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IMPACT AND MODELING OF TOPOGRAPHIC EFFECTS ON P-BAND SAR BACKSCATTER FROM BOREAL FORESTS

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ABSTRACT

P-band SAR backscatter has been proven to be useful for forest biomass prediction. However, there is a need for further studies on effects of topography on P-band backscatter. In this paper, two prediction models for backscatter are evaluated, one using only biomass as predictor and one which also includes topographic corrections. Data from the BioSAR 2007 and BioSAR 2008 campaigns are used to evaluate the models. A multi-scale error model which is able to handle data from several imaging directions is used. For HH, the slope correction on stand level used in this paper is unable to correct for topographic effects. This is consistent with previous results that within stand topographic variability has a significant impact on HH P-band backscatter. For HV and VV, the model which considers topography gives lower prediction errors than the model which does not include topography. Moreover, for these polarizations topographic the correction strongly reduce the variability in backscatter measurements between imaging directions for stands with ground slopes larger than about 5 degrees.

***Index Terms*—** Synthetic aperture radar, forest biomass, backscatter, topography

1. INTRODUCTION

With the continued threat of global warming, the need to improve climate models is strong. An essential part of this process is to obtain to global maps of forest biomass with limited errors. Several studies (e.g. [1, 2, 3]) have shown that P-band backscatter has great potential for estimation of forest biomass. The European Space Agencys (ESAs) Candidate Earth Explorer Mission named BIOMASS is a P-band Synthetic Aperture Radar (SAR) satellite mission which aims to provide global biomass maps [4].

In this context some questions are in need of further studies, one of which is the impact of topography on P-band backscatter data. In this paper, data from the BioSAR 2007 and 2008 experiments are used to evaluate two prediction models for backscatter, one based solely on biomass and one which also model effects of topography. These prediction models include multi-scale errors (mixed-effects model), which is able to handle correlated measurements, e.g. backscatter measurement from the same stand but different imaging directions. As a complementary analysis tool, the variation in backscatter between imaging directions is used.

In section 2 the experimental data are described, and in section 3 the prediction model and analysis methods are presented. Section 4 contains the results of the analysis, and finally conclusions are drawn in section 5.

2. EXPERIMENTAL DATA

In this paper data acquired within the BioSAR 2007 and BioSAR 2008 campaigns are used. The BioSAR 2007 campaign was conducted in Sweden the spring of 2007. L- and P-band SAR data were acquired from a hemiboreal forest sited called Remningstorp (58 30' N, 13 40' E), located in southern Sweden. Remningstorp is fairly flat with ground slopes at stand level less than 5 degrees, although some local topographic variability exists. Details on the BioSAR 2007 campaign can be found in [2, 5]. In BioSAR 2008, L- and P-band SAR data from a boreal forest in Krycklan (64° 14 N, 19° 46 E) in northern Sweden was acquired in October 2008. In contrast to Remningstorp, Krycklan has a strongly undulating terrain with ground slopes on stand level up to 20 degrees. For details on BioSAR 2008 see [6].

2.1. *In-situ* and Laser Scanning Data

In conjunction with both BioSAR campaigns, *in-situ* data and helicopter borne laser scanning data were collected. These data were used to estimate above ground dry biomass on stand level. Species stratification based on aerial photography was also used to aid biomass estimation based on laser scanning data. Different data collection strategies and estimation procedures were used for the two campaigns, for details see [2, 5, 6]. In the subsequent analysis, stands for which the biomass is estimated based only on *in-situ* data are called validation stands while stands for which the biomass was estimated based on laser scanning data are called training stands. The training stands in Krycklan have not been presented in any previous publication. These stands are circular

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with a radius of 50 meters, and their biomass is obtained from a biomass map derived from laser scanning data, which covers the entire test site [6]. The stands were selected so that the ground surface within the stands is well described by a planar surface, and so that they are covered by all four flight headings. The number of available training and validation stands for the two test sites is presented in Table 1.

Test Site	Stand Type	# Stands	Primary data source
Re	Training	58	laser scanning
Re	Validation	10	*in-situ*
Kr	Training	97	laser scanning
Kr	Validation	29	*in-situ*

Table 1. Summary of available forest stands in Remningstorp (Re) and Krycklan (Kr). Only stands completely covered by P-band SAR data are included.

