

A COMPARISON OF FOREST CANOPY MODELS DERIVED FROM LIDAR AND INSAR DATA IN A PACIFIC NORTHWEST CONIFER FOREST

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ABSTRACT:

Active remote sensing technologies, including interferometric radar (InSAR) and airborne laser scanning (LIDAR) have the potential to provide accurate information relating to three-dimensional forest canopy structure over extensive areas of the landscape. In order to assess the capabilities of these alternative systems for characterizing the forest canopy dimensions, canopy- and terrain-level elevation models derived from multi-frequency InSAR and high-density LIDAR data were compared to photogrammetric forest canopy measurements acquired within a Douglas-fir forest near Olympia, WA. Canopy and terrain surface elevations were measured on large scale photographs along two representative profiles within this forest area, and these elevations were compared to corresponding elevations extracted from canopy models generated from X-band InSAR and high-density LIDAR data. In addition, the elevations derived from InSAR and LIDAR canopy models were compared to photogrammetric canopy elevations acquired at distinct spot elevations throughout the study area. Results generally indicate that both technologies can provide valuable measurements of gross canopy dimensions. In general, LIDAR elevation models acquired from high-density data more accurately represent the complex morphology of the canopy surface, while InSAR models provide a generalized, less-detailed characterization of canopy structure. The biases observed in the InSAR and LIDAR canopy surface models relative to the photogrammetric measurements are likely due to the different physical processes and geometric principles underlying elevation measurement with these active sensing systems.

1. INTRODUCTION

Spatially-explicit information relating to the three-dimensional structure of the forest canopy is needed to support a variety of ecosystem management applications, including habitat monitoring, timber harvest planning, and wildfire fuel mapping. While aerial photography is routinely used for forest type classification in local and national forest inventory programs, the use of manual photogrammetric techniques for mapping forest canopy structure over large areas is generally not considered a cost-effective approach.

The use of active remote sensing technologies, including airborne laser scanning (LIDAR) and interferometric synthetic aperture radar (InSAR) can provide direct, and therefore automatic, three-dimensional measurement of the forest canopy structure over extensive areas. While these technologies are both active ranging systems utilizing precise airborne geopositioning systems, they represent fundamentally different sensing processes. LIDAR systems are optical sensors, typically operating in the near-infrared portion of the electromagnetic spectrum, while InSAR systems are based upon microwave sensing principles. Multi-

frequency InSAR and small-footprint, discrete-return LIDAR are both commercially mature technologies which can provide canopy- and terrain-level elevation models as standard deliverable products. The difference of the canopy elevation and underlying terrain elevation yields a canopy height model that represents a spatially-explicit description of canopy structure (i.e. volume, height, biomass, etc.) over a given area of forest.

In the case of LIDAR, the forest canopy surface model is generally derived from the distribution of the laser first reflections (returns), while the LIDAR-based digital terrain model is generated through filtering of the laser last returns to isolate ground reflections. The use of LIDAR-based canopy height models for forest structure characterization has been well established (Andersen *et al.*, 2001; Persson *et al.*, 2002; Schardt *et al.*, 2002).

The surface models obtained via interferometric radar are largely dependent upon the wavelength of the microwave system. In forested areas, X-band systems, with wavelengths of 3 cm, provide reflections from the surface of the canopy, while P-band

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systems, with a longer wavelength of 72 cm, penetrate the forest canopy and provide measurements of the terrain surface elevation (Hofmann *et al.* 1999; Schwabisch and Moreira, 1999). The use of multi-frequency (X-band and P-band) InSAR systems for forest mapping has emerged more recently, where research efforts have largely focused on improving forest classification techniques (Hofmann *et al.*, 1999; Dutra *et al.* 2002; Mura *et al.*, 2001).

Ultimately, the value of either LIDAR or InSAR as a source of data in the forestry context will be directly dependent upon the accuracy of the system in measuring both the canopy surface and underlying terrain surface, given the requirements (i.e. error and precision tolerances) of the specific management application. Previous studies have compared large-footprint LIDAR and C-band InSAR for analysis of forest structure in the Pacific Northwest (Harding *et al.*, 1995). While several studies have compared the accuracy of LIDAR-based and InSAR-based digital terrain models (Mercer, 2001; Norheim *et al.*, 2002), the comparative accuracy of canopy surface models (and, by extension, the resulting canopy height models) generated from these two technologies over varied canopy types is not well established. In this study, an investigation was conducted to determine the accuracy of LIDAR and InSAR for the measurement of canopy surface structure within 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, 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 and the locations of photogrammetric measurements used in the analysis are shown in an orthophoto in Figure 1. 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 LIDAR data

High-density LIDAR data were acquired over the study area with a SAAB TopEye system mounted on a helicopter platform in March, 1999. The system settings and flight parameters are shown in Table 1. The vendor provided the coordinates of all laser reflections as well as a dataset containing the coordinates of “ground” returns extracted via a proprietary filtering algorithm.

