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Seasonal effects on the estimation of height of boreal and deciduous forests from interferometric TanDEM-X coherence data

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ABSTRACT

The aim of this study is to assess the performance of single-pass X-band bistatic SAR interferometric forest height estimation of boreal and temperate deciduous forests under variable seasonal conditions. For this, twelve acquisitions of single- and dual-polarized TanDEM-X coherence images over 118 forest stands were analyzed and compared against LiDAR forest height maps. Strong correlations were found between interferometric coherence magnitude and LiDAR derived forest stand height for pine forests (r^2=0.94) and spruce forest (r^2=0.87) as well as for deciduous trees (r^2=0.94) during leaf-off conditions with temperatures below 0°C. It was found that coherence magnitude based forest height estimation is influenced by leaf-on and leaf-off conditions as well as daily temperature fluctuations, height of ambiguity and effective baseline. These factors alter the correlation and should be taken into account for accurate coherence-based height retrieval. Despite the influence of the mentioned factors, generally a strong relationship in regression analysis between X-band SAR coherence and LiDAR derived forest stand height can be found. Moreover, a simple semi empirical model, derived from Random Volume over Ground model, is presented. The model takes into account all imaging geometry dependent parameters and allows to derive tree height estimate without a priori knowledge. Our results show that X-band SAR interferometry can be used to estimate forest canopy height for boreal and deciduous forests in both summer and winter, but the conditions should be stable.

Keywords: Forest height, radar interferometry, synthetic aperture radar (SAR), TanDEM-X, vegetation mapping, X-band

1. INTRODUCTION

The global coverage of TanDEM-X (TDX) bistatic observations and high spatial resolution X-band interferometric data [1] have opened up opportunities to develop new large-scale forestry applications. Satellite-based forest height estimation has great potential to offer benefits to many global forestry sectors by adding valuable information about logging detection, biomass and forest value estimation and also provide input for carbon cycle models [2], [3]. The sensitivity of interferometric coherence to forest height can be applied for deriving aboveground forest biomass [4], [5], detect changes in forests or improve the inventory data for remote areas [6], [7].

An operational service requires stability and understanding of the SAR technical parameters as well as environmental factors that influence the height estimation accuracy in different conditions and with varying imaging geometry. The canopy height estimation accuracy achieved through interferometric coherence magnitude relies on factors such as the effective baseline between the satellites, SAR frequency, tree species, forest stand structure and the seasonal conditions. The dielectric properties of the forest medium affects the way SAR microwaves penetrate the vegetation and thus the results during frozen and unfrozen conditions.

Temporal variability of TanDEM-X interferometric measurements has been investigated on summer and autumn images [8], [9] and winter images [10] of boreal forests. It was found that leaf-on and leaf-off conditions as well as temperature, frost and moisture affect the signal penetration into the vegetation [8], [9], [10]. It was also noted that deciduous and mixed forests have higher temporal variations than coniferous forests as leaf-on and leaf-off conditions affect the SAR signal penetration depth [8], [9]. In addition, temperatures below zero result in deeper penetration into the forest canopy [10].

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Selection of baseline can also affect the height retrieval as short baselines can reduce the sensitivity to forest height and large baselines can lead to low coherence levels that are limiting the height mapping range [11], [12].

The Random Volume over Ground (RVoG) model is often used for forest height inversion. It provides a simple description of relation between the forest height, properties of the forest layers and polarimetric interferometric coherence [11], [13], [14]. The same model framework is also utilized in this work. The aim of this paper is to investigate the seasonal dynamics over different forest types and describe the possible influential environmental factors that can cause the variation in height estimation results.

2. TEST SITES AND DATA

The study was carried out on Soomaa test site (Figure 1) located in south-western Estonia in Soomaa National Park. The selected forested areas are located on a flat terrain between large mires and rivers and cover 275 hectares in total. The centre coordinates of the site are 58° 24' 26.53"N, 25° 6' 45.75"E. All together 118 subcompartments were maintained in the frame of the 12 TanDEM-X image footprints with the mean stand size of 2.33 ha. Over half of the site is covered with pine stands (70 plots) and the rest with deciduous stands (32 plots) dominated by birch and some alder trees and spruce stands (16 plots).

