for landscape-level variations in ground brightness and surface object reflectivity, resulting in non-calibrated intensity values. Most commonly, depending on the sensor, 3–5 returns are possible per laser pulse. It is recommended that a sensor capable of at least three returns be specified. Some sensors and post-processing software assign additional return values that are data flags and not new measurements. These additional returns reference whether a return is single or one of several: first, intermediate (2nd, 3rd, etc.) or last. For example, data collected by TerraPoint® for the Puget Sound Lidar Consortium collected up to four returns per pulse. Return levels were 1–4 for returns when there were not last returns and 5–7 when there were last returns.

3) Pulse density

Pulse density is the horizontal spacing between laser footprints (Table 1). This should not be confused with the actual density of lidar returns, which includes the vertical domain and is influenced by above ground objects. Since there can be multiple measurements recorded in a single pulse and there is overlap in the flight-lines, the point density is calculated as; $[n * f] \times 2$ (where; $n$—Maximum number of potential returns per pulse and $f$—Number of laser pulses per areal unit. A value of 2 is assumed with 50% flight-line overlap, representing two separate sets of measurements for the same area associated with flight-line overlap).

The range of pulse densities is quite large (0.3 to 12 pulses/m$^2$) and the optimum is indicated by application. Sparser spacing allows for higher flying altitudes thus reducing the acquisition cost. However, higher data densities allow a broader range of applications by providing better resolution of terrestrial features and potentially a better ground model. For vegetation applications 4–6 pulses/m$^2$ is a good balance between cost and support of the application.

4) Scan angle

Scan angle is the off-nadir angle at which the sensor acquires during scanning. High scan angles can reduce cost due to more ground being covered in a single flight line, resulting in less time acquiring data. Holmgren and Nilsson [24] simulated effects of scan angle on canopy characteristics and found that measurement error is introduced with scan angles >10° off-nadir. Unfortunately, using a 10° threshold significantly increases the acquisition cost by increasing the number of flightlines required for complete coverage of an area while maintaining 50% overlap between adjacent flight lines. A maximum 15° scan angle was recommended to reduce measurement error, particularly in areas with very high relief [24]. A general recommendation is a < 12° off-nadir scan angle, which equates to a < 24° total look angle (Table 1).

**Table 1.** Common lidar sensor parameters for natural resource applications.

| **Parameter** | **Value** |
|---|---|
| Wavelength | 1.064 µm |
| Pulse Repetition Rate (PRF) | ~50–150 kHz |
| Returns per pulse | 3–4 |
| Pulse width | 10 nano-seconds |
| Beam divergence | 10–80 m rad |
| Scan angle | <15° off-nadir, 30° total look |
| Scan pattern(s) | Ziz-zag, parallel, elliptical, sinusoidal |
| GPS frequency | 1–2 Hz |
| INS frequency | 50 Hz (200 Hz max) |
| Operating altitude | 100–3,000 m (6,000 m max), average ~2,000 m |
| Footprint size | 0.10–0.30 cm |
| Pulse Density | > 4 pulse/m$^2$ |
| Accuracy (Vertical/Elevation) | <0.15 m |
| Delivery format | Binary lidar exchange format (LAS) |

5) Flight line overlap

Overlap of flight lines is an important factor to ensure proper representation of objects. Data should be acquired with at least 50% overlap of parallel flight lines. By acquiring lidar data with 50% overlap, objects are scanned with multiple look angles, providing more complete 3-dimensional representation of any given object. Also, parallel flight lines allow more rigorous and efficient swath-to-swath adjustments to remove swath biases.

6) Data collection schedule

Data should not be collected while there is snow cover (unless snow monitoring is the application) nor during inclement weather conditions (high winds, rain, fog, low cloud cover, or smoke) that would significantly diminish the quality of the data. Another consideration is planning the acquisition during leaf-on or leaf-off periods. Lidar collected during leaf-off periods can have more ground returns in densely vegetated areas (e.g., riparian), however the trade off is often a reduced temporal acquisition window given the competing consideration of no snow cover. With the high point densities that current lidar sensors collect, it is highly probable that a good ground surface can be derived during leaf-on periods depending on the prominent land cover types in the study area.

7) Geodetic control

Geodetic GPS Base Station locations should be control points in the High Accuracy Reference Network (HARN) or the Continuous Operation Reference System (CORS) with orthometric or ellipsoidal elevations determined by differential leveling or a GPS collecting multiple occupations with control base lines of <18 mm. The vendor should report which base points were used on particular flights and areas and should also provide kinematic GPS ground survey locations with accuracy of <2 cm root mean squared error (RMSE) across the project area.

