# Estimating Forest Structure Parameters on Fort Lewis Military Reservation using Airborne Laser Scanner (LIDAR) Data

*HANS-ERIK ANDERSEN*
*JEFFREY R. FOSTER*
*STEPHEN E. REUTEBUCH*

**Abstract**—Three-dimensional (3-D) forest structure information is critical to support a variety of ecosystem management objectives on the Fort Lewis Military Reservation, including habitat assessment, ecological restoration, fire management, and commercial timber harvest. In particular, the Forestry Program at Fort Lewis requires measurements of shrub, understory, and overstory canopy cover to monitor vegetation response to various management approaches. At present, these measurements are acquired through field-based procedures, which are relatively costly and time-consuming. The use of remotely sensed data, such as airborne laser scanning (LIDAR), has the potential to significantly reduce the cost of acquiring these types of measurements over large areas. As an active remote sensing technology, LIDAR provides direct, three-dimensional measurements of the forest canopy structure and underlying terrain surface. LIDAR-based cover measurements can be related to forest vegetation cover through a mathematical function based upon the Beer-Lambert law, which accounts for scanning geometry and vertical foliage density. This study was carried out to determine the utility of small-footprint, discrete-return LIDAR for estimation of forest canopy cover at Fort Lewis. LIDAR-based structural measures were compared to spatially-explicit field measurements acquired from inventory plots in five forest stands representative of the various forest types at Fort Lewis and a variety of terrain. Results indicate that LIDAR-based cover estimates for overstory and understory are generally related to field-based estimates.

## INTRODUCTION

Forests are structured as complex systems in three-dimensional (3-D) space. The 3-D structural organization of forest canopies is the primary determinant of the understory light regime, micro-climate, and habitat structure. In the Pacific Northwest, the vertical distribution of canopy elements is one of the more important components describing the spatial structure of a forest stands. For example, the Forestry Program at Fort Lewis Military Reservation requires this structural information to guide an active silvicultural program designed to promote the development of forests with more diverse structures and composition, and to provide habitat for the northern spotted owl (*Strix occidentalis caurina*). Fort Lewis has implemented an inventory program to document and monitor the spatial structure of the installation's forests. Three-dimensional forest structure is quantified by measuring vegetation cover of the overstory, understory, shrub, and ground layers.

Vegetation cover, expressed as the proportion of the forest floor covered by the vertical projection of vegetation within a layer of the forest canopy, is a conventional measure of forest structure (Jennings et al., 1999). As the inventory program currently relies upon ocular, field-based measurements of vegetation cover, inventory costs could be significantly reduced through the use of remote sensing technology.

In particular, actively-sensed airborne laser scanning (LIDAR) technology has the potential to provide information relating to spatial structure throughout the depth of the forest canopy and understory. Previous studies have

shown that large-footprint, continuous-waveform LIDAR data can be used to characterize the vertical distribution of canopy foliage (Harding et al., 2001; Lefsky et al., 1999; Means et al., 1999). Researchers have related the vertical distribution of small-footprint, first-and multiple-return LIDAR data to empirical- and model-based estimates of leaf area distribution within Pacific Northwest forests (Magnussen and Boudewyn, 1998; Andersen, 2003). Other studies have shown that quantitative measures derived from the vertical distribution of small-footprint, discrete return LIDAR data are related to important stand parameters, such as volume, height, and biomass (Means et al., 2000).

While LIDAR-derived measures of canopy cover have been used as independent variables in estimation of forest stand parameters (Means et al., 2000), the utility of LIDAR for differential characterization of canopy and subcanopy forest structure components has not been assessed. In this paper, a methodology for measurement of vegetation cover within discrete canopy layers using first return LIDAR data will be presented and evaluated.

## STUDY AREA AND DATA

### Study sites within Fort Lewis, Washington

Five stands considered to be representative of the variety of forest types present at Fort Lewis were selected as study areas for the project. The first two stands were located in the southwestern portion of Fort Lewis on an old recessional moraine of the Vashon Glaciation with hummocky topography and location variation in vertical relief of ca. 10 m. Area 1 was a 65-year-old mixed red alder/Douglas-fir stand, and Area 2 was a 75-year-old Douglas-fir stand. The other three stands were located on flat glacial outwash. Area 3, ca. 3 km southeast of Areas 1 and 2, was an 85-year-old mixed white oak/Douglas-fir stand. Areas 4 and 6 were 95-year-old Douglas-fir stands in the northeastern portion of Fort Lewis. (Area 5 was in a prairie and therefore was not used in this study).

Approximately 35 plots were located within each stand (169 total) to validate the remote sensing estimates (Figure 1). These plots were established in a systematic pattern of clusters to ensure a well-distributed sample within each stand type. Plot coordinates were established by a highly accurate total station topographic survey. An additional 300 topographic check points were established in these stands to assess the accuracy of the LIDAR digital terrain models.

### LIDAR data

LIDAR data were acquired over two 50-km$^2$ areas on Fort Lewis in August, 2000 (fig. 1). These data were acquired with an Earthdata Aeroscan laser scanning system operating from a fixed-wing platform. System specifications and flight parameters are shown in Table 1.

