

Accuracy of an IFSAR-derived digital terrain model under a conifer forest canopy

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Abstract. Accurate digital terrain models (DTMs) are necessary for a variety of forest resource management applications, including watershed management, timber harvest planning, and fire management. Traditional methods for acquiring topographic data typically rely on aerial photogrammetry, where measurement of the terrain surface below forest canopy is difficult and error prone. The recent emergence of airborne P-band interferometric synthetic aperture radar (IFSAR), a high-resolution, microwave remote sensing technology, has the potential to provide significantly more accurate terrain models in forested areas. Low-frequency, P-band radar energy physically penetrates through the vegetation canopy and reflects from the underlying terrain surface, allowing for accurate measurement of the terrain surface elevation even in areas with dense forest cover. In this study, the accuracy of a high-resolution DTM derived from P-band IFSAR data collected over a mountainous forest area in western Washington State was rigorously evaluated through a comparison with 347 topographic checkpoints measured with total station survey equipment and collected under a variety of canopy densities. The mean DTM error was -0.28 ± 2.59 m (mean $\pm$ standard deviation), and the root mean squared error (RMSE) was 2.6 m. DTM elevation errors for four canopy cover classes were -0.67 ± 1.20 m (RMSE = 1.38 m) for clearcut, -0.62 ± 1.00 m (RMSE = 1.18 m) for heavily thinned, -0.41 ± 2.32 m (RMSE = 2.36 m) for lightly thinned, and 0.20 ± 3.31 m (RMSE = 3.32 m) for uncut.

Résumé. Les modèles numériques d'altitude (MNA) précis sont nécessaires pour une variété d'applications dans la gestion des ressources forestières, incluant la gestion des bassins versants, la planification des opérations de coupe et la gestion des incendies de forêt. Les méthodes traditionnelles d'acquisition de données topographiques s'appuient généralement sur la photogrammétrie aérienne, où les mesures de la surface du terrain sous le couvert forestier est difficile et sujette aux erreurs. L'émergence récente des données interférométriques radar aéroporté à synthèse d'ouverture en bande P (IFSAR), une technologie de télédétection micro-onde à haute résolution, pourrait fournir des modèles d'altitude significativement plus précis dans les zones forestières. L'énergie à basse fréquence du radar en bande P pénètre physiquement à travers le couvert de végétation et est réfléchi par la surface sous-jacente du terrain permettant la mesure précise de l'altitude à la surface du terrain, même dans les zones de couvert forestier dense. Dans cette étude, la précision d'un MNA à haute résolution dérivé des données IFSAR en bande P acquises au-dessus d'une zone forestière montagneuse dans l'ouest de l'état de Washington a été évaluée de façon rigoureuse par le biais d'une comparaison avec 347 points de contrôle topographiques mesurés à l'aide d'équipement de levés par station totale et collectées pour une variété de densités de couvert. L'erreur moyenne au niveau du MNA était de $-0,28 \pm 2,59$ m (moyenne $\pm$ ET) et l'erreur quadratique (RMSE) était de 2,6 m. Les erreurs d'altitude du MNA pour quatre classes de couvert étaient: coupes à blanc $-0,67 \pm 1,20$ m (RMSE = 1,38 m), éclaircies fortes $-0,62 \pm 1,00$ m (RMSE = 1,18 m), éclaircies légères $-0,41 \pm 2,32$ m (RMSE = 2,36 m) et zones non coupées $0,20 \pm 3,31$ m (RMSE = 3,32 m).

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Introduction

Digital terrain models (DTMs) are used extensively in forest resource management, supporting a wide variety of applications including watershed management, timber harvest planning, and fire management. At present, resource managers in the United States rely on topographic data provided by the United States Geological Survey (USGS). The USGS provides DTMs covering the entire United States at a grid resolution of 10 m and 30 m. These topographic data products are produced using standard photogrammetric measurement techniques and can be quite inaccurate in forested areas, where forest canopy cover obscures the underlying terrain. In a previous study that evaluated the accuracy of USGS DTMs in 13 large forested sites in areas of dense canopy in western Washington, the samples gave a root mean squared error (RMSE) of 9 m (Carson and Reutebuch, 1997). In another study carried out in North Carolina, the accuracy of level 1 USGS DTMs (produced

using the Gestalt Photomapper system), when compared with elevations of 1470 surveyed checkpoints, was reported as 7.43 m (Hodgson et al., 2003).

