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Assessment of stand-wise stem volume retrieval in boreal forest from JERS-1 L-band SAR backscatter

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JERS-1 L-band SAR backscatter from test sites in Sweden, Finland and Siberia has been investigated to determine the accuracy level achievable in the boreal zone for stand-wise forest stem volume retrieval using a model-based approach. The extensive ground-data and SAR imagery datasets available allowed analysis of the backscatter temporal dynamics. In dense forests the backscatter primarily depended on the frozen/unfrozen state of the canopy, showing a ~4 dB difference. In sparse forests, the backscatter depended primarily on the dielectric properties of the forest floor, showing smaller differences throughout the year. Backscatter modelling as a function of stem volume was carried out by means of a simple L-band Water Cloud related scattering model. At each test site, the model fitted the measurements used for training irrespective of the weather conditions. Of the three *a priori* unknown model parameters, the forest transmissivity coefficient was most affected by seasonal conditions and test site specific features (stand structure, forest management, etc.). Several factors determined the coefficient's estimate, namely weather conditions at acquisition, structural heterogeneities of the forest stands within a test site, forest management practice and ground data accuracy. Stem volume retrieval was strongly influenced by these factors. It performed best under unfrozen conditions and results were temporally consistent. Multi-temporal combination of single-image estimates eliminated outliers and slightly decreased the estimation error. Retrieved and measured stem volumes were in good agreement up to maximum levels in Sweden and Finland. For the intensively managed test site in Sweden a 25% relative rms error was obtained. Higher errors were achieved in the larger and more heterogeneous forest test sites in Siberia. Hence, L-band backscatter can be considered a good candidate for stand-wise stem volume retrieval in boreal forest, although the forest site conditions play a fundamental role for the final accuracy.

1. Introduction

The assessment of boreal biome natural resources represents a key issue in current discussions concerning the status of the Earth. Because of massive wood trade,

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illegal logging and severe damages due to fires, insects and pollution, it is necessary to monitor boreal forests on a large-scale, frequently and accurately. While traditional ground-based survey methods become inconsistent when considering the vastness and remoteness of boreal forests, space-borne Synthetic Aperture Radar (SAR) is suitable for monitoring since it can provide a global view of the whole boreal area with high temporal resolution. Furthermore, forest parameter estimation has been under investigation for more than a decade, showing that results improve with decreasing radar frequency (Dobson *et al.* 1992, Le Toan *et al.* 1992, Israelsson *et al.* 1994, Rignot *et al.* 1994, Imhoff 1995, Hallikainen *et al.* 1998).

For space-borne SAR the lowest frequency so far available is L-band (1.25 GHz, 23.5 cm). At L-band, scattering is diffuse and occurs within the forest canopy volume, thus carrying information about parameters of major relevance to forest inventory (e.g. stem diameter, volume of the tree stems, aboveground dry biomass). Studies have shown that in boreal forests the scattering mechanisms depend upon the environmental conditions at the time of acquisition, indicating seasonal variations (Rignot *et al.* 1994, Pulliainen *et al.* 1999) and temporal consistency of the backscatter (Harrell *et al.* 1995, Baker and Luckman 1999). Investigations based on L-band backscatter provided by the Japanese Earth Resource Satellite (JERS-1 or, more commonly, JERS) SAR showed that in boreal forests the backscatter has strong sensitivity to stem volume, i.e. aboveground dry biomass in young and regenerating forests whereas saturation occurs for higher biomass. At Swedish and Finnish boreal forest test sites it has been shown that the backscatter saturated slightly above $100\,m^3\,ha^{-1}$ (Israelsson *et al.* 1995, Fransson and Israelsson 1999, Kurvonen *et al.* 1999).

The retrieval of stem volume from JERS backscatter was investigated by Fransson and Israelsson (1999), who reported correlation equal to 0.78 between measured and retrieved stem volume for a test site in northern Sweden. In Kurvonen *et al.* 1999, the use of two JERS images was shown to improve the stem volume estimates obtained from four European Remote Sensing (ERS) C-band SAR backscatter images, reaching a relative estimation uncertainty of 25% with a correlation coefficient of 0.73. In an evaluation of several remote sensing data sources by Hyyppä *et al.* (2000) it was concluded that for forest parameter estimation the JERS backscatter is more promising than the ERS backscatter but still inferior to the ERS coherence.

Although these studies have reported detailed results on forest L-band SAR backscatter properties and envisaged the possibility of retrieving forest biophysical parameters from L-band data, they generally had a limited set of images available and focused on one area. All investigations reported in the previous paragraphs were based on one or a few images, thus not allowing a complete evaluation of the temporal consistency of the backscatter. Furthermore, since each individual study referred to only one test site, the question currently is whether the retrieval methods and retrieval accuracies presented for a test case can be considered valid for larger areas up to an entire biome. Knowledge of which environmental conditions are most favourable for the retrieval of biophysical parameters represents an important reference for (i) evaluation of already acquired data, (ii) planning of image acquisition, and (iii) definition of future space-borne missions. Knowledge of the factors affecting the relationship between the SAR backscatter and the biophysical parameters of interest to foresters, allows (i) current retrieval techniques to be improved and (ii) retrieval strategies for large area mapping to be defined.

This study aims to investigate the feasibility of forest stem volume retrieval from JERS backscatter in the boreal zone. Such analysis is possible thanks to the extensive ground-truth and JERS SAR imagery datasets from several test sites in northern Europe and Siberia. Specific case studies have already been published (Smith *et al.* 1998, Schmullius *et al.* 2001, Eriksson *et al.* 2002, 2003, Santoro *et al.* 2002a, 2003, Askne *et al.* 2003a,b). Furthermore, the test sites have also been considered in previous investigations focusing on the retrieval of biophysical parameters using ERS SAR interferometry (Santoro *et al.* 1999, 2002b, Fransson *et al.* 2001, Koskinen *et al.* 2001, Schmullius *et al.* 2001, Balzter *et al.* 2002, Wagner *et al.* 2003).

At first we analyse spatial and temporal patterns of the SAR backscatter under several environmental conditions. Then we define to which extent an extended Water Cloud scattering model can describe the forest backscatter as a function of stem volume and we discuss to which extent a model-based stem volume retrieval method can be considered valid for the entire boreal zone.

2. Test sites

As test sites the forest estate of Kättböle, Sweden (60°00′ N, 17°07′ E), the forested area of Tuusula, Finland (60°17′ N, 25°00′ E) and four forest compartments of the forest enterprise of Bolshe-Murtinsky, Siberia (lower left coordinate: 56°50′ N, 91°50′ E; upper right coordinate: 57°20′ N, 94°00′ E) were considered. The test sites are all located at the southern edge of the boreal zone.

Kättböle is an intensively managed forest estate covering 5.5 km^2, whereas Tuusula is a 20 km^2 large forested area, including lakes, bogs and fields. Boreal coniferous Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*) dominate even though some broad-leaf tree species, mostly birch (*Betula pendula*), are also present. Both test sites are characterized by almost flat ground topography, at around 100 m above sea level.

The four Siberian forest compartments are part of the Bolshe-Murtinsky territory, located north of the city of Krasnoyarsk along the Yenisey River in central Siberia. Bolshe-Murtinsky is one of the 13 territories studied in the SIBERIA project (SAR Imaging for Boreal Ecology and Radar Interferometry Applications) for large-area forest mapping from ERS and JERS data (Schmullius *et al.* 2001). For sake of clarity, the compartments have been identified in this work by means of an index referring to their geographical location (Bolshe-NE, Bolshe-NW, Bolshe-SE and Bolshe-SW). Bolshe-NW and Bolshe-SW are located west of Yenisey, Bolshe-NE and Bolshe-SE are located east of the river (figure 1). At Bolshe-NW and Bolshe-SW tree species consist mainly of spruce (*Picea sibirica*) and fir (*Abies sibirica*) and Siberian cedar or stone pine (*Pinus sibirica*). Birch (*Betula pendula*) is also common, in particular at Bolshe-SW. At Bolshe-NE and Bolshe-SE both coniferous and deciduous species are present. Bolshe-NE is mainly covered with birch and aspen (*Populus tremula*) as well as fir, whereas at Bolshe-SE also pine (*Pinus sylvestris*) and spruce grow. Other species, such as larch (*Larix dahurica* and *Larix sibirica*) and willow (*Salix*), have minor percentages.

The four compartments cover between 211 km^2 and 278 km^2, with varying topography (figure 1). Topography is rather gentle west of the Yenisey River, with heights between 220 m and 260 m at Bolshe-NW, and 300 m and 330 m at Bolshe-SW. Nevertheless at this test site there are some steep slopes along the border. Topography east of the river is more varied. Except for a few valleys with riverbeds

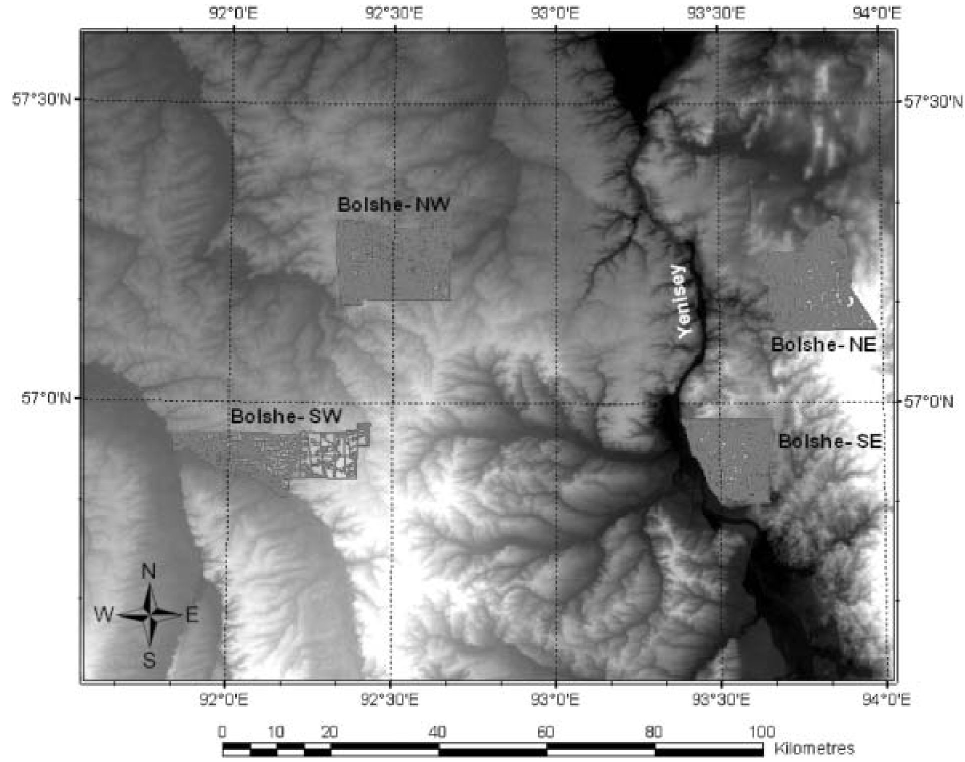

Figure 1. Location of the Bolshe-Murtinsky forest compartments. The forest stand masks have been superimposed onto the DEM of the area.

at an average height of 200 m above sea level, Bolshe-NE is rather hilly with local height differences between 50 m and 200 m. At Bolshe-SE the height rapidly increases by 140 m moving from the river to the inland because of a steep relief. On the plateau, at a height of 300 m, topography is undulating but rather gently, with a maximum height difference of around 50 m.

Different levels of anthropogenic transformation of the forests occur on the western and the eastern bank of the river, thus implying different heterogeneity of the forest stands at Bolshe-NE and Bolshe-SE with respect to Bolshe-NW and Bolshe-SW. At Bolshe-NW and Bolshe-SW forests were intensively harvested for decades. These forests are even-aged and currently more homogenous. Bolshe-NE and Bolshe-SE are located at the foothills of the Yenisey *krjag*, a hilly-mountain territory, and are mostly dominated by uneven-aged species. These areas have been less impacted by harvest and are much more heterogeneous, also because of the hilly relief.