Table 1. System specifications for Earthdata Aeroscan LIDAR system.

| Pulse rate | 15,000 per second |
|---|---|
| Ground spacing between pulses | 1 meter (nominal) |
| Laser wavelength | 1.064 μm |
| Scan pattern | Sinusoidal |
| Pulse length | 12 ns |
| Attitude precision | 0.004 degrees |
| Range resolution | 3 cm |
| Range accuracy | 2-4 cm |

### LIDAR-based digital terrain models

A filtering technique coded in IDL (Interactive Data Language version 5.5, Research Systems, Inc.) was used to identify the probable ground reflections within the last-return LIDAR data (Haugerud and Harding, 2001). An interpolation algorithm was used to generate a digital terrain model (DTM) on a grid, with a post spacing of 5×5 m, for the two areas covered by the LIDAR dataset. Figures 2a and 2b show hill-shade graphics of the DTMs.

Figure 1. LIDAR coverage and study areas within Fort Lewis Military Reservation, Washington.
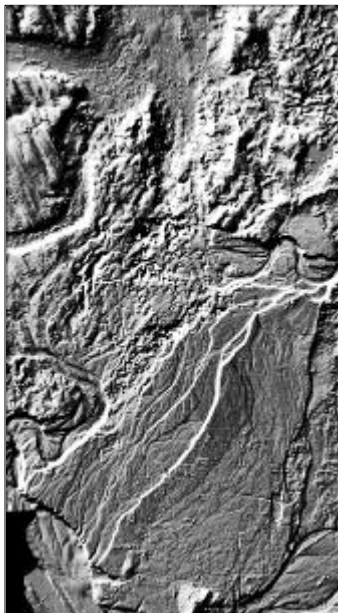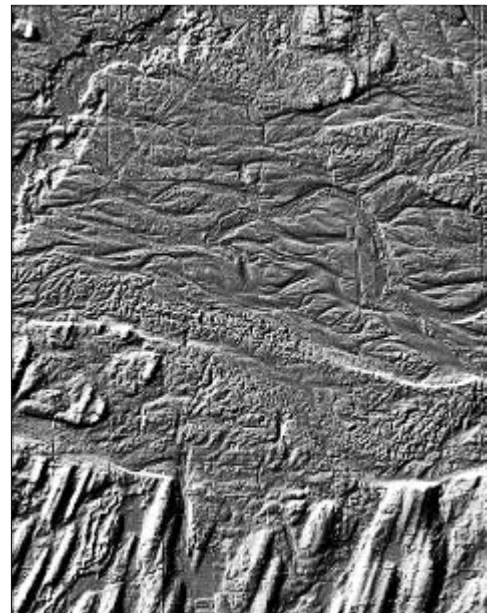


(a) Southwest area  (b) Northeast area

Figure 2. LIDAR-based DTMs (5-m resolution) within Fort Lewis Military Reservation.

A comparison of LIDAR-estimated elevation from the DTMs to the elevations of 225 topographic survey points indicated a mean absolute error of -0.14 meters and a root mean square error (RMSE) of 1.00 meters for the southwestern Fort Lewis LIDAR DTM. A similar comparison for the northwestern Fort Lewis LIDAR DTM (244 topographic survey points) indicated a mean absolute error of -0.05 meters and an RMSE of 0.72 meters.

**Field cover data**

To compare LIDAR-based measures of vegetation cover to conventional inventory metrics, field-based observations of vegetation cover were acquired at each of the 169 plots located in the five stands. Following the established field protocol of the Fort Lewis inventory program, ocular estimates of vegetation cover within the overstory, understory (1.8 m - base of overstory), and

shrub (0.46 m – 1.8 m) were made at each plot (Figure 3). Overstory and understory cover were estimated for an 809 m$^2$ circular plot, and shrub and ground cover for an 81 m$^2$ circular plot. It should be noted that while the base of the upper and lower boundaries of the shrub and ground layers are at fixed heights in the inventory protocol, the height of the base of the overstory layer is a local characteristic of forest structure and was subjectively estimated at each plot. Cover was defined as the proportion of the total area "filled" by the two-dimensional (2-D) vertical projection of tree crowns and shrubs onto the ground.
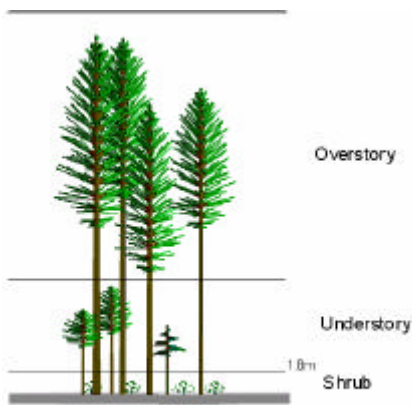


Figure 3. Canopy layers used for cover estimation.

## METHODS

To convert LIDAR coordinate data into vegetation height data, the elevation of the underlying terrain (interpolated from the LIDAR DTM) was calculated for each LIDAR return; then, this terrain elevation was subtracted from the LIDAR return elevation to yield vegetation height.

