

ESTIMATING CANOPY FUEL PARAMETERS IN A PACIFIC NORTHWEST CONIFER FOREST USING MULTIFREQUENCY POLARIMETRIC IFSAR

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ABSTRACT:

Fire researchers and managers need accurate, reliable, and efficiently-obtained data for the development and application of crown fire behavior models. In particular, reliable estimates of critical canopy structure characteristics, including canopy bulk density, canopy height, canopy base height, and canopy fuel weight are required to accurately map fuel loading and model fire behavior over the landscape. The use of polarimetric interferometric synthetic aperture radar (IFSAR), a high-resolution active remote sensing technology, provides for accurate and efficient estimation of crown fire behavior variables over extensive areas of forest. In this study, estimates of crown fuel variables were developed from the polarimetric backscatter and interferometric information (elevation, coherence and phase) for an IFSAR dataset acquired within a coniferous forest in western Washington State, USA. Multiple regression analysis showed that plot-level IFSAR-based canopy fuel estimates were highly correlated with field-based fuel measurements of canopy height ($R^2 = 0.91$), canopy base height ($R^2 = 0.92$), canopy bulk density ($R^2 = 0.80$), and canopy fuel weight ($R^2 = 0.81$).

1. INTRODUCTION

Accurate estimates of canopy height, canopy base height, canopy bulk density, and canopy fuel weight would improve the data layer creation process for wildfire simulation models such as FARSITE (Finney, 1998) or future fire spread models. Previously, these data layers were generated using the output from stand-level growth models such as the Forest Vegetation Simulator (FVS), which depend upon a tree list to drive the simulations (Beukema et al., 1997). Since the stand-level estimates generated from these models are based upon a relatively sparse sample of inventory attributes, they will be subject to sampling error and will be unable to capture variability in stand structure at finer spatial scales over the landscape. If such variables could be accurately estimated using remotely-sensed data, in a spatially explicit format, the application of fire spread models to landscapes would be significantly improved.

Synthetic aperture radar (SAR) is an active sensing technology that emits and records the reflection of microwave radio energy. Airborne SAR systems typically collect data from very high flying heights, allowing them to collect data at a rate of approximately 1000 km²/hour with a cost that ranges from \$10 - \$80/km² for typical X-band digital surface models (Mercer, 2001). The information content of radar data in forested terrain

varies depending upon the wavelength of the transmitted pulses – energy with short wavelengths (~ 1 cm) is reflected from the canopy surface while radar energy with longer wavelengths (~ 1 m) penetrates the foliage in the canopy and reflects from large branches, tree stems and the terrain surface. Microwave remote sensing, in contrast to optical remote sensing, can penetrate cloud and smoke cover, allowing data collection in most weather conditions. The resulting image represents the intensity of the radar backscatter throughout the illuminated region. While previous studies have shown that SAR backscatter amplitude can be used to estimate forest biomass (Hussin et al., 1991), it has been noted that the biomass saturation limits for even long-wavelength SAR systems (~ 100-150 tons/ha) are too low to reach levels present in temperate closed forests (~300 tons/ha) (Imhoff, 1995; Mette et al., 2003).

The availability of three-dimensional interferometric radar (IFSAR) data in recent years has the potential to significantly expand the applicability of radar analysis for forest structure analysis. Radar interferometry uses the difference in phase, or phase shift, between two radar images acquired from slightly different locations to acquire information relating to the elevation angle to an imaged point, which is used in conjunction with the range information to determine the three-dimensional location of this imaged point (Hagberg et al., 1995). Varying the

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wavelength of the emitted energy will allow for collection of different three-dimensional structure data – sensors emitting pulses with short wavelength measure the canopy surface while sensors with longer wavelength will collect information about sub-canopy and terrain features. The difference between the canopy elevation (X-band) and underlying terrain elevation (P-band) yields a canopy height model that represents a spatially-explicit description of canopy structure (i.e. volume, height, biomass, canopy fuel density) over a given area of forest. It has been shown that interferometric observables, such as coherence and phase, are more sensitive than radar power (backscatter) to forest structural parameters and biomass over a large range of forest types (Treuhaft and Siqueira, 2004). The use of IFSAR therefore reduces the effect of radar saturation and provides for more accurate measurement of forest structure parameters over a wide range of forest densities.

