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Seasonal and topographic effects on growing stock volume estimates from JERS-1 backscatter in Siberian forests

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ABSTRACT: In this paper a methodology for growing stock volume retrieval in boreal forests is devised. The methodology is developed at stand level and uses a multi-temporal set of spaceborne SAR data acquired at L-band by the Japanese satellite JERS-1 over an interval of four years. The test area consists of four large forest compartments, being part of the forest enterprise of Bolshe-Murtinsky, Siberia. Although two compartments were characterized by marked topography, the backscatter did not seem to be affected, in particular in dense forests. Seasonal effects were more relevant. SAR imagery acquired under dry-unfrozen conditions consistently showed the largest dynamic range and the absence of saturation in the interval 0-350 m^3/ha. By means of a semi-empirical model the inversion of backscatter measurements was performed and growing stock volume was estimated. Dry-unfrozen conditions were the most suitable for the retrieval, although the effect of spatial heterogeneities within the compartments increased the error. For changing weather conditions, saturation at 200 m^3/ha limited the retrieval to sparse forests. Frozen conditions were the least suitable. Multi-temporal combination of single-image estimates helped in increasing the accuracy. Using a rough correction for the errors in the ground-truth, the growing stock volume estimates were reasonably accurate and in line with studies carried out at other boreal sites, being mainly affected by spatial differences of the backscatter in the test area and the properties of the growing stock volumes used for model training. This study shows the importance of L-band backscatter for the retrieval of growing stock volume in the boreal belt, thus being an important aspect for the forthcoming ALOS mission.

1 INTRODUCTION

Siberian boreal forests represent one of the most important biomes because of environmental and economic reasons. Siberia includes roughly half of the world's growing stock volume of coniferous species, thus giving a significant contribution to the carbon budget for the whole planet. On the other hand, the massive trade of wood, the intensive forest management, the considerable amount of illegal logging and damages due to fires, insects, pollution and storms make Siberian boreal forests a very dynamic environment, for which periodic and accurate monitoring is needed.

In boreal forests, spaceborne ERS C-band SAR interferometric coherence has been proved to provide accurate information concerning the retrieval of forest attributes at stand level (Balzter *et al.* 2002, Santoro *et al.* 2002b, Wagner *et al.* 2003). Inversion of backscatter has been acknowledged as providing results with increasing accuracy for decreasing frequency. For the L-band JERS backscatter, saturation of the signal has been reported to occur between 150 and 225 m^3/ha (Fransson & Israelsson 1999, Kurvonen *et al.* 1999). This result shows the usefulness of the JERS backscatter for stem volume mapping in boreal forests, although in dense forests large errors can characterize the estimates. The saturation depends on weather conditions at acquisition, as well as on the forest structure, thus influencing the retrieval accuracy (Pulliainen *et al.* 1999, Santoro *et al.* 2002a, Askne *et al.* 2003).

For several forest compartments located in Central Siberia a model-based inversion procedure for the estimation of stand-wise growing stock volume from JERS backscatter was analyzed. An extensive dataset of JERS images acquired at different environmental conditions allowed to determine the most suitable conditions for growing stock volume retrieval. The effect of different topographic features on the backscatter measurements was considered as well. For the inversion, the properties of the training set are fundamental; therefore, we considered the impact on the retrieval accuracy of different training sets. Finally, in order to filter the rather noisy estimates, which are likely to occur in dense stands, the availability of several images allowed performing a multi-temporal combination of retrieved volumes from single images.

2 GROUND-TRUTH DATA

As test sites four compartments within the forest enterprise of Bolshe-Murtinsky were considered. The compartments are located north of the city of Krasnoyarsk, along the river Yenisey in central Siberia (Fig. 1). This is one of the 13 territories used in the SIBERIA project (SAR Imaging for Boreal Ecology and Radar Interferometry Applications) (Schmullius *et al.* 2001). In accordance with the numbering introduced in the project, the compartments are identified by means of an index. The major tree species are spruce, fir and birch. In the two eastern compartments aspen is one of the dominant species too. Few stands include pine, larch, cedar and salix trees.