### Vertical point quadrat sampling

Ground-based measures of canopy cover are typically based upon a sample of measurements acquired with a vertical sighting instrument. The percent cover is computed as the proportion of sample points where the sky is obscured by vegetation (Jennings et al., 1999). As Jennings noted, a limitation of this approach is that it is highly susceptible to sampling error.

When the vertical heights from the ground to first contact with vegetation within each canopy layer are measured above each sample point, the canopy cover for a given canopy layer can be estimated as the ratio of the number of measured heights within a layer to the total number of sample points. This approach has been used to estimate vertical foliage distributions and is termed vertical point quadrat sampling (Ford and Newbould, 1971). When an optical range finding device, such as a laser, is used to measure the height to first leaf contact, this sampling technique is termed optical point quadrat sampling (MacArthur and Horn, 1969; Aber, 1979; Radtke and Bolstad, 2001).

### LIDAR-based cover estimation

If the geometry of the laser range-finding is inverted, an estimate of cover within a given layer of the canopy can be generated from LIDAR data, where cover within each layer is calculated as the ratio of the number of first return LIDAR reflections within a layer to the total number of LIDAR pulses entering the layer (Figure 4).
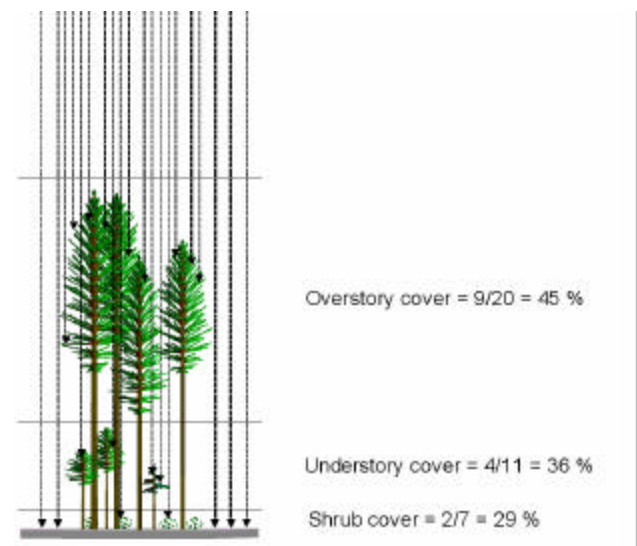


Figure 4. LIDAR-based cover estimation for overstory, understory, and shrub layers. Vertical lines represent LIDAR pulses.

A LIDAR-based cover estimate, based on first return data, was generated for overstory, understory, and shrub layers for each of 169 plots Although field cover estimates for the shrub layer were based upon an 81 m$^2$ plot, all LIDAR estimates were based upon an 809 m$^2$ plot to maintain an adequate sample area. Estimates based upon the larger area will not bias the results.

A single value for height was used to characterize the base of the overstory within each stand. A K-means clustering algorithm was applied to the LIDAR data within each forest stand to estimate the height that separated the understory and overstory layers (Mardia et al., 1995). This height was 10.0 meters for Area 1, 21.4 meters for Area 2, 7.5 meters for Area 3, 23.7 meters for Area 4, and 21.3 meters for Area 6.

Figure 5 is a 3-D representation of a plot within Area 2 (75-year-old Douglas-fir stand) created using the Stand Visualization System (McGaughey, 1997). Figure 6 shows a 3-D perspective view of the distribution of first return LIDAR data used to generate LIDAR-based cover estimates.

If all LIDAR measurements were acquired at nadir, there is a linear relationship between the LIDAR-based cover measurement, generated using the theory developed in the previous section, and the field-based cover estimate for each layer. In practice, due to scanning geometry, LIDAR measurements are acquired at some off-nadir angle (-25 degrees to +25 degrees in the Aeroscan system used in this study). This off-nadir angle affects the probability of a laser pulse passing through a given layer of vegetation and influences the functional form of the relationship between a LIDAR-based measurement of cover and the cover estimate observed in the field.
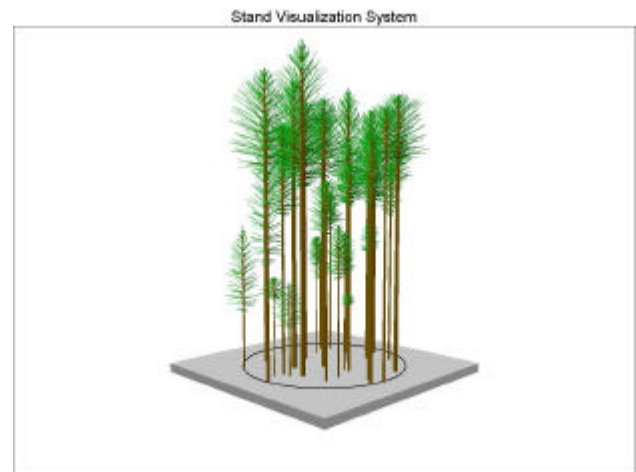


