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**Forest Service – Engineering**

**Remote Sensing Applications Center**

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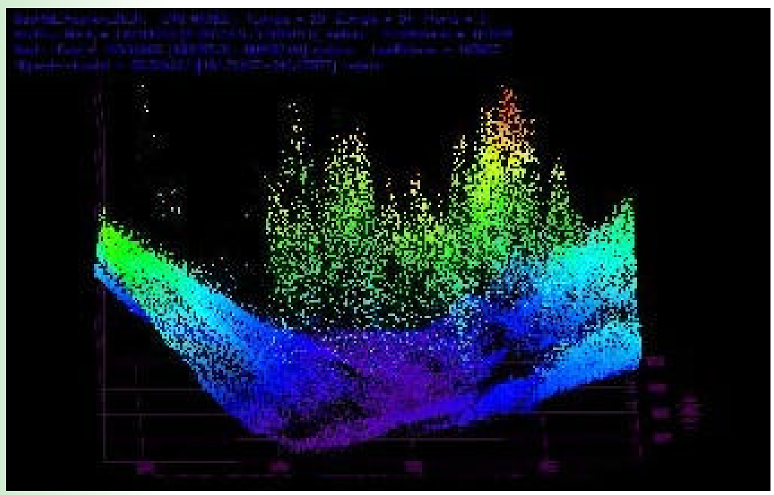
# Evaluation of Multi-Return LIDAR for Forestry Applications

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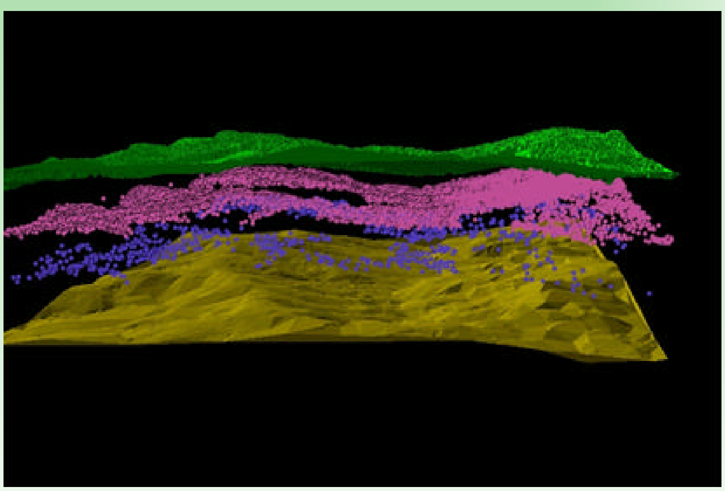


Report Prepared for:
**The Inventory & Monitoring Steering Committee**
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## Table of Contents

## Foreword

This report was initiated and funded by the Inventory and Monitoring (I&M) Steering Committee of the USDA Forest Service. The I&M Steering Committee was chartered by the Inventory and Monitoring Institute as a means to investigate new and emerging technologies, and determine their potential to aid with Forest Service I&M issues. The Remote Sensing Applications Center wishes to acknowledge the I&M Steering Committee for their guidance and direction, and for the program oversight provided by the San Dimas Technology and Development Center. The authors believe that the input provided resulted in a more specific final report that addresses field needs.

## Abstract

Spencer B. Gross, Inc. (SBG) was selected to evaluate multi-return LIDAR (Light Detection And Ranging) technology for USDA Forest Service applications. The data sets used for this study are in the northwest United States (Oregon, Washington, and Montana). Three sites had existing data, and new LIDAR data were collected for three additional sites. These sites were selected as having representative samples of northwest vegetation associations, slope characteristics, and having land management treatments. For many of these sites, ancillary data (e.g., maps, photos, inventory data) and existing relationships (i.e., university personnel and students, forest industry contacts, government contacts) were available for validation purposes.

Geospatial information provides the basis for effective forest management practices. Obtaining quality data using traditional techniques including aerial photography, photogrammetry, and fieldwork is relatively expensive and time intensive. Some data elements, such as a bare earth terrain model of reliable 20' contours in northwest forestlands, are very difficult to obtain.

Multi-return LIDAR offers an opportunity to capture dense point data defining the first surface (canopy) and penetration into the vegetation cover with many points hitting the ground. The potential therefore exists to "map" the canopy, the bare earth, and many of the structural characteristics such as canopy height, volume, and basal diameter from a single flight.

## LIDAR: The Technology

The development of airborne laser scanning goes back to the 1970s with early NASA systems. Although cumbersome, expensive, and limited to specific applications (such as simply measuring the accurate height of an aircraft over the earth's surface), these early systems demonstrated the value of the technology.

These systems operate by emitting a laser pulse. By precisely measuring the return time of a laser pulse, the “range” can be calculated using the speed of light. This is similar to using a total station surveying instrument.

The advent of GPS in the late-80s provided the necessary positioning accuracy required for high performance LIDAR. It wasn’t long until rapid pulsing laser scanners were developed and linked to the GPS system. The systems became complete with ultra-accurate clocks for timing the LIDAR return and Inertial Measurement Units (IMU) for capturing the orientation parameters (tip, tilt, and roll angles) of the scanner.

A modern LIDAR system has a rapid pulsing laser scanner (with continuous wave lasers which obtain range values by phase measurements), precise kinematic GPS positioning, orientation parameters from the IMU, a timing device (clock) capable of recording travel times to within 0.2 of a nanosecond, a suite of robust portable computers, and substantial data storage (100 GB per mission).

From the earliest applications of airborne laser scanning, the mapping community was aware that vertical accuracies of a 15 cm Root Mean Square Error (RMSE) were possible, with horizontal accuracies about two times the footprint size (approximately 90 cm for this study). Maximizing this technology greatly reduces the time and fieldwork required by most traditional methods.