8) Equipment and processing software

The vendor should list all equipment, hardware, and software that will be used during the course of the project including: aircraft, laser equipment, IMU, GPS equipment, and processing software. Also, the vendor should indicate availability of equipment as well as capability of software to accommodate the project requirements in terms of deliverables.

9) Accuracy

Methodologies for determining and reporting vertical and horizontal accuracy should adopt standards as outlined in FGDC-STD-007 (Federal Geographic Data Committee, 1998) and NGS-58 (NOAA, 1997). For bare earth surface on low to moderate slopes, the data should conform to a minimum accuracy standard of <15 cm vertical and <55 cm horizontal RMSE (Root Mean Square Error).

a) Horizontal control should be established and as necessary adjusted to the HARN utilizing dual frequency receivers with surveys done to at least third-order, Class 1 specifications as promulgated by the Federal Geodetic Control Subcommittee (FGCS). Vertical control should be established using differential levels according to third-order Class 1 FGCS specifications. Vertical control should be tied to NGS benchmarks in a specified vertical datum (e.g., NAVD88).

b) Accuracy can be assessed by comparison of laser points to independent, real time kinetic (RTK) ground level survey data and/or level A National Geodetic Survey (NGS) controls. Control measurements across multiple flight lines can be used to compare laser points collected along a variety of surfaces (e.g., roads, vegetation types, and varying slopes). Accuracy assessment will provide the root mean square errors, skewness of the distribution, and error percentiles.

c) Precision is a measure of the ability to place consistent points on the same target, below a desired range of deviation. Precision can be assessed by comparison of independent lidar returns reflected from the same object. Laser points that paint a given target, whether sampled in the same flight line or overlapping lines, must provide consistent measurements.

10) Data voids

Data voids are commonly considered areas greater than four times the post-spacing of data. Data voids caused by system malfunctions, data dropout, or flight line data gaps are considered unacceptable and should require new flights. Water absorbs near-infrared light, reducing pulse intensity and resulting in data dropouts; thus, water bodies are an unavoidable and acceptable source of data voids.

11) Vendor references

The vendor should provide a list of projects similar in scope and complexity as the proposed project. Included should be a brief description of relevant projects, services provided, type of terrain including vegetation, project cost, accuracy, and any other pertinent information. Optionally, the customer can request a sample of lidar data the vendor has produced in similar physical settings with similar acquisition parameters.

12) Aerial photography

For many, digital aerial imagery or photography is a tempting product to acquire coincidentally with lidar. However, the optimal parameters for lidar acquisitions differ substantially from those for aerial photography. Photography is better acquired at much higher altitudes where the atmosphere is much more stable. Moreover, topographic and canopy shadowing constrain the optimal acquisition window to +/− 2 hrs from solar noon, while lidar is not limited by this constraint (indeed, lidar may be flown at night). Thus, standardizing flight parameters for simultaneous lidar and photography acquisitions overly constrains the lidar acquisition window and can compromise the quality of both data collections. From either a technical or a business standpoint, it makes little sense to mount lidar and camera systems on board the same aircraft, so few vendors do it.

## 3. Data Processing

With a few exceptions (e.g., Puget Sound Lidar Consortium, NOAA), there is a notable lack of standards regarding processing, deliverables, and data quality. We review a few issues relating to data processing and quality and propose four levels of processing that are intended as a starting point for standardization of data deliverables. We hope this will provide the reader with an understanding and an expectation of what lidar can provide.

### *3.1. Data Evaluation*

Much of the quality assessment, with regard to relative accuracy, will be provided by the vendor. Geometric accuracy, in reference to local controls, should be reported as well as consistency of measurements between adjacent flight lines. It should become common practice to have an independent validation data for quality assurance.

### *3.2. Ground Surface Model Generation*

The first step in generating a ground surface (Digital Elevation Model) and deriving heights from the elevation measurements is to separate ground from non-ground returns. This is accomplished through the application of a classification or filtering model to the point cloud. Several methods have been proposed [14,25-27] covering a gambit of statistical and mathematical solutions. Many approaches require extensive manual post processing to arrive at a surface with minimal errors of omission (classifying ground returns as non-ground) or commission (classifying non-ground returns as ground). Several methodologies use fixed kernel sizes and assume ground returns are local minimums within the point cloud, or that the ground cannot exhibit slopes steeper than a set angle [27]. Although such methods have been useful in urban settings and gentle terrains, they have had limited success in dense forest with step terrains due to complex slope and vegetation interactions [14]. Such fixed kernel-based methods exhibit considerable errors when encountering features without a characteristic size. To overcome these issues, Evans and Hudak [14] proposed an iterative multiscale spline model to identify positive curvatures that represent non-ground returns in densely forested areas occurring in complex terrains.

