Multitemporal Repeat-Pass SAR Interferometry of Boreal Forests

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***Abstract*—Multitemporal European Remote Sensing satellites 1 and 2 (ERS-1/2) and the Japanese Earth Resources Satellite 1 (JERS-1) interferometric synthetic aperture radar (InSAR) data from a boreal forest test site in Sweden (stem volumes up to 335 m^3/ha, equivalent to above-ground dry biomass of ∼200 tons/ha) are studied in order to estimate stem volume using coherence and backscatter. The changes of JERS-1 backscatter and ERS-1/2 tandem coherence between images are consistent over the area studied, in contrast to ERS-1/2 backscatter. A model-based regression analysis has been performed, and the use of the model for inversion is discussed and compared with other approaches found in the literature. The model parameters are discussed in terms of their relation to wind speed and temperature. Results from the different acquisitions are combined to improve the stem volume estimation. The accuracy in terms of rms error (RMSE) for standwise estimated stem volume is ≈10 m^3/ha using ERS-1/2 coherence. Using backscatter and coherence from JERS-1 we obtain an RMSE of ≈30–35 m^3/ha. Finally, conditions for accurate retrieval of stem volume using multitemporal InSAR observations are discussed. We conclude that C- and L-band repeat-pass InSAR can provide stem volume estimates in boreal forests with accuracies similar to those of standard *in situ* measurements.**

***Index Terms*—Borel forest, European Remote Sensing satellite (ERS), Japanese Earth Resources Satellite (JERS), interferometric sythetic aperture radar (InSAR), multitemporal.**

I. Introduction

There is an increasing need for forest information related to its importance for the environment and global climate (e.g., monitoring for the Kyoto protocol) as well as forest management aspects. In particular, satellite observations can be useful for environmental studies, since an internationally accepted, consistent, and robust method is required for monitoring on a large scale.

The synthetic aperture radars (SARs) on the European Remote Sensing 1 and 2 satellites (ERS-1/2) and the Japanese Earth Resources Satellite 1 (JERS-1) missions have provided not only the possibility for multitemporal acquisitions independent of clouds but also interferometric SAR (InSAR) observations. This study reports an investigation of the use of multitemporal InSAR data for stem volume retrieval at a boreal forest test site. The interferometric water–cloud model (IWCM) [1], [2] is used for retrieval, and properties of the model are discussed and also compared with other approaches described in the literature. Accurate estimates of stem volume based on field measurements are used for training and testing the model. The data used and the model-based estimation are presented and discussed. Previous results from [3]–[7] are summarized. Finally, the usefulness of C- and L-band InSAR observations of boreal forests are discussed based on experience from two sites, Kättböle (60° N 17° E) in Sweden and Tuusula (60° N 25° E) in Finland.

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II. Test Site and Data

A. Test Site

The test site used for this investigation is 5.5 km^2 in size, and located near Kättböle, Sweden (60° N 17° E) in the southern part of the boreal forest belt. The area is dominated by typical boreal coniferous species, Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*), but some broad-leaf trees are also present, the commonest being birch (*Betula pendula*). Till is the dominating soil type. The topography is relatively flat varying between 75 and 110 m above sea level.

In 1995 and 1996, an inventory was carried out, and accurate estimates of forest stem volume, determination of tree species, etc. were made [6]. Data from 42 forest stands were used in this study. A stand is the primary inventory unit in forested areas and consists of relatively homogeneous forest in terms of tree cover and site conditions. Stand boundaries can also be defined by obstacles such as rivers or steep slopes. Forest properties of each stand have been determined by measuring trees in a number of randomly located circular plots, each with a 10-m radius (approximately ten plots per stand, but the exact number varying depending on stand size and shape). The diameter at breast height (1.3 m above the ground) was measured for all trees on each plot, and for randomly selected sample trees, chosen with a probability proportional to basal area, tree heights were also measured. From these measurements, allometric equations were used to calculate the average stem volume at stand level. Stem volume is the volume of the tree trunks, including bark but excluding branches and stumps, per unit area (cubic meters per hectare), and related to above-ground dry biomass, which can be estimated as approximately 0.6 × stem volume for boreal forest, e.g., 100 m^3/ha ≈ 60 tons/ha [8]. The 42 stands are characterized by stem volumes (with an estimated 18% standard error at stand level) varying between 8 and 335 m^3/ha (mean 140 m^3/ha) and areas ranging from 2–14 ha in size. The species percentage for pine, spruce, and

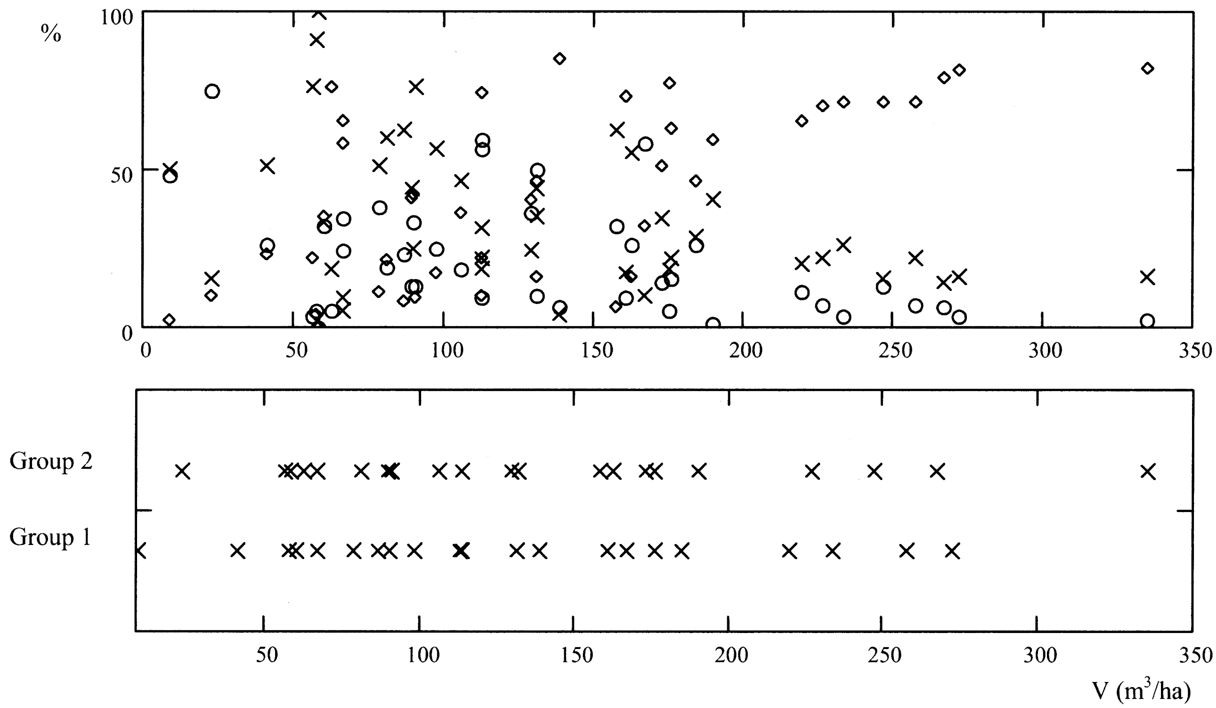

Fig. 1. Illustrating the percentage occurrence of different tree species (pine: marked by crosses, spruce: diamonds and birch: circles) for stands with different stem volumes (upper part). The forest stands were divided into two groups by choosing every other stand when sorted by stem volume (as indicated in the lower part of the figure).