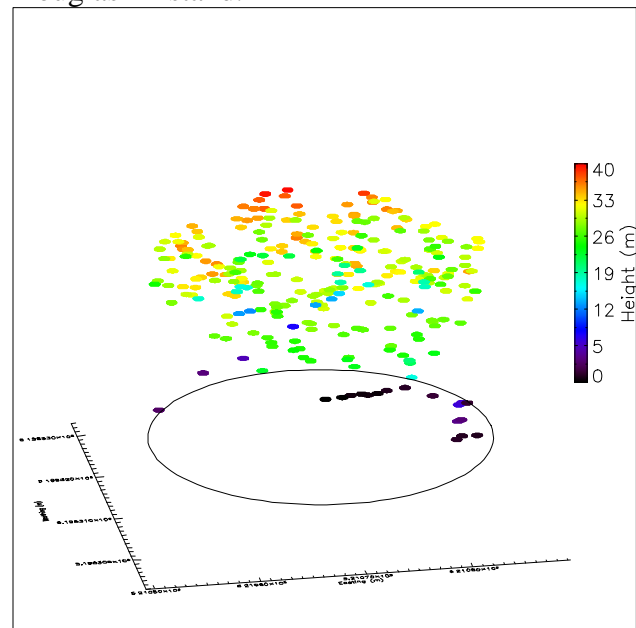Figure 5. Visualization of 809 m$^2$ plot within Douglas-fir stand.



Figure 6. Distribution of first return LIDAR data within 809 m$^2$ plot within Douglas-fir stand.

**Simulation of LIDAR data and cover estimates**

A simulation approach was used to investigate the effect of scanning geometry and foliage density on the relationship between field-based and LIDAR-based cover estimates. In this simulation, a 3-D array was used to simulate the 3-D "envelope" containing the canopy vegetation within a 100×100×60-meter area of forest. The cover within each layer of the canopy (i.e. overstory, understory (to 25 meters), and shrub) was held fixed by randomly assigning a value of either 0 or 1 to each layer

until the two-dimensional (2-D) projection of the "filled" area for each layer equaled the specified cover percentage. A specified density in the vertical dimension was also randomly allocated throughout the layer, while keeping the 2-D projection of cover fixed for each layer.

The paths of LIDAR pulses traveling at some specified off-nadir angle through the 3-D array were calculated and the coordinates (x, y, height) for the "first vegetation contact" (i.e. first encounter with a cell with code "1") were recorded as simulated first return LIDAR measurements. A simulated LIDAR-based cover estimate was then generated using the approach described in the previous section. These simulated LIDAR estimates were then compared to the specified, fixed ("simulated field") cover values used in filling the 3-D array.

Figures 7 and 8 show the influence of the off-nadir angle on simulated LIDAR-based cover estimates. Figure 7 shows the cover estimates with the off-nadir angle fixed at zero. Perhaps not surprisingly, there is a linear relationship between LIDAR- and field-based cover estimates. Figure 8 shows the relationship between LIDAR-based and field-based cover estimates when the off-nadir angle for each pulse is a random draw between -25 and +25 degrees and the foliage density within each layer is randomly chosen.

Clearly the relationship is no longer linear, and appears to follow a relatively smooth curve. While this effect is apparent in the overstory and understory layers (Figures 8a and 8b) it is not evident in the shrub layer (Figure 8c), where the relationship exhibits a more linear form.

The form of the mathematical function describing the relationship between LIDAR-based cover and field-based cover can be obtained from the principles of radiative transfer theory (Martens et al., 1993). Martens and others showed that the relationship between leaf area index and *gap fraction*, or the ratio of the
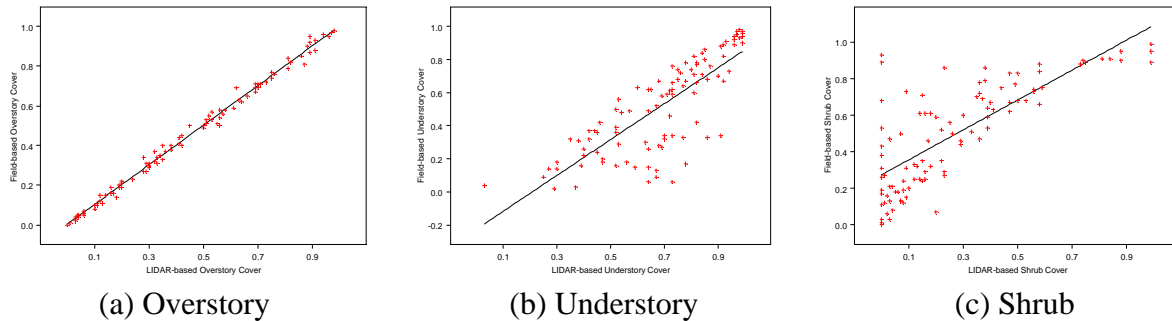
| (a) Overstory | (b) Understory | (c) Shrub |
|---|---|---|

Figure 7. Simulated cover estimates with off-nadir of 0 degrees.

