In: Wagner W., Székely, B. (eds.): ISPRS TC VII Symposium – 100 Years ISPRS, Vienna, Austria, July 5–7, 2010, IAPRS, Vol. XXXVIII, Part 7B

THE CAPABILITIES OF TERRASAR-X IMAGERY FOR RETRIEVAL OF FOREST PARAMETERS

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Technical Commission VII Symposium 2010

KEY WORDS: Forestry, Mapping, Photogrammetry, Classification, DEM/DTM, SAR, High resolution.

ABSTRACT:

The TerraSAR-X mission was launched in June 2007 operating a very high resolution X-band SAR sensor. In Spotlight mode images are collected with 0.75m GSD and also at various look angles. The presented paper reports methodologies, algorithms and results emerged from the Austrian research project "Advanced Tools for TerraSAR-X Applications in GMES" with emphasis on retrieval of forest parameters. For deriving forest features like crown closure, vertical stand structure or stand height a digital forest canopy model serves as an important source of information. The procedures to be applied cover advanced stereo-radargrammetric and interferometric data processing, as well as image segmentation and image classification. A core development is the multi-image matching concept for digital surface modelling based on geometrically constrained matching, extending the standard stereo-radargrammetric approach. Validation of surface models generated in this way is made through comparison with LiDAR data, resulting in a standard deviation height error of less than 2 meters over forest. Image classification of forest regions is then based on TerraSAR-X backscatter information (intensity and texture), a 3D canopy height model and interferometric coherence information yielding a classification accuracy above 90%. Such information is then directly utilized to extract forest border lines. Overall, the TerraSAR-X sensor delivers imagery that can be used to automatically retrieve forest parameters on a large scale, being independent of weather conditions which often cause problems for optical sensors due to cloud coverage.

1 INTRODUCTION

TerraSAR-X is the first German satellite out of a public private partnership (PPP) between German Aerospace Center (DLR) and Astrium GmbH and was launched in June 2007. The novel X-band SAR sensor can acquire image products in Spotlight, Stripmap and ScanSAR mode at very high resolutions down to 0.75m (Eineder et al., 2008). One main aspect of the Austrian research project "Advanced Tools for TerraSAR-X Applications in GMES" (AT-X) dealt with the derivation of forest related parameters using TerraSAR-X imagery. The first part consists of precise image matching of such imagery for fully automatic derivation of digital surface models (DSM) which are subsequently used to derive a canopy height models (CHM). The second part concerns image classification with the focus on distinguishing forest from non-forest regions.

2 OUR METHODS

The big picture of our workflow is sketched in Figure 1. As seen, a DSM is extracted using multi-image radargrammetry. This DSM is utilized together with InSAR products and backscatter information to derive a forest classification. Finally, this segmentation helps to correct the height of canopy regions resulting in the final corrected DSM.

2.1 Multi-Image DSM Generation

The accurate 3D reconstruction of timbered regions using TerraSAR-X imagery alone is very challenging due to two reasons. First, the traditional InSAR-based processing does not yield appropriate results over forest as the InSAR phase decorrelates within the 11 days TerraSAR-X repeat cycle (Bamler et al., 2008). Second, even in cases of temporal phase correlation the resulting canopy height is systematically

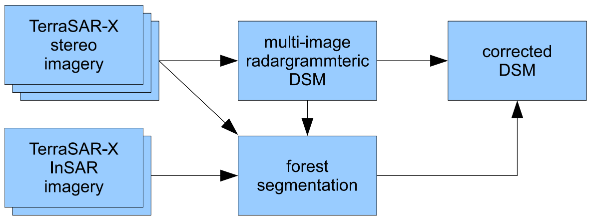

Figure 1: Proposed workflow for deriving forest parameters using TerraSAR-X data.

underestimated. The reason for that is the fact, that the SAR signal in X-band penetrates into the forest canopy changing the InSAR phase center and therefore the reconstructed height. This aspect has been observed on InSAR-based processing of airborne X-band data (Izzawati et al., 2006, Tighe et al., 2009). To tackle all these difficulties we first derive digital surface models using a multi-image stereo-radargrammetric approach. Then, the resulting DSMs are corrected (undoing the canopy height underestimation) by applying an empirically learned correction model on regions of forest.
The radargrammetric processing is described in detail in (Raggam et al., 2010a) and can be applied successfully due to the very exact pointing accuracy of the TerraSAR-X sensor (Bresnahan, 2009, Raggam et al., 2010b). The main steps in the DSM extraction are pairwise stereo matching followed by a joint point intersection procedure. To get robust matching results image triplets are used, i.e. three TerraSAR-X images acquired under different look angles. The main point is, that adjacent images (similar look angles) provide good matching, however unfavorably geometric properties. Therefore, for triplets image 1 can be matched to image 2 and image 2 to image 3. Thus, points from image 1 are transferred to image 3 yielding a large intersection angle and therefore a more robust result. In addition image 1 and image 3 are directly matched resulting in