Flying height	200 m
Flying speed	25 m/s
Swath width	70 m
Forward tilt	8 degrees
Laser pulse density	3.5 pulses/m ²
Laser pulse rate	7000 Hz

Table 1. LIDAR system parameters

2.3 InSAR data

InSAR data was acquired over the Capitol State Forest study area in September, 2002 using the AeS-1 system developed by Aerosensing Radarsysteme, GmbH, now owned and operated by Intermap Technologies Corporation. This multi-frequency system provides Xband interferometric data in a single-pass configuration and Pband interferometric data in a repeat-pass mode. Parameters for the AeS-1 system area shown in Table 2.

Parameter	X-band	P-band
Carrier frequency	9.5 GHz	415 MHz
Wavelength	3 cm	72 cm
Bandwidth	499 MHz	70 MHz
Average power	83 W	24 W
Polarization	HH	VV, HH, VH, HV
PRF	26 kHz	16 kHz
Look angle	30–50 degrees	23–56 degrees
Swath width	2000 m	4000 m
Flying height	3657 m	4877 m
Flying speed	130 m/s	130 m/s

Table 2. InSAR system parameters

Strip elevation data from the X-band interferometric system were generated for eight different passes and were provided as separate images in a binary format. The vendor also provided a digital elevation model developed from an optimized integration of the polarimetric P-band interferometric data. The post spacing for X-band and P-band elevation data was 2.5 meters. Additional data provided by Intermap Technologies Corp. included multi-polarization SAR backscatter orthoimages, look-angle images, coherence images, and interferograms.

2.4 Aerial photography

Aerial photographs at several different scales were acquired over the study area. Normal color photographs covering the entire area at scales of 1:7000 and 1:12000 were acquired in August of 1999. In addition, five normal color stereo-triplets at 1:3000-scale were acquired over selected areas within the study site in June of 2000.