The test site tree height and elevation was measured by Estonian Land Board with Leica ALS50-II LiDAR (Light Detection And Ranging) in June 2010. The density of the used LiDAR point cloud is 0.45 points per m^2 and the maximum distance between two points is up to 2.6 m. For every forest stand, mean forest height was calculated using the 90 percentile (P90) height above the ground values of the first echoes. Stands with mean plot forest height under five metres were neglected to avoid recently logged forest plots. For detailed analysis, forest stands were picked on the basis of inventory data from Estonian Forest Registry. Only homogenous stands with one tree layer and no understory layer were selected. The proportion of the dominant tree species was tresholded to be more than 75%. Forest stand polygons were buffered 20 metres inside to avoid border effects caused by the neighbouring plots. The buffered area was also approximately half of the processed coherence image resolution on the ground.

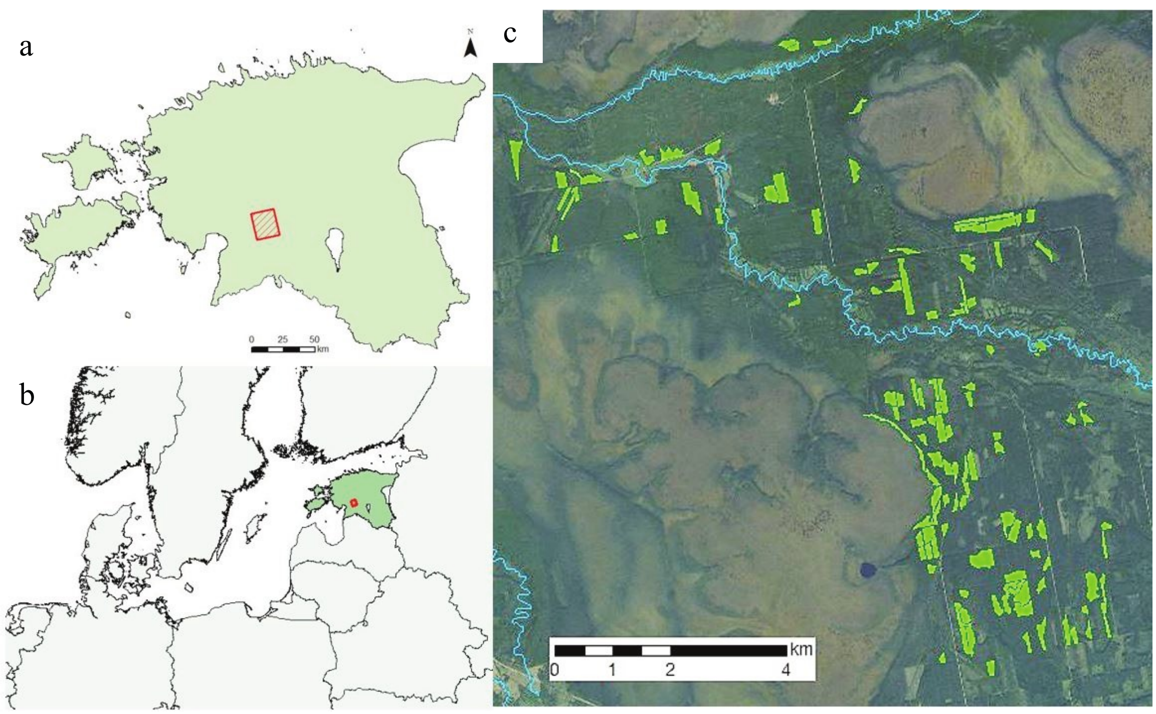

Figure 1. TDX image footprint marked with red rectangle shows Soomaa test site (a) in south-western Estonia (b) and corresponding satellite image (c) with selected forest stands (green). Satellite image source: Esri, DigitalGlobe, GeoEye, i-cubed, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community.

Forest registry data were processed to match the requirement of stands being larger than 1 hectare. The mean stem volume density over the test site was 160 m^3/ha with the maximum of 345 m^3/ha and mean stand height 17 m, with the tallest measurement being 29.4 m.

The interferometric SAR dataset consists of twelve TanDEM-X Stripmap HH/VV dual polarization and HH single polarization images acquired from winter 2010 to autumn 2012 (Table 1). Ascending pass TanDEM-X co-registered images have effective baselines ranging from 78 to 255 m and incidence angles ranging from 23° to 45°.

Table 1. TanDEM-X data over Soomaa test site. All images were acquired on ascending orbit and in bistatic mode. HoA is the height of ambiguity and k_Z is the mean vertical wavenumber.