## System Components

Modern LIDAR systems are the result of rapid advances in technology during the last several years. The following are components of the AeroScan LIDAR system, used in this study.

*The Scanner:*

High-performance scanners are capable of emitting up to 15,000 pulses per second with a variable-scanning angle of 1° to 75°. With continuous wave laser pulses, multiple return values for each pulse may be recorded – up to 5 return values per pulse. Operating in the near infrared (1064 nm), pulse values may be recorded after diffusion and reflection on the ground. GPS and IMU technology is integrated into the scanner, as well as a robust timing mechanism (clock). In addition to recording returned pulse range values, some scanners also provide signal intensity, amplitude, and pulse angle.

*GPS, IMU and Timing Clock:*

Precise kinematic positioning by differential GPS and orientation parameters by the IMU of the scanner is critical to the performance of the LIDAR system. The GPS provides the coordinates of the scanning laser source and the IMU provides the direction of the pulse. With the ranging data accurately measured and time-tagged by the clock, the position of the “return point” can be calculated.

*Software:*

The four primary components of a LIDAR system (Scanner, GPS, IMU and Clock) each operate within an independent plane-of-reference. As a result, the assembly of components requires sophisticated software for accurate intercommunication. The delivery of each pulse carries a time tag, position value, and orientation parameters. Multiple returns from each pulse require cataloging and a nearly perfect storage protocol. In some cases the hardware manufacturers provide a complete system with software; the highest performance systems usually require custom software for component integration.

*Computer Support:*

Each primary component [scanner, GPS, clock and IMU] requires dedicated computer support. In addition, another computer supports the aircraft navigation, and yet another acts as a server managing data storage.

Figure 1 is a composite illustration of the AeroScan LIDAR System used in this study, showing the Scanner, IMU, and supporting hardware.

Figure 1. The AeroScan System.

## System Operation

*Bore Sighting the System:*

Once the system is assembled, a “bore sight” is required for calibration. By collecting LIDAR data of a pre-measured target, the internal referencing of the system is modeled, so that the configuration of the components is known. These values are used in post-processing to calculate the accurate location for LIDAR return values to an external referencing system. Each time the system is removed, a new bore sight is required.

*Data Collection:*

LIDAR data collection begins with a well-defined flight plan meeting the project's requirements. The average post-spacing of the points must be at a density to support the level required for a Surface Elevation Model (SEM). Changing the flight altitude of the aircraft or the scan angle of the scanner allows for modifying the density of the post-spacing. Urban areas with tall buildings and steep terrain require special consideration to avoid holes in the data.

For the kinematic GPS, a base station of known location with a multi-channel GPS must be initialized with the GPS receiver on-board the aircraft. This initialization lock must remain in place during the entire flight. For this reason, very shallow turns are made between flight lines during data acquisition.

LIDAR data may be acquired quite rapidly: a system emitting 15,000 pulses per second with the capability to record 5 returns per pulse could potentially capture 75,000 values per second. In reality, the number of returns from such a system collecting data for a Northwest forest is closer to 35,000 values per second. At 900,000 pulses per minute, a typical 3-hour mission results in about 162 million pulses.

Since LIDAR is an active illumination system (Figure 2), data can be captured in all 'clear' conditions – day or night. This factor is very useful in taking advantage of good weather conditions and the opportunity to capture data at night in busy air space around airports. As mentioned, most terrain mapping LIDAR systems use a near infrared laser, so pulses hitting standing water are completely absorbed.

Upon landing after a mission, the system is de-initialized (LIDAR system is turned off), and quality assurance of the data begins. Since all of the data collected are georeferenced, it can be viewed in-situ using GIS software to verify coverage of the site. Also, to validate the accuracy of the collection, known survey data and a check of the bore site should be completed in-situ. Without proper quality assurance at this phase, the

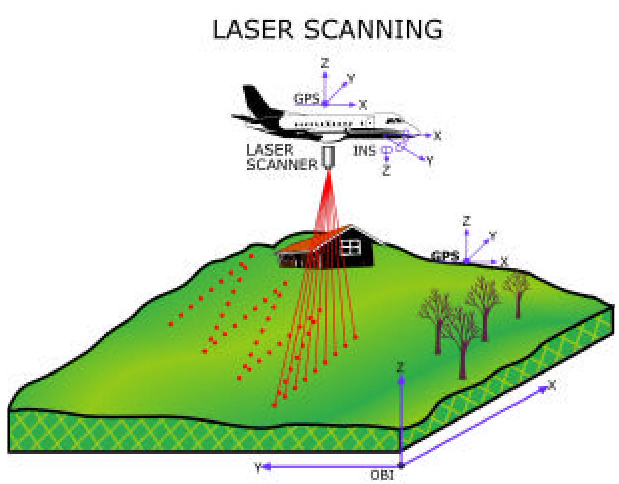


Figure 2. The operational characteristics of LIDAR data collection. The red dots represent LIDAR points hitting the ground at a specified post-spacing, in a wave-like scanning pattern.


Figure 3. This illustrates an immediate data collection validation procedure, which converts a portion of the LIDAR points to a raster file for display using GIS software. Note that the scanner was not disabled while the aircraft turned (pink flight line) showing the complete flight path for this single pass.