The topography is rather gentle west of the river Yenisey. In Bolshe-2 heights are between 220 and 260 m, whereas in Bolshe-4 the heights vary between 300 and 330 m, except along the border where steep slopes are visible. In Bolshe-1 the topography becomes stronger when moving towards the Eastern part of the compartment. Having as reference the height of approximately 200 m a. s. l., the height difference increases from 50 to 200 m. In Bolshe-4 because of a steep mountainous relief at the westernmost part of the compartment, the height rapidly increases of 140 m. On the plateau, at a height of 300 m, the topography is undulated but rather gentle, with a maximum height difference of around 50 m.

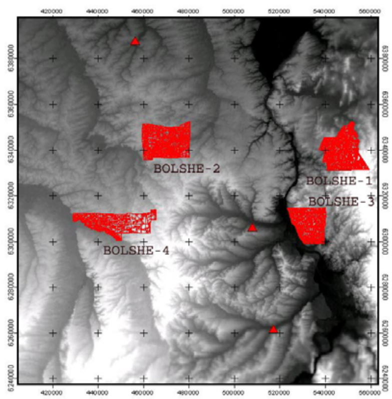

Figure 1. The four forest compartments of Bolshe-Murtinsky have been superimposed onto the DEM of the area. The triangles represent the position of the three closest weather stations. The Yenisey River flows west of the Bolshe-1 and –3 compartments. Projection used: UTM zone 46. Ellipsoid: WGS 84.

The ground-truth data consisted of forest stand boundary maps in digital form and field measurements of several forest parameters, including growing stock volume. Growing stock volume is the most common parameter in forest inventory for measuring the forest density. It is expressed in m^3/ha and is defined as the volume of the tree trunks for all living species in the stand per unit area. In young stands all stems are considered, whereas in mature stands stems with a diameter at “breast height” (1.3 m) smaller than 6 cm are discarded.

The digital forest masks were provided at 50 by 50 m. The forest parameter measurements originated from regular forest surveys performed by Russian foresters and were part of an extensive GIS forest database updated in 1998. No correction for the year of acquisition of the images could be performed. Based on information from the Russian forest inventory standards, stem volume accuracy was between 15% and 20%, depending on the age of the forest (Schmullius*, et al.* 2001). Nevertheless, the values reported in the database were rounded values and were characterized by confidence interval up ±20 m^3/ha (Balzter*, et al.* 2002). Exact figures for the four compartments were not available.

In Table 1 the main properties for each compartment are listed. Statistics refer to all stands that in the database had growing stock volume above 0 m^3/ha. Furthermore, several stands were discarded after an initial analysis of the backscatter signatures. Typical was the case of stands that appeared as clear-cuts in the images but where still reported as dense forest in the ground-truth database.

To aid interpretation, weather statistics in form of temperature, precipitation, snow cover and snow depth were used. The data were acquired at six weather stations of the World Meteorological Organization in the region of Bolshe-Murtinsky. Although the area covered was very large (see Fig. 1), the weather conditions were rather similar. The temperatures reported in Table 2 represent averages of values measured at the six stations. The temperature slightly increased for decreasing latitude.

Table 1. Main attributes of the four compartments in Bolshe-Murtinsky. The area of each compartment is measured in km^2. The area of the stands is reported in ha. The growing stock volume is measured in m^3/ha.

	Bolshe-1	Bolshe-2	Bolshe-3	Bolshe-4
Area (km^2)	278	262	211	246
Topography	Varying	Gentle	Mostly gentle	Gentle
No. of stands	1489	1144	868	492
Stand area (min - max)	1 - 248	3 - 209	1 - 199	3 - 683
Volume (min - max)	5 - 450	5 - 470	5 - 410	5 - 470
Mean volume	182.3	230.6	179.1	176.6
Std. Dev.	101.1	106.6	80.3	104.2

3 SATELLITE IMAGERY

Imagery acquired by the HH polarized L-band (1.25 GHz, 23.5 cm) SAR mounted on the Japanese satellite JERS-1 at a nominal incidence angle of 35° was used. Since the four compartments were imaged along different tracks, the whole forest territory could not be viewed at once. Table 2 lists the acquisitions dates and the compartments imaged at each acquisition. Imagery grouped under one image number was characterized by similar environmental conditions.

The images were all in Single Look Complex format (SLC) since they were primarily supposed to be used for interferometric processing (Eriksson *et al.* accepted). Since this product is characterized by a calibration error of 1-2 dB, it is not the most suitable for investigating the backscatter. This aspect has been taken into account in the interpretation of the results, in particular when comparing with investigations that used different calibration procedures.

