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Experiences in Boreal Forest Stem Volume Estimation from Multitemporal C-Band InSAR

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1. Introduction

During the last two decades synthetic aperture radar (SAR) and interferometric synthetic aperture radar (InSAR) have become important tools for airborne and satellite remote sensing. SAR delivers a high resolution image of the radar backscatter and by means of InSAR a second image from almost the same orbit is combined with the first one to provide the relative phase difference and stability/coherence of the backscattered signal. Principles of InSAR can be found in various review articles (Bamler and Hartl, 1998; Massonnet and Feigl, 1998; Rott, 2009). This presentation will focus on the use of InSAR observations for investigation of forest stem volume or above ground biomass.

Satellite methods are important to determine forest above-ground biomass on a global scale in order to follow changes in a consistent manner over long periods of time as part of climate modeling. Methods to determine forest stem volume are also important for the economical management of forest areas. For these applications many remote sensing techniques have been investigated. Our interest will focus on a radar method. In contrast to methods based on optical images, a semi-empirical, physically-based relation between measurements and stem volume/biomass can be established because microwaves penetrate the forest canopy to a certain extent and the backscattered signal is therefore modulated by the forest structural properties.

With the early C-band SAR systems, the European Remote Sensing Satellites ERS-1 and ERS-2, and in particular the observations during the tandem period with one day interval between the observations, large amounts of InSAR data became available, which allowed the possibility to retrieve forest parameters. One argument against C-band for forest applications has been that the backscatter is originating from the top layer of the forest with little relation to the major components of the biomass, such as the stem and then saturate for low biomass values (Imhoff, 1995). However, this changed with repeat pass InSAR data, and coherence can under certain conditions provide high accuracy stem volume estimates up to the stem volumes available in the test areas studied below, i.e. up to 539 m^3/ha or approximately 265 tons/ha. Microwave penetration into forests is related to the vegetation properties including the gaps in the vegetation. Since the density of boreal forests is often low this is a fundamental property for the application of C-band and higher frequencies, where gaps as small as some wavelengths will allow penetration and result in a contrast between the relatively high ground coherence, and the relatively low canopy coherence induced by wind effects on the canopy. In addition, part of the coherence, the volume decorrelation, which increases with baseline length, is dependent on forest height. This means that C-band tandem coherence measurements include information about forest density as well as height, thus being related to the above ground stem volume/biomass.

This paper will describe methods and results giving insight into the applicability of C-band InSAR coherence data for retrieval of stem volume in boreal forests. The semi-empirical model, the Interferometric Water Cloud Model, IWCM, relating the InSAR coherence to forest parameters will be presented. The possibility to determine or reduce the number of parameters in the IWCM will be discussed, e.g. the possibility to express the mean tree height as a function of stem volume in form of an allometric relation. For this, a large number of measurements from ground surveys in Sweden will be used. The model parameters which vary with the meteorological conditions will in the first step be determined by training the model by means of known forest sites. In a second step, a method for the estimation of the model parameters without such training sites will be presented.

The goal is to investigate the possible accuracy of C-band InSAR for retrieval of forest stem volume and thus biomass by means of forest sites with accurate *in situ* data, Brattåker, Remningstorp, Tuusula, and Kättböle. Since the usefulness of a semi-empirical model is related to the possibility to validate the model and demonstrate its accuracy, four different test sites with different properties have been studied, and results are presented. As part of the goal, IWCM is developed in various ways, and new results derived.

2. Model for InSAR data from a forest, the Interferometric Water Cloud Model

A model describing the relation between the remote sensing observables and the stem volume should present a fairly simple formulation if the aim is to invert it to retrieve stem volume from InSAR coherence values. The Interferometric Water Cloud Model, IWCM, which is extensively presented elsewhere (Askne et al., 1997; Santoro et al., 2002; Askne et al., 2003), assumes a volume above ground of randomly distributed scatterers with gaps (within canopy as well as between trees), and takes into account the backscatter and coherence variations, decorrelation of the ground and the vegetation layer including the volume decorrelation. The canopy cover or the areafill η represents the relative percentage of the area covered by vegetation. Leaf area index and gap fraction are associated aspects (Nilson, 1999). The backscatter and coherence will be described in terms of the attenuation back and forth through the partially covering vegetation layer, $exp(-\alpha h)$, but also in terms of an empirically related variation with stem volume (Pulliainen et al., 1994), $exp(-\beta V)$. The forest backscatter components also determine the weight of the statistically independent coherence components.

$$\sigma^0_{for} = \eta\left[\sigma^0_{gr}e^{-\alpha h} + \sigma^0_{veg}\left(1-e^{-\alpha h}\right)\right] + (1-\eta)\sigma^0_{gr} = \sigma^0_{gr}e^{-\beta V} + \sigma^0_{veg}\left(1-e^{-\beta V}\right) \quad (1)$$

$$\gamma_{for} = \eta\left[\gamma_{gr}\sigma^0_{gr}e^{-\alpha h} + \gamma_{veg}\gamma_{vol}\sigma^0_{veg}\left(1-e^{-\alpha h}\right)\right] + (1-\eta)\gamma_{gr}\sigma^0_{gr} + \varepsilon_{noise} = \gamma_{gr}\sigma^0_{gr}e^{-\beta V} + \gamma_{veg}\gamma_{vol}\sigma^0_{veg}\left(1-e^{-\beta V}\right) + \varepsilon_{noise} \quad (2)$$

σ^0_{gr} is the backscatter from ground, σ^0_{veg} the backscatter from the vegetation layer, γ_{gr} and γ_{veg} represent the temporal decorrelation of the ground scatterers and the vegetation scatterers. If the variation of scattering and stability with height is only determined by the attenuation, the volume decorrelation is determined by

$$\gamma_{vol} = \frac{\int_0^{h(V)} e^{-\alpha z'} * e^{-jK(B_n)z'} dz'}{\int_0^{h(V)} e^{-\alpha z'} dz'} = \frac{\alpha}{\alpha - jK(B_n)} \frac{e^{-jK(B_n)} - e^{-\alpha h(V)}}{1 - e^{-\alpha h(V)}} \tag{3}$$

where $K=4\pi B_n/\lambda R \sin\theta$. α and $h(V)$ are assumed to be known. α was shown to be ≈ 1 dB/m during winter conditions and 2 dB/m during summer conditions (Santoro et al., 2007b), however, the possibility to determine α from the measurements will be studied here. To reduce the number of forest parameters, the height is parameterized as a function of stem volume, *h(V)*. This relationship is assumed to be given by an allometric relation between height and stem volume, see below.

For the two expressions in (1) and (2) to agree, a demand is obtained that the areafill factor $\eta(V)$ is given by a relation between α and β

$$\eta(V) = \frac{1 - e^{-\beta V}}{1 - e^{-\alpha h(V)}} \tag{4}$$

Traditionally an extinction coefficient, κ, is used to define the attenuation through a homogeneous vegetation layer. From above $\frac{2\kappa h(V)}{\cos\theta_i} = \beta V$ or with (4)

$$\kappa(V) = -\frac{\cos\theta_i}{2h(V)} \ln\left[1 - \eta(V)\left(1 - e^{-\alpha h(V)}\right)\right] \tag{5}$$

illustrating how the extinction coefficient is dependent on stem volume, height, areafill, as well as temperature, humidity etc. through α.

3. Forest properties influencing the model

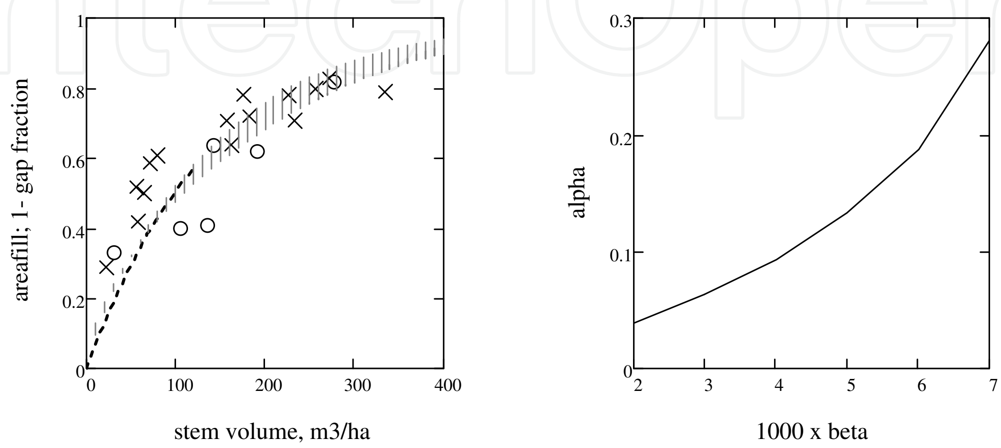
The formulation of the IWCM in Eq. (1) and (2) highlights that the modeled coherence depends on a number of parameters related to the scattering properties of the forest and the forest structure. Scope of this Section is to investigate the relationship among some of these parameters. α and *h(V)* will be discussed, and also the relation between stem volume and biomass, since above ground biomass is an important parameter for climate modeling.

3.1 Areafill and attenuation

The areafill is the fraction of ground covered by the vegetation, looking in the direction of the satellite. The areafill can be observed by different methods, and some results are given in Fig. 1a. The three observed areas are showing the same trend.

α is the attenuation factor per unit height of the radar wave going back and forth the idealized vegetation layer. If α is made dependent of β in the way described by Eq. (6), an areafill variation is obtained in line with the observations in Kättböle. When β is varying from 0.002 to 0.007 in steps of 0.001 as shown in Fig 1b, the range of values of the associated areafill is marked by the vertical lines in Fig. 1a. α has normally a small effect on the final retrieval result and a fixed value of 0.23 can be used for winter conditions and 0.46 for summer conditions. Such a fixed value is needed if not the areafill information is available.

$$\alpha(\beta) = -\frac{1}{7.4}\ln\left(1 - \frac{\beta}{0.008}\right) \tag{6}$$



a b

Fig. 1. Observations of areafill/gap fraction, x based on hemispherical photography of Kättböle stands (Santoro et al., 2002), o based on results in (Nilson, 1999) from a neighboring area; dashed line: regression line from MODIS observations in Northern Sweden (Västerbotten) (Cartus et al., 2010). Note that the uncertainties in the observations are large. Vertical lines are illustrating range of values of areafill variations for $0.002 < \beta < 0.007$ in Eq. (6).

