COMPARISON OF CANOPY HEIGHT MODELS DERIVED FROM SRTM/NED AND NEXTMAP® USA ELEVATION DATA

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ABSTRACT

Vegetation canopy height is one of the fundamental structural parameters for estimating forest biomass and evaluating forest carbon balance. Remote sensing technologies like interferometric synthetic aperture radar (abbreviated as IFSAR or IFSAR) may provide a means to extract vegetation canopy heights remotely. A comparison of canopy height estimates derived from IFSAR scattering phase center height (h_{spc}) and a newly proposed method to derive canopy height model (CHM) using the IFSAR elevation data is presented for shrub/scrub and evergreen forest vegetation classes and various terrain slopes ranging between 0° - 30° for two study sites in Minnesota, USA. The X-HH IFSAR h_{spc} was derived from the subtraction of the NEXTMap® USA digital terrain model (DTM) from the NEXTMap® digital surface model (DSM). The C-HH IFSAR h_{spc} was derived from the subtraction of the National Elevation Data (NED) from the NASA-JPL Shuttle Radar Topography Mission (SRTM) first surface elevation dataset. The X- and C-band-derived h_{spc} were compared against *in-situ* measured tree heights. Both h_{spc} models underestimated the canopy height with an overall 5.4 m root mean square error (RMSE) and 8.9 m for the NEXTMap® and SRTM-NED data, respectively. The CHM derived NEXTMap® and the SRTM/NED CHMs compared to the *in-situ* measurements for vegetation of heights greater than 10 m received an overall accuracy of 2.18 m RMSE and 3.41 m RMSE, respectively.

INTRODUCTION

A variety of forestry applications require reliable three dimensional forest metrics that estimate both the horizontal (e.g. forest canopy type, stem diameter, and density) and vertical (e.g. forest canopy height) components of vegetation. Such metrics are important ecological parameters because they are strongly correlated to timber volume, fire models, biomass and hence carbon stocks (Treuhaft *et al.,* 2004; Anderson *et al.,* 2006; Baltzer et al., 2007a;2007b). However, obtaining these measurements via field work is labor intensive, time consuming and expensive. The ability to derive forest canopy heights and vegetation maps remotely would therefore be of great benefit. Significant advances in remote sensing technologies have led to a new era of global topographic observations, where reliable forest measurements are becoming a possibility (Homer *et al.,* 2007). Foremost among these technologies are laser altimetry referred to as LiDAR (Lefsky *et al.,* 2002; Næsset, 2002; Drake *et al.,* 2002) and interferometric synthetic aperture radar cited as IFSAR or IFSAR (Madsen *et al.,* 1993; Hensley *et al.,* 2001; Walker *et al.,* 2007). Both technologies are generating high resolution surface and terrain elevation models and land cover maps which are supporting more detailed measurements of forest canopy structure such as canopy height, cover and density (Dobson *et al.,* 1995; Kobayashi *et al.,* 2000; Means *et al.,* 2000; Brown *et al.,* 2005; Dall, 2007). The costs of acquiring high-density LiDAR data (approximately US$3/ha; Anderson *et al.,* 2005) are still prohibitive for regional and national applications.

IFSAR data, on the other hand, are acquired in most weather conditions and from a platform flying at a higher altitude and higher speed than LiDAR systems, leading to a much higher data collection rate at a lower cost (US$0.10– 0.80/ha for X-band data; Anderson *et al.,* 2005). IFSAR is a well-established remote sensing technology that provides highly accurate x, y, and z coordinates of a location imaged by two radar beams (Graham, 1974; Zebker and Goldstein, 1986; Madsen *et al.,* 1993; Rabus *et al.,* 2003). This is accomplished using the interferometric phase difference from the two SAR data collections. The phase difference is the quantity from which the height of a pixel, with respect to a reference, is retrieved. IFSAR elevation models contain elevation values of the first surface the sensor comes in contact with. For example, vegetation canopy heights measured by IFSAR sensors represent scattering phase center heights which are wavelength dependent (Treuhaft *et al.,* 1996; Dall, 2007, Walker *et al.,* 2007). Scattering phase center heights are located below true vegetation canopy heights and consequently, the elevation recorded by the IFSAR sensor is biased downward. Consequently, elevations measured from IFSAR represent relative heights of surface features, where in non-vegetated areas, this "surface" is at (or very near) the bare earth elevation, and in forested areas, the surface can lie anywhere within a forest canopy (Mercer, 2004; Kellndorfer *et al.,* 2004; Walker *et al.,* 2004).

