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Tandem-X interferometry in the prediction of forest inventory attributes in managed boreal forests

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ABSTRACT

Forest inventory attributes can be estimated using forest height data derived from remote sensing datasets. In this study, we estimated forest inventory attributes; i.e. stem volume, basal area, and Lorey's height using Tandem-X (TDX) interferometric synthetic aperture radar (InSAR) elevation models and coherence data assisted by ancillary terrain models. It is well known that SAR interferometry is sensitive to the structural changes taking place in the target between image acquisitions; e.g. changes caused by wind in vegetated areas. As regards non-simultaneous InSAR imaging, temporal changes in the target lead to loss of coherence and consequently to digital elevation models of low quality. Therefore, repeat-pass InSAR data have limited use in forest resource mapping. The problem of low coherence in forested areas can be partially avoided by using simultaneous InSAR data acquisition, e.g. the bistatic TDX SAR satellite system, which was launched in June 2010. We processed five interferometric TDX pairs from a test site located in Southern Finland, and collected data from 335 field plots, to study the accuracy of TDX InSAR elevation models and coherence data in forest resource mapping at a resolution of 314 m^2. The SAR-derived elevation models (16 m^2 pixel size) were converted to heights above the ground level using a digital terrain model based on airborne laser scanning data. The random forest (RF) method was used to create a model for estimating the forest attributes using remote-sensing-derived metrics as the predictors. The results for accuracy of prediction were the following: the relative RMSE of 32% was obtained for stem volume, 20% for Lorey's height, and 29% for basal area. The forest inventory attributes were derived from the TDX data with an accuracy equivalent with the accuracy of other remote sensing techniques. This result shows the potential of TDX data in robust and cost-effective forest inventory covering large areas.

1. Introduction

Information on forest resources is required for forestry purposes as well as for global carbon cycle modeling related to climate change (Le Toan et al., 2011). Detailed and up-to-date information is required for allocation of forestry activities and also for national and international reporting obligations. To allocate forestry activities, information on forest structure and quality (e.g. amount of stem volume, basal area, Lorey's height) has to be mapped. Nowadays, detailed mapping data on various forest inventory attributes, such as stem volume, basal area, and biomass, can be produced using airborne laser scanning (ALS) data (Hyyppä et al., 2008) or by using point clouds generated from aerial imagery (Bohlin, Wallerman, & Fransson, 2012; Nurminen, Karjalainen, Yu, Hyyppä, & Honkavaara, 2013; Vastaranta et al., 2013). When the ALS is used, the laser pulses penetrate even through dense and multi-layered canopies, and there is a strong correlation between laser height profiles (or point clouds) and above ground biomass (AGB) and stem volume (VOL) (e.g. Kellndorfer et al., 2010; Lefsky, Harding, Cohen, Parker, & Shugart, 1999; Lim & Treitz, 2004; Nelson, Krabill, & Tonelli, 1988; van Aardt, Wynne, & Oderwald, 2006). In the typical approach (also known as the area-based approach, ABA), forest inventory attributes are measured from field plots and then the ground data are generalized over the entire area of interest using the ALS data or aerial imagery-derived point cloud data (Næsset, 2002; White et al., 2013). The ABA is capable of providing wall-to-wall estimates and maps of inventory attributes, such as basal area or volume, with enhanced accuracy when compared to traditional mapping-based inventories (Holopainen et al., 2010; Næsset, 2004). When using ALS or digital surface models (DSMs) from digital stereo imagery to predict VOL or AGB, the relative root-mean-square error (RMSE %) at a resolution of 300–400 m^2 has been between 20% and 35% (Bohlin et al., 2012; Kankare et al., 2013; Nurminen et al., 2013; Vastaranta et al., 2012, 2013).

However, airborne data collection over large-areas can be more time-consuming and expensive when compared to spaceborne techniques (Vastaranta, 2012). Thus, satellite-based remote sensing plays an important role in the mapping of large and remote forested areas. Optical satellite images, such as Landsat, have been used to generate wall-to-wall data from field inventory data using three statistical

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techniques, including the RF (Powell et al., 2010). Moreover, several countries employ or have tested this kind of approach in addition to solely ground-based national forest inventories (NFIs) (Tomppo & Schadauer, 2012). Although major advances have been made in optical satellite-based remote sensing technologies in recent years, the major challenge remaining is how to correctly estimate high levels of AGB or stem volume (VOL) (Gómez et al., 2014). This challenge is typically referred as the saturation level, which depends on the satellite data used in estimation. Moreover, the estimation accuracies are low, for example, using Landsat imagery VOL RMSEs of 65% and 75%, and, basal area (BA) RMSEs of 56% and 46% have been obtained at plot level (Franco-Lopez, Ek, & Bauer, 2001; Tuominen & Haakana, 2005). Holmström and Fransson (2003) obtained an RMSE accuracy of 64% for VOL using SPOT-4 multispectral imagery at 400 m^2 resolution (plot level).

The saturation problem in biomass estimation using optical satellite data can be overcome by adopting techniques enabling 3D measurements, e.g. ALS. 3D-data can be derived also from spaceborne SAR satellite imagery. Compared to optical satellite data, SAR penetrates clouds and is daylight independent, however, some weather related effects may occur especially when sort wavelengths are used (Danklmayer, Döring, Schwerdt, & Chandra, 2009). There are two main techniques available in obtaining 3D measurements from SAR: radargrammetry and interferometry. In addition to 3D data, SAR intensity can be used in the prediction of forest inventory attributes (e.g. Ho Tong Minh et al., 2014; Holopainen et al., 2010; Lucas et al., 2010; Santoro et al., 2011), but then the same saturation problems exists as with optical satellite data. Using intensity data, Holopainen et al. (2010) achieved an RMSE accuracy of 56%.