3.2 Allometric relation for h(V)

The IWCM describes the forest coherence as a function of two forest parameters: stem volume and height. Since we are primarily after stem volume, we investigated the possibility to replace height with a function related to stem volume. The volume decorrelation is dependent on the forest height and increasing with baseline although typically of lower importance than temporal decorrelation. For this reason, a simple allometric relation for *h(V)* has been considered. Replacement of the actual height with an allometric equation assumes that this does not introduce significant errors in the modeled coherence. In (Askne et al., 1997) an expression based on a very limited dataset was given, but this expression has also been found to be applicable for other areas investigated below using InSAR data, although an allometric relation can be expected to be dependent on forest type, growing conditions etc.

$$h(V)=(2.44\ V)^{0.46} \tag{7}$$

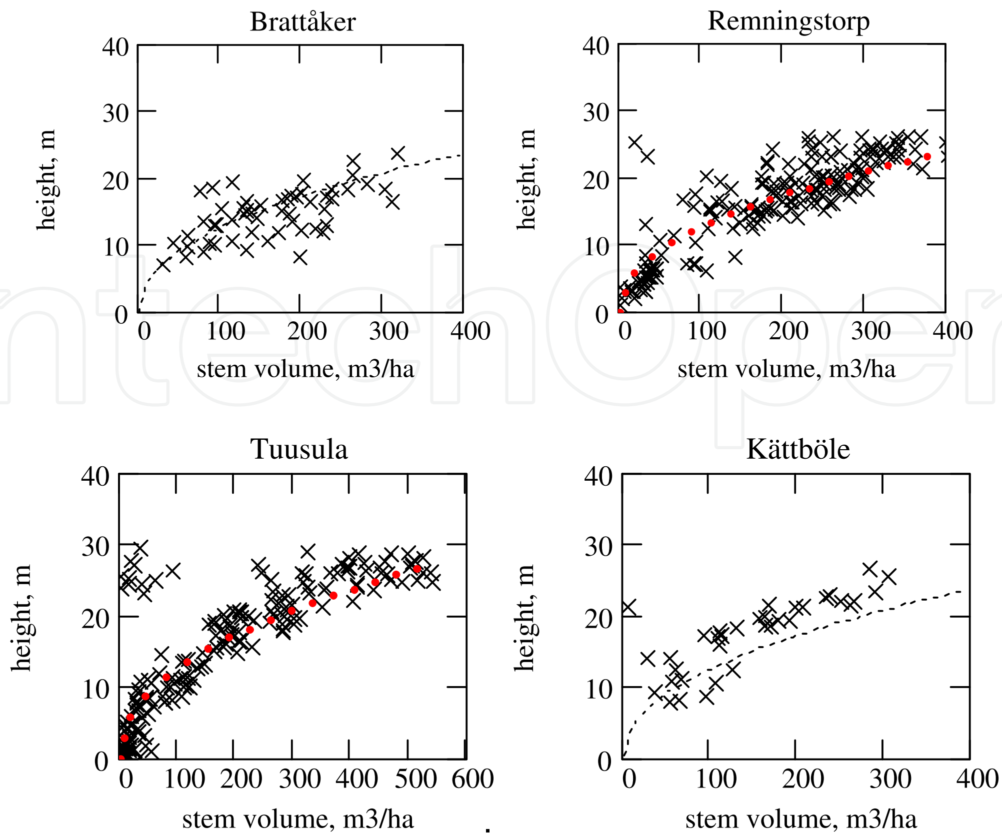


Fig. 2. Illustrating forest properties for investigated test sites in the form of the relation between height and stem volume (stand averages) together with the allometric relation in Eq. (7), dotted curve.

Height versus stem volume is illustrated in Fig. 2 for the test sites studied below. From the figures some anomalies associated with e.g. seed trees and thinning practice can be noticed.

In order to investigate the allometric relation for more general conditions, a large number of statistically sampled measurements from the Swedish National Forest Inventory (courtesy Anders Lundström and Göran Kempe) have been used. In total, forest parameters from 3046 plots (in productive forest) with 10 m diameter (permanent plots) or 7 m diameter (temporary plots) have been used. The measurements took place between 2002 and 2006. The measurements are presented for four areas of Sweden, Skaraborg County (N 57° 38′ – 59° 02′, O 12° 35′ – 14° 35′), Uppsala County (N 59° 28′ – 60° 38′, O 16° 47′ – 18° 39′) and Västerbotten County (N 63° 30′ – 65° 49′, O 14° 54′ – 21° 45′). Västerbotten County is divided in two parts, the coast land and the inland.

The measured heights and stem volumes for the plots are illustrated in Fig. 3 by the dots. The scatter plots have been limited to heights up to 30 m and stem volumes up to 600 m^3/ha (only eight stands fall outside these plots). Since coniferous are dominating at the test sites, plots with more than 70% coniferous have been marked with circles. For each region, Eq. (5) has also been included as reference. In Fig. 4 the regression function for each region has been included and only a slight difference between the curves relative the spread of values around the regression curves is seen, as shown in Fig. 2 and 3.

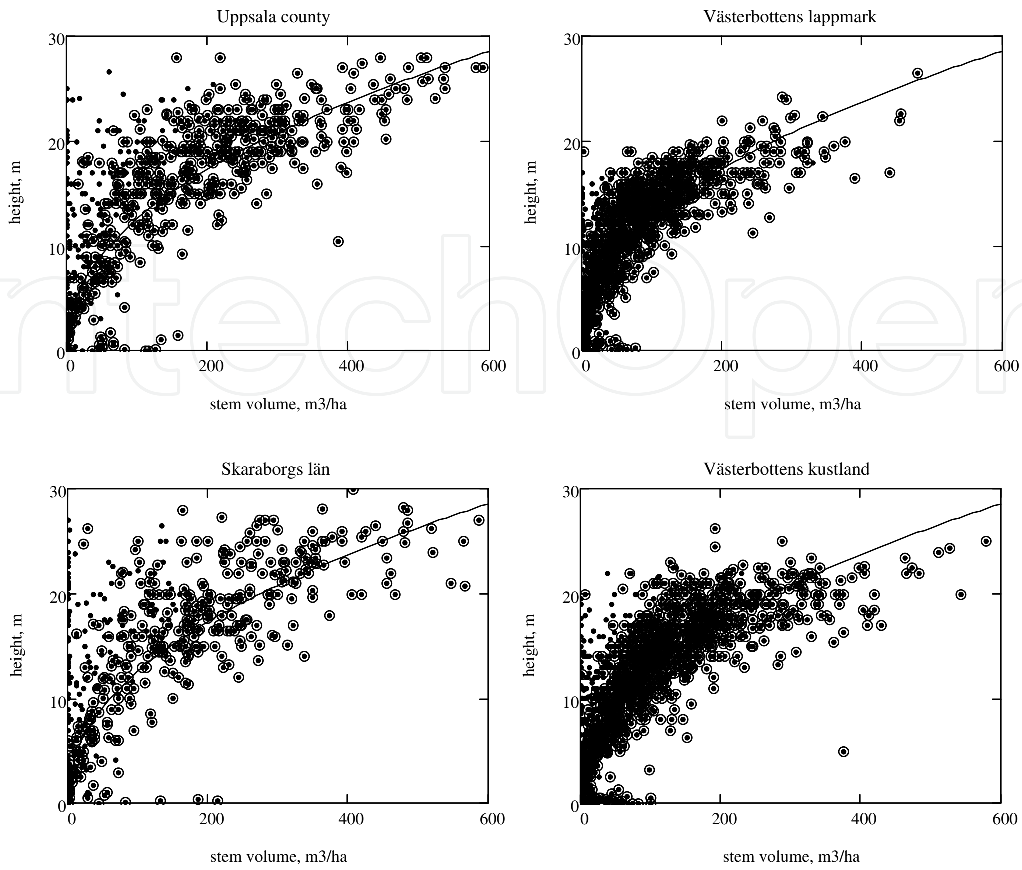


Fig. 3. Plot wise values for height and stem volume. All plots included in the dataset are marked by black dots, and those with > 70% coniferous are marked with an added circle. The black curve represents Eq. (7), while the regression curves to the observations are included in Fig. 4.

The rather constant allometric relation between height and stem volume for the investigated areas in Sweden confirmed the plausibility of the assumption on replacing the true height with Eq. (7) in the IWCM. The deviation between the allometric *h(V)* relation from the *in situ* observations means an uncertainty in the volume decorrelation term of IWCM. For Uppsala county, illustrated in Fig. 3, and for a perpendicular baseline of 200 m, this would imply a coherence shift of up to 10% (or 0.04) with a maximum for stem volumes around 200 m^3/ha, adding to the model errors from other sources.

Since the analysis is based on National Forest Inventory plots, and then typical for the Swedish landscape, the heterogeneity of the forest explains the large spread around the allometric expression. In turn, this indicates that retrieval of stem volume based on an allometric equation and height estimated for example with a remote sensing technique might be affected by significant uncertainty. For example, if only the height had been measured, e.g. by PolInSAR, and the allometric relation for the county of Uppsala, had been used to determine the stem volume in this county, this would result in a relative Root Mean Square Error (RMSE) of 51% and a mean value of 219 m^3/ha instead of 192 m^3/ha obtained from *in situ* measurements of stem volume. Therefore, if the goal is to determine stem volume or biomass, it is not sufficient to determine the height by remote sensing, but also the forest density has to be estimated.