over-determination in the spatial point intersection.
Stereo matching of a TerraSAR-X image pair is improved by including geometric constraints. First, one image is pseudo epipolar registered based on an affine polynomial transformation using both sensor models. Second, in image matching a starting location for each pixel is predicted, again using sensor models and a coarse DSM (SRTM or ASTER model).
The presented approach yields an areal digital surface model. When subtracting a reference digital terrain model (DTM), e.g. available from airborne laser scanning, a canopy height model (CHM) can be extracted (cf. Figure 2 and Eq. (1)). Such CHMs serve as an important information for the retrieval of forest parameters. As mentioned before, the canopy height underestimation can be quantified using laser scanner ground truth data. Such comparison enables to determine the underestimation factor τ in percent. In regions of forest the TerraSAR-X DSM is then corrected by multiplication with the factor $1/(1 - \tau/100)$. The forest segmentation presented in the next section is then used to correct the canopy height bias (see Figure 1). It should be noted that this problem is not straight forward, as such underlying image segmentation often is just not available.

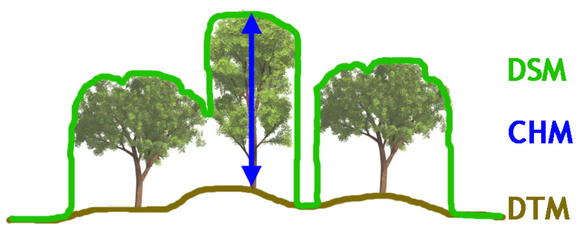

Figure 2: Explanation of relation between digital surface model (DSM), digital terrain model (DTM) and canopy height model (CHM).

$$\mathrm{CHM} = \mathrm{DSM} - \mathrm{DTM} \tag{1}$$

2.2 Forest Segmentation

The proposed forest segmentation should allow separating regions of forest from non-forest areas. Recently, first results on this topic were published in (Breidenbach et al., 2009). They perform the classification on TerraSAR-X backscatter mean and standard deviation statistics alone. We extend their method by including backscatter intensity and texture information, a 3D canopy height model and interferometric coherence information. For classification a supervised approach is chosen by selecting multiple regions together with their ground truth class labels (forest / non-forest) and training a maximum likelihood classifier. This classifier is then applied to the whole spatial extent of given images. The resulting classification is constructed with a GSD of 5 meters. Next, very small areas are rejected based on a region labeling approach.

Texture Description. As observed in (Breidenbach et al., 2009) regions of vegetation are less textured, i.e. more homogenous, than regions of settlements or agricultural areas. (Haack et al., 2000) suggest to describe this texture information by a variance filter. However, our tests showed that such simple parameter is not working satisfactorily on TerraSAR-X data. Therefore, we choose the Texture-transform (Tavakoli Targhi et al., 2006) which is invariant to illumination, computationally simple and easy to parameterize so that it also performs reasonably on high resolution radar data. This transform can be seen as a spatial frequency analysis, where the key idea is to investigate the singular values of matrices formed directly from gray values of local image patches (the backscatter information in our case). More specifically, the gray values of a square patch around a pixel are put into a matrix of the same size as the original patch. The texture descriptor is computed as the sum of some singular values of this matrix. The largest singular value encodes the average brightness of the patch and is thus not useful as a texture description. However, the smaller singular values encode high frequency variations characteristics of visual texture. Therefore, the singular values of this matrix are sorted in decreasing order. Then the Texture-transform at each pixel is defined as the sum of the smallest singular values. For the tests several window sizes and singular values ranges were chosen, where a window of size 33×33 and a range of 20 to 33 smallest singular values performed best.

Canopy Height Model. Obviously, vegetation heights are a useful information to segment regions of forest. The canopy height model is extracted employing the methodology described in Section 2.1.