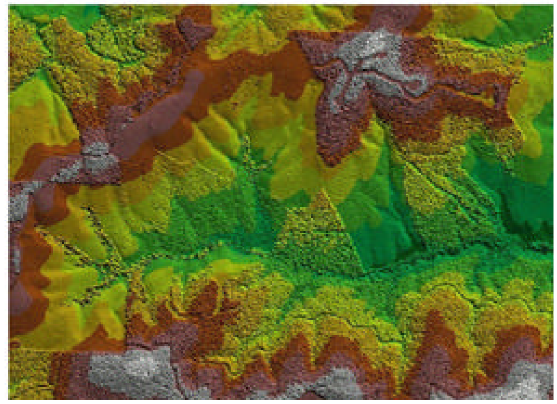

Figure 4. A TIN of first-return LIDAR.

absolute accuracy of the data collected should be suspect.

## Processing Methodologies

*Data Pre-Processing:*

LIDAR data processing is composed of two phases. First, the data must be filtered for noise, differentially corrected (as with any high accuracy GPS survey), and assembled into flight lines by 'return layer'. This processing computes the laser point coordinates from the independent data parameters: scanner position, orientation parameters, scanner angular deflection, and the laser pulse time of flight, or slant range. LIDAR data sets are remarkably large. Therefore, it is common to validate data coverage in near real-time, before completing a mission (Figure 3). Most LIDAR providers assemble the returns as a basic ASCII file of x, y, and z values, which have been transformed into a local coordinate system. A typical flight line, six miles long with a 40° scan width, produces an ASCII file of about 5 MB for $1^{st}$ return values only. Very robust data processing software and hardware is a fundamental requirement to work with data sets of this size.

*Data Post-Processing:*

The LIDAR data must undergo further analysis to derive the final products: DEM, SEM, or intermediate return information. These surfaces are derived using skilled technical staff and GIS modeling software. Current aerial photography, satellite imagery, and existing maps are required to derive these products with a high confidence level. Figure 4 is a Triangulated Irregular Network (TIN) of 'first-return'

LIDAR data for a forested site.

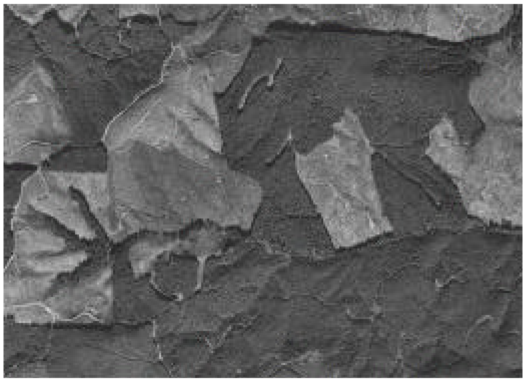

Figure 5. A digital orthophoto of the site in Figure 4.

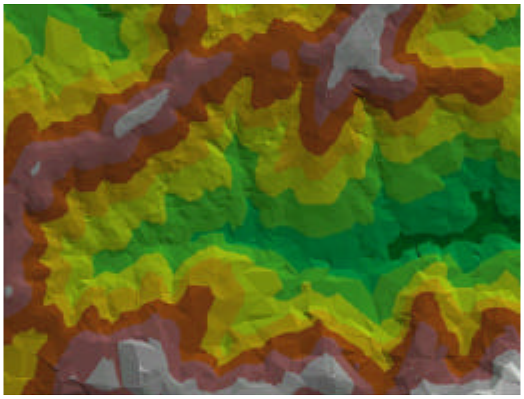

Figure 6. A TIN generated from a bare earth DEM.

If current imagery is not available, collecting georeferenced 4096 x 4096 pixel digital imagery (integrated to the same IMU and ABGPS as the scanner) with a calibrated camera/lens is effective. This imagery may be quickly ortho-rectified using the captured orientation parameters (without aerotriangulation) and the LIDAR DEM. Imagery allows for efficient processing with higher confidence. Mapping forests exhibiting a diversity of management treatment options are processed quite effectively through the combination of digital imagery and LIDAR. Figure 5 is a digital orthophoto of a forested site, which was generated from an image flown before the LIDAR data collection. The orientation parameters from this image, and the LIDAR DEM were used to rectify the image.

Firms providing LIDAR services typically have a suite of in-house algorithms for deriving the canopy layer, or SEM, and a bare earth DEM. These software modules analyze the multi-surfaces mapped by the multiple return LIDAR data sets. The processing for bare earth begins with the LIDAR points with the highest likelihood of being on or near the earth's surface. The LIDAR Analyst
proceeds by moving from the "known to the unknown", making reference to the imagery, and removing above ground points selectively.

Figure 6 is a TIN of the bare earth DEM for the forested site shown in Figures 4 and 5. For this four square mile area, much of which is covered with mature forest. The LIDAR point density supported 20' contours. Most of the area contained 10' supplemental contours.

As a final check, representative sites within the project area should be verified photogrammetrically on a stereo plotter. LIDAR points are easily visible on the 3D stereo model for analysis, and from this check, an accuracy statement for the data set can be developed for the final Report of Survey.

*Data Delivery:*

Data delivery is typically in a format ready-for-use in GIS or CAD software in the correct coordinate system. Existing accuracy standards should be utilized to the greatest extent possible: the ASPRS large-scale Mapping Standard and the National Spatial Data Accuracy Standard. For example, if the density of 'ground points' does not support the accuracy required, these areas should be annotated and noted for low confidence.

To accompany the deliverables (typically a bare earth DEM, canopy layer, and a SEM) a Record Of Survey should outline the procedures for data collection and post-processing, the intended post-spacing, flight parameters, kinematic GPS reports, and referencing of the base station.

## Study Sites

Six sites in Oregon, Washington, and Montana were selected for their representation of northwest forest conditions, including a broad range of forest management conditions. New LIDAR missions, as well as existing data from previous missions, were flown at post-spacings from 1.5 meters to 8 meters. These data sets were capable of generating DEMs and SEMs with contours of 3 to 20 feet. The results and discussion that follows is a synopsis from analysis of all study sites.