Although curvature based approaches appear robust in forested environments they do not perform well in urban environments, specifically in identifying returns associated with buildings. Zhang *et al.* [25] introduced a method using a mathematical morphology filter and a progressive window size that filters points associated with buildings with minimal error. The ideal solution for ground classification would be a hybrid approach, exploiting the strengths of multiple methods that address the complex geometries inherent in real landscapes characterized by lidar point clouds [14].

If the contract specifies that the vendor derive a bare earth model, then it should also specify standards on accuracy, review, and editing. The vendor should also provide information on the model including: model/software used and any specific details relating to modifications in the normal work flow (i.e., application of methods to account for specific terrains or vegetation).

## 4. Deliverables

Following the logic commonly used in delivering image products in spectral remote sensing (e.g., Landsat), we propose deliverables be divided into 5 levels of processing.

**Level 0**—Level 0 products are the raw sensor data as recorded on the aircraft. Obtaining data in this form would not be of interest to the vast majority of users in the natural resource fields. However, recognizing that those in engineering and other more technical fields may be interested in developing, testing, or applying their own IMU or GPS corrections, the raw data should be archived and made available for such uses. Data should be archived as ellipsoidal heights to accommodate future improvements to the geoid and facilitate subsequent reprocessing. Since this paper is focused on natural resource applications, no further mention of Level 0 products will be made, other than to recognize that this proposed naming convention for different levels of lidar product deliverables is meant to accommodate all potential users of lidar data.

**Level 1**—Level 1 processing consists of corrections performed by the vendor to address conversion of data from raw format, geo-correction of raw returns using GPS base station and IMU data, projection and datum transformations, tiling, sensor corrections, and data-format.

Geometric correction—Vendor will extract data from sensor and perform geometric correction and transformation into a specified geographic projection system and vertical datum with orthometric elevations.

Sensor Corrections—Vendor will perform all post processing to correct for pitch, yaw, and roll of the aircraft. Outlier points should be identified and removed. Common sources of outliers are birds and multi-path returns that record an elevation below the ground surface.

Tiling—Tiling is a convenient way of standardizing and controlling the quantity of data in a given file by dividing data into manageable blocks. It is imperative that the vendor provide the source flight line identifier (PointSourceID in LAS file), so that overlap error can be assessed and the original flightlines reconstructed if necessary. Tiling can be specified as original flight lines, by area of each tile (e.g., 1 km blocks), or maximum number of points per tile. Specialized tiling schemes can also be requested with provided data (e.g., watershed boundaries).

Data format—Lidar data should be delivered in LAS format following the American Society for Photogrammetry and Remote Sensing (ASPRS) format standards (http://www.lasformat.org). At a minimum, this includes X-coordinate, Y-coordinate, elevation, return number, intensity, and scan angle for each return. The data should be delivered with a metadata file describing field notation of the acquisition.

**Level 2**—Products derived from basic post-processing utilize procedures common to all discrete return lidar. This processing can be requested from the vendor for an extra cost or performed by a qualified lidar analyst.

Classified Ground Returns—Point coverage of classified ground returns derived using a classification or filtering model. These can be flagged in a unique classification field (a value of 2 in LAS point classification), can be set to 0 in a height attribute, or can be a separate point dataset, although this is not recommended unless the original integrity (i.e., spatial location) of the data is maintained. It is very important that the original spatial location and density of returns be retained to enable full analytical capacity.