InSAR Coherence. For forest segmentation the interferometric coherence, which is a measure of the interferogram's quality, can be of great value since regions of vegetation suffer from temporal decorrelation (see also the detailed study on interferometric decorrelation (Zebker and Villasenor, 1992)). The standard coherence estimation is based on a local complex cross-correlation and is known to over-estimate the real coherence value. In general, a larger window within cross-correlation provides a better coherence estimate. At the time of radar sensors like ERS the standard procedure was to estimate the coherence over the same window used for multi looking. As the multi looking sizes become smaller for TerraSAR-X imagery the coherence was highly over-estimated resulting in a noisy coherence image. Therefore, a decoupling of the window size of multi looking and cross-correlation is introduced. The resulting coherence estimate uses a correlation window of 10×10 pixel and a multi looking window of 2×3 pixel (azimuth $\times$ range). Regions of very low coherence correspond mainly to vegetation (forests and agricultural areas). Thus, such coherence information is used in the classification process as one feature.

3 TEST DATA

Within the AT-X project the proposed algorithms have been applied to several test sites. For the presented study only a single test site called "Burgau" is chosen to keep the results clearly arranged. The test site of interest spans an area of 12×12 km^2 in Austria. This rural test area covers agricultural as well as forest areas and shows flat to slightly hilly terrain, the ellipsoidal heights ranging from 270 to 445 meters above sea level (cf. Figure 3). The forested regions in the area mainly consists of dense stands of deciduous trees.

Multi-Image DSM Generation. For multi-image DSM derivation the test data consist of multiple TerraSAR-X multi-look ground range detected (MGD) Spotlight products from ascending, respectively descending, orbit. All images were ordered as single-polarization products (HH) with science orbit accuracy and were acquired in the period of July and August 2009. Table 1 reports the major parameters of the "Burgau" test site. It should be noted that the images acquired at steep look angles (i.e. MGD_asc1 and MGD_dsc1) have a lower GSD than all other products.

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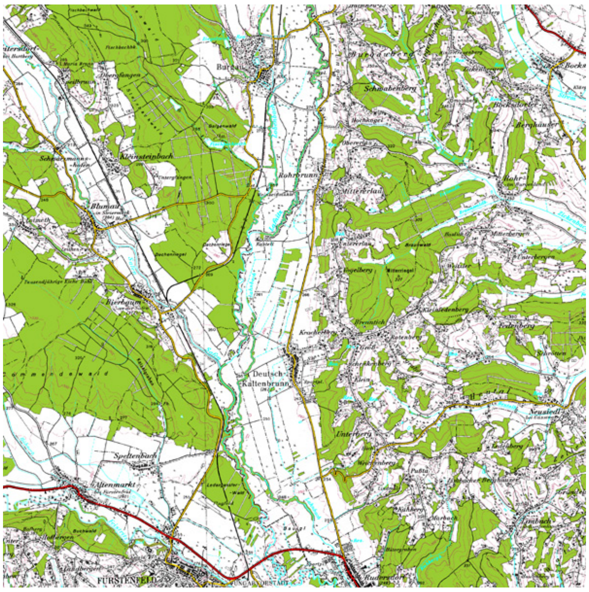


Figure 3: Overview of the test site "Burgau". This topographic map shows regions of forest in green color.

Name	Look angle	GSD	Date
MGD_asc1	22.3°	1.25m	2009-07-28
MGD_asc2	37.2°	0.75m	2009-08-02
MGD_asc3	48.5°	0.75m	2009-08-07
MGD_dsc1	21.3°	1.25m	2009-07-30
MGD_dsc2	36.5°	0.75m	2009-08-05
MGD_dsc3	48.0°	0.75m	2009-07-31

Table 1: Detailed parameters for the Spotlight images.

Forest Segmentation. The InSAR coherence used in the segmentation process is derived from a TerraSAR-X single look complex (SSC) InSAR pair (see Table 2). These images were ordered as dual-polarization products (HH,VV) with science orbit accuracy and were acquired in March 2008.

Name	Look angle	Date
SSC_dsc1	36.0°	2008-03-17
SSC_dsc2	36.0°	2008-03-28

Table 2: Detailed parameters for the Spotlight InSAR pair.

Reference Data. To enable quantitative evaluations LiDAR data is used as ground truth information. The LiDAR reference data covers four measurements per square meter, which are processed to highly accurate DSMs and DTMs. While the DSMs are automatically extracted, the DTMs are semi-automatically generated by classifying regions of vegetation, building, bridges and other man-made structures.
To evaluate the DSMs derived using TerraSAR-X multi-image radargrammetry, 30 regions on bare ground and 70 regions in forest are selected. The average residual height error over such regions describes the DSM quality. Over forest, the average canopy height underestimation τ is extracted and used to correct the canopy height.
To evaluate the image segmentation quality a ground truth reference mask is derived using LiDAR data. The 1m GSD LiDAR CHM is filtered with an order-statistic filter of size 7×7 and order 37, i.e. the 75^{th} percentile. The CHM is then down sampled to a GSD of 5m using a 5×5 average resampling. Next, pixels with a height larger than 8 meters are considered as forest regions and small regions are filled to eliminate noise.