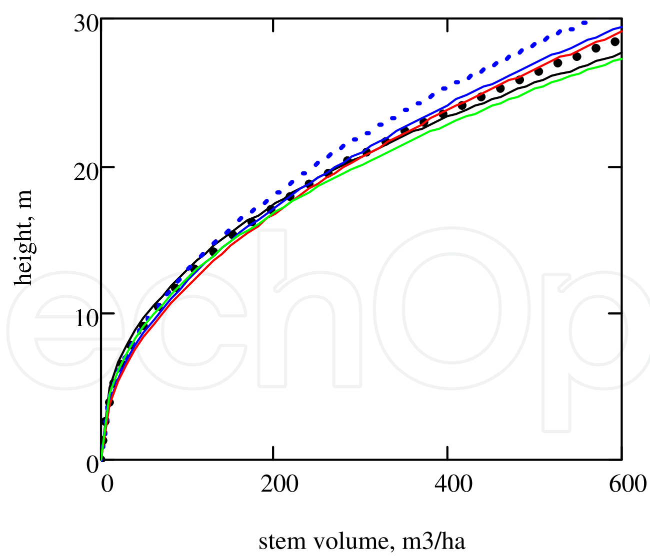


Fig. 4. Regression curves for the different data sets: black solid line: all investigated areas (3046 plots); black dotted line: allometric expression $h(V)=(2.44\ V)^{0.46}$. With only those with >70% coniferous are included: green solid line: Skaraborgs County (343 plots); red solid line: Uppsala County (455 plots); blue dotted line: Vasterbotten County inland (855 plots); blue solid line Vasterbotten County coast land (1070 plots)

It is important to remark that the allometric relation *h(V)* is area-dependent and may be valid for the managed forests in Scandinavia. For the area of the former USSR, yield tables derived from inventory data can be used to relate height and stem volume. The relationship depends on the productivity, see (Santoro et al., 2007b) Eq. (7) can be applied for forests with high relative stocking representing a more managed type of forest, while stands with low relative stocking are characterized by larger tree heights. For German forests presented in (Schober, 1995; Mette et al., 2004) the *h(V)* relation is quite different from Swedish forests.

3.3 Relation between stem volume and biomass

Stem volume has been the property of interest for forest administration purposes and for the Swedish NFI. However for climate modeling applications the above ground biomass is of interest. The International Panel on Climate Change (IPCC) guidelines for national greenhouse gas inventories (IPCC, 2006) give biomass expansion factors for boreal forest depending on growing stock level. For pine, it is 0.45-0.58 and for spruce 0.45-0.605 in both cases for a growing stock level > 100 m^3/ha. The factors are multiplied by the growing stock in m^3/ha to obtain the above ground biomass in tons/ha. (Formally the boreal climatic zone is defined by ≤ 3 months at a temperature > 10°C but still seems most relevant for the test sites.) There is more specific information on the relation between stem volume and biomass for two sites, Remningstorp and Krycklan (35 km north Brattåker). For Remningstorp, stem volume and above ground biomass have been calculated from tree level by means of allometric equations according to (Näslund, 1947) for stem volume and (Marklund, 1988) for above ground biomass while for Krycklan the updated HEUREKA expressions have been used (ESA, 2010). It is concluded that the conversion factor between stem volume and above ground biomass is 0.47, (regression formula 0.47 x stem volume +12.7) and that stem volume and above ground biomass are highly correlated (0.98).

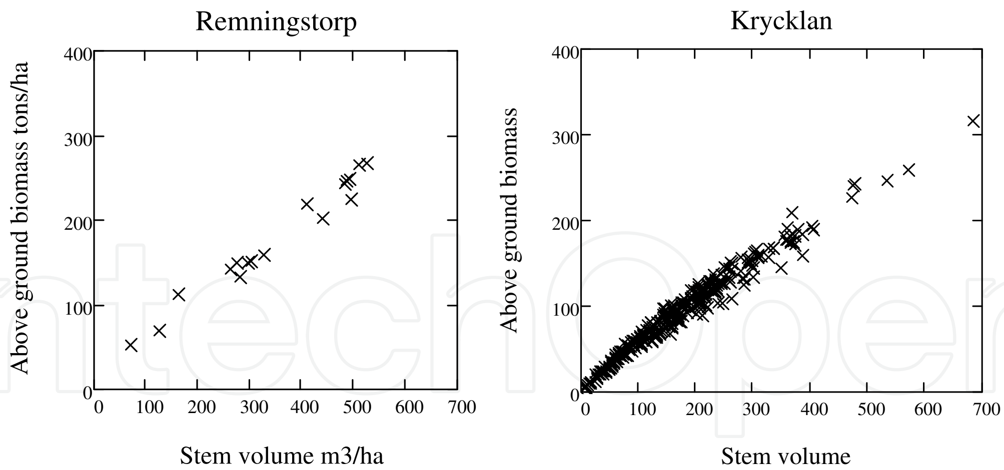


Fig. 5. Relation between above ground biomass, tons/ha, and stem volume, m3/ha (correlation 0.99, slope 0.471 for Remningstorp, correlation 0.98, slope 0.465 for Krycklan) Data courtesy: Gustaf Sandberg for Remningstorp, BioSAR 2008 campaign for Krycklan.

4. Test sites for stem volume retrieval

For testing the retrieval accuracy of C-band InSAR data from ERS-1/ERS-2 tandem period four forest areas have been investigated. The areas, Brattåker, Remningstorp, Tuusula, and Kättböle, see Fig. 6, were selected based on the availability of accurate *in situ* data, and represent examples of boreal forest in northern Europe – two of them at the southern edge, and Remningstorp just south of the edge, see Fig. 6. They are managed by different organizations/companies. All are covered mainly with typical boreal coniferous species, i.e. Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*); but some deciduous species are also present, the commonest being birch (*Betula pendula*). The areas are divided in stands consisting of relatively homogeneous forest properties and site conditions.

Brattåker (lat. 64°16′ N; long. 19°33′ E) is a forest research park located in northern Sweden and managed by the Swedish forest company Holmen Skog AB. It covers approximately 6000 ha. Elevations in the test site range from 160 to 400 m above sea level and slopes up to 12° are common. For one stand the mean slope angle is 21°. The *in situ* data included 54 stands carefully inventoried (at the 10% level) in 2000. Based on growth factors the status for the year of acquisition of the ERS data, i.e., 1996, was estimated. However possible thinning etc could have decreased the accuracy of the *in situ* data.

Tuusula (lat. 60° 25′N long. 25° 1′E) consists of 210 stands of which eight stands were smaller than the SAR image pixel size and thus too small for estimates of backscatter and coherence. Elevations in the test site ranged from 35 to 90 m above se level. *In situ* data were collected in summer 1997 as part of the EUFORA project (Hallikainen et al., 1997). The *in situ* data together with InSAR data been analyzed in several papers (Santoro et al., 1999; Pulliainen et al., 2003; Engdahl et al., 2004; Askne and Santoro, 2005). It resulted that 37 of the 202 measured stands could be labeled as being suitable for retrieval of stem volume because of being large and homogeneous (Santoro et al., 1999).

Kättböle (lat. 59° 59′ N long. 17°7′ E) is a forest estate covering 550 ha, with relatively flat topography where elevation ranges between 75 and 110 m above sea level. Accurate *in situ*

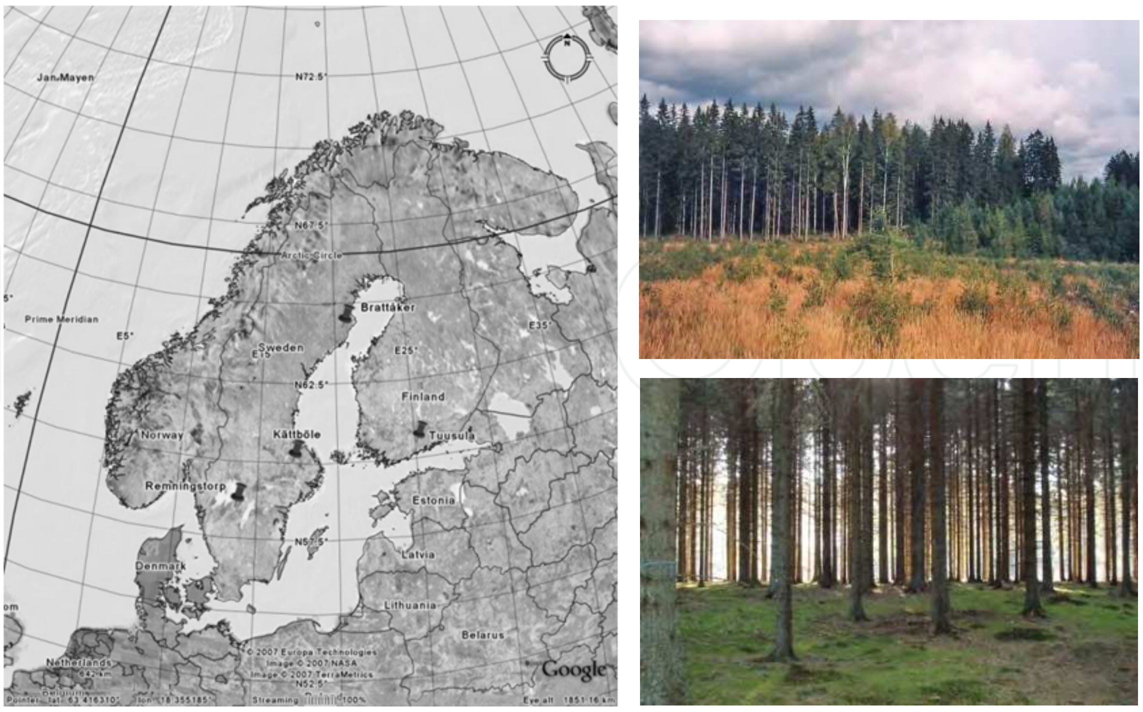


Fig. 6. Map with test sites marked (courtesy Google) and forest photos from Tuusula and from Remningstorp (courtesy Leif Eriksson) to the right.

data were collected 1995 and 1996 and those from 1995 corrected by growth factors. 42 stands were studied. This test site was analyzed in (Fransson et al., 2001; Santoro et al., 2002)

Remningstorp (lat. 58°30′ N; long. 13°40′ E) is a 1200 ha forest estate run by Skogssällskapet AB. This is a site used in many remote sensing verification experiments (Holmgren, 2003; Magnusson and Fransson, 2004a; ESA, 2008; Sandberg et al., 2011). Elevations in the test site range from 120 to 145 m above sea level. The *in situ* data included 105 stands inventoried at the 10% level. The inventory took place during 1997-2002. To decrease the uncertainties in the *in situ* values associated with unknown thinnings etc, stands that were inventoried not later than 2000 were considered and growth factors were applied to estimate the status in 1996.