The use of multifrequency (X-band and P-band) IFSAR systems for forest mapping has emerged recently, where research efforts have largely focused on improving forest type classification (Hofmann et al., 1999; Dutra et al., 2002; Mura et al., 2001). Previous studies have shown that IFSAR can be used to estimate biomass and other forest inventory parameters (Andersen et al., 2004; Mette et al., 2003; Treuhaft and Siqueira, 2004). In this paper, we present and evaluate an approach to estimating several critical canopy fuel metrics, including canopy fuel weight, canopy bulk density, canopy base height, and canopy height, using polarimetric, dual-frequency IFSAR data in a Pacific Northwest conifer forest.

2. STUDY AREA AND DATA

2.1 Study area

The study area for this investigation was a 5.2 km² area within Capitol State Forest, western Washington State, USA. This forest is primarily composed of coniferous Douglas-fir (*Pseudotsuga menziesii*) and western hemlock (*Tsuga heterophylla*) and, to a lesser degree, hardwoods such red alder (*Alnus rubra*) and maple (*Acer spp.*). The extent of the study area is shown in an orthophoto in Figure 1.



Figure 1. 1999 orthophoto of Capitol Forest study area (courtesy Washington State Department of Natural Resources)

This site is the study area for an ongoing experimental silvicultural trial, and contains coniferous commercial forest stands of varying age and density. An extensive topographic survey was conducted throughout the area to enable rigorous evaluation of a variety of technologies relevant to precision forest management, including high-resolution remote sensing and terrestrial geopositioning systems.

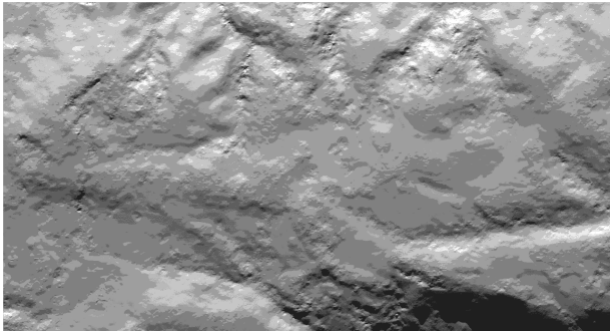
2.2 IFSAR Data

IFSAR data were acquired over the Capitol State Forest study area in September, 2002, using the TOPOSAR System (formerly AeS-1, developed by Aerosensing Radarsysteme, GmbH, and now owned, operated and further developed by Intermap Technologies Corp.). This two-frequency, multi-polarization system provides X-band interferometric data in a single-pass mode and P-band interferometric data in a repeat-pass mode. X-band and P-band data are not collected simultaneously owing to recording bandwidth limitations. The salient parameters of the systems are shown in Table 1.

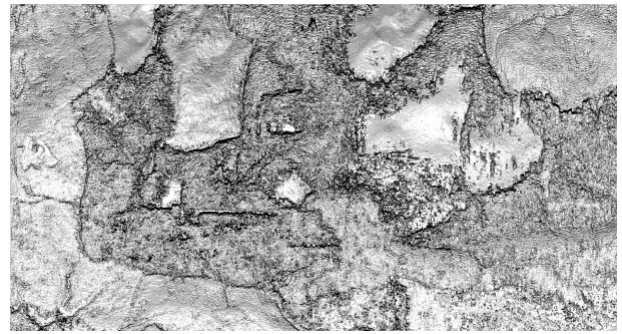
Table 1. TOPOSAR System Parameters.