## Results and Discussion

*Surface Elevation Model (SEM) Generation:*

This study validates the usefulness of LIDAR to create a SEM. The density, or post-spacing, of the data points drives the resolution of the SEM. Relatively course data (6-7 meters) can readily identify various timber stand parameters including 30' buffers along streams. Higher density data, such as a transect (1.5-meters) approach provides the opportunity to identify individual features such as narrow roads and small streams, as well as individual trees.

*Digital Elevation Model Generation and Contours:*

*Table 1 graphically illustrates the predicted level of contour generation that could be anticipated, based on post-spacing, within variable forest conditions.*

Table 1. Contour generation from variable post-spaced LIDAR.

| Post-Spacing (m) | Anticipated Contours (m) | Forest Characteristics |
|---|---|---|
| 3 | 3-6 | Mixed Douglas-fir |
| 1-5 | 3 | Mixed Douglas-fir |
| 6-7 | 6 | Mixed Douglas-fir |
| | | |
| 2 | 1.2 | Mature Pine |
| 3 | 2 | Mature Pine |
| 5 | 1* | Mature Pine |

*LIDAR data set was flown with a larger post-spacing (i.e., 5 meters) but at a lower altitude and lower HZ rate, thus a stronger pulse. This comparison indicates that at this site the same number of 'points hitting the ground' is very similar to the other two modes.

*Forest Biomass Characteristics:*

Preliminary results from the 1.5 meter post-spacing LIDAR data for predicting average height of canopy, total basal area, and bole volume of Douglas-fir forests are shown in Figures 7, 8, and 9. Each forest exhibits unique variability, and having multi-return LIDAR at 1.5 meter density with digital imagery and current plot sampling data, potentially meets or exceeds the requirements for volume analysis by industrial forestland management. Additional work needs to be conducted on 3-4 meter density data. It will likely not yield as high $R^2$ values, but should be sufficient for forest management needs, at a much lower cost per acre. In cooperation with Oregon State University, SBG participated in a study to predict stand-level forest characteristics: canopy height, volume, and basal area. They had LIDAR available for 19 inventory plots, containing the diversity of age classes desired in a typical northwest forest environment. Table 2 outlines the characteristics of the plots.

Table 2. Characteristics of study plot sites.

| Serial Stage | Number of Plots | Height (m) | Basal area (m2/ha) | Volume (m3/ha) |
|---|---|---|---|---|
| Shrub | 1 | 7.4 | 5.8 | 5 |
| Young | 7 | 1734-28.0 | 25.9-49.0 | 86-180 |
| Mature | 3 | 29.6-42.4 | 46.6-69.6 | 145-251 |
| Old Growth | 8 | 35.0-52.5 | 71.3-132.1 | 317-513 |

Stand height is the average height of all dominant and co-dominant trees in the stand. Basal area is the basal area of all species. Volume is the total cubic volume of wood in the bole including the top and stump but not including branches, which is one of the most common measures of volume used in the timber industry today. These stands were selected to contain at least 80 % Douglas-fir basal area, so the results of this study apply only to such Douglas-fir dominated stands. This is a very reasonable restriction on the west side of the Oregon and Washington Cascades as the results will still apply to millions of hectares of commercial and public forestlands.

There were five steps in the analysis; the first four involved writing programs in the Interactive Data Language (IDL) to process LIDAR data, and finally fitting regressions using Statistical Analysis Software (SAS) to explore relationships between LIDAR data and ground plot measurements.

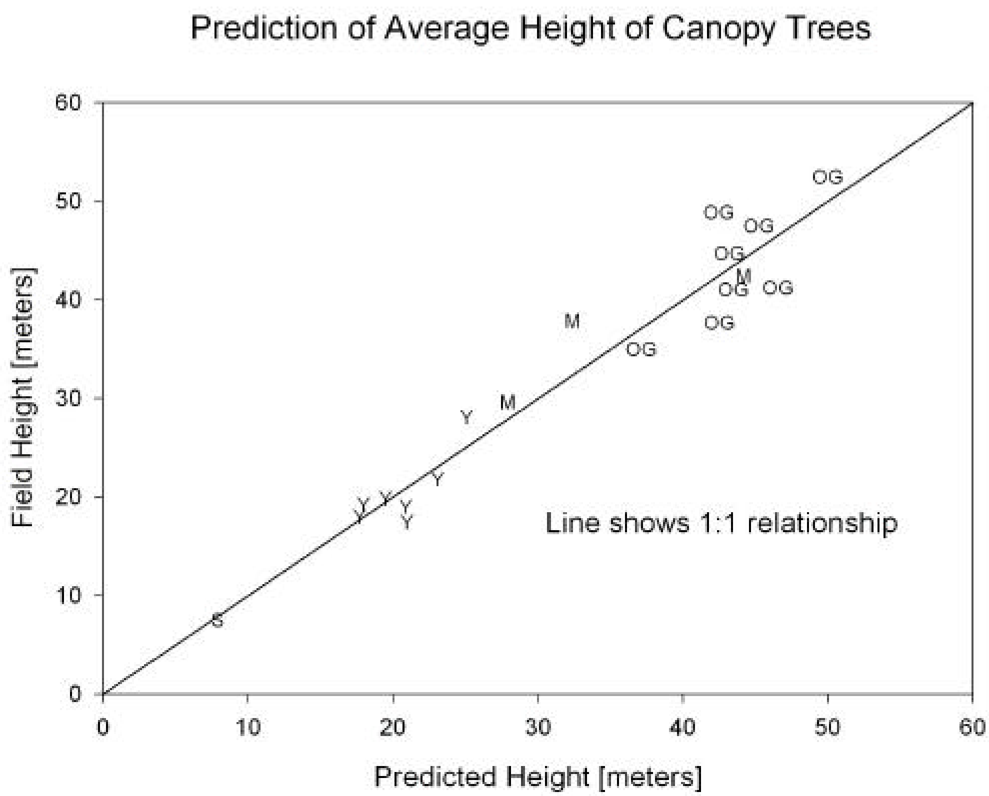


Figure 7. Prediction of Average Height of Douglas-fir stands using small-footprint LIDAR data. **PRELIMINARY RESULTS ($R^2$ = .94).** Seral stage codes: S = shrub-dominated, Y = young, M = mature, OG = old growth.

