Estimation of Forest Parameters Using CARABAS-II VHF SAR Data

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***Abstract*—The use of airborne CARABAS-II VHF (20–90 MHz) SAR data for retrieval of forest parameters has been investigated. The investigation was performed at a test site located in the southwest of Sweden consisting mainly of Norway spruce forests. Regression models predicting forest parameters from radar backscattering amplitude were developed and evaluated. The results showed a linear relationship between backscattering amplitude and forest stem volume, stem diameter, and tree height. The analysis also showed that the radar signal is strongly affected by ground slope conditions. The root mean square errors from the regression analysis, restricted to forest stands on near-horizontal ground, were found to be 66 m^3 ha^{-1}, 3.2 cm, and 2.3 m for stem volume, stem diameter, and tree height respectively. No saturation of the backscattered signal was observed up to the maximum stem volume of 625 m^3 ha^{-1}, corresponding to a biomass of 375 tons ha^{-1}. The results imply that VHF SAR data have significant potential for operational use in forestry.**

***Index Terms*—CARABAS, SAR, VHF, forest parameter estimation.**

I. INTRODUCTION

IN forestry activities, reliable data are needed for both short- and long-term planning. The traditional methods used for acquiring forest data at reasonable accuracy are very expensive and labour intensive. New cost-effective methods for data collection are needed to meet the requirements being imposed on timber supplies and environment conservation. In a global perspective, information about forest resources is also needed for climate modeling [1] and monitoring of deforestation.

In this context, remote sensing in combination with field measurements is of interest for forest monitoring and inventory due to the possibility of covering large, sparsely populated areas at low cost with high temporal resolution. Recently, promising results have been shown using radar and optical data from both airborne and spaceborne systems.

In forestry planning, the most important parameter is the stem volume measured in m^3 ha^{-1}, i.e. the average volume per hectare of all trees in a stand, including bark but excluding branches and stumps. A related and commonly used parameter in climate studies, is the dry above-ground biomass measured in tons ha^{-1}. The two parameters are approximately related by a factor 0.6 in Scandinavian conditions [2], i.e. 100 m^3 ha^{-1} $\approx$ 60 tons ha^{-1}.

Optical remotely sensed data from satellites have shown to be useful for monitoring of major changes in forests, i.e. clear-cuttings, forest fires, and other deforestation. At a regional level and sub-regional level, i.e. areas >100 ha, satellite optical data also give reasonable estimates with a root mean square error (RMSE) of 10% for stem volume in boreal forests [3]. A study performed at forest stand level (5 ha) using satellite optical data resulted in RMSE's of 24–38% for stem volume in the range of 0–305 m^3 ha^{-1} [4]. In a global view, the availability of optical remotely sensed data is however, limited due to the requirement for cloud free conditions and daylight. By using radar sensors, imaging can be performed in almost any weather conditions and independently of daylight. However, it has been shown that the backscattered radar signal saturates at a constant level for SAR systems using microwave frequencies at forest biomass above 40–100 tons ha^{-1} [5]. This is due to the high attenuation in the canopy and that twigs, needles, and smaller branches in the top layers of the canopy are the major scatterers at these wavelengths. Using lower frequencies, e.g. P-band (440 MHz), the sensitivity to biomass increases, but saturation still occurs for rather low biomasses (100–200 tons ha^{-1}) [5], [6].

A different approach is to use SAR interferometry for forest parameter retrieval, i.e. two or more coherent SAR images of the same area [7]. In [4] ERS-1/2 one-day repeat-pass coherence measurements were found to be linearly related to standwise forest stem volume. For the best interferogram the RMSE was approximately 26 m^3 ha^{-1} throughout the range of stem volume (0–305 m^3 ha^{-1}). However, varying external conditions, like wind speed, precipitation, and temperature are likely to degrade the robustness of this method.

Clearly, the above-mentioned results using UHF-band (P-band) and microwave SAR suggest that lower SAR frequencies are necessary to facilitate forest parameter retrieval for medium/high biomass forest stands. The airborne coherent all radio band sensing (CARABAS) SAR operates at even lower frequencies, i.e. 20–90 MHz in the VHF-band [8]. Flight campaigns conducted with the first version of the sensor showed promising results over oak forests. No saturation level was observed for the maximum forest stand volume of 280 m^3 ha^{-1} [9], [10]. During the last two years, flight campaigns over various forested areas have been conducted using the improved CARABAS-II system. In [11], no saturation of the backscattered signal was observed over boreal conifer forests for the maximum stem volume of 550 m^3 ha^{-1}.