To obtain true vegetation canopy heights from IFSAR data suites, corrections must be applied to IFSAR digital surface models. Investigations to derive true vegetation canopy heights from IFSAR data by equating the downward bias with penetration depth have been limited to small study areas consisting of uniform vegetation cover (Treuhaft *et al.,* 1996; Rignot *et al.,* 2001; Varekamp and Hoekman, 2002). Motivated by the need to remotely derive vegetation canopy height and in the advances in and availability of IFSAR technologies for collecting surface and bare earth elevation models this paper focuses on the analysis of canopy heights derived from airborne (X-band) and spaceborne (C-band) IFSAR data over a study site in Colorado to assess the relation between the scattering phase center heights of the X/C data sets against *in-situ* canopy measurements. The second goal of the paper is to report on a new method to derive canopy height data from IFSAR DSMs and corresponding DTMs by correcting for the microwave penetration over the proposed land cover.

DATA AND STUDY AREA

Study Area

Study Site 1: Ely, Minnesota, USA. Ely, a city in St. Louis County, Minnesota, USA is comprised of dense homogenous coniferous and deciduous and heterogeneous mixed forests with little understory in a temperate environment. It is situated in the Vermilion Iron Range (Figure 1). Geographically, the region is located approximately between 47°52'30" N and 47°37'30" N latitudes and 91°52'30" W and 91°37'30" W longitudes. The study site covers an area of 169.8 km^2 and is dominated by rolling topography with irregular slopes (0°-18.7°) and many craggy outcrops of bedrock. The elevation range is 422 – 506 m (Δ 94 m). Most of the site is forested with red (*Pinus resinosa*) and white pine (*Pinus strobus*), Douglas fir (*Pseudotsuga menziezii*), black spruce (*Picea mariana*), and red maple (*Acer rubrum*).

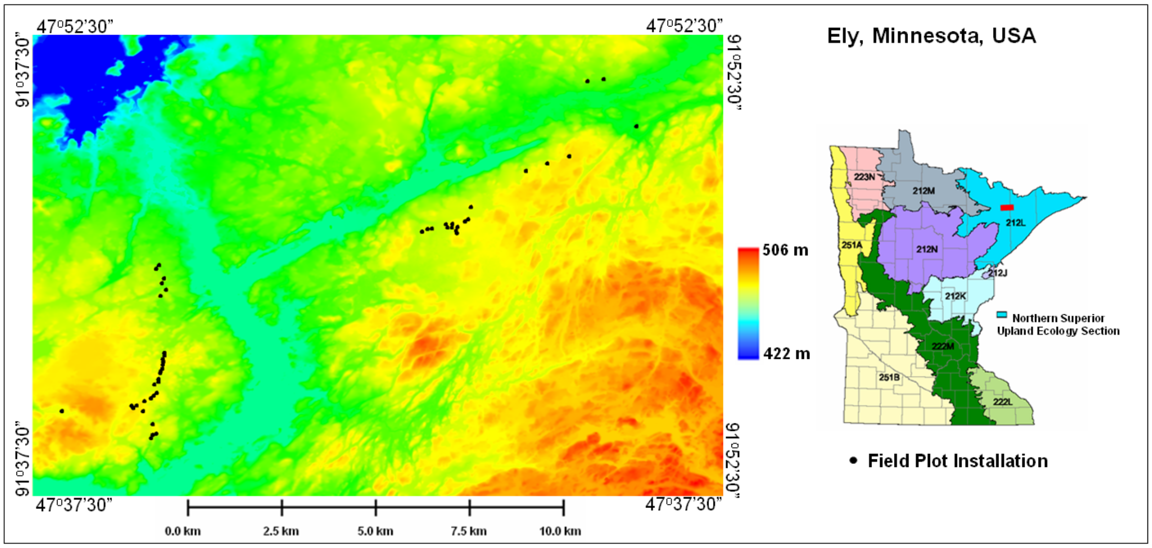

Figure 1. Ely, Minnesota study site with 54 collected circular field plot installation locations represented as black dot superimposed on the NEXTMap® DTM.