Models developed from regression analysis were all strong predictors and offer encouragement that commercial applications of small-footprint LIDAR for forest inventory may be feasible. Some caution is merited however. Note that the highest $R^2$ values are for the log-transformed values. This caused the low values for shrub-stand basal area and volume to weigh heavily in the regression fit and artificially inflates the $R^2$. Also, the wide range of the response variables (Table 1) made it more likely the $R^2$ would be high. Even with these reservations, the relationships are strong, as can be seen in the following three figures (Figures 7-9).

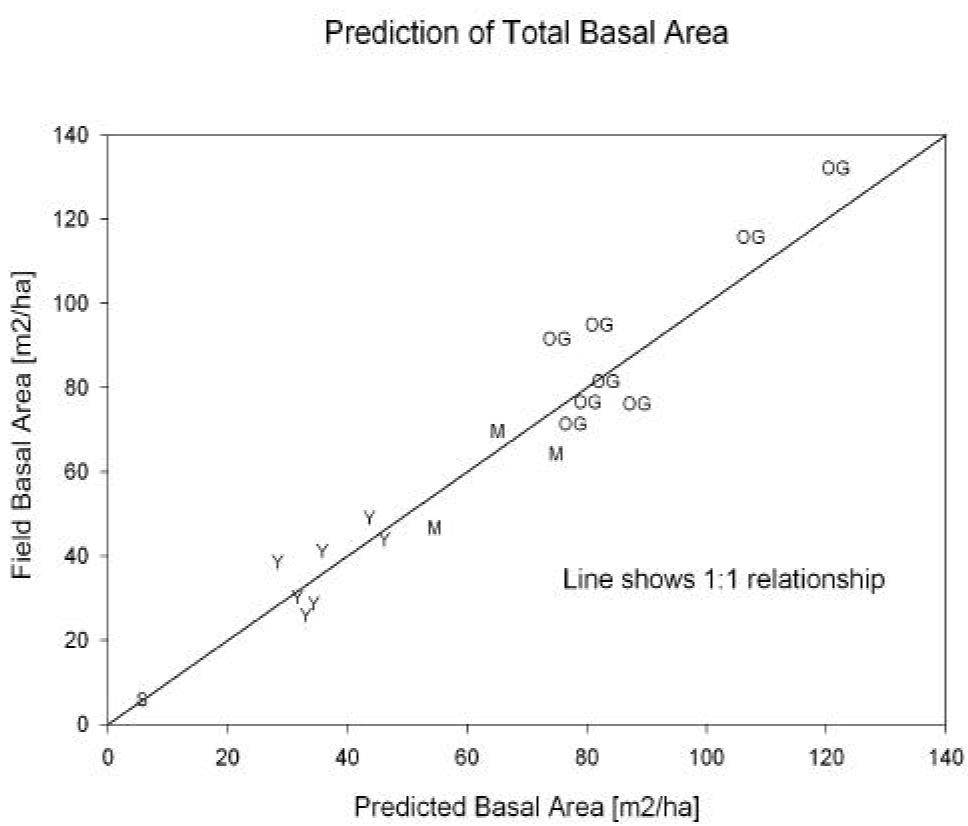


Figure 8. Prediction of Total Basal Area of Douglas-fir stands using small-footprint LIDAR data**. PRELIMINARY RESULTS ($R^2$ = .95).** Seral stage codes: S = shrub-dominated, Y = young, M = mature, OG = old growth.