Date	Season	Incidence angle	Effective baseline (m)	HoA (m)	k_Z	24H min. ground temperature (C°)	Temperature during TDX acquisition (C°)	24H preci-pitation (mm)	Polari-zation
2010-12-29	Winter	44.6°	187	**84.3**	0.075	-9.2	-6.8	0	HH
2011-08-01	Summer	36.2°	126	**92.7**	0.068	12.0	18.6	0	HH
2012-03-03	Spring	23.4°	78	**88.2**	0.071	-5.3	0.9	0	HH/VV
2012-03-08	Spring	34.8°	84	**131.7**	0.048	-22.9	-2.7	0	HH/VV
2012-03-14	Spring	23.4°	80	**86.1**	0.073	-5.5	-0.4	0	HH/VV
2012-03-25	Spring	23.4°	80	**86.7**	0.072	-3.5	0.9	9.9	HH/VV
2012-04-05	Spring	23.4°	213	**32.4**	0.194	-8.4	4.6	0	HH/VV
2012-04-15	Spring	45.2°	255	**62.9**	0.100	-2.0	10.8	0	HH
2012-05-02	Spring	34.8°	223	**49.7**	0.126	-2.2	13.4	0	HH/VV
2012-10-03	Autumn	34.8°	163	**68.0**	0.092	5.6	10.2	0	HH/VV
2012-11-16	Autumn	34.8°	173	**64.0**	0.098	0.6	5.5	0	HH/VV
2012-11-11	Autumn	23.3°	175	**39.3**	0.160	-0.2	5.1	0	HH/VV

3. RESULTS AND DISCUSSION

TanDEM-X CoSSC format images were processed to calculate the interferometric coherence γ [15]. SAR coherence image was compared against LiDAR data by calculating statistics and mean values for each forest plot. The plot selection was based on the classification in the National Forest Registry into sufficiently homogeneous forests in their origin, age, height, growing stock and subject to common methods of management. Object-based averaging method was preferred over pixel-based calculations as it can reduce the impact of extreme measurement values to the model fitting and gives opportunity to make more generalized analyses.

Forests were divided into three groups: pine, spruce and mixed deciduous forest stands. Correlation coefficients (r^2) and standard error (SE) were calculated between TDX coherence values and LiDAR derived forest height values for every forest plot and are presented in Table 2. Standard error describes the TDX coherence based height calculation uncertainty in metres, with respect to LiDAR height reference values. The similarity of TDX coherence pattern to LiDAR derived forest height can be seen in Figure 2 where black polygons indicate the forest stands used in the statistical regression analysis.

The results in Table 2 confirm that interferometric coherence is sensitive to forest height and strong correlations can be achieved for pine, spruce and mixed deciduous forest stands when the weather and forest biophysical conditions are favourable. High correlation coefficients were achieved for the Scots pine on both HH and VV channel on March images. Similar results were achieved for mixed deciduous trees with the exception of 25 March HH channel image where strong deviation between coherence and tree height is likely to be caused by a flooding event of a nearby river.