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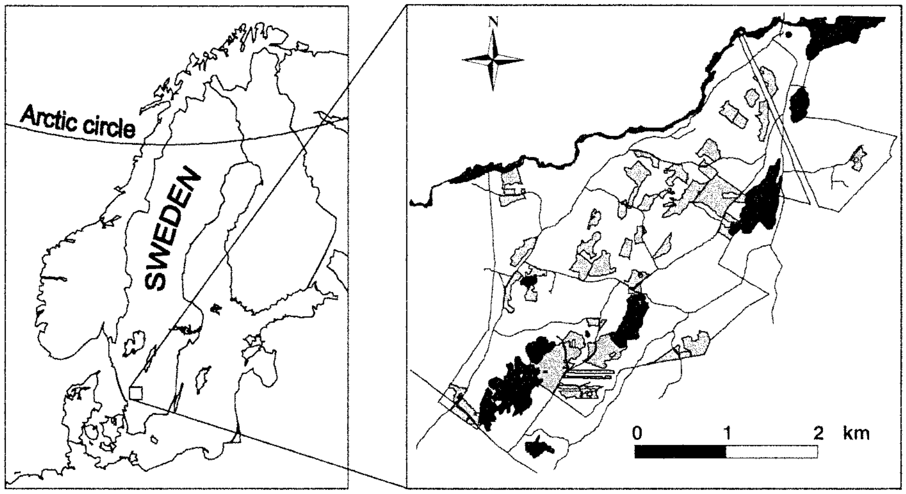

Fig. 1. Test site location showing the 41 randomly sampled and objectively inventoried forest stands shaded grey.

The objectives of this study are to investigate the use of CARABAS-II ultra-wideband VHF SAR data for standwise estimation of forest stem volume, stem diameter, and tree height, and to investigate the saturation level of the backscattered radar signal for forest stem volume. The forest parameters investigated are some of the most important variables for planning of forestry activities, according to major Swedish forest companies [12].

II. Test Site Description

The test site, Tönnersjöheden, is located in the southwest of Sweden, at Lat. 56° 41′ and Long. 13° 06′ (Fig. 1). Tönnersjöheden is a forest research park managed by the Swedish University of Agricultural Sciences, with about 1000 ha of mainly conifer forest. The prevailing tree species is Norway spruce (*Picea abies*) but some Scots pine (*Pinus sylvestris*) and deciduous tree species (e.g., beech *Fagus sylvatica*) are also present. The tree species composition is approximately 75% spruce, 11% pine, 11% deciduous trees, and 3% foreign species. The test site is located in one of the most productive areas concerning stem volume, holding the highest stem volumes found in Sweden. The dominant soil type is till (i.e., coarse and mainly podsolic soils of glacial origin, with a field layer consisting of blueberry, *Vaccinium myrtillus*, cowberry *Vaccinium vitis-idaea*, and different grass and herb species). The ground elevation varies from 55 to 140 m above sea level.

III. Ground Data

In forestry planning, inventories are usually performed at forest stand level where a number of forest parameters are measured, including stem volume, stem diameter, and tree height. A forest stand consists of a relatively homogeneous forest in terms of tree species composition, site, and logging conditions. The stand constitutes the primary mapping and description unit used for forestry planning.

Standwise field measurements at Tönnersjöheden were carried out in 1998 and 1999, including both a subjective and an objective field inventory. A subjective inventory is characterized by field crew judgements, supported by sparse measurements at subjectively chosen plots, whereas an objective inventory is strictly performed according to statistical sampling theory, guaranteeing unbiased results. The subjective measurements were performed across the entire research park in order to update the existing forest stand data base. The standard error for the subjective measurements is difficult to determine, but typically, the error is 20% of the estimated stem volume [13]. The subjective inventory also resulted in a digital forest map of approximately 800 forest stands. The subjective data set was used for selecting forest stands to be measured in the subsequent objective inventory. Forest stands consisting of more than 70% Norway spruce, located on relatively flat terrain, with soil moisture class mesic [14] and with an area larger than 2 ha were selected. The data set containing the selected forest stands was stratified on stem volume into six strata in the ranges of 0–99, 100–199, 200–299, 300–399, 400–499, and $>500 \mathrm{m}^3\mathrm{ha}^{-1}$. The stratification was carried out in order to assure full coverage of stem volumes in the analysis. From the stratified data set, eight forest stands were randomly drawn from each stratum. In strata with eight stands or less, all stands were selected. Ground data were measured *in situ* for 41 sampled stands using "the forest management planning package" [15]. In each stand, circular sample plots with a radius of 5 or 10 m were placed in a randomly positioned systematic grid (Fig. 2). The plots with 5-m radii were used for forest stands with more than 1700 stems per hectare. On average, nine sample plots were measured in each stand. All trees on each plot were calipered at breast height (i.e. 1.3 m above ground surface), and for randomly selected sample trees, chosen with a probability proportional to basal area, tree height was also measured. Hence, ground data were collected using an objective and unbiased method. The stem volumes were in the range of 0–625 m^3 ha^{-1}, with an average stem volume of 312 m^3 ha^{-1}. The average accuracy at stand level, in terms of standard error, was 10% for the stem volume estimates.