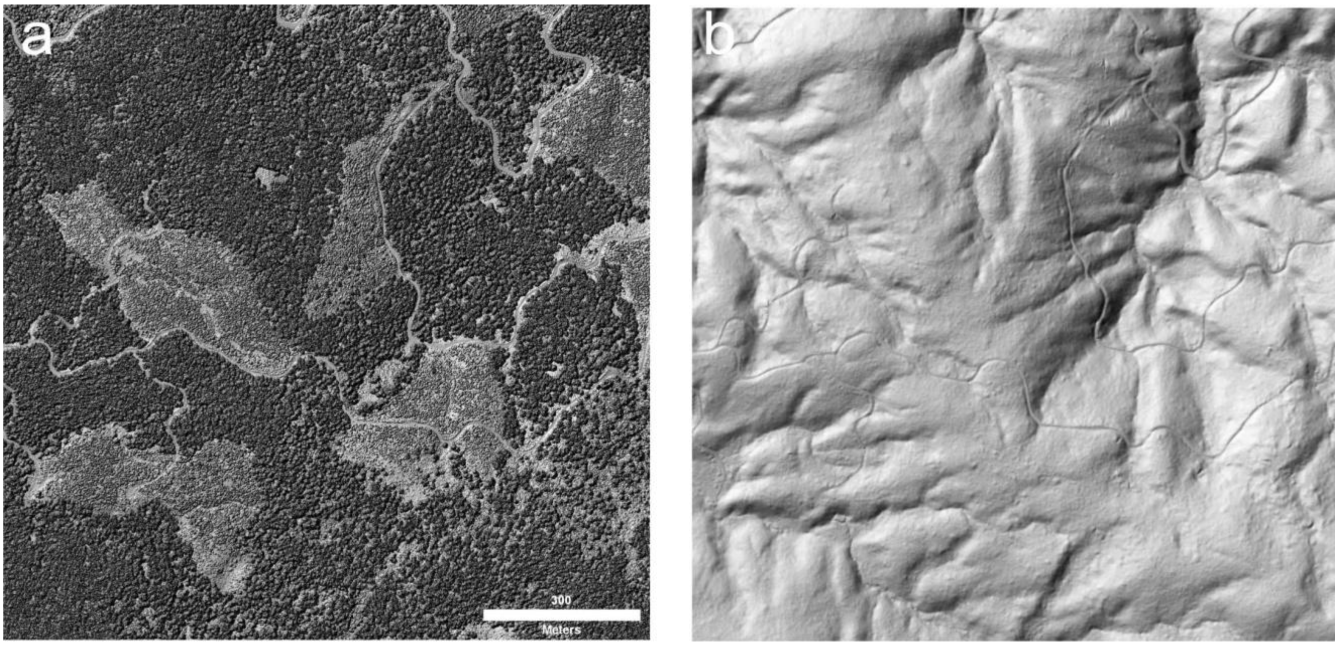
Digital Elevation Model (DEM)—Raster or triangulated irregular network (TIN) elevation layer interpolated from the classified lidar ground returns, representing the bare ground surface (Figure 1a).

Digital Surface Model (DSM)—Interpolated raster or a triangulated irregular network (TIN) of elevations using all or first lidar returns, representing the surface of all objects in the landscape (Figure 1b).

Intensity—Interpolated raster or a triangulated irregular network (TIN) of intensity values of first returns. The intensity image is analogous to a digital orthophoto. However, intensity values are acquired using a variable gain making the values non-calibrated.

Point heights—Point data of above ground surface heights for all returns in the point cloud. This is an added attribute field in the lidar point cloud, which first requires the points to be classified as ground/non-ground, and the interpolated ground DEM surface subtracted from the point elevations, to derive point heights. We propose that a point height attribute be added as a standard field to future versions of the LAS format.

**Figure 1.** Shaded relief of: **(a)** all return Digital Surface Model (DSM), and **(b)** ground return Digital Elevation Model (DEM).