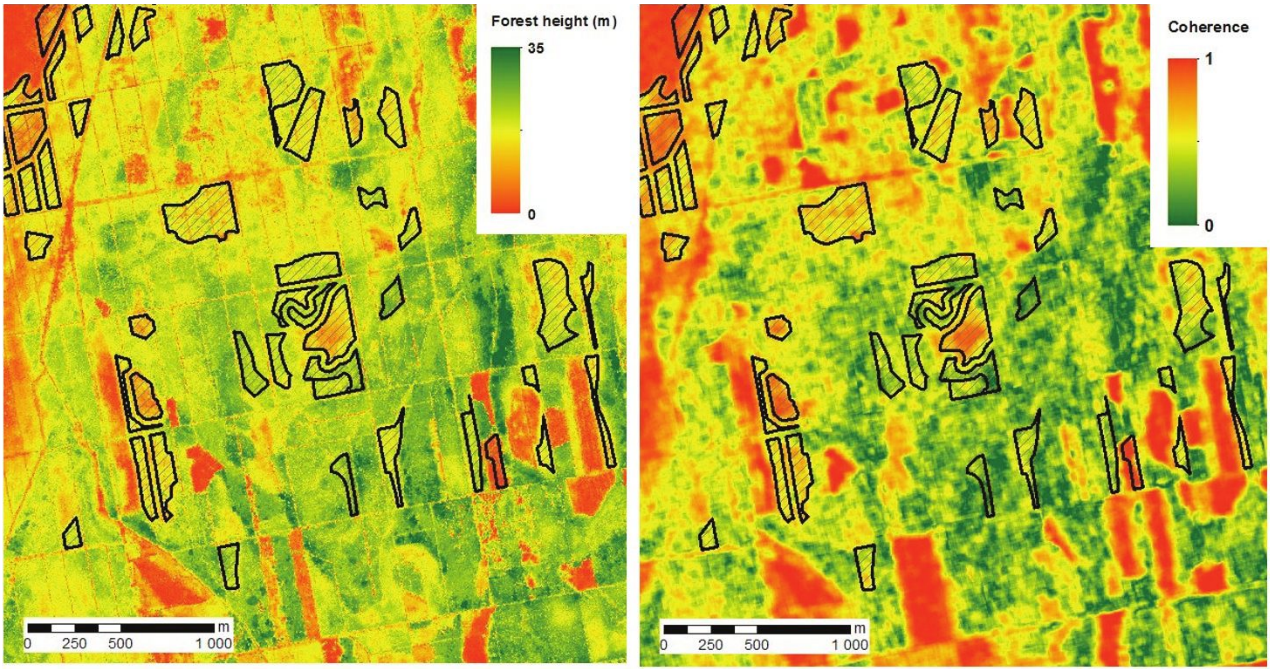

Figure 2. LiDAR derived forest height from 2010 on the left compared with the corresponding HH coherence image from 3 March 2012 on the right, scaled from 1 (red) to 0 (green).

Table 2. Results from regression analysis between LiDAR derived tree height and TanDEM-X interferometric coherence.

Acquisition date	HH coherence pine (70 plots)		HH coherence spruce (16 plots)		HH coherence mixed deciduous (32 plots)		VV coherence pine (70 plots)		VV coherence spruce (16 plots)		VV coherence mixed deciduous (32 plots)	
Correlation coefficient	**r^2**	SE (m)	**r^2**	SE (m)	**r^2**	SE (m)	**r^2**	SE (m)	**r^2**	SE (m)	**r^2**	SE (m)
2010-12-29	**0.65**	1.75	**0.87**	1.75	**0.89**	1.85	-	-	-	-	-	-
2011-08-01	**0.62**	1.83	**0.70**	2.68	**0.59**	3.49	-	-	-	-	-	-
2012-03-03	**0.94**	0.72	**0.76**	2.39	**0.77**	2.62	**0.94**	0.71	**0.75**	2.41	**0.80**	2.44
2012-03-08	**0.90**	0.95	**0.79**	2.21	**0.89**	1.80	**0.89**	1.00	**0.82**	2.08	**0.94**	1.35
2012-03-14	**0.94**	0.71	**0.66**	2.82	**0.82**	2.34	**0.94**	0.70	**0.68**	2.75	**0.84**	2.17
2012-03-25	**0.93**	0.78	**0.59**	3.10	**0.31**	4.56	**0.94**	0.74	**0.76**	2.40	**0.76**	2.67
2012-04-05	**0.28**	2.52	**0.04**	4.75	**0.26**	4.72	**0.28**	2.52	**0.03**	4.78	**0.29**	4.62
2012-04-15	**0.25**	2.57	**0.82**	2.07	**0.20**	4.89	**-**	-	**-**	-	**-**	-
2012-05-02	**0.01**	2.95	**0.59**	3.13	**0.11**	5.16	**0.02**	2.94	**0.70**	2.68	**0.30**	4.59
2012-10-03	**0.73**	1.55	**0.85**	1.86	**0.43**	4.12	**0.75**	1.49	**0.85**	1.88	**0.43**	4.12
2012-11-16	**0.64**	1.77	**0.87**	1.79	**0.40**	4.23	**0.66**	1.72	**0.87**	1.74	**0.40**	4.24
2012-11-11	**0.34**	2.40	**0.07**	4.70	**0.03**	5.40	**0.31**	2.46	**0.09**	4.63	**0.15**	5.04

The water levels in the Halliste river had risen from 80 cm to 373 cm flooding the surrounding forested areas. The impact of flood is better seen in HH channel and less for VV channel as HH has greater penetration through mainly vertically oriented canopy structures and thus giving higher ground contributions which are especially amplified during flooding. VV channel interacts more with canopy and less with ground and as a result is less affected by the double bounce scattering during flooding [16], [17].

