FINAL REPORT
JFSP Project 01-1-4-07:

THE USE OF HIGH-RESOLUTION REMOTELY SENSED DATA IN ESTIMATING CROWN FIRE BEHAVIOR VARIABLES

Hans-Erik Andersen*
USDA Forest Service
PNW Research Station
Anchorage, Alaska

Robert J. McGaughey
Stephen E. Reutebuch
USDA Forest Service
PNW Research Station
Seattle, Washington

Gerard Schreuder
James Agee
College of Forest Resources
University of Washington
Seattle, Washington

SUMMARY

Airborne laser scanning (LIDAR) and interferometric synthetic aperture radar (IFSAR) datasets, along with standard aerial photographs, were acquired over two forested sites in Washington State: second-growth Douglas-fir stands at Capitol Forest in moist western Washington, and mixed pine/fir stands at the Mission Creek Fire/Fire Surrogates site in dry eastern Washington. Forest inventory plots were measured and carefully geo-located on both sites. High resolution orthophotographs were generated for each site. Canopy fuel variables were computed for each plot using these ground measurements.

For each study site regression analysis was used to develop predictive models relating a variety of LIDAR- and IFSAR-based metrics to the canopy fuel parameters. Strong relationships were found for virtually all parameters between remotely sensed metrics and field-based fuel estimates (R^2 ranging from 0.74 to 0.98).

Software and algorithms were developed for processing LIDAR data into a suite of vegetation metrics. The Fusion data visualization system and LIDAR Data Visualization (LDV) system allow users to process, display, and fuse LIDAR data with other remote sensing and GIS spatial data. Working with the Remote Sensing Applications Center (RSAC), software distribution and training materials were developed and are available through the RSAC website.

Additionally, a software suite titled the "Canopy Fuel Estimator" (CFE) was developed that processes LIDAR data into spatially mapped GIS canopy fuel and vegetation structure metrics. This user-friendly package will be released Fall 2006. A ½-day workshop on its use has been proposed for the 2nd Fire Behavior and Fuels Conference in March 2007, targeted for fuels managers and fire remote sensing specialists.

Deliverables to date from the project include: 11 workshop presentations on LIDAR and IFSAR, 12 proceedings papers, 6 peer-reviewed publications (3 additional in review or preparation), 2

* Formerly a research scientist at the University of Washington, College of Forest Resources.

web pages, and 2 software suites. Appendix A includes a list of these deliverables and a CD containing publications and selected presentations is included with this final report.

Deliverables Crosswalk Table

Crosswalk between proposed and delivered research activities, as indicated in our proposal, dated August 24, 2001. See Appendices A and B for detailed list of each output/product.

Proposed	**Delivered**	**Status**
Develop LIDAR/IFSAR canopy fuels estimators	Regression models for canopy fuel variables were developed and published for both LIDAR and IFSAR, based on the Capitol Forest Study site. Regression models for the Mission Creek FFS site and combined Capitol Forest and Mission Creek site will be developed. A publication will be submitted in Dec. 2006.	Done Dec. 2006
Develop LIDAR/IFSAR processing software	The Fusion visualization system was developed to allow users to display LIDAR or IFSAR 3D data with tradition 2D imagery (e.g., orthophotos, satellite images, maps). The LIDAR Data Visualization (LDV) suite was developed to allow display, ground and canopy surface generation, and direct 3D measurements from LIDAR (and IFSAR) datasets.	Done Done
LIDAR processing software distribution & training website	In conjunction with RSAC a website was developed for distribution and training of the LIDAR processing and visualization software: http://www.fs.fed.us/eng/rsac/fusion/ A project website is available at: http://www.cfr.washington.edu/research.pfc/research/jfsp/ The Canopy Fuels Estimator (CFE) software suite will be completed and distributed in Fall 2006.	Done Done Oct. 2006
Workshops	LIDAR/IFSAR results were presented at 11 workshops (see Appendix B for detailed list). A ½-day workshop on the LIDAR Canopy Fuel Estimator has been proposed for the 2nd Fire Behavior and Fuels Conference in March 2007, targeted for fuels managers and fire remote sensing specialists.	Done March 2007
Presentations	35 presentations to federal, state, local, academic, and professional groups were made, including 7 presentations at international meetings.	Done
Archived Database	An archive of all ground and remote sensing data was created and is stored at the University of Washington.	Done
Published Outputs	5 journal articles and 1 book chapter were published. 1 journal article is in review. 2 additional journal articles are planned for submission. 12 proceedings papers were published. PNW Science Update highlighting LIDAR for vegetation measurement was published for more general audiences.	Done Dec. 2006 Done Done

PROJECT OVERVIEW

Fire researchers and managers are dependent upon accurate, reliable, and efficiently obtained data for the development and application of crown fire behavior models. In particular, reliable estimates of critical crown characteristics, including crown bulk density, canopy height, crown base height, and canopy closure are required to accurately map fuel loading and model fire behavior over at the landscape scale. The emergence of a new generation of high-resolution remote sensing systems in recent years, as well as the development of more accurate field measurement techniques, allow for more accurate and efficient estimation of crown fire behavior variables. With spatial resolutions often less then one meter, the spatial data provided by these sensors can support more detailed measurement of the forest canopy structure. Analytical techniques and associated software were developed to automatically and efficiently extract the required information from the enormous quantity of data provided by these high-resolution remote sensing systems.

Project Objectives, Study Sites, and Datasets

We carried out an extensive investigation of the utility of A) active infrared scanning (LIDAR) sensor data and B) active microwave (interferometric synthetic aperture radar, IFSAR) sensor data for this application, and C) compared remote sensing estimates with field-based techniques for the estimation of crown fire fuel density, type and condition. Two sites were used: 1) mixed-conifer [ponderosa pine (*Pinus ponderosa*), Douglas-fir, grand fir (*Abies grandis*)] stands in the Mission Creek Fire/Fire Surrogates study site in Wenatchee National Forest in the eastern Cascades of Washington State; and, 2) 70-yr-old second growth stands dominated by Douglas-fir (*Pseudotsuga menziesii*), western hemlock (*Tsuga heterophylla*), and western redcedar (*Thuja plicata*) in the Blue Ridge area of Capitol State Forest in western Washington State (Figure 1).

Figure 1. Location of study areas. (Photo credits: Blue Ridge: Gordon Bradley (University of Washington), Mission Creek: http://www.fs.fed.us/ffs/slideshow.html).

The Mission Creek site is one of thirteen (13) Fire and Fire Surrogates (FFS) sites distributed nationwide and designed to investigate the economic and ecological effects of fire and fire surrogate treatments in a number of different forest types and conditions in the United States (FFS Project Executive Summary). This site contains twelve (12) treatment units (3 thinned and burned, 3 thinned, 3 burned, and 3 control), where six (6) 20 m × 50 m vegetation plots were established within each unit (Figure 2). In this project, highly accurate (~ 1 m error) positions were established for these plots using a differentially corrected GPS and laser surveying instruments in 2003 and 2004.