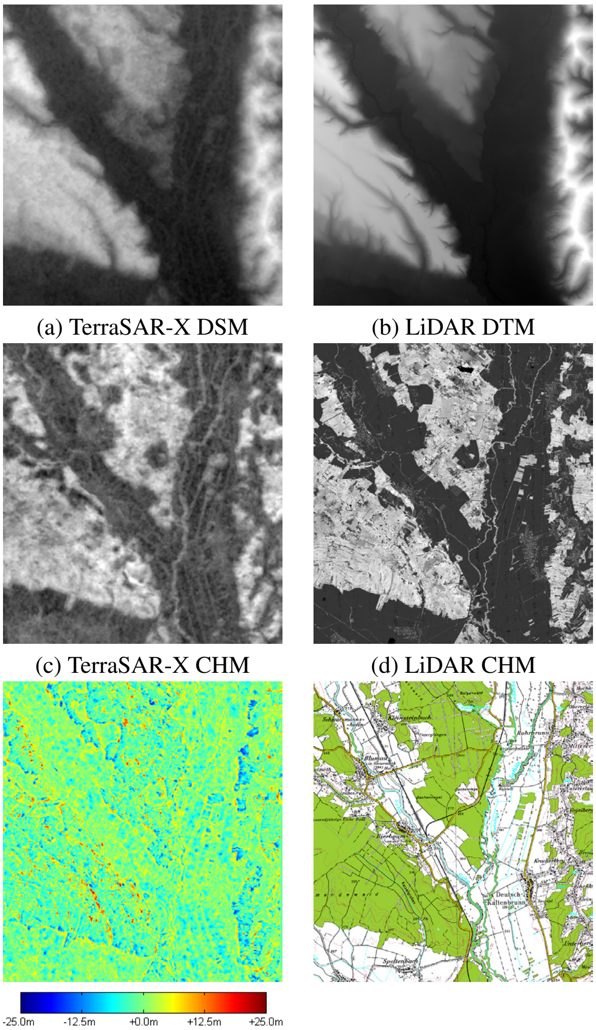
4 RESULTS AND DISCUSSION

Multi-Image DSM Generation. For visual interpretation some detailed results are shown in Figure 4. All results are given with a GSD of 2 meters in UTM33 projection. Figure 4(a) shows the TerraSAR-X DSM, (b) the LiDAR reference DTM, (c) the TerraSAR-X and LiDAR based CHM, (d) the pure LiDAR CHM, (e) the TerraSAR-X based height error (i.e. the ground truth LiDAR DSM subtracted from the TerraSAR-X derived DSM) and (d) a topographic map. The TerraSAR-X CHM corresponds visually very well to the LiDAR CHM and to the topographic map, however the TerraSAR-X DSM is too low over forest, as seen in Figure 4(e). Regions of bluish color indicate height underestimations and such regions are placed in forests or on forest borders. The quantitative accuracy analysis is listed in Table 3. Heights over bare ground are reconstructed with very high accuracy (mean value below 20 cm and standard deviation of about 2 meters). The canopy height however is systematically underestimated by approximately 27.5% for this test site. In our previous work we estimated an average underestimation using Spotlight and Stripmap imagery and multiple scenes which was 26.6%±1.4% (Perko et al., 2010). When correcting the height bias with this learned value the reconstruction over forest becomes a lot better. In particular it decreases to a residual height error of 20 cm, like on bare ground (see Table 3 bottom). Figure 5 and Figure 6 show detailed analyses of the canopy height underestimation w.r.t. the canopy height before and after the discussed correction, clarifying that the underestimation over forest can be corrected for this test site.

	bare ground		forest		
	μ [m]	σ [m]	μ [m]	σ [m]	τ [%]
asc	0.07	2.04	-5.81	1.87	28.5
dsc	0.18	1.90	-5.45	1.83	26.4
			forest after height correction		
		asc	0.22	1.87	-1.16
		dsc	0.08	1.83	-0.42

Table 3: Detailed 3D height analysis of the TerraSAR-X derived DSMs.