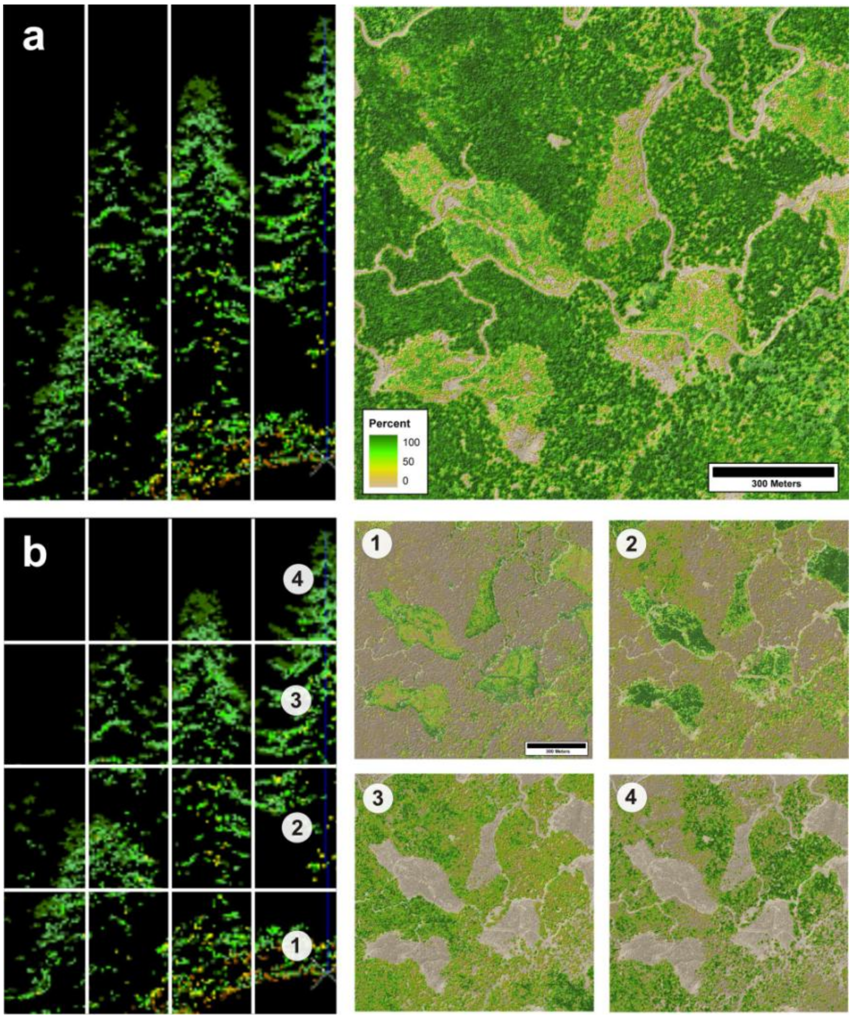

**Level 3**—These products are tailored for specific applications and are based on transformations, ratios, and simple calculations. Vendors do not usually offer this level of processing but they can be performed by a qualified lidar or GIS analyst. These variables are not derived using predictive models. Here are a few examples:

Canopy height—Raster of maximum vegetation height within a defined bin (Figure 1).

Canopy density—Raster of density of aboveground vegetation returns within a defined bin. Analogous to canopy cover (Figure 2a). A ground threshold (*t*) can be applied where the height denoting vegetation returns is >*t*. This allows for vegetation density that is close to the ground to be excluded, providing a better representation of trees. Calculated as; $[(n_v > t)/n\ ] \times 100$ (where; $n_v$ = Number of vegetation returns, $n$ = total number of returns, and $t$ = is the ground threshold).

Stratified canopy density – Rasters of vegetation density within a defined bin, stratified by height ranges (Figure 2b). Calculated as; $[n_i/n] \times 100$ (where; $n_i$ = Number of returns in height range $i$ and $n$ = total number of returns).

**Figure 2**. Cross-sectional canopy density. **(a)** Vertical white lines represent vertical bins and **(a)** corresponding vegetation density grid. **(b)** Stratified vertical bins with 4 corresponding strata; vertical white lines represent vertical bins and horizontal lines represent cross-sectional height ranges (1. 1 m–5 m, 2. 5 m–20 m, 3. 20 m–30 m, 4. >30 m).




**Level 4**—These are variables derived from lidar height, density, and intensity data distributions and are designed for specific modeling applications such as: tree density, biomass, basal area, volume, crown competition factor, and slope stability. Predicting these variables requires field or some form of ancillary data. Vendors do not commonly offer this level of processing and modeling should be performed by an experienced analyst that specializes in the desired application. Table 2 includes some commonly used and newly proposed metrics used in vegetation modeling [16,21,22] based on the distribution of point values within a bin. Because these metrics are calculated within bins they can easily be mapped and rescaled based on the binning approach. Metrics fall into two groups; 1) Metrics calculated on numeric values (i.e., intensity, elevation, canopy height). 2) Metrics representing density of points (i.e., canopy density, stratified canopy density). Given the resolution of lidar data common geomorphometric variables such as watershed or flood-plain delineation can be challenging often requiring an experienced lidar analyst. For a review of additional variables used in natural resources please see Hudak *et al*. in this issue.