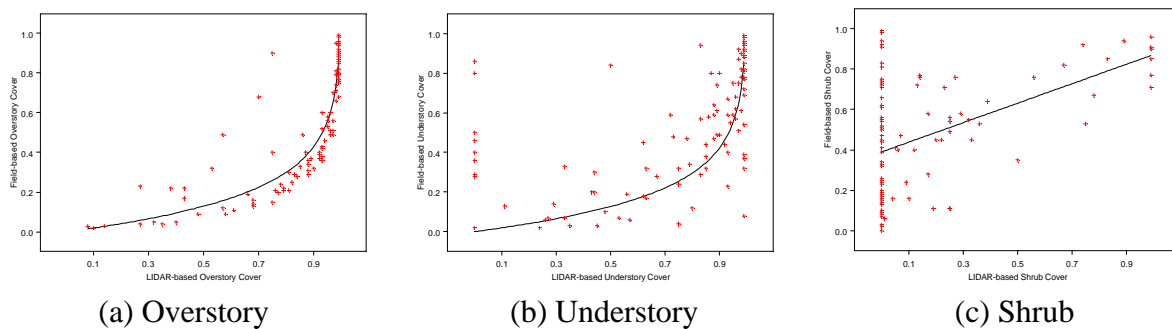| (a) Overstory | (b) Understory | (c) Shrub |
|---|---|---|

Figure 8. Simulated cover estimates with off-nadir angles ranging between -25 and +25 degrees.

amount of light beneath a canopy layer to the amount of light above a canopy layer, is given by the Beer-Lambert law, with the following form:

$$LAI = (-1/k)\ln(gap\ fraction),$$

where $k$ is the extinction coefficient governing the attenuation of light as it passes through the canopy.

In the context of cover estimation, the relationship between the field-based cover estimate (i.e., 2-D projection of vegetation onto terrain surface) and LIDAR-based cover can be estimated by the following function:

$$Field\ cover = (a)\ln[1/(1 - LIDAR\ cover)]$$

where $a$ is the parameter related to the extinction coefficient in Beer-Lambert law shown above, and cover values are expressed as fractions.

Density of vegetation in the vertical dimension will also influence this relationship between field- and LIDAR-based measures of cover. The parameter $a$ in the above function will represent the combined effect of off-nadir angle and vertical foliage density. Figures 9 and 10 show the influence of varying the vertical density of foliage. Figure 9 shows the relationship between simulated field- and LIDAR-based estimates of cover with a relatively high density of foliage in the vertical dimension, while Figure 10 shows this relationship for a low density of foliage, with fitted curves superimposed.

These graphics indicate that both off-nadir angle and vertical foliage density will influence the relationship between field- and LIDAR-based estimates of cover. It also appears that the mathematical functional form can be adequately represented by the logarithmic model based upon the Beer-Lambert law given above, where the parameter of the function will represent the effects of scan angle and foliage density.

## RESULTS

LIDAR-based cover estimates obtained using first return LIDAR data were compared to the field-based cover estimates for the 169 plots on Fort Lewis. The relationship between LIDAR- and field-based estimates for each forest type was quantified using regression analysis, with the results shown in Figures 11-14. The coefficient of determination ($r^2$) of each regression model is shown as well.

The results indicate that LIDAR-based cover estimates for overstory and understory are generally related to field-based estimates. There does not appear to be a significant relationship between LIDAR- and field-based estimates of shrub cover for any forest types.

Relationships between LIDAR- and field-based estimates are strongest in the mature Douglas-fir stand on flat terrain (Figure 11) and the mixed white oak/Douglas-fir prairie stands (Figure 14). It should be noted that the relationship for the overstory and understory layers in Area 3 did not exhibit a curvilinear form, so results for this area were based upon untransformed lidar cover values (Figure 14a and 14b). Relationships are still apparent, although less strong, within the Douglas-fir stand with hummocky topography (Figure 13). Relationships within the mixed red alder/Douglas-fir stand are extremely weak (Figure 12).

## DISCUSSION

The graphical and quantitative results indicate that LIDAR has the potential to provide information relating to vegetation cover in multiple canopy layers within forest stands. The weaker relationship between field- and LIDAR-based cover estimates for the shrub layer is most likely due to sampling error. Occlusion of subcanopy vegetation by overstory and understory foliage will reduce the number of first returns penetrating to the shrub layers, effectively decreasing the sample size and increasing the error of cover estimation. Results here indicate that sampling error is the primary

source of variation in the estimation of shrub cover across all forest types.

The results obtained from simulations and field data suggest that the interaction of off-nadir LIDAR scanning geometry and the vertical distribution of canopy foliage introduces a significant source of variability in LIDAR-based cover estimation. The geometry of LIDAR sensing leads to measurements of forest structure that are more representative of 3-D canopy *density* than 2-D (i.e. orthogonal) canopy *cover*. However, if vertical structure is relatively constant over a forest stand, then vertical density can be modeled, allowing for a more accurate mapping of the LIDAR-based cover estimate to the 2-D vegetation cover.

It should be noted that using a single height for separating overstory from understory layers adds a significant source of variability in LIDAR-based cover estimation. Again, error will be decreased when the stand is more structurally homogeneous. In stands exhibiting extremely complex vertical structure (e.g. the mixed red alder/Douglas-fir stand in Area 1), this classification error may lead to gross errors in cover estimation.