High-resolution, active remote sensing technologies, including airborne laser scanning (lidar) and interferometric synthetic aperture radar (IFSAR), have the capability to provide much more accurate, and detailed, terrain surface models in areas with dense forest canopy. In the case of high-density lidar, a significant percentage of the laser pulses will penetrate forest

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cover through gaps in the canopy and provide measurements of the underlying terrain surface elevation. In contrast, IFSAR operates in the microwave portion of the electromagnetic spectrum, where high-frequency (i.e., X-band) radar energy reflects from the canopy surface and low-frequency (i.e., P-band) energy penetrates through the canopy and reflects from tree stems and the terrain surface.

Previous studies have shown that terrain models derived from high-density airborne lidar can be very accurate in forested areas. In a rigorous evaluation of the accuracy of a high-resolution lidar-based DTM in a conifer forest of western Washington, the mean error of the DTM was shown to be 0.22 ± 0.24 m (mean $\pm$ standard deviation (SD)), with an RMSE of 0.32 m (Reutebuch et al., 2003).

The costs of acquiring high-density lidar data (approximately US\$3/ha) are still prohibitive, however, for many forest management applications. Although IFSAR-derived topographic data are typically of lower resolution and accuracy than lidar terrain data, they are acquired from a platform flying at a higher altitude and higher speed, leading to a much higher data collection rate and a lower cost (US\$0.10–0.80/ha for X-band data). Therefore, IFSAR technology has the potential to provide relatively low cost topographic data with a significantly higher accuracy than standard USGS products. The accuracy of X-band and P-band IFSAR-derived DTMs in nonforested areas has been assessed in previous studies, with the overall accuracy of the P-band terrain models reported as 5 m (Hofmann et al., 1999) and the accuracy of an X-band DTM reported as 20 cm (Schwabisch and Moreira, 1999). Hodgson et al. (2003) evaluated the accuracy of X-band IFSAR DTMs in a mixed deciduous forest area within North Carolina and reported an overall RMSE of 10.7 m. It is expected that a DTM derived from X-band IFSAR would have low accuracy in forested areas, since the X-band radar energy reflects from the canopy, not the terrain surface. Hodgson et al. also found that the magnitude of IFSAR DTM error increased with an increase in slope. While the accuracy of X-band DTMs in forested areas has been assessed in previous studies, the accuracy of a P-band IFSAR-derived terrain model in a forested area has not been rigorously evaluated through comparison to high-accuracy ground truth data prior to this study. Initial results from this study and a comparison to high-density lidar data collected at this site were reported by Mercer et al. (2003) and Mercer (2004). In this paper, we present an evaluation of a P-band IFSAR-derived DTM under varying canopy densities within a conifer forest located in the Pacific Northwest region of the United States using ground checkpoints obtained from a high-accuracy topographic survey. This paper also provides a comparison of the P-band DTM accuracy with the observed accuracy of the standard USGS 10 m DTM for this area.

Study area and data

Study area

The study area for this project was a 5.2 km² area within Capitol State Forest in western Washington State, USA. The forest was primarily composed of coniferous Douglas-fir (*Pseudotsuga menziesii*), western hemlock (*Tsuga heterophylla*), and, to a lesser degree, hardwoods such as red alder (*Alnus rubra*) and maple (*Acer* spp.). The site is located in a mountainous area, with elevations ranging from 150 to 400 m and ground slopes varying from 0% to 83%. As part of an experimental silvicultural trial, this 70 year old forest was partially harvested in 1998, resulting in units falling into four different residual canopy density classes (Curtis et al., 2004). The residual stand density is 0 trees per hectare (TPH) in clearcut units; in heavily thinned units, approximately 40 TPH remain, dominant height is 43.5 m, and quadratic mean diameter (QMD) is 59.2 cm; in lightly thinned units, approximately 175 TPH remain, dominant height is 44.4 m, and QMD is 56.6 cm; and in the uncut units, 280 TPH remain, dominant height is 47.3 m, and QMD is 52.6 cm. **Figure 1** shows terrestrial photographs depicting the canopy densities found in these units.