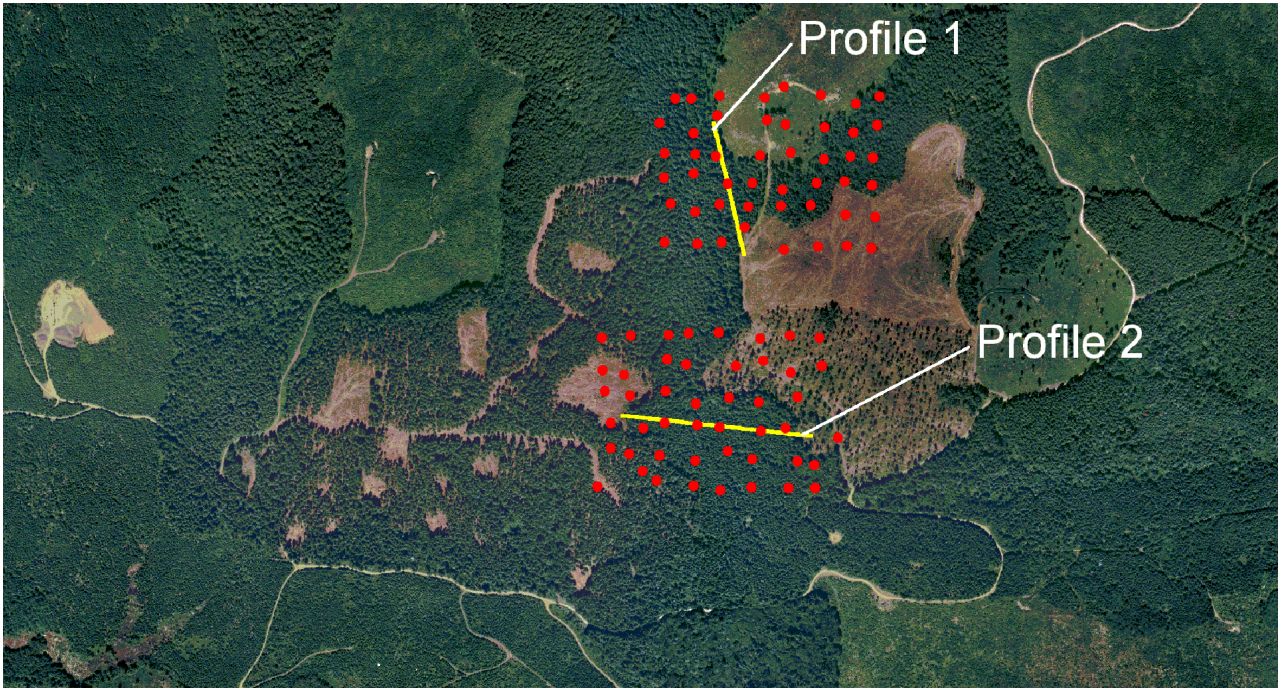


Figure 1. Locations of profile measurements and spot elevations within Capitol Forest study area

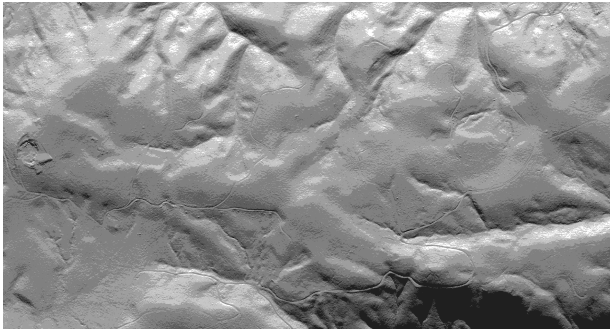


Figure 2. LIDAR-based digital terrain model.

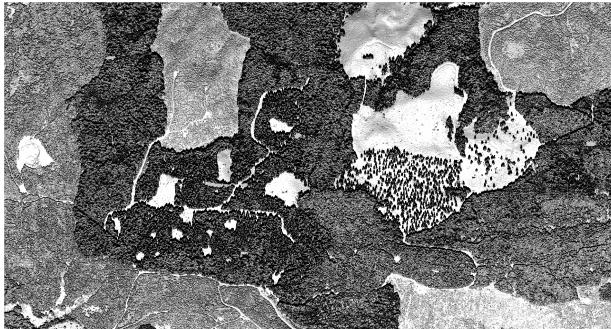


Figure 3. LIDAR-based canopy surface model.

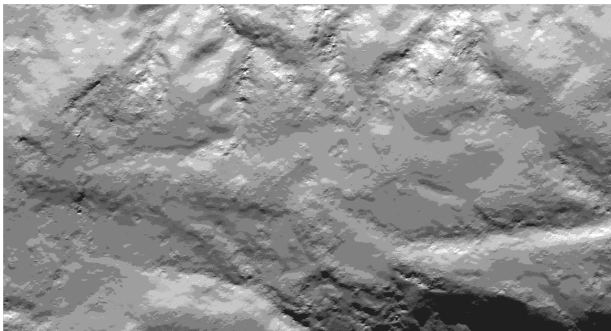


Figure 4. InSAR P-band digital terrain model.

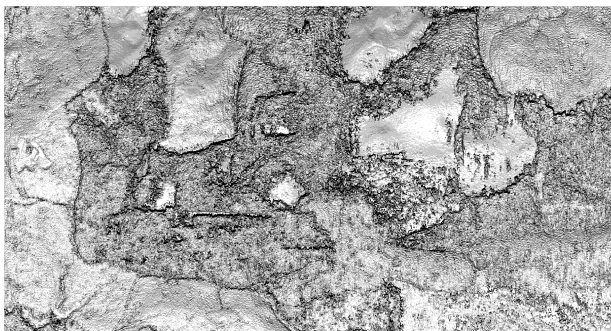


Figure 5. InSAR X-band canopy surface model.

3. METHODOLOGY

3.1 Data processing

In order to facilitate comparison of the elevation models, the data sets were processed to convert all data to a common grid system with common origin and cell size. The coordinate system was Universal Transverse Mercator (UTM) zone 10 (meters), horizontal datum NAD 83, elevations in meters, vertical datum NAVD 88. In order to maintain the detail of the canopy surface models, the grid cell resolution for all surfaces was chosen to be one meter.