TABLE I
ERS-1/2 RESULTS. MULTITEMPORTAL APPROACH USING THE FOUR BEST COHERENCE IMAGES: RMSE = 10.0 m^3/ha (RMSE CORRECTED FOR *IN SITU* SAMPLING ERRORS FROM [7])

Dates of ERS-1/2	Baseline m	RMSE m^3/ha
$11^{th}/12^{th}$ June 1995	86	151.5
$16^{th}/17^{th}$ July 1995	16	123.8
$20^{th}/21^{st}$ August 1995	75	88.5
$24^{th}/25^{th}$ September 1995	219	73.6
$29^{th}/30^{th}$ October 1995	18	96.9
$12^{th}/13^{th}$ March 1996	218	20.9
$17^{th}/18^{th}$ March 1996	66	38.4
$16^{th}/17^{th}$ April 1996	74	35.8
$21^{st}/22^{nd}$ April 1996	55	35.6

birch are illustrated together with the distribution of stem volumes in Fig. 1. Spruce is the dominant species, particularly for stands with stem volumes greater than 200 m^3/ha. The fraction of the area covered by the canopy, the "area fill," has been determined by upward looking photography for some of the stands (see [7] and [9]).

B. ERS-1/2 SAR Scenes

Nine ERS-1/2 tandem pairs (ascending and descending) from 1995 and 1996 with baselines perpendicular to the range direction varying from 16–218 m have been analyzed (see Table I). The scenes cover approximately a full year. Radar backscatter and coherence for the 42 forest stands are illustrated in Fig. 2(a) and (c) for the acquisitions on March 12 and 13, 1996.

C. JERS-1 SAR Scenes

The JERS-1 dataset consists of nine descending-pass observations from 1997 and 1998 [see Table II(a)]. The scenes cover more than a full year. The coherence has been investigated for four pairs [see Table II(b)], with baselines varying from 170 to 1088 m. The analysis includes two pairs with 44 days between the acquisitions of the images, one with 88 days and one with 176 days. Radar backscatter and coherence for the 42 forest stands are illustrated in Fig. 2(b) and (d) for the acquisitions of April 15 and May 29, 1998.

D. Meteorological Data

Meteorological data in the form of temperature, wind speed and direction, precipitation, and snow depth were obtained from meteorological stations located close to the test site. From the meteorological data, we may divide the ERS-1/2 scenes in two groups: stable weather conditions (both pairs from March 1996, August 1995, and the second pair from April 1996) and changing weather conditions [June, July, September 1995 (all affected by rain), October 1995, and the first pair from April 1996 (affected by freezing and thawing)]. Similarly, we find that the two JERS-1 InSAR pairs with a 44-day interval are represented by unstable weather conditions for both image pairs (April 15/May 29, 1997: ≈ 0 °C/+6 °C and some precipitation, no snow on the ground in either case; January 4/February 17, 1998: +2 °C and rain/−2 °C and some precipitation, no snow on the ground in either case).

III. DATA ANALYSIS AND DATA CONSISTENCY

The InSAR processing was carried out using the European Space Agency (ESA) ISAR and the Centre National d'Etudes

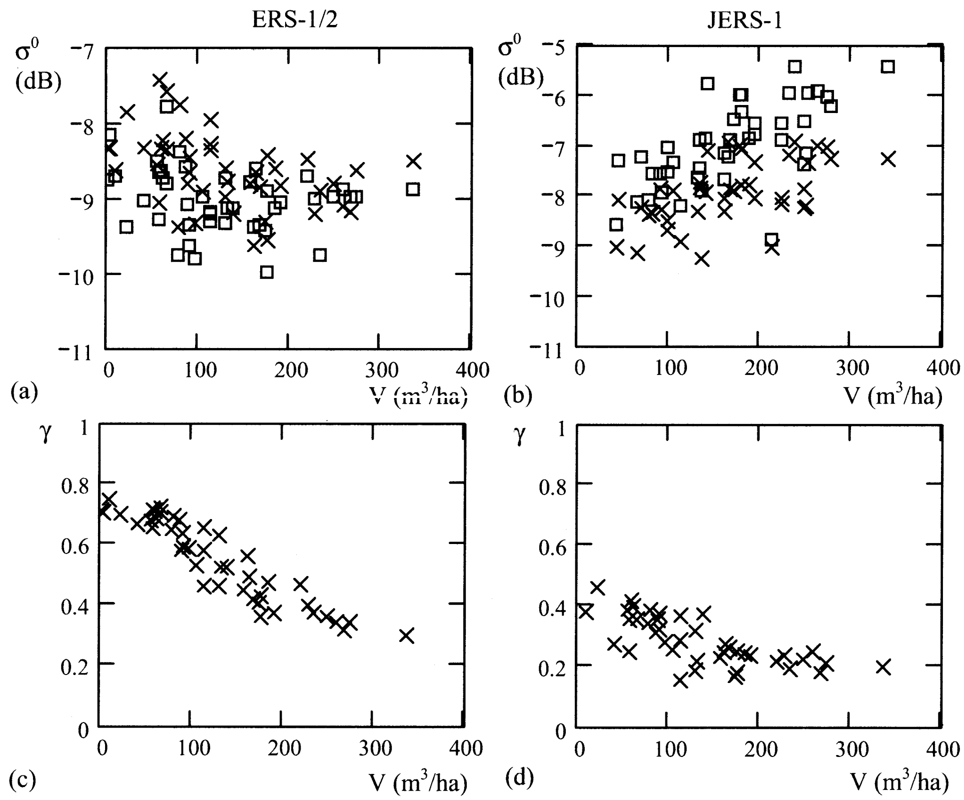

Fig. 2. Observations from ERS-1 and ERS-2 on March 12 and 13, 1996 and JERS-1 on April 15 and May 5, 1997 plotted as a function of stem volume for the 42 forest stands in Kättböle. (a) ERS-1/2 backscatter, (b) JERS-1 backscatter, (c) ERS-1/2 coherence, and (d) JERS-1 coherence.