Parameter	X-band	P-band
Mode (Non-Simultaneous)	Single-Pass	Repeat-Pass
Antenna Baseline (meters)	2.4	As Desired (50, 80)
Centre Wavelength (cm)	3	74
Image Resolution (m)	2, 1, 0.5	2.5
Swath Width (km)	2, 4, 7	4
Polarization	HH	HH or (HH,VV,HV/VH)
Typical Flying Altitude (m)	5,000	5,000

As shown in Table 1, several operational configurations are possible. The X-band configuration selected for this project included 2 km swath, 1 meter resolution imagery and digital surface model (DSM) sample spacing. There were 4 strips of X-band acquired, including two partially overlapping swaths from each of two opposite viewing directions. In the case of the P-band, the 2.5 meter data were acquired with overlapping swaths from four orthogonal viewing directions. The vendor also provided a digital elevation model developed from an optimized integration of the polarimetric P-band data. A composite digital terrain model (DTM) was created from the X-band (in open areas) and P-band (beneath the canopy) data. The root-mean-square error (RMSE) of this DTM, based upon a comparison to 350 high-accuracy topographic survey points, (of which 270 were located in uncut or lightly thinned forest) was 2.59 meters (Mercer et al., 2003). The DTM sample spacing was 2.5 meters, although a smoothing function reduced the effective independent spacing width by several meters.

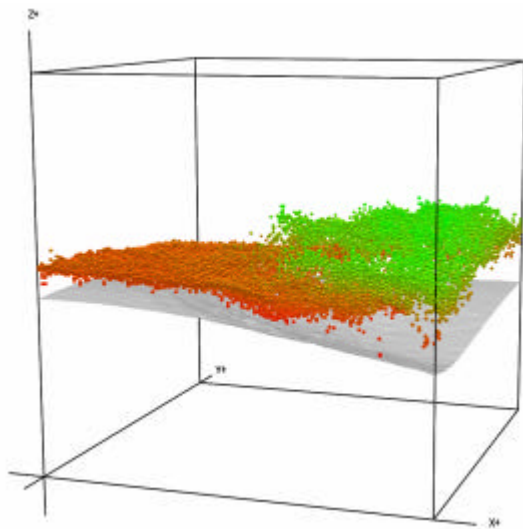


a)

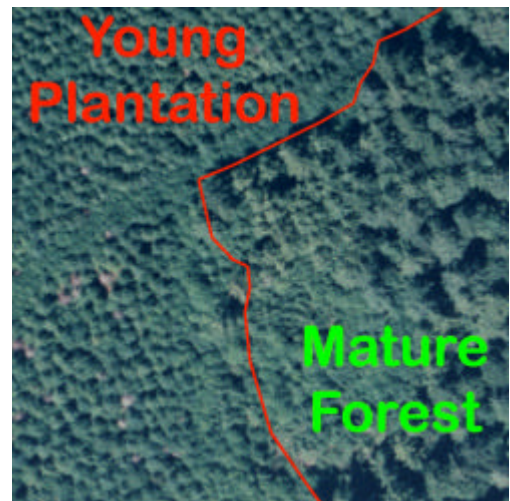


b)

Figure 2. Shaded relief graphics of a) IFSAR P-band digital terrain model, and b) IFSAR X-band canopy surface model.



a)



b)

Figure 3. Three-dimensional graphical visualization of a) IFSAR X-band elevation measurements (color-coded by height) overlaid on P-band digital terrain model and b) corresponding orthophoto.

Additional data provided by Intermap Technologies Corp. included multi-polarization SAR backscatter orthoimages, look-angle images, coherence images and phase information. The DTM is shown in Figure 2a, and the X-Band DSM - effectively a canopy surface model in this project - is shown in Figure 2b.

The X-band elevation strip data were merged into a single file for the purposes of the analysis. X-band elevation data overlaid on the P-band digital terrain model in a selected area containing both mature and young forest stands are shown in Figure 3a.