LIDAR data

The irregularly-spaced filtered ground LIDAR returns were gridded into a digital terrain model using the inverse distance interpolation algorithm and a 4-sector search with a radius of 60 meters. A hillshade graphic of this LIDAR-based digital terrain model is shown in Figure 2.

A block maximum algorithm was used to extract the LIDAR returns representing measurements of the canopy surface. This algorithm essentially extracts the LIDAR measurement having the highest elevation within each cell of size 1 meter \times 1 meter over the entire area. Due to the high density of the LIDAR data, there were very few voids in this filtered canopy data set, and the data were gridded using an inverse distance interpolation algorithm and a 3-sector search with a radius of 3 meters. This gridding algorithm is equivalent to a linear interpolation using the three closest points. A hillshade graphic showing the LIDAR-based digital canopy model is shown in Figure 3.

InSAR data

An analogous procedure was developed to generate a canopy surface model using the X-band strip elevation data. First, a surface was generated for each individual strip using a linear interpolation algorithm. Second, the elevation from all eight surfaces was calculated at each point within a 1 meter \times 1 meter grid, and the highest elevation from these eight interpolated values was used to generate a canopy surface model. In order to reduce the bias due to shadow effects, only grid elevations with valid elevation data in all surrounding posts were used in the generation of the canopy surface model. The InSAR data were regridded to a 1-meter resolution using an inverse distance 3-sector interpolation algorithm. A hillshade graphic of the P-band digital terrain model is shown in Figure 4, and a hillshade graphic of the X-band canopy surface model is shown in Figure 5.

Aerial photography

Large scale aerial photos covering three different areas within the study area were oriented within an analytical stereoplotter. These large-scale photos were georegistered using control points acquired from a single, previously-controlled 1:7000-scale stereo pair.

3.2 Forest canopy profile measurements

Photogrammetry

In order to assess the accuracy of InSAR and LIDAR canopy and terrain-level elevation models acquired in forested areas, two profiles were measured photogrammetrically using large (1:3000) scale aerial photography oriented on an analytical stereoplotter. Three-dimensional coordinates of the canopy surface were digitized along representative straight-line profiles within two stereo models. Profile 1 is located in a mature, 70-year-old Douglas-fir stand, with a stand density of 280 trees per hectare, while Profile 2 is located in a younger, 35-year-old Douglas-fir stand with a stand density of 290 TPH. These planimetric coordinates were converted to the UTM projection and used to generate forest canopy surface profiles. The location of these two profiles is shown in an orthophotograph covering the area in Figure 1. These photogrammetric profiles are shown as a black line in Figures 6 and 7.

LIDAR and InSAR

Elevations along each profile within the X-band InSAR and LIDAR canopy surface model were calculated using bilinear interpolation, and the planimetric location from the photogrammetric profiles. These profiles are shown in Figure 6 and 7.

3.3 Forest canopy spot elevation measurements

Photogrammetry

A photo overlay with a regular grid was used to guide the operator while collecting photogrammetric spot elevation measurements of the forest canopy surface at uniform spacings throughout the entire area of each stereomodel. The location of the most distinct (and easily visible) feature within each cell of the grid, such as a tree top, was digitized to enable a quantitative assessment of the accuracy of the canopy and terrain surface models. Spot elevations were coded as canopy or terrain measurements. The location of each spot elevation is shown in Figure 5. Forty-seven and forty-eight spot elevation measurements were acquired for each stereo model, respectively.

LIDAR and InSAR data

The corresponding elevation within the LIDAR and InSAR (X-band) canopy models at each photogrammetric spot measurement location was calculated using bilinear interpolation.

4. RESULTS

4.1 Canopy surface profiles

Forest canopy surface profiles generated using photogrammetry, InSAR and LIDAR data are compared in Figures 6 and 7. These profiles provide a measure of the general agreement between the canopy- and terrain-level surfaces generated from these different data sources. These figures indicate that there is a fairly close qualitative agreement between the terrain-level profiles generated from the InSAR and LIDAR. While the InSAR canopy surface model provides a relatively close approximation of the photogrammetric canopy surface profile, the InSAR profile does

