TREE HEIGHT ESTIMATION FROM MULTI-TEMPORAL ERS SAR INTERFEROMETRIC PHASE

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ABSTRACT

Multi-temporal sets of ERS-1/2 SAR interferometric (InSAR) phase have been evaluated at several test sites in Europe for tree height estimation. Atmospheric artefacts affected a large number of image pairs. These were generally well compensated in case of large-scale artefacts over small forests, whereas for large forests their effect could only be assessed. Hence, the amount of pairs utilizable for further investigation considerably decreased. The interferometric tree height, i.e. the forest "topography" seen by an InSAR system, did not show temporal consistency because of the target phase noise, ranging from slightly below the ground level to slightly above the true tree height. With a multi-temporal combination, the estimates were below the true tree height, depending on the canopy closure. To retrieve the total true height from InSAR tree height measurements, the Interferometric Water Cloud Model was used. Modelled InSAR tree heights resulted generally in reasonable agreement with observations. Nevertheless, because of the strong noise components and the weak contrast between ground and vegetation coherence, the compensated tree height showed an almost constant value, independent of the true height. Hence, the several sources of error and uncertainty strongly limit the usefulness of C-band repeat-pass SAR interferometry for tree height estimation.

1 INTRODUCTION

Forest resources monitoring requires frequent and accurate estimation of several biophysical parameters, possibly using techniques valid worldwide. Spaceborne synthetic aperture radar, SAR, has the advantage of being independent from day-night cycle and cloud cover, thus providing imagery of the whole globe on a roughly monthly basis. The inversion of the European Remote Sensing, ERS, "tandem" coherence has been shown to provide accurate estimates of stem volume, i.e. aboveground dry biomass, [1-3]. For tree height, several studies have discussed the possibility to invert the ERS SAR interferometric (InSAR) phase, showing that the retrieved quantity, the interferometric tree height, is smaller than the true tree height [4-8].

This paper summarises the results of investigations carried out at several test sites for tree height retrieval from multi-temporal sets of ERS InSAR imagery. The influence of atmospheric artefacts and weather conditions on the number of pairs utilizable for the retrieval is discussed. For the utilizable image pairs, the properties of stand-wise InSAR tree height estimates are presented. To retrieve the total tree height, compensation for attenuation and volume decorrelation is needed. InSAR tree height modelling using the semi-empirical Interferometric Water Cloud Model (IWCM) is performed and the compensated tree height is compared to *in situ* measurements.

2 TEST SITES AND GROUND-TRUTH DATA

Four test sites located in Sweden, Finland, Germany and France have been considered. The 5.5 km^2 large forest estate of Kättböle, Sweden, (59°59' N, 17°07' E) and the 20 km^2 large forested area of Tuusula, Finland, (60°28' N, 24°59' E) are within the boreal belt and are mainly covered with coniferous species with a small percentage of deciduous birch trees. The wooded area of the Bois de Boulogne, Paris, France (48°52' N, 2°15' E) covers 8.6 km^2 including broadleaf tree species and few pine plantations. The three test sites are characterised by almost flat ground topography. In Germany we initially considered the entire mountainous Thüringer Wald region, focusing then on the 12.5 km^2 large forested area around the town of Wümbach (50°42' N, 11°00' E) because of the much flatter topography.

The ground-truth data available consisted of forest stand boundary maps in digital form and stand-wise measurements of tree height (all test sites) and stem volume (not for the Bois de Boulogne) [1, 9, 10]. To aid interpretation,

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measurements of several meteorological parameters taken periodically during the day were available from weather stations nearby the test sites.

3 SATELLITE IMAGERY

At each test site multi-temporal sets of ERS-1/2 “tandem” pairs, acquired under several meteorological conditions, could be formed. A summary of the “tandem” image pairs available is reported in Table 1. For each pair we generated the coherence image and the differential interferogram, except for the Bois de Boulogne where the topographic interferograms were used. Because of the completely flat topography within the Bois, it could be assumed that the differential and the topographic interferograms coincided. All images were processed in order to match the digital forest maps.

Table 1. Acquisition date and perpendicular baseline component for “tandem“ pairs available at each test site.