The accuracy of the subjective stem volumes can be improved by calibration. Forest stands with both subjectively and objectively estimated stem volumes were used to derive a calibration function through linear regression analysis according to

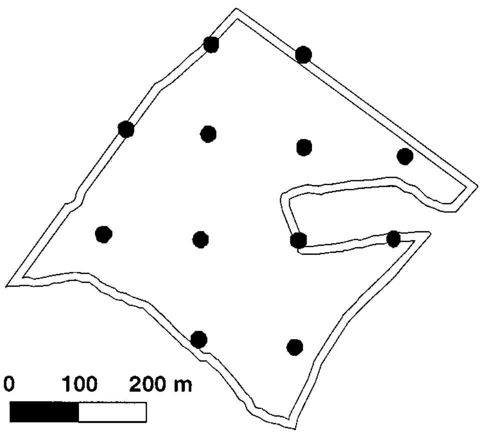

Fig. 2. Objectively inventoried forest stand with a buffer zone of 10 m and sample plots (i.e. the filled circles) in a randomly positioned systematic grid. The positions of the sample plots were determined by posterior GPS measurements.

Madansky [16]. The derived calibration function was $v_{\rm cal} = 25.2 + 1.028v_{\rm subj}$, indicating an underestimation of the subjective stem volume of about 25 m^3 ha^{-1} or more. Thus, by applying the calibration function, the systematic errors of the subjective stem volume estimates were removed.

For the subjective data set, a selection criterion of more than 70% of conifers (*Picea abies, Picea sitchensis, Picea mariana, Pinus sylvestris, Larix decidua, Larix leptolepis, Larix eurolepis, Abies grandis, Abies alba, Pseudotsuga menziesii*) and stand sizes larger than 0.5 ha was used. In total, 347 forest stands were left for the subsequent analyses.

IV. SAR Data

The airborne CARABAS-II SAR system operates at HH-polarization with frequencies from 20 to 90 MHz (VHF-band), corresponding to wavelengths between 3.3 and 15 m [8]. Two wideband dipoles are mounted in the front of the aircraft, illuminating a half-plane to either the right or left side of the flight track.

The flight campaign over Tönnersjöheden, CARTOON, was conducted in October 1997. The SAR data were acquired from eight different flight paths illuminating the test site in four directions, perpendicular or parallel to each other. The data were captured at a flight altitude of 3600 m above sea level at various depression angles ϕ.

The SAR processing was performed by global back projection, which rigorously integrates all image resolution cells in the range-compressed radar data along the flight path. A nominal reference height, corresponding to the average elevation of the area studied, was applied in order to focus each specific target in space while the platform was deviating from a straight flight path [17]. Flight track positions were provided by two GPS receivers, one onboard and one on the ground, from which data were postprocessed in a phase-differential mode to achieve dm accuracy. Subsequent radio interference rejection and frequency-domain filtering were carried out for all images. A trihedral, deployed in an open field adjacent to the forest, was used to perform radiometric calibration of the images [11] at an accuracy better than ± 1 dB. The radar cross section (RCS) in m^2 is determined from the calibrated SAR image by squaring the magnitude of the complex pixel value.

The SAR processing resulted in 2×2 km complex slant range images with a spatial resolution of approximately 3×3 m and a pixel size of 1×1 m. In total, eight images acquired from one single flight path were used for the analyses, with incidence angles θ in the range of 45°–67°.

In order to efficiently extract SAR data from the complex slant range images, the digital forest map was transformed to slant range by using an automatic geocoding algorithm [18]. The geocoding algorithm utilizes the recorded flight parameters and a coarse scale (50×50 m) digital elevation model (DEM) for the transformation of data from ground range to slant range. The average displacement between forest stand boundaries and corresponding boundaries visually identified in the images was found to be 3.4 m, with a maximum displacement of about 10 m. The displacements were mainly caused by the coarse scale DEM and errors in the digital forest map. Therefore, the original forest stand boundaries were shrunk by a distance of 10 m (Fig. 2). This action did not improve the accuracy of the forest parameter estimates and thus, the original stand boundaries were used. Disturbing nonforest objects (e.g. power lines, buildings, and fences were manually detected and excluded from the extraction of image data). Areas affected by image artefacts (i.e., produced by strong scattering objects originating from the opposite illumination side of the flight path) were also excluded from the images.