Forest Segmentation. The features used for forest segmentation are shown in Figure 7. Obviously, the most important information for the segmentation are the InSAR coherence and the canopy height model. The confusion matrix in Table 4 reveals that 90% of pixels (here one pixel has a GSD of 5 meters) are correctly classified. About 8% of non-forest regions are classified incorrectly as forest. This especially happens in small forest clearances which are not seen due to the slant range SAR geometry or which result from image matching failures. The 2% of pixels classified wrongly as non-forest are mainly small forest stands where image matching is unsuccessful and thus such regions get interpolated. In addition it should be noted that this evaluation is relative to the LiDAR ground truth segmentation. Therefore, the achieved accuracy is most likely above the 90% since some artifacts exist in the LiDAR model. For instance some power supply lines are classified as forest. In comparison to the state-of-the-art classification of TerraSAR-X data in (Breidenbach et al., 2009) the proposed method performs very well. On first glance their method also reaches a classification accuracy of 90%. However, the evaluation is based on image blocks with 20×20 m^2. When reducing the GSD to 5 meters, like in our study, the classification accuracy of (Breidenbach et al., 2009) drops to 72.5%. Obviously, our method performs better as a diversity of information like canopy height model, coherence or texture descriptors is incorporated into the classification process.



(a) TerraSAR-X DSM (b) LiDAR DTM
(c) TerraSAR-X CHM (d) LiDAR CHM
(e) TerraSAR-X DSM error (f) topographic map

Figure 4: Exemplary results of DSM and CHM extraction. The TerraSAR-X DSM (a), LiDAR reference DTM (b), TerraSAR-X CHM (c), LiDAR CHM (d), color coded TerraSAR-X height error (e), and a topographic map for visual comparison (f). A subset of 7.1 × 7.6 km² is shown.

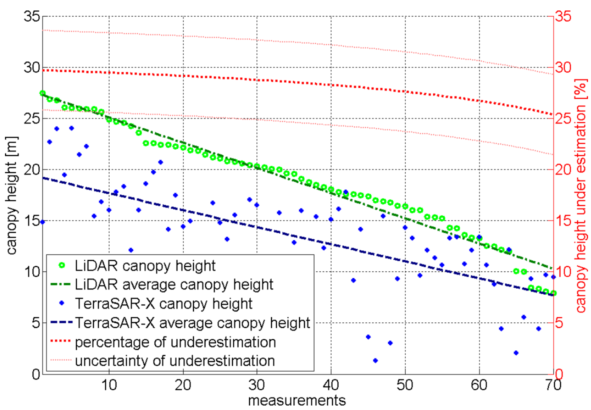


Figure 5: Canopy height underestimation for the ascending triplet before the proposed height correction.

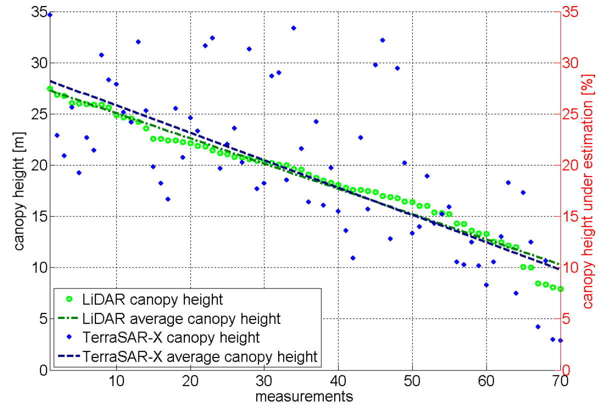
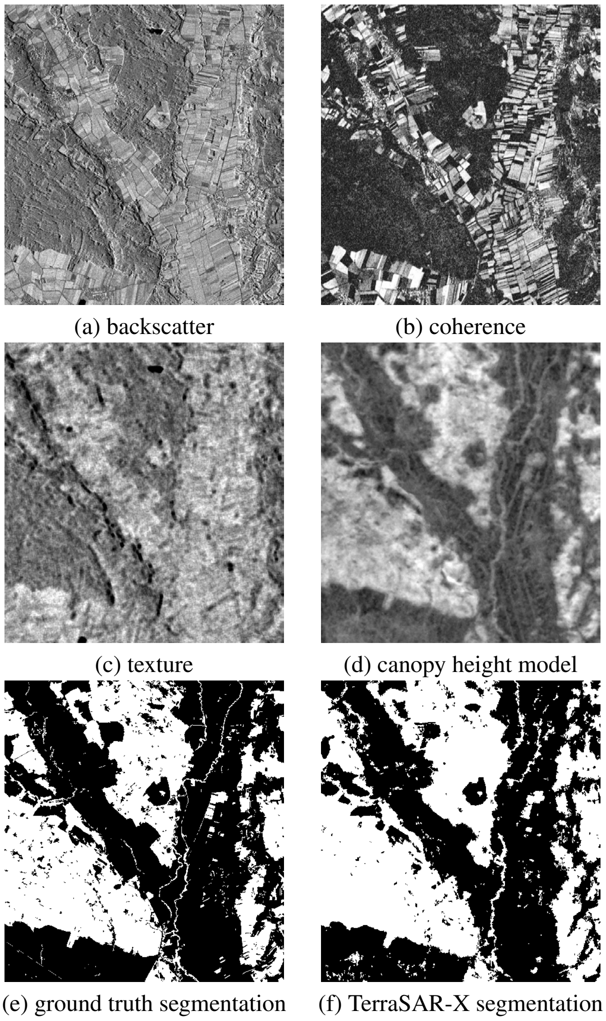


