New inversion approach for robust stem-volume retrieval from L-band SAR measurements with semi-empirical boreal forest model

Oleg Antropov(1) Yrjö Rauste(1) Jaan Praks(2) Martti Hallikainen(2) Tuomas Häme(1)
(1) VTT Technical Research Centre of Finland, P. O. Box 1000, FI-02044 VTT, Finland, oleg.antropov@vtt.fi
(2) Aalto University, School of Electrical Engineering P.O. Box 13000, FI-00076 AALTO, Finland jaan.praks@aalto.fi

Abstract
This paper discusses stem volume retrieval based on inversion of SAR data, and proposes a new robust inversion approach. The method used employs model fitting with an inverted semi-empirical boreal forest SAR model, and takes advantage of the multitemporal aspect in order to improve the stability and accuracy of stem volume estimation. The approach is demonstrated using multitemporal dual-pol SAR imagery acquired by ALOS PALSAR sensor during the summer-autumn 2007. Reference data used for training the model included stand-wise forest inventory data from two boreal forest sites situated in central Finland. Multitemporal combination of model output in a multivariate regression framework allows volume estimates to be obtained with an RMSE about 43% of the mean of 110 m³/ha, and a coefficient of determination R of 0.71. The methodology used can be employed to produce large-area stem volume maps from dual-pol ALOS PALSAR imagery mosaics.

1 Introduction
One of popular approaches for forest stem volume estimation based on analysis of SAR backscatter employs the so-called semi-empirical boreal forest SAR model. This model was originally introduced for use with X- and C-band SAR data [1]. However, due to a relatively weak double-bounce backscattering mechanism observed in boreal forest, which can be attributed to influence of the forest floor vegetation and hilly terrain [2] – [6], the model was found to give satisfactory results also at L-band [3], [7]. The model takes advantage of nonlinear dependency in representing the relationship between the SAR backscatter and forest stem volume, and was demonstrated to provide useful results in boreal forest mapping. However, the usual approach used for inversion of the model suffers from several inversion artifacts; those are discussed in more detail further along with a new robust inversion approach proposed.

2 Methods: SAR data analysis aimed at boreal forest stem volume retrieval
The original semi-empirical boreal forest SAR model assumes a relatively homogeneous forest canopy within a forest stand; the forest canopy backscatter is described as a function of stem volume and volumetric vegetation moisture [1], [3]. The general expression for backscatter from a forest stand with stem volume \( V \) takes the following form

\[
\sigma_{\text{model}}^0 = (C_1 - 2C_2)\left[1 - e^{2C_2 V}\right] + C_3 e^{2C_2 V},
\]

where the first additive term represents the backscattering component of the forest canopy and the second part is the backscattering contribution from the ground. At L-band, the coefficients \( C_i \) are basically empirical, and should be estimated from the training (reference) data and SAR data. An alternative formulation of the model, making it somewhat easier to provide interpretation, was given in e.g. [4]:

\[
\sigma_{\text{model}}^0 = \sigma_{\text{veg}}^0 \left[1 - e^{-\beta V}\right] + \sigma_{\text{gr}}^0 e^{-\beta V},
\]

where \( \sigma_{\text{veg}}^0 \) and \( \sigma_{\text{gr}}^0 \) are the backscatter contributions from the vegetation and ground, respectively, and \( \beta \) is a given parameter.
where $\sigma_{\text{veg}}^0$ and $\sigma_{\text{gr}}^0$ denote backscatter from the vegetation and ground respectively, and $\beta$ is an empirical coefficient. Then, on the first step of inversion, the model training is performed using nonlinear least-squares fitting for available $N$ training forest stands:

$$\hat{\beta}, \hat{\sigma}_{\text{veg}}^0, \hat{\sigma}_{\text{gr}}^0 = \arg\min_{\beta, \sigma_{\text{veg}}^0, \sigma_{\text{gr}}^0} \left\{ \sum_{i=1}^{N} \left( \sigma_{i,\text{meas}}^0 - \sigma_{i,\text{model}}^0 \right)^2 \right\},$$

(4)

where $<\sigma_{i,\text{meas}}^0>$ denotes measured backscattering coefficient spatially averaged over the $i$-th training forest stand. On the second step, the model inversion for the $j$-th stand with backscattering coefficient $\sigma_{j,\text{meas}}^0$, and stand-wise stem volume estimation for the total test site area is performed as:

$$V_{j,\text{model}} = \left( -1/\beta \right) \ln \left( \frac{\sigma_{\text{veg}}^0 - \sigma_{j,\text{meas}}^0}{\sigma_{\text{veg}}^0 - \sigma_{\text{gr}}^0} \right).$$

(5)