According to Smith and Ulander [11], a simple model of the dihedral ground-trunk mechanism can often be used for explaining VHF-band backscattering from mature coniferous trees on horizontal ground. The radar cross section σ_j of a single tree j on horizontal ground is hence modeled by

$$\sigma_j \propto V_j^2 \tag{1}$$

where V_j is the volume of the single tree. The Fresnel amplitude reflection coefficient, the two-way loss caused by the attenuation in the forest canopy, and the dielectrical properties of the single trees are assumed to be constant for the investigated stands.

For a distributed target (e.g., a forest stand, the backscattering coefficient σ° is modeled by

$$\sigma^\circ \propto \frac{\sum_{j=1}^{N} V_j^2}{\rm area} \tag{2}$$

where N is the number of trees.

The backscattering coefficient for each forest stand was calculated from SAR image data according to

$$\sigma^\circ = \frac{1}{n}\sum_{k=1}^{n}\left({\rm Re}_k^2 + {\rm Im}_k^2\right)\frac{\cos\psi_k}{dx\,dr} - \sigma^\circ_{\rm noise} \tag{3}$$

where n is the number of pixels for a given forest stand ${\rm Re}_k$ and ${\rm Im}_k$ are the real and imaginary part of the complex kth pixel value, $\cos\psi_k$ is the projection factor for slope correction [19] associated with pixel k (calculated using the DEM), dx and

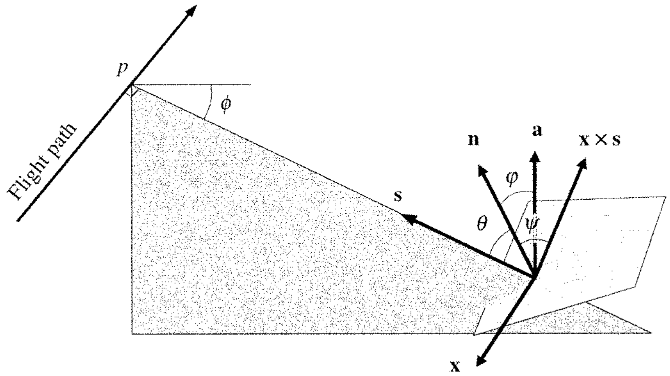

Fig. 3. Three-dimensional geometry of a surface patch viewed from the sensor at position p. The angles depicted are the local incidence angle θ, depression angle ϕ, ground slope φ, and the angle between the surface plane normal and slant range image normal ψ, used for calculation of the projection factor. The vector $\mathbf{n}$ is the surface normal calculated from a triangulation of the DEM (i.e., the light grey surface region $\mathbf{a}$ is the horizontal surface normal, $\mathbf{x}$ is the vector parallel to the flight path $\mathbf{s}$ is the slant range vector, and $\mathbf{x} \times \mathbf{s}$ is the slant range image normal.

dr are the pixel sizes in azimuth and slant range direction, and $\sigma^\circ_{\text{noise}}$ is the noise constant calculated as

$$\sigma^\circ_{\text{noise}} = \frac{1}{m}\sum_{k=1}^{m}\left(\text{Re}_k^2 + \text{Im}_k^2\right)\frac{\cos\psi_k}{dx\,dr} \tag{4}$$

where m is the number of pixels over a smooth lake surface within the test site, assumed to have an average signal near the system noise floor.

In order to use model (2), knowledge of stem volume distribution and stem number density is required. Instead, standwise radar backscattering amplitude s° was calculated in order to directly relate stem volume to radar backscattering. Derived from model (1), the backscattering amplitude is modeled by

$$s^\circ \propto \frac{\sum_{j=1}^{N} V_j}{\text{area}}. \tag{5}$$

The models (2) and (5) require that the single trees are resolved in the SAR image data.

The backscattering amplitude for each forest stand was calculated from SAR image data according to

$$s^\circ = \frac{1}{n}\sum_{k=1}^{n}\sqrt{\left(\text{Re}_k^2 + \text{Im}_k^2\right)\frac{\cos\psi_k}{dx\,dr} - \sigma^\circ_{\text{noise}}}. \tag{6}$$

Additionally, standwise local incidence angle θ, depression angle ϕ, and ground slope φ were also calculated (Fig. 3).

V. Methods

The analysis was divided into two parts where the objective and subjective forest data sets were investigated separately. The accuracy assessment of forest parameter estimations using SAR data was carried out using the objective measurements. The subjective data set, with a larger number of observations, formed the basis of a sensitivity analysis in which the effect of ground slope on backscattering amplitude was examined. All analyses were performed at forest stand level.