2.2. SAR Data

SAR data from several occasions were collected within the BioSAR 2007 campaign. Since the objective of this study is to investigate effects of topography rather than temporal changes, only data from one of these occasions are used, namely 2 May 2007. This acquisition occasion was selected to match the BioSAR 2008 data as closely as possible in terms of moisture conditions. On 2 May 2007, data from two flight tracks were acquired, with flight headings 179° and 200° relative north. Most forest stands were imaged at steeper incident angles for the track with heading 179° than for the other track. In BioSAR 2008, SAR data from four flight headings were collected, with flight headings 43°, 134°, 314° and 358° relative north. Flight tracks were selected so that the part of the test site with strongest topographic variability was covered by data from all flight headings.

3. METHOD

Two forward models were analyzed, one including topography and one with only the biomass as predictor. The models were formulated on a logarithmic scale in order to obtain linear models with additive errors. To be able to include data from two test sites and several flight headings in the same model, it was necessary to use a multi-scale error model (mixed-effects model). This model is able to deal with the fact that measurements from the same stand but different flight headings are correlated. It also provides a means account for differences between test sites not explained by the model. The models are formulated in Eq. 1 and 2 below.

$$\log(\sigma^0_{ijk}) = \beta_0 + \beta_1 \log(W_i) + a_i + b_j + \epsilon_{ijk} \quad (1)$$

$$\log(\sigma^0_{ijk}) = \beta_0 + \beta_1 \log(W_{ij}) + \beta_2 \log(\cos(\theta_{ijk})) + a_i + b_j + \epsilon_{ijk} \quad (2)$$

σ^0_{ijk} [m^2/m^2] is the measured backscatter corresponding to stand i, site j and flight heading k, W_i [tons/ha] is the stand level biomass and θ_{ijk} is the local incidence angle. Slope and incident angle corrections of the form in 2 has been used in e.g. [7]. The last three terms in the models are error terms corresponding to model errors on stand, site and observation level, respectively. The errors are assumed to be independent and normally distributed with constant variance. Since there are only two test sites, the parameter b_j represents a constant offset in backscatter level between the sites. All parameters in the model were estimated using restricted maximum likelihood using the R-package lme4 [8]. Separate estimates were made for each polarization (HV, HH and VV) using data from the training stands. A slope correction to σ^0 could be obtained as

$$\log(\sigma^{0sc}_{ijk}) = \log(\sigma^0_{ijk}) - \hat{\beta}_2 \log(\cos(\theta_{ijk})) \quad (3)$$

$\hat{\beta}_2$ is the estimated value for β_2. The usefulness of the topographic correction can be assessed by analyzing if the prediction model which includes topography is able to predict measurements better than the model with only biomass as predictor. In particular, the variance of the error ϵ_{ijk} should be smaller for Eq. 2 than Eq. 1 if the dependence on slope and incident angle is adequately modeled. A complementary method to investigate the usefulness of the proposed slope correction is to study how much the backscatter varies when a stand is viewed from different directions. In this paper we choose to study the range of backscatter , defined as

$$R(\sigma^0_{ijk}) = \max_k \log(\sigma^0_{ijk}) - \min_k \log(\sigma^0_{ijk}) \quad (4)$$

The range of backscatter should decrease after successful slope correction.

4. RESULTS

HV and HH both show a strong dependence on biomass, while the biomass dependence for VV is weak. In fact, the regression coefficients β_1 in Eqs. 1 and 2 are not significantly different from zero for VV (see Table 3 for a list of regression coefficients).

The polarization which is most strongly affected by topography is HH. For this polarization, the range of backscatter can be up to 5 dB even for stands in Krycklan with ground slopes less than 5 degrees. In [9], it is shown that HH backscatter at UHF frequencies (including P-band) is strongly affected by within stand topographic variability. Thus, the stand level slope model used in this paper were not expected to be able to describe the dependence on topography for HH. This expectation is confirmed in Table 2, were it is seen that the results for the two models are similar.