Processing and radiometric calibration from JERS-1 level 0 to SLC format accounted for JERS sensitivity gain control, automatic gain control, and corrected for the JERS range antenna pattern. In addition, data were filtered for radio frequency interference.

The SAR images were geocoded in order to match with the digital forest masks. Images no. 12 and 13 were acquired during the SIBERIA project and geocoded using the global GTOPO30 Digital Elevation Model (DEM) (Wiesmann *et al.* 1999) with a 50 by 50 m pixel size. For the remaining images the GTOPO30 DEM was used together with a DEM obtained from interferometric ERS "tandem" data, which partly covered the region under investigation. These were geocoded to a 25 by 25 m pixel size (Wegmüller *et al.* 2002) and then downsampled to 50 by 50 m to match the forest mask.

Table 2. Summary of images available in terms of identification number, acquisitions date, areas covered and weather conditions at acquisition. *T* indicates temperature in °C, *SD* indicates snow depth.

Image no.	Date	Area	Weather conditions
1	06.01.1994	2,4	T≈-17°, SD: 39 cm, Snowfall
2	19.02.1994	2,4	T≈-17°, SD: 45 cm, Snowfall
3	14.10.1996	2,4	T≈ 2°
4	25.11.1996	1,3	T≈-25°, SD: 20-45 cm
	27.11.1996	2,4	T≈-25°, SD: 20-45 cm
5	10.01.1997	2,4	T≈-20°, SD: 20-60 cm
6	21.02.1997	1,3	T≈-2°, SD: 30-80 cm
7	23.02.1997	2,4	T≈-18°, SD: 25-75 cm
8	06.04.1997	1,3	T≈2°, SD:10-40 cm, Snowmelt
	08.04.1997	2,4	T≈7°, SD: 5-30 cm, Snowmelt
9	20.05.1997	1,3	T≈18°
10	03.07.1997	1,3	T≈15°
11	16.08.1997	3	T≈17°
12	22.06.1998	2,4	T≈22°, Rainfall
13	05.08.1998	2,4	T≈19°, Rainfall

Using the digital forest stand map, forest stands were localized in the geocoded SAR images and for each stand the mean backscatter was computed. In order to reduce border effects and localization errors on the backscatter measurements, the stands were decreased in size by removing a two pixels wide zone along the perimeter of each stand. Since stands reported having stem volume of 0 m^3/ha may be erroneous, they were discarded. Furthermore, to limit the effect of speckle, only stands including at least 32 pixels (i.e. 8 ha) after shrinking were retained. Although these operations strongly reduced the amount of stands, they did not change significantly the distribution of growing stock volumes except in Bolshe-1, as shown in Table 3.

Table 3. Forest attributes statistics for the stands used in the investigation (i.e. larger than 8 ha and having growing stock volume above 5 m^3/ha).

	Bolshe-1	Bolshe-2	Bolshe-3	Bolshe-4
No. of stands	91	146	113	156
Volume (min - max)	5 - 330	5 - 400	5 - 410	15 - 400
Mean volume	111.9	221.6	188.3	162.8
Std. Dev.	101.4	115.0	74.5	116.2

4 FOREST BACKSCATTER MODELING

L-band backscatter from forests depends not only on the forest structure (density of foliage, branches and trunks, moisture content of trees and ground, and soil roughness) but it is also related to the SAR imaging system (i.e., incidence angle, spatial resolution, polarization). The wavelength of L-band (23.5 cm) is such that in forested areas the wave partly penetrates into the upper layers of the canopy, interacts with the main branches and can give rise to double-bounces between trunk and ground.

4.1 *L-band water cloud model*

For this analysis, we assumed that the tree-ground double bounce is negligible with respect to the direct scattering from ground and vegetation, in accordance with previous studies carried out in boreal forests (Askne *et al.* 1995, Israelsson *et al.* 1995, Baker & Luckman 1999, Fransson & Israelsson 1999). The assumption can be motivated considering the rough topography of the ground, which can significantly deflect the double-bounce away from the radar (Ranson & Sun 1994, Pulliainen*, et al.* 1999), and the thick and dense canopy, which can strongly attenuate the incoming wave (Ulaby *et al.* 1990, Chauhan *et al.* 1991, Shinohara *et al.* 1992, Fleischman *et al.* 1996).