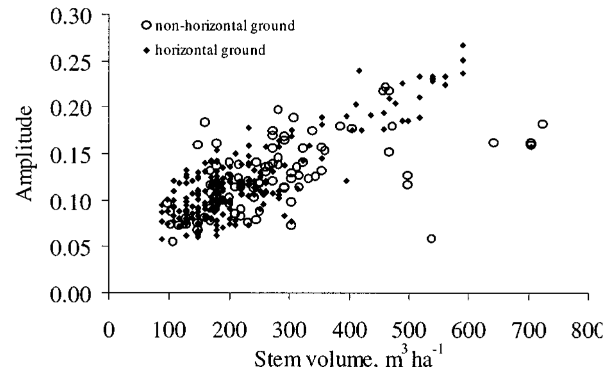

Fig. 4. Backscattering amplitude plotted against calibrated subjective stem volume for forest stands on nonhorizontal ground ($\varphi > 4^\circ$) and on horizontal ground ($\varphi \leq 4^\circ$).

The sensitivity analysis showed that the slope conditions strongly affected the radar backscattering, as illustrated in Fig. 4. However, this variability was not possible to investigate further due to the limited number of observations in the objective data set, originally selected from forest stands located on near-horizontal ground. Based on this finding, all forest stands in the objective data set with ground slope φ greater than 4° were excluded. The reason for choosing 4° as a threshold was to obtain a reasonable number of sample stands without including the ground slope extremes. Furthermore, stands with stem volumes less than 80 m^3 ha^{-1} were also excluded due to the fact that the average radar signals from these stands are near the system noise floor. This can be explained by the reduction of direct backscattering from the trees and the absence of ground-trunk and trunk-ground scattering from small trees, which are the dominant scattering mechanisms at the wavelengths used. In total, 30 objectively inventoried stands with an average area of 4.6 ha (in the range of 2–17 ha) were used in the analyses. The subjective data set was reduced for the same reasons: firstly on the criterion of stem volume and secondly on the criterion of ground slope, resulting in 296 and 201 stands respectively.

Linear regression models could now be developed for the objective data set. The selection of predictors was based on residual and coefficient of determination studies and the statistical significance of the estimated regression coefficients. The local incidence angle θ was not found to be significant as an independent variable explaining the forest parameters and was therefore excluded from further analyses.

The reduced objective data set was used to evaluate the accuracy of stem volume (m^3 ha^{-1}), stem diameter (cm) at breast height, and tree height (m) estimations using backscattering amplitude s° calculated according to (6). The following linear model was used for relating backscattering amplitude to stem volume

$$s_i^\circ = \beta_0 + \beta_1 v_i + \varepsilon_i \tag{7}$$

where s_i° is the backscattering amplitude for forest stand i, v_i is the stem volume for stand i, β_0 and β_1 are the regression coefficients, and ε_i is the random deviation for the ith stand. The variable ε_i is assumed to be normally distributed with zero expectation and variance $Var(\varepsilon)$. The coefficients β_0 and β_1 were estimated by means of ordinary least squares (OLS).

The following linear model was used for relating stem volume to backscattering amplitude

$$v_i = \alpha_0 + \alpha_1 s_i^\circ + \varepsilon_i + \delta_i \tag{8}$$

where ε_i is the random deviation from the true volume for forest stand i, and δ_i is the sampling error for the ith stand. The variables ε_i and δ_i are assumed to be independent and normally distributed with zero expectations and variances $Var(\varepsilon)$ and $Var(\delta_i)$ for each i. The regression coefficients α_0 and α_1 were estimated by means of OLS. Furthermore, corresponding models were also developed for stem diameter and tree height.

Finally, a regression model relating the backscattering coefficient σ° to the squared stem volume per hectare v^2 was developed

$$\sigma_i^\circ = \gamma_0 + \gamma_1 v_i^2 + \varepsilon_i. \tag{9}$$

When calculating the accuracy of the stem volume estimation, the effects of the sampling errors were removed from the mean sum of squared residuals MS_{res}. To a good approximation, it can be shown that

$$MS_{\text{res}} - \frac{1}{l}\sum_{i=1}^{l} \hat{Var}(\delta_i) \tag{10}$$

is an unbiased estimator of the $Var(\varepsilon)$, where l is the number of stands. For regression model (8), the variance of the sampling error $Var(\delta_i)$ is based on the ground sample plots within stands and is estimated as

$$\hat{Var}(\delta_i) = 0.5(SE_i)^2 \tag{11}$$

where SE_i is the standard error in m^3 ha^{-1} for stand i calculated from the single sample plot values. The factor 0.5 is a correction due to systematic sampling design in accordance with empirical investigations by Lindgren [20]. For the function derived from regression model (8), the accuracy was calculated using the root mean square error (RMSE) in m^3 ha^{-1}

$$RMSE = \sqrt{MS_{\text{res}} - 0.5\frac{1}{l}\sum_{i=1}^{l}(SE_i)^2}. \tag{12}$$

To evaluate the regression models, cross-validation was performed. This technique was used instead of splitting the data set into a training and validation set due to the limited number of observations (30 stands).