Study Site 2: International Falls, Minnesota, USA. International Falls, Minnesota represents dense homogenous coniferous and deciduous and heterogeneous mixed forests with little understory in a temperate environment. The International Falls site covers a region approximately 16.35 km^2. Geographically, the region is located approximately between 48°37'30" N and 48°30'00" N latitudes and 93°30'00" W and 93°15'00" W longitudes (Figure 4). Like the Ely site, it too a part of the LMF. It is located in the Littlefork-Vermilion Uplands subsection of the Northern Minnesota and Ontario Peatlands Section. The western edge of the subsection lies just west of the Littlefork River. The soils are clayey to loamy and formed from lake-laid sediments and glacial till. Topographic relief is less than 30 m across the study site. The elevation grades from 335 m in the northwest corner to 365 m east. The site sits on a lake plain with slopes less than 1.0°. The site is dominated by white pine (*Pinus strobus*), white spruce (*Picea glauca*), and balsam fir (*Abies balsamea*) conifers. The eastern portion was dominated by white pine, red pine (*Pinus resinosa*), and jack pine (*Pinus banksiana*) forest.

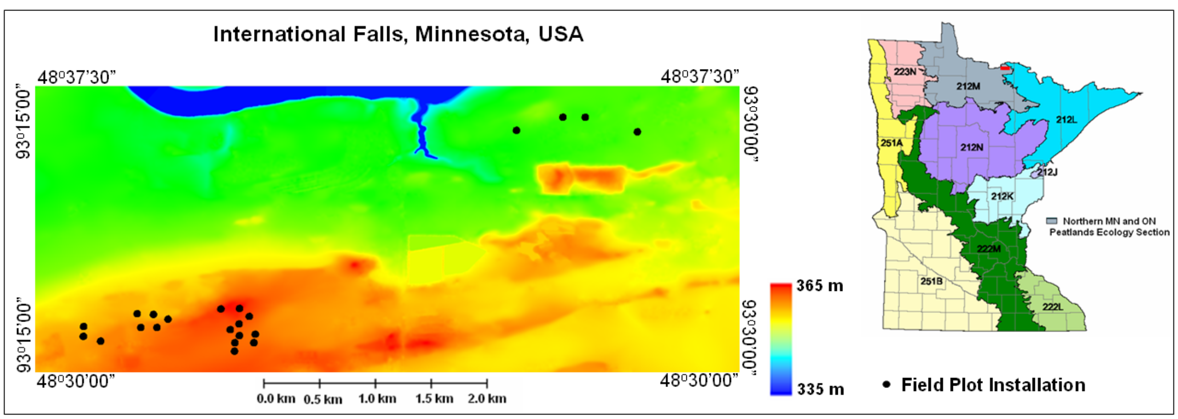

Figure 2. International Falls, Minnesota study site with 22 collected circular field plot installation locations represented as black dot superimposed on the NEXTMap® X-band IFSAR DTM.

Table 1. Land cover classes and their description (Modified after Homer et al., 2007).

Land Cover Type	Class Description modified from NLCD (Homer et al., 2007)
Deciduous Forest	Areas dominated by trees generally > 5 m tall, and >20% of total vegetation cover. More than 75% of the tree species shed foliage simultaneously in response to seasonal change.
Evergreen Forest	Areas dominated by trees generally > 5 m tall, and > 20% of total vegetation cover. More than 75% of the tree species maintain their leaves all year. Canopy is never without green foliage.
Mixed Forest	Areas dominated by trees generally >5 m tall, and >20% of total vegetation cover. Neither deciduous nor evergreen species are >75% of total tree cover.