5. Retrieval of stem volume from the traditional model training

The retrieval of stem volume requires that the model parameter, unknown *a priori*, are estimated first. The traditional estimation approach relies on measurements of stem volume, coherence and backscatter forming a model training dataset. The parameters are then estimated with non-linear least squares regression techniques (Santoro et al., 2002). In Eq. (1) and (2), σ_{gr}, σ_{veg}, γ_{gr}, γ_{veg}, and β are estimated. Although α can also change depending on the seasonal condition, in the analysis it was instead fixed to 0.23 (i.e., 1 dB/m).

While the inversion of Eq. (1) to retrieve stem volume from a backscatter measurement is straightforward, the inversion of Eq. (2) cannot be expressed in a closed form and a numerical approach is required (Santoro et al., 2002). Finally, if multiple measurements of coherence and backscatter are available, a multi-temporal estimate of stem volume based on a linear combination of individual estimates can be obtained. Details of the inversion process including the multitemporal averaging are described in (Santoro et al., 2002).

Modelling and retrieval using the traditional model training approach have been carried out using stand-wise averages of stem volume, coherence and backscatter to limit the effect of pixel-wise noise.

For assessing the retrieval accuracy of stem volume, the stands were sorted for increasing stem volume and divided in two groups by taking each second stand. One of the groups was used for training and one for testing. The groups were interchanged and mean results determined. For Remningstorp, however, all stands were used for training as well as testing. For improved statistical significance, cross-validation can be used, but the simple methods have been chosen due to a relatively large number of stands and also in the conviction that the errors are mainly due to the variability of forest properties and the environmental conditions which will vary from site to site.

For each site, the coherence distribution versus stem volume for the "best" image (i.e., characterized by the highest retrieval accuracy) is illustrated in Fig. 7. Results of the InSAR observations are summarized in Table 1 together with baselines and environmental conditions for the three best image pairs. First will some comments related to each of the test sites be given and then general experience from all the test sites. Which observations can be assumed to be most suitable for retrieval of stem volume from repeat-pass coherence will be discussed below.

The retrieval accuracy is here reported in form of the relative Root Mean Square Error (RMSEr), i.e., the RMSE relative to the true mean stem volume. Typically a value between 10% and 20% is considered acceptable by forest inventories. Larger uncertainties can be accepted by the carbon and climate communities.

Brattåker: Five pairs from the winter season were selected but two were only partly overlapping with the forest site and only three image pairs were used. Of these, for the two image pairs acquired in 1996 the temperature varied close to zero degrees during the day between acquisitions causing decorrelation due to changes of the dielectric and structural properties of the snow layer. The topography varies over the area more than the other investigated areas for which the topography was mainly negligible; however, no effect due to the topography was detected on the retrieval accuracy. For a multitemporal combination RMSEr = 33% was obtained.

Remningstorp: Five image pairs, acquired when the temperature is close to the freezing point, were available. The maximum temperature during the day in between acquisitions was in all cases above 0° C, causing decorrelation due to changes in the snow layer. The retrieval accuracy was related to stand size and quality of the *in situ* data. For 34 stands including at least 24 pixels or at least 1.5 ha large, a multitemporal RMSEr of 32% was obtained. For 30 stands including at least 18 pixels and with inventory data collected not later than 1997, a multitemporal RMSEr of 27% was obtained.

Tuusula: For this site 15 image pairs were available of which 4 with temperatures below zero. By applying a multitemporal combination RMSEr = 20% is obtained for 37 selected stands. In (Askne and Santoro, 2005) all 202 stands were considered and RMSEr = 58%. However, when stands less than 4 pixels were excluded and those with *in situ* stem volume less than 100 m^3/ha RMSEr = 26% (85 stands) is obtained. This explains that the high RMSEr for all 202 stands originates from small stands and stands with small stem volume. For larger stem volumes one might have expected larger errors associated with saturation, but from the analysis of the stands in Tuusula including stands up to 539 m^3/ha (≈ 265 tons/ha) this was not seen, cf. Fig. 6. Similar investigations of other test sites gave the same tendency.

Kättböle: For this site nine image pairs were available of which two with temperatures below zero. The multitemporal combination of all nine pairs resulted in RMSEr = 19% for 42 stands.

In total 34 ERS-1/2 tandem pairs covering the four test sites have been investigated. Forest properties of 338 forest stands have been determined by foresters, for two sites (Kättböle and Tuusula) within one year and for the other two within two to four years time difference relative the ERS tandem observations. The analysis illustrates the importance of having *in situ* data close in time with the acquisitions. The topography, mostly gentle, did not seem to have much effect on the retrieval accuracy.

The Interferometric Water Cloud Model was found to well describe the observations, under all environmental conditions and interferometric geometries. The retrieval results have illustrated that the accuracy is related to:

- **Weather conditions**: Best with temperatures consistently a few degrees below the freezing point, a dry snow layer on the ground (characterizing high ground coherence) and a wind corresponding to an at least moderate breeze (characterizing low vegetation coherence)
- **Stem volume**: small stem volumes present larger relative retrieval errors than large stem volumes, no saturation limit identified – RMSEr decreases with increasing stem volume
- **Stand size**: at least 1.5 ha (large and homogeneous stands give best agreement with *in situ* data)
- **Baseline of image pair**: Of the 34 image pairs studied seven had baselines in the range 200 – 250 m. Five of these belong to the best twelve image pairs in Table 1.

With the northern location of Brattåker one would have expected suitable environmental conditions to occur relatively often, still no acquisitions were obtained under optimal conditions. This is probably related to the limited number of acquisitions in this area., The winter season 1995/96 included 120 days with temperature < 0° C of which 70 days with wind speed at least 3 m/s and a snow layer or 35 days with wind speed at least 4 m/s and a snow layer. For the southernmost, hemi-boreal site, Remningstorp, as a mean per winter season based on observations from 1993 – 1998 78 days had temperature < 0° C of which 52 days with wind speed at least 3 m/s (of which 33 with a snow layer) or 11 days with wind speed at least 4 m/s (6 also with a snow layer). If the acquisition plan for ERS-1 and ERS-2 had taken into account the conditions for optimal meteorological conditions for forest stem volume retrieval, it is expected that it would have been possible to obtain a reasonable number of images with strong sensitivity of the coherence to stem volume each winter season in the boreal zone.

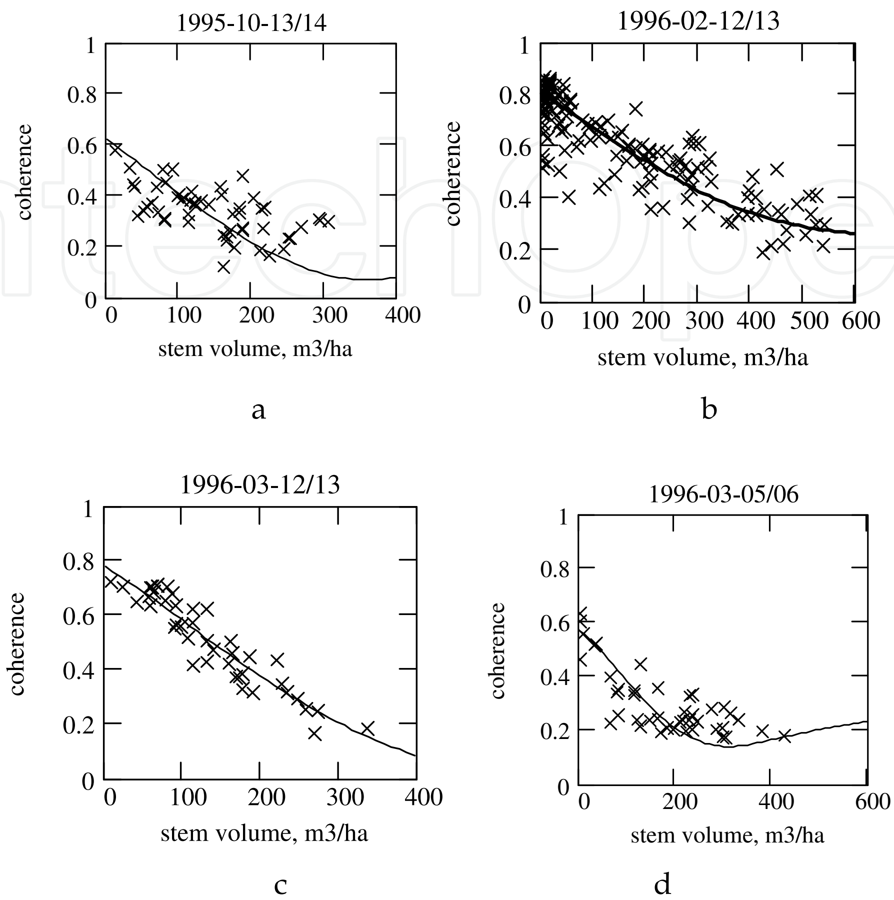


Fig. 7. Measured and modeled coherence as a function of stem volume for each of the best image pairs from a) Brattåker; b) Tuusula; c) Kättböle and d) Remningstorp.

6. Consistency plots

To analyze the properties of a multitemporal set of coherence and backscatter values, the so called "consistency plots" can be investigated, the plots of two observations of the same area from different dates versus each other. The plots show to what extent the observed quantity for the same pixels change consistently or randomly and then if the variations can be described by a model. With n observations there are $\frac{1}{2}\, n(n-1)$ different combinations. As an example Fig. 8 illustrates the observations from two coherence images of forest pixels in the Kättböle area and also the corresponding ERS-1 backscatter observations. If the temporal coherence had been exactly the same at the two occasions the points had fallen more or less along a straight line (depending on baseline). Lowest coherence would correspond to the forest with highest stem volume and highest coherence to bare surface. From Fig. 8 it can be concluded that there has been a certain consistent change in the coherence observations and in addition a spread due to noise and temporal variation of forest properties. For the backscatter there is no or very little trend due to the mostly weak sensitivity of the backscatter upon stem volume. From the consistency plot the density of observation values can be determined and the corresponding matrix values presented as a contour plot or "density plot" (2D-histogram).