Spatiales (CNES) DIAPASON software packages, as well as internally developed software. The coherence was estimated using

$$\hat{\gamma} = \sum_{i=1}^{N} g_{1,i} g_{2,i} e^{-j\varphi_i} \Big/ \sqrt{\sum_{i=1}^{N} |g_{1,i}|^2 \sum_{i=1}^{N} |g_{2,i}|^2} \qquad (1)$$

where $g_{1,i}$ and $g_{2,i}$ are pixel values representing the backscatter amplitudes in the first and second image; φ_i is the phase from the differential phase image; and N is the number of pixels within the estimation window. The window size in the ERS-1/2 case was set to 5 × 25 pixels in range and azimuth, and in the JERS-1 case to 7 × 21 pixels or approximately 100 × 100 m^2 in both cases. For further details on the InSAR processing, see [5].

The backscatter and coherence were averaged over each forest stand after exclusion of a small boundary region in order to avoid localization errors. In the remainder of this paper, we focus on the backscatter and coherence values described as functions of the average stem volume of each forest stand. Since the stand sizes vary from 2–14 ha, the standard error of the backscatter measurements due to speckle vary between 0.2–0.4 dB, and the standard error for the coherence values are between 0.03–0.07. We have concentrated on the dependence on stem volume, since it is the single most important parameter characterizing the forests for use in different applications. However, the backscatter and coherence values depend on several forest parameters (leaves/needles, branches, gaps in the canopy, etc.) as well as on several meteorological parameters (moisture, temperature, and wind, etc.). Scattering associated with these different forest parameters may be sensitive to the meteorological variations in different ways.

The change in backscatter and coherence between the different acquisitions was investigated by studying the correlation between the different observations of the 42 forest stands. The correlation indicates the degree to which the backscatter and coherence change consistently (i.e., whether the relationships between measurements from different stands are consistent), which may be related to the robustness of using backscatter and coherence to characterize stem volume. We find that the ERS-1/2 backscatter values for different acquisitions vary inconsistently from one image to another, which may be due to temporal change or speckle "noise." The Pearson correlation coefficient (r) was typically less than 0.3. From the 18 image acquisitions, there were only seven cases (out of 153 combinations) where the pairwise correlation coefficient was above 0.6, and of these only three cases where the time difference between the acquisitions was one day. In comparison, we find that the ERS-1/2 coherence values change much more consistently. From nine coherence images we formed 36 combinations. For 17 combinations, we obtained $r > 0.6$ (and $r > 0.8$ for 11 of those). An illustration of this is given in Fig. 3.

Looking at JERS-1 the picture is different. Here the correlation coefficient between the backscatter for the nine acquisitions is generally of the order of 0.8 (only in one case as low as 0.57) and although the backscatter level may vary, the relationships between stands is quite well preserved (i.e., stands with high backscatter in one image are more likely to have high backscatter in a second). Since only one interferogram

TABLE II
JERS-1 RESULTS (RMSE CORRECTED FOR *IN SITU* SAMPLING ERRORS). (a) BACKSCATTER, (b) COHERENCE, (c) MULTITEMPORAL APPROACH: RMSE (m^3/ha) FOR ESTIMATES OF STEM VOLUME USING COMBINATIONS OF DIFFERENT NUMBERS OF BACKSCATTER (σ) AND COHERENCE (γ) IMAGES

Dates of JERS-1	RMSE m^3/ha [1)]	RMSE m^3/ha [2)]
15th April 1997	48.6	83.5
29th May 1997	36.5	67.0
12th July 1997	42.3	95.1
9th October 1997	45.7	63.1
4th January 1998	80.1	140.1
17th February 1998	68.1	72.0
2nd April 1998	85.4	111.3
16th May 1998	51.8	88.2
12th August 1998	46.4	69.5

1) training on Group 1, testing on Group 2
2) training on Group 2, testing on Group 1

(a)

Dates of JERS-1	Baseline m	RMSE m^3/ha [1)]	RMSE m^3/ha [2)]
15th April /29th May, 1997	218	61.3	54.0
4th January/17th February, 1998	170	3)	3)
17th February/16th May, 1998	1088	3)	3)
17th February/12th August, 1998	748	3)	3)

1) training on Group 1, testing on Group 2
2) training on Group 2, testing on Group 1
3) coherence image not possible to form (too low coherence)

(b)

training group	RMSE m^3/ha 3σ	RMSE m^3/ha $3\sigma + 1\gamma$	RMSE m^3/ha 9σ	RMSE m^3/ha $9\sigma + 1\gamma$
training on Group 1	33.5	27.2	36.4	32.2
training on Group 2	62.9	38.0	59.0	49.8

(c)

was formed with JERS-1 data a consistency analysis between different coherence observations was not possible.

Dividing the stands in two groups with 21 stands with stem volumes below and above 120 m^3/ha, respectively, we find{a lower correlation between C-band backscatter from the low stem volume stands than between the high stem volume stands. For L band we find no such difference. This could be explained by the C-band backscatter from stands with low stem volumes being dominated by the scattering from the ground, which shows greater temporal variation than the scattering from dense forest canopies [10]. At L band, the vegetation backscatter dominates even at low stem volumes, and hence the total backscatter shows less temporal variability.

We conclude that the JERS-1 backscatter and ERS-1/2 tandem coherence from the 42 forest stands change in a consistent manner in spite of varying meteorological conditions. This is in contrast to ERS-1/2 backscatter.

IV. MODEL FOR ANALYSIS

A. IWCM

Any model to be used for inversion is a compromise between a small number of parameters describing the most essential phenomena and a large number of parameters describing the phenomena in more detail. In a "simple" model "effective" parameters represent complex phenomena. Still these model parameters can yield information on details in the scattering process.

For radar backscatter from a boreal forest a simple model in line with the water–cloud model [11] but with the extinction in the forest depending on stem volume (V) is given by [12]

$$\sigma^0_{\rm for} = \sigma^0_{\rm gr} e^{-\beta V} + \sigma^0_{\rm veg}(1 - e^{-\beta V}). \tag{2}$$

This result is based on C-band helicopter-borne scatterometer measurements. For boreal forest, the same expression has been found valid at L band, cf. [13]. The contribution from the ground surface ($\sigma^0_{\rm gr}$) and the contribution from the vegetation layer ($\sigma^0_{\rm veg}$) could be separated in the scatterometer measurements, and it was found that the two-way forest transmissivity was exponentially related to stem volume with the coefficient, β. The forest transmissivity is interpreted in [1] and [2] as caused not only by radiation going back and forth through the canopy, but also from radiation going through gaps of the canopy. The "area fill" (η) was introduced, describing to what extent the canopy fills the resolution cell, and $1-\eta$, to what extent the resolution cell is described by gaps in the canopy. The canopy transmissivity, i.e., the two-way attenuation through the canopy with height h (forest height and canopy height are considered equal), is determined by $\exp(-\alpha h)$, where α is the canopy transmissivity coefficient. As an alternative to (2) we can then describe $\sigma^{\rm o}_{\rm for}$ by means of

$$\sigma^0_{\rm for} = \eta \left[\sigma^0_{\rm gr} e^{-\alpha h} + \sigma^0_{\rm veg}(1 - e^{-\alpha h})\right] + (1-\eta)\sigma^0_{\rm gr}. \tag{3}$$

We find (2) and (3) to be identical when

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

The forest transmissivity [$\exp(-\beta V)$] is then understood as the result of two contributions, the gaps and the canopy transmissivity, i.e., we have introduced one parameter for the horizontal and one for the vertical variation of the forest. In the case of C-band observations we believe that the canopy transmissivity is small and that the main scattering is coming from the treetops. This means that β is mainly determined by the gaps in the vegetation, i.e., by the area fill. Equation (3) has consequences for the interpretation of the influence of canopy moisture and also on the difference between having scatterers homogeneously or inhomogeneously horizontally distributed due to differences in the penetration depth. Consequences for L band will be described below.