Kättböle (Sweden)		*Tuusula (Finland)*		*Bois de Boulogne (France)*		*Wümbach (Germany)*	
Acquisition date	*Baseline*	*Acquisition date*	*Baseline*	*Acquisition date*	*Baseline*	*Acquisition date*	*Baseline*
10/11.06.1995	-86 m	09/10.09.1995	-34 m	16/17.06.1995	-106 m	30.09/01.10.1995	345 m
16/17.07.1995	16 m	14/15.10.1995	273 m	21/22.07.1995	-32 m	04/05.11.1995	-141 m
20/21.08.1995	-75 m	02/03.03.1996	-95 m	25/26.08.1995	-56 m	23/24.03.1996	-87 m
24/25.09.1995	219 m	29/30.03.1996	-38 m	29/30.09.1995	351 m	21/22.04.1996	90 m
29/30.10.1995	-18 m	06/07.04.1996	45 m	03/04.11.1995	-140 m	27/28.04.1996	-94 m
12/13.03.1996	220 m	17/18.04.1996	-106 m	08/09.12.1995	-101 m		
17/18.03.1996	66 m	15/16.06.1996	61 m	16/17.02.1996	78 m		
16/17.04.1996	74 m	20/21.07.1996	146 m	22/23.03.1996	-92 m		
21/22.04.1996	-55 m			26/27.04.1996	-88 m		

When weather changes between acquisitions occurred (e.g. rainfall, snowmelt), the interferogram appeared completely noisy and was discarded. Furthermore, many of the remaining interferograms revealed the presence of atmospheric phase contributions, mostly due to the different weather and atmospheric conditions between the acquisitions. To filter out the atmospheric component, phase screens obtained using either Permanent Scatterers (PS) [11], a reference grid of open areas [12] or tropospheric delay estimates [13] were considered.

The Bois de Boulogne was the only test site where the PS technique could be applied because of the sufficient number of PS surrounding the test site. PS-filtered interferograms showed an almost constant phase over open areas. For Tuusula and Wümbach an atmospheric phase screen was obtained from the interpolation of the differential InSAR phase over open areas within the test sites. The compensation was good when the distribution of the atmospheric phase was uniform within each field. Because of the small number of PS and open areas, over Kättböle it was not possible to compensate for atmospheric artefacts. For Kättböle, it was only possible to evaluate the incidence of atmospheric artefacts on the measured phase by means of tropospheric delay estimates and phase shifts over open areas [14]. Pairs acquired under stable dry weather conditions and homogeneous atmospheric properties, at night, during winter were found to be the least influenced by the atmosphere. Table 2 shows the strong decrease of pairs suitable for further analysis because of weather changes and atmospheric artefacts.

Table 2. Comparison between number of pairs available, those considered suitable for filtering (i.e. not completely decorrelated) and those either correctly filtered or not affected by atmospheric artefacts.

	Kättböle	*Tuusula*	*Bois de Boulogne*	*Wümbach*
No. of images available	9	8	9	5
No. of images suitable for filtering	6	8	7	2
No. of images left for further analysis	3	3	7	0

Table 3. Main attributes of the forest stands under investigation.

	Kättböle	*Tuusula (stands)*	*Tuusula (grouped stands)*	*Bois de Boulogne*
No. stands	42	37	6	4
Area	2 – 14 ha	1.25 – 6 ha	12 – 30 ha	16 – 30 ha
Tree height	2 – 23 m	-	10 – 27 m	18 – 23 m
Stem volume	8 – 335 m^3/ha	3 – 535 m^3/ha	89 – 435 m^3/ha	Not av.

For each pair left we computed the stand-wise mean value of the coherence and the phase of the stand-wise complex mean value from the differential interferogram. To limit errors in the measurements, stands were edge eroded and only those larger than a given threshold were considered for analysis. Table 3 lists the main attributes of the retained forest stands. Due to the small size of the stands in Tuusula, the original stands were used for model training whereas for tree height estimation from InSAR phase large stands obtained by grouping neighbouring stands were considered.

4 THEORY AND METHODOLOGY

4.1 Interferometric tree height

Within a resolution cell, forest scattering encompasses a large number of contributions coming from the forest canopy and the ground, resulting in a scattering centre, located between the ground and the treetops. At C-band the forest "topography" seen by the SAR is likely to change between to acquisitions due to the temporal instability of the canopy and to possible changes of the ground dielectric properties. Hence, in an interferometric repeat-pass configuration the differential InSAR phase of a forest includes a significant intrinsic noise component. By analogy to topography detection using InSAR, the inversion of the differential InSAR phase difference between a forest and a neighbouring flat area allows obtaining the interferometric tree height, i.e. the forest "topography" as seen by an InSAR system. Besides phase and atmospheric noise, the interferometric tree height is affected by DEM errors.