Date	Baseline m	Temp. °C	Wind speed m/s	Snow depth cm	Prec mm	RMSEr %
Brattåker, stem volume:< 305 m^3/ha, multitemporal RMSEr = 33%						
1995-10-13/14	219.7	+5.4/+8.4	5/10	0/0	0/0	42
1996-03-03/04	228.5	-2.3/-2.5	3/3	36/40	0/0	38
1996-03-17/18	84.3	-1.7/-2.6	3/3	33/33	0.1/0	44
Tuusula, stem volume: < 539 m^3/ha, multitemporal RMSEr = 58% For 37 large, homogeneous stands: 20%, for 85 stands > 4 pixels and V > 100 m3/ha: 26%						
1996-02-12/13	85	-14.9/-10.8	5/1	16/19	1.4/0	60
1996-03-02/03	76	-4.2/-5.5	4/3	32/32	0.1/0	74
1995-10-14/15	220	+8.6/+6.2	6/1	0/0	0/0	82
Kättböle, stem volume: < 335 m^3/ha, multitemporal RMSEr = 18%						
1996-03-12/13	219.2	-4.9/-4.4	2.5/2.5	10/10	0/0	19.8
1996-03-17/18	65.6	-1.7/-2.8	1.7/0.9	10/10	0/0	38.0
1996-04-21/22	-54.0	+12.8/+12.5	2.3/1.3	0/0	0/0	31.6
Remningstorp, stem volume: < 494 m^3/ha, multitemporal RMSEr = (32 or) 27%						
1996-03-05/06	250.2	-0.6/-1.2	1/1	8/7	0/2.3	46
1996-04-11/12	-89.1	-3.1/-3.1	5/5	0/0	0/0	45
1996-04-27/28	-84.5	+2.4/+6.6	3/5	0/0	0.8/0	44

Table 1. List of the three best image pairs in terms of relative RMSEr, weather conditions and retrieval statistics. Weather conditions refer to the time of acquisition of the SAR data.

For backscatter, in contrast to coherence, the density plot is roughly circular and there is no evident sensitivity to different forest properties.

For the Tuusula area it was noted (Askne and Santoro, 2007) that the large and homogeneous stands resulted in the high retrieval accuracy while small stands and those with small stem volume resulted in low retrieval accuracy. Part of the small retrieval accuracy could be related to errors in the *in situ* observations, but the question is if the coherence observations could provide some indication about the properties of forest stands and the possible accuracy that can be obtained by studies of the consistency plots. For this purpose the “outlier concept” was introduced in (Askne and Santoro, 2007), as based on a measure of the spread of coherence values between different image pairs. High outlier values are related to pixels located in the outer contours of the consistency plots related to the coherence values for the same pixel from two coherence images. It was shown in (Askne and Santoro, 2007) that the highest stem volume retrieval accuracy is obtained for large stem volumes, large stand areas and for small outlier values. All of these properties can then be estimated from remote sensing, and pixels for which the stem volume accuracy can be suspected to be low can be identified, cf Fig. 9.

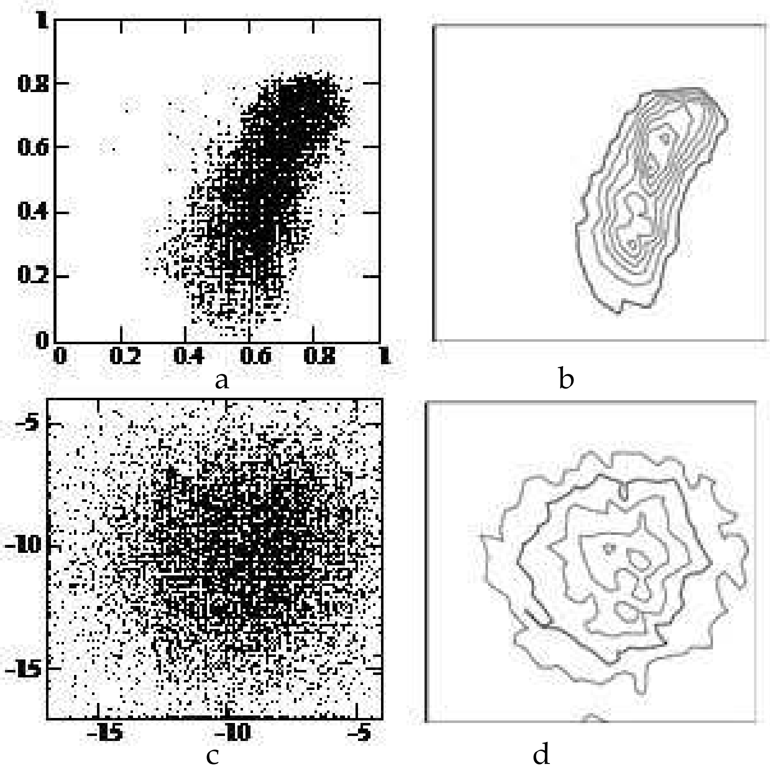


Fig. 8. Illustrating coherence observations from Kattböle from 12/13 March 1996 versus 16/17 April, a and b, and the corresponding ERS-1 backscatter in dB, c and d. Consistency plots showing pair of pixel values, a and c, and the corresponding density plots illustrating the density of points, b and d (with the same scale as in a and c).

The reason for the low accuracy could be aspects related to the forest properties, properties not related to stem volume having a relatively high and varying influence. The major conclusion is that high accuracy of stem volume for a forest stand can be retrieved only when the pixels show up in the consistency plots with little spread, i.e. low outlier value.

7. Retrieval of stem volume with modeling without training stands

There is always a need for reference sites for verification of the accuracy of satellite data. However the need for training data for the interpretation is an issue since such data have to be available on distances related to the spatial scale of weather changes. This is a problem for all remote sensing methods sensitive to environmental properties.

A proposal for an automatic training method of ERS tandem coherence and JERS backscatter data was presented in (Wagner et al., 2003). A matching technique between different frames was used such that the 10th and 90th percentiles of the histograms within the overlap areas of two frames were matched to those of the image with the greater frame coverage. The technique was combined with an exponential coherence model for interpretation of the observations of stem volumes in three classes up to 80 m³/ha and a fourth class above.

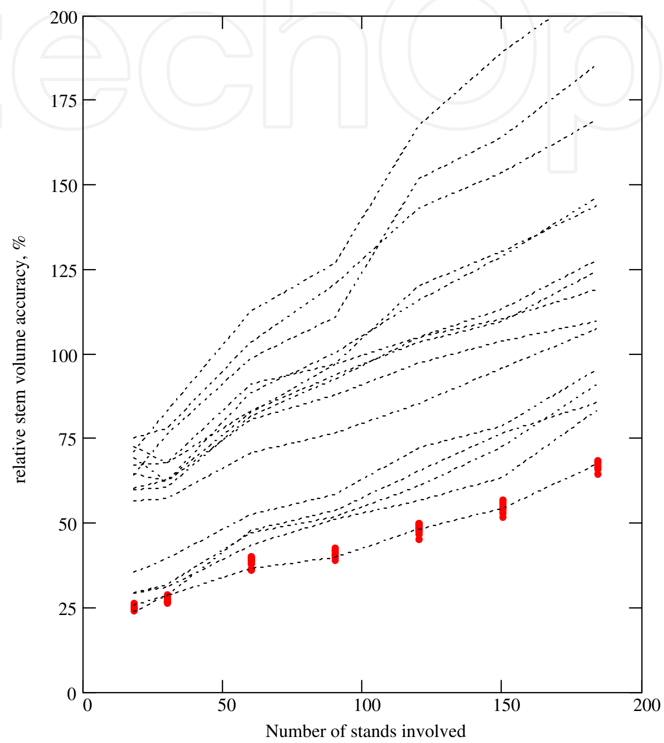


Fig. 9. Results based on 18 stands used for training and 10 up to 180 for testing with increasing outlier value. The dotted lines illustrate the RMSEr of the individual pairs. The solid red intervals illustrate the RMSE when multitemporal analysis is used combining up to 15 image pairs. From (Askne and Santoro, 2007).

A method using the IWCM for interpretation of ERS tandem coherence data without ground reference data was proposed in (Cartus et al., 2007; Cartus et al., 2011). The IWCM parameters were determined by taking statistics of coherence and backscatter of open areas and dense vegetated areas, identified by means of the MODIS Vegetation Continuous Fields, VCF, tree canopy cover product. A fixed value of 0.006 is used for β.

Another method based on multitemporal and multibaseline ERS tandem data was presented in (Askne and Santoro, 2009). The technique is based on consistency plots and density plots introduced in § 6. The majority of forest pixels cluster along a central "ridge" while those more affected by noise and temporal decorrelation will be located in the external parts. It was also shown in § 6 that in the case of the Tuusula data set those forest plots with data along the ridge are those most accurately described by the model, while those consistently further away from the ridge result in lower accuracy. In other words, it is demanded that the model parameters should be such that modeled coherence will follow the ridge, when the stem volume varies.

7.1 Kättböle

The method is simplest to demonstrate for a dataset with relatively limited noise and temporal variability, and the Kättböle test case will be used. It is assumed that *a priori* information is available of the highest stem volumes in the region of interest, from e.g. NFI information. If there is no information on typical areafill variations a value for α corresponding to 1 dB/m can also be assumed. For simplicity it will also be assumed in this analysis that the pixels studied already have been classified as forest pixels. However it has been shown, see e.g. (Wegmüller and Werner, 1995; Dammert et al., 1999; Engdahl and Hyyppä, 2003) that InSAR can be used to differentiate between forest and non-forest pixels, and that the entire classification process then can be based on ERS tandem data.