**Table 2.** Proposed metrics used in vegetation modeling. Metrics are calculated directly on binned point cloud and can be calculated on elevation, heights, intensity, and point densities. Where; *x* = numeric variable, *n* = number of observations, μ = mean, σ = standard deviation, *λ* = frequency.

| Metric | Description |
|---|---|
| Minimum | Minimum value (*x*) |
| Maximum | Maximum value (*x*) |
| Range | [maximum (*x*) − minimum (*x*)] |
| Arithmetic Mean (μ) | $\frac{\sum_{i=1}^{N} x_i}{N}$ |
| Standard Deviation (δ) | $\sqrt{\frac{\sum x_i^2 - \frac{(\sum [X_i)^2]}{N}}{n-1}}$ |
| Variance ($\delta^2$) | $\frac{\sum [(X]_i - X)^2}{n-1}$ |
| Percentiles | $5^{th}$, $10^{th}$, $25^{th}$, median ($50^{th}$), $75^{th}$, $95^{th}$ percentile values (*x*) |
| Median Absolute Deviation from Median | $median_i\left(X_i - median_j(X_j)\right)$ |
| Dominate Mode | Value of the dominate mode in a kernel density estimate (*x*) |
| Skewness | $\frac{\sqrt{n}\sum_{i=1}^{n}(x_i-\mu)^3}{\left(\sum_{i=1}^{n}(x_i-\mu)^2\right)^{3/2}}$ |
| Kurtosis | $\frac{\frac{1}{n}\sum_{i=1}^{n}(x_i-\mu)^4}{\left(\frac{1}{n}\sum_{i=1}^{n}(x_i-\mu)^2\right)^2}-3$ |
| Interquartile Range | [$75^{th}$ percentile (*x*) - $25^{th}$ percentile (*x*)] |
| Coefficient of Variation | $(\sigma/\mu)100$ |
| Number of Modes | Number of modes from a kernel density estimate (*x*) |
| Difference between Min and Max Mode | [maximum mode – minimum mode] from a kernel density estimate (*x*) |
| Canopy Relief Ratio | $\frac{\mu(height)-\min(height)}{\max(height)-\min(height)}$ |
| Percentage of Returns That are First, Second, Third, etc. | $\frac{[n_i \mid returnnumber \mid]}{N}100$ |
| Texture | $\sigma(n_i \mid > height(0) and <= height(1) \mid)$ |
| Number of Ground Returns | *n*\| Classified Ground Returns \| |
| Number of Non-ground Returns | *n*\| Classified Non-Ground Returns \| |
| Density | $\frac{[n_i \mid nonground \mid]}{N}100$ |
| Stratified Density | $\frac{[n_i \mid > x_1 and < x_2 \mid]}{N}100$ |

## 5. Discussion

The efficiency and utility of lidar in predicting and improving our understanding of vegetation structure, ecosystem dynamics, landscape change, and habitat utilization has been demonstrated [1-3,8]. Besides predicting currently used environmental and vegetation metrics, lidar remote sensing can be used to develop new metrics that may push forward understanding of forest structure and the spatial dynamics of ecosystem processes.

Although the initial cost of lidar seems high, the benefits of high-resolution, landscape-level structural data easily counterbalance cost considerations. Comparison to traditional inventory methods is difficult, partially due to lidar producing a landscape-level representation of structural metrics whereas stand-based inventories capture little landscape variation and may not even follow a sampling design. Lidar also shows great promise as a sampling tool over a subset of an area and as an unbiased source of inventory information. A subsampling approach, although not spatially explicit, could provide very accurate inventory information over large areas for a fraction of the cost of a landscape-wide acquisition. Applications aimed at vegetation modeling (e.g., biomass assessment, carbon inventory, stand development) often require that plot data be acquired within a comparable time frame to the lidar data. This can be accomplished through the implementation of a well-considered sample and plot design with accurate georeferencing of ground plots. The nature of physically-based high-resolution data is that locational and temporal differences between lidar and plot reference data can translate into comparatively large errors [3]. Photo-interpreted stands tend to be highly spatially and structurally variable making them an inappropriately scaled unit for relating to lidar based on stand level inventories. The optimal sampling and plot designs for relating field and lidar data differ from traditional stand exam based inventories, adding additional considerations to plot design that are beyond the scope of this paper. Further insight may be gained from Hudak *et al.* (this issue).

Lidar provides a means of exploring complex landscape-level ecological relationships. With the current need for a more holistic assessment of forest ecosystems balancing commercial timber resources with noncommercial vegetation, invertebrate and vertebrate ecology, water quality, soil fertility, along with the recreational and cultural resources, arguments for standards are strongly supported. Before nation-wide acquisitions are implemented, planners should ensure that the ensuing data can be leveraged across as many disciplines as possible.

## 6. Conclusions

The parameters and deliverables outlined in this paper are proposed as a starting point to achieve a standardization of lidar data that will provide a wide array of useful products to the broad user community. It should be stressed that lidar technology is developing at a rapid rate along with new applications. As technology standards continue to evolve and improve, data acquisition, parameters, processing approaches, and deliverables should remain fluid and be reassessed on a regular basis. Developing technologies such as; small footprint waveform, single photon, and flash sensors may provide alternatives to discrete return lidar. However, discrete return lidar will continue to play an important role in natural resource decision making for the foreseeable future.