VI. Results

In Fig. 4, backscattering amplitude is plotted against calibrated subjective stem volume. The plot is based on the calibrated subjective data set consisting of 296 forest stands, with stem volume in the range of 80–725 m^3 ha^{-1}. The plot clearly reveals that ground slope affects the radar backscattering.

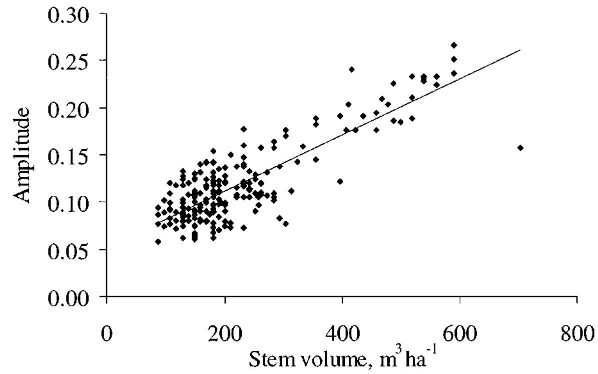

Fig. 5. Backscattering amplitude plotted against calibrated subjective stem volume with corresponding fitted regression function, derived from 201 forest stands on near-horizontal ground.

TABLE I
Results from the Regression Models Relating Backscattering Amplitude s° to Stem Volume, Stem Diameter, and Tree Height

Predictor	Predicted	β_0	β_1	R^2 (%)	*RMSE*
stem volume	s°	0.0388	0.000341	82.9	0.0261
stem diameter	s°	0.0176 *	0.00606	89.7	0.0203
tree height	s°	-0.0177 *	0.00830	90.2	0.0198

*non-zero coefficient not significant ($p > 0.05$)

In Fig. 5, the plot is based on the reduced data set consisting of 201 forest stands, excluding stem volumes less than 80 m^3 ha^{-1} and ground slopes φ greater than 4°. The stem volumes are in the range of 80–704 m^3 ha^{-1}. Furthermore, the correlation coefficient is 0.83 between backscattering amplitude and stem volume. The outlier in Fig. 5, at 704 m^3 ha^{-1} has an average ground slope of 3.96°, which is on the limit for inclusion in the data set.

Forest parameters from 30 objectively inventoried forest stands were used to evaluate the models (7) and (8), including the models for stem volume, stem diameter, and tree height. The average stem volume, stem diameter, and tree height for the selected stands were 339 m^3 ha^{-1}, 23 cm, and 21 m, respectively. The standard errors for these estimates were 10%, 4%, and 2.5%. On average, nine sample plots per stand were inventoried. In Table I, results from the regression models relating the backscattering amplitude to stem volume, stem diameter, and tree height are presented. In Table II, results from the regression models relating stem volume, stem diameter, and tree height to backscattering amplitude are presented.

In Fig. 6, backscattering amplitude is plotted against stem volume, stem diameter, and tree height for the 30 objectively inventoried forest stands with corresponding fitted regression functions.

For model (9), relating backscattering coefficient to squared stem volume per hectare v^2, the coefficient of determination R^2 was 87.8%, which corresponds to a correlation coefficient of 0.94. In Fig. 7, a plot of this relation is shown.

TABLE II
RESULTS FROM THE REGRESSION MODELS RELATING STEM VOLUME, STEM DIAMETER, AND TREE HEIGHT TO BACKSCATTERING AMPLITUDE s°

Predictor	Predicted	α_0	α_1	R^2 (%)	*RMSE*
s°	stem volume	-31.9 *	2451	82.9	65.8 m^3 ha^{-1}
s°	stem diameter	-0.36 *	148	89.7	3.2 cm
s°	tree height	3.89	109	90.2	2.3 m

*non-zero coefficient not significant ($p > 0.05$)