The complex coherence can be divided in a number of different contributions, of which some are either negligible or may be corrected by appropriate data processing [2]. One of these effects is the baseline decorrelation, which has been corrected for in the case of surface scattering [14]. When the scattering occurs from a volume where the scattering varies only with height (i.e., the volume may be represented as a layered medium), the

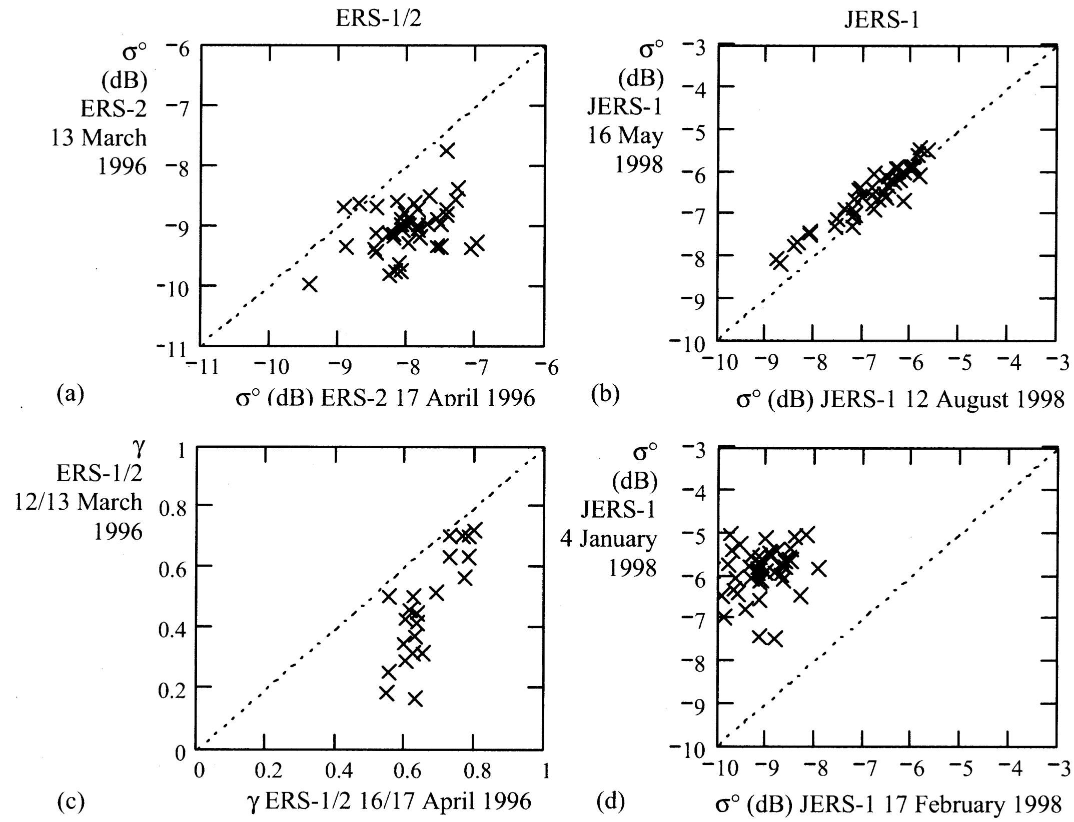

Fig. 3. Illustrating backscatter and coherence for 42 forest stands in Kättböle observed at two occasions. Note that the 42 observed values are averaged over forest stands with sizes varying between 2 and 14 ha. (a) ERS-2 backscatter from March 13, 1996 compared to April 17, 1996 (with correlation coefficient (r) of 0.33), (b) JERS-1 backscatter from May 16, 1998 compared to December 8, 1998 ($r = 0.94$), (c) ERS-1/2 coherence from March 12/13, 1996 compared to April 16/17, 1996 ($r = 0.82$, and for the associated ERS-1/2 backscatter pairs $r = 0.61$ and 0.60, respectively), and (d) JERS-1 backscatter from January 4, 1998 compared to February 17, 1998 ($r = 0.57$).

effect of volume decorrelation (γ_{volume}) and temporal vegetation coherence (γ_{veg}) can be described by [2]

$$\gamma_{\text{volume}}\gamma_{\text{veg}} = \int_0^h \sigma^0_{\text{ve}}(z')e^{-jK_z z'}\,dz' \bigg/ \int_0^h \sigma^0_v(z')\,dz' \tag{5}$$

where $K_z = 4\pi B_n/(\lambda R \sin\theta)$, B_n is the normal component of the baseline, θ the incidence angle, λ the wavelength, and R the distance to the scatterers. $\sigma^0_v(z')$ denotes the volumetric backscattering coefficient for the two passes (assumed to be equal), and $\sigma^0_{\text{ve}}(z')$ is the volumetric backscattering coefficient for stable scatterers for the two passes. We could express $\sigma^0_{\text{ve}}(z')$ as $\gamma_{\text{ve}}(z')\sigma^0_v(z')$ where $\gamma_{\text{ve}}(z')$ represents the fraction of stable scatterers.

The factor $\exp(-jK_z z')$ complicates (5), and we will first neglect this factor, i.e., assuming zero baseline. We have two independent types of scatterers within the resolution cell associated with the ground surface on one hand and the vegetation layer on the other. The forest coherence (γ_{for}) is then determined by the normalized value for the stable parts of each type of scattering weighted by the backscatter intensity, i.e.,

$$\gamma_{\text{for}} = \frac{\gamma_{\text{gr}}\sigma^0_{\text{gr}}e^{-\beta V} + \gamma_{\text{veg}}\sigma^0_{\text{veg}}(1 - e^{-\beta V})}{\sigma^0_{\text{for}}} \tag{6}$$

where γ_{gr} and γ_{veg} represent the temporal coherence for ground and vegetation (or alternatively the fractions of stable scatterers), respectively.