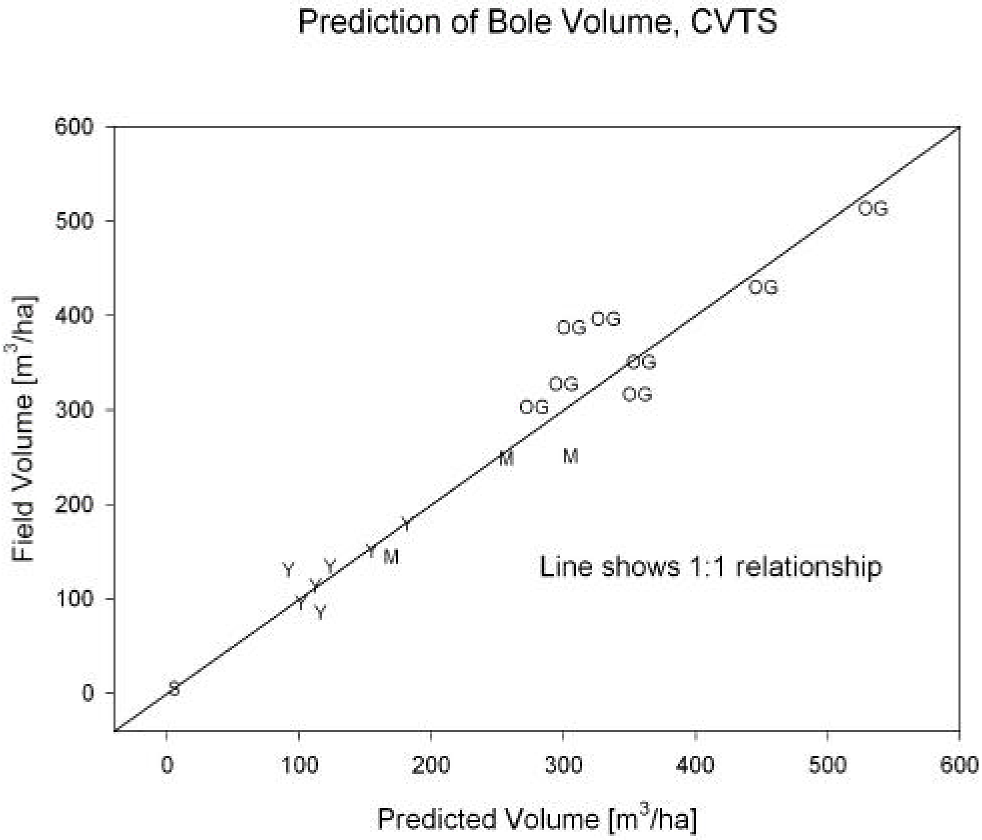


Figure 9.  Prediction of Bole Volume of Douglas-fir stands using small-footprint LIDAR data. **PRELIMINARY RESULTS ($R^2$=.97).** Seral stage codes: S = shrub-dominated, Y = young, M = mature, OG = old growth.

**Note:** Detailed results of this study are scheduled to be published in *Photogrammetric Engineering & Remote Sensing* in the December 2000 issue (Means, et. al.).

*General Cost Analysis:*

For small projects (4 sq. miles) that are nearby the LIDAR provider, costs start at approximately $12,000. Many factors can influence the costs of LIDAR acquisition, such as, difficult weather areas resulting in crew layover, steep slopes requiring supplemental flights, islands and lakeshores requiring control flights, and difficult flight operations, which may include airport Tower Control Area (TCA) or military airspace. High density (1.5 m to 2.5 m post-spacing) can also greatly increase the costs. Table 3 is a guideline of cost per acre for 'forestry production projects' based on mobilization, reference station survey, aircraft costs, IMU & ABGPS services, LIDAR with 3-4 meter post-spacing, and pre and post-processing for a bare earth DEM and SEM formatted for GIS. Table 4 is a similar guideline of LIDAR costs based on various post-spacings and two project sizes.

Table 3. LIDAR project costs with a post-spacing of 3-4 meters.

| Acreage Range | Cost per Acre |
|---|---|
| 5,000 to 10,000 | $3.50 |
| 10,000 to 30,000 | $3.00 |
| 40,000 to 60,000 | $2.75 |
| 60,000 to 100,000 | $2.50 |
| 100,000 to 250,000 | $2.00 |
| > 250,000 | $1.75 |

Table 4. LIDAR project costs based on various post-spacings.

| **Based on a 15,000 Acre Project:** **AVERAGE POST-SPACING** | **COST/ACRE** | **PROBABLE DEM GRID** |
|---|---|---|
| 1.5 M | $5.00 | 3 M |
| 2.5 M | $3.45 | 4 M |
| 3.5 M | $2.60 | 6 M |
| 6 M | $2.00 | 10 M |
| 9 M | $1.75 | 15 M |
| **Based on a 250,000 Acre Project:** **AVERAGE POST-SPACING** | **COST/ACRE** | **PROBABLE DEM GRID** |
| 1.5 M | $3.00 | 3 M |
| 2.5 M | $2.50 | 4 M |
| 3.5 M | $1.70 | 6 M |
| 6 M | $1.50 | 10 M |
| 9 M | $1.15 | 15 M |

*Comparison of Traditional Inventory Procedures vs. LIDAR Predictions:*

The forest variables estimated from LIDAR data include height, basal area, and volume, and are of key interest to the timberland managers and represent information that is expensive to collect in the field. Typical forestry field sampling includes tree height, basal area, and tree form in some sub-sample (plots) of the forestlands.

Forest analysis tools would allow an entire forest to be mapped from LIDAR data using a small field sample; or, as a more cost-effective alternative, a multi-stage sampling design could be used. LIDAR data would be collected over a sample of the forest. Within the LIDAR coverage area, an appropriate number of field samples (plots) could be collected to build the relationships between LIDAR-derived variables and stand attributes that could be extended to the entire LIDAR sample and, in turn, to the forested area being evaluated.

Following this approach, a cost comparison example is considered (Table 5) for a typical even-aged, managed forest of 500,000 acres. Each year, two percent of 10,000 acres (200 acres) are sampled to determine what management steps are needed. This cost comparison is favorable; however, actual costs will be different for proportions of area sampled on the ground and other components of the traditional and LIDAR-supplemented sampling designs.

Table 5. An example cost comparison between current, traditional field methods of forest inventory and a potential LIDAR-based method.

| | **Time Estimate** | **Cost Estimate** |
|---|---|---|
| **Traditional Methods (field Work and analyses)** | **14 Weeks** | **$32,000** |
| | | |
| *LIDAR methods:* | | |
| LIDAR data collection (200 acres @ $7 per acre + $5,000 staging fee) and delivery | 1 week | $6,400 |
| Field sampling (10% if LIDAR coverage = 20 acres) | 1 week | $3,200 |
| LIDAR analysis | 2 weeks | $7,000 |
| **Total for LIDAR methods** | **4 weeks** | **16,600** |
| | | |
| **Savings per year with LIDAR methodology** | **10 weeks** | **$15,400** |

*Digital Imagery:*

Procuring digital imagery in concert with LIDAR collection maximizes the opportunity to collect ancillary data at a very low cost taking advantage of the platform's expense already incorporated into the mission overhead. A good example is 4096 x 4096 pixel, panchromatic imagery collected with a calibrated, Kodak Mega-Plus Sensor. This type of imagery devise is available off-the-shelf, a stabilized CCD technology, and relatively inexpensive. The 4k x 4k footprint (4096 pixels x 4096 pixels) provides a footprint large enough to coordinate the same footprint as the LIDAR swath (Figures 10 and 11).