Figure 6: Canopy height underestimation for the ascending triplet after the proposed height correction.



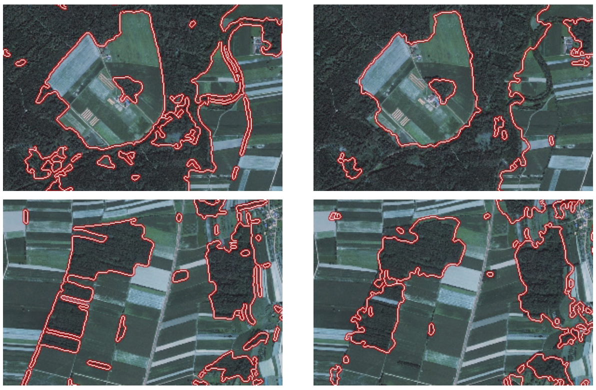
(a) backscatter (b) coherence
(c) texture (d) canopy height model
(e) ground truth segmentation (f) TerraSAR-X segmentation

Figure 7: Exemplary input data used for image segmentation (a-d), ground truth segmentation based on laser scanner vegetation height model (e) and TerraSAR-X based segmentation (f).

correct: 90.37%		ground truth	
		forest	non-forest
estimation	forest	40.01%	7.68%
	non-forest	1.96%	50.36%

Table 4: Confusion matrix of forest segmentation.

Forest Border Lines. Finally, forest border lines can directly be extracted from the segmentation result via edge detection. Figure 8 shows some examples. Overall, the quality of extracted forest border lines is higher for huge dense forests than for small isolated stands (this aspect was also observed in (Breidenbach et al., 2009)), where small stands are often not detected at all. Nevertheless, forest border lines are in general very well extracted and their accuracy is directly dependent on the forest segmentation.



ground truth TerraSAR-X derived

Figure 8: Detailed views on forest border line extraction for two subsets. On the left ground truth border lines are given and on the right the automatically extracted borders using TerraSAR-X alone.

5 CONCLUSIONS AND FUTURE WORK

TerraSAR-X imagery enables the retrieval of certain forest parameters. In particular, multiple TerraSAR-X images representing the same area on ground under different look angles can be used to fully automatically derive accurate DSMs. In case when reference DTMs are available the canopy height model can be extracted. Such forest canopy height is an important parameter as it is strongly correlated with forest parameters, such as forest biomass, timber volume or carbon stocks. Furthermore, it serve as an important cue for classification of forest types and condition, forest morphology, crown closure, vertical structure and stands height (Hyyppä et al., 2000). The presented study revealed that the height of the canopy is systematically underestimated as the SAR signal in X-band penetrates into the canopy. Therefore, a forest segmentation is proposed yielding an accuracy of 90%. This segmentation result is subsequently applied to correct the canopy height bias in regions of forest. Incorporating this approach, the TerraSAR-X DSMs have an average height accuracy of 20 cm and a standard deviation of about 2 meters on bare ground and over forest.
However, the canopy underestimation depends on various aspects, including tree species, forest stand density, tree height and look angles. The forest used in the presented study domiciles more or less exclusively dense stands of deciduous trees. It is therefore expected that the canopy underestimation will be larger for coniferous trees and for clearer stands.
Future work should focus on a comparison to TanDEM-X DSMs compromising multiple InSAR pairs with different look angles to further understand the penetration into the canopy of X-band signals.

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