However, for $K_z \neq 0$ some of the scattering from the forest comes from different heights within the canopy and hence is associated with phase shifts. For simplicity we may assume that the stability is constant with height as is the number density of scatterers. The variation of the scattering is then determined by a single parameter, the penetration depth, i.e., $\sigma^0_v(z') \propto e^{-\alpha(h-z')}$, and we obtain

$$\gamma_{\text{volume}}(B_n, h, \alpha) = \frac{\alpha}{\alpha - jK_z}\,\frac{e^{-jK_z h} - e^{-\alpha h}}{1 - e^{-\alpha h}} \approx e^{-jK_z(h-1/\alpha)} \tag{7}$$

where the approximation is correct only if α is large [15]. From (7), we see that γ_{volume} depends on the actual scattering, i.e., on α. These assumptions are of course simplifications compared to the true variation of the scattering, as measured e.g., in [16], and with the true stability varying with height. However, in [17] it was indicated that the interferometric effective height seemed to be determined by the actual height corrected by the penetration depth, i.e., as given as an approximation in (7). Taking the volume decorrelation into account the expression for the complex forest coherence is given by

$$\gamma_{\text{for}} = \frac{\gamma_{\text{gr}}\sigma^0_{\text{gr}}e^{-\beta V} + \gamma_{\text{veg}}\sigma^0_{\text{veg}}(1 - e^{-\beta V})\gamma_{\text{volume}}}{\sigma^0_{\text{for}}}. \tag{8}$$

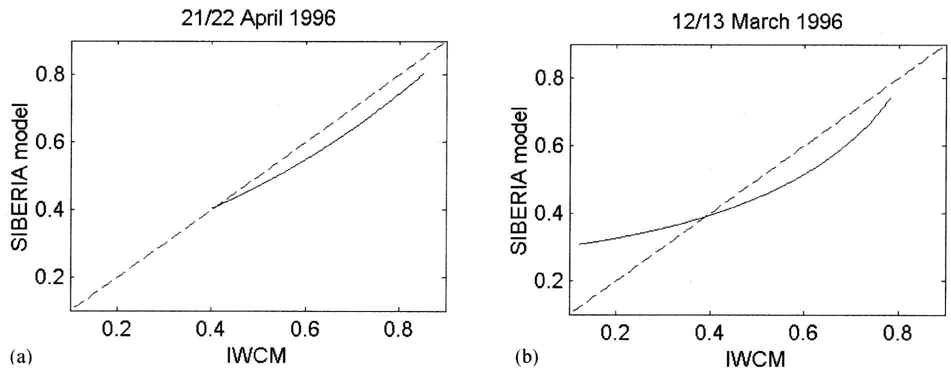

Fig. 4. Illustrating values for coherence as derived from IWCM and from model used in the SIBERIA project. (a) Short baseline case ($B_n = 55$ m). (b) Long baseline case ($B_n = 218$ m).

In (3), the area fill concept is only of importance for the interpretation of the transmissivity, but for (8) α as well as β (and therefore the area fill) are involved.

The so-called IWCM (8) was, in principle, derived in [1] and [2], where special height variations of the scattering and the stability of scatterers were assumed. From (8), the repeat-pass interferometric forest height can also be determined from the phase of the complex coherence, but experience has shown that the interferometric height is very sensitive to spatial variations of the atmospheric delay and is of limited use for estimating stem volume [15].

For the forest height included in (7) we use an allometric expression, which has been found to apply for other boreal forest areas as well [2], [4] (Hökmark in Northern Sweden, and Tuusula in Southern Finland)

$$h = h(V) = (2.44 \cdot V)^{0.46}. \tag{9}$$

Expression (5) is not sensitive to the exact relation $h(V)$, since temporal decorrelation dominates over volume decorrelation. Errors caused by the approximations in (9) are then expected to be small. Furthermore, typical values for α and η may be considered for boreal forest. For ERS-1/2, α is typically high and η is not very sensitive to the exact value. Thus, if α is assumed known we can estimate the area fill from (4) based on observations of β. For JERS-1 α can then be derived assuming the same area fill as for ERS-1/2 (since the area fill is determined by the forest structure, and the variation due to the different incidence angles of the satellites is relatively small). The remaining unknown parameters are then $\sigma_{\rm gr}$, $\sigma_{\rm veg}$, β, $\gamma_{\rm gr}$, and $\gamma_{\rm veg}$. Due to the temporal variations of the observations of backscatter and coherence the model parameters have to be determined for each acquisition, which we have done by fitting the model to a training set of forest stands with known stem volumes.

When the model parameters have been determined the inversion of observations from the unknown stands is performed. From (2), it is simple to express V as a function of $\sigma^0_{\rm for}$, but the presence of the volume decorrelation in (8) prevents an analytic solution for coherence. However, a simple way to invert (8) is first to introduce the following expression with $\gamma_{\rm tree} = \gamma_{\rm veg}\gamma_{\rm volume}$

$$\hat{\gamma}_{\rm for} = \gamma_{\rm gr} e^{-\mu V} + \gamma_{\rm tree}(1 - e^{-\mu V}). \tag{10}$$

Equation (10) agrees with (8) for extreme values of V. For the range of V of interest, we minimize the difference between (8) and (10) using the values for $\gamma_{\rm gr}$, $\gamma_{\rm veg}$, and $\gamma_{\rm volume}$ determined previously. This minimization determines the value on μ, which will be dependent on the baseline. Equation (10) can now be used directly to invert from coherence values to stem volume in a similar manner to that for inversion of backscatter measurements.

B. Other Model Approaches

Several different models have been proposed in the literature for the relationship between coherence and stem volume, and in this section we compare them to (8). If we neglect the volume decorrelation we would obtain (6), which was recently proposed in [18] by means of regression analysis. If $\sigma^\circ_{\rm for}$ also had been constant, irrespective of stem volume, we would obtain an exponential variation of the coherence as function of stem volume. An expression of the same form as (10) has been used in the SIBERIA project [19], with parameters estimated from a histogram analysis of coherence observations.[1] None of these models give the possibility to correct for volume decorrelation caused by variations of forest height and interferometric baseline, the latter being a system effect necessary to take into account in order to make results comparable. As regression models any of these two expressions may be equally good due to the typical noisiness of the data, but $\gamma_{\rm veg}$ is then to be considered as a regression coefficient with no physical meaning. For example, in the case illustrated in Fig. 2(a) and (c) we have $B_n = 218$ m. If we neglected the volume decorrelation term, we would have obtained a negative value of the temporal vegetation decorrelation, which is unphysical [7]. When the model in [19] was applied using forested pixels only, some discrepancies between the modeled curves were found. These are most evident for large baselines, as shown in Fig. 4.

Treuhaft *et al.* [20] and [21] present a detailed analysis related to (single pass) interferometric polarimetric SAR. This application has been investigated in a number of papers [22], [23] using an expression of the form (neglecting the phase term related to ground topography)

$$\gamma = \frac{\gamma_{\rm volume} + m}{1 + m} \tag{11}$$

[1] See http://www.siberia1.uni-jena.de/

where m is the effective ground-to-volume magnitude ratio determined from measurements. We obtain agreement with (8) if

$$m = \frac{\sigma^0_{\rm gr} e^{-\beta V}}{\sigma^0_{\rm veg}(1-e^{-\beta V})} \quad \text{and} \quad \gamma_{\rm gr} = 1 = \gamma_{\rm veg}. \tag{12}$$

In the polarimetric case, the expression is different for the three polarizations, and with certain assumptions, there is a possibility to invert the expression and not use a training dataset as in the repeat-pass case.