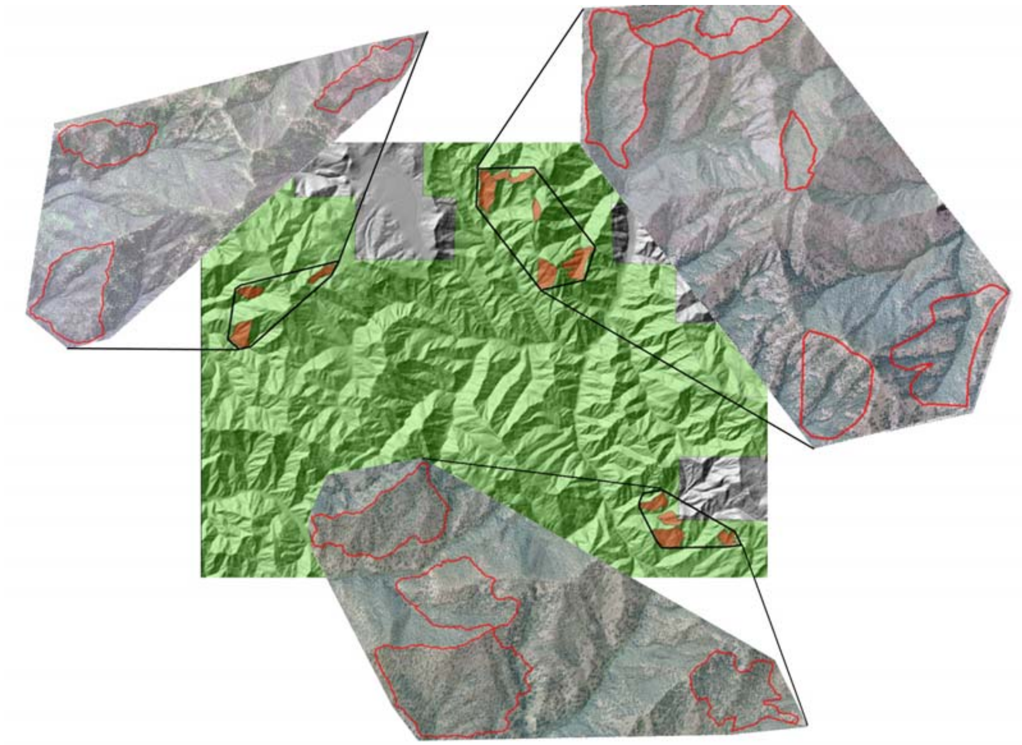


Figure 2. Mission Creek FFS study site (general location and individual orthophotographs of each treatment unit).

The Blue Ridge area is the site for an ongoing silvicultural trial investigating the effects of several different harvest treatments designed to create a variety of different residual stand densities: clearcut [0 trees per ha(TPH)], heavily-thinned (40 TPH), lightly-thinned (175 TPH), and control (280 TPH). A systematic grid of 101 inventory plots was established across a range of different stand types in this study area. These plots were georeferenced as part of a high-accuracy topographic survey carried out in 1999 (Figure 3).

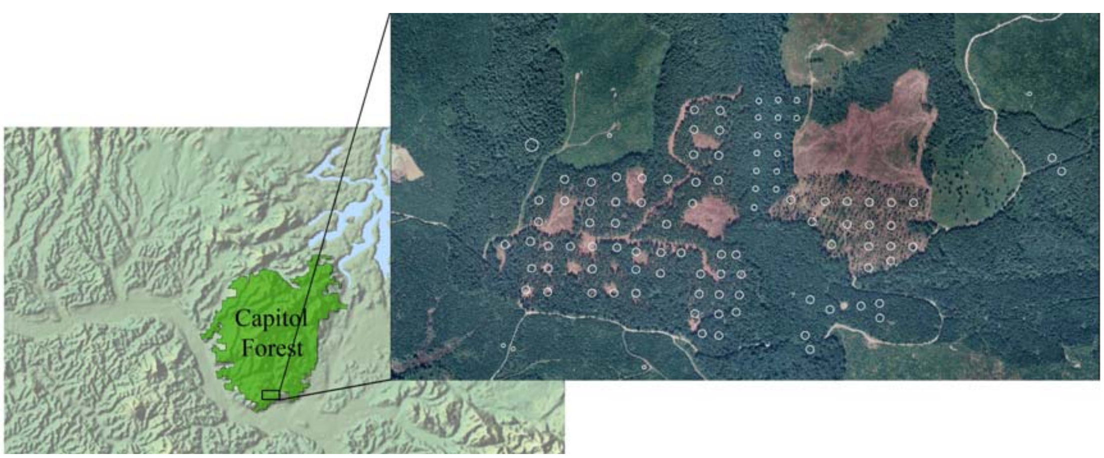


Figure 3. Orthophotograph of Blue Ridge study site. White circles indicate ground plots.

Both study sites are mountainous, with elevations ranging from 150 to 400 meters at the Blue Ridge site and 650 to 1500 meters at the Mission Creek site.

On both sites high-resolution LIDAR and IFSAR datasets were acquired using commercially available sensors flown in fixed-wing aircraft. Ground plot data were collected at both sites and these datasets were then analyzed to determine if a suite of remotely sensed variables were significantly correlated with ground measured canopy fuel variables at the plot level.

RESULTS

Accuracy of remotely sensed digital terrain models (DTMs) under forest canopy

An important question that was investigated was the accuracy of ground surface models or DTMs generated from LIDAR and IFSAR data. This DTM accuracy influences the estimation of any vertical vegetation structure variables. To address this question, a network of three-hundred and forty-seven (347) high accuracy topographic check points (Figure 4) was established at the Blue Ridge study site by the Washington Department of Natural Resources, PNW Research Station, and the University of Washington under stands with varying forest canopy densities (clearcut (0 trees per hectare (TPH)), heavily-thinned (40 TPH), lightly-thinned (175 TPH), and uncut (280 TPH)). After a least-squares adjustment of the survey network, the accuracy of the check points was 15 cm (horizontal) and 3 cm (vertical). The accuracy of the LIDAR- and IFSAR-derived digital terrain models (Figure 5) acquired at the Blue Ridge site was assessed via comparison to the topographic checkpoints (Reutebuch *et al*., 2003; Andersen *et al*. 2005a).

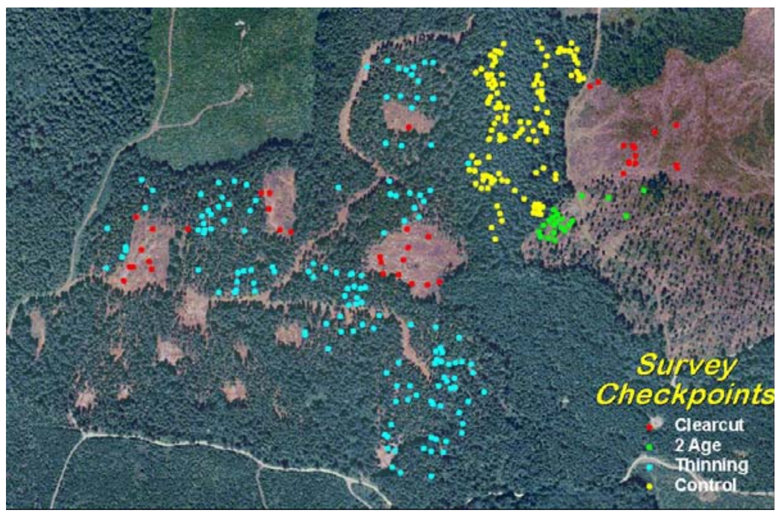


Figure 4. Orthophotograph, Blue Ridge site. Dots indicate the location of ground-surveyed elevation checkpoints.

Accuracy of LIDAR-derived DTM under forest canopy

The mean LIDAR DTM error over the entire site was 0.22 ± 0.24 m (mean ± SD), with a root-mean-square-error (RMSE) of 0.32 m. The DTM error increased slightly with increased canopy density but the differences were strikingly small and of virtually no practical significance. In general, the LIDAR DTM was found to be extremely accurate even under very dense conifer stands that are characteristic of Pacific Northwest forests.