Topographic survey data

Three hundred and forty-seven (347) topographic checkpoints located in the central part of the study area were surveyed using a Topcon ITS-1 total station surveying instrument (**Figure 2**). A large proportion (85%) of the checkpoints were under forest canopy. The ground survey was made up of three closed traverses that started at reference points established using a survey-grade global positioning system (GPS). Upon adjustment of the traverses, the accuracy of the checkpoints was approximately 3 cm vertical and 15 cm horizontal.

IFSAR data

IFSAR data were collected over the study areas in September 2002 using the TopoSAR X- and P-band system (formerly AeS-1, developed by Aerosensing Radarsysteme GmbH, and now owned and further developed by Intermap Technologies Corp.). The salient system parameters for IFSAR data collection are shown in **Table 1**. In the case of P-band, the 2.5 m data were acquired within overlapping swaths from four orthogonal viewing directions. The vendor provided a DTM generated from an optimized integration of the fully polarimetric P-band data. Using the fact that polarimetric response varies between different components of the canopy-ground system, an internally developed coherence optimization scheme was developed by researchers at Intermap Technologies Corp. (Mercer, 2004). This methodology assumed that the polarization state corresponding to the optimum coherence in forested areas is associated with the ground response. It should be noted that, although the DTM post spacing was 2.5 m,