Data

Four remotely sensed digital elevation data sets (Table 2) were chosen for comparison to the compared to the NGS and *in-situ* measurements.

Table 2. Elevation data source specifications

Data Source	NEXTMap DTM Intermap	NEXTMap DSM Intermap	NED DTM USGS	SRTM DTM NASA/JPL
Coverage	USA, Western Europe, SE Asia, Parts of Australia	USA, Western Europe, SE Asia, Parts of Australia	USA	World - between 56° N and 56° S latitudes
Collection Platform	Airplane	Airplane	Airplane	Shuttle
Ground Sampling Distance (GSD)	5 m	5 m	10 m	30 m
Published Accuracy	1 m	1 m	2-3 m	16 m
Reference	Intermap, 2009	Intermap, 2009	Gesch, 2007	Rabius, 2003

Intermap Data: DTM and DSM. Intermap Technologies commercially operates several airborne single-pass across-track 3 cm wavelength (X-HH) IFSAR sensors mounted in airborne platforms which collect nationwide radar imagery and elevation data (Intermap, 2009; Tighe et al., 2009). Data collected from these IFSAR platforms are called NEXTMap. The NEXTMap® data were interferometrically processed by Intermap using a proprietary IFPROC processor which included averaging of multiple data takes (from overlapping flight lines and tie lines), filtering of the interferogram to reduce phase noise. The NEXTMap data utilized consisted of digital terrain and surface models (DTM, DSM) processed in 7.5-minute tiles according to the USGS index. The DSM is derived from the return signals received by two radar antennas mounted on Intermap's aircraft. The signals bounce off the first surface they strike, be it the ground or vegetation canopy, and thus will contain elevations of, for example, buildings and vegetation. DTM is derived from the DSM by experienced IFSAR editors using Intermap's semi-automated proprietary three dimensional IFSAR editing software and a set of edit rules described in Intermap's Product Handbook (Intermap, 2009). The NEXTMap® DTM and DSM data are processed to 32-bit floating 5 m GSD in grid format using a WGS84 datum with geographic coordinates. The elevation data have a 1 m root mean square error (RMSE) vertical and 2 m horizontal RMSE accuracy in regions of flat and unobstructed terrain (Intermap, 2009).

National Elevation Data (NED). The U.S. Geological Survey (USGS) produced the National Elevation Dataset (NED) by merging the highest-resolution, best-quality elevation data available across the continental United States, Alaska, Hawaii, and the island territories into a seamless raster format. NED is the result of the maturation of the USGS effort to provide 1:24,000-scale digital elevation model (DEM) data for the conterminous United States and 1:63,360-scale DEM data for Alaska. NED has a consistent projection (geographic), resolution (1 arc second), and elevation units (meters; Osborn et al., 2001). The accuracy of the NED varies spatially because of the variable quality of the source DEMs. As such, the NED "inherits" the accuracy of the source DEMs. This accuracy information has limited usefulness because it is a relative measure of how well the DEM fits the source material from which it was generated (Gesch et al., 2007). Ten meter GSD NED data were obtained from the United States Geological Survey (USGS) website (http://ned.usgs.gov/) for the study site.

Shuttle Radar Topography Mission (SRTM). SRTM was flown on board the Space Shuttle Endeavour during mission STS-99 February 11-22, 2000. Additional details of the SRTM data are found in (Farr and Kobrick, 2000; Hensley et al., 2000). 99.97% of the targeted land mass was mapped with at least one data pass (i.e., one Shuttle overpass), 94.59% with at least two data passes, 49.25% with at least three data passes, and 24.10% with at least four data takes. The SRTM dataset was developed from raw radar echoes into digital surface models (DSM), which are available at 1 arc second resolution (30 m ground sampling distance) for the study site (USGS, 2006). The SRTM is projected into a geographic coordinate system (GCS) with the WGS84 horizontal datum and the EGM96 vertical datum (USGS, 2006). Voids, or no data holes, in SRTM data are attributed to the complexity of IFSAR technology and topographic shadowing from dense vegetation. The quality of the SRTM data may suffer from mast motion and phase noise errors (Mercer et al., 2004; Becek, 2008). Interferometric Terrain Height Data 1 (DTHD-1) specifications, which include a 30 m GSD, 16 m absolute vertical height accuracy, and 16 m absolute horizontal accuracy and at the same mapping projection (WGS84), were obtained for the study site in grid format. All accuracies are quoted at the 90% confidence level (Rabus et al., 2003).