3. Ground data

The ground data available consisted of forest stand boundary maps in digital form and field measurements of several forest parameters at stand level. A stand is the primary forest inventory unit in boreal forest inventory and is defined in terms of homogeneous forest cover and forest properties. The stand as a unit ranges from 0.5 ha to 20 ha in Sweden and Finland. In Siberia, stands are on average much larger, reaching in some cases 500 ha. The most common parameter used in boreal forest inventory is the volume of the tree stems for all living species per area unit, including bark but excluding branches and stumps. This quantity is referred to as stem volume in Sweden and Finland, and as growing stock volume in Russia. Both parameters are measured in $m^3 ha^{-1}$. For the sake of clarity, the term 'stem volume' will be used throughout the article. Stem volume is basically used to estimate aboveground living biomass (expressed in tons ha^{-1} of dry matter or carbon) by using simple conversion factors (Häme *et al.* 1992) or multi-dimensional regressions including biometric characteristics of stands (Shvidenko *et al.* 2004).

At Kättböle, an inventory was conducted mainly during 1995 using plots systematically distributed over the entire estate. Some measurements of randomly distributed plots were performed in 1996 as a complement. Plot-wise measurements were aggregated at stand level. Stand-wise measurements of stem volume were characterized by an overall estimation standard error of 18% (Fransson *et al.* 2001). Since the SAR images were acquired in 1997 and 1998, stem volumes were empirically corrected to the year of image acquisition using the site index. In addition, the area-fill factor, defined as the fraction of ground covered by tree crowns from the radar's perspective (Smith 2000), was measured at 18 stands. Although the measurements were obtained relative to an incidence angle of 23° (i.e. for the ERS SAR case), they have been considered in this study assuming that the fraction of ground covered by the tree crowns at 35–40° (i.e. the JERS–1 SAR incidence angle) should not have been significantly different.

The Tuusula test site was inventoried with a relascope method during summer 1997 with 210 forest stands being measured (for details see (Hallikainen *et al.* 1997)). Stand boundaries were identified from aerial photography and stand-wise estimates of forest parameters were obtained from the aggregation of sample plot measurements taken within the stands (Hallikainen *et al.* 1997). Depending on size and homogeneity of the stand, the number of relascope areas was between 2 and more than 10. The relascope areas were chosen visually based on the criteria that they represented areas of homogeneous canopy characteristics. It has been reported in Smith and Ulander (2000) that stem volume estimated with such a subjective inventory method is characterized by a standard error of about 20%. Nonetheless, according to Manninen and Ulander (2001), who used CARABAS data for stem volume retrieval in Tuusula, the retrieval error estimated to be $60\,m^3 ha^{-1}$ was of the order of the *in situ* data.

For the four compartments of Bolshe-Murtinsky, the forest parameter measurements originated from regular forest surveys and were part of an extensive Geographical Information System (GIS) forest database updated in 1998. Each compartment included between 500 and 1500 stands. Compared to Kättböle and Tuusula, where continuous management is carried out, the forest stands at Bolshe-Murtinsky were mostly labelled as 'natural stands', i.e. stands of growing trees that result from natural regeneration following a forest disturbance (mostly harvest or fire). In some areas, a stand could be generated by a number of pieces of different species composition and with substantially different stem volumes. The stem volume estimates reported in the database were rounded values in steps of $5\,m^3 ha^{-1}$ up to $50\,m^3 ha^{-1}$ and in steps of $10\,m^3 ha^{-1}$ for greater values. No correction for the year of acquisition of the SAR images could be performed. The accuracy of the forest inventory was of unknown magnitude. Although Russian forest inventory standards state that stem volume accuracy should legally be between 12% and 20%

(confidential probability 0.95), depending on economic value and age of the forest (FFSR 1995, Schmullius *et al.* 2001), this is often not the case. It was reported in Balzter *et al.* (2002) that some forest stands can present confidence intervals up $\pm 20\,\mathrm{m}^3\,\mathrm{ha}^{-1}$. Even larger errors can occur depending on the forest stand structure and location.

To aid interpretation, weather statistics in the form of temperature, precipitation, snow cover and snow depth were used. For Kättböle one to seven daily measurements were obtained from three weather stations located near to the test site. For Tuusula, data acquired with a three-hour interval at the weather station of Helsinki-Vantaa airport (approximately 10 km from the test site) were used. In the region of Bolshe-Murtinsky, data were acquired at six weather stations. The values of the weather parameters reported in this article represent averages of the measurements recorded at the six stations. Although the distance between the stations was big, the weather conditions were rather homogeneous (e.g. the temperature differed by 1–2°C, being higher at the southernmost stations).

4. SAR imagery

Imagery acquired by the HH-polarized JERS-1 L-band SAR at a nominal incidence angle of 35° was used. Over Kättböle, nine SAR images were available, acquired between April 1997 and August 1998. Over Tuusula, three images were obtained, between February and June 1997. Since the four compartments of Bolshe-Murtinsky were imaged along different satellite tracks, the whole forest compartment could not be viewed at once. For each compartment between five and nine images were available, mostly acquired in 1996 and 1997 but also in 1994 and 1998. A summary of acquisition dates and main weather conditions at the time of acquisition is reported in tables 1, 2 and 3 for Kättböle, Tuusula and Bolshe-Murtinsky. Over Kättböle and Tuusula the available images were mostly acquired between spring and fall, under unfrozen conditions, whereas over Bolshe-Murtinsky more than half of the images were acquired during winter, at temperatures well below freezing point. Only a few images were acquired under unfrozen conditions. At each test site several images were acquired when thaw occurred.

As reference for the radiometry, we considered the imagery from Bolshe-Murtinsky processed by Gamma Remote Sensing as described in Wiesmann *et al.*

Table 1. Weather conditions at image acquisition for the Kättböle test site. T, temperature; SD, snow depth.

Image no.	Acquisition date	Weather conditions	Summary of weather conditions
1	15 April 1997	T≈1°C, SD: 9 cm, precipitation	Thaw, wet
2	29 May 1997	T≈7°C, little rain	Unfrozen
3	12 July 1997	T≈18°C	Unfrozen
4	8 October 1997	T≈12°C, little rain	Unfrozen
5	4 January 1998	T≈2°C, SD: 5 cm, melting snow, precipitation	Thaw, wet
6	17 February 1998	T≈−2°C, SD: 25 cm, precipitation	Thaw, wet
7	2 April 1998	T≈1°C, SD: 0 cm, precipitation before pass	Thaw, wet
8	16 May 1998	T≈19°C	Unfrozen
9	12 August 1998	T≈21°C	Unfrozen

Table 2. Weather conditions at image acquisition for the Tuusula test site. T, temperature; SD, snow depth.

Image no.	Acquisition date	Weather conditions	Summary of weather conditions
1	17 February 1997	T≈−9°C, SD: 25 cm	Frozen
2	16 May 1997	T≈11°C, little rain	Unfrozen
3	29 June 1997	T≈17°C	Unfrozen

(1999), since it was provided with complete radiometric calibration information. Imagery from Kättböle was processed by the Japan Aerospace Exploration Agency (JAXA). Although absolute calibration information was not provided, it was possible to obtain a correction factor for the calibration since we had available one scene in raw format that we could process in the same manner as those from Bolshe-Murtinsky (see Santoro *et al.* 2002a for details). The Tuusula images were also processed by Gamma Remote Sensing but were originally provided without relative calibration information. As a consequence, it was not possible to determine calibrated sigma nought values.

All images were geocoded using digital elevation models (DEMs) of the test sites. If necessary, the geocoded images were downsampled using pixel aggregation in order to match with the digital forest masks. For Kättböle and Tuusula the pixel sizes of the geocoded images were 12.5 m by 12.5 m and 25 m by 25 m, respectively. At Bolshe-Murtinsky, images were either directly geocoded to match with the forest mask pixel size (50 m by 50 m) or were downsampled from the original 25 m by 25 m pixel size (see Santoro *et al.* 2002a for details).

Table 3. Weather conditions at image acquisition for the four Bolshe-Murtinsky forest compartments. T, temperature; SD, snow depth.

Image no.	Acquisition date	Area	Weather conditions	Summary of weather conditions
1	6 January 1994	NW, SW	T≈−17°C, SD: 39 cm, snowfall	Frozen
2	19 February 1994	NW, SW	T≈−17°C, SD: 45 cm, snowfall	Frozen
3	14 October 1996	NW, SW	T≈2°C	Unfrozen
4	25 November 1996	NE, SE	T≈−25°C, SD: 20–45 cm	Frozen
	27 November 1996	NW, SW		
5	10 January 1997	NW, SW	T≈−20°C, SD: 20–60 cm	Frozen
6	21 February 1997	NE, SE	T≈−2°C, SD: 30–80 cm	Thaw (one-day)
7	23 February 1997	NW, SW	T≈−18°C, SD: 25–75 cm	Frozen
8	6 April 1997	NE, SE	T≈2°C, SD: 10–40 cm, snowmelt	Thaw (winter-spring)
	8 April 1997	NW, SW	T≈7°C, SD: 5–30 cm, snowmelt	
9	20 May 1997	NE, SE	T≈18°C	Unfrozen
10	3 July 1997	NE, SE	T≈15°C	Unfrozen
11	16 August 1997	NE	T≈17°C	Unfrozen
12	22 June 1998	NW, SW	T≈22°C, rainfall	Unfrozen, wet
13	5 August 1998	NW, SW	T≈19°C, rainfall	Unfrozen, wet

5. Measurements

Using the digital forest stand map, forest stands were localized in the geocoded SAR images. For each stand the mean backscatter coefficient and the standard deviation were computed. Stands with stem volume equal to $0\,m^3\,ha^{-1}$ were discarded since the stem volumes for such stands were likely to include large uncertainties. To decrease border effects and localization errors caused by the geocoding, the stands were decreased in size by removing a buffer zone along the perimeter of each stand. The width of the buffer zone was 1 or 2 pixels (i.e. between 12.5 m in Kättböle and 100 m in Siberia) depending on the geocoding accuracy.

To limit the effect of (i) speckle on the stand-wise backscatter measurements and (ii) biases and uncertainty on the *in situ* reference data, we considered only stands larger than a given threshold. For each test site the threshold was set empirically depending on the number of stands left for further investigations. Since Sweden and Finland are typically characterized by small-sized stands, the number of stands suitable for the analysis in Kättböle and Tuusula decreased significantly. In Kättböle only stands larger than 2 ha after shrinking were considered; as a consequence, 42 stands were left. In Tuusula, the on average smaller stand size implied that the threshold had to be lower in order to have enough stands for stem volume retrieval (see §6 for details). With a threshold set to 1.25 ha, corresponding to 20 pixels in the geocoded images, 35 stands were left for investigation. A higher threshold would have caused a strong decrease in the number of stands, whereas with a lower threshold the effect of speckle would have increased. In Bolshe-Murtinsky only stands with more than 32 pixels after shrinking of the $50\,m \times 50\,m$ pixel size images were considered. This corresponded to all the stands that were at least 8 ha large after shrinking. On a compartment basis, only between 6% and 31% of the total number of stands were left. However, the distribution of stem volume did not show any significant change, so the remaining stands could still be considered representative for the whole forest compartments (Santoro *et al.* 2003). In table 4 a summary of the main characteristics of each test site is reported.

Figure 2 illustrates the distribution of stem volume at each of the six test sites. For better understanding, two subplots have been created. Compared to Kättböle and Tuusula, the distribution at the Siberian forest compartments is less uniform, this

Table 4. Main attributes of the test sites under investigation. The values reported refer to the stands used for modelling and stem volume retrieval investigations.