Finally, developments of interferometric model aspects aiming at various sensitivity analyses, etc. can be carried out starting from tree growth models in combination with scattering theories, e.g., see [16] and [24]–[27].

V. Model Parameters and Decorrelation Mechanisms

From the model (8), we conclude that the coherence will show a large dynamic range and, hence, give good possibility for inversion, as long as the ground decorrelation is low and the vegetation decorrelation is high. A certain baseline, 100–200 m for ERS-1/2, will also decrease the coherence values typical for the maximum stem volumes considered here for boreal forests, i.e., approximately 350 m^3/ha, and improve the potential for stem volume estimates.

The temporal coherence factors associated with the vegetation layer and the ground are related to different time scales. A vegetation layer is sensitive to changes in the position of scatterers caused by wind. Since leaves/needles and small branches in the treetops are very unstable, the stable scattering is assumed to be caused by slightly larger branches reached by the radiation through gaps in the vegetation. While the temporal stability of the vegetation may depend on the height of the vegetation, and the fraction of large branches, we believe that the decorrelation of the major scatterers at C band is usually almost complete for all but the smallest trees. Hence, we assume, that the temporal vegetation coherence ($\gamma_{\rm veg}$) is independent of stem volume. However, the relative importance of the vegetation contribution in (8) increases as stem volume increases, since the ground contribution is more strongly attenuated. This is also the situation for the changes in the relative contributions to the total backscatter. However, the coherence is more useful for stem volume retrieval than backscatter intensity at C band because the difference between the vegetation and the ground contributions is higher, and hence more often significant, for coherence than for backscatter [28]. Low temperatures (<0 °C) over sufficient time periods will freeze the water content in the forest canopy, and then increase the penetration through the vegetation layer and decrease the effect of the vegetation layer. However, based on a study of the meteorological data, this is not believed to be the situation for the measurements from Kättböle.

For the ground, changes in the soil moisture distribution within a resolution cell, are considered to be a major effect causing temporal decorrelation [29]. The variation of the soil moisture is caused mainly by variation of the porosity of the soil and the depth to the groundwater table and varies considerably due to soil properties, root concentration, and small-scale topography. When the ground is frozen, scattering caused by free water will disappear, and the ground coherence can be expected to increase. A snow layer on the ground may keep the understorey vegetation stable in spite of the wind. However, strong winds may change the distribution of snow and cause decorrelation.

VI. Results for Model Parameters

A. ERS-1/2 Observations

Model parameters for each interferometric pair were determined in [7]. The quadratic difference between the observed and the predicted values from (2), and (8), was minimized in an iterative manner using all 42 forest stands. Since the coherence values have a smaller random variation compared to the total dynamic range, they are most useful for inversion. Some approximate values for $\sigma^0_{\rm gr}$ and $\sigma^0_{\rm veg}$ were first assumed and used in (8) from which β, $\gamma_{\rm gr}$, and $\gamma_{\rm veg}$ were derived assuming $\alpha = 2$ dB/m. The value obtained for β was then used in (2) to derive $\sigma^0_{\rm gr}$ and $\sigma^0_{\rm veg}$, after which the procedure was repeated until the parameter values converged, typically using two iterations.

The results for $\sigma^0_{\rm gr}$ and $\sigma^0_{\rm veg}$, $\gamma_{\rm gr}$ and $\gamma_{\rm veg}$ are illustrated in Fig. 5(a) and (c). The nine pairs cover almost a full year, but are considered too few to draw conclusions regarding seasonal variations of the backscatter due to the high sensitivity to short-term meteorological conditions. The coefficient β was found to be relatively constant. Excluding one outlier from June 11/12, 1995 we obtained $\beta = 0.0064 \pm 0.0012$. The temperature interval was -4.5 °C to 19.5 °C, and the wind speed varied from 0–4 m/s. To investigate changes of the parameters with time, we calculated their correlation coefficient to temperature and wind speed, with significant correlation found only between $\gamma_{\rm gr}$ and $\gamma_{\rm veg}$, $\gamma_{\rm gr}$ and β, $\gamma_{\rm veg}$ and wind, and $\sigma^0_{\rm veg}$ and temperature. The correlation coefficient between $\sigma^0_{\rm veg}$ and temperature was found to be 0.86 [see Fig. 6(a)], showing a increase of $\sigma^0_{\rm veg}$ when temperature increases. This may be related to increased evapotranspiration and water content of the main scatterers at higher temperatures. To explain the correlation between $\gamma_{\rm veg}$ and wind, we assume that $\gamma_{\rm veg} = e^{-(2k\delta_{\rm rms})^2/2}$ with $k = 2\pi/\lambda$ and $\delta_{\rm rms}$ is the rms shift due to motion of the scatterers along the line of sight to the satellite [30]. We found a correlation coefficient of 0.71 between $\delta_{\rm rms}$ and the maximum wind speed measured at the two acquisitions for each of the ERS-1/2 tandem pairs [see Fig. 6(c)]. This is in line with the assumption that wind causes decorrelation of the vegetation layer, and the results would indicate complete decorrelation of the vegetation layer at approximately 4 m/s. A similar indication of the effect of wind is reported in [31].[2] Effects of wind on coherence are also reported in [32], illustrating the sensitivity to wind direction due to wind shadows related to the topography.

B. JERS-1 Observations

Since the backscatter observations are relatively noisy a three-parameter fit between the observed and the predicted values from (2) was not used for each of the acquisitions. Instead it was assumed that β is the same for all acquisitions. $\sigma^\circ_{\rm gr}$ and $\sigma^\circ_{\rm veg}$ were determined for each observation of the 42