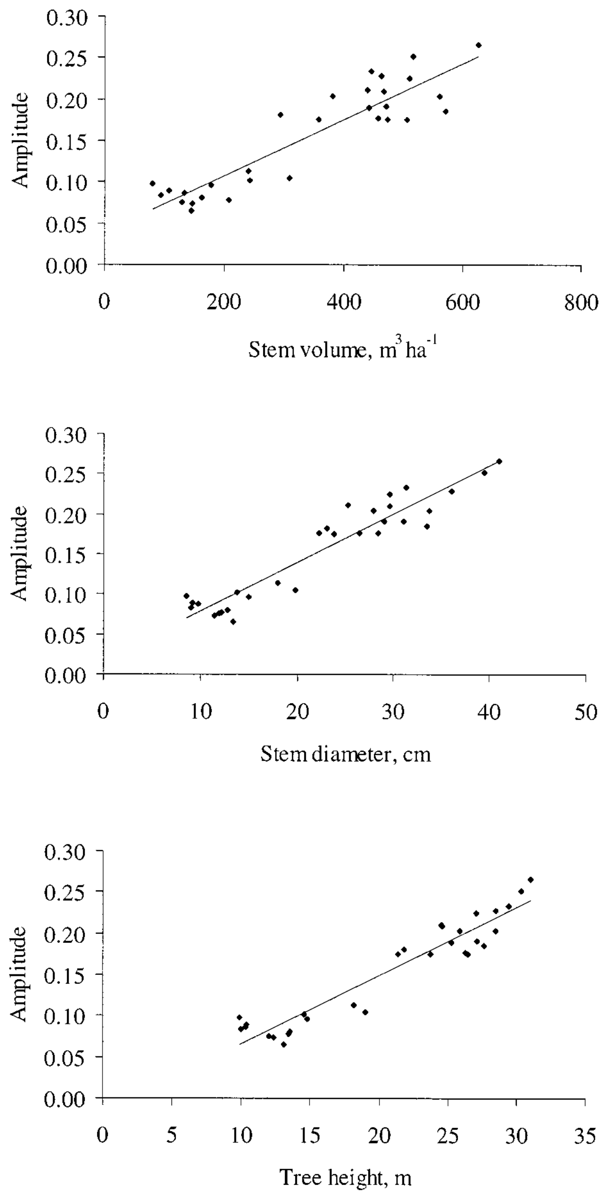

Fig. 6. Backscattering amplitude plotted against stem volume, stem diameter, and tree height for the 30 objectively inventoried forest stands on near-horizontal ground with corresponding fitted regression functions.

VII. DISCUSSION

In this study, CARABAS-II VHF SAR data have been related to forest parameters. Empirical models were constructed based on objectively inventoried stem volume, stem diameter, and

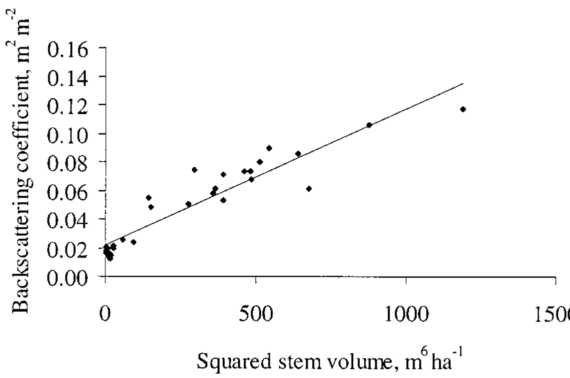

Fig. 7. Backscattering coefficient plotted against squared stem volume for the 30 objectively inventoried forest stands on near-horizontal ground with corresponding fitted regression function.

tree height in order to evaluate the estimation accuracy of these forest parameters. A larger subjectively inventoried data set was also examined to study the radar signal sensitivity to ground slope conditions. Two different radar quantities, backscattering coefficient σ°, and backscattering amplitude s° were calculated from the CARABAS-II images and related to ground data. All analyses were performed at forest stand level.

No saturation of the backscattered signal up to the maximum stem volume of 625 m^3 ha^{-1} corresponding to a biomass of 375 tons ha^{-1} was identified for the objectively inventoried data set, restricted to forest stands located on near-horizontal ground. The dynamic range of the backscattered signal over the forested areas was about 14 dB, which is clearly higher compared to conventional SAR systems using microwave frequencies [9].

For the models predicting stem volume, stem diameter, and tree height from backscattering amplitude, the RMSE's were 66 m^3 ha^{-1}, 3.2 cm, and 2.3 m, respectively. The cross-validation procedure indicated that the models were not overfitted. For the model explaining backscattering amplitude from stem volume, the offset coefficient β_0 is significant (i.e. $\beta_0 \neq 0$). This indicates that other objects or features on the ground (e.g., larger stones, small scale topography, and fallen trees, might contribute to the total backscattering from the forest. At present, however, it cannot be ruled out that the offset is not due to an error in the noise level estimate.

The coefficient of determination R^2 for the model relating backscattering coefficient to squared stem volume (87.8%) is higher than for the model relating backscattering amplitude to stem volume (82.9%). However, the former model requires *a priori* knowledge of stem volume distribution and stem number density. It is therefore preferable to use the latter model in an operational scenario.

The subjectively inventoried data set reveals that ground slope strongly affects the backscattering from forest stands, as illustrated in Fig. 4. For the densest forest stand, with a stem volume of 725 m^3 ha^{-1} and an average ground slope of 12°, the approximate drop in backscattering coefficient is 10 dB.