	Kättböle	Tuusula	Bolshe-NE	Bolshe-NW	Bolshe-SE	Bolshe-SW
Area (km^2)	5.5	20	278	262	211	246
Topography	Flat	Flat	Varying	Gentle	Mostly gentle	Gentle
No. of stands	42	35	91	146	113	156
Stand size (ha) (min−max)	2–21	1.25–7	8–248	8–209	8–199	8–683
Volume ($m^3\,ha^{-1}$) (min−max)	16–344	5–535	5–330	5–400	5–410	15–400
Mean volume ($m^3\,ha^{-1}$)	144	257	111.9	221.6	188.3	162.8
Standard deviation ($m^3\,ha^{-1}$)	76	172	101.4	115.0	74.5	116.2

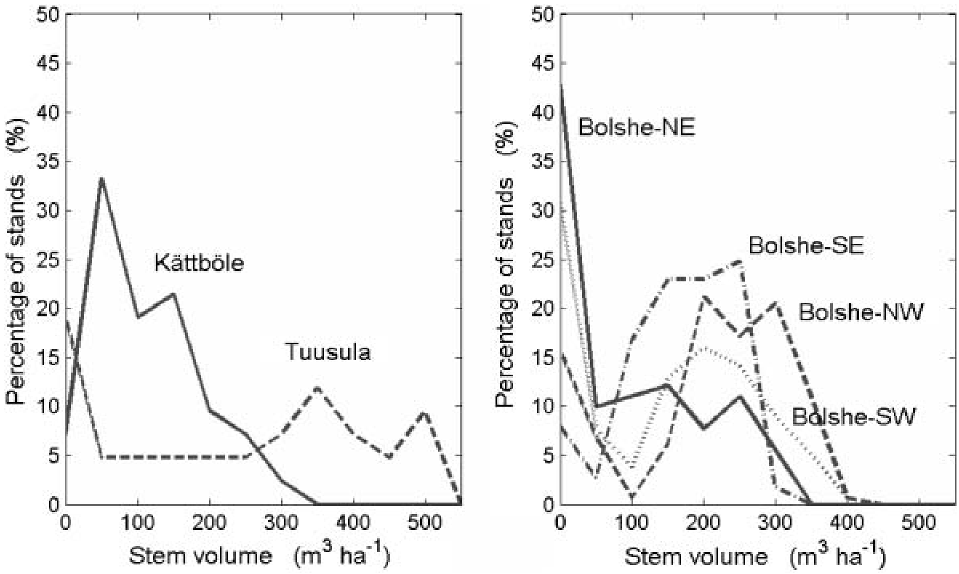

Figure 2. Stem volume distribution at each test site under investigation.

probably being a consequence of the different forest management practice performed in northern Europe and Siberia. Besides mature forests, both Kättböle and Tuusula included areas of regeneration, regrowth and thinning. In Bolshe-Murtinsky, either very young or dense forests were dominant because of the intensive harvest during past decades, whereas the intermediate growth stage between $50\,m^3\,ha^{-1}$ and $150\,m^3\,ha^{-1}$ was almost completely missing.

At L-band the effect of sloped terrain on the backscatter has to be taken into account and possibly compensated for as shown by Rauste (1990), Van Zyl (1993), Luckman (1998) and Castel *et al.* (2001). Whilst the topography at Kättböle and Tuusula did not require a compensation for the backscatter, the Bolshe-Murtinsky test sites were locally characterized by varying ground topography, which might have introduced artefacts in some of the backscatter measurements. Table 5 shows that for the forest stands retained in this study the range of local incidence angles was small. Nevertheless, we investigated the relevance of the local slopes on the forest backscatter using the semi-empirical method proposed by (Castel *et al.* 2001).

$$\frac{\sigma^o(\theta_{loc})_{pq}}{\sigma^o\left(\theta_{ref}\right)_{pq}} = \left(\frac{\cos\theta_{loc}}{\cos\theta_{ref}}\right)^n \qquad (1)$$

Table 5. Distribution of mean local incidence angles for the Bolshe-Murtinsky compartments in terms of mean (θ_{mean}) and standard deviation ($\theta_{std\ dev}$). Local incidence angle for flat terrain was 39°.

	θ_{mean} (°)	$\theta_{std\ dev}$ (°)
Bolshe-NE	38.1	2
Bolshe-NW	38.8	2
Bolshe-SE	38.9	0.8
Bolshe-SW	40.5	1

where $\sigma^0(\theta_{loc})$ and $\sigma^0(\theta_{ref})$ represent sigma nought for the local incidence angle θ_{loc} and for a reference flat ground θ_{ref}, respectively; p and q represent the polarisation status; and n is a factor dependent on physical crown parameters (e.g. optical depth and extinction) and satellite acquisition geometry. Because of the limited variability of the local incidence angle, the difference between corrected and original backscatter was less than 0.5 dB for the stands located on the steepest slopes and the sensitivity of the corrected backscatter to n was negligible. It has to be noted that, since the DEM available for Bolshe-Murtinsky was affected by topographic features due to vegetation (ERS 'tandem' DEM) and the difference between the original and the corrected data was small, we preferred to keep the original backscatter measurements for further analysis.

6. Methodology

6.1 *Modelling*

The complexity of SAR backscatter from a forest requires backscatter modelling approaches to be based on a number of assumptions concerning the scattering elements (type, amount, distribution and dielectric properties) and on the scattering mechanisms to be included. Since this study was conceived to assess the retrieval of stem volume from forest backscatter measurements, we preferred to model the backscatter using an approach that expresses the forest backscatter in terms of the main scattering components and as a function of as few forest parameters as possible.

Similarly to the Water Cloud Model for vegetation (Attema and Ulaby 1978), we considered a simple model based on radiative transfer through a horizontal scattering and attenuating layer with gaps (Askne *et al.* 1995):

$$\sigma^o_{for} = (1-\eta)\sigma^o_{gr} + \eta\sigma^o_{gr}T_{tree} + \eta\sigma^o_{veg}(1-T_{tree}) \qquad (2)$$

Compared to models that include all different factors governing the scattering in a forest, this approach has the advantage of allowing a straightforward inversion to estimate forest parameters, as will be shown in §6.3. Similar approaches have been used in Fransson and Israelsson (1999) and Kurvonen *et al.* (1999) for the retrieval of stem volume from ERS and JERS SAR backscatter in boreal forest.

In equation (2), the forest backscatter, $\sigma^0{}_{for}$, is given by the sum of direct scattering from the ground through the canopy gaps, ground scattering attenuated by the tree canopy and direct scattering from the vegetation. The direct ground backscatter is given by the backscatter coefficient of the ground, $\sigma^0{}_{gr}$, weighted by the percentage of ground not covered by vegetation. This is expressed as $(1-\eta)$ where η is the area-fill factor, representing the percentage of ground covered with vegetation. The attenuated ground scattering is determined by the ground backscatter coefficient, attenuated by the vegetation layer, ηT_{tree}. The direct scattering from the vegetation is given by the backscatter coefficient of the vegetation layer, $\sigma^0{}_{veg}$, weighted by the area-fill factor and the two-way tree transmissivity T_{tree}. This term can be expressed as $e^{-\alpha h}$, where α is the two-way attenuation per metre through the tree canopy and h is the thickness of the attenuating layer. If α is given in dB m^{-1}, the two-way attenuation per metre can be converted into penetration depth, δ, by using:

$$\delta = \left(2 \ln 10^{\frac{\alpha}{10}}\right)^{-1} \tag{3}$$

Although several studies have showed the importance of the trunk-ground scattering mechanism at L-band (Sun and Simonett 1988, Sun *et al.* 1991, Saatchi and McDonald 1997), in equation (2) double-bounces and higher order reflections have not been taken into account because we assumed the attenuation of the electromagnetic wave in the canopy to be relevant and the forest floor non-perfectly flat. In Sun *et al.* (1991) and Karam *et al.* (1992) the influence of a rough forest floor on the modelled backscatter has been questioned, whereas in Pulliainen *et al.* (1999) it was concluded that a double-bounce term in boreal forests is negligible, probably because of the rough ground. The combined effect of rough surface and strong attenuation in boreal coniferous and broadleaf types of forest explained the negligible double-bounces reported by (Ranson and Sun 1994). Dominance of volume scattering relative to double-bounce effects was shown by Baker and Luckman (1999) at a test site close to Kättböle. Further support to our assumptions was found in penetration depth values between 4 m and 10 m reported by Chauhan *et al.* (1991), Shinohara *et al.* (1992) and attenuation measurements between 10 dB and 15 dB reported by Ulaby *et al.* (1990) and Fleischman *et al.* (1996).

In order to highlight the scattering components from the ground and the vegetation, equation (2) can be rearranged:

$$\sigma^o_{for} = \sigma^o_{gr} T_{for} + \sigma^o_{veg}\left(1 - T_{for}\right) \tag{4}$$

where

$$T_{for} = \left[(1-\eta) + \eta e^{-\alpha h}\right] \tag{5}$$

Although the formulation of the model as a function of area-fill factor is physically valid, equation (2) is not suitable for inversion since the area-fill factor is not commonly used for forest inventory. For retrieval purposes it is more convenient to use the expression reported by Pulliainen *et al.* (1994), in which the two-way forest transmissivity has been expressed as $e^{-\beta V}$, where V is the stem volume and β is an empirically defined coefficient expressed in ha m^{-3}:

$$\sigma^o_{for} = \sigma^o_{gr} e^{-\beta V} + \sigma^o_{veg}\left(1 - e^{-\beta V}\right) \tag{6}$$

Hence equation (5) can be rewritten as:

$$\eta = \frac{1 - e^{-\beta V}}{1 - e^{-\alpha h}} \tag{7}$$

6.2 *Model training*

In equation (6) $\sigma^0{}_{gr}$, $\sigma^0{}_{veg}$ and β are unknown and need to be estimated using a training set of backscatter and stem volume measurements. We also considered the case with fewer unknowns in order to limit the uncertainty in the model parameter estimates and, in the end, in the modelled backscatter. Taking into account that the two-way forest transmissivity should not be significantly season-dependent and that the spread of the measurements can strongly affect the slope of model in equation (6), the coefficient β was assumed constant, thus decreasing the number of unknowns to two. This approach has been considered in (Askne *et al.* 2003a) for Kättböle, where β=0.004 ha m^{-3} was obtained after minimizing the quadratic difference between observations and model predictions. Using area-fill factor measurements, the estimate of the two-way tree attenuation, α, from equation (7) was equal to 0.5 dB m^{-1} and the corresponding penetration depth, δ, from equation (3) was equal to 7 m, thus being in agreement with experimental values of wave penetration in forests at L-band.

In this study the model was trained both to get an understanding of the model parameter properties, referred from this point onwards as forest backscatter modelling and to allow the retrieval of stem volume. In forest backscatter modelling we investigated the properties of the model parameters; for each test site the backscatter values of all stands as reported in table 4 were used. Conversely, stem volume retrieval required that one part of the stands is used to test the model. Hence, the model has been trained using part of the stands, the remaining stands forming the test set (details are provided in §6.3). In both cases model training was performed by means of non-linear least-squares minimization between the backscatter measurements available in the training set and the corresponding modelled values obtained from equation (6).

6.3 *Stem volume retrieval*

By inverting equation (6), for each test stand the stem volume estimate, $\hat{V}$, corresponding to the forest backscatter measurement, $\sigma^o_{for,meas}$, is obtained as:

$$\hat{V} = -\frac{1}{\beta}\ln\left(\frac{\sigma^o_{veg} - \sigma^o_{for,meas}}{\sigma^o_{veg} - \sigma^o_{gr}}\right) \tag{8}$$

In Kättböle and Tuusula, where the amount of stands available was limited (see table 4), the stands were sorted for increasing stem volume and divided into two halves, including respectively each second stand. In Kättböle both halves included 21 stands; in Tuusula the two halves included respectively 18 and 17 stands. Although we tried to ensure that both sets had as similar stem volume distribution as possible, the mean values of the stem volume were slightly different. This division has been presented and discussed in previous studies concerning the retrieval of stem volume using C-band ERS and L-band JERS SAR and interferometric SAR data (Santoro *et al.* 2002b, Askne *et al.* 2003b). To assess the dependency of the model on the specific training set used, at both test sites the two groups of stands were interchanged using each once for training the model and once for testing the model.