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

$$\sigma^o_{for} = (1-\eta)\sigma^o_{gr} + \eta\left[\sigma^o_{gr}T_{tree} + \sigma^o_{veg}(1-T_{tree})\right] \quad (1)$$

The forest backscatter, σ^0_{for}, is modeled as a sum of 1) direct scattering from the ground through the canopy gaps, 2) direct ground scattering attenuated by the canopy and 3) direct scattering from the forest canopy. The first two terms form the ground contribution; the third expresses the vegetation contribution to the total forest backscatter. In order to take into account the gaps in the canopy, each term is weighted by the area-fill factor, η. This coefficient represents the fraction of ground covered by tree crowns from the radar's perspective and is a forest property that should be independent from frequency and viewing angle.

In (1) σ^0_{gr} and σ^0_{veg} represent the backscatter from the ground and the vegetation layers respectively, while T_{tree} is the two-way transmissivity through the tree canopy. This expresses how much the incoming energy gets attenuated when it passes through the tree canopy. Equation (1) can be rearranged in order to highlight the scattering components from the ground and the vegetation:

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

where

$$T_{for} = \left[(1-\eta) + \eta T_{tree}\right] \quad (3)$$

represents the two-way transmissivity through the whole forest canopy.

In (Pulliainen *et al.* 1994) the forest transmissivity has been expressed as $e^{-\beta V}$, where V is the stem volume and β is an empirically defined coefficient. Hence, the forest backscatter in (2) can be expressed as a function of stem volume and (3) becomes:

$$\sigma^o_{for} = \sigma^o_{gr}e^{-\beta V} + \sigma^o_{veg}\left(1-e^{-\beta V}\right) \quad (4)$$

4.2 *Model training*

Equation (4) includes three unknown parameters: the ground and vegetation backscatter coefficients (σ^0_{gr} and σ^0_{veg}) and the two-way forest transmissivity coefficient, β, which need to be estimated using a set of backscatter and growing stock volume measurements (training set).

In (Kurvonen*, et al.* 1999, Santoro*, et al.* 2002a) a least squares regression between measured and modeled backscatter was considered. Nevertheless, it can be argued that the two-way forest transmissivity does not change in time significantly; therefore, it can be assumed to be constant, thus reducing the number of unknowns to two. In (Askne*, et al.* 2003) a comparison between the two approaches has been carried out at a forest estate in Sweden, showing β=0.004 ha/m^3 at stable meteorological conditions. In this work a constant β equal to 0.004 ha/m^3 has been used.

4.3 *Model inversion*

Model training was performed at each test separately. Due to the large area of each compartment and the rather large number of stands, two different types of training and test sets were formed:

1) The compartment was divided in four equal sectors and all stands in one area were used for training, whereas the rest was used for testing. The part showing the most uniform distribution of volumes in the interval of values measured in the compartment was chosen as training set.
2) After sorting the stands for increasing volume, three groups were considered and every third stand was included in each group. With this procedure, three sets with almost the same distribution of growing stock volumes were obtained. Alternately, one group was used for training whereas the other two formed the test set.

Although the first method was more rigorous, since training was performed on a small area (40-50 km^2), the estimates of growing stock volume from the inversion were likely to be affected by spatial heterogeneities of the environmental conditions in the large test area. With the second method the spatial heterogeneity was included in the training set, thus affecting the accuracy of the model parameters estimates. Nevertheless, we ensured that the training and the test set were as similar as possible in terms of volumes distribution and had similar backscatter properties.

Once the unknown parameters have been estimated, it is possible to invert Equation (4) to retrieve growing stock volume from stand-wise forest backscatter measurements, using a set of data independent from those used for training the model. Because of the increasing trend for increasing growing stock volume, the retrieved growing stock volume was put equal respectively to 0 m^3/ha or the highest growing stock volume measured in the training set, depending whether the measured backscatter was below the smallest backscatter or above the highest backscatter obtained from the model.

To evaluate the accuracy of the retrieval the coefficient of determination (R^2) and the root mean square error (*RMSE*) have been considered. Correction for the errors in the *in situ* measurements could not be performed, although a rough correction factor of 20% has been included in the final evaluation. Since the four compartments were characterized by different growing stock volume distributions, comparison of results was carried out by means of the relative RMSE, defined as ratio between the RMSE and the mean ground-truth growing stock volume.