[2]See http://www.estec.esa.nl/ceos99/abstracts/a00152.html

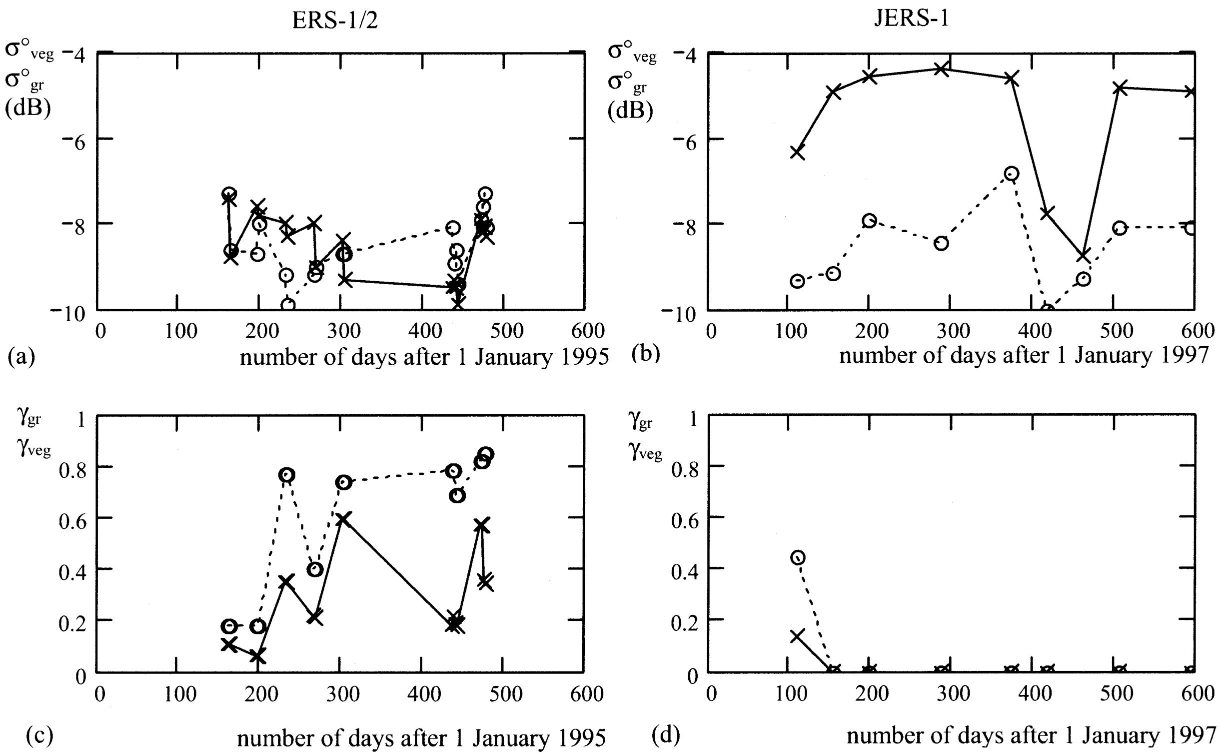

Fig. 5. Variations of model parameters (x for vegetation value, o for ground value) describing ERS-1/2 and JERS-1 backscatter and coherence over a period of approximately 500 days. (a) ERS-1/2 backscatter, (b) JERS-1 backscatter, (c) ERS-1/2 coherence, and (d) JERS-1 coherence.

stands for a range of β-values. Then the quadratic difference between observations and model predictions from (2) for all the observations was determined, and finally β was determined by minimizing the quadratic difference. Using this approach, we obtained $\beta = 0.004$, and the results for σ^0_{gr} and σ^0_{veg}, γ_{gr} and γ_{veg} are illustrated in Fig. 5(b) and (d). Since the area fill (η) depends mainly on the forest properties, the results obtained for ERS-1/2 were also used for JERS-1 (i.e., assuming the changes due to the incidence angle and wavelength differences are negligible). α can then be determined using (4), giving a value of ≈0.5 dB/m (i.e., approximately the ERS-1/2 extinction scaled linearly by wavelength). The values derived for α and β were used together with (8) to determine γ_{gr} and γ_{veg} from the coherence observations. Using these values, the model given by (10) was fitted to the measurements, with a minimum RMSE found with $\mu \approx 1.75\beta$ for one coherence image (with a baseline of 218 m). The difference between μ and β shows a different stem volume dependence of coherence and backscatter. In Fig. 6(b), the variation of $\sigma^{\circ}_{\text{veg}}$ with temperature is illustrated, and $\sigma^{\circ}_{\text{veg}}$ was found to increase for temperatures around 0 °C.

VII. Retrieval of Forest Stem Volume

For details of the ERS-1/2 retrieval of stem volume, see [7]. In order to determine model parameters and analyze the influence of meteorological parameters we used all the 42 stands. For studying the possibility of stem volume retrieval, we divided the stands into two groups, Group 1 and Group 2, consisting of every other stand in a list where all the stands were sorted by stem volume. In this manner, a similar set of stem volumes are included in each group. The training group was used to derive the model parameters, and the test group was used to estimate the accuracy of stem volume retrieval based on these parameters. Since the models used are essentially exponential, they approach an asymptotic limit, and in some cases the observation values fall outside of the range covered by the model curve. In these cases a strict inversion of the model would result in either infinite or negative stem volumes, both of which are unphysical. Therefor, the estimates for these stands were arbitrarily set equal to the maximum in the training set or zero respectively. This strategy affects the retrieval accuracy, since the maximum values in the two groups are different [see Fig. 1(a)]. Hence, it is important to have two sets with as similar properties as possible. To illustrate this, the training and test sets were interchanged in the JERS-1 case and differences analyzed (see Table II).

To assess the accuracy of the stem volume retrieval, the rms error (RMSE) was calculated according to

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\hat{V}_i - V_i)^2 - 0.5\frac{1}{n}\sum_{i=1}^{n}(\text{SE}_i)^2} \qquad (13)$$

where n is the number of stands in the test dataset, and $\hat{V}_i$ and V_i are the retrieved stem volumes and the stem volume estimated from field measurements respectively for the ith stand. The second term takes into account the sampling errors, where SE_i is the simple random sampling standard error for the ith stand, and the factor 0.5 is a correction due to the systematic sampling design [33]. The square root of the second term in (12) was estimated to be 14.6 m^3/ha. A multitemporal combination of the different image pairs, where each pair was weighted by the RMSE, was performed as described in [7].

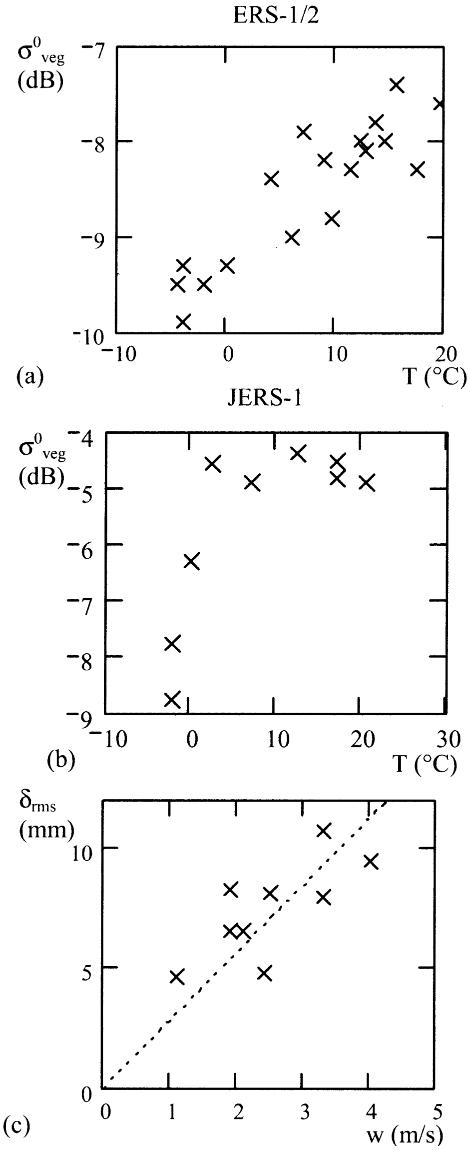

Fig. 6. Relation between model results for $\sigma^\circ_{\rm veg}$ for ERS-1/2 and JERS-1 and temperature, and between ERS-1/2 $\gamma_{\rm veg}$ and wind speed, w. (a) ERS-1/2 $\sigma^\circ_{\rm veg}$, (b) JERS-1 $\sigma o_{\rm veg}$, and (c) ERS-1/2 $\gamma_{\rm veg}$ ($\delta_{\rm rms}$ represents rms scatterer location).