For Bolshe-Murtinsky, model training was performed at each compartment separately. Since each compartment was very large and included many more stands compared to the north European test sites, in a first study we divided each compartment into areas of similar sizes and trained the model using the stands located in one area, the remaining stands forming the test set. By dividing each compartment into four quarters, we obtained areas generally 40–50 km^2 large, which mostly included at least 20% of the stands available (see table 6). With this choice we tried to ensure the distribution of the training stands throughout the range of stem

Table 6. Number of stands in each quarter after the division of each forest compartment at Bolshe-Murtinsky in four parts of similar size. In brackets the corresponding percentage with respect to the total number of stands available is given.

	Quarter 1	Quarter 2	Quarter 3	Quarter 4	Total number of stands
Bolshe-NE	19 (21%)	18 (20%)	36 (39%)	18 (20%)	91
Bolshe-NW	47 (32%)	29 (20%)	33 (23%)	37 (25%)	146
Bolshe-SE	24 (21%)	41 (36%)	5 (5%)	43 (38%)	113
Bolshe-SW	75 (48%)	44 (28%)	21 (14%)	16 (10%)	156

volumes to be as uniform as possible and to have enough stands for limiting the uncertainties related to the number of stands used in the training phase.

In a second study, in a similar manner to Kättböle and Tuusula, all the stands were sorted for increasing stem volume, and groups of stands were then formed. Having available many more stands than at Kättböle and Tuusula, three groups could be formed and every third stand was included in each group. Training was performed using one group at a time whereas the other two groups formed the test set; hence the retrieval could be performed three times using slightly different training sets. In table 7 we have reported for each forest compartment the number of stands in each of the three groups and the corresponding number of training and test stands.

Although the first method is more rigorous, it is likely that the distribution of the backscatter with respect to stem volume somewhat differs in the test set, especially if the areas considered in the test set are very large and the forest has different properties. With the second approach, the training set can be characterized by stands with larger differences in terms of forest and ground properties compared to the first approach. Nevertheless, in this way we ensure that the training and test sets have similar distributions of stem volumes.

If backscatter measurements are outside the interval of modelled values, from equation (8) we would obtain stem volume estimates that are either negative or outside the range of stem volumes measured at the test site. To solve this problem, it was decided to correct such estimates by putting them equal to zero when they were negative and equal to the highest stem volume in the training set when they were above the modelled backscatter. Nonetheless, if the backscatter was at least two standard deviations distant from the modelled backscatter, the corresponding stand was classified as an outlier, in which case the stem volume was not estimated.

In order to describe the results of the retrieval, the rms error and the coefficient of determination R^2 between measured and retrieved stem volume were used. In addition, the relative rms error (ratio between rms error and mean stem volume) was

Table 7. Number of stands for the three groups in which each forest compartment at Bolshe-Murtinsky has been divided, and the corresponding number of training and test sets.

	Number of stands per group	Number of training stands	Number of test stands
Bolshe-NE	30 or 31	30 or 31	60 or 61
Bolshe-NW	48 or 49	48 or 49	97 or 98
Bolshe-SE	37 or 38	37 or 38	75 or 76
Bolshe-SW	52	52	104

computed to allow a comparison of retrieval accuracies. Since the ground data included a certain error percentage, correction of the rms error statistics was considered. For Kättböle and Tuusula the forest inventory sampling errors were subtracted according to the procedure presented in Fransson *et al.* (2001). For Bolshe-Murtinsky we considered applying an approximate correction since detailed *in situ* measurements were not available. Following the indications presented in Balzter *et al.* (2002), a 20% relative error was subtracted.

If several images are available, it is possible to combine stem volume estimates from individual images in a multi-temporal approach. In this study we used a linear combination of the estimates based on weights defined by single-image retrieval accuracy values (Santoro *et al.* 2002b).

7. Results

7.1 *Backscatter spatial and temporal variations*

The dependence of the backscatter upon weather conditions strongly depends on the scattering mechanisms occurring in a forest. In sparse forests, where the canopy covers only a small fraction of the forest floor, the ground contribution to the backscatter is dominant. In dense, i.e. mature, forests instead the canopy covers most of the ground; therefore, the volume scattering within the vegetation layer makes the ground contribution less important. In this study forest stands were labelled as sparse or dense depending on their stem volume, this parameter being somewhat a measure of the forest density. The thresholds for the sparse and the dense class represented a trade-off between having many samples in each class and limiting the dependence of the backscatter upon any biophysical parameter. Forest stands with stem volume below $50\,m^3\,ha^{-1}$ were identified as sparse forests. Although below $50\,m^3\,ha^{-1}$ the dependence of backscatter upon stem volume occurred, a lower threshold would have decreased considerably the number of samples available, thus deteriorating the class statistics. Forest stands with stem volume close to the biggest measured value were included in the dense forest class. The lower limit for this class depended on the stem volume distribution at each test site. For example, the threshold was set to $250\,m^3\,ha^{-1}$ for Kättböle and $400\,m^3\,ha^{-1}$ for Tuusula, since the highest measured stem volumes were $335\,m^3\,ha^{-1}$ and $535\,m^3\,ha^{-1}$, respectively.

Figure 3 reports mean values and standard deviations of the SAR backscatter for the two classes at Kättböle and Bolshe-Murtinsky. Because of the uncalibrated data and the small number of images available, the statistics for Tuusula have not been included in the figure. The solid and the dashed lines have been used for the sparse and the dense forest class, respectively. The mean values reported in figure 3 show clear seasonality related to the frozen/unfrozen weather conditions. The length of the vertical bars, i.e. the spread of the measurements in the two classes, depended on several factors, namely (i) heterogeneities of the dielectric properties of the vegetation and the forest floor within the test site, (ii) forest stand structure, (iii) sensitivity of the backscatter to stem volume, and (iv) number of stands available in a class.

To aid interpretation of the results, correlation coefficients and scatterplots of backscatter measurements were obtained. The distribution of backscatter as a function of stem volume was also taken into account (figure 4). The six plots reported in figure 4 were chosen in order to illustrate that the relationship between

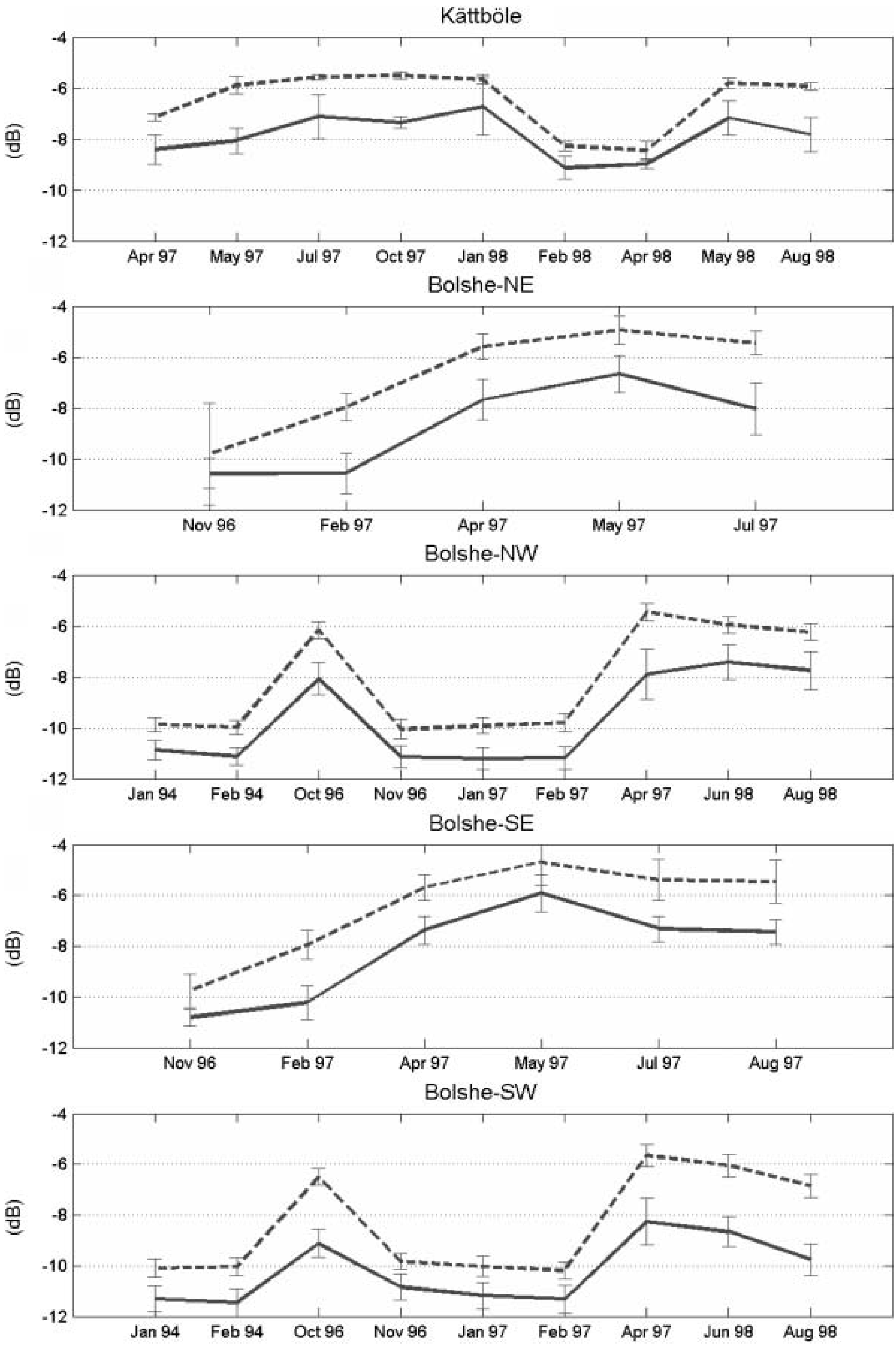

Figure 3. JERS backscatter dynamics in sparse and dense forests stands. The sparse forest class refers to stands with stem volume below 50 $m^3 ha^{-1}$ (solid lines). The dense forest class included stands with stem volume greater than 250 $m^3 ha^{-1}$ both at Kättböle and Bolshe-Murtinsky (dashed lines). The vertical bars represent one standard deviation in the stand-wise backscatter measurements.

