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Prediction of stem volume in complex temperate forest stands using TanDEM-X SAR data

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ABSTRACT

Reliable estimations of stem volume are important for sustainable forest management planning as well as for monitoring of global changes. However, the derivation of stem volume in cubic meters per hectare based on traditional sampling-based forest inventories (usually with a repetition rate of ten years) is very expensive, labor-intensive and only available for the minority of the forest areas worldwide. Thus, spaceborne synthetic aperture radar (SAR) data can provide estimations of forest parameters with sufficient spatial and temporal resolution for large areas. Height information extracted from two interferometric dual-polarized TanDEM-X data sets were used to investigate the potential of polarimetric interferometric X-band SAR data for stem volume estimation in the complex forest stands of the Traunstein forest in Southeast Bavaria, Germany. In contrast to other studies of forest parameter estimation from X-band SAR data carried out in boreal or tropical forest stands, the current study investigated stem volume estimation based on X-band SAR data in complex temperate forest stands. A linear regression model based on the allometric relationship of forest height (estimated from SAR data combined with an airborne LiDAR-based Digital Terrain Model) and stem volume per unit area (deduced from traditional forest inventory) was derived. Moreover, the model was extended and thus improved by integrating novel parameters derived from the co-occurrence matrix as surrogates for horizontal forest structure. This linear regression model predicted stem volume at plot (circular plots of 500 m^2) level with a coefficient of determination of $R^2 = 69\%$ and a root mean square error of RMSE = 155 m^3 ha^{-1} and stand (areas of 1.5 to 6.4 ha) level with $R^2 = 94\%$ and RMSE = 44 m^3 ha^{-1} respectively.

1. Introduction

Stem volume is one of the key parameters in forest inventory. Reliable estimations of stem volume per unit area have been the basis for sustainable forest management planning since the beginning of the 18th century (von Carlowitz, 1713) as well as for monitoring of global changes in recent times (IPCC, 2014). Especially in the context of climate change, felling budget can be adapted to damages caused by increasing extreme weather events and calamities. Moreover, stem volume can be directly related to stem biomass as a function of the tree species-specific wood density. For generalization and simplification, a first-order approximation with a density of 500 kg m^{-3} (corresponding to a density factor of 0.5 t m^{-3}) is assumed (Pretzsch, 2009), while the Food and Agriculture Organization of the United Nations (FAO) suggests generalized region-specific density factors of about 0.6 t m^{-3} (FAO, 2001). The total above ground biomass can be estimated by the additional use of the biomass expansion factor, which expands stem biomass to account for non-merchantable biomass components such as branches, foliage, and non-commercial trees (Brown, 1997). Stem volume estimations provide the required basis for sustainable management, and by means of conversion into biomass a crucial parameter to understand and quantify the global carbon cycle. Carbon is stored by building up biomass and emitted to the atmosphere by destroying biomass due to fire, logging with subsequent energetic use, storms, decomposition, etc. (Houghton, Hall, & Goetz, 2009). By means of forest management strategies this process can be controlled and the CO_2 emissions can be reduced (Schlamadinger & Marland, 1996).

Stem volume per unit area is expressed in cubic meters per hectare. For the purpose of this study we use its definition as harvested timber volume under bark which is most widespread among practitioners. It can be derived from terrestrial forest inventory based on diameter at breast height (dbh) and tree height measurements (Pretzsch, 2009). Traditional forest inventories, like National Forest Inventory in Germany, Sweden or Great Britain (usually with a repetition rate of ten years) are very expensive, labor-intensive and only available for the minority of the forest areas worldwide. A unique example at global scale is the Forest Resources Assessment (FRA) conducted by the FAO every five to ten years in order to assess the areal extent and changes of forests worldwide (FAO & JRC, 2012). This information can be used as the basis for global sustainable forest management but is still lacking more detailed information on forest volume, associated biomass and its

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changes. For this purpose, remote sensing offers area-wide information with high spatial and temporal resolution and thus can enable sustainable forest management planning and detailed monitoring of changes in a global context.