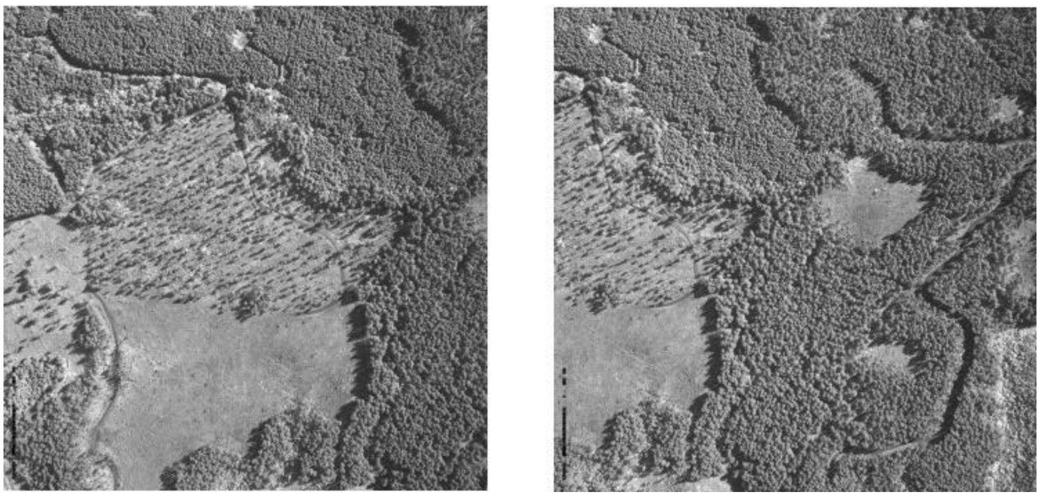


Figure 10. An example of 4k x 4k digital imagery (reduced resolution).

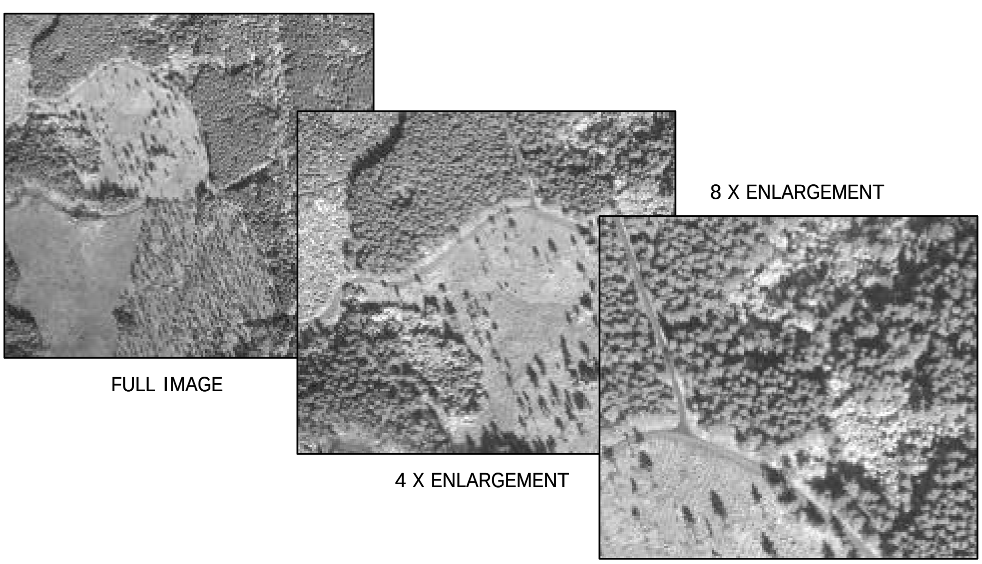


Figure 11. An example of 4X and 8X enlargements of 4k x 4k digital imagery (reduced resolution).

Having the sensor mounted to the LIDAR scanner assembly with the offset distances (i.e., center pixel of the CCD to the center of the scanner) accurately measured allows for capturing ABGPS and IMU parameters for each image. With the calibrated geometry (modeled principal point/fiducials and orientation parameters), an image may be ortho-rectified using the LIDAR SEM. Images collected in stereo may be directly input into a softcopy photogrammetric workstation or printed out as hardcopy for traditional stereo viewing.

Digital imagery collected during a LIDAR mission is invaluable for post-processing. Subtle or confusing features (for example, a pile of gravel vs. a large bush) are usually identified and processed accordingly.

*Resource Management Applications:*

All staff groups requiring information about forested areas can benefit from the use of LIDAR information. Forest parameters that can be derived from LIDAR could be inputs to ecosystem assessment projects. Gap Analysis (a USDI nation-wide program to identify gaps in conservation of biological diversity), for example could benefit from enhanced information, such as canopy closure. Further research may discover additional variables that will be of use in such projects. Figure 12 is a diagram of the number of returns per pulse, color-coded (light being lowest number, dark being highest number) for a small-forested watershed. Such an analysis is processed very quickly in a GIS and provides a preliminary assessment of canopy closure and biomass location.

Wildfire fuel mapping is another potential application for LIDAR-derived forest information. Traditionally, fuel mapping has been done with expensive ground surveys. However, understory components, such as ladder fuels, are very important in the fuels mapping process and are difficult to derive from optical imagery. Although not performed in this study, the derivation of understory characteristics from LIDAR is promising, and could be a useful input to fuel mapping projects.