3. METHODOLOGY

3.1 Field-based canopy fuel estimates

Field-based estimates of canopy fuels were generated using the methodology developed for the Fire and Fuels Extension to the Forest Vegetation Simulator (FFE-FVS) (Beukema et al., 1997). In this approach, the foliage of each tree is estimated using the equations developed by Brown and Johnson (1976). These equations generate estimates of the total dry weight of live and dead material for each individual tree crown, and provide a break-down of the proportion of the total crown weight that is associated with foliage and different size classes of branchwood. Following the methodology of Scott and Reinhardt (2001), crown fuels are defined as foliage and fine branchwood (50 percent of the 0 to 6 mm diameter branchwood). These crown

weight equations can then be used to generate total crown fuel weight estimates for each tree in a plot given a tree list with information including species, diameter at breast height (DBH), crown ratio, and crown class. It should be noted that since crown class was not collected for all plots used in this study, crown weight could not be adjusted for relative position of the tree within the stand.

In this model, it is assumed that the crown material on each tree crown is evenly distributed along a crown's length. In order to generate an aggregate measure of canopy bulk density at the plot level, the total fuel weight for all trees within the plot are summed at 0.3048 meter increments from the ground to the top of the tallest tree. The canopy bulk density is then defined as the maximum 4.6 m running mean of crown fuel density within the plot. Following Scott and Reinhardt (2001), canopy base height is calculated as the lowest height at which the canopy fuel density exceeds a critical threshold (0.011 kg/m^3). Analogously, canopy height is defined as the highest height at which the canopy fuel density is greater than 0.011 kg/m^3 . Using this methodology, estimates of canopy fuel weight, canopy bulk density, canopy base height, and canopy height were generated for each plot within the study area. An example of fuel parameter estimates for an inventory plot in the control unit is shown in Figure 4.

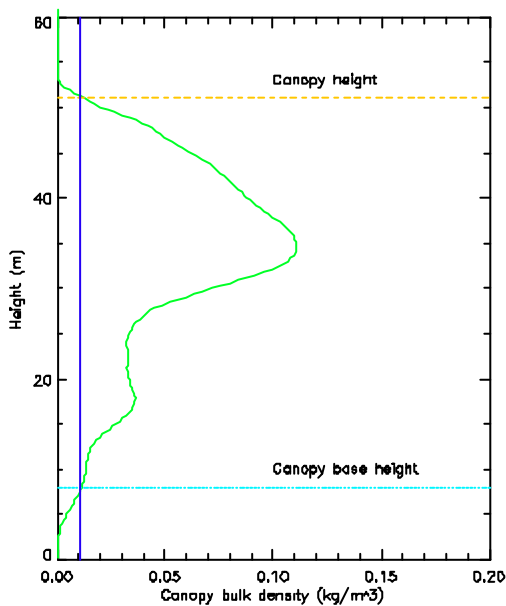


Figure 4. Estimation of fuel parameters at inventory plot within dense canopy unit, Capitol Forest study area.

3.2 IFSAR canopy fuel estimation

Multiple regression analysis was used to develop a mathematical model relating the radar backscatter and interferometric information to the observed fuel parameters at the plot level. At each inventory plot, the observed IFSAR data from all passes were extracted and aggregated.

Summary statistics for each set of aggregated plot-level IFSAR observables were then calculated and used as predictor variables. These data included mean, median, maximum, minimum, and coefficient of variation of:

1. Canopy heights (X-band minus P-band elevations)
2. X-band backscatter
3. X-band coherence
4. P-band VV backscatter
5. P-band VH backscatter
6. P-band HH backscatter
7. 1st optimized coherence (P-band)
8. 2nd optimized coherence (P-band)
9. 3rd optimized coherence (P-band)
10. Wrapped phase (X-band)
11. 3rd optimized unwrapped phase (P-band)

In addition, an IFSAR-based canopy density estimate was calculated as the percentage of observed canopy elevations greater than 2 meters in height. Stepwise regression was then used to develop the “best fit” model for each fuel parameter at the plot level.

4. RESULTS

4.1 Canopy height

The correlation between IFSAR observables and canopy height was quite high, with a coefficient of multiple determination (R^2) of 0.91 and an adjusted R^2 of 0.89. It should be noted that the adjusted R^2 measure will place a penalty on models with numerous extraneous predictor variables. A scatterplot of field-based canopy height measurements versus predicted values is shown in Figure 5.