5 RESULTS

The backscatter of stands with a marked topography (i.e. standard deviation of height greater than 5 m) did not show a clear difference when compared to stands having flat topography. Furthermore, a radiometric correction for the topography did not seem to have a strong effect (see Fig. 2). The correction was performed using the local angle between the surface normal and image plane normal (Ulander 1996) obtained from the DEMs and the orbital data.

The dependence of the backscatter upon the environmental conditions for sparse (V < 50 m^3/ha) and dense forests (V > 250 m^3/ha) is illustrated in Fig. 3 as function of the image number. For each acquisition, the conditions were rather similar at all compartments, which explain the short error bars indicating the standard deviation of the backscatter.

Table 4 reports the highest retrieval accuracy measured at each compartment using one third of the stands as training set. Since the distribution of volumes within the three groups of stands was very similar, the retrieval did not show relevant differences. Worse results were obtained when training was based on the first procedure presented in the previous Section, using one of the four sectors. The spatial differences in the relationship between backscatter and growing stem volume were the main reason for the lower accuracy. Furthermore, when a training sector included an insufficient and non-uniformly distributed set of samples, an additional error source worsened the estimates of the model parameters, thus introducing a relevant noise component in the retrieved growing stock volume.

Whichever combination of estimates was considered, multi-temporal filtering allowed reducing the estimation error slightly. A rough correction for the uncertainty in the *in situ* measurements was further applied. A relative error of 20% was considered reasonable. The multi-temporal retrieval error after correction has been reported in Table 5.

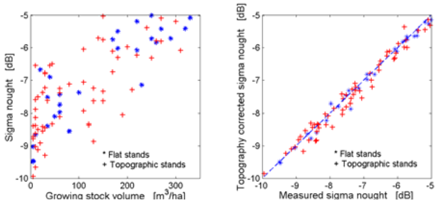

Figure 2. Distribution of the backscatter coefficient as function of growing stock volume (left) and comparison between measured and corrected sigma nought (right) at Bolshe-1 for the image acquired on 3 July 1997.

6 DISCUSSION

6.1 *Topographic effects*

The results presented in Fig. 2 should be due to the strong volume scattering occurring at L-band and the inaccuracy of the DEMs used for the determination of the topography. At L-band the dominant scattering related to volume effects in the forest canopy makes the ground contribution to the total forest backscatter negligible (see the following Section as well). Hence, the effect of the ground topography on the backscatter can be considered not as relevant as at higher frequencies, where an accurate estimation of the slopes is needed (Rauste 1990, van Zyl 1993, Luckman 1998, Smith *et al.* 2001). The GTOPO30 DEM is rather accurate in Siberia (18 m) but has a resolution of 30 arc seconds, which is too coarse considering the fine topographic details of the area of interest (see (Balzter*, et al.* 2002)). The interferometric DEM, despite being more accurate and having higher resolution, rigorously speaking is not the most suitable product for topographic correction in areas where vegetation grows. Since forests introduce additional topographic features, which furthermore are characterized by strong noise due to the low coherence, the interferometric DEM does not give a true representation of the ground topography.

6.2 *Seasonal dynamics*

The sensitivity of the L-band backscatter to forest attributes is shown in Fig. 3 by the clear difference between the values registered in sparse and dense forests. In sparse forests, the ground contribution was dominant and the backscatter was mainly affected by the dielectric properties of the forest floor. In dense forests, the total forest backscatter was determined by the volumetric effects in the forest canopy. The level of power scattered back to the radar depended mostly on the dielectric properties of the vegetation.

Table 4. Best RMSE (in m^3/ha), relative RMSE (in %) and corresponding R^2 for the retrieval based on a single image.

	RMSE	Rel. RMSE	R^2	Date
Bolshe-1	61	56	0.71	Feb 97
Bolshe-2	86	39	0.52	Apr 97
Bolshe-3	95	51	0.35	Feb 97
Bolshe-4	71	43	0.7	Apr 97 Aug 98

Table 5. Best corrected RMSE (in m^3/ha) and relative RMSE (in %) for the multi-temporal combination of all images available at a forest compartment.

	RMSE	Rel. RMSE
Bolshe-1	57	51
Bolshe-2	74	33
Bolshe-3	87	46
Bolshe-4	63	39

For unfrozen conditions (image numbers from 9 to 13) both in sparse and dense forests the backscatter was found to be higher than for frozen conditions (image numbers 1, 2, 4, 5 and 7). A frozen canopy and a frozen ground scatter with less power because the dielectric constant is much smaller. Moreover, an incoming wave penetrates the canopy deeper and the percentage of ground seen by the radar increases. Similar results were reported in (Pulliainen*, et al.* 1999) using a set of JERS images for a Finnish forest and in (Rignot *et al.* 1994) where 35° incidence angle AIRSAR data from Alaska showed an increase of 6 dB from winter-frozen to spring conditions.