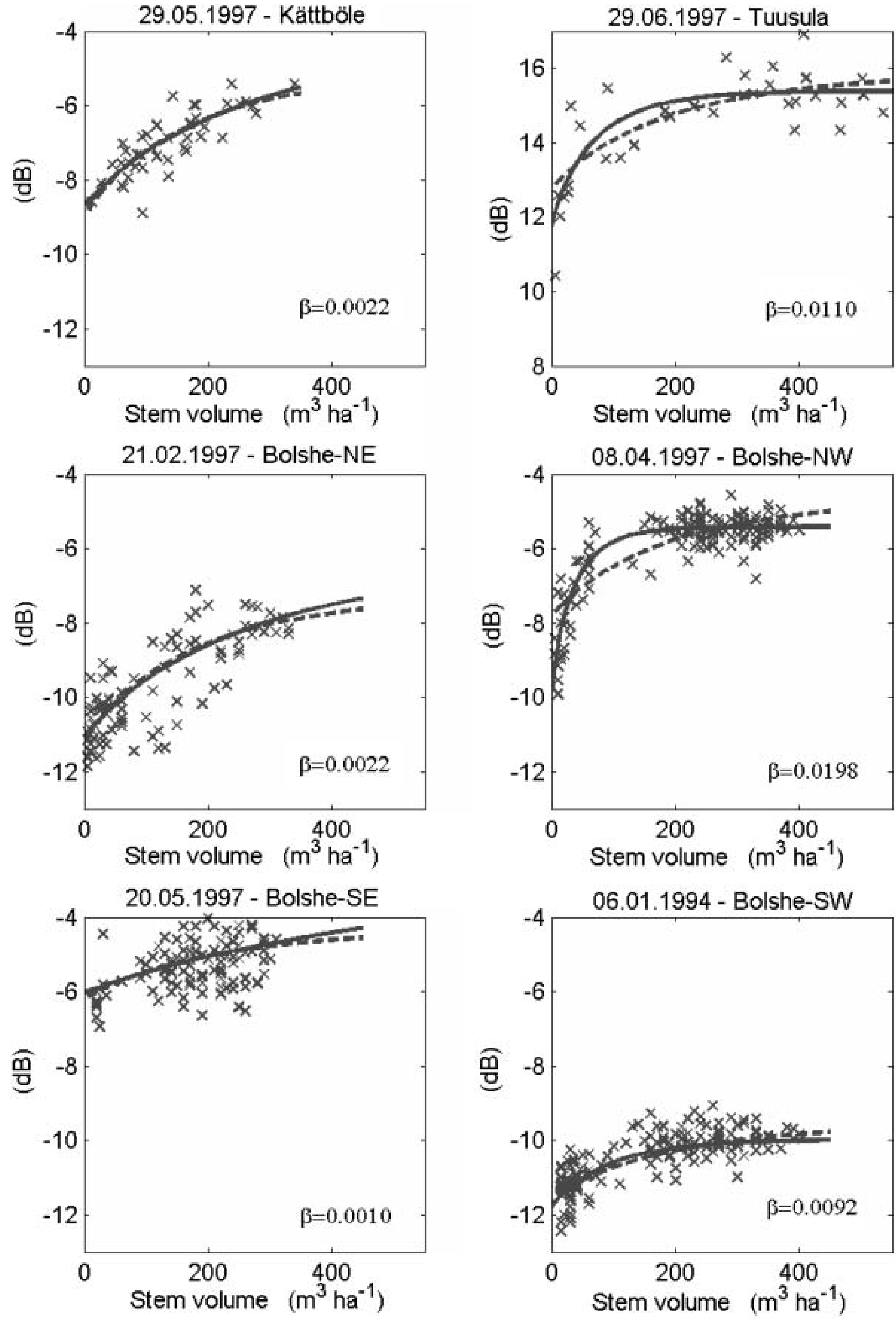

Figure 4. Distribution of backscatter as a function of stem volume and modelled backscatter using equation (6). Each plot includes the model lines obtained by training with β=0.004 ha m^{-3} (dashed line) and having assumed β unknown (solid line). For this case, the estimates of β from the model training are reported at the bottom right corner of each plot. Model training has been carried out using the stands described in table 4.

backscatter and stem volume depends on seasonal conditions as well as on the test site forest stand structure and forest management.

7.2 *Forest backscatter modelling*

Figure 4 shows the modelled backscatter as a function of stem volume using equation (6). The fit obtained from training with the three model parameters unknown has been reported in figure 4 with solid lines. Because of the spread of the measurements and the non-uniform distribution of stem volume at some test sites, we also investigated the uncertainty in the parameter estimate, i.e. analysed whether other solutions were feasible. To quantify the uncertainty, a sensitivity analysis was carried out. Assuming a constant β, the model in equation (6) was trained with only $\sigma^0{}_{gr}$ and $\sigma^0{}_{veg}$ unknown. The regression was performed for a range of β values between 0 and 0.03 ha m^{-3}, the latter value corresponding to complete two-way attenuation of the radiowave in forests with stem volume below 100 m^3 ha^{-1} (figure 5). The result from each regression was then compared with the modelled backscatter using three unknowns, i.e. the best fit to the training set. For each plot in figure 4, the dashed line corresponded to model training with β=0.004 ha m^{-3}, this representing a particular case of the sensitivity analysis.

The sensitivity analysis showed that the two backscatter coefficients $\sigma^0{}_{gr}$ and $\sigma^0{}_{veg}$ were rather constant, whereas β could present a large range of acceptable values even for a difference between modelled backscatter and the best fit as small as 5%. For each image from Kättböle and Bolshe-Murtinsky, figure 6 illustrates the estimate of β corresponding to the best fit and the interval of acceptable β values. As for figure 4, results for Tuusula have not been included because of the limited number of images and the uncalibrated data available.

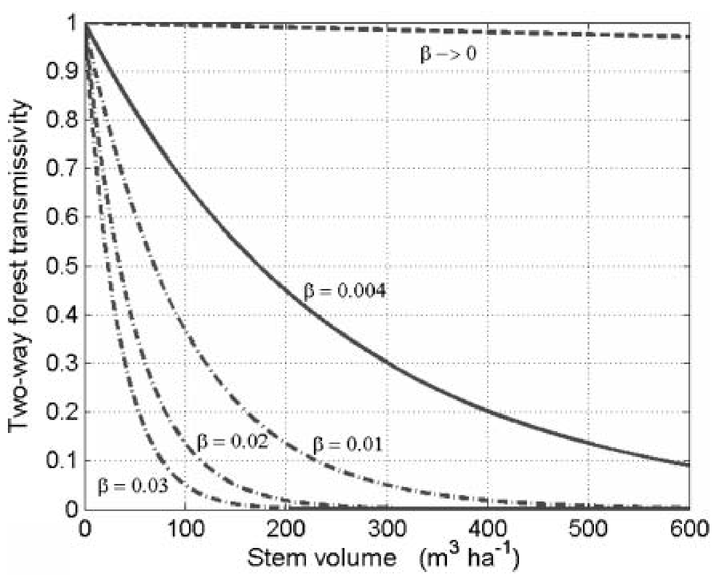

Figure 5. Two-way forest transmissivity as function of stem volume for increasing β.

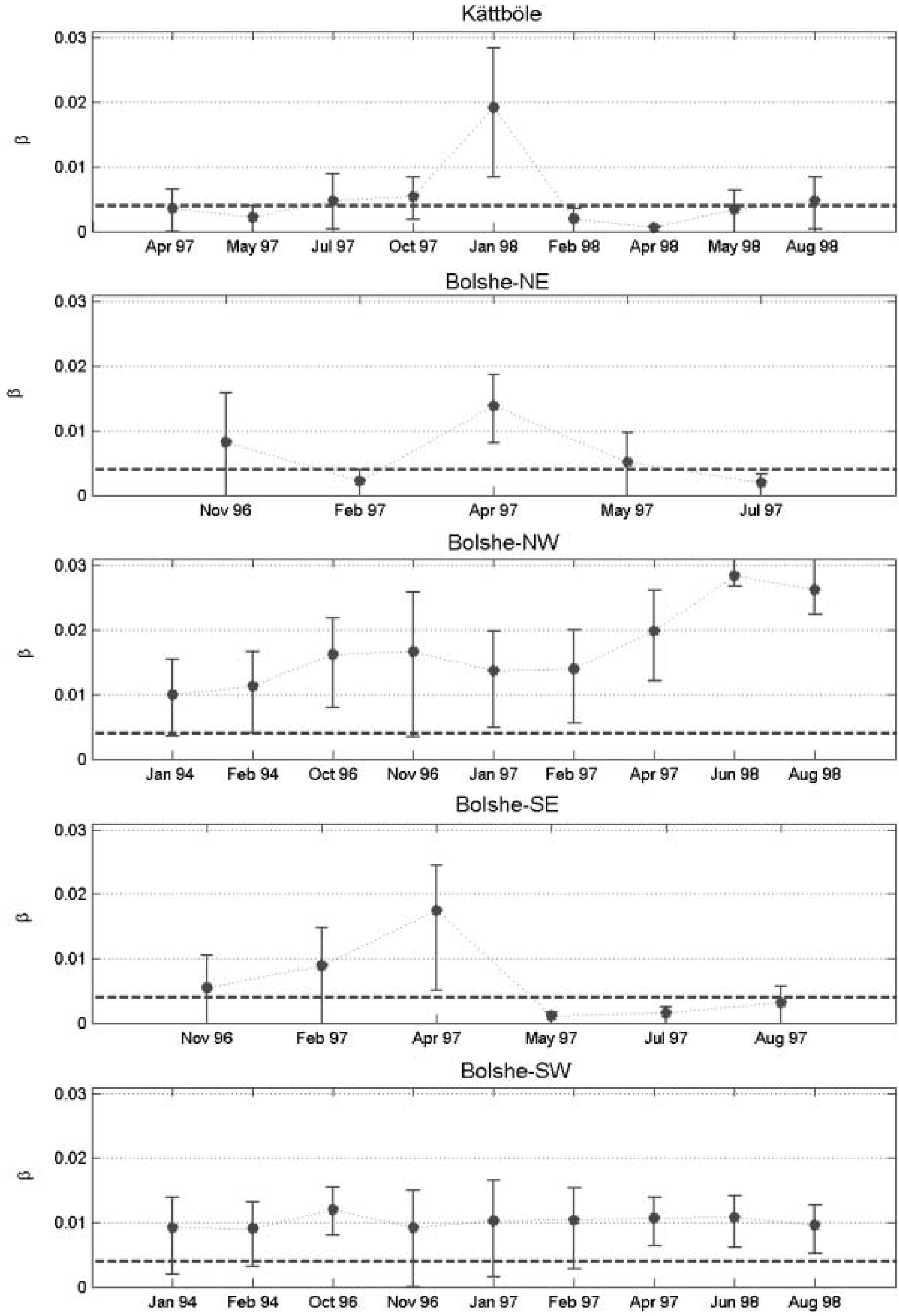

Figure 6. Estimates of β (asterisks) and intervals of β for which the increase in regression error of equation (5) with respect to the best fit was below 5% (vertical bars). All values are given in ha m^{-3}. The dashed line represents the level β=0.004 ha m^{-3}.

Table 8. Statistics for stem volume retrieval based on an individual image (best rms error, relative rms error, R^2 coefficient and corresponding weather condition at the time of image acquisition).

	Rms error ($m^3 ha^{-1}$)	Relative rms error (%)	R^2	Weather conditions
Kättböle	36	25	0.76	Unfrozen
	49	34	0.64	Thaw, wet
Tuusula	117	46	0.64	Unfrozen
	152	59	0.53	Frozen
Bolshe-NE	57	52	0.71	Thaw (one-day)
	63	56	0.72	Unfrozen
	74	68	0.60	Thaw (winter-spring)
	96	85	0.40	Frozen
Bolshe-NW	74	35	0.53	Thaw (winter-spring)
	86	39	0.45	Unfrozen, wet
	87	39	0.49	Frozen
Bolshe-SE	86	46	0.25	Unfrozen
	87	47	0.35	Thaw (one-day)
	91	49	0.24	Thaw (winter-spring)
	116	61	0.14	Frozen
Bolshe-SW	63	39	0.70	Unfrozen, wet
	64	40	0.63	Thaw (winter-spring)
	75	47	0.63	Frozen

7.3 *Stem volume retrieval*

For stem volume retrieval, model training using both β constant and β unknown were used. Stem volume estimates did not present relevant differences and the rms errors were mostly similar. For the sake of clarity, in the discussion we will refer to the results obtained using β constant. At each site, depending on the training set used, the retrieval error differed slightly in a few cases, thus highlighting that the training and test sets should be as similar as possible, i.e. the training set should encompass the best possible distribution of stem volumes in the area under investigation (Askne *et al.* 2003b).

For Bolshe-Murtinsky, only the results obtained from using one third of the stands as the training set (see §6.3) will be discussed in more detail. For each test site, table 8 reports the best stem volume retrieval accuracy corresponding to a given weather condition at the time of image acquisition. When one quarter of a compartment was used for model training, worse results were obtained. This result could be explained primarily as a consequence of the very large areas investigated. While the training set covered a relatively small area where forests and soils were likely to have similar characteristics, the test set included much larger areas where different distributions of the forest backscatter with respect to stem volume could be noticed, thus affecting the retrieval in a negative way (figure 7).

Whichever combination of estimates was considered, with multi-temporal filtering outliers did not occur and the estimation error marginally decreased. Multi-temporal corrected rms errors and relative rms errors are reported in table 9. Figure 8 shows a comparison between measured and retrieved stem volume at each test site.