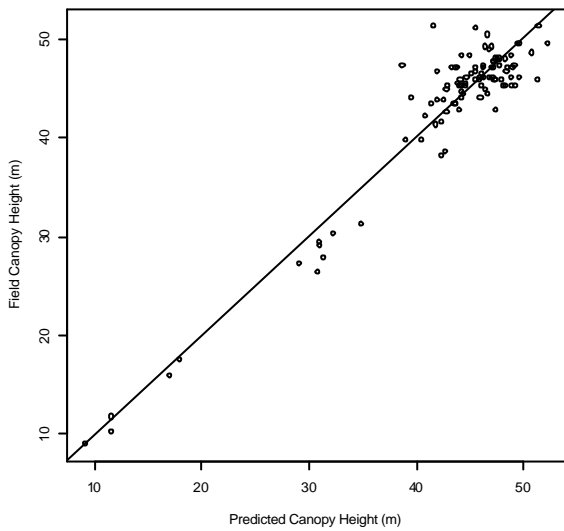


Figure 5. Field-based versus predicted canopy height measurements (with 1:1 line shown).

4.2 Canopy base height

The regression model developed to predict canopy base height had an R^2 of 0.92 and adjusted R^2 of 0.90. A scatterplot of field-based canopy base height measurements versus predicted values is shown in Figure 6.

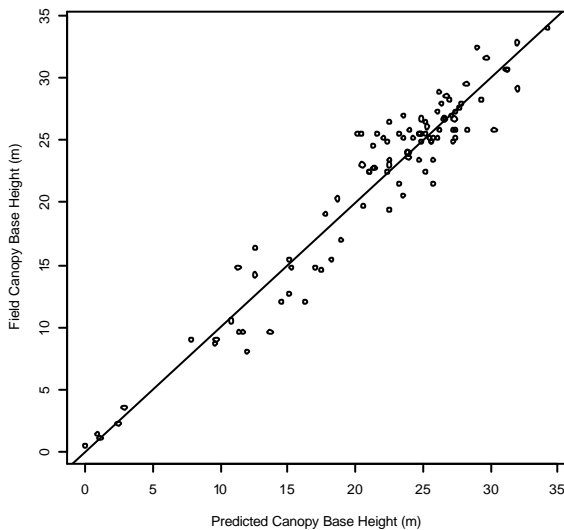


Figure 6. Field-based versus predicted canopy base height measurements (with 1:1 line shown).

4.3 Canopy bulk density

The regression model developed to predict canopy bulk density had an R^2 of 0.80 and an adjusted R^2 of 0.75. In this case a logarithmic transformation of the independent variable was used to stabilize the error variance. It should be noted that the reported R^2 values are therefore valid only for the transformed

space. A scatterplot of field-based $\ln(\text{canopy bulk density})$ measurements versus predicted values is shown in Figure 7.

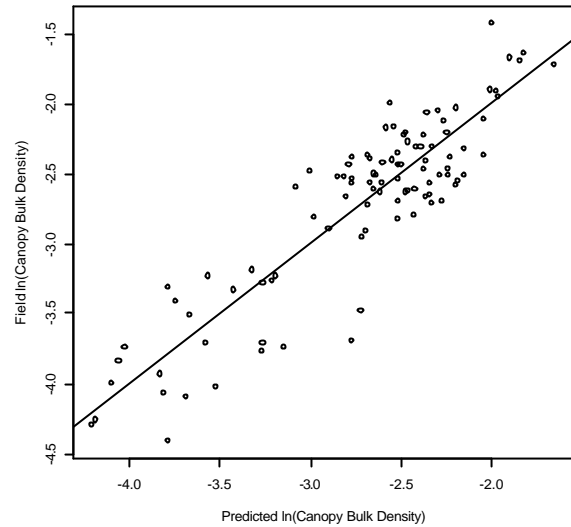


Figure 7. Field-based versus predicted (log-transformed) canopy bulk density measurements (with 1:1 line shown).