It should also be noted that there is no assumption in this study that the field-based, ocular estimate of vegetation cover represents a "true" measurement. Although attempts were made to "calibrate" the estimates through comparisons to the estimates of other observers, these measurements are inherently subjective and susceptible to bias. In the management context of Fort Lewis, however, it has been determined that ocular estimation remains the most economically viable approach to estimating the spatial characteristics of vegetation cover efficiently and quickly over the extent of the installation.
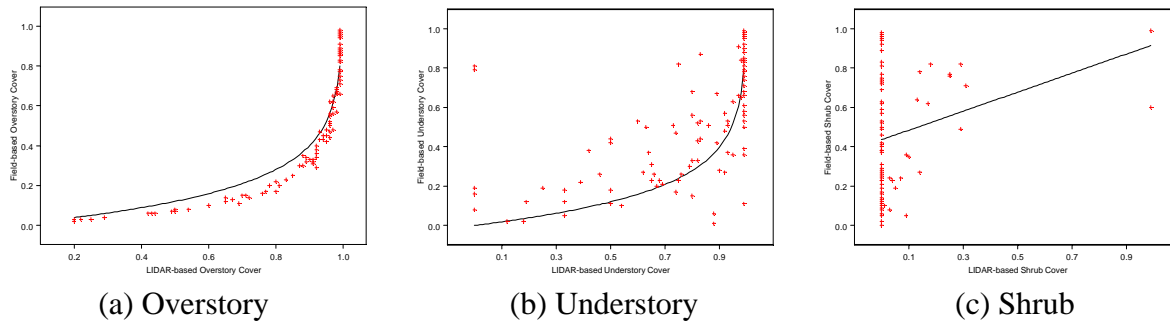


| (a) Overstory | (b) Understory | (c) Shrub |

Figure 9. Simulated cover estimates with high density of foliage in vertical dimension.



| (a) Overstory | (b) Understory | (c) Shrub |
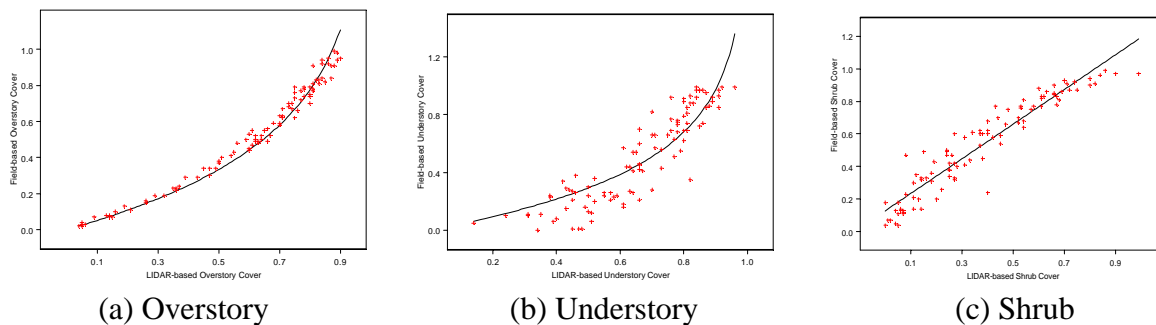
Figure 10. Simulated cover estimates with low density of foliage in vertical dimension.

(a) Overstory ($r^2 = 0.63$)  (b) Understory ($r^2 = 0.53$)  (c) Shrub ($r^2 = 0.15$)
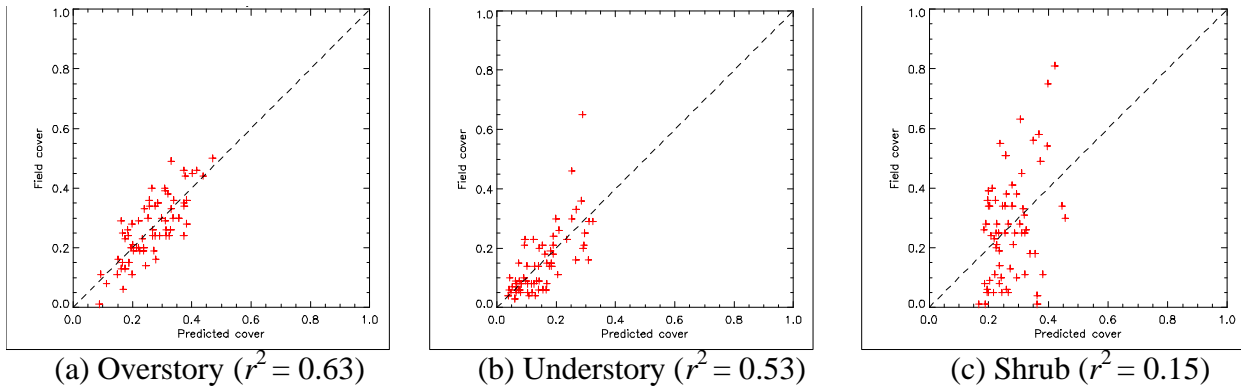
Figure 11. Field-measured vs. predicted cover within 95-year-old Douglas fir stands (Areas 4 and 6). Dashed line shows 1:1 relationship.