In terms of slope dependence, the HV and VV polarizations are very similar, as seen in Table 3. Moreover, the standard deviation of ϵ_{ijk} is decreased with about 0.5 dB for both

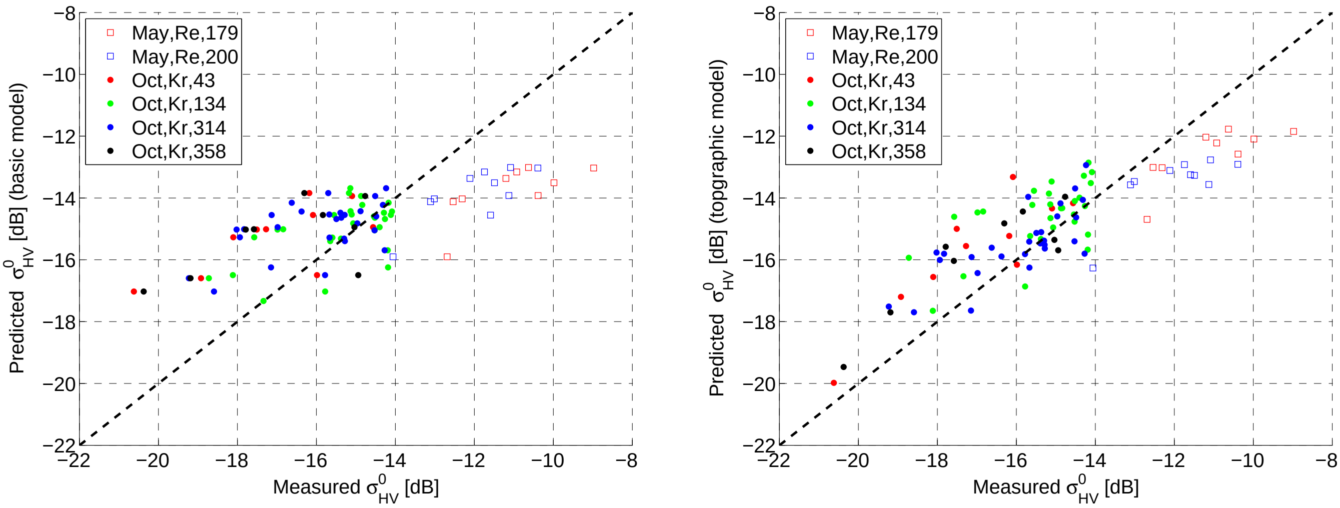

Fig. 1. Scatter plots of predicted vs. measured HV-backscatter from validation stands for prediction model (left) without and (right) with topographic corrections. Squares and circles correspond to data from Remningstorp and Krycklan, respectively, and the colors represent different flight headings as indicated in the legends. The model with topographic corrections is in better agreement with the measurements than the model without topographic corrections.

Polari-zation	**Model**	std(a_i) [dB]	std(ϵ_{ijk}) [dB]	**Offset between sites [dB]**
HV	Eq. 1	0.77	1.25	3.49
	Eq. 2	0.82	0.75	2.37
HH	Eq. 1	1.85	1.36	4.08
	Eq. 2	1.74	1.24	3.40
VV	Eq. 1	1.26	1.23	4.39
	Eq. 2	1.15	0.88	3.40

Table 2. Estimated standard deviations (std) for the error terms in Eqs. 1 and 2. Since only two sites were available, offsets between sites were reported instead of standard deviations for the error term corresponding to site level variations (i.e. b_j).

HV and VV. It is also interesting to note that the offset between sites decrease with about 1 dB for both HV and VV when ground slope in included in the models. However, the variation between stands is larger for VV than for HV since the dependence on biomass is weak for VV. For HV, Figure 1 shows predicted backscatter vs. measured backscatter for the validation stands. The model which considers topography is clearly better able to describe the measurements. In Figure 2 the range of backscatter for HV is plotted vs. ground slope. The strong reduction in the range of backscatter after slope correction for stands with high slopes clearly indicates the usefulness of the slope correction model. It should be noted that topography is not the only source of variability in backscatter between flight headings, inhomogeneities in forest structure as well as border effects are other sources of variability.