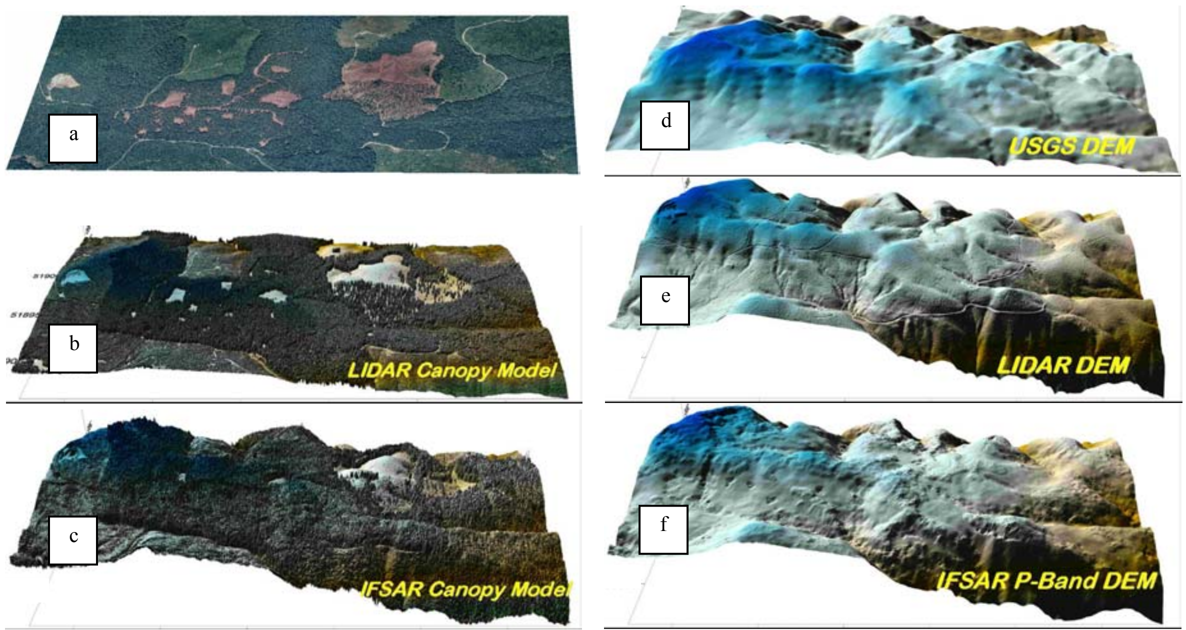


Figure 5. 1999 orthophotograph (a); 1999 LIDAR canopy surface model (b); 2002 IFSAR canopy surface model (c); USGS 10m resolution DTM (d); LIDAR 1m resolution DTM (e); IFSAR 1m resolution DTM (f), Blue Ridge site.

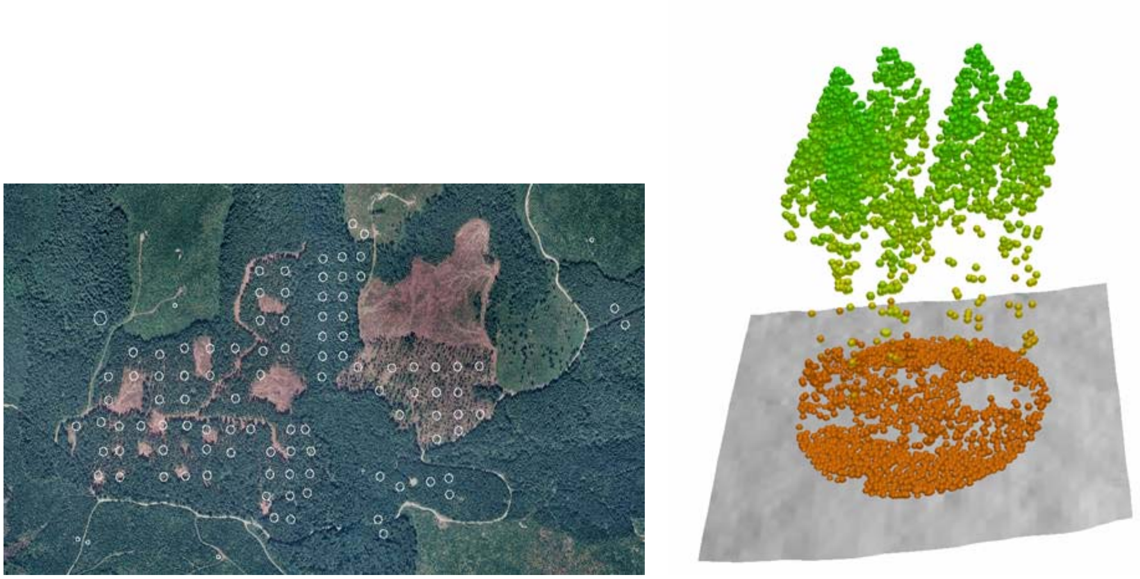
Accuracy of IFSAR-derived DTM under forest canopy

The accuracy of a P-band IFSAR-derived DTM was also assessed via comparison to these high-accuracy topographic check points (Andersen *et al*, 2005a). Low-frequency P-band radar energy physically penetrates through the vegetation canopy and reflects from the underlying terrain surface (Andersen *et al*., 2006). The mean error of the P-band DTM was -0.28 ± 2.59 m (RMSE = 2.6 m), and the accuracy of the DTM did degrade in areas with higher canopy density. However, the accuracy of the P-band DTM was significantly higher than that of the standard USGS 10-meter DTM available for this area (RMSE = 8.8 m). It should be noted that the availability of P-band IFSAR data in the contiguous United States will be limited due to restrictions on frequencies imposed by the Federal Communication Commission (FCC).

Estimating canopy fuels parameters using LIDAR data

A methodology was developed to estimate several critical forest canopy fuel parameters using LIDAR data and ground vegetation plot data (Andersen *et al*., 2005b). At the Blue Ridge study site, canopy fuel parameters were measured at 101 fixed area field inventory plots established in 1999 and 2003 over a range of stand conditions (Figure 6).

Field-based estimates of canopy fuel parameters, including canopy height, canopy base height, canopy bulk density, and canopy fuel weight, were generated using the methodology developed for the Fire and



a b

Figure 6. Location of field plots (white circles) at Blue Ridge study site (a) and example of LIDAR point cloud within 1/5th acre plot (b).

Fuels Extension to the Forest Vegetation Simulator (FFE-FVS). Multiple regression analysis was used to develop the mathematical relationships between the plot-level fuel parameters and a number of LIDAR-derived structural metrics. A leave-one-out cross validation procedure was used to assess the predictive value of each regression model.

Strong relationships between LIDAR-derived metrics and field-based fuel estimates were found for all parameters [sqrt(canopy fuel weight): $R^2=0.86$; ln(crown bulk density): R^2=0.84; canopy base height: R^2=0.77; canopy height: R^2=0.98]. Figure 7 illustrates correlations between LIDAR-derived and ground measured canopy fuel variables at Blue Ridge. In another study, this same methodology was used to estimate several important inventory parameters at the plot level at the Blue Ridge site [sqrt(basal area): $R^2=0.91$; sqrt(stem volume): R^2=0.92; dominant height: R^2=0.96; sqrt(biomass): R^2=0.91] (Andersen *et al*., 2005).