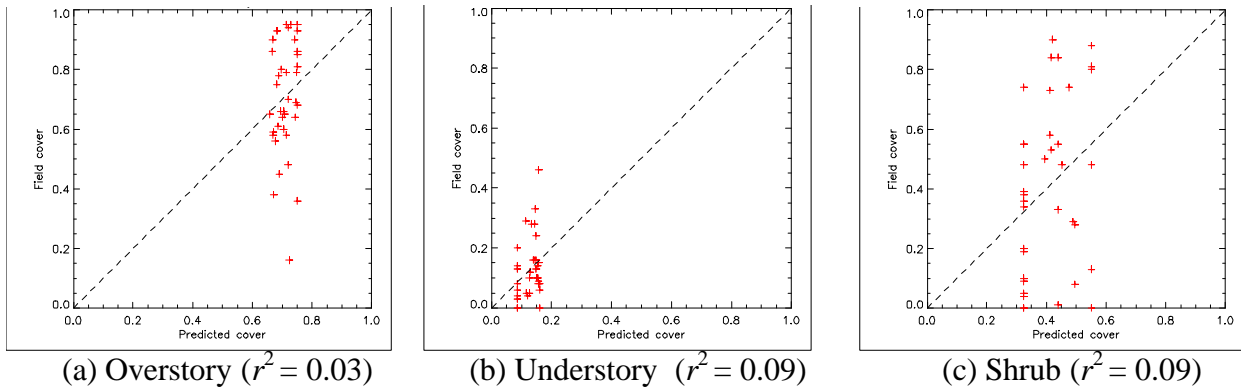(a) Overstory ($r^2 = 0.03$)  (b) Understory ($r^2 = 0.09$)  (c) Shrub ($r^2 = 0.09$)

Figure 12. Field-measured vs. predicted cover within 65-year-old mixed red alder/Douglas-fir stand (Area 1).



(a) Overstory ($r^2 = 0.42$)  (b) Understory ($r^2 = 0.38$)  (c) Shrub ($r^2 = 0.22$)
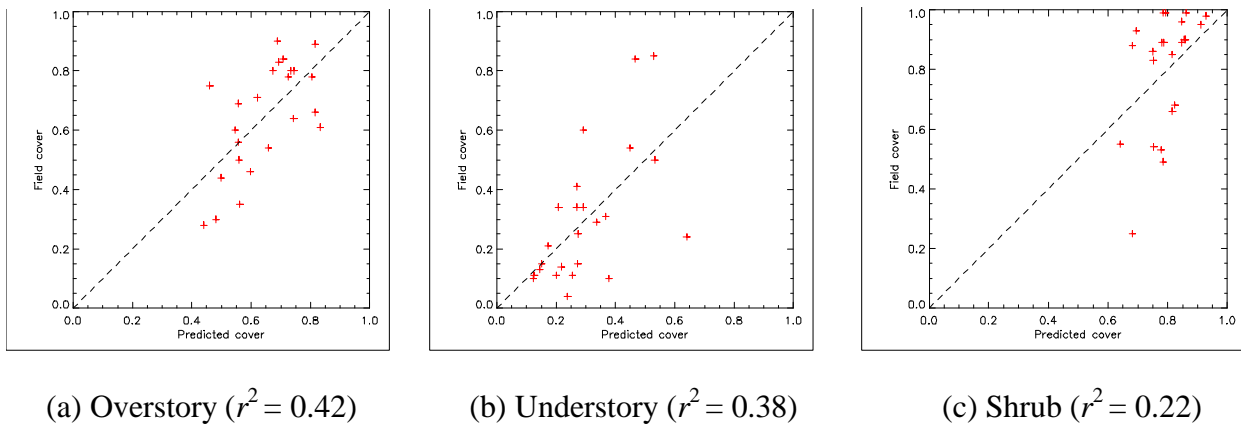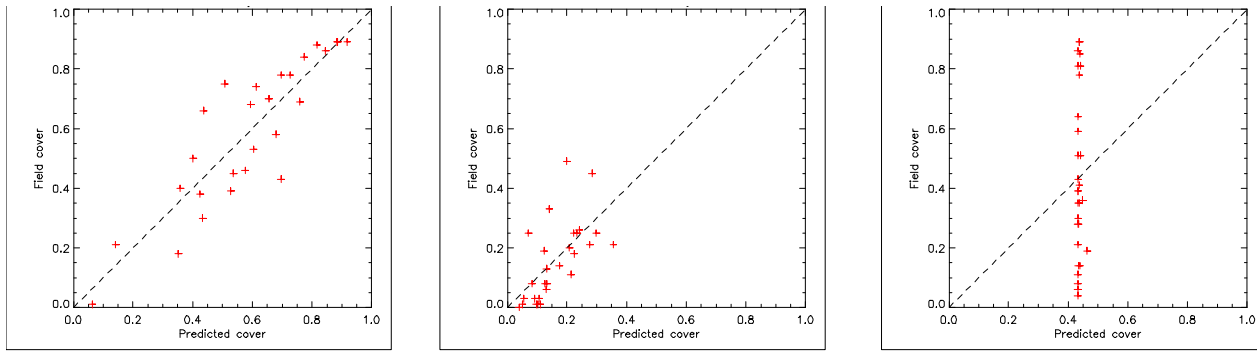
Figure 13. Field-measured vs. predicted cover within 75-year-old Douglas-fir stand in an area with varied, hummocky topography (Area 2).