In Fig. 10 the coherence values for the forest pixels associated with the four coherence image pairs for the Kättböle area (12.5 m pixels) are shown in consistency plots. The IWCM parameters now have to be determined such that, when co-plotted, the IWCM curves for the four cases go through the ridges of the six consistency plots. For Kättböle the areafill variation with stem volume is known and a β- dependent attenuation according to Eq. (6) is

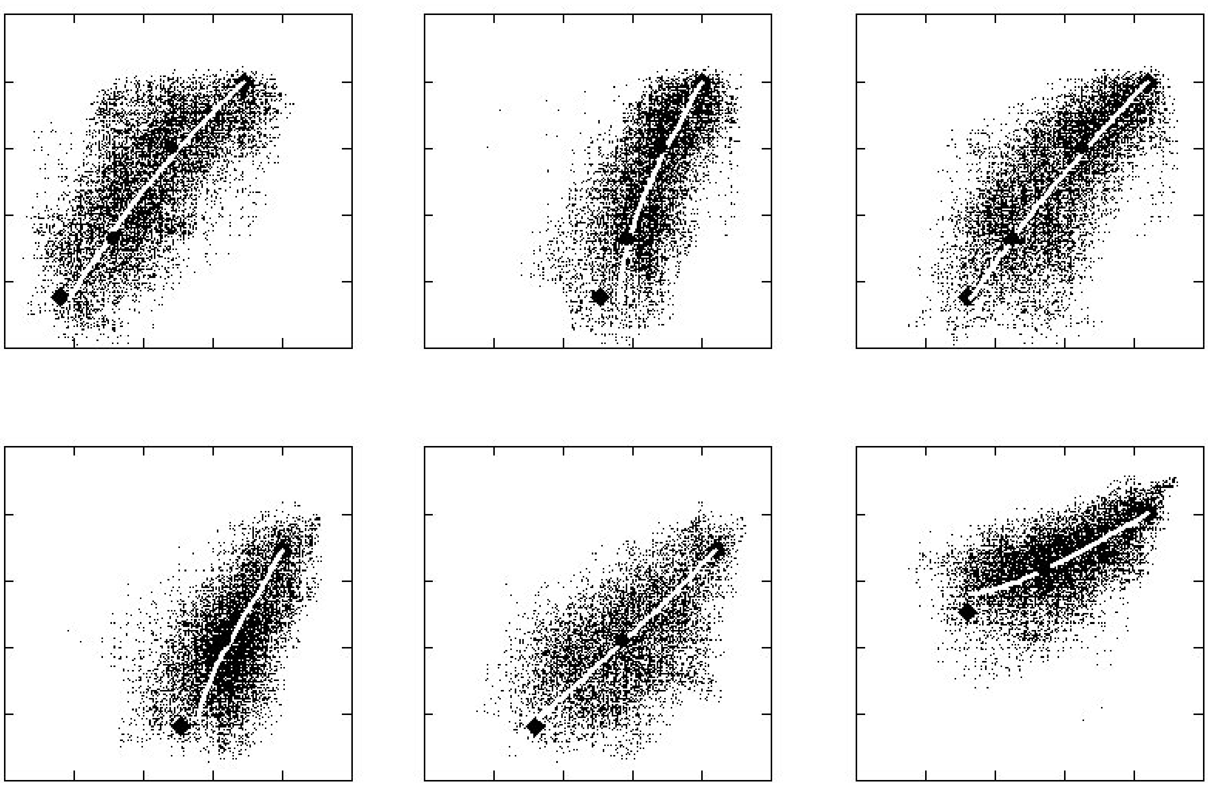


Fig. 10. Illustrating coherence observations and model variations for the four coherence image pairs for the Kättböle area, denoted $\gamma1$, $\gamma2$, $\gamma3$, and $\gamma4$, of observations for the Kättböle area. In upper row $\gamma1$ versus $\gamma2$, $\gamma1$ versus $\gamma3$, $\gamma1$ versus $\gamma4$, and lower row: $\gamma2$ versus $\gamma3$, $\gamma2$ versus $\gamma4$, and $\gamma3$ versus $\gamma4$. The model curves spans the interval 0 – 378 m^3/ha. Reference points are marked along the ridge, γ_{gr} , γm, and γ_{dv}, see text.

used. From the coherence distributions of each image it is first determined what pixel fall in the upper 10% and the lower 15% (more noise influences the lower coherence values) and these are defined as potential pixels representing ground and dense vegetation respectively. Those pixels in common for all image pairs are then defined as ground and dense vegetation pixels. From these pixels the average coherence and backscatter are determined, σ_{gr} and γ_{gr}, and values for "dense vegetation", σ_{dv} and γ_{dv}.

The model parameters σ_{veg} and γ_{veg} represent the backscatter and temporal coherence for an infinitely opaque forest and to derive these from σ_{dv} and γ_{dv} model corrections have to be made by means of an assumption on the stem volume corresponding to dense vegetation, V_{dv}. The stem volume distribution has reached 80% of the cumulative stem volume histogram typical for the region (e.g. determined from NFI-plots) at 315 m^3/ha, cf. Fig. 3, and a 20% higher value or 378 m^3/ha is here considered as typical for V_{dv}. Since the backscatter is normally saturated we may assume that $\sigma_{veg} \approx \sigma_{\mathrm{dv}}$. To obtain γ_{veg} Eq. (5) has to be solved for each coherence image

$$|\gamma(V_{dv}, \gamma_{veg}, \beta)| - \gamma_{dv} \leq \varepsilon \tag{8}$$

starting from guess-values, to be discussed below. ε is the uncertainty in the coherence value of the manually determined point, say ε = 0.02. When the baseline is such that IWCM has a minimum in the coherence versus stem volume plane, then the meaning of γ_{dv} changes, see § 7.2.

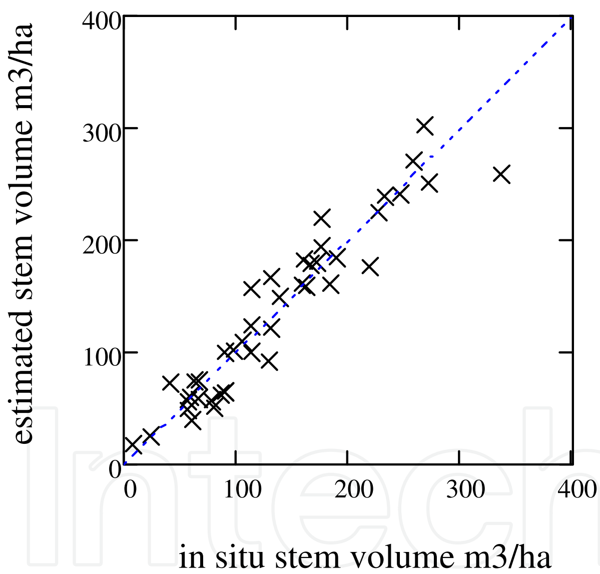
The demand now is that the model curve should follow the "ridge" identified in the density or consistency plots. The ridge is identified by manual inspection and one or two points along the ridge may be identified, γm_{pair}, for each one of the coherence pairs, see Fig. 10. These points are associated with unknown values for the stem volume, say V1 and V2. Together with the four unknown β-values there are six unknowns, beside Eq. (8) regarding γ_{veg}, with demands like $\gamma1(V1,\beta1) - \gamma m1_1 < \varepsilon$, $\gamma2(V1,\beta2) - \gamma m1_2 < \varepsilon$, $\gamma3(V1,\beta3) - \gamma m1_3 < \varepsilon$, and $\gamma4(V1,\beta4) - \gamma m1_4 < \varepsilon$. Four other conditions are related to V2. Minimizing these expressions with a Levenberg-Marquardt algorithm starting from some initial guess values, expressions for the β:s are obtained. Since the algorithm is sensitive to the initial guess the process is initiated by assuming $\gamma_{veg} = \gamma_{dv}$ and a manual variation of the β-values over a range 0.003 – 0.007 in order to make the model curves follow as closely as possible to the "ridges". Also γ_{veg} may be adjusted.

Once stem volume has been retrieved for each individual coherence observation, the individual estimates are combined to form the multi-temporal stem volume value. The multitemporal stem volume value is determined from the individual image results using relative weights determined by the coherence contrast in each image between the values for ground and for dense vegetation, and by the percentage of observations that fall within this range.

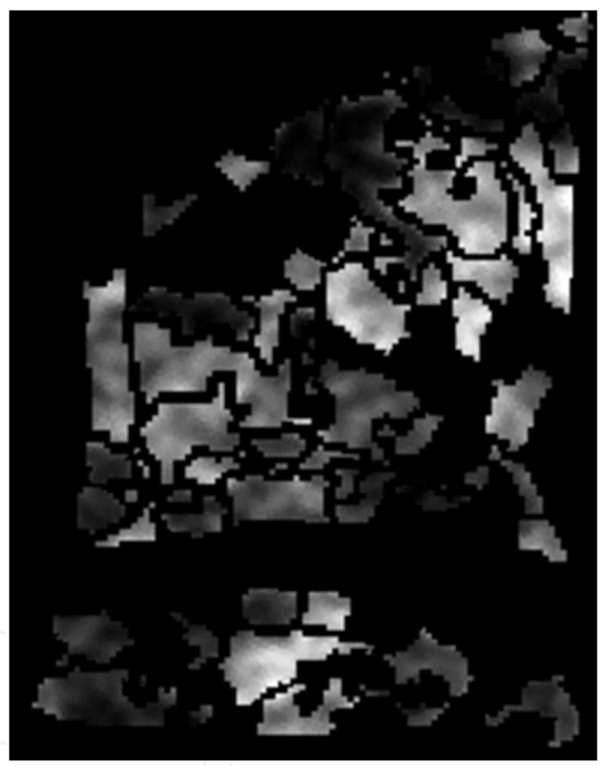
The results from the traditional training method were reported in Table 1 and the results without training are presented in Table 2 for the case illustrated in Fig. 10. The derived β-values are 0.0034, 0.0043, 0.0060, and 0.0045. R^2 is the square of the correlation between estimated stem volumes and *in situ* values, RMSEr is the relative root mean square error and the Bias stands for the difference between the estimated mean volume for all stands and the corresponding *in situ* value. All steps in the process are based on pixel values, but the

	IWCM	IWCM	Exp
Vegetation attenuation, α	1 dB/m	variable	
R^2	0.91	0.91	0.91
RMESr, multitemporal	17%	17%	18%
Bias	0.3 m^3/ha	-3.5 m^3/ha	-1.6 m^3/ha
RMSEr 1996-03-12/13	22.4	22.9	27.0
RMSEr 1996-03-17/18	33.4	33.2	34.6
RMSEr 1996-04-16/17	34.8	34.4	36.5
RMSEr 1996-04-21/22	31.5	31.5	31.7

Table 2. Statistical measures on the accuracy of stem volume estimates using no training data based on the Kättböle area illustrated in Fig. 8b with 42 stands. The first column refers to results obtained with the IWCM and constant α value. The second column refers to results obtained with the IWCM and α based on area-fill and β estimates. The third column refers to results obtained with a simplified IWCM model that does not take into account volume decorrelation.



a



b

Fig. 11. a: Stand averages of stem volume compared with *in situ* values; b: Gray scale image of stem volume variation in Kättböle site (stand boundaries marked). The image is normalized such that white corresponds to the highest estimated stem volume of 378 m3/ha in a single pixel.

comparison with *in situ* data is done for stand averages. Results for α fixed to 0.23 corresponding to 1 dB/m are given as well as β-dependent α-values. The values of α in the last case are 0.31, 0.45, 0.80, and 0.48 dB/m. This is corresponding to an extinction coefficient between 0.1 and 0.2 dB/m for a 22 m vegetation. The temperature varied between - 5° and

+13° C with the lowest extinction at -5° C. The results are in line with observations reported in (Treuhaft et al., 1996). We conclude that the results without training stands are in line with those derived by means of training stands.