Although for unfrozen conditions the dynamic range was larger than for frozen conditions, the variability of the measurements was stronger in the first case. In sparse forests this was due to the strong sensitivity of the backscatter to the growing stock volume, whereas in dense forests the sensitivity was almost absent and the dispersion could be related to inhomogeneity of the environmental conditions in the area investigated (Fig. 4).

For unfrozen conditions two cases of rainfall at acquisition were registered (images no. 12 and 13). Surprisingly the backscatter was lower than for dry conditions (images no. 9, 10 and 11) both in sparse and in dense forests. For a test site in Sweden it was shown that at similar environmental conditions rain did not seem to affect the backscatter (Santoro*, et al.* 2002a, Askne*, et al.* 2003). Hence, a possible explanation could be the different processing methods used for the calibration of images no. 12 and 13 with respect to the others.

The only clear case of freezing was registered in October 1996 (image no. 3). The backscatter in sparse forests was closer to values measured for frozen conditions, whereas dense forests still showed a backscatter typical of unfrozen conditions. Probably the fluids in the trees were still active but the moisture in the ground had already turned to the solid state.

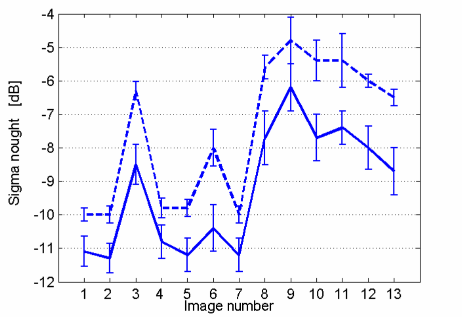

Figure 3. Run of the backscatter coefficient in sparse forests, i.e. with volumes below 50 m^3/ha, (solid line) and in dense forests, i.e. with volumes above 250 m^3/ha, (dashed line).

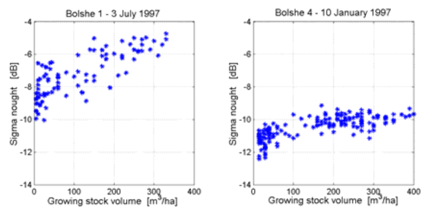

Figure 4. Distribution of backscatter as function of growing stock volume for unfrozen (left) and frozen (right) conditions.

Thaw could be easily identified in April 1997 when the temperature had been above 0 °C for some days before the acquisition (image no. 8). Compared to the previous acquisition, the backscatter increased, reaching a level typical of unfrozen conditions. It is interesting to notice that, although images no. 6 and 7 were acquired with an interval of two days, the backscatter in particular in dense forests showed different levels. The weather data reported temperature around 0 °C and a decrease of the snow layer at the first acquisition, after which the temperature dropped to –30 °C in one day. 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 increase of the backscatter. The large spread of the measurements showed the spatial heterogeneities of the snow conditions. Because of refreezing, the backscatter registered at the second acquisition had returned to values typical of frozen conditions.

6.3 *Backscatter modeling*

The estimates of the two model parameters unknown in Equation (4) coincided with the backscatter values reported in Fig. 3. The model-based curves obtained from using a constant β did not differ significantly from the one determined assuming three unknown parameters in the model. Discrepancies were found only in cases of changing weather conditions (snowmelt or rainfall), thus confirming the results presented in (Askne*, et al.* 2003) at another boreal test site.

The accuracy of the two backscatter coefficients σ^0_{gr} and σ^0_{veg} was much bigger than for the coefficient β. The uncertainty in the estimates of β was particularly relevant when the growing stock volumes used for training were not uniformly distributed in the interval of values typical for the area. This was mostly a consequence of the fact that the percentage of stands in the interval of volumes where commonly saturation of the signal at L-band occurs (i.e. between 50 and 150 m^3/ha) was small. On one hand this allowed the use of constant β=0.004, because it was a value that performed as good as many others, on the other hand it did not permit to state whether such value is the most correct to be used.

6.4 *Growing stock volume retrieval*

Retrieval of growing stock volume depended on the seasonal conditions and on the accuracy of the model training.