National Geodetic Survey and in-situ Check Points. The extents of each of the study sites were used to extract verification check points (VCPs) representing bare ground which are part of the National Geodetic Survey (NGS) database. A total of 40 NGS bare ground points (23 – Ely, MN; 17 – International Falls) fell within the study site extents. All points where combined with the *in-situ* bare ground measurements (54 – Ely, MN; 22 – International Falls) to assess the accuracy of the DTM (NEXTMap and NED) in various terrain slopes ranging from $0^{\circ} – 30^{\circ}$. A total of 178 tree height in-situ measurements (112 – Ely, MN; 66 – International Falls) were utilized to assess the accuracy of the derived X/C-band h_{spc} and CHM

National Land Cover Database (NLCD). The 2001 USGS National Land Cover Database (NLCD) generated from Landsat 5 and 7 data and consisting of sixteen land cover classes and 10 canopy closure (vegetation density) classes at a 30m cell size are digitally available for the US sites. Full legend class descriptions were published in Homer et al. (2007). This data were utilized in the selection of the plot installations, further explained in the Field Method section.

METHODS

Field Method

Field programs for the study sites were conducted in July-August 2008. The goal of the field programs were to acquire survey-grade, bare-ground elevation measurements in open areas as well as beneath vegetation canopy and to measure tree and shrub heights for a variety of tree cover types. Field plots, 54 Ely and 22 International falls, were installed. The NLCD and NEXTMap® elevation data were utilized to select candidate field plot locations from the desktop that were modified in the field to non-random samples near roads and open fields evenly distributed across the study site. A center coordinate for each planned plot was loaded in a handheld Leica 500, dual-frequency L1/L2 survey-grade GPS receiver. This was paired with a Leica AT502 antenna and a surveyor tripod GPS system and used in the field to measure the final selected center coordinate. The logging rate was set at 30 seconds, with a minimum occupation time of 15 minutes for each GCP. The GPS measurements were differentially post-processed to provide a vertical accuracy of 10 cm for the plot center in the shrub/scrub and medium-dense forested vegetation and 10-30 cm in the dense forested vegetation. The horizontal accuracy was <50 cm regardless of the vegetation class. Plots were established in uniform and representative example areas of each land cover (i.e., no mixing of land cover types in a given plot) over a radius of at least 30.48 m (100 feet) (measured using a chain). Vegetation cover type at six locations within the circular plots (five planned and one where the tree heights were measured was recorded to assist in the validation of the X-band and C-band IFSAR derived CHMs. A total of 93 evergreen, 98 deciduous and 44 mixed forest vegetation heights were collected. 76 Bare ground measurements, representing a combination of in-situ and NGS sample points were available for barren ground and utilized in testing the accuracy of the DTM elevation models.