According to the results in Table 2 the correlation coefficients were considerably lower in April, May and November for pine and deciduous forests. This can be the results of two factors: the long baseline and temperatures around 0 degrees. The results also suggest that deciduous trees provide significantly higher correlation coefficients during leaf-off season (March, December) compared to leaf-on period which in Estonia starts generally in late April and ends in November, depending of the year. Poorer results of leaf-on period indicate to insufficient penetration capability into the denser vegetation in late spring and summer months [11]. Depending on a particular deciduous forest stand, plots can have uneven distribution and amount of leaf biomass, causing differences in volume decorrelation. This results in loss of correlation between forest height and SAR coherence. Leaf-off conditions provide higher forest height estimation accuracy as deciduous plots without leaves are more similar in their structure. In addition, the results are also affected by the daily temperature fluctuation. Clear influence of the temperature changes can be seen on the images acquired on days when the minimum temperature and the temperature during acquisition have been changed from below zero to more than +1 C° above zero. According to Table 1, these are 5 April, 15 April, 2 May and 11 November images.

Similar instability, probably caused by thawing processes, also occur on other images but in a smaller scale. Another finding was that cold weather and temperatures below 0 C° seem to increase the height estimation accuracy as can be seen from the 29 Dec, 3 March, 8 March, 14 March, 25 March images but only when the daily temperatures have not warmed up the ground and the canopy well above zero degrees during the acquisition time. Freezing reduces the dielectric constant drastically and temperatures well below 0 C° cause deeper penetration into the forest canopy and provide therefore sufficient volume scattering contribution [9], [10]. These changes have more influence on pines and deciduous trees and less on spruces. Spruce forests seem to be less influenced by the temperature changes and provide strong correlation all year round. For the case of spruce, it can also be said that the low correlations on 5 April and 11 November can be a consequence of long baselines and small HoA values (32 and 39 m). Similar finding in [10], [18] showed that small HoA values can increase phase noise and height ambiguities. The phase noise is considerably increased if the baseline is large and HoA small which is the case for 5 April, 2 May and 11 Nov images. In general either frozen or unfrozen conditions should be preferred [10] as SAR is sensitive to water and unstable weather conditions can cause trees to freeze unevenly thus introducing another factor affecting the coherence and breaking the relation with height.

A semi empirical model (sinc model), derived by simplifying the Random Volume over Ground (RVoG), was introduced for forest height inversion [19]. The model takes into account the imaging parameters as it depends on vertical wavenumber and incidence angle. From Figure 3 and Figure 4 it can be seen that the introduced model (blue line) is in good agreement with the measurements, especially for pine and spruce forest. The inversion model provides good estimates of height on both boreal and deciduous sites and is consistent for pines and deciduous trees during leaf-off season, when assuming that the scattering centre height is about third of the height lower than the treetops [14]. The used sinc model should be preferred for height inversion as it does not contain totally unknown empirical constants like regression model. Coniferous forest give best agreement with the introduced sinc model as could be seen in Figure 3.

4. CONCLUSION

TanDEM-X HH and VV polarization channel coherence images were studied over 275 ha of forest stands in Estonia and compared against LiDAR data for estimating tree height of coniferous and deciduous forests. Our results demonstrate that forest height estimation from TanDEM-X coherence show high correlation between single-pol coherence amplitude and LiDAR-derived forest height without using any external Digital Terrain Model (DTM) data. Seasonal changes in Northern Europe have a significant effect on height estimation for both coniferous and deciduous trees. The forest height estimation algorithm works best for coniferous forests. We have investigated the feasibility of this method for estimating canopy height in winter, spring, summer and autumn conditions. Forest height estimation was mostly influenced by three effects: season (leaf-on and leaf-off conditions), daily temperature fluctuations and height of ambiguity. Temperatures below 0 C° resulted in accurate height estimates for all homogeneous pine, spruce and deciduous forests. Leaf-on period leads to a variable penetration capability into the canopy in summer depending on the different amounts of foliage in different plots and consequently causes a drop in the correlation coefficients for mixed deciduous forests. Higher stability over different weather conditions was found for spruce forests, while thawing processes had greater influence on the accuracy of pine and deciduous forests. In addition, small HoA affected the height estimates and resulted in reduced correlations. The reason for the reduced sensitivity in case of small HoA remains largely unknown and should be studied in the future analysis.