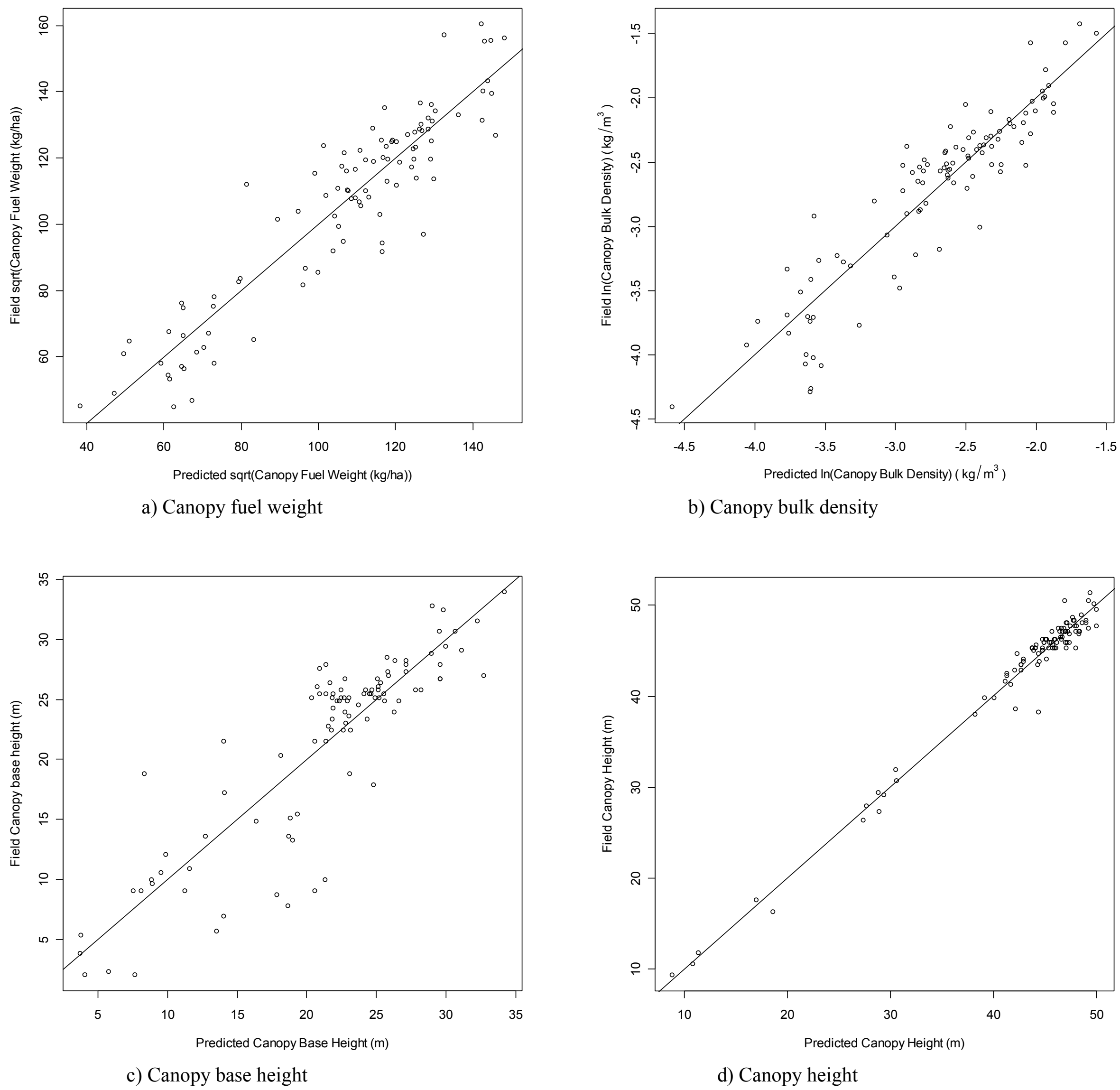


Figure 7. Scatter plots showing correlations between field- and LIDAR-based estimates of canopy fuel variables at Blue Ridge site. Lines represent 1:1 relationship.

A similar approach has been used to estimate canopy fuel parameters at the Mission Creek (FFS) site. The results of an analysis comparing the results obtained at the Blue Ridge and Mission Creek sites will be reported in a future paper (Andersen *et al*., in prep). The predictive models developed in these analyses will be provided in the equation library of the Canopy Fuels Estimator tool (described below in the LIDAR & IFSAR Tools of this report).

Estimating canopy fuel parameters using IFSAR data

A similar approach was used to estimate inventory and fuel parameters using dual-frequency X-/P-band IFSAR data acquired over the Blue Ridge site in 2002 (Andersen *et al*., 2004a). Multiple regression was used to develop mathematical models relating a number of IFSAR-derived variables [canopy height (X-band canopy surface elevation minus P-band ground surface elevation), X-band coherence, X-band backscatter, P-band VV backscatter, P-band VH backscatter, P-band HH backscatter, P-band coherence, and IFSAR-derived canopy density] and plot-level canopy fuel estimates. The correlations between IFSAR observables and canopy fuel variables were generally quite high (canopy height: $R^2=0.89$; canopy base height: $R^2=0.85$; canopy bulk density: R^2=0.74; canopy fuel weight: R^2=0.77).

Due to the FCC restrictions on radar frequencies, we were not able to collect dual-frequency (X-/P-band) IFSAR data over the Mission Creek site. However, high resolution X-band data were collected over Mission Creek in 2005.

In order to evaluate the influence of interferometric processing and flying height on the quality of the canopy height information provided by X-band IFSAR, the vendor (Intermap Technologies Inc.) delivered elevation data acquired at two different flying heights and processed the data using four different levels of interferogram filtering. A subsequent analysis of these data and comparison to high resolution LIDAR data found that differences in flying heights and levels of interferogram filtering had little effect on the accuracy of canopy height measurements, while sensing geometry can have a significant effect on the quality of IFSAR-derived canopy measurements (Andersen *et al*., 2006; Andersen *et al*., in prep). These results suggest that the typical mission parameters used for high resolution IFSAR topographic survey may also be adequate for forest monitoring applications, and also support the conclusion that acquiring data from multiple look directions may be the most important consideration in the planning of IFSAR flights for forest mapping applications.

LIDAR & IFSAR TOOLS

A major component of this project was the development of specialized remote sensing software systems that could efficiently process, analyze, and display the extremely large LIDAR and IFSAR datasets that were acquired over the study sites. For instance, there are 40 million data points in the LIDAR dataset covering the 2 square mile Blue Ridge study site and approximately 10 times this amount of data covering the Mission Creek site. Commercial remote sensing packages did not have the capacity to handle such large datasets.

FUSION LIDAR/IFSAR data conversion, processing, and display software suite

To address this need, a LIDAR/IFSAR data conversion, analysis, and display software suite, known as FUSION was developed (McGaughey and Carson, 2003). FUSION allows 3-dimensional terrain and canopy surface models and LIDAR/IFSAR data to be fused with more traditional 2-dimensional imagery (e.g., orthophotographs, topographic maps, satellite imagery, GIS shapefiles).

FUSION processes raw LIDAR data into a number of vegetation metrics. Canopy- and ground-level surface models can be produced; and then, by simple differing, canopy height models can be generated (Figure 8) FUSION includes algorithms that allow the user to manually measure individual tree attributes or use automated capabilities to characterize individual tree attributes over large areas (McGaughey *et al*., 2004).