The ERS-1/2 results from the test dataset are presented in Table I as given in [7]. In practice, only the coherence observations of the four best ERS-1/2 image pairs contribute to the multitemporal result. In this case the RMSE, corrected for the sampling error was 10 m^3/ha. If instead of using 21 forest stands, we would have used the individual 216 forest plots (7–10-m radius) in the testing dataset, we would obtain an RMSE of 55 m^3/ha [7]. This illustrates the importance of averaging over forest stands due to the resolution of the coherence estimates and the variability of the forest, as well as geometric localization errors.

The JERS-1 results are presented in Table II. Results from the multitemporal combination of stem volume estimates using all available images show a relatively small improvement compared to the best individual estimate. As an alternative to using all the images it is possible to select those which provide the best stem volume retrieval. The selection rule is based on the saturation in the backscatter (or similarly for coherence) as function of stem volume, $V_{\rm sat}$, defined by

$$\left.\frac{d\sigma^0_{\rm for}}{dV}\right|_{V_{\rm sat}} = \frac{\Delta\sigma}{\Delta V} \tag{14}$$

(or equivalently for the coherence values). The left-hand side is determined from the model curve fitted to the training data. $\Delta\sigma$ is the standard deviation about the model curve, and ΔV is an arbitrary change of stem volume, here chosen to 50 m^3/ha. The three best estimates based on backscatter were combined with the single estimate based on coherence to give the best RMSE [see Table II(c)].

VIII. Discussion and Conclusions

We have described a model for inversion of InSAR data, analyzed the sensitivity of observations to meteorological parameters, and evaluated stem volume retrieval using InSAR data for a test site from which we have accurate field measurements. High accuracy of stem volume estimates from *in situ* data is crucial for verification of InSAR data, and data modeling, but is not very often available due to the cost of such inventory.

The test site studied is typical for forest areas in the central part of Sweden, but the method for analysis probably applies also for northern areas, where the stem volume is lower [34]. We believe that the forest structure and then also the forest management practice may be important for the results, since the gaps in the forest play an essential role. For this reason the results cannot easily be extended to nonboreal forests.

The analysis has concentrated on the Kättböle test site, since the *in situ* data were believed to be best from this area. However, for conclusions regarding the potential of interferometric SAR for boreal forest stem volume estimation, it is important to compare results with other boreal sites, since the forest as well as meteorological conditions may be different. The results reported in [3] from the Tuusula test site in Finland show that the RMSE for stem volumes estimated from ERS-1/2 coherence are not particularly good, while values derived based on JERS-1 intensity are similar to those obtained from Kättböle. The ERS-1/2 ground coherence values were sometimes low for the Tuusula cases due to unstable weather conditions, but like Kättböle there were two cases (March 2/3 and March 29/30, 1996) with relatively high ground coherence. At the time of acquisition, the temperature was below 0 °C, and there was a snow layer covering the ground. Based on these conditions we expect that the stem volume estimation should be quite accurate. However, in the first of these two cases light snowfall occurred between the acquisitions and in the second there was heavy snowfall. Snow on the trees may damp wind induced motions and increase the vegetation coherence. In the first case the temperature was consistently below 0 °C the preceding week, which may influence the vegetation penetration through freezing of the canopy. In the second case we had temperatures varying between ±10 °C during day and night, i.e., large freeze/thaw changes, which will affect the scattering from snow on the vegetation and the ground (the snow layer on the ground was 35–40 cm). Since the area fill concept is of importance for the coherence, one possible explanation for the differences between results from Kättböle and Tuusula is that the relationship between area fill and stem volume appears to be less pronounced in Tuusula than in Kättböle [28]. In spite of this, we believe that the meteorological conditions are the major reason for not obtaining a sufficient span of coherence values, although the limited number of acquisitions available prevent us from reaching a definite conclusion. Since weather patterns in Scandinavia often change over periods of 4–6 days, shorter repeat cycles are favorable for stable conditions. Finally, it can be noted that Kättböle and Tuusula are both located at latitude 60° N at the southern edge of the boreal forest belt in Scandinavia, and that further north we can expect longer periods with temperatures below freezing and snow cover, which were the best conditions identified from Kättböle.

The investigation in this paper has concentrated on the model-based regression analysis and on comparison between observations using C band and L band, short and long repeat cycles, etc. Comparing with results in [6] we conclude that the RMSE is improved substantially in four out of five cases using IWCM as compared to linear regression. The importance of taking the baseline into account is stressed and from the model an increased accuracy is expected for ERS-1/2 baselines in the range of 100–200 m. Since temporal decorrelation dominates over volume decorrelation in repeat-pass interferometry there is, however, only a weak tendency to improved accuracy for increased baselines (cf. Table I).

Compared to results in [7] where the retrieval accuracy for boreal forests based on multitemporal ERS-1/2 coherence data was found to be 10 m^3/ha, the multitemporal JERS-1 backscatter shows accuracies of the order of 30–35 m^3/ha, in both cases corrected for *in situ* sampling errors. During the best weather conditions C-band ERS-1/2 tandem coherence data can provide an unsurpassed accuracy, and L-band JERS-1 data also provide very good and stable results for boreal forest stem volume estimation. Since the method is based on the availability of datasets for training, accurately known forest stands of sufficient size are crucial. The maximum distance between the training and testing area depends on the spatial variability of meteorological conditions and forest properties. This important question is partly addressed in [7], where a 4235-km^2 large area neighboring Kättböle was analyzed. However, lack of accurate *in situ* data for forest stands limited the analysis.

Satellite data of the type analyzed here are presently only available from the archives. For limited time periods ERS-2/Envisat and Radarsat-1/Radarsat-2 combinations may be a possibility, with baselines chosen to compensate the small frequency differences. Future possibilities to use Cartwheel type interferometry [35] without the problem of temporal decorrelation and with a volume decorrelation depending on forest height and baseline is very promising as well as repeat-pass polarimetric PALSAR data, or other possible missions designed for interferometric SAR applications.

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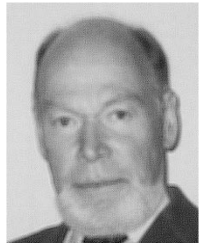

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