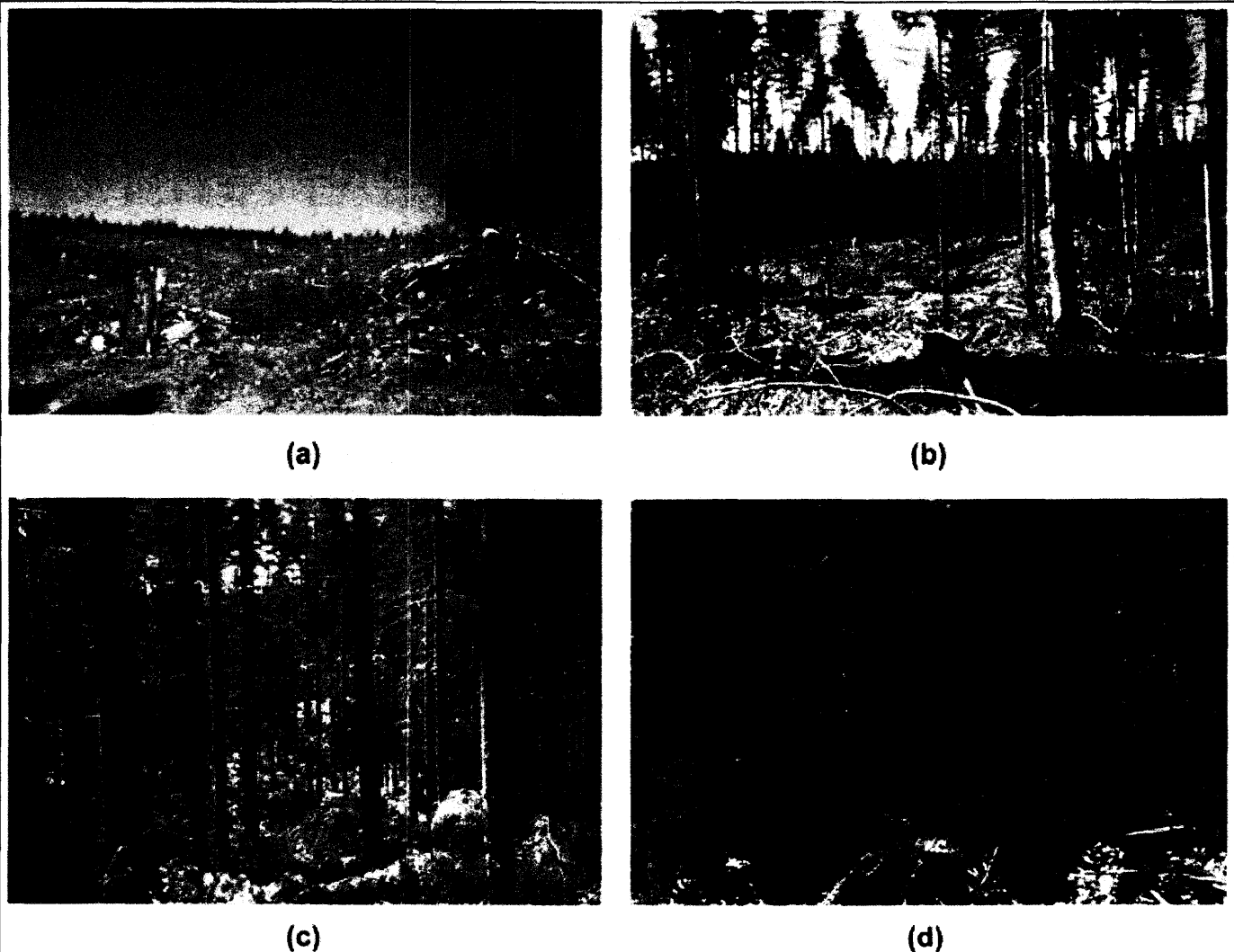


Figure 1. Photographs of four typical areas in the 70-year-old conifer forest represented in this study: (a) clearcut, (b) heavily thinned, (c) lightly thinned, and (d) uncut.

application of a smoothing function reduced the effective independent spacing width by several metres. A three-dimensional perspective view of the P-band IFSAR-derived DTM is shown in **Figure 3**.

Results

IFSAR DTM accuracy assessment

The elevation of the DTM at the position of each checkpoint was calculated using bilinear interpolation. The difference between the two elevations (DTM minus checkpoint) was then calculated as the DTM error. **Figure 4** shows the distribution of the DTM errors. The mean of the elevation differences between the IFSAR DTM and the 347 checkpoints was -0.28 ± 2.59 m (mean $\pm$ SD). The RMSE was calculated as 2.60 m. For the purposes of comparison, the accuracy of the standard USGS 10 m DTM was also evaluated using the same topographic checkpoints. The mean error of the USGS DTM was found to

be 7.3 ± 4.9 m (mean $\pm$ SD), with a maximum observed error of 18.07 m and a minimum of -4.91 m. The RMSE of the USGS DTM was calculated as 8.8 m. Interestingly, this was quite close to the accuracy of approximately 9 m reported in Carson and Reutebuch (1997).

Effect of tree canopy density on IFSAR DTM accuracy

The checkpoints were assigned to four canopy classes, and checkpoints falling on unit boundaries were eliminated, leaving 326 points. Summary statistics of the DTM error in each canopy class are given in **Table 2**. While the mean error was negative for all treated units (i.e., DTM under the true terrain elevation), in the uncut unit the mean error was positive. The standard deviation of the error also tended to increase with increased canopy density (although there is little difference between clearcut and heavily thinned). The range between minimum and maximum also tended to increase with higher canopy densities.