4.4 Canopy fuel weight

The regression model for (log-transformed) canopy fuel weight had an R^2 of 0.81 and an adjusted R^2 of 0.77. A scatterplot of field-based $\ln(\text{canopy fuel weight})$ measurements versus predicted values is shown in Figure 8.

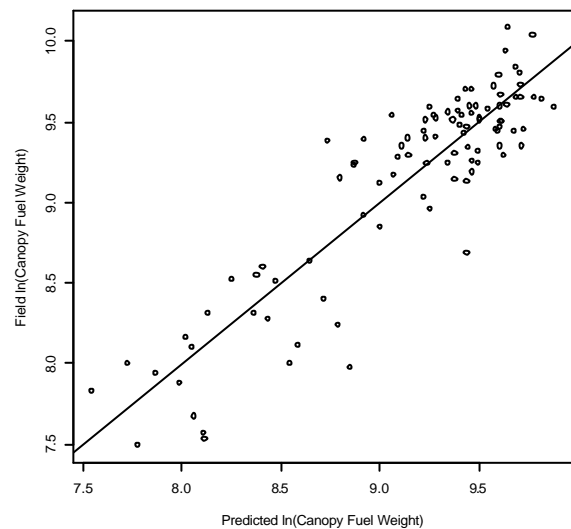


Figure 8. Field-based versus predicted (log-transformed) canopy fuel weight measurements (with 1:1 line shown).

5. DISCUSSION

The results indicate that information related to three-dimensional geometry, interferometric observables, and backscatter characteristics of the forest canopy provided by multi-frequency, polarimetric IFSAR systems can be used to

obtain accurate measurements of canopy fuel parameters. Although the mature conifer forest stands within the study area are of fairly uniform height (see Figure 5), the interferometric observables and polarimetric backscatter data explain variability in the vertical structural characteristics of these forest stands, as evidenced by high correlation between field-based and predicted canopy base heights (see Figure 6).

The use of model-based estimates for the various fuel parameters will also introduce a significant source of variability in the regression model. The fuel models use a number of assumptions (i.e. uniform vertical distribution of crown fuels) that are clearly over-simplifications of reality. More detailed crown fuel models will be needed in the future if they are to be used as ground truth in comparison to high-resolution remotely-sensed estimates.

Although each predictive model contained a large number of independent variables, the adjusted R^2 values were not significantly lower than the R^2 for any of the models, indicating that none of the models contained a large number of extraneous variables working to artificially inflate this measure of fit. Correlation matrices for the regression models also indicate that there is little multicollinearity in these models. Admittedly, the large number of predictor variables make it difficult to establish a physical interpretation for these regression models. Further work will certainly be needed to fully understand the physical relationships between IFSAR observables and the array of forest structural parameters.

It should also be noted that at this time, most IFSAR processing algorithms are (perhaps not surprisingly) optimized for extraction of bare earth elevations, not for accurate measurement of canopy surface structure. For example, some errors in the X-band measurement of canopy height were due to filtering of the interferogram (Mercer, 2004). Although it is unclear what effect this may have on the results, future work will look at optimizing X-band processing for the forest measurement application.

6. CONCLUSIONS

Results of this analysis indicate that IFSAR can be used to generate accurate estimates of canopy fuel parameters efficiently and economically over extensive areas of forest. Given the capability of IFSAR to penetrate clouds and smoke, there may be potential for near real-time collection of fuels data in fire-prone areas. As extensive areas of the world begin to be covered through large-scale terrain mapping campaigns (NextMapBritain, NextMapUSA, etc.) IFSAR data will be increasingly available for forest mapping applications.

Once the regression analysis have been carried out and the predictive models developed, canopy fuel parameters can be mapped over the entire extent of the IFSAR coverage, resulting in a GIS coverage that could be used to support fire behavior modelling or fuels management programs.

Future research will be focused on analysis of multifrequency, polarimetric IFSAR data acquired over different forest types. A rigorous model validation will be carried out to determine the sensitivity of the model form to changes in forest type and stand density.

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