The simplified model (1), which is the basis for the models (2) and (5), neglects several physical mechanisms and may thus induce additional variability in the data. Examples of such factors, in addition to the previously mentioned ground slope, are interfering direct scattering from stems, scattering from primary branches, and dielectric variations of the ground or stems. Additionally, if more than one tree is positioned within a single SAR resolution cell, signal interference will inevitably occur. This effect will not produce pure speckle, since the major scattering elements (i.e., the stems) are nonuniformly distributed. At the present resolution of CARABAS-II data (3×3 m), the interference effect may become significant for forest stands with about 1000 stems per hectare or more. This corresponds to young forest stands up to approximately 200 m^3 ha^{-1} for the present forest data set. Future research should address this effect in more detail.

Today, subjective ground-based inventory methods are used in Swedish forestry to acquire forest data at forest stand level, with or without using remotely sensed data. For Scandinavian forest conditions, these methods yield standard errors of 15–25% for stem volume, 10–15% for stem diameter, and about 10% for tree height estimations [13]. The corresponding objective ground-based methods, which are seldom used for full coverage inventories, yield standard errors of about 10% for stem volume and less than 5% for both stem diameter and tree height [13]. However, the accuracy of these methods strongly depends on the number of sample plots used and the homogeneity of the forest stands, as well as personnel skills. In comparison, the average standard errors for the 30 objectively inventoried stands in this study were 10% (4–22%), 4% (2–11%), and 2.5% (1–6%) for stem volume, stem diameter, and tree height, respectively. For statistical reasons, the calculation of the standard error is performed as if the sample plots were selected as random samples. Consequently, the used systematic sampling design will overestimate the standard errors [20]. However, this overestimation should be low, since a relatively large number of sample plots were used for each stand.

The subjective and objective methods based solely on ground measurements require a lot of fieldwork and are therefore time consuming and expensive. For larger forest enterprises in Sweden, the use of aerial photo interpretation combined with field controls is the traditional way of gaining knowledge about the forests at a reasonable accuracy [21]. This corresponds to the lowest relative standard errors presented for the subjective methods above. For high stem volumes, as in the case of this study, the canopy is often fully closed. Under these conditions, the standard errors will increase considerably.

In this study, the accuracy in terms of RMSE was found to be approximately constant throughout the range of stem volumes for the forest parameters investigated. This implies that the relative accuracy increases as the stem volume, stem diameter, and tree height increase. For forestry planning, this is an advantage, as the requirements on accuracy increase as the forest approaches the final stage of harvesting. The results obtained in this study are comparable to subjective forest inventories above 320 m^3 ha^{-1} (20%), 32 cm (10%), and 22 m (10%) for stem volume, stem diameter, and tree height, respectively.

VIII. Conclusion

The ground-trunk scattering is the main scattering mechanism from conifer forests at the wavelengths used. A scattering model has been used to develop parameter-retrieval algorithms. However, sloping terrain, attenuation in the forest canopy, dielectric variation between tree species, and direct backscattering have not been taken into account in the models. Further research on modeling the factors mentioned has to be performed in order to explain the total variation in data. For forest stands on near-horizontal ground, the above factors are of second-order effects, when relating forest stem volume, stem diameter, and tree height to backscattering amplitude. The results are satisfactory and comparable to better subjective inventories for denser forest stands larger than 2 ha. The influence of varying incidence angle is of no significance for the backscattering mechanism, which also has been indicated in [11].

The investigation shows the great importance of using high spatial resolution ground data with high and measurable accuracy. Otherwise, the variation caused by the factors above cannot be explained or validated.

In order to study even smaller units on the ground (e.g., sample plots and single trees), the digital elevation model must have a much higher resolution than the coarse scale DEM used in this study. This is a prerequisite for improving geocoding, correctly calculating the correct projection factor, and for studying effects of ground slopes. In [22], Ulander and Frölind concluded that ultra-wideband SAR interferometry, using the CARABAS-II sensor, has a potential for automated and rapid high spatial resolution, wide-area topographic mapping.

The tools for automatic geocoding [18] and extraction of CARABAS-II image data and forest data have been developed towards an operational remote sensing tool. The analysis is performed as automatically as possible with only a small amount of manual intervention. The size of the calculation unit is only limited by the SAR image resolution cell (3×3 m) and the resolution of the DEM, and can therefore theoretically be used in studies over single sample plots or single trees. The CARABAS-II sensor is also capable of capturing data with a large areal coverage rate of 1–2 km^2 s^{-1}. Altogether, these factors are prerequisites for an operational forest inventory scenario. New studies or applications using CARABAS-II data can be carried out efficiently and reliably. In conclusion, the results imply that the CARABAS-II system has significant potential for operational use in forestry.

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