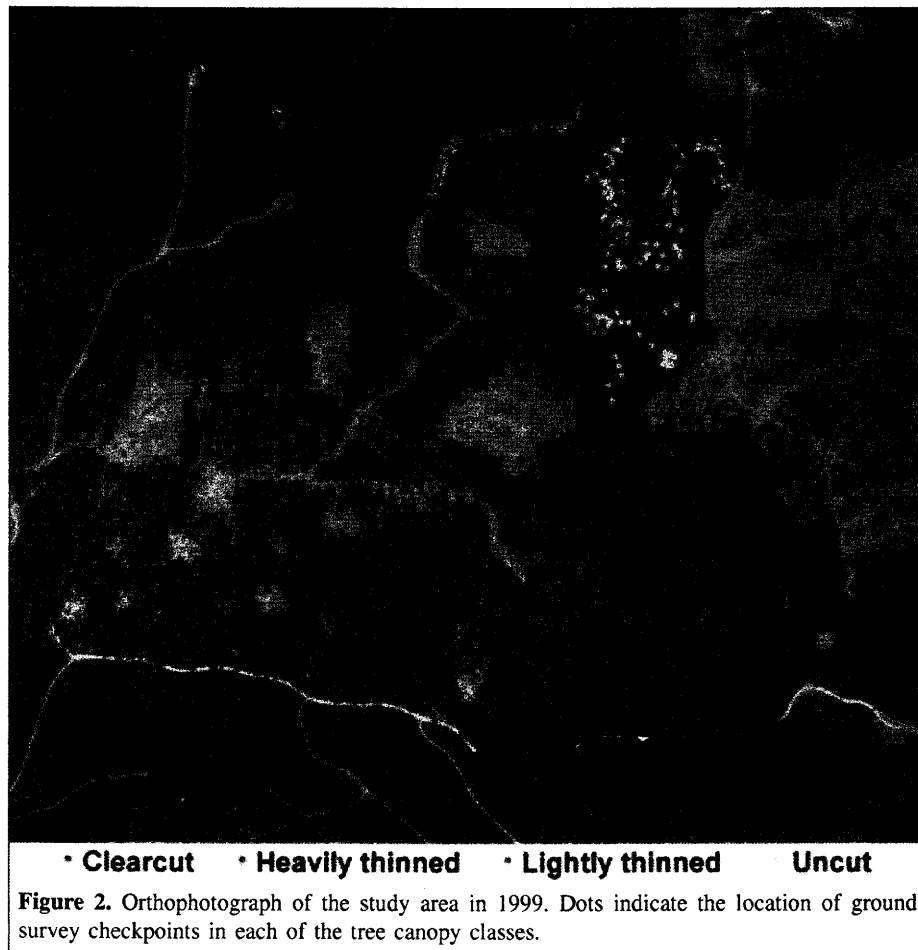


Figure 2. Orthophotograph of the study area in 1999. Dots indicate the location of ground survey checkpoints in each of the tree canopy classes.

Table 1. Flight parameters and P-band IFSAR system settings.

Mode	Repeat pass
Antenna baseline (m)	83
Centre wavelength (cm)	74
DTM resolution (m)	2.5
Swath width (m)	4000
Polarization	HH, VV, HV, VH
Flying altitude (m)	4877

Effect of terrain slope on IFSAR DTM accuracy

Summary statistics for DTM error classified by slope class are shown in **Table 3**. Although mean error for low slopes (<19%) was negative (−0.60 m) and the mean error for high slopes (>19%) was positive (+0.21), the difference between the standard deviations of the error was negligible (2.57 m versus 2.58 m). The RMSE difference between the slope classes was also minimal (2.64 m versus 2.59 m).

Discussion

The IFSAR-derived DTM, generated using P-band data, was shown to be quite accurate, even in this dense forested area. The

overall error of the IFSAR-derived DTM (RMSE = 2.6 m) was significantly lower than the overall error of the USGS 10 m DTM (RMSE = 8.8 m).

The IFSAR DTM error observed in this study was lower than the overall error of 5 m for the P-band derived DTM in a nonforested area reported by Hofmann et al. (1999). This may be due to the fact that low-frequency P-band radar energy can actually penetrate a short distance into the ground, where penetration depth is dependent upon the dielectric characteristics of the soil. In forested areas, the P-band reflectance is dominated by corner reflections at the interface between tree stems and the terrain surface; in fact, it has been noted that P-band interferometric measurements may be more accurate in areas with thin forest cover than in areas with dry, bare soil (B. Mercer, personal communication, 2005). In this study, the DTM error in the heavily thinned unit (RMSE = 1.18 m) was slightly lower than the error in the clearcut unit (RMSE = 1.38 m). The DTM error is significantly higher in areas with relatively dense forest cover, where the magnitude of the error ranged from 2.3 to 3.3 m. It should be noted that, although clearcut and heavily thinned areas had lower overstory canopy cover, they were still in rough terrain, with shrubs, stumps, and residual slash material present.