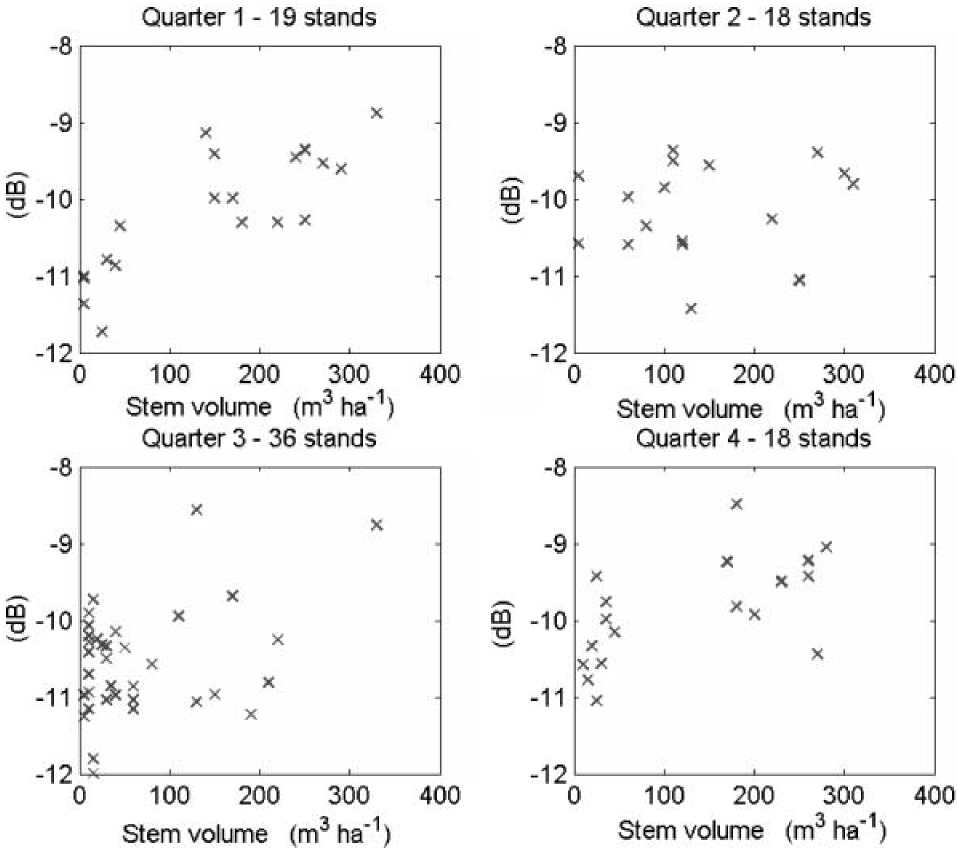

Figure 7. Distribution of forest backscatter with respect to stem volume for each quarter obtained at Bolshe-NE.

8. Discussion

8.1 *Backscatter spatial and temporal variations*

Figure 3 shows that the backscatter in dense forests was always higher than in sparse forests. The backscatter levels and the dynamic range, i.e. the difference between backscatter in dense and sparse forests, strongly depended on the environmental conditions at the time of image acquisition, since these affected the dielectric

Table 9. Statistics for stem volume retrieval based on a multi-temporal combination of individual images (best rms error, relative rms error, R^2 coefficient and number of images combined).

	Rms error ($m^3 ha^{-1}$)	Relative rms error (%)	R^2	Number of images
Kättböle	36	25	0.76	9
Tuusula	102	40	0.68	3
Bolshe-NE	57	51	0.73	5
Bolshe-NW	74	33	0.57	9
Bolshe-SE	87	46	0.31	6
Bolshe-SW	63	39	0.69	9

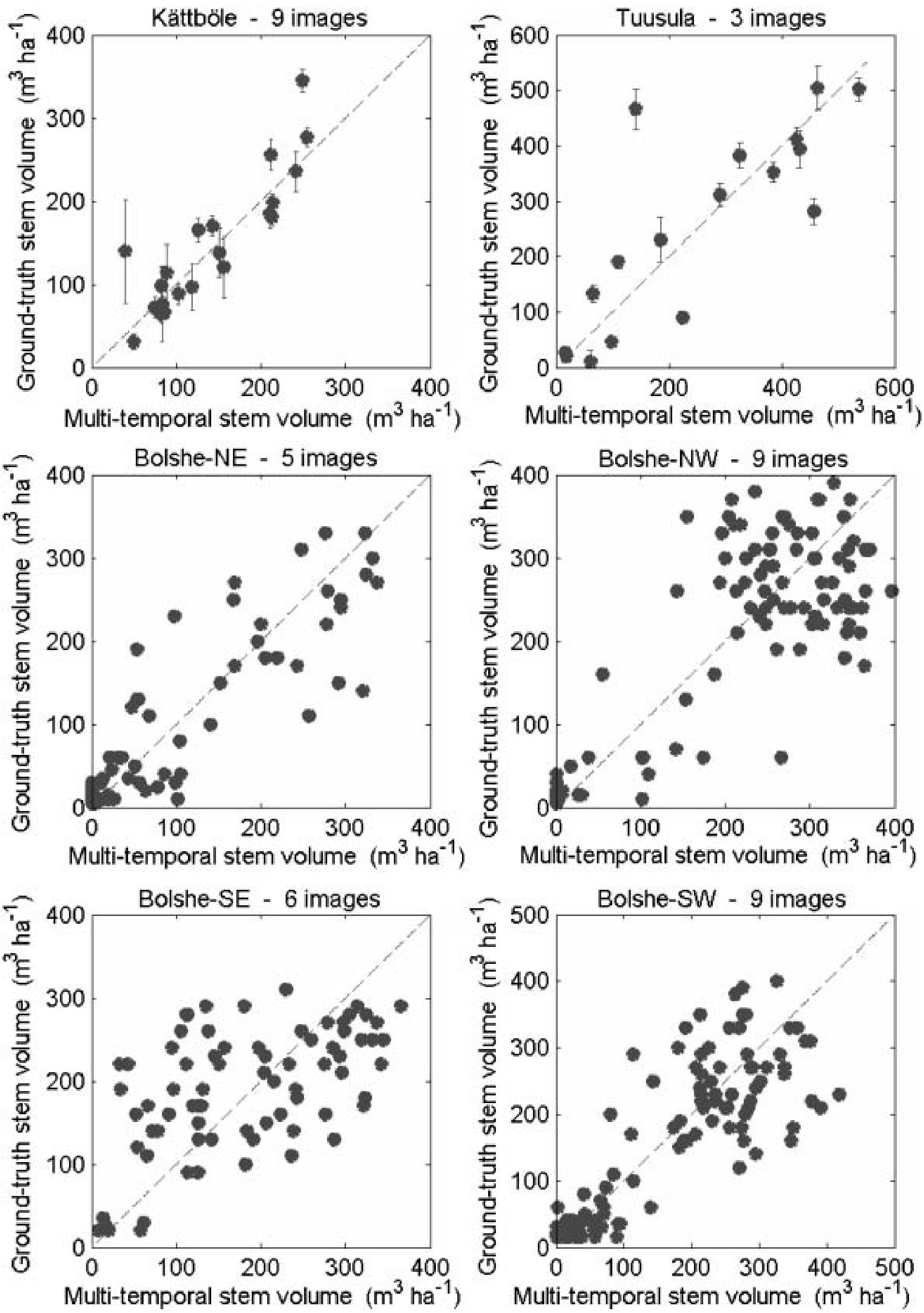

Figure 8. Multi-temporal and *in situ* stem volume for each test site. The vertical bars represent one standard deviation in the *in situ* measurements. This information was not available for Bolshe-Murtinsky.

properties of the vegetation and the forest floor. At all test sites, the mean backscatter was consistently lowest under frozen conditions and highest at unfrozen conditions. A 3–5 dB difference was measured in dense forests, whereas it was slightly lower in sparse forests, being in agreement with results presented by Rignot *et al.* (1994) and Pulliainen *et al.* (1999). When thaw occurred the backscatter was primarily influenced by the meteorological conditions at the time of image acquisition (e.g. precipitation, snow melt and temperature).

Unfrozen conditions were registered (i) at Kättböle between May and October 1997 and then again starting from May 1998, (ii) at Bolshe-NE and Bolshe-SE between May and August 1998, (iii) at Bolshe-NW and Bolshe-SW in October 1996 and then in June and August 1998 and (iv) at Tuusula in May and June 1997. The difference between the backscatter from dense and sparse forests was 2–3 dB. Values were commonly between −6 dB and −4 dB in dense forests and between −9 dB and −6 dB in sparse forests (see figure 3). Furthermore, the high correlation (always above 0.8) and the narrow distribution along the 1 : 1 line in the scatterplots of the backscatter measurements allow the conclusion that the backscatter acquired under unfrozen conditions was temporally consistent. Although we could notice in some cases differences between backscatter acquired under dry conditions and when rainfall occurred, the differences were not found to be significant nor could any trend be identified. The effect of precipitation on the backscatter could however not be fully assessed since we did not have available at any of the test site images acquired both in dry and very wet conditions.

For increasing stem volume the backscatter typically increased by 3–4 dB, the slope and the spread of the backscatter measurements being different depending on the test site. At Kättböle (see plot in figure 4), the spread was smallest and the backscatter increased almost linearly with stem volume without apparent sign of saturation up to 350 $m^3 ha^{-1}$. At Bolshe-NE a similar trend was found, although the backscatter measurements were characterized by a larger dispersion. Large spread of the backscatter and almost no correlation with stem volume was found at Tuusula and Bolshe-SE (see plots in figure 4). At Bolshe-NW and Bolshe-SW, saturation of the backscatter occurred slightly above 100 $m^3 ha^{-1}$; this behaviour was consistent for images acquired under frozen conditions and when thaw occurred as well (see plot for Bolshe-NW in figure 4).

The results could be interpreted as the combined effect of:

(i) Size of the test site. At larger test sites, for example Bolshe-Murtinsky, heterogeneity in the dielectric properties were more likely to occur than at Tuusula and Kättböle, thus explaining part of the spread. The significant spread found at Tuusula could also be explained in terms of variable dielectric properties of the test site.

(ii) Forest management and stand structure. Since a natural type of forest presents a more mixed forest structure than an intensively managed forest, it is reasonable to assume that for the former the relationship between backscatter and stem volume is more ambiguous. Hence, we could explain the larger spread of the backscatter at Bolshe-Murtinsky. Furthermore, since the forest backscatter is determined by the forest structural features (and only indirectly by the stem volume) it is reasonable to assume that in the case of different structures, the relationship between backscatter and stem volume differs, thus explaining the different trends observed between backscatter and stem volume. Additionally, the impact of different crown structures should be considered since at Bolshe-NW and Bolshe-SW we have mostly very dense coniferous forests, for which the penetration of the microwave through the canopy is principally different from less dense and deciduous forest types.

(iii) The effect of the ground data accuracy should not be neglected since local inventory errors in the ground data can significantly affect the distribution of the backscatter measurements with respect to stem volume.

Frozen conditions occurred at Bolshe-Murtinsky in January and February 1994, and in November 1996 and January 1997. The dynamic range was around 1 dB (figure 3). The backscatter was consistently around −10 dB in dense forests and around −11 dB in sparse forests and saturation typically occurred at around 100 $m^3 ha^{-1}$ (see plot for Bolshe-SW in figure 4). Since in frozen conditions the dielectric constant is very small, the power scattered back to the radar both by the forest canopy and the forest floor is low. Moreover, an incoming wave penetrates the canopy deeper and the percentage of ground seen by the radar increases, thus explaining the small contrast between the sparse and the dense forest class.

Thaw events were grouped depending on the environmental conditions characterizing the period of the acquisition.