Radar systems are all-weather systems, which is an advantage over optical systems. The penetration depth of microwaves into the forest canopy depends on the wavelength. The TanDEM-X mission is composed of the two almost identical satellites TerraSAR-X (launched in 2007) and TanDEM-X (launched in 2010) flying in a closely controlled formation. The TanDEM-X mission provides high resolution, multi-polarized, single-pass interferometric X-band (9.65 GHz) data. Especially single-pass interferometry is very suitable for forest applications due to the simultaneous acquisition of the two interferometric images (Kugler, Schulze, Hajnsek, Pretzsch, & Papathanassiou, 2014). The simultaneous acquisition avoids possible errors due to temporal decorrelation and atmospheric disturbances, which is one of the significant benefits of the TanDEM-X mission (Krieger et al., 2007).

Numerous studies investigate the potential of SAR data at different wavelengths from different sensors on satellite and airborne platforms for biomass and stem volume estimation over boreal, temperate and tropical forests. At lower frequencies like P- (0.3–1 GHz) and L- (1–2 GHz) band, the radar signals penetrate deep into the forest canopy and are backscattered at big branches, tree trunks and the ground (Dobson et al., 1992; Le Toan, Beaudoin, Riom, & Guyon, 1992). Due to the high penetration capability and thus high sensitivity to vertical forest structure, the intensity of radar backscatter at longer wavelengths are in particular suitable for biomass retrieval (e.g. Engelhart, Keuck, & Siegert, 2011; Luckman, Baker, Honzák, & Lucas, 1998; Rauste, 2005) but can also be used for stem volume estimations (e.g. Antropov, Rauste, Ahola, & Häme, 2013; Askne, Smith, & Santoro, 2004; Gonçalves, Santos, & Treuhaft, 2011). In contrast, microwaves with higher frequencies (i.e. shorter wavelength) such as C- (4–8 GHz) and especially X- (8–12 GHz) band are just as well able to penetrate down to the ground but are mostly backscattered in the upper part of the crowns (Gama, Santos, & Mura, 2010; Pulliainen, Engdahl, & Hallikainen, 2003). Consequently, the radar backscatter intensity at these bands is less sensitive to the vertical forest structure but hence is well suited to derive height information of the canopy by use of ancillary information on ground elevation (e.g. LiDAR-based DTM). Thus, C- and X- band microwaves tend to be more appropriate for both biomass (e.g. Gama et al., 2010; Solberg, Riegler, & Nonin, 2015; Treuhaft et al., 2015) and stem volume (e.g. Karila, Vastaranta, Karjalainen, & Kaasalainen, 2015; Solberg, Astrup, Breidenbach, Nilsen, & Weydahl, 2013; Wagner et al., 2003) estimation by means of height information derived from SAR data. Biomass and stem volume estimations by means of height information derived from shortwave radar data are based on either SAR radargrammetry (e.g. Karjalainen, Kankare, Vastranata, Holopainen, & Hyyppä, 2012; Solberg et al., 2015; Vastaranta, Holopainen, Karjalainen, Kankare, & Hyyppä, 2014) or SAR interferometry (e.g. Gama et al., 2010; Solberg et al., 2013; Treuhaft et al., 2015).