4.2 Interferometric Water Cloud Model

The IWCM [2, 15-18] explains the forest complex coherence, γ_{for}, as a sum of a ground and a vegetation term, here expressed for inversion purposes as function of stem volume, V, and tree height, h.

$$\gamma_{for} = \gamma_{gr} \frac{\sigma^o_{gr}}{\sigma^o_{for}} e^{-\beta V} + \gamma_{veg} \frac{\sigma^o_{veg}}{\sigma^o_{for}} \left(1 - e^{-\beta V}\right) \left(\frac{\alpha}{\alpha - j\omega} \right) \left(\frac{e^{-j\omega h} - e^{-\alpha h}}{1 - e^{-ah}} \right) \tag{1}$$

The dependency on tree height can be removed by applying simple empirical formulas that relate tree height to stem volume (see [2] for boreal forest test sites). In Eq. 1 γ_{gr} and γ_{veg} represent the ground and vegetation temporal coherence, σ^0_{gr} and σ^0_{veg} the ground and vegetation backscatter, $e^{-\beta V}$ the two-way forest transmissivity and σ^0_{for} the total forest backscatter, expressed according to [19] as function of stem volume. The volume decorrelation due to a scattering layer with two-way tree attenuation α and height h is given in Eq. 1 by the first complex quantity in brackets. By analogy to topographic phase, the complex exponential in Eq. 1 expresses the topographic phase, thus being related to the InSAR system geometry by means of ω. In the IWCM five parameters are unknown (γ_{gr}, γ_{veg}, σ^0_{gr}, σ^0_{veg} and β) and need to be determined using an accurate training set. Although α should also be treated as unknown, a given value was used in order to limit the number of unknowns; nonetheless, we checked the sensitivity of the model parameters for different two-way tree attenuation values up to 2 dB/m.

For large α and when the normal component of the baseline is below 100 m, the volume decorrelation becomes negligible and the IWCM can be expressed as:

$$\gamma_{for} = \gamma_{gr} \frac{\sigma^o_{gr}}{\sigma^o_{for}} e^{-\beta V} + \gamma_{veg} \frac{\sigma^o_{veg}}{\sigma^o_{for}} \left(1 - e^{-\beta V}\right) e^{-j\omega\left(h - \alpha^{-1}\right)} \tag{2}$$

In this case, when the ground contribution is negligible (i.e. in dense forests), the interferometric system sees a topographic feature with height equal to the tree height minus the penetration depth, $h - \alpha^{-1}$.

By inverting the IWCM it is possible to retrieve the total tree height:

$$h = -\frac{\varphi_{veg}}{\omega} + \frac{1}{\alpha} \tag{3}$$

where φ_{veg} represents the phase difference between the vegetation and reference ground level. The vegetation phase is related to measured coherence, $\left|\gamma_{for}\right|$, and differential InSAR phase, φ_{for}, i.e. to the interferometric tree height [6]:

$$\varphi_{veg} = \sin^{-1}\left[\frac{\left|\gamma_{for}\right|}{\left|\Gamma_{veg}\right|}\sin\varphi_{for}\right] \tag{4}$$

where the vegetation term Γ_{veg}, i.e. the second term in the IWCM, is obtained from Eq.1 using model parameter values derived from fitting the IWCM to coherence and backscatter measurements over the range of stem volumes found at a test site.

5 RESULTS

As shown in Table 2, the InSAR phase could be exploited for a few pairs over Kättböle, Tuusula and Paris. All pairs were characterized by stable dry weather conditions and limited atmospheric contributions. For Kättböle and Tuusula mostly winter pairs were left, whereas for Paris all seasons were represented.

For each stand the InSAR tree height and the corresponding uncertainty were determined. As reference ground level we used open areas nearby the forest stands. Fig. 1 reports two examples of InSAR tree height as function of tree height in boreal forest during winter. For Paris larger temporal dynamics of the estimates were found and no clear seasonal effects were noticed. Fig. 2 shows multi-temporal estimates of InSAR tree height compared to *in situ* measurements [10]. Model training could be carried out in Kättböle and Tuusula only. Sets of coherence, backscatter and stem volume measurements were used. The InSAR phase was found to have a negligible effect on the parameter values and was therefore discarded (for details see [2, 14]). Fig. 3 shows two examples of measured and modelled InSAR tree height as function of stem volume. For each case two model lines are reported; the solid lines correspond to model training with α = 2 dB/m, the dashed lines have been obtained from parameter tuning using smaller α values. In all cases the model parameters had physical meaning; furthermore, the coherence, the backscatter and the area-fill were correctly modelled.

Tree height retrieval was carried out in Kättböle because it was the only test site that included a number of stands sufficient for both training and testing the IWCM. The retrieval was characterized by rms errors between 7.2 m and 11 m, and several outliers. With a multi-temporal combination the outliers disappeared and the rms error decreased (7 m), showing an almost constant retrieved tree height between 10 and 15 m.

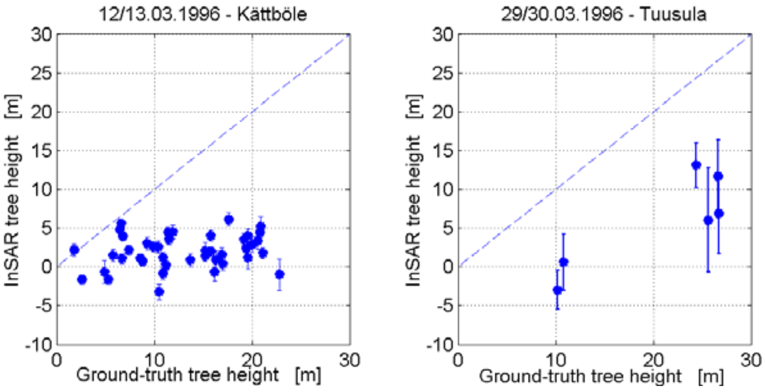

Fig .1. Interferometric versus measured tree height. The bars represent one standard deviation in the estimates.