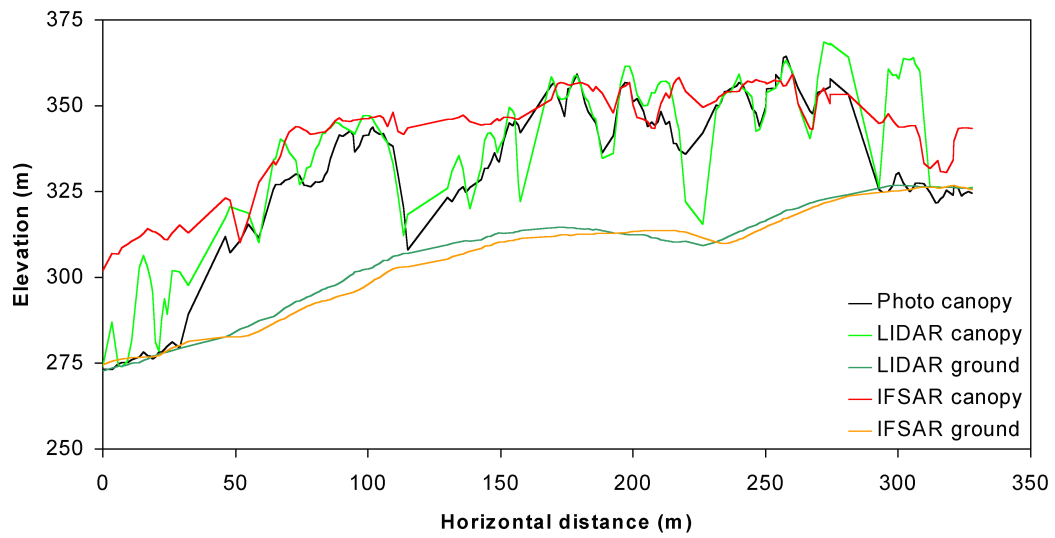


Figure 6. Profile 1

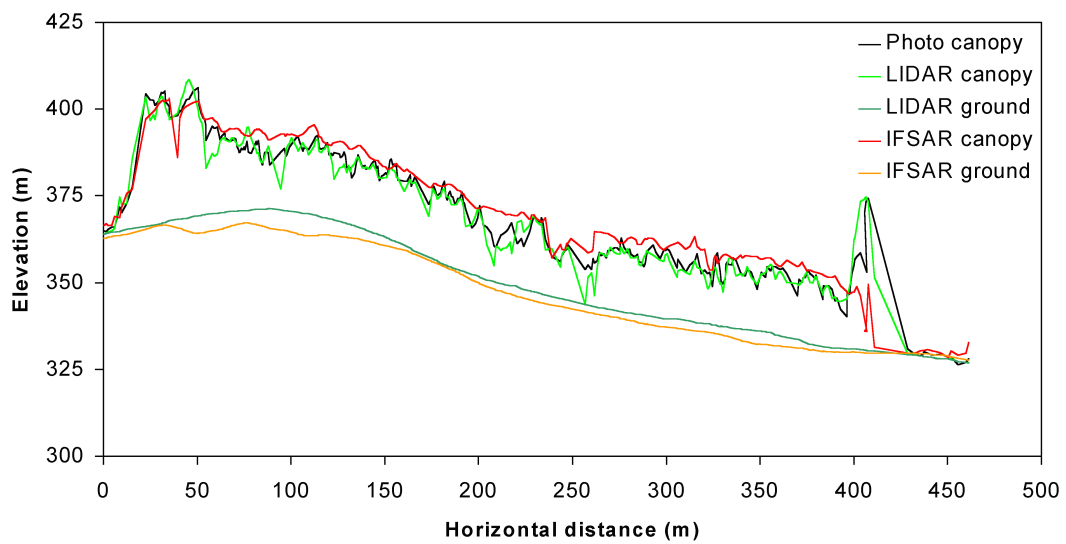


Figure 7. Profile 2

not appear to contain the localized, high-frequency detail that most likely corresponds to the location of individual tree crowns composing the canopy surface.

In contrast, the LIDAR canopy surface measurements appear to provide a relatively close match to the photogrammetric profiles and more accurately represent the complex morphology of the canopy surface. Areas with a large discrepancy between the photo-measured and InSAR/LIDAR surface elevation are most likely caused by shadow effects, which preclude accurate photogrammetric measurement of canopy elevation. In some cases, edge effects at the fringes of tree crowns led to large differences between the LIDAR and photogrammetric canopy surface elevations. This effect is evident at the ends of profile 1.

4.2 Canopy spot elevations

Summary statistics for the distribution of the differences between the LIDAR and InSAR surface elevations and the corresponding photo-measured elevations are shown in Table 3.