The stand averaged multitemporal estimate is compared with the *in situ* values of stem volume in Fig. 11a and an image of the estimated stem volume variation in the test area is illustrated in 11b for possible comparison with laser scanning data in the future.

In (Cartus et al., 2011) it was argued that the performance of the IWCM suffers from errors under certain environmental conditions that reduce the sensitivity of the coherence to stem volume. An exponential model, corresponding to $\gamma_{vol} \equiv 1$, appeared to be more suitable to describe the coherence as a function of stem volume in such cases. For completeness, we compared the retrieval performance of the IWCM and the simple exponential model, cf column 3 in Table 2. The results were similar except for pair 1 with a baseline of 229 m. The reason is that IWCM tends to an exponential form when the baseline is zero, whereas there is a difference when volume decorrelation is introduced by the long baseline.

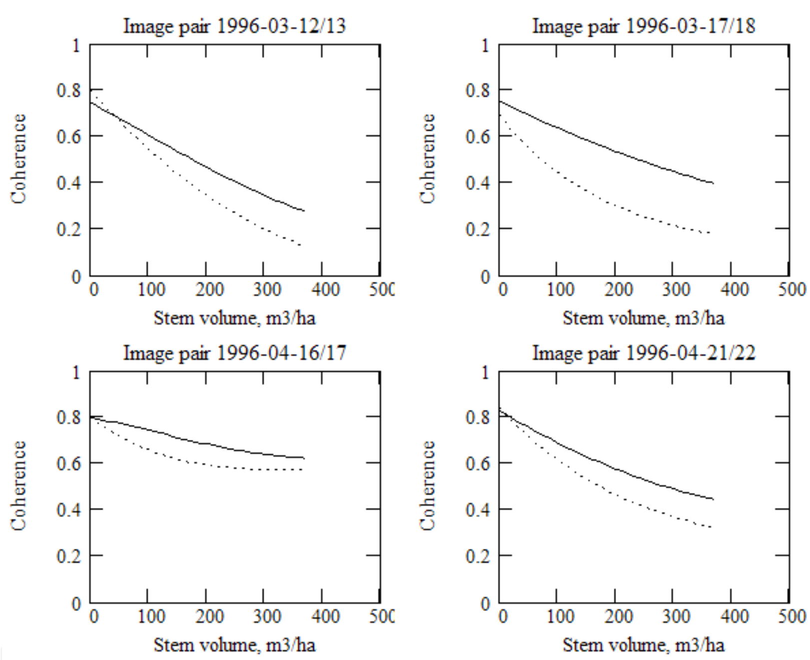


Fig. 12. Model curves for the four coherence images centered on the test site of Kättböle. Solid line for model realizations determined for an area 25 km away from Kättböle, and dotted line model realizations for the Kättböle area. The model spans the interval 0 – 378 m^3/ha.

To test whether the retrieval approach based on consistency plots is adaptive to variations of the coherence due to different environmental conditions across the coherence image, we looked at an area covered by the same ERS scenes, 25 km SE of the Kättböle site. In an earlier analysis (Santoro et al., 2002), it was noted that there were spatial variations of the coherence as a consequence of possible differences of the environmental conditions with respect to the Kättböle area. From the consistency plots for the new area it is realized that the model curve, see Fig. 12, (solid line) is shifted from the model curve derived for the Kättböle area (dotted line). These changes could be interpreted as caused by a lower wind speed in the new area.

The results indicate the need of a spatially adaptive method to retrieve stem volume from coherence data to avoid significant retrieval errors by using a single realization of the coherence model.

7.2 Remningstorp

For Remningstorp the environmental conditions were not as optimal as for Kättböle (see Table 1). Fig. 13 shows the consistency plots in the case of four images and 100 stands, 39 being smaller than 10 pixels. The curves are concentrated around low coherence values, and the structure is less clear compared to the consistency plots shown in Fig. 10 for Kättböle.

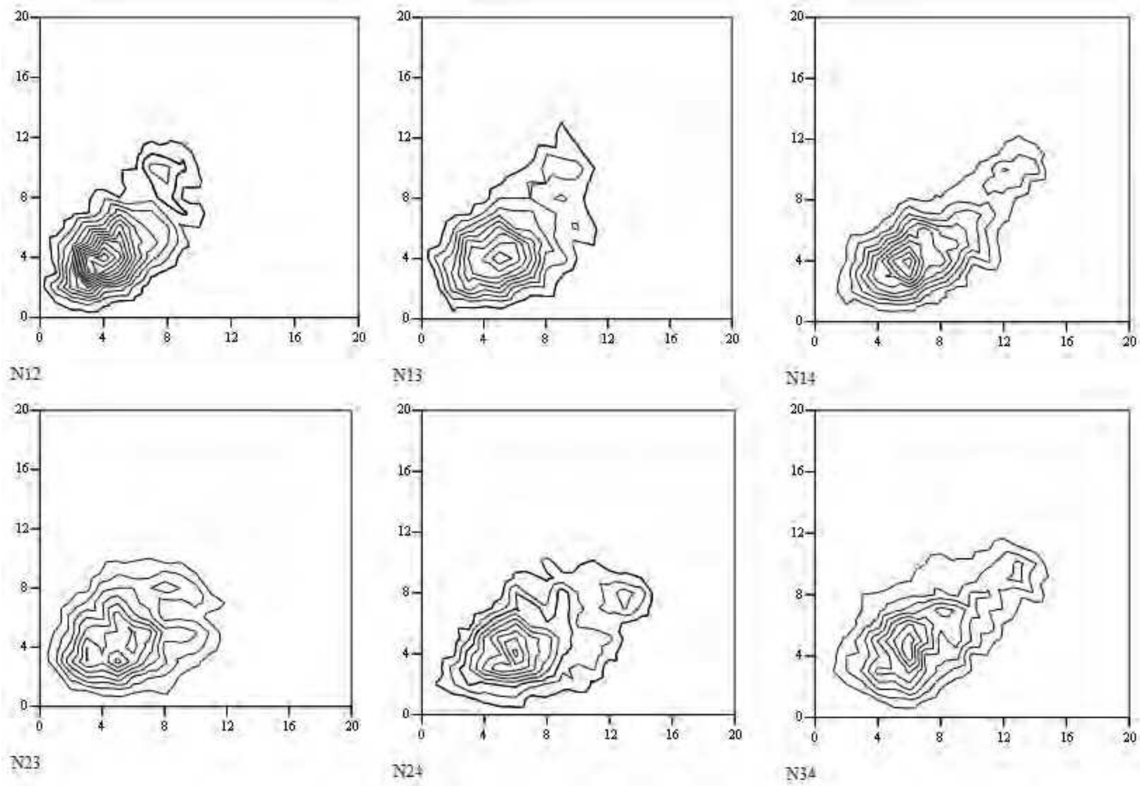
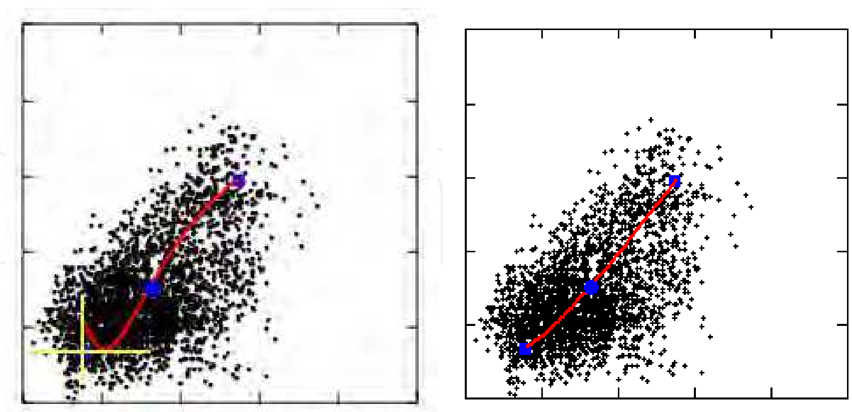


Fig. 13. Density curves for coherence observations from Remningstorp from 1996-03-057/06 ($\gamma 1$); 1996-03-07/08 ($\gamma 2$); 1996-04-09/10 ($\gamma 3$); and 1996-04-11/12 ($\gamma 4$). N12 stands for density curves associated with $\gamma 1$ versus $\gamma 2$ etc. The coherence range 0 to 1 is represented by 0 to 20.