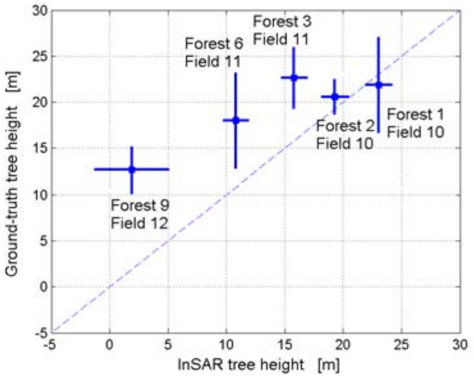

Fig. 2. Measured tree height and multi-temporal InSAR tree height, relative to nearby open areas, computed from seven pairs over the Bois de Boulogne. The bars represent one standard deviation in the estimates.

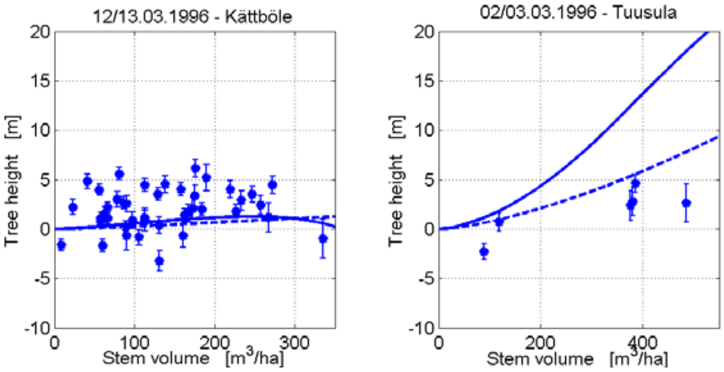

Fig. 3. Modelled and measured InSAR tree height as function of stem volume. The solid line corresponds to training with $\alpha = 2$ dB/m. The dashed lines correspond to training with $\alpha = 0.3$ dB/m for Kättböle and 0.25 dB/m for Tuusula. The vertical bars represent one standard deviation in the estimates.

6 DISCUSSION AND CONCLUSIONS

Applications of InSAR phase in forestry are strongly hindered by weather changes and atmospheric heterogeneities, which considerably decrease the number of pairs usable for investigations. Although atmosphere-filtering algorithms are able to provide good corrections in urban and unvegetated areas, their requirements are difficult to be met in large forested areas. In this case a more sensible approach would be to consider pairs not affected by artefacts (e.g. acquired at night, under stable weather and atmospheric conditions).

InSAR tree height measurements change over time, being largely affected by intrinsic phase noise due to the unstable canopy and the dielectric properties of the ground. Furthermore, phase components that are not perfectly removed (due to topography, baseline and atmosphere) may strongly alter the measurements. Under winter conditions in boreal forests the InSAR tree height was generally much below the true height. Spread of the measurements coincided with changed conditions of the snow cover (right plot in Fig .1). In the Bois de Boulogne the InSAR tree height measurements oscillated around the true height. Multi-temporal estimates were a few meters below the true height in dense stands (being in accordance with C-band attenuation values) and even slightly lower in sparser forests because of the opener canopy (Fig. 2).

The studies have illustrated that phase effects occur in forests and must be taken into account when modelling the interferometric signatures as function of forest attributes. For correct modelling, the noise and the uncertainty in signatures should be small, the atmospheric effects between open fields should be within a few meters and β should be in the range 0.003 - 0.007 ha/m^3 (or slightly below under frozen conditions) to have reasonable values for the area-fill, i.e. the canopy closure [2, 18]. The IWCM has been shown to describe reasonably well the trend between InSAR tree height and stem volume. By tuning model parameters, several model fits to the InSAR tree height measurements were obtained, which still preserved the area-fill factor without degrading the modelled coherence and backscatter.

According to the IWCM, for tree height retrieval from InSAR phase large sensitivity of the IWCM ground and vegetation contribution to stem volume is required. Since these conditions were not encountered and we generally observed remarkable error and noise sources, tree height retrieval was not accurate. These results show that tree height retrieval from InSAR phase has severe limitations. Comparing with [2] where stem volume estimates comparable to ground-truth values have been reported, a procedure based on inversion of coherence to retrieve stem volume, from which tree height can then be estimated, should be preferred.

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