SAR interferometry (Bamler & Hartl, 1998; Massonnet & Feigl, 1998) is based on the phase differences between two complex SAR images, which are then converted to tree height differences in the target area. By using a short radar wavelength, backscattering from the canopy is obtained in forested areas, and the canopy height can be estimated. It should be noted, that due to signal penetration in the target, there is underestimation of the actual height (Praks, Antropov, & Hallikainen, 2012). DSMs with resolutions ranging from 25 m^2 to 100 m^2 are usually derived using radargrammetry or interferometry, even higher resolution is possible using the latest satellite data. DSMs based on ALS or digital stereo imagery are more detailed; resolutions vary between 0.25 m^2 to 1 m^2. However, when using SAR-based DSMs in conjunction with ALS-derived digital terrain model (DTM), prediction RMSE accuracies close to 30% have been obtained for stem volume and AGB (Karjalainen, Kankare, Vastaranta, Holopainen, & Hyyppä, 2012; Perko, Raggam, Deutscher, Gutjahr, & Schardt, 2011; Raggam, Gutjahr, Perko, & Schardt, 2010; Vastaranta, Holopainen, et al., 2014; Vastaranta et al., 2012). The accuracy achieved at the stand level, is higher (Persson & Fransson, 2014; Vastaranta, Niemi, et al., 2014).

Interferometric coherence information of SAR images has been used in forest attribute retrieval (e.g. Askne, Santoro, Smith, & Fransson, 2003; Fransson, Smith, Askne, & Olsson, 2001; Hagberg, Ulander, & Askne, 1995; Hyyppä et al., 2000; Santoro, Askne, Smith, & Fransson, 2002). In Hyyppä et al. (2000) the RMSE % of VOL was 58% (stand-level). In Askne et al. (2003) the relative RMSE of VOL retrieval from single coherence images varied between 15% and 108% (stand level) and in multitemporal combination plot-level RMSE of 34% was achieved. Successful interferometric height measurements require adequate coherence between the two images. For forested areas, adequate coherence for DSM generation is obtained by acquiring the images simultaneously; in special conditions e.g. in winter-time in frozen conditions also repeat pass data may be applicable. Previously simultaneous data have been available only from airborne systems and from the Shuttle Radar Topography Mission (SRTM) (Werner, 2001). Both airborne InSAR data (Hyde et al., 2007; Praks et al., 2012) and SRTM data (Solberg, Astrup, Bollandsås, Næsset, & Weydahl, 2010; Solberg, Astrup, Gobakken, Næsset, & Weydahl, 2010; Sun et al., 2011) have been tested in the estimation of forest characteristics. Currently, single-pass InSAR satellite data are available from the Tandem-X (TDX) satellite mission (Krieger et al., 2007).

In previous studies (e.g. Askne, Fransson, Santoro, Soja, & Ulander, 2013; Praks et al., 2012; Solberg, Astrup, Breidenbach, Nilsen, & Weydahl, 2013; Solberg, Astrup, Gobakken, et al., 2010), it has been shown that using an accurate ALS-derived DTM for terrain height, a canopy height model (CHM) can be calculated from InSAR DSM (DSM-DTM). In this way, 3D data derived from SAR data can be used to create fairly good forest resource maps. As regards wide-area mapping, the main obstacle is the availability of ALS-based terrain models. However, ALS coverage is increasing rapidly, and large-scale ALS surveys are currently carried out in many countries; e.g. in the USA, Canada, Sweden, and Spain (GIM International, 2014).

As yet, TDX data have been used in only very few studies in the mapping of forest inventory attributes of boreal forest (Askne et al., 2013; Kugler, Schulze, Hajnsek, Pretzsch, & Papathanassiou, 2014; Soja, Persson, & Ulander, 2015; Solberg, Weydahl, & Astrup, 2014; Solberg et al., 2013), and more knowledge is needed of different forest conditions. The aim of this study is to validate the estimation accuracy of forest inventory attributes at a resolution of 314 m^2 using TDX InSAR height data combined with coherence data. We are carrying out tests to determine whether it is possible to carry out detailed forest attribute mapping using TDX data and investigating the effect of coherence data on accuracy. An InSAR-based canopy height model (CHM) obtained from bistatic TDX images (converted to heights above ground using detailed airborne laser scanning based DTM) and coherence data are used in the prediction of forest inventory attributes. TDX data acquired using two angles of incidence are compared and geometrical and temporal stability are analyzed. The prediction accuracy is validated by using field plots on the Evo test site. The Random Forest classification technique is used to carry out the predictions. Also the importance of different InSAR features in the predictions is estimated. In the previous study by Solberg et al. (2013), AGB and VOL were estimated from TDX data; however, coherence data were not used and only spruce-dominated forest plots were studied. Our field data also included plots representing several forest types, although they were pine-dominated. In our study,

Table 1
Tandem-X pairs from Evo.

#	Date and time (UTC)	Baseline	HoA	Angle of incidence	Scene center	Temperature, humidity, wind
1	14.8.2012 16:03	192 m	−45 m	48°	61.25N, 25.18E	22 °C, 47%, 5 m/s
2	29.6.2013 16:03	139 m	−61 m	48°	61.25N, 25.18E	18 °C, 88%, 1 m/s
3	30.6.2013 15:46	120 m	40 m	31°	61.30N, 25.33E	22 °C, 47%, 3 m/s
4	21.7.2013 16:03	120 m	71 m	48°	61.25N, 25.19E	17 °C, 59%, 5 m/s
5	22.7.2013 15:46	100 m	−49 m	31°	61.30N, 25.33E	13 °C, 94%, 5 m/s