Frozen conditions were found to be the less suitable for the retrieval because of the reduced sensitivity to forest properties and the saturation occurring at very low stem volumes. Periods of thaw and freezing were characterised by strong sensitivity up to approximately 150-200 m^3/ha, after which saturation set in, thus decreasing the accuracy of the retrieval. Similar results were obtained for unfrozen conditions in case of rainfall. Dry-unfrozen conditions seemed to be the most suitable for the retrieval. We did not notice saturation in the intervals of growing stock volumes given in the database (i.e. up to 400 m^3/ha), although the large dispersion of the measurements in dense forests introduced relevant errors in the growing stock volume estimates.

In absolute terms the best accuracy was obtained at dry-unfrozen conditions in Bolshe-1. Cases of changing weather conditions were found to be reasonable as well (see Table 4 for Bolshe-4). The unsuitable weather conditions for retrieval and the rather high stem volumes at Bolshe-2 explained the large RMS error. Although the weather conditions were the same when images were acquired over Bolshe-1 and Bolshe-3, worse results were obtained at the second compartment because of the lack of stands up to 100 m^3/ha. This affected the model training negatively and therefore the accuracy of the inversion.

When comparing retrieval accuracies, the values obtained at Bolshe-2 and Bolshe-4 were lower than at Bolshe-1 because of the different distribution of stem volumes at each compartment (see Table 4). Compared to the best accuracy obtained at the Swedish test site of Kättböle (25 %), the error in Siberia was higher probably because of the much larger area investigated in this study and the inaccurate *in situ* measurements (Santoro, *et al.* 2002a, Askne, *et al.* 2003). Moreover, the effect of different managements systems should be taken into account.

Using a multi-temporal combination of single-image estimates, the amount of images used did not seem to be relevant. The values reported in Table 5 corrected for a conservative and approximate error in the ground-truth data showed that it is possible to obtain estimates of growing stock volume comparable to the values obtained using the traditional inventory method in the region of Bolshe-Murtinsky. In particular the accuracy of the retrieval is high up to 200 m^3/ha, suffering from errors in very dense forests.

7 CONCLUSIONS

In this paper we have shown how seasonal conditions, topographic effects, ground-truth reference data and a model-based approach affect the retrieval of growing stock volume at four forest compartments in Siberia using JERS L-band backscatter measurements at stand level.

Topography does not seem to influence the backscatter in dense forested areas, because of the strong volume scattering. Even in sparse forests, where the ground contribution is stronger, a topographic correction did not seem necessary. The unavailability of an accurate DEM limits the conclusions to the true effect of the topography on the backscatter.

In Siberia the strong seasonal differences are shown by the backscatter both in dense and in sparse forests. The dielectric properties of the ground and the vegetation are the main causes of the backscatter level. At frozen conditions the backscatter is lower than at unfrozen conditions. Intermediate levels are observed in cases of thaw and freezing. The dynamic range is larger for unfrozen conditions, which suggests that images acquired in spring and in summer are more suitable for forest parameters estimation. Nevertheless it must be taken into account that spatial heterogeneities within the imaged scene can cause large dispersion of the backscatter, thus reducing the estimation accuracy.

Backscatter modelling by means of the Water Cloud Model has shown the importance of the ground-truth data. These must be accurate and uniformly distributed in the range of growing stock volumes typical for the area under investigation. Large errors and strong uncertainty affect the model parameters especially in training sets lacking stands with volumes around the saturation level at L-band.

Model-based retrieval of growing stock volume performs best at unfrozen conditions, being mainly influenced by spatial heterogeneities of the backscatter. When weather changes occur (thaw, freeze and rainfall), although there is high sensitivity for low volumes, saturation in dense forests limits the retrieval accuracy. Frozen conditions are the least suitable for the inversion. With a multi-temporal combination the estimation error decreases, but still the effects of the weather conditions are considerable.

Results are slightly worse than those obtained at a small Swedish test site, from which accurate *in situ* measurements were available. This is mainly due to the size of the area investigated and to the inaccuracy of the ground-truth data. Nevertheless the retrieval accuracy can be considered reasonable, thus showing the consistency of L-band backscatter measurements for the retrieval of forest stem volume in the whole boreal belt. This can be considered an important benchmark for the forthcoming ALOS satellite, which will carry a fully polarimetric L-band sensor onboard.

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