(a) Overstory ($r^2 = 0.79$)    (b) Understory ($r^2 = 0.38$)    (c) Shrub ($r^2 = 0.0005$)

Figure 14. Field-measured vs. predicted cover within 85-year-old mixed white oak/Douglas-fir stand (Area 3).

The results of this study are, therefore, intended to show the correspondence between field-based estimates, acquired using established inventory protocol at Fort Lewis, and LIDAR-based estimates, and do not represent a true assessment of the accuracy of LIDAR-based cover estimates. Even though LIDAR-based cover estimation is subject to both systematic and random errors, due to the effects of sensing geometry, occlusion, and sampling rate discussed above, it provides for objective, spatially-explicit mapping of forest vegetation cover over extensive areas.

## CONCLUSIONS

LIDAR has the potential to be an extremely useful source of data for mapping of forest structure characteristics, including canopy cover within overstory and understory layers. The increased sampling error at greater depths in the canopy, due to the occlusion effect, limits the utility of LIDAR for estimation of cover within the shrub layer. The off-nadir scanning geometry of LIDAR and the vertical foliage distribution can have significant effects on the functional relationship between LIDAR-based cover measurements and field-based observations of cover based upon the 2-D projection of tree crowns. In forest areas with homogeneous structural characteristics, these

factors can be modeled using a mathematical function based upon radiative transfer theory.

The methodology presented in this paper will be further developed and evaluated through comparison to intensive, objective field-based canopy cover estimates acquired at the same time as the LIDAR data.

A possible extension of this research would be the use of multiple-return or continuous-waveform (i.e. "single photon"), small footprint LIDAR data. The use of multiple-return data with intensity information may allow for more sophisticated and accurate modeling of foliage density and vegetation cover.

A follow-up project will use these results to model the spatial patchiness of canopy cover within Fort Lewis Military Reservation to support habitat monitoring and silvicultural programs.

## LITERATURE CITED

Aber, J.. 1979. A method for estimating foliage height profiles in broad leaved forests. *Journal of Ecology* 67:35-40.

Andersen, H.-E.. 2003. Estimation of critical forest structure metrics through the spatial analysis of airborne laser scanner data.

Unpublished Ph.D. dissertation, University of Washington, Seattle, WA.

Ford, D. and P. Newbould. 1971. The leaf canopy of a coppiced deciduous woodland: I. development and structure. *Journal of Ecology* 59:843-862.

Harding, D., M. Lefsky, G. Parker, J. Blair. 2001. Laser altimeter canopy height profiles: Methods and validation for closed-canopy, broadleaf forests. *Remote Sensing of the Environment* 76:283-297.

Haugerud, R. and D. Harding. 2001. Some algorithms for virtual deforestation (VDF) of lidar topographic survey data. *International Archives of Photogrammetry and Remote Sensing*, XXXIV-3/W4:211-217.

Jennings, S.B., N. Brown, and D. Sheil. 1999. Assessing forest canopies and understory illumination: canopy closure, canopy cover and other measures. *Forestry* 72(1): 59-73.

Lefsky, M., W. Cohen, S. Acker, G. Parker, T. Spies, and D. Harding. 1999. Lidar remote sensing of the canopy structure and biophysical properties of Douglas-fir western hemlock forest. *Remote Sensing of the Environment* 70:339-361.

MacArthur, R. and H. Horn. 1969. Foliage profile by vertical measurements. *Ecology* 50:802-804.

McGaughey, R.. 1997. Visualizing forest stand dynamics using the stand visualization system. In: *Proceedings of the 1997 ACSM/ASPRS Annual Convention and Exposition, vol. 4, pages 248-257, Bethesda, MD, April, 1997.* American Society for Photogrammetry and Remote Sensing.

Magnussen, S. and P. Boudewyn. 1998. Derivations of stand heights from airborne laser scanner data with canopy-based quantile estimators. *Canadian Journal of Forest Research* 28:1016-1031.

Mardia, K., J. Kent, J. Bibby. 1995. *Multivariate Analysis*. Academic Press, London.

Martens, S., S. Ustin, and R. Rousseau. 1993. Estimation of tree canopy leaf area index by gap fraction analysis. *Forest Ecology and Management* 61:91-108.

Means, J., S. Acker, D. Harding, J. Blair, M. Lefsky, W. Cohen, M. Harmon, and W. McKee. 1999. Use of large footprint scanning airborne lidar to estimate forest stand characteristics in the western Cascades of Oregon. *Remote Sensing of the Environment* 67:298-308.

Means, J., S. Acker, B. Fitt, M. Renslow, L. Emerson, C. Hendrix. 2000. Predicting forest stand characteristics with airborne scanning lidar. *Photogrammetric Engineering and Remote Sensing* 66(1):1367-1371.

Radtke, P. and P. Bolstad. 2001. Laser point-quadrat sampling for estimating foliage-height profiles in broad-leaved forests. *Canadian Journal of Forest Research* 31:410-418.