However, in, e.g., [4], [8] the fitting was performed using the forward model in the manner given by (4). Here, we use the inverted model (5) in the fitting procedure, in order to avoid some of the drawbacks, associated with inversion of the model fitted by (4). In particular, this can help with the problem of the impossibility of estimating stem volume for plots exhibiting $\sigma_{j,\text{meas}}^0 \geq \sigma_{\text{veg}}^0$, or producing negative stem volume estimates under $\sigma_{j,\text{meas}}^0 < \sigma_{\text{gr}}^0$. The parameters of model (5) are estimated using nonlinear least-squares optimization:

$$\hat{\beta}, \hat{\sigma}_{\text{veg}}^0, \hat{\sigma}_{\text{gr}}^0 = \arg\min_{\beta, \sigma_{\text{veg}}^0, \sigma_{\text{gr}}^0} \left\{ \sum_{i=1}^{N} \left( V_i - V_{i,\text{model}}(\sigma_{i,\text{meas}}^0, \beta, \sigma_{\text{veg}}^0, \sigma_{\text{gr}}^0) \right)^2 \right\}.$$

(6)

In the case that some estimates of stem volume still are negative, a simple decision is to mask out these areas as non-forested areas, and to set the stem volume level for them to zero. If several SAR scenes are available, they can be used in a multiple regression approach [7], considering stem-volume estimate from each particular scene as an independent variable. Then the final estimation of stem volume based on $k$ SAR images will be a linear combination of stem volume estimates from each individual SAR image. The expression for the optimal regressor takes the form

$$V_{j,\text{est}} = \overline{L_{j}V_{j,\text{est}}} + L_{2},$$

where $\overline{V_{j,\text{est}}}$ is an optimal estimate of stem volume of forest stand, $V_{j,\text{est}}$ is a vector of length $k$ of stem volume estimates of the same $j$-th stand from $k$ individual SAR images according to (5). Parameter $L_2$ is required to compensate for systematic bias, expected due to non-accounted scattering mechanisms in model (1), e.g., the missing contribution from ground-trunk interaction. Regression parameters $\overline{L_1}$ and $L_2$ are obtained at the training stage by solving the optimization problem in the least squares sense.

3 Experimental data and results

Forest stem volume mapping was studied at two sites in Finland – Kuortane and Heinävesi, which vary somewhat in forest stem volume and topography. The Kuortane site (center: 62°49’N, 23°32’E) is located in western Finland. The forest at the Kuortane site is primarily conifer-dominated mixed forest. The Heinävesi site (center: 62°17’N, 28°26’E) is located in eastern Finland. The area is covered by coniferous (mainly spruce dominated) and mixed forest. The SAR data was represented by a set of six dual-pol (HH and HV) ALOS PALSAR scenes acquired at 39 degree incidence angle between June and September 2007, mostly shortly after rain. The pixel spacing of ortho-rectified scenes was set to 12.5 meters. The scenes were averaged over five azimuth lines in order to obtain images with pixel dimensions approximately corresponding to the 12.5 m grid spacing. Bi-linear interpolation method was used for resampling in connection with the ortho-rectification. Radiometric normalization was performed.
The model prediction for the training dataset using SAR image acquired over Kuortane on June 27, 2007, HH-polarization. Use of model (6) resulted in a broader dynamic range for $[\sigma^0_{gr};\sigma^0_{veg}]$ and less curved exponent. Similar behavior is generally expected for validation dataset as well, provided that the training dataset is representative enough. Visual inspection of Fig. 1 shows that there is a number of forest stands for which stem volume prediction was not possible, the ones that had backscatter out of the dynamic range $[\sigma^0_{gr};\sigma^0_{veg}]$, as in [8]. They are shown with zero stem volume on X-axis in Fig. 1, c. Generally, a possible solution is to set some predefined value for all such plots that exhibit backscatter higher than that estimated by the model [5], e.g., maximum stem volume for a stand from the training dataset, or an apparent saturation point value. When using fitting of the inverted model (6), no such problem occurred (Fig. 1, d), though one can see that the inverted model predictions of backscatter agree less. Visual inspection of Fig. 1 also confirms systematic bias toward lower estimates noted in [8] when model (4) is used. On the other hand, one can observe bias towards overestimation of plots with stem volume lower than 100 m$^3$/ha when model (6) was used in fitting the data. Thus, the main benefit of using the described approach is in avoiding ill-posed results when performing the model inversion.

Multitemporal combination of model output in a multivariate regression framework allowed volume estimates to be obtained with an RMSE about 43% of the mean of 110 m$^3$/ha, and a coefficient of determination $R$ of 0.71 in the best case. The results of this study compare
favorably with previous L-band SAR studies in boreal forest. More details, analysis and discussion on the results obtained can be found in [9].

4 Conclusions

Here we discussed approaches for model-based stem volume retrieval from SAR imagery and concentrated on developing a robust approach to stem volume retrieval at L-band, with particular focus on multitemporal ALOS PALSAR imagery. A simple semi-empirical model was shown to provide reasonable results also when applied to relatively small forest stands. Particular problems associated with the discussed approach were overcome by using the proposed modification of the model fitting procedure. The methodology used can be employed to produce large-area stem volume maps from dual-pol [10] and quad-pol [11] spaceborne L-band SAR imagery mosaics, in particular from ALOS PALSAR or forthcoming missions alike.

Acknowledgements

The authors would like to thank the European Space Agency (ESA) and the Japan Aerospace Exploration Agency (JAXA) for providing the ALOS PALSAR data used in the study.

References