DTM Accuracy Assessment

A digital terrain model **(**DTM), or "bald-Earth" model, is a digital elevation model (DEM) that simulates true earth-surface elevations minus ground features such as trees, buildings, and above ground obstructions (Podobnikar, 2009). Critical to the development of a canopy height model is the availability of an accurate bare ground elevation model that represents the bare ground. One that is most useful in the forestry context if one could expect that the accuracy would be uniform and not vary significantly beneath forest canopy, over bare ground and in sloped terrain. However, insight suggests that these site conditions could have a significant effect on DTM accuracy derived from any first surface sensor (Baltzer et al., 2007; Andersen et al., 2008). The NEXTMap® DTM data accuracy specification of 1 m vertical RMSE applies to unobstructed areas on slopes less than ten degrees (Tennant et al., 2003; Tighe, 2003; Mercer, 2004; Intermap, 2008). The NED DTM's accuracy ranges from ~3-8 m RMSE (Osborn et al., 2001). This accuracy assessment is designed to assess the magnitude of vegetation and terrain effects on the NEXTMap and NED DTMs against the NGS and *in-situ* bare ground measurements. This was accomplished by creating slope maps containing three classes ($<10^o$, $11\text{-}30^o$, $>30^o$) generated from the DTM data. The x-y coordinates for each NGS and *in-situ* bare ground measurement in unobstructed areas as well as within forested canopies was superimposed on the NEXTMap and NED DTMs and slope maps to extract the slope and elevations values. The Root Mean Square Error (RMSE) and Linear Error (LE) 95% confidence level were used to test the accuracy of the DTMs compared to the NGS and *in-situ* bare ground measurements. All statistics were tabulated for comparison (Table 3).

Scattering Phase Center Estimation

IFSAR sensors retrieve the mean height of the main scattering elements in a resolution cell known as the scattering phase center height, commonly abbreviated as h_{spc}. The h_{spc} was directly estimated from X- and C-Band phased IFSAR by subtracting the NEXTMap and NED DTMs from the NEXTMap and SRTM DSMs (Figure 2), respectively. Using the in-situ x-y coordinates, heights were derived from the X- and C-Band h_{spc} surfaces and compared against the *in-situ* height measurements by calculating the Root Mean Square Error (RMSE), 95% linear error confidence level (LE95%) and the mean, maximum and minimum height, as well as the standard deviation. Statistics were recorded in Table 4.

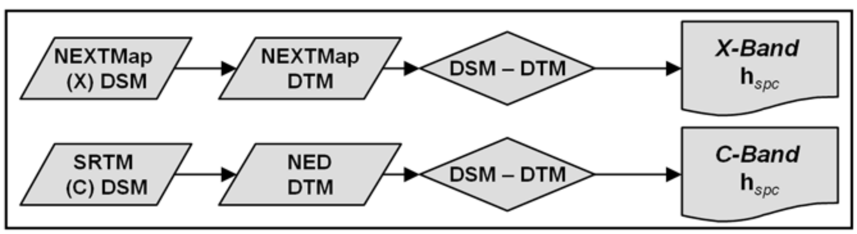

Figure 2. Methodology to calculate scattering phase center height.

Canopy Height Model

A method to account for the attenuation of the microwave radiation into the canopy at X-HH and C-HH Band IFSAR is presented in Figure 3 (Tighe et al., 2009). The percentage of tree height underestimation caused by penetration of microwave radiation into the canopy (Tighe et al., 2009), the type of vegetation canopy (given by NCDL and verified in the field) and the scattering phase center height (h_{spc}) are inputs to derive a canopy height model (CHM) from X-band and C-Band IFSAR data (Figure 3). The x-y coordinates for each *in-situ* vegetation height measurement was superimposed on the X- and C-Band CHMs to extract the elevations values. The RMSE, LE95%, mean, maximum, minimum, and standard deviation were used to test the accuracy of the CHMs compared to the *in-situ* measurements. All statistics were tabulated for comparison (Table 5).

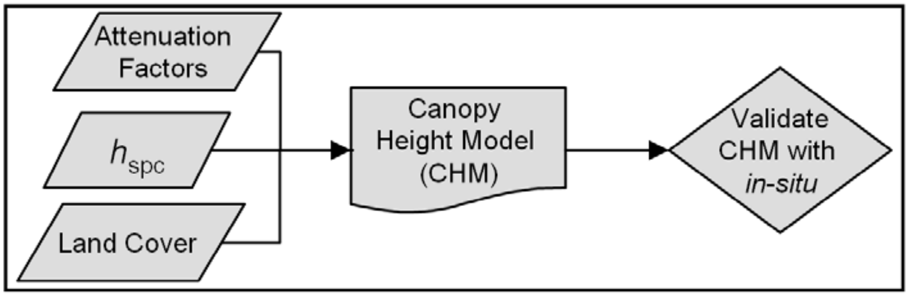

Figure 3. Methodology to create Canopy Height Models (CHMs).