Offsets between sites are smaller for Eq. 2 than for Eq. 1, but the difference between sites is still large. At present the cause of this difference is unclear. Possible explanations are differences in forest structure (most notably stem number density), moisture conditions and topographic effects not included in Eq. 2. However, data from additional test sites are required to be able to fully understand the differences in backscatter level between sites.

Polari-zation	**Model**	$\hat{\beta}_0$	$\hat{\beta}_1$	$\hat{\beta}_2$
HV	Eq. 1	-5.3	0.41	-
	Eq. 2	-4.8	0.42	1.7
HH	Eq. 1	-3.7	0.47	-
	Eq. 2	-3.5	0.47	1.0
VV	Eq. 1	-2.1	0.02	-
	Eq. 2	-1.7	0.03	1.5

Table 3. Estimated values for the regression coefficients in the prediction models. The estimates of β_1 for VV are not significantly different from zero. The estimated standard error for all other regression coefficients are at least four times smaller than the corresponding estimates.

5. SUMMARY AND CONCLUSIONS

Two prediction models for P-band SAR backscatter have been evaluated, one based only on forest biomass and one which also utilizes topographic information. Three major conclusion can be drawn based on the results in this paper. First, the

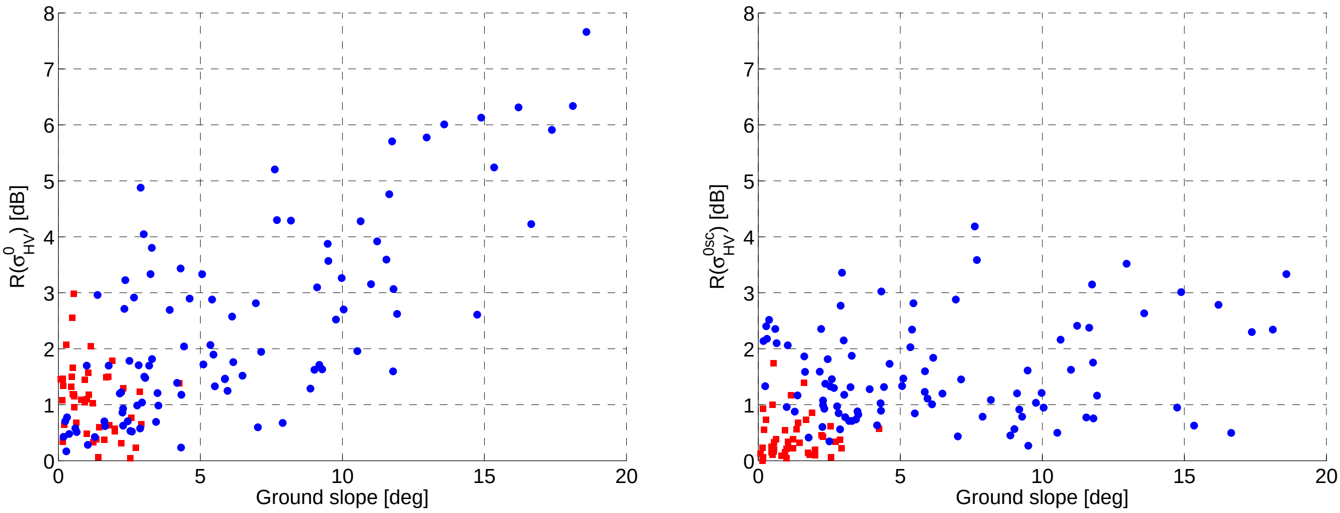

Fig. 2. Scatter plots of range of backscatter (see Eq. 4) vs. ground slope from training stands for prediction model (left) without and (right) with topographic corrections (Eq. 3). Red squares and blue circles correspond to data from Remningstorp and Krycklan, respectively. After slope correction, the variability in the backscatter is significantly after topographic correction. Note that only stands covered by all available flight headings are included in the figure.

HV and HH polarization are strongly dependent on biomass, while VV show only weak (non-significant) dependence on biomass. Secondly, the stand level slope corrections investigated in this paper are insufficient to describe the variability due to topography for HH data. Last, the proposed topographic corrections are shown to be successful for HV and VV. In particular, the error term embedding topographic variability is reduced by 0.5 dB when topography is included in the prediction model. Moreover, a clear reduction of the range of backscatter (between imaging directions) is seen for HV and VV.

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