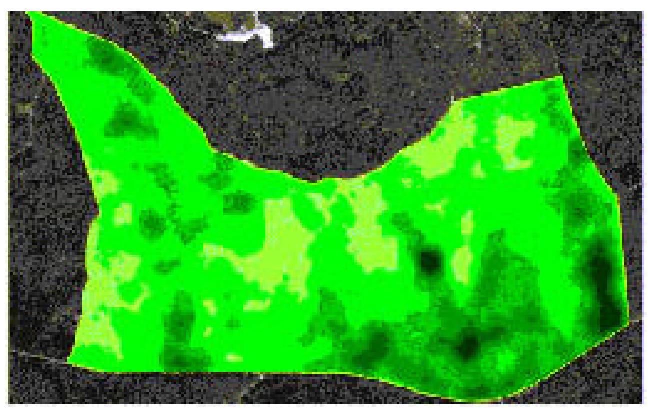

Figure 12. Multiple-Return Isopleths. The digital orthophoto background validates the location of the LIDAR for this watershed.

*Riparian Vegetation Mapping:*

Riparian habitat is a key component of stream habitat for fish. The Oregon State Department of Environmental Quality, the US Army Corps of Engineers and the Federal Emergency Management Agency are seeking to map riparian vegetation in the whole Willamette Valley of Oregon. Key components of this mapping are vegetation height (tree size) and location relative to the stream, because they influence shading of streams from solar radiation and eventual input of logs to streams; woody debris in streams provides important habitat and structure. Estimates using traditional air photo techniques indicate 5-7 years to complete the mapping. LIDAR technologies, including the tools developed here, will allow this to be done in three years or less, and the maps of vegetation height and area of coverage will meet or exceed the required accuracy standards. Figure 13 is a TIN of First-Return LIDAR from the McDonald-Dunn Research Forest, covering a 1 mile x 1.5 mile area of the Willamette Valley. The area is typical of a stream network feeding the Willamette River influenced by human interaction. The vegetation has been GIS color-coded by height. Inspection of the full resolution data allows for the interpretation and classification of vegetation and cultural features (roads, property lines, etc.) and evaluation of the potential flood plain.

These examples use a fusion of remotely sensed imagery and LIDAR. In addition to the spectral information contained in the image data, LIDAR provides, at a minimum, height information that can aid in automated classification or photo interpretation. For example, two tree types may appear very similar in an image, but may be better identified by their heights, which could be derived from LIDAR. The fusion of LIDAR and imagery may yield whole new data products that have not been possible from imagery alone.

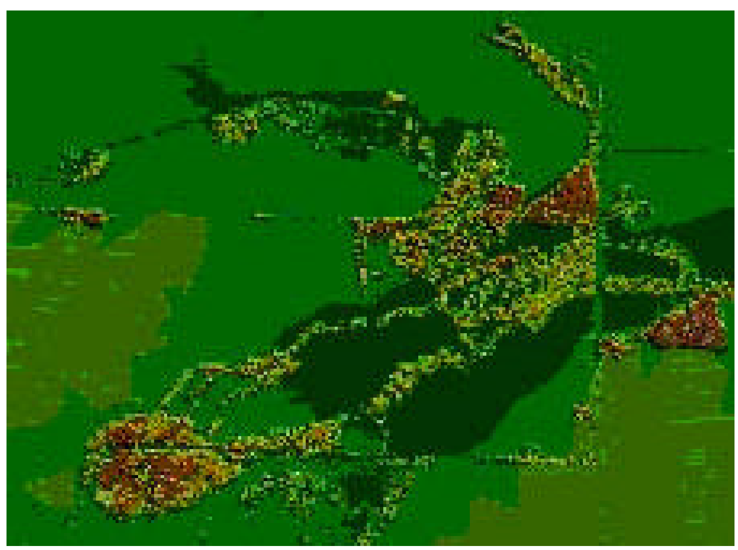

Figure 13. TIN of First-Return LIDAR.

*LIDAR Performance in Eastern Forest Types:*

The results presented in this report have been drawn from predominately single forest species types, such as Douglas-fir. These initial studies have focused on such areas because of the economic value of these species and their dominance in northwest forest environments. Additional work in mixed conifer and deciduous forest types is warranted.

The ability of multi-return LIDAR to map mixed conifer forest types requires point spacing of suitable density to distinguish the crown shape. LIDAR points spaced at 0.7-1.0 meter should provide sufficient data to map crown shape of Douglas-fir. In mature stands, this process should yield similar results for mixed conifers.

Deciduous forest types are straightforward to identify from first-return LIDAR, post-processed to a Canopy Layer, and interpreted much like aerial photography. To derive a bare earth DEM covered with deciduous vegetation, the preferred scenario is to collect the LIDAR in leaf-off conditions. However, multi-return LIDAR can penetrate leaves of deciduous trees if the canopy is high and filtered light strikes the forest floor. Dense leaves resulting in low-light forest conditions are difficult for LIDAR to penetrate.

## Conclusions

Small format LIDAR has become a commercially viable remote sensing platform in the past several years. Its ability to map topography (bare earth DEMs) and the forest canopy (SEMs) with an extremely high level of accuracy is uncommon to most other remotely sensed data. Preliminary research, attempting to model average canopy height, total basal area, and bole volume, has been very promising for northwestern forest types.

Existing and potential applications for small format LIDAR include: topographic mapping, forest canopy mapping, forest fuels mapping, and riparian vegetation mapping. LIDAR is now a commercially viable and highly operational remote sensing technology, and there exists a high potential for many additional applications.

Future work might include focusing on further investigation of modeling average canopy height, total basal area, and bole volume using wider post-spacing and higher altitudes, while hopefully lowering acquisition and processing costs. Also, cost estimates need to be compared with traditional inventory estimates for acquiring similar information from ground plots.