(i) Thaw under dry conditions was registered at Bolshe-Murtinsky in April 1997. The temperature had been above 0°C for some days before the acquisitions and the thickness of the snow layer had been constantly decreasing. Compared to the backscatter level registered at frozen conditions, the backscatter had increased, reaching a level typical of unfrozen conditions (figure 3).
(ii) One-day thaw occurred at Bolshe-Murtinsky on 21 February 1997. The temperature rapidly increased from −20°C to around freezing point. The backscatter measured at Bolshe-NE and Bolshe-SE on this day (image no. 6) was 1–2 dB higher than two days later at Bolshe-NW and Bolshe-SW (image no. 7) when −18°C was reported. It can be argued that for image no. 6, the wet conditions of the snow on the trees and on the ground contributed to the higher backscatter. The large spread of the measurements was probably caused by spatial heterogeneities of the snow conditions. Because of refreezing, the backscatter registered at the second acquisition had returned to values typical of frozen conditions. For increasing stem volume, the backscatter either constantly increased (see plot for Bolshe-NE in figure 4) or was almost constant (Bolshe-SE).
(iii) Thaw under wet conditions. Four cases of thaw characterized by precipitation before or during the image acquisition were registered at Kättböle (April 1997, January, February and April 1998). One case was registered at Tuusula (February 1997). Figure 3 does not show a consistent trend in the measurements of the backscatter either in sparse or dense forests. The result is confirmed by the low correlation coefficients and the noisy scatterplots. For increasing stem volume the backscatter showed a small increase (1–2 dB), in some cases being characterized by saturation. The variability of the results could be explained in terms of the different dielectric properties of the snow cover both on the forest floor and on the trees.

8.2 *Forest backscatter modelling*

For each image, the estimates of $\sigma^0{}_{gr}$ and $\sigma^0{}_{veg}$ can be said to correspond to the mean backscatter values reported in figure 3 for sparse and dense forests, respectively and did not change significantly when performing the sensitivity analysis. The estimates of β and the vertical bars generated by the sensitivity analysis were instead variable both in time and in space. The temporal variations of β were related to the environmental conditions at the time of image acquisition. The length of the vertical bars and the levels of the β estimates illustrated in figure 6 were with highest probability affected by forest stand structural features.

Under the assumption that the forest transmissivity can be expressed in terms of a simple exponential function of stem volume, at Kättböle the estimates of β obtained under unfrozen conditions corresponded well to theory. At Tuusula the larger dispersion of the measurements caused a significant variability in the estimates. Further support to the results was provided by the estimates of the two-way tree transmissivity coefficient α obtained using area-fill factor measurements in equation (7) and the corresponding penetration depths from equation (3) (see Santoro *et al.* 2002a for details), which were in line with experimental values at L-band. When thaw occurred, β was either very high (January 1998) or very low (April 1998), corresponding to an almost opaque and a very transparent forest canopy respectively (figure 5). Such cases could be explained in terms of a 'noise' contribution to the forest backscatter, which affected the dependence of the latter upon stem volume, thus biasing the estimate of β. Bolshe-NE and Bolshe-SE were also characterized by significant temporal variations. Images acquired under both frozen and unfrozen conditions showed an almost constant level, close to the 0.004 ha m^{-3} level. Once again, when thaw occurred (February and April 1997), the backscatter contribution related to the environmental conditions fooled the regression and in most cases β became a mere regression factor.

The vertical bars were longer at Tuusula and Bolshe-Murtinsky because of the significant spread of the measurements. Figure 6 in particular shows that the estimates of β at Bolshe-NW and Bolshe-SW were consistently higher than at the other test sites, thus implying very strong forest attenuation. Although Bolshe-NW and Bolshe-SW contain mainly dense coniferous forests, such a situation was rather improbable when taking into account that many images had been acquired under frozen conditions when the attenuation should have been at its minimum. Errors and uncertainty were certainly introduced by the very small number of training samples in the interval of stem volumes where saturation at L-band commonly occurs, i.e. around 100 m^3 ha^{-1} (see figure 2). Nonetheless, this was not sufficient to explain the temporal consistency of the high β estimates, which could instead be related to forest stand structural features.

Figure 4 shows that the curves obtained from model training with three unknowns and from using constant β=0.004 ha m^{-3} generally overlapped. Only when a very large spread of the backscatter (see Tuusula in figure 6) or specific environmental conditions such as thaw (see Bolshe-NW in figure 6) occurred did the two curves slightly differ. In such cases the vertical bars in figure 5 are significantly far from the 0.004 ha m^{-3} reference level.

8.3 *Stem volume retrieval*

At each test site the retrieval accuracy and the number of outliers for an individual image strongly depended on the weather conditions at the time of image acquisition (table 8). Images acquired under unfrozen conditions were generally characterized by the lowest rms error, which was furthermore temporally consistent. Frozen conditions were found to be least suitable for retrieval because of the small sensitivity of the backscatter to forest features. When thaw occurred, the retrieval error was different depending on the type of thaw and on the test site. At Kättböle wet thaw conditions resulted in high error, whereas at Bolshe-NE and Bolshe-SE the almost linear relationship between backscatter and stem volume occurring at the time of the one-day thaw contributed to the best result achieved. Winter-spring thaw was commonly characterized by a rapid increase in backscatter with stem volume in young stands followed by saturation, which strongly decreased the retrieval error.

The relative rms error showed that the retrieval performed best at the small and intensively managed test site of Kättböle where the correlation between backscatter and stem volume was very high (table 8). At Tuusula, the higher error should have been due to the heterogeneous forest stand dielectric properties and partly due to the accuracy of the ground data. In Siberia, heterogeneity of the dielectric properties, the effect of the forest structural features on the relationship between backscatter and stem volume and local inaccuracies in the ground data could explain the large errors.

With the multi-temporal combination of the stem volume estimates from the individual images, it was possible to partially improve the retrieval accuracy. Figure 8 shows that for Kättböle and, to a lesser extent, for Tuusula there is a reasonable agreement between measured and retrieved stem volume without apparent sign of saturation. For the Siberian forest compartments, the results were affected by significant dispersion and different patterns. Bolshe-NE presented the best correlation but was affected by large spread along the 1 : 1 line, whereas Bolshe-SE showed almost no relationship between measured and retrieved stem volume. At Bolshe-NW and Bolshe-SW measured and retrieved stem volumes were in agreement up to $100\,m^3\,ha^{-1}$ whereas for higher stem volumes the saturation of the backscatter worsened the retrieval. The reason for the large spread and the different behaviours has to be attributed to the different test site properties, as well as to the ground data accuracy. Furthermore, on the basis of the results obtained at Kättböle, the availability of a larger number of images acquired under unfrozen conditions would have probably improved the retrieval.

9. Conclusions

This paper covers several aspects concerning the retrieval of stem volume in boreal forests at stand level using JERS L-band SAR backscatter. Six test sites located in Sweden, Finland and Siberia have been considered, thus allowing the first ever assessment of L-band backscatter attributes and stem volume retrieval methods from locations spread over a large and diverse part of the boreal zone.

Backscatter in dense forest is consistently higher than in sparse forest, the difference depending on the seasonal conditions. In dense forest the backscatter is constant under unfrozen conditions and decreases by approximately 4 dB when the temperature is below freezing. In sparse forest, the moisture content of the forest floor is the main variable affecting the backscatter. Weather conditions and forest stand structure are the main factors affecting the trend of the backscatter as a function of stem volume. The largest sensitivity to stem volume occurs for unfrozen conditions, whereas under frozen conditions, small sensitivity and saturation of the signal occur. Thaw introduces a noise term in the forest backscatter, this term being strongly related to precipitation and length of thaw.

The Water Cloud Model, including vegetation gaps, describes the relationship between backscatter and stem volume well, the quality of the fit being strongly dependent on the test site, i.e. on forest stand structure and forest management. The most sensitive model parameter is the coefficient of the two-way forest transmissivity, β, which can be affected by seasonal conditions and test site-specific features (e.g. size of the test site, forest stand structural heterogeneities, forest management). Model training using a fixed β can perform equally well as with three unknowns. Using an *a priori* defined value for β has the advantage of limiting model fitting errors in the case of small training sets, large spread of the backscatter measurements or non-uniform stem volume distribution in the training set. Using a simple approach for backscatter modelling throughout the boreal zone, it is however necessary to know the relationship existing between forest structural features and *in situ* measurements in order to define the value of β to be used. A similar conclusion was reported in Castel *et al.* (2002), who recognized the importance of forest stand structure on the relationship between the forest backscatter and the forest biomass in a plantation in Venezuela and the necessity of taking such information into account. Finally, accurate ground data are also vital since errors in the training set can strongly influence the modelling results.

Retrieval of stem volume performs best under unfrozen conditions. The error slightly increases when thaw occurs and becomes unacceptable for frozen conditions. The retrieval error is strongly site-dependent, increasing from small forested areas where intensive management is carried out to large areas with natural forest stands. The role of the ground data accuracy has also to be taken into account. The relative rms error of 25%, achieved with a multi-temporal combination of several images acquired at an intensively managed test site with homogeneous forest stand structure, shows the potential of stem volume retrieval using L-band backscatter in boreal forests. Nonetheless, the different levels of accuracy achieved stress that for stem volume retrieval in the boreal zone the accuracy could be improved if information about the site conditions in some way could be taken into account. These aspects should be considered as recommendations to the planning of the forthcoming L-band space-borne SAR missions (PALSAR and TerraSAR-L) for boreal forest mapping.

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References

ASKNE, J., DAMMERT, P., FRANSSON, J., ISRAELSSON, H. and ULANDER, L.M.H., 1995, Retrieval of forest parameters using intensity and repeat-pass interferometric SAR information. *Proceedings of Retrieval of Bio- and Geophysical Parameters from SAR Data for Land Applications*, Toulouse, 10–13 October 1995 (Toulouse: ACTES), pp. 119–129.

ASKNE, J., SANTORO, M., SMITH, G. and FRANSSON, J., 2003a, L-band observations of boreal forest stem volume. *Proceedings of 23rd EARSeL Annual Symposium*, Gent, 2–5 June 2003 (Rotterdam: Millpress), pp. 159–166.

ASKNE, J., SANTORO, M., SMITH, G. and FRANSSON, J.E.S., 2003b, Multitemporal repeat-pass SAR interferometry of boreal forests. *IEEE Transactions on Geoscience and Remote Sensing*, **41**, pp. 1540–1550.

ATTEMA, E.P.W. and ULABY, F.T., 1978, Vegetation modeled as a water cloud. *Radio Science*, **13**, pp. 357–364.

BAKER, J.R. and LUCKMAN, A.J., 1999, Microwave observations of boreal forests in the NOPEX area of Sweden and a comparison with observations of a temperate plantation in the United Kingdom. *Agricultural and Forest Meteorology*, **98–99**, pp. 389–416.

BALZTER, H., TALMON, E., WAGNER, W., GAVEAU, D., PLUMMER, S., YU, J.J., QUEGAN, S., DAVIDSON, M., LE TOAN, T., GLUCK, M., SHVIDENKO, A., NILSSON, S., TANSEY, K., LUCKMAN, A. and SCHMULLIUS, C., 2002, Accuracy assessment of a large-scale forest cover map of central Siberia from synthetic aperture radar. *Canadian Journal of Remote Sensing*, **28**, pp. 719–737.

CASTEL, T., BEAUDOIN, A., STACH, N., STUSSI, N., LE TOAN, T. and DURAND, P., 2001, Sensitivity of space-borne SAR data to forest parameters over sloping terrain. Theory and experiment. *International Journal of Remote Sensing*, **22**, pp. 2351–2376.

CASTEL, T., GUERRA, F., CARAGLIO, Y. and HOULLIER, F., 2002, Retrieval biomass of a large Venezuelan pine plantation using JERS-1 SAR data. Analysis of forest structure impact on radar signature. *Remote Sensing of Environment*, **79**, pp. 30–41.

CHAUHAN, N.S., LANG, R.H. and RANSON, K.J., 1991, Radar modeling of a boreal forest. *IEEE Transactions on Geoscience and Remote Sensing*, **29**, pp. 627–638.

DOBSON, M.C., ULABY, F.T., LE TOAN, T., BEAUDOIN, A., KASISCHKE, E.S. and CHRISTENSEN, N., 1992, Dependence of radar backscatter on coniferous forest biomass. *IEEE Transactions on Geoscience and Remote Sensing*, **30**, pp. 412–416.