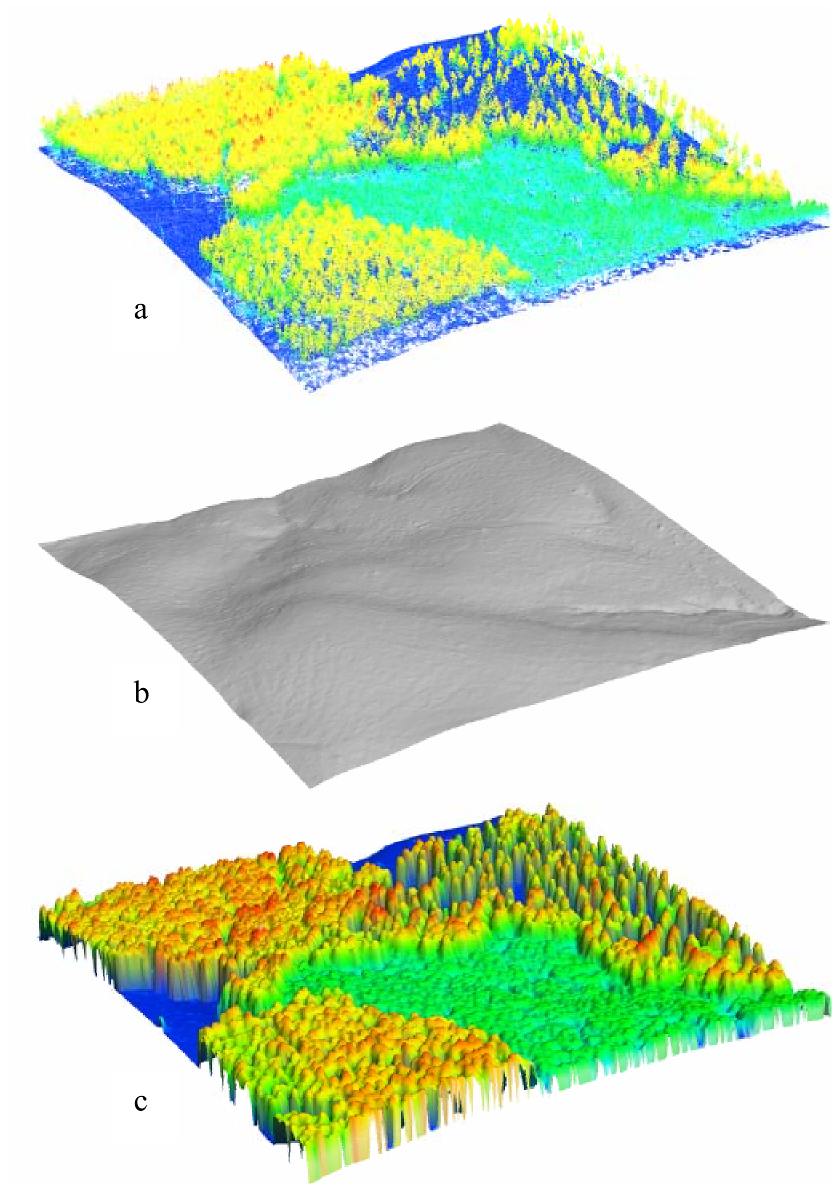


Figure 8. Raw LIDAR point cloud (a); LIDAR-derived terrain model (b); LIDAR-derived canopy surface model (c), Blue Ridge site.

FUSION technology transfer

Through several workshops and presentations, the FUSION software was refined and enhanced to make it useful and accessible to forest managers (see Appendix B). In 2006, working in conjunction with the USDA Forest Service, Remote Sensing Applications Center (RSAC), a FUSION tutorial, installation guide, and example datasets were generated and are now available over the internet through RSAC (http://www.fs.fed.us/eng/rsac/fusion/). A FUSION installation CD was distributed to over 150 attendees of the 2006 RSAC Remote Sensing Workshop and a

FUSION demonstration booth was included at the Salt Lake City 2006 workshop. FUSION is publicly available worldwide through the internet.

Canopy Fuel Estimator—CFE Fuel characterization using airborne laser scan data

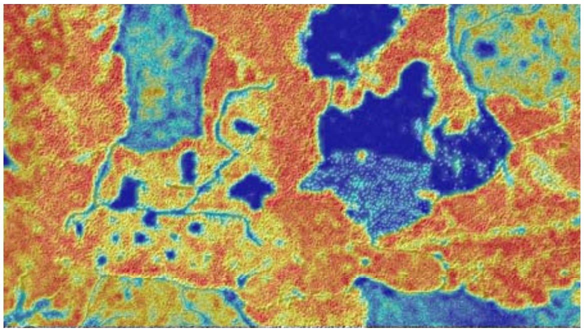
To assist resource managers in the use of LIDAR to characterize canopy fuels over the landscape, a LIDAR processing tool titled the Canopy Fuel Estimator (CFE) is under development and scheduled from release in Fall 2006.

The overall objective of the Canopy Fuel Estimator (CFE) is to use data from airborne laser scanner (small-footprint LIDAR) systems to characterize fuel conditions over extensive land areas. The primary reference for the methodology is Andersen *et al*. (2005b). Processing is accomplished in a raster environment using input layers and ground surface models derived from LIDAR point data. While the CFE is primarily designed to estimate canopy fuel parameters, its design is flexible enough to support a variety of analysis tasks that involve LIDAR point data, production of data layers derived from the point data, and, optionally, application of a "model" to predict a variable of interest.

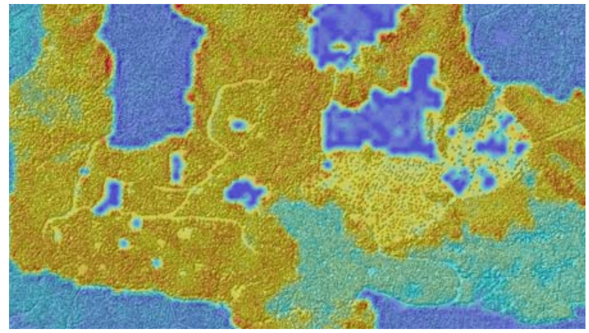
CFE overview

CFE computes LIDAR-derived variables for the maximum, mean, and coefficient of variation of the LIDAR canopy heights, several quantile-based metrics describing the LIDAR canopy height distribution, and a canopy density metric. The CFE includes models that use these LIDAR-derived variables to predict canopy fuel weight, crown bulk density, canopy base height, and canopy height over the landscape. Models included with the CFE are applicable to forests in western and eastern Washington. Additional models can be defined using a combination of LIDAR-derived metrics and either pre-defined or user-supplied model forms. The CFE reads industry-standard LAS LIDAR data files and produces raster output that is compatible with most Geographic Information System (GIS) environments.

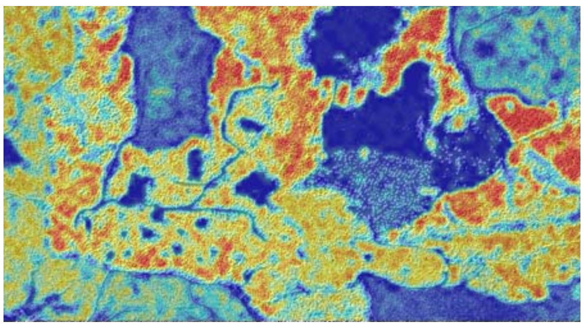
The CFE is designed as a stand-alone program that uses a graphical interface to guide the user through data processing and analysis. CFE is designed in such a way that it can be "connected" to ArcMap at a later date. This connection will most likely consist of adding a menu option or button to ArcMap that launches the CFE and providing the ability to create an ArcMap project that includes the input data, intermediate data products, and final outputs as layers in the project. The CFE will perform its own processing without relying on ArcObjects but will interact with ArcObjects to access and manage the ArcMap project. Output from the CFE is a series of new spatial data layers that describe fuel characteristics and the distribution of forest canopy over the project area (Figure 9).