RESULTS/DISCUSSION

NEXTMap and NED DTM Accuracy

There were not enough NGS or in-situ bare ground measurements within each vegetation class to derive statistical error per vegetation cover. As a result, the overall accuracy of the DTM data, in unobstructed and obstructed (vegetated) and all sloped terrain were derived and presented in Table 3.

Table 3. DTM Data Accuracy Error Assessment Against *in-situ* and NGS Measurements

All Vegetation Types	# Samples	NEXTMap DTM			NED DTM		
		RMSE (m)	SD	LE95%	RMSE (m)	SD	LE95%
Overall	76	1.84	1.62	3.18	2.05	1.89	4.03

Scattering Phase Center Height Comparison

The accuracy of the vegetation heights derived from the scattering phase center heights for the NEXTMap and the NED/SRTM data sets are presented in Table 4. Both the X and C-band data underestimated the vegetation heights. The mixed vegetation had the greatest error possible due to the variation in tree heights as well as the variation in tree density given by the mixture of tree types. As expected the C-band data, operating at longer wavelength (6 cm) than the X-band data (3 cm), received greater errors due to greater penetration into the vegetation canopies.

Table 4. Scattering Phase Center Error Assessment Against *in-situ* Vegetation Canopy Measurements

Vegetation Cover	# Samples	Average Tree Height Given by *in-stu* (m)	X-Band h_{spc}		C-Band h_{spc}	
			RMSE (m)	SD	RMSE (m)	SD
Evergreen	93	15.01	6.73	3.85	13.43	3.75
Deciduous	98	14.26	6.81	3.27	8.40	2.12
Mixed	44	14.64	9.97	6.75	12.56	5.69
Overall	235	15.12	6.14	3.92	10.74	4.22

Canopy Height Model Comparison

The accuracy of the vegetation heights derived from the CHMs for the NEXTMap and the NED/SRTM data sets are presented in Table 5.

Table 5. Canopy Height Model Error Assessment Against *in-situ* Vegetation Canopy Measurements

Canopy Type	# Samples	Average Tree Height Given by *in-situ* (m)	X-Band CHM		C-Band CHM	
			RMSE (m)	SD	RMSE (m)	SD
Evergreen	93	15.21	2.17	0.94	3.73	1.22
Deciduous	98	14.26	2.13	0.80	3.16	0.90
Mixed	44	14.74	2.18	0.74	3.41	0.87
Overall	235	15.12	2.16	0.85	3.45	1.06

CONCLUSIONS

The results of this study indicate that both the NEXTMap and the NED DTM data proved to be viable technologies for the generation of DTM data. The NEXTMap DTM data was more accurate over the NED data, as to be expected given the spatial resolution of the the NEXTMap DTM (5 m) compared to the NED DTM (10 m). The NEXTMap DTM error in these forested areas (1.84 m) is lower than the standard USGS 10 m DTM (2.05). Given the demonstrative capabilities of the X-band IFSAR to provide accurate elevation data in vegetated areas, it is expected that this technology will receive increasing interest in the forestry community. The need for accurate estimation of three dimensional (3D) forest attributes, such as canopy height is required in forest management applications. Typically collected using traditional field survey techniques, and are expensive and labor-intensive to acquire. The results presented in this study provide an alternative to field techniques. The remotely sensed data, acquired from either airborne (NEXTMap) or spaceborne (SRTM) platforms, are potentially cheaper and less labor intensive to acquire, and are spatially extensive, thereby providing an alternative to traditional field techniques. The results presented in this study may provide the forest management community with the expectation to have accurate, and highly-detailed, digital canopy height information provided as standard remote sensing deliverables. The demonstrated capability of the NEXTMap and SRTM systems to provide a direct measurement of three dimensional structure and terrain, enabled foresters to implement a site-specific approach to environment management, optimizing use and therefore increasing the value of the forest resource.

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