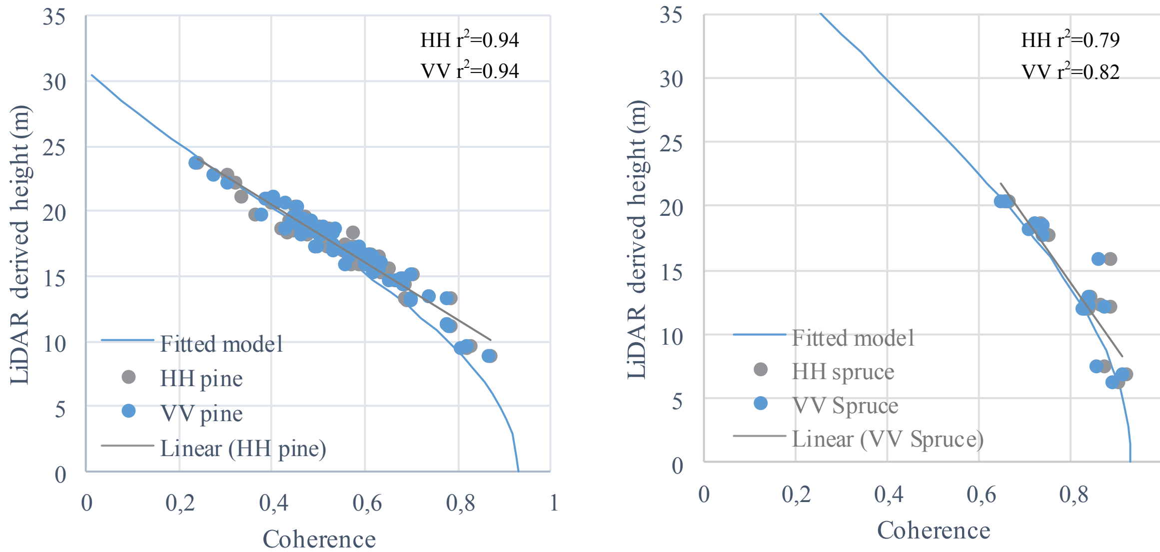

Figure 3. Pine linear regression model on the left show the best-case linear plot fit of SAR HH and VV coherence and a good alignment with the LiDAR derived forest height on 3 March 2012. The blue line shows the RVoG derived sinc model fit. A good alignment with spruce forest on 8 March 2012 image is presented on the right.

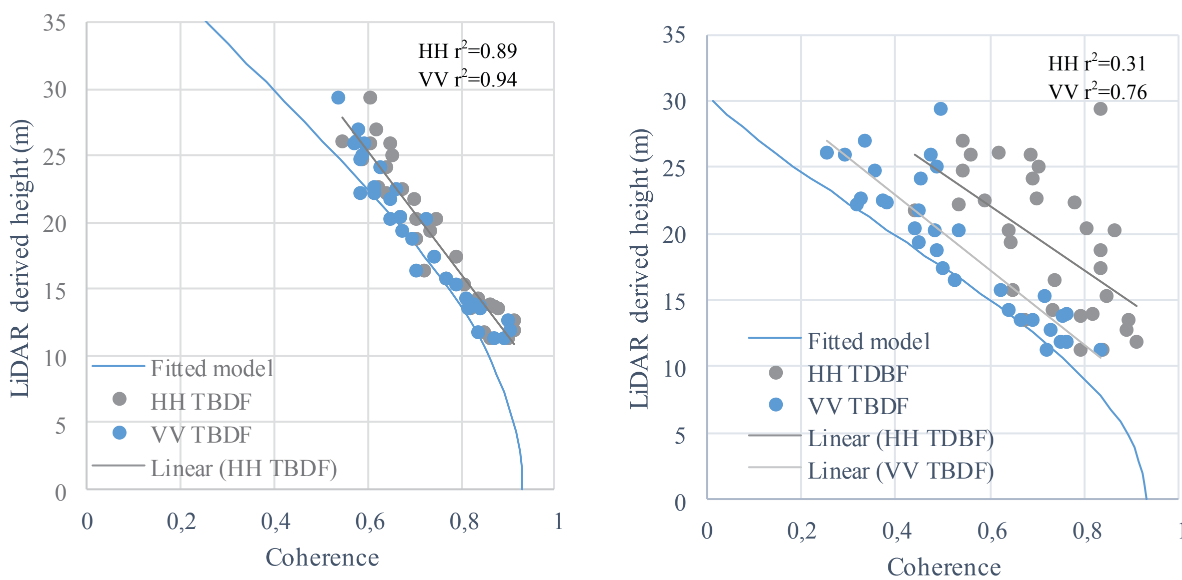

Figure 4. The sinc model shows a good alignment with the leaf-off temperate broadleaf deciduous forests (TBDF) on 8 March 2012 image, whereas the effect of flooding can be clearly seen on 25 March 2012 image on the right. During leaf-off period, VV channel (blue dots) contains less ground contribution than HH channel (grey dots) and results in higher correlation coefficient as it is more connected with canopy scattering volume decorrelation.

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