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**Appendix A—Glossary of Lidar Related Terms**

**Accuracy**: The statistical comparison between known (surveyed) points and measured laser points. Typically measured as the standard deviation ($\sigma^2$) and root mean square error (RMSE).
**Bin**: A set of aerial units that can be overlaid on the lidar point cloud to summarize or aggregate the data. Commonly a raster surface with a defined cell size is used, although a bin can be any set of landscape units such as stand boundaries.
**Canopy Height Model (CHM)**: The maximum lidar height value identified in a cell after the lidar point data are binned or interpolated.
**Classification**: The process of identifying points as ground or non-ground (also referred to as filtering). The LAS standard defines several classes including: ground, low vegetation, medium vegetation, high vegetation, building, and water.
**Contours**: Lines that represent known elevations with intervals typically recorded in feet. It is standard practice to develop minimum contour intervals with data that have an accuracy of two standard deviations ($\sigma^2$).
**Canopy Cover (Crown Cover)**: The proportion of ground covered by a vertical projection of the outermost perimeter of the natural spread of foliage or plants, including small openings within the canopy.
**Canopy Density (Crown Density)**: Amount and compactness of the foliage of the crowns of trees and shrubs.
**Digital Elevation Model (DEM)**: A raster surface derived from interpolating the elevation values of the classified lidar ground points.
**Digital Surface Model (DSM)**: A raster surface derived from interpolating the elevation values of all lidar points.
**Filtering**: A term commonly used for point classification based on the notion of filtering out (discarding) non-ground points.
**Footprint**: The size (radius) of the laser pulse once it starts interacting with objects.
**Geometric Correction**: The process correcting the GPS readings, tying the data to local controls, and applying a coordinate system to the lidar point cloud. Geometric correction is performed by the vendor and is a critical step in the QA/QC. Error should be reported as vertical and horizontal.
**Height**: A value calculated for every lidar point representing the height of a point above the ground surface once the ground elevations are subtracted. See also, canopy height model (CHM).
**Intensity**: The peak power ratio of the laser return to the emitted laser. This is a function of surface reflectivity.
**Last Return:** The last measurement in a laser pulse.

**LAS (lidar data exchange format)**: American Society for Photogrammetry and Remote Sensing (ASPRS) industry standard binary file format. Current LAS version is 1.1 and is available for download at; http://www.lasformat.org/documents

**Nadir**: A single point or locus of points on the surface of the Earth directly below a sensor as it progresses along its line of flight.

**Overlap**: The area shared between flight lines, typically measured in percents; 50% overlap of adjacent flightlines is essential to ensure complete coverage and reduce laser shadows. Requiring 50% overlap provides multiple look angles for objects.

**Pitch**: Rotation around the lateral or transverse axis—an axis running from left to right and parallel to the wings; thus the nose pitches up and the tail down.

**Point Cloud**: A term referring to a mass of lidar point measurements.

**Point Density**: A measure of lidar resolution, measured as total returns per square meter. Not the same as post spacing or pulse density.

**Post Spacing**: A measure of lidar resolution, measured as the average distance between laser footprints. Not the same as point density or pulse density.

**Pulse Density**: A measure of lidar resolution, measured as total pulses reaching the surface per square meter. Not the same as post spacing or point density.

**Precision:** The repeatability with which a surface feature location is measured with independent LiDAR measures; e.g., in overlapping flightlines. Commonly referred to as ―relative accuracy” by lidar vendors.

**Pulse Repetition Frequency (PRF)**: The rate at which laser pulses are emitted from the sensor; typically measured as pulses per second. A PRF of 30 kHz would be 30,000 laser pulses per second and is directly related to achievable post spacing.

**QA/QC (Quality Assessment / Quality Control)**: The process of assessing lidar data adherence to the accuracy standards established by the contract and the vendor. This should be done initially by the vendor as a matter of course but could be superceded by an independent assessment to insure contract compliance.

**Real-Time Kinematic (RTK) Survey**: GPS surveying is conducted with a GPS base station deployed over a known monument with a radio connection to a GPS rover. Both the base station and rover receive differential GPS data and the baseline correction is solved between the two. This type of ground survey is accurate to 1.5 cm or less.

**Return Levels**: For every laser pulse emitted a discrete return sensor can record multiple measurements within the footprint. Portions of the laser energy that return earliest are the highest element in multi-tiered surfaces and portions of the laser energy that return last are the lowest element. Commonly, three to five returns are possible.