Several recent studies demonstrated the estimation of biomass and stem volume by means of interferometric information derived from X-band SAR data. Karila et al. (2015) employed a nearest neighbor prediction model for stem volume estimation based on InSAR heights from TanDEM-X data in boreal forest stands in Southern Finland. In Treuhaft et al. (2015), coherence from TanDEM-X InSAR data was deployed for biomass estimation using linear regression in a tropical forest in Brazil. Schlund, von Poncet, Kuntz, Schmullius, and Hoekman (2015) estimated biomass by linear and non-linear regression models based on TanDEM-X coherence in a tropical forest test site in Indonesia. Rahlf, Breidenbach, Solberg, Naesset, and Astrup (2014) used InSAR heights from TanDEM-X in combination with a LiDAR-based DTM (Digital Terrain Model) for stem volume estimation in a boreal forest in Southern Norway. Solberg et al. (2013) compared linear and non-linear regression of interferometric height and biomass or stem volume based on TanDEM-X SAR data in a boreal forest test site. In Solberg, Astrup, Gobakken, Naesset, and Weydahl (2010) a non-linear, mixed regression model based on InSAR height derived from TanDEM-X data was applied to estimate biomass in boreal forest stands, whereas Gama et al. (2010) used airborne X-band data for linear regression of interferometric height and stem volume in tropical forest.

In contrast to previous studies which were carried out in boreal or tropical forest stands using X-band radar data, the current study investigates stem volume estimation based on height information derived from polarimetric interferometric SAR (PolInSAR) data from TanDEM-X in temperate complex forest stands. Nevertheless, few studies based on non-X-band interferometric SAR data already exist in temperate forests. Li, Chen, Li, Ke, and Zhan (2015) estimated biomass from vertical reflectivity profiles based on airborne L-band data in temperate forest stands in Traunstein, Southeast Germany. Neumann, Ferro-Famil, and Reigber (2010) derived forest height information based on polarimetric interferometric airborne L-band SAR data in temperate forest stands in Traunstein. In Lavalle, Solimini, Pottier, and Desnos (2010) the potential of compact-polarimetric airborne InSAR data of multiple frequencies was investigated for estimation of forest parameters in temperate forest stands of Traunstein forest.

The objective of this study is to explore the potential of height information derived from X-band PolInSAR data for stem volume estimation based on a statistically fitted regression model in temperate forest stands. Thereby, this study is linked to previous studies which investigate the potential of X-band PolInSAR data to derive height information over complex temperate and tropical forest stands (e.g. Hajnsek, Kugler, Lee, & Papathanassiou, 2009; Kugler et al., 2014) while applying the derived height information for stem volume estimation. In detail, the aims of this study were defined as (i) estimation of stem volume per unit area at plot (circular plots of 500 m^2) and stand level (areas of 1.5 to 6.4 ha) based on height information derived from polarimetric interferometric TanDEM-X data in combination with airborne LiDAR data and terrestrial measurements and (ii) improvement of the predictions by integration of texture parameters representing the horizontal stand structure.

2. Materials

2.1. Study area

The study area (Fig. 1) is located in a highly structured, mixed, temperate municipality owned forest close to the city of Traunstein, Germany (47°52′ N, 12°38′ E). Traunstein forest covers an area of about 580 ha and is supervised and used as teaching and research forest by the Chair for Forest Growth and Yield Science of the Technische Universität München (TUM). The study area is limited to a forest area of 243 ha bounded by the districts Bürgerwald and Heiligengeistwald. The topography ranges from 630 to 720 m a.s.l. and includes small areas with steep slopes. The soils are composed of glacier sediments which belong to the pre-alpine moraine landscape. The climatic conditions are characterized by a mean annual temperature of 7.3 °C and precipitation of up to 1600 mm/year. The main tree species are Norway spruce (*Picea abies*), European silver fir (*Abies alba*), European beech (*Fagus sylvatica*) and Sycamore maple (*Acer pseudoplatanus*). The forest stands are very complex concerning tree species richness and heterogeneous stand structures due to close-to-nature silviculture (Pretzsch, 1996) which is reflected by the distribution of tree species (Table 1) and percentage of development stages (Table 2) within the study area.

2.2. Remote sensing data

Two dual-polarized interferometric TanDEM-X image pairs acquired on January 09, 2012 and May 18, 2013 were used. The images were acquired in bistatic StripMap mode in ascending orbit and almost identical incidence angles of roughly 43°. The baseline between the two sensors was 108.74 m and 142.72 m, respectively. A summary of