ERIKSSON, L., SANTORO, M., WIESMANN, A. and SCHMULLIUS, C., 2002, Multi-seasonal study of the SIBERIA classification procedure. *Proceedings of ForestSAT Symposium*, Edinburgh, 5–9 August 2002 (Edinburgh: Forest Research, Forestry Commission) CD-ROM.

ERIKSSON, L.E.B., SANTORO, M., WIESMANN, A. and SCHMULLIUS, C., 2003, Multi-temporal JERS repeat-pass coherence for growing stock volume estimation of Siberian forest. *IEEE Transactions on Geoscience and Remote Sensing*, **41**, pp. 1561–1570.

FFSR 1995, Manual of Forest Inventory and Planning in Forest Fund of Russia, Part 1 (Moscow: Federal Forest Service of Russia) in Russian.

FLEISCHMAN, J.G., AYASLI, S., ADAMS, E.M. and GOSSELIN, D.R., 1996, Foliage penetration experiment. Part I: Foliage attenuation and backscatter analysis of SAR imagery. *IEEE Transactions on Aerospace and Electronic Systems*, **32**, pp. 135–144.

Fransson, J.E.S. and Israelsson, H., 1999, Estimation of stem volume in boreal forests using ERS-1 C- and JERS-1 L-band SAR data. *International Journal of Remote Sensing*, **20**, pp. 123–137.

Fransson, J.E.S., Smith, G., Askne, J. and Olsson, H., 2001, Stem volume estimation in boreal forests using ERS-1/2 coherence and SPOT XS optical data. *International Journal of Remote Sensing*, **22**, pp. 2777–2791.

Hallikainen, M., Hyyppä, J., Koskinen, J., Roschier, M. and Ahola, P., 1997, EUFORA Campaign plan, Version 2, Laboratory of Space Technology, Helsinki University of Technology, Helsinki, Finland.

Hallikainen, M., Mäkynen, M., Laakso, S., Rantala, A., Tares, T., Uusitalo, J., Koskinen, J., Pulliainen, J., Hyyppä, J. and Hyyppä, H., 1998, Experimental results on radar response to boreal forests. *Proceedings of Second International Workshop on Retrieval of Bio- and Geo-physical Parameters from SAR Data for Land Applications*, ESTEC, Noordwijk, 21–23 October 1998 (Noordwijk: ESA Publications Division), pp. 325–332.

Häme, T., Salli, A. and Lahti, K., 1992, Estimation of carbon storage in boreal forests using remote sensing data. In Pilot study. In M. Kanninen and P. Anttila (Eds), *The Finnish Research Program on Climate Change, Progress Report*, pp. 250–255 (Helsinki: Academy of Finland, 1992).

Harrell, P.A., Bourgeau-Chavez, L.L., Kasischke, E.S., French, N.H.F. and Christensen Jr, N.L., 1995, Sensitivity of ERS-1 and JERS-1 radar data to biomass and stand structure in Alaskan boreal forest. *Remote Sensing of Environment*, **54**, pp. 247–260.

Hyyppä, J., Hyyppä, H., Inkinen, M., Engdahl, M., Linko, S. and Zhu, Y.-H., 2000, Accuracy comparison of various remote sensing data sources in the retrieval of forest stand attributes. *Forest Ecology and Management*, **128**, pp. 109–120.

Imhoff, M.L., 1995, Radar backscatter and biomass saturation: ramifications for global biomass inventory. *IEEE Transactions on Geoscience and Remote Sensing*, **33**, pp. 511–518.

Israelsson, H., Askne, J. and Sylvander, R., 1994, Potential of SAR for forest bole volume estimation. *International Journal of Remote Sensing*, **15**, pp. 2809–2826.

Israelsson, H., Askne, J., Fransson, J. and Sylvander, R., 1995, JERS-1 SAR analysis of boreal forest biomass. Volume II, Ministry of International Trade and Industry, National Space Development Agency of Japan, Tokyo.

Karam, M.A., Fung, A.K., Lang, R.H. and Chauhan, N.S., 1992, A microwave scattering model for layered vegetation. *IEEE Transactions on Geoscience and Remote Sensing*, **30**, pp. 767–784.

Koskinen, J.T., Pulliainen, J.T., Hyyppä, J.M., Engdahl, M.E. and Hallikainen, M.T., 2001, The seasonal behavior of interferometric coherence in boreal forest. *IEEE Transactions on Geoscience and Remote Sensing*, **39**, pp. 820–829.

Kurvonen, L., Pulliainen, J. and Hallikainen, M., 1999, Retrieval of biomass in boreal forests from multitemporal ERS-1 and JERS-1 SAR images. *IEEE Transactions on Geoscience and Remote Sensing*, **37**, pp. 198–205.

Le Toan, T., Beaudoin, A., Riom, J. and Guyon, D., 1992, Relating forest biomass to SAR data. *IEEE Transactions on Geoscience and Remote Sensing*, **30**, pp. 403–411.

Luckman, A.J., 1998, The effects of topography on mechanisms of radar backscatter from coniferous forest and upland pasture. *IEEE Transactions on Geoscience and Remote Sensing*, **36**, pp. 1830–1834.

Manninen, A.T. and Ulander, L.M.H., 2001, Forestry parameter retrieval from texture in CARABAS VHF-band SAR images. *IEEE Transactions on Geoscience and Remote Sensing*, **39**, pp. 2622–2633.

Pulliainen, J.T., Heiska, K., Hyyppä, J. and Hallikainen, M.T., 1994, Backscattering properties of boreal forests at the C- and X-bands. *IEEE Transactions on Geoscience and Remote Sensing*, **32**, pp. 1041–1050.

PULLIAINEN, J.T., KURVONEN, L. and HALLIKAINEN, M.T., 1999, Multitemporal behavior of L- and C-band SAR observations of boreal forests. *IEEE Transactions on Geoscience and Remote Sensing*, **37**, pp. 927–937.

RANSON, K.J. and SUN, G., 1994, Mapping biomass of a northern forest using multifrequency SAR data. *IEEE Transactions on Geoscience and Remote Sensing*, **32**, pp. 388–396.

RAUSTE, Y., 1990, Incidence-angle dependence in forested and non-forested areas in Seasat SAR data. *International Journal of Remote Sensing*, **11**, pp. 1267–1276.

RIGNOT, E., WAY, J., WILLIAMS, C. and VIERECK, L., 1994, Radar estimates of aboveground biomass in boreal forests of interior Alaska. *IEEE Transactions on Geoscience and Remote Sensing*, **32**, pp. 1117–1124.

SAATCHI, S.S. and MCDONALD, K.C., 1997, Coherent effects in microwave backscattering models for forest canopies. *IEEE Transactions on Geoscience and Remote Sensing*, **35**, pp. 1032–1044.

SANTORO, M., ASKNE, J., DAMMERT, P.B.G., FRANSSON, J.E.S. and SMITH, G., 1999, Retrieval of biomass in boreal forest from multi-temporal ERS-1/2 interferometry. *Proceedings of Fringe 99 Second International Workshop on ERS SAR Interferometry*, Liége, 10–12 November 1999 (Noordwijk: ESA Publications Division, ESTEC), CD-ROM.

SANTORO, M., ASKNE, J., ERIKSSON, L., SCHMULLIUS, C., WIESMANN, A. and FRANSSON, J.E.S., 2002a, Seasonal dynamics and stem volume retrieval in boreal forests using JERS-1 backscatter. *Proceedings of SPIE 9th International Symposium on Remote Sensing*, Agia Pelagia, Crete, 22–27 September 2002 (Bellingham, WA: SPIE), pp. 231–242.

SANTORO, M., ASKNE, J., SMITH, G. and FRANSSON, J.E.S., 2002b, Stem volume retrieval in boreal forests with ERS-1/2 interferometry. *Remote Sensing of Environment*, **81**, pp. 19–35.

SANTORO, M., ERIKSSON, L., SCHMULLIUS, C. and WIESMANN, A., 2003, Seasonal and topographic effects on growing stock volume estimates from JERS-1 backscatter in Siberian forests. *Proceedings of 23rd EARSeL Annual Symposium*, Gent, 2–5 June 2003 (Rotterdam: Millpress), pp. 151–158.

SCHMULLIUS, C.E., BAKER, J., BALZTER, H., DAVIDSON, M., ERIKSSON, L., GAVEAU, D., GLUCK, M., HOLZ, A., LE TOAN, T., LUCKMAN, A., MARSCHALK, U., MCCALLUM, I., NILSSON, S., ÖSKOG, A., QUEGAN, S., RAUSTE, Y., ROTH, A., ROZHKOV, V., SOKOLOV, V., SHVIDENKO, A., SKUDING, V., STROZZI, T., TANSEY, K., VIETMEIER, J., VOLOSHUK, L., WAGNER, W., WEGMÜLLER, U., WIESMANN, A. and YU, J.J., 2001, SIBERIA—SAR Imaging for Boreal Ecology and Radar Interferometry Applications. Final Report, EC—Center for Earth Observation, Project Reports, Contract No. ENV4-CT97-0743-SIBERIA.

SHINOHARA, H., HOMMA, T., NOHMI, H., HIROSAWA, H. and TAGAWA, T., 1992, Relation between L-band microwave penetration/backscattering characteristics and state of trees. *Proceedings of IGARSS'92*, Houston, 26–29 May 1992 (Piscataway, NJ: IEEE), pp. 539–541.

SHVIDENKO, A., NILSSON, S., SHEPASHENKO, D. and BOULOUI, Y., 2004, 'Base-line' models for assessing biological productivity of Northern Eurasia forest. *Ecological Modeling*, submitted.

SMITH, G., DAMMERT, P.B.G., SANTORO, M., FRANSSON, J.E.S., WEGMÜLLER, U. and ASKNE, J., 1998, Biomass retrieval in boreal forest using ERS and JERS SAR. *Proceedings of Second International Workshop on Retrieval of Bio- and Geo-physical Parameters from SAR Data for Land Applications*, ESTEC, Noordwijk, 21–23 October 1998 (Noordwijk: ESA Publications Division, ESTEC), pp. 293–300.

SMITH, G., 2000, Radar remote sensing of forests using CARABAS and ERS. PhD thesis, Technical Report, 393, Department of Radio and Space Science, Chalmers University of Technology, Göteborg, Sweden.

SMITH, G. and ULANDER, L.M.H., 2000, A model relating VHF-band backscatter to stem volume of coniferous boreal forest. *IEEE Transactions on Geoscience and Remote Sensing*, **38**, pp. 728–740.

SUN, G. and SIMONETT, D.S., 1988, Simulation of L-band and HH microwave backscattering from coniferous forest stands. A comparison with SIR-B data. *International Journal of Remote Sensing*, **9**, pp. 907–925.

SUN, G., SIMONETT, D.S. and STRAHLER, A.H., 1991, A radar backscatter model for discontinuous coniferous forests. *IEEE Transactions on Geoscience and Remote Sensing*, **29**, pp. 639–650.

ULABY, F.T., WHITT, M.W. and DOBSON, M.C., 1990, Measuring the propagation properties of a forest canopy using a polarimetric scatterometer. *IEEE Transactions on Antennas and Propagation*, **38**, pp. 251–258.

VAN ZYL, J.J., 1993, The effect of topography on radar scattering from vegetated areas. *IEEE Transactions on Geoscience and Remote Sensing*, **31**, pp. 153–160.

WAGNER, W., LUCKMAN, A., VIETMEIER, J., TANSEY, K., BALZTER, H., SCHMULLIUS, C., DAVIDSON, M., GAVEAU, D., GLUCK, M., LE TOAN, T., QUEGAN, S., SHVIDENKO, A., WIESMANN, A. and YU, J.J., 2003, Large-scale mapping of boreal forest in SIBERIA using ERS tandem coherence and JERS backscatter data. *Remote Sensing of Environment*, **85**, pp. 125–144.

WIESMANN, A., WEGMÜLLER, U. and STROZZI, T., 1999, JERS SAR processing for the boreal forest mapping project SIBERIA. *Proceedings of CEOS SAR Workshop*, Toulouse, 26–29 October 1999 (Noordwijk: ESA Publication Division, ESTEC), pp. 19–23.