**Roll:** Rotation around the longitudinal axis—an axis drawn through the body of the vehicle from tail to nose in the normal direction of flight.

**Scan Angle**: The angle from nadir to the edge of the scan, measured in degrees. Laser point accuracy typically decreases as scan angles increase beyond 15° with flying elevation <2000 meters.

**Yaw**: Rotation about the vertical axis—an axis drawn from top to bottom, and perpendicular to the other two axes.

## Appendix B—Lidar resources

### FREE SOFTWARE

**ALDPAT (Processing software with ground classification)**
http://mitigation.fiu.edu/
**GeoQue LAS reader for ArcMap (Reads LAS files into ArcMap, requires ArcMap)**
http://www.niirs10.com/Products/LAS%20Reader%20for%20ArcGIS%209.htm
**GeoCue PointVue (LAS lidar viewer)**
http://www.niirs10.com/Products/lidar1.htm
**GEON Portal (On line lidar ground classification)**
https://portal.geongrid.org:8443/gridsphere/gridsphere
**ITT Visual Solutions ENVI lidar Toolkit (Requires ENVI)**
http://www.ittvis.com/groups/index.asp?gid=234
**LAS Tools (Code and software for reading and writing LAS files)**
http://www.cs.unc.edu/~isenburg/lastools/
**LASUtility (A set of GUI utilities for import and export of LAS)**
http://home.iitk.ac.in/~blohani/LASUtility/LASUtility.html
**LibLAS (A BSD C++ library for reading/writing LAS format, supports GDAL)**
http://liblas.org/
**Virtual Geomatics VG4D data viewer.**
http://www.govg4d.com/freeviewer.html
**USFS-RSAC FUSION software (Visualization and processing software)**
http://www.fs.fed.us/eng/rsac/fusion/
**USFS-Rocky Mountain Research Station MCC Code (Ground classification, requires ArcInfo)**
Please contact corresponding author (jeffrey_evans@tnc.org) or Dr. Andy Hudak (ahudak@fs.fed.us)
**USFS-Rocky Mountain Research Station lidar metrics**
Please contact corresponding author (jeffrey_evans@tnc.org) or Dr. Andy Hudak (ahudak@fs.fed.us)
**Full Analyze – Open source discrete and waveform software.**
http://fullanalyze.sourceforge.net/

### COMMERCIAL SOFTWARE

**GeoQue Lidar QuePack (Software for managing processing workflows)**
http://www.niirs10.com/Products/lidar1.htm
**Leica LIDAR Analyst for ArcGIS (Requires ArcMap)**
http://gi.leica-geosystems.com/LGISub1x286x0.aspx
**LP360 (Requires ArcMap)**
http://www.qcoherent.com/
**MARS (Processing and classification)**
http://www.merrick.com/servicelines/gis/mars.aspx
**Virtual Geomatics VG4D (Processing and classification, with optional ArcGIS module)**
http://www.virtualgeomatics.com

**ProLogic Lidar Explorer for ArcGIS (Requires ArcMap)**
http://lidar.prologic-inc.com/lidar/MainPages/LE_Main_Index.html
**Terrasolid/Terrascan (Processing and classification, requires MicroStation)**
http://www.terrasolid.fi/
**Toolbox for Lidar Data Filtering and Forest Studies *(*TIFFS)**
http://globalidar.com/default.aspx
**VLS lidar Analyst**
http://www.featureanalyst.com/lidar_analyst.htm
**QT Modeler**
http://www.appliedimagery.com/

GENERAL RESOURCES

**Idaho State University (Lidar utilities and information)**
http://www.isu.edu/geology/BCAL/index.shtml
**Forestry lidar resource page (Forestry lidar list-serve)**
http://lists.reynolds.net.au/mailman/listinfo/forestry.lidar
**NCALM Berkeley (Lidar information, resources and literature)**
http://calm.geo.berkeley.edu/ncalm/resources.html
**University of Victoria, BCCARMS**
http://carms.geog.uvic.ca/
**University of Idaho (Lidar resources and tutorial)**
http://www.cnrhome.uidaho.edu/remotesensing/lidar
**University of Florida (NCLAM)**
http://www.ncalm.ufl.edu/
**USGS CLICK lidar resource page (Lidar resource and list-serve)**
http://lidar.cr.usgs.gov/
**Center for Ecological Applications of Lidar**
http://ceal.warnercnr.colostate.edu

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