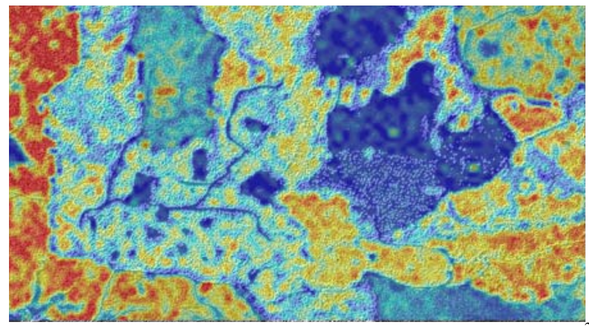
a) Canopy cover (Blue: 0% cover, Red: 100% cover)



b) Canopy height (Blue: 0 m, Red: 60 m)



c) Canopy fuel weight (Blue: 0, Red: 27,000 kg/ha)



d) Canopy bulk density (Blue: 0.00, Red: 0.28 kg/m^3)

Figure 9. Canopy fuel maps (30 m resolution), Blue Ridge site.

LIDAR-derived canopy metrics and canopy fuel layers

The LIDAR points used for all derived canopy metrics is the set of LIDAR returns that are 2 meters (user defines this canopy threshold height) or more above the LIDAR bare-ground surface. This subset of LIDAR returns represents "vegetation points". The following variables are computed from the raw LIDAR point data and the bare-ground surface model.

LIDAR-derived metric	**Description**
h_{max}	Maximum height for the vegetation points within a grid cell
h_{mean}	Mean height for all vegetation points within a grid cell
h_{CV}	Coefficient of variation of the vegetation point heights
h_{10}	10^{th} percentile height of the vegetation points
h_{25}	25^{th} percentile height of the vegetation points
h_{50}	50^{th} percentile height of the vegetation points
h_{75}	75^{th} percentile height of the vegetation points
h_{90}	90^{th} percentile height of the vegetation points
D	Canopy density metric defined as the proportion of first returns whose height is 2 meters or greater divided by the total number first returns (0.0 to 1.0).

The following spatially explicit canopy fuel layers are generated from the LIDAR-derived canopy metrics in a GIS-compatible raster format.

Canopy fuel layer	Description
Fuel weight	Total canopy fuel (kg per ha)
Crown bulk density	Density of canopy fuels (kg per m^3)
Base height	Lowest height where crown bulk density exceeds 0.011 kg/ m^3
Canopy height	Highest height where crown bulk density exceeds 0.011 kg/ m^3

CFE metadata

Output from the CFE consists of a plain text report and an HTML report. The plain text report documents the input data, model set, and output layers. It contains enough information for a user could re-create the run if necessary. The HTML report contains all of the information from the plain text report but also provides links to images representing the input data and output layers. FUSION is used to automatically generate the images and image legends.

CFE technology transfer

CFE is currently under development and planned for release in Fall 2006. In addition, a workshop has been proposed for the 2nd Fire Behavior and Fuels Conference in March 2007, targeted for fuels managers and fire remote sensing specialists. A tutorial, installation package, and example dataset will be developed and distributed over the internet.

MANAGEMENT IMPLICATIONS

Results of this project demonstrate that canopy fuel variables can be estimated and mapped over the landscape using LIDAR and IFSAR at a cost of approximately $1-2 per acre in mature conifer forests of Washington. Additional testing in other forest types is needed to geographically extend the methodology; however, it is expected that similar results would be achievable in most conifer forests with canopy heights greater than 10 m. Remotely sensed GIS layers of key canopy fuel variables can be generated and used in fire spread and fire behavior models to help prioritize fuel treatment planning at the landscape level.

LIDAR/IFSAR can provide baseline data on the terrain surface and vegetation structure for a host of resource monitoring, measurement, and inventory activities. LIDAR/IFSAR metrics can be used in many other resource areas that need objective, landscape level estimates of key vegetation cover such as inventory, wildlife habitat, slope stability analysis, geologic mapping, stream channel mapping, and road design.

LIDAR data collected at approximately 4 returns per square meter is sufficient to generate vegetation structure metrics that are adequate for most analysis. Specialized software that can handle the immense volume of data typically collected with such high-resolution LIDAR/IFSAR missions has been developed and is being distributed as freeware through the USDA Forest Service, Remote Sensing Application Center.

APPENDIX A: PUBLISHED OUTPUTS

Peer-reviewed Publications

Andersen, H.-E., S.E. Reutebuch, and R.J. McGaughey. 2006. Chapter 3: Active remote sensing. In Computer Applications in Sustainable Forest Management, Edited by G. Shao and K. Reynolds. Springer-Verlag, Dordrecht. *In press.*

Reutebuch, S.E., H.-E. Andersen, and R.J. McGaughey. 2005. Light Detection and Ranging (LIDAR): An emerging tool for multiple resource inventory. *J. of Forestry* 103(6):286-292.

Andersen, H.-E., S.E. Reutebuch, and R.J. McGaughey. 2005a. Accuracy of an IFSAR-derived digital terrain model under a conifer forest canopy. *Canadian J. of Remote Sens.* 31(4):283-288.

Andersen, H.-E., R.J. McGaughey, and S.E. Reutebuch. 2005b. Estimating forest canopy fuel parameters using LIDAR data. *Remote Sensing of Environment* 94:441-449.

Zhao, G., G. Shao, K. M. Reynolds, M.C. Wimberly, T. Warner, J.W. Moser, K. Rennolls, S. Magnussen, M. Kohl, H.-E. Andersen, G.A. Mendoza, L. Dai, A. Huth, L. Zhang, J. Brey, Y. Sun, R. Ye, B.A. Martin, and F. Li. 2005. Digital Forestry: A White Paper. *J. of Forestry* 103(1):47-50.

Reutebuch, S.E., R.J. McGaughey, H.-E. Andersen, and W. Carson. 2003. Accuracy of a high-resolution LIDAR-based terrain model under a conifer forest canopy. *Canadian Journal of Remote Sensing* 29(5): 1-9.

Conference Proceedings and Public Articles

McGaughey, R.J., H.-E. Andersen, and S.E. Reutebuch. 2006. Considerations for planning, acquiring, and processing LIDAR data for forestry applications. In Proceedings of the eleventh Biennial USDA Forest Service Remote Sensing Applications Conference, Salt Lake City, ID, April 24-28, 2006. American Society of Photogrammetry and Remote Sensing, Bethesda, MD. *In press*.

Andersen, H.-E., R.J. McGaughey, and S.E. Reutebuch. 2006. Assessing the influence of flight parameters and interferometric processing on the accuracy of X-band IFSAR-derived forest canopy surface models. In: Koukal, T. and W. Schneider, eds., *Proceedings of the EARSeL Workshop on 3D Remote Sensing in Forestry, Vienna, Austria, February 14 - 15, 2006.*University of Natural Resources and Applied Life Sciences (BOKU), Vienna.