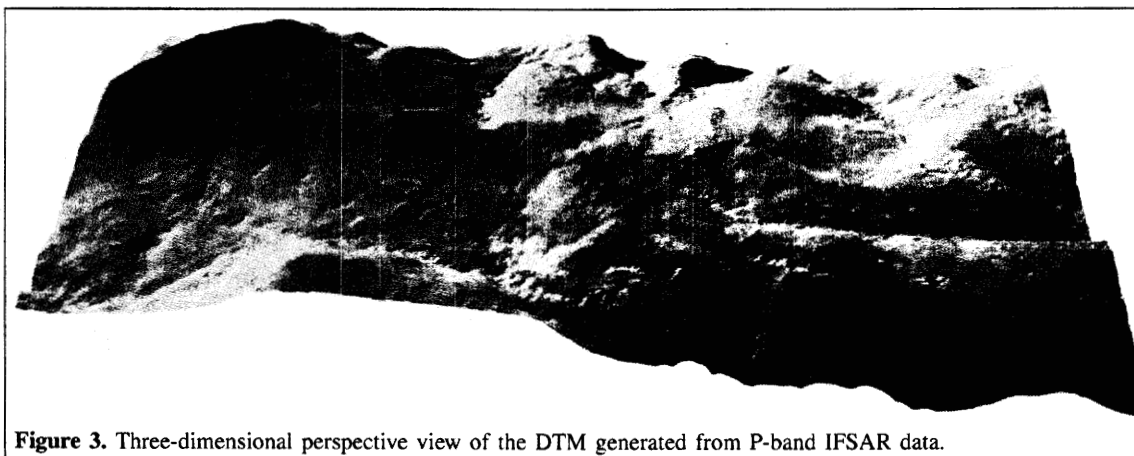


Figure 3. Three-dimensional perspective view of the DTM generated from P-band IFSAR data.

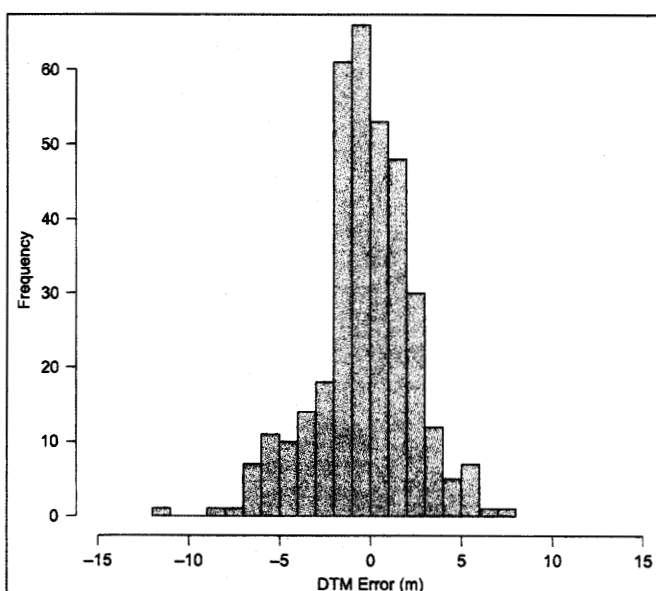


Figure 4. Distribution of IFSAR DTM error compared with 347 surveyed checkpoints.

The results indicate that overall DTM error, as expressed by RMSE, was not significantly different between high and low slope classes (2.59 m versus 2.64 m, respectively), although the mean error was quite different (0.21 m versus -0.60 m, respectively). Although the geometry of side-looking IFSAR acquisition, characterized by look angles ranging from 20° to 55°, can often lead to large elevation errors in steep terrain due to shadowing effects, this problem was mitigated in this study by acquiring P-band data from four different (orthogonal) look directions.

Conclusions

The results of this study indicate that IFSAR technology can provide accurate terrain data, even in areas with dense forest cover. The IFSAR DTM error in this forested area (2.6 m), although certainly higher than that of lidar-derived DTMs (~0.32 m), is significantly lower than the error of the

Table 2. IFSAR DTM elevations minus surveyed checkpoint elevations, segregated by canopy density class.

Canopy class	Mean (m)	SD (m)	RMSE (m)	Min. (m)	Max. (m)	No. of checkpoints
Clearcut	-0.67	1.20	1.38	-3.34	2.34	38
Heavily thinned	-0.62	1.00	1.18	-2.48	1.49	21
Lightly thinned	-0.41	2.32	2.36	-7.05	6.00	147
Uncut	0.20	3.31	3.32	-11.13	7.36	120

Table 3. IFSAR DTM elevations minus surveyed checkpoint elevations, segregated by slope class.

Slope class	Mean (m)	SD (m)	RMSE (m)	Min. (m)	Max. (m)	No. of checkpoints
Low slopes (<19%)	-0.60	2.57	2.64	-11.13	5.51	177
High slopes (>19%)	0.21	2.58	2.59	-7.05	7.36	149

Note: Local slopes at checkpoint locations ranged from 0% to 83%.

standard USGS 10 m DTM product (8.8 m) that is in widespread use by forest managers today. Given the demonstrated capability of long-wavelength P-band IFSAR to provide accurate elevation measurements under dense forest canopy, it is expected that this technology will receive increasing interest in the forestry community.

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