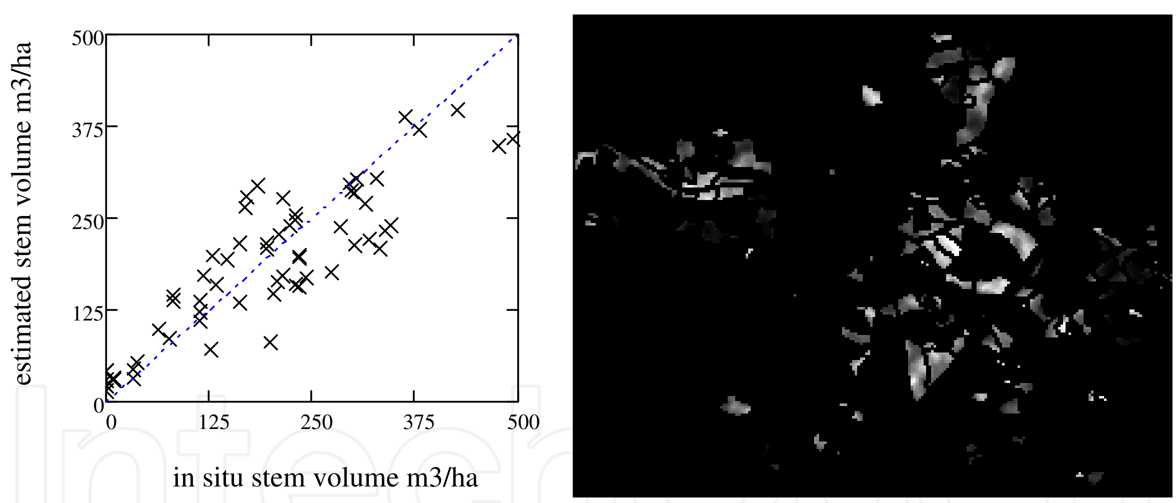
Since no knowledge about the areafill is available it was assumed that α = 0.23 (1 dB/m). An estimate of the maximum stem volume, SVmax, can be obtained from NFI information, cf Fig. 3. Since not available, we will for simplicity assume SVmax, to be 30% above that in Kättböle (located 200 km north Remningstorp). The first pair has a baseline of 250 m and a coherence minimum, which means that the low coherence value we have identified as γ_{dv} represents this minimum, and γ_{veg} is larger than otherwise expected. This is realized when fitting the model curves to the consistency plots, see Fig. 14. For this reason the exponential model may seem easier to fit and was also used. For the 61 stands > 10 pixels and for four images an RMSEr of 27.3% is obtained using IWCM and 27.4% using the exponential model. The result is not sensitive to the assumed SVmax; RMSEr $\leq$ 30% for 350 $\leq$ SVmax $\leq$ 650 m^3/ha. The insensitivity to SVmax is in line with results in (Cartus et al., 2011).

The stand averaged multitemporal estimate is compared with the *in situ* values of stem volume in Fig. 15a and an image of the estimated stem volume variation in the test area is illustrated in 15b.



a b

Fig. 14. Illustrating consistency plots for coherence pair 1 and 3, cf Fig. 13, and co-plotted model curve (red lines) for stem volumes from 0 to SVmax. a. IWCM, b. exponential model. The yellow lines, crossing in the point γ_{dv}, indicate the levels for the lowest coherence levels for these coherence pairs when the stem volume is ≤ SVmax. The blue points represent γ_{gr}, γm, and γ_{dv}.



a b

Fig. 15. a: Stand averages of stem volume for 61 stands in Remningstorp compared with *in situ* values. b: a pixel based map over the Remningstorp stands (white corresponds to maximum estimated stem volume of 491 m^3/ha).

8. Conclusions and future outlook

A large dataset of ERS tandem InSAR data has been investigated with focus on the accuracy by which stem volume can be estimated in boreal forest. For this purpose data from four test sites with *in situ* data of high quality have been used. Since the accuracy is related to the environmental conditions the analysis has been concentrated on winter-time images, which are considered to give the best conditions for high retrieval accuracy (sub zero temperature, dry snow layer, moderate breeze). Although individual images may have relatively high RMSEr, a multitemporal RMSEr of 20% may be obtained for such conditions. In case of less favorable environmental conditions with temperature conditions close to zero degrees, but also the *in situ* data less accurate, the RMSEr is in the 30% range. Stands with small stem volumes (< 100 m^3/ha) showed the largest relative retrieval errors, whereas mature forests showed the highest accuracy when investigated for Tuusula, while this was not as clear for Kättböle, where large area was most important for high accuracy. Since the ultimate goal is to have a method that allows retrieving stem volume for large areas it has to be taken into account that the environmental conditions, e.g. wind speed, can vary on a relatively small scale. For this reason a method without the need for *in situ* data for estimating model parameters has been introduced. In the investigated cases, it has been demonstrated that the estimation of stem volume is characterized by the same accuracy as when the model is trained by means of *in situ* measurements. The technique is based on a method to analyze multitemporal data by means of consistency plots. Such plots could also illustrate for what forest stands the coherence observations are less stable and the expected accuracy worse than for those closer to the ridge in the plots.

Observations using other sensors have been performed for the same test sites as studied here, cf. (Smith and Ulander, 2000; Fransson et al., 2001; Fransson et al., 2004; Magnusson and Fransson, 2004b; Magnusson and Fransson, 2004a). Looking at individual acquisitions, optical images (SPOT and Landsat) are reported to have RMSEr 24 – 38%. In the other end of the frequency range there is CARABAS, an airborne VHF-SAR, with much higher spatial resolution and with RMSEr 19 – 30% excluding stands with small stem volume. Other sensors are based on accurate height observations to determine stem volume and for laser scanning from helicopter the RMSEr for Remningstorp is reported to 19 – 26% on plot level and 11% on stand level (Holmgren, 2003). For standard methods like photo-interpretation, one can find figures in the literature indicating accuracies such as 26 – 39%. The accuracy of *in situ* observations may vary 10 – 34% with a mean of 21.4% cf. (Haara and Korhonen, 2004). Polarimetric SAR interferometry is a technique estimating forest height from the volume decorrelation at different polarizations assuming the temporal decorrelation to be negligible or small (Cloude and Papathanassiou, 1998; Papathanassiou and Cloude, 2001). Flights were made over Remningstorp in 2007 and an L- and P-band as part of the ESA project BIOSAR 2007 (ESA, 2008). For L-band data, the best results reported to our knowledge were obtained using HV-polarized backscatter, giving an RMSEr between 31% and 46%. Using HV- or HH-polarized P-band backscatter or both HV and HH, the RMSEr:s were between 18 and 27% (Sandberg et al, 2011).

Values on RMSEr for other sensors given above apply for individual images and can be expected to improve by multitemporal acquisitions when such are suitable. However, thanks to the multitemporal character of satellite radar acquisitions, C-band repeat pass interferometry becomes an interesting alternative for estimation of stem volume and biomass above ground in boreal forests over large areas with potential of accuracy comparable to standard *in situ* methods, without the need for training data and without showing saturation in the relative accuracy for the investigated areas covering up to 539 m^3/ha or ≈ 265 tons/ha.

For large area studies using ERS tandem coherence the best reported result is given in (Santoro et al., 2007b) obtaining an RMSEr of 30% for two of the ten acquired coherence pairs. (Wagner et al., 2003) used tandem coherence and an exponential model in combination with JERS-1 backscatter to determine stem volume in Siberia. In (Drezet et al., 2006; Drezet, 2007) a set of coherence images over UK with a good coherence range was used. Instead of biomass or stem volume, age was used as variable, and results cannot be compared. Finally, (Cartus et al., 2011) used a large number of images in order to cover large areas in China and Siberia. Environmental unstable conditions caused problems and IWCM, used without training data, but with MODIS VCF data as complement, was in many cases not successful and an exponential model was often preferred. It is concluded that, although a high accuracy in stem volume or biomass estimation can be obtained by short-repeat C-band InSAR data, large scale investigations have had complications due to limitations in the number of data acquisitions for optimal environmental conditions and due to limited access to accurate *in situ* data for verification of the results.

An important aspect is that the result is strongly dependent on the short-repeat pass and on timeliness of acquisitions, which puts demands on the acquisition program and also on a short repeat cycle of such a spaceborne interferometric configuration. Currently there are no plans for configurations similar to the ERS-1/2 tandem period. The ERS-ENVISAT configuration offered some possibility for short repeat cycle (Santoro et al., 2007a) but the very long baseline requirement was a major complication because of the strong volume decorrelation. The 12 day repeat cycle of Sentinel-1A is decreased to 6 days with Sentinel-1B and the temporal decorrelation can be acceptable, since the ERS-1 3-day period was showing good coherence up to at least a 6-day interval for winter conditions (Smith et al., 1996). An interesting alternative may be found using X-band missions with more than one satellite such as Tandem-X or COSMO-SkyMed in pursuit mode. Typically the coherence is decreasing with higher frequencies, but, with the possibility to have two acquisitions within seconds, the ground coherence (contributing through gaps in the canopy) is expected to be very close to one while the vegetation layer should still decorrelate because of foliage movement induced by wind even in a few seconds. The extinction at X-band is higher than at C-band and the effective vegetation layer causing volume decorrelation is thinner, but still the volume decorrelation will add to the temporal decorrelation. This should mean a possibility for high contrast between ground and dense vegetation and therefore a potential for high accuracy of stem volume estimates.

9. Acknowledgment

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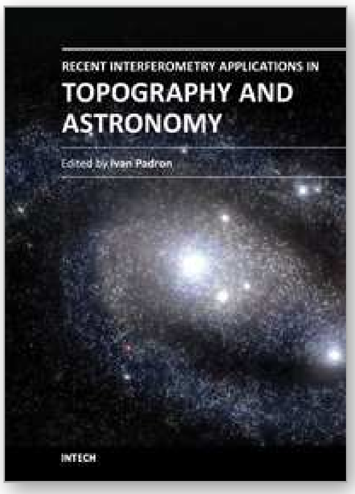

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This book provides a current overview of the theoretical and experimental aspects of some interferometry techniques applied to Topography and Astronomy. The first two chapters comprise interferometry techniques used for precise measurement of surface topography in engineering applications; while chapters three through eight are dedicated to interferometry applications related to Earth's topography. The last chapter is an application of interferometry in Astronomy, directed specifically to detection of planets outside our solar system. Each chapter offers an opportunity to expand the knowledge about interferometry techniques and encourage researchers in development of new interferometry applications.