Andersen, H-E, R.J. McGaughey, and S.E. Reutebuch. 2005. Forest measurement and monitoring using high-resolution airborne LIDAR. In: Harrington, C.A. and S.H. Schoenholtz, eds., *Productivity of Western forests: A Forest Products Focus*, General Technical Report PNW-GTR-642. U.S. Department of Agriculture Forest Service, Pacific Northwest Research Station, Portland, OR.

Rapp, V. 2005. Monitoring forests at the speed of light. Science Update. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR. Issue 12. 11 p.

Andersen, H.-E., R.J. McGaughey, S.E. Reutebuch, G.F. Schreuder, J. Agee, and B. Mercer. 2004a. Estimating canopy fuel parameters in a Pacific Northwest conifer forest using multifrequency polarimetric IFSAR. *International Archives of Photogrammetry and Remote Sensing*, Istanbul, Turkey, Vol. XXXV, Part B.

Andersen, H.-E., R.J. McGaughey, S.E. Reutebuch, W.W. Carson and G.F. Schreuder. 2004b. Estimating forest crown fuel variables using LIDAR data. *Proceedings of the Annual ASPRS Conference, Denver, May 23-28, 2004*. American Society of Photogrammetry and Remote Sensing, Bethesda, MD.

McGaughey, R.J., W.W. Carson, S.E. Reutebuch, and H.-E. Andersen. 2004. Direct measurement of individual tree characteristics from LIDAR data. *Proceedings of the Annual ASPRS Conference, Denver, May 23-28, 2004*. American Society of Photogrammetry and Remote Sensing, Bethesda, MD.

Carson, W., Andersen, H.-E., S.E. Reutebuch, and R.J. McGaughey. 2004. LIDAR applications in forestry: An overview. *Proceedings of the Annual ASPRS Conference, Denver, May 23-28, 2004*. American Society of Photogrammetry and Remote Sensing, Bethesda, MD.

Andersen, H.-E., R.J. McGaughey, W.W. Carson, S.E. Reutebuch, B. Mercer, and J. Allan. 2003a. A comparison of forest canopy models derived from LIDAR and IFSAR data in a Pacific Northwest conifer forest. *International Archives of Photogrammetry and Remote Sensing*, Dresden, Germany, Vol. XXXIV, Part 3 / W13.

Andersen, H.-E., J. Foster, and S.E. Reutebuch. 2003b. Estimating forest structure parameters within Fort Lewis Military Reservation using airborne laser scanner (LIDAR) data. 2003. *Proceedings of the Second International Precision Forestry Symposium, USA, June 16-18, 2003.*

McGaughey, R. J. and W.W. Carson. 2003. Fusing LIDAR data, photographs, and other data using 2D and 3D visualization techniques. In: *Proceedings of Terrain Data: Applications and Visualization – Making the Connection,* October 28-30, 2003; Charleston, South Carolina: Bethesda, MD: American Society for Photogrammetry and Remote Sensing. pp. 16-24.

Reutebuch, S.E., H.-E. Andersen, K. Ahmed, T. Curtis. Evaluation of laser light detection and ranging (LIDAR) measurements in a forested area. 2003. In: Curtis, R., D. Marshall, and D. DeBell, eds., *Silvicultural options for young-growth Douglas-fir forests: The Capitol Forest Study--Establishment and First Results.* General Technical Report PNW-GTR-598. U.S. Department of Agriculture Forest Service, Pacific Northwest Research Station, Portland, OR.

Papers in preparation

Andersen, H.-E., S.E. Reutebuch, and R.J. McGaughey. A rigorous assessment of tree height measurements obtained using airborne LIDAR and conventional field methods. *Canadian Journal of Remote Sensing*. *In review*.

Andersen, H.-E., T. Marsh, S.E. Reutebuch, and R.J. McGaughey. Assessing the influence of flight parameters and interferometric processing on the accuracy of X-band IFSAR-derived forest canopy height and cover estimates. *In prep*.

Andersen, H.-E., Y. Li, R.J. McGaughey, and S.E. Reutebuch. Estimating canopy fuel parameters in fire-prone forests of the eastern Cascades using LIDAR data. *In prep*.

APPENDIX B: PRESENTATIONS

McGaughey, R.J., H.-E. Andersen, and S.E. Reutebuch. 2006. Characterizing Vegetation Structure Using Discrete-Return, Airborne Laser Scanner Data. *Presentation at the National meeting of The Wildlife Society. Sept 2006. Anchorage, AK.*

Andersen, H.-E., S.E. Reutebuch, and R.J. McGaughey. 2006. Forest measurement and monitoring using high-resolution airborne LIDAR. *Society of American Foresters (SAF) North Puget Sound Chapter meeting, June 14, 2006, Mount Vernon, WA.*

Andersen, H.-E., S.E. Reutebuch, and R.J. McGaughey. 2006. Forest measurement and monitoring using high-resolution airborne LIDAR. *Oregon State University American Society of Photogrammetry and Remote Sensing (ASPRS) Student Chapter meeting, June 2, 2006, Corvallis, OR.*

McGaughey, R.J., H.-E. Andersen, and S.E. Reutebuch. 2006. Considerations for planning, acquiring, and processing LIDAR data for forestry applications. *Eleventh Biennial USDA Forest Service Remote Sensing Applications Conference, April 24-28, 2006, Salt Lake City, UT.*

Andersen, H.-E., S.E. Reutebuch, and R.J. McGaughey. 2006. Forest measurement and monitoring using high-resolution airborne LIDAR. *Society of American Foresters (SAF) South Puget Sound Chapter meeting, March 16, 2006, Fife, WA.*

McGaughey, R.J., H.-E. Andersen, and S.E. Reutebuch. 2006. LIDAR Remote Sensing for Characterizing and Visualizing Vegetation Structure. *Presentation to NOAA National Marine Fisheries Staff. March 15, 2006, Seattle, WA.*

Andersen, H.-E., R.J. McGaughey, and S.E. Reutebuch. 2006. *EARSeL Workshop on 3D Remote Sensing in Forestry, Vienna, Austria, February 14 - 15, 2006. University of Natural Resources and Applied Life Sciences (BOKU), Vienna, Austria. .*

McGaughey, R.J., H.-E. Andersen, and S.E. Reutebuch. 2005. LIDAR applications in forestry. *Presentation to the annual University of Washington, College of Forest Resources Alumni Association. Nov 4, 2005. Seattle, WA.*

McGaughey, R.J., H.-E. Andersen, and S.E. Reutebuch. 2005. LIDAR Remote Sensing for Characterizing and Visualizing Vegetation Structure. *Presentation at the National Meeting of the Society of American Foresters. Oct 19-23, 2005, Fort Worth, TX.*

Andersen, H.-E., S.E. Reutebuch, and R.J. McGaughey. 2005. Remote Sensing Research within the UW Precision Forestry Cooperative. *Weyerhaeuser Western Forestry Research Conference, October13, 2005, Skamania, WA.*

McGaughey, R.J., H.-E. Andersen, and S.E. Reutebuch. 2005. Comparing Estimates of Canopy Structure Derived from Leaf-On and Leaf-Off Airborne Laser Scanner Data. *Silviscan: LIDAR Applications in Forest Assessment and Inventory, September 29 - October 1, 2005, Blacksburg, VA.*

Andersen, H.-E., R.J. McGaughey, and S.E. Reutebuch. 2005. Assessment of LIDAR-derived forest measurements as a source of data for forest growth models. *Silviscan: LIDAR Applications in Forest Assessment and Inventory, September 29 - October 1, 2005, Blacksburg, VA.*