	(LIDAR – photo)		(InSAR – photo)	
	Canopy	Terrain	Canopy	Terrain
Mean	-2.24	0.02	-5.03	-0.27
Median	-2.27	0.02	-3.54	0.03
Minimum	-10.20	-2.86	-35.25	-4.52
Maximum	3.06	2.82	20.92	3.59
St. Dev.	2.72	1.51	8.76	2.12
<i>n</i>	68	27	68	27

Table 3. Summary statistics for differences between LIDAR, InSAR surfaces and photogrammetric measurements for the canopy spot elevations (in meters).

The summary statistics calculated based upon 27 terrain-level photogrammetric spot elevation measurements indicate that both the LIDAR and InSAR (P-band) terrain surfaces provide an unbiased model of the terrain in areas without heavy vegetation cover, with mean differences of 0.02 and -0.27 meters, respectively. These statistics generally agree with the results reported in previous studies of the accuracy of LIDAR and InSAR (P-band) digital terrain models in this study area (Reutebuch *et al.*, 2003; Mercer *et al.*, 2003).

The LIDAR canopy surface, in general, is negatively biased relative to the photogrammetric spot elevations (mean difference of -2.24 meters). It should be noted that at least one meter of this bias can be explained by the tree height growth over the one year which elapsed between the time of LIDAR acquisition (March, 1999) and the photo flights (June, 2000). This indicates that there is a negative bias of approximate one meter for the LIDAR canopy model. The InSAR (X-band) canopy model also underestimates the elevation of the canopy in comparison to

photogrammetric measurements (mean difference of -5.03 meters, median difference of -3.54 meters). The magnitude of this bias should be increased by approximately 2 meters to account for the two years of growth between dates of photo acquisition and InSAR acquisition (September, 2002). Therefore, the InSAR X-band surface underestimates canopy height, at the location of the spot height measurements, by approximately 7 meters.

5. DISCUSSION

The results indicate that both LIDAR and InSAR technologies have the capability to provide relatively accurate models of the canopy surface and underlying terrain. In general, qualitative assessment of the canopy profiles, and quantitative assessment of the measurement biases, suggest that canopy-level models generated from high-density laser scanning will provide a more detailed representation of the forest canopy surface than that produced via X-band radar interferometry.

The relatively small (~ 1 m) negative bias in the LIDAR canopy surface elevations relative to the photo-measured canopy-level elevations can largely be attributed to the limited capability of the LIDAR system to detect and measure the elevation of a conifer tree top (with a cross-section of approximately 2-3 cm). LIDAR pulses are distributed in an irregular spatial pattern, and it is improbable that a strong reflection will be recorded from the precise apex of the tree crown.

The canopy profiles suggest that the geometry of side-looking airborne radar limits the capability of the system to resolve fine details of the forest canopy surface. This side-looking InSAR system measures the microwave energy reflected from the canopy surface at relatively high look angles ranging from 30 to 50 degrees, therefore shadows and occlusion effects can dramatically limit the resolution of canopy surface features (i.e. tree crown tops, canopy gaps) in the range direction. In contrast, the near-nadir geometry of LIDAR acquisition enables these detailed canopy features to be resolved in the canopy surface model (in fact, the profiles indicate that in some cases LIDAR is *more* successful than photogrammetry in detecting canopy gaps). It is therefore not surprising to observe a negative bias of 5-7 meters in the comparison of photogrammetric spot elevations (acquired at tree tops in many cases) to the corresponding elevations in the InSAR canopy surface model.

6. CONCLUSIONS

A comparison of InSAR- and LIDAR-derived digital elevation models to photogrammetric canopy surface measurements indicates that both of these active remote sensing technologies have the potential to provide critical, spatially-explicit information relating to forest canopy structure, biomass, and volume. The LIDAR technology is well suited for acquisition of intensive forest structure information, and provides more detailed information relating to the complex morphology of the canopy surface, but also requires cloudless conditions. In contrast, InSAR technology provides a less detailed

representation of the canopy surface but has an all-weather capability, and is therefore well suited for acquisition of less-detailed forest structure mapping over extensive areas where real-time information is critical (i.e. wildfire fuels mapping).

Future work will focus on integration of interferometric information, including coherence, phase, and look-angle with multi-polarization and multi-frequency radar backscatter information to characterize vertical forest structure and the distribution of crown bulk density and biomass.

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