Schreuder, G.F. and H.-E. Andersen. 2005. Precision Forestry: Application of Advanced Technologies to Forest Resource Management. *XXII IUFRO World Congress, August 8-13, 2005, Brisbane, Australia.*

Andersen, H.-E., S.E. Reutebuch, and R.J. McGaughey. 2005. Forest measurement and monitoring using high-resolution airborne LIDAR. *Briefing at USDA Forest Service Washington Office. July 14, 2005, Washington DC.*

Andersen, H.-E., S.E. Reutebuch, and R.J. McGaughey. 2005. Forest measurement and monitoring using high-resolution airborne LIDAR. *Seminar at United States Geological Survey (USGS) National Headquarters, July 13, 2005, Reston, VA.*

Schreuder, G.F., H.-E. Andersen, R.J. McGaughey and S.E. Reutebuch. 2005. Precision Forestry: Application of Advanced Technologies to Forest Resource Management. *Western Mensurationists' Meeting, July 4-7, 2005, Hilo, Hawaii.*

Andersen, H.-E., S.E. Reutebuch, and R.J. McGaughey. 2005. Forest measurement and monitoring using high-resolution airborne LIDAR. *LIDAR workshop sponsored by the USDA Forest Service Remote Sensing Applications Center. May 17-19, 2005. Salt Lake City, UT.*

Andersen, H.-E., S.E. Reutebuch, and R.J. McGaughey. 2005. The Use of High-Resolution Interferometric Synthetic Aperture Radar for Forest Measurement Applications. *LIDAR workshop sponsored by the USDA Forest Service Remote Sensing Applications Center. May 17-19, 2005. Salt Lake City, UT.*

McGaughey, R.J., S.E. Reutebuch, and H.-E. Andersen. 2005. Interactive Visualization of LIDAR Project Data: Pulling it All Together. *LIDAR workshop sponsored by the USDA Forest Service Remote Sensing Applications Center. May 17-19, 2005. Salt Lake City, UT.*

Andersen, H.-E., R.J. McGaughey, and S.E. Reutebuch. 2005. The use of high-resolution, active airborne remote sensing technologies to support precision forestry. *Second Appalachian Remote Sensing Conference, West Virginia University, May 11, 2005, Morgantown, WV.* Keynote speaker.

Reutebuch, S.E. 2005. Demonstration of FUSION LIDAR software for terrain and vegetation measurements. *Idaho Panhandle National Forest, Supervisors Office, January 26, 2005, Coeur d'Alene, ID.*

Reutebuch, S.E. 2004. Measuring topography and forest structure with LIDAR: applications in forestry. Fall Forestry Educational Seminar: Forest Technology. *University of Washington Pack Research Forest, November 13, 2004, Eatonville, WA.*

Andersen, H.-E., R.J. McGaughey, and S.E. Reutebuch. 2004. Forest measurement using high-resolution airborne LIDAR. *Productivity of Western Forests: A Forest Products Focus, September 21-23, 2004, Olympia, WA.*

Reutebuch, S.E. 2004. Introduction to LIDAR. *Natural Resource Monitoring Workshop, AmericaView Conference 2004. EROS Data Center, September 20-22, 2004, Sioux Falls, SD.*

Andersen, H.-E., R.J. McGaughey, S.E. Reutebuch, G.F. Schreuder, J. Agee, and B. Mercer. 2004. Estimating canopy fuel parameters in a Pacific Northwest conifer forest using multifrequency polarimetric IFSAR. *ISPRS XXth Congress, July 12-23, 2004, Istanbul.*

Andersen, H.-E., G.F. Schreuder, R.J. McGaughey, S.E. Reutebuch, and W.W. Carson. 2004. Estimating forest inventory parameters using high-resolution LIDAR and IFSAR. *1st International Workshop on Digital Forestry, June 14-18, 2004, Beijing,China.*

Reutebuch, S.E. 2004. Demonstration of FUSION LIDAR software for vegetation measurements. *1st Annual Forest PARC Workshop, LIDAR: Technical Workshop, Univ. of Idaho & Upper Midwest Aerospace Consortium (UMAC), May 17- 19, 2004, Moscow, ID.*

Andersen, H.-E., G.F. Schreuder, J. Agee, R.J. McGaughey, and S.E. Reutebuch. 2004. Canopy fuels measurement with LIDAR and IFSAR. *Joint Fire Science Program (JFSP) Principal Investigator's Workshop, April 13-15, 2004*, *Phoenix, Arizona.* Received "Best Presentation Award" out of 67 presentations.

Andersen, H.-E., S.E. Reutebuch, R.J. McGaughey, W.W. Carson, and K. Winterberger. 2004. LIDAR & IFSAR for Vegetation Measurement & Monitoring. *Seminar at PNW Research Station Forestry Sciences lab, March 9, 2004, Olympia, WA.*

Reutebuch, S.E. 2004. LIDAR as a tool for forest inventory. 2004. *National Forest Inventory and Analysis (FIA) All bands Meeting, Feb. 24, 2004, San Diego, CA.*

Mercer, B., J. Allan, C. Hoffman, M. Schwaebisch, S.E. Reutebuch, W. Carson, and H.-E. Andersen. 2003. P-Band Polarimetric InSAR (PolInSAR) for extraction of ground DTM beneath forest canopy. *International Geoscience and Remote Sensing Symposium, July 21-25, 2003, Toulouse, France.*

Mercer, B., J. Allan, N. Glass, C. Hoffman, M. Schwæbisch, S.E. Reutebuch, W. Carson, and H.-E. Andersen. 2003. Extraction of Bare-Earth DEMs Beneath Forest Canopy Using P-Band Polarimetric InSAR (PolInSAR). *Advanced SAR Workshop, June 25-27, 2003, Saint-Hubert, Quebec, Canada.*

Andersen, H.-E., R.J. McGaughey, W. Carson, S.E. Reutebuch, B. Mercer, and J. Allan. 2003. An evaluation of canopy height models obtained from LIDAR and InSAR data in a Pacific Northwest conifer forest. 2003. *ISPRS Workshop on Three-dimensional mapping using LIDAR and InSAR, June, 2003, Portland, OR.*

Mercer, B., J. Allan, N. Glass, S. Reutebuch, W. Carson, and H.-E. Andersen. 2003. Extraction of ground DEMs beneath forest canopy using P-band polarimeteric InSAR (PolInSAR). *ISPRS Workshop on Three-dimensional mapping using LIDAR and InSAR, June, 2003, Portland, OR.*

Andersen, H.-E., R.J. McGaughey, W.W. Carson, S.E. Reutebuch, B. Mercer, and J. Allan. 2003. A comparison of forest canopy models derived from LIDAR and IFSAR data in a Pacific Northwest conifer forest. *Proceedings of the ISPRS working group III/3 workshop "3-D reconstruction from airborne laser scanner and InSAR data*" October 8-10, 2003, Dresden, Germany.

Andersen, H.-E., R.J. McGaughey, W. Carson, S.E. Reutebuch, B. Mercer, and J. Allan. 2003. An evaluation of canopy height models obtained from LIDAR and InSAR data in a Pacific Northwest conifer forest. *Second International Precision Forestry Symposium, June 16-18, 2003, Seattle, USA.*

Andersen, H.-E. 2003. Estimation of critical forest structure metrics through the spatial analysis of airborne laser scanner data. *Olympic Natural Resources Center Winter 2003 GIS Conference, February 27-28, 2003*, *Forks, WA.*