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POLARIMETRIC-INTERFEROMETRIC BOREAL FOREST SCATTERING MODEL FOR BIOMASS END-TO-END SIMULATOR

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ABSTRACT

A polarimetric-interferometric forward model (FM) for extended covariance matrix modeling is presented. The FM has been designed to be used within the end-to-end simulator for BIOMASS, a new ESA satellite mission aiming at the global mapping of above-ground forest biomass with P-band synthetic aperture radar (SAR). The FM uses linear regression models for prediction of backscatter intensity and HH-VV correlation coefficient, and the random volume over ground (RVoG) model for the prediction of the interferometric correlation coefficients. For boreal forest, parameter values for these sub-models have been derived using polarimetric-interferometric SAR data acquired within the BioSAR 2007 campaign over the Swedish test site Remningstorp. The FM is evaluated qualitatively in a boreal forest scenario through a side-by-side comparison with BioSAR 2007 data. The general agreement is good, although there are regions with structures which cannot be reproduced by the model, probably due to insufficient forest description by the input parameters.

***Index Terms*—** BIOMASS, forward model, extended covariance matrix

1. INTRODUCTION

In May 2013, European Space Agency (ESA) selected the BIOMASS satellite for the 7th Earth Explorer mission. The main goal of the mission is accurate, high-resolution mapping of global forest resources in terms of above-ground biomass (total mass of living forest tissue), biomass change, and forest height. This will aid global carbon cycle modelling, and eventually lead to improved climate change predictions [1].

BIOMASS will feature the first P-band synthetic aperture radar (SAR) in space, and also the lowest frequency SAR in space. The main advantage of P-band radar are its penetration capabilities. In forestry, this means that a P-band radar has the capability to see through the canopy and it is sensitive to scattering from trunks and large branches, which is where most biomass is stored. These structures are also significantly more stable in time (compared to the canopy), which means that temporal decorrelation at P-band is relatively low, and repeat-pass, multi-baseline interferometry and tomography will routinely be carried out. Also, with the fully polarimetric capabilities of BIOMASS, estimation of forest height will be done from polarimetric-interferometric SAR (PolInSAR) data.

In order to be able to evaluate the performance of the future BIOMASS satellite, a BIOMASS end-to-end simulator (BEES) has been implemented for both boreal and tropical forests [2]. Using the simulator, system effects can be modeled, and error budgets can be estimated. An important part of BEES is the forward model, which predicts the extended covariance matrix for different forest biomes from a small number of input parameters. A preliminary version of the model has been presented in [3]. In this paper, the boreal forest version of the forward model will be presented in its final version, and its performance in 2D modelling will be assessed qualitatively on data from BioSAR 2007.

2. DATA

SAR data were acquired with a flight heading of 200° over Remningstorp, a hemi-boreal test site located in southern Sweden, by the airborne ESAR system in May 2007 during BioSAR 2007 [4]. Small-footprint lidar-based estimates of biomass and forest height for 58 forest stands have been used for the estimation of model parameters. The errors of the FM have been estimated using ten $80\,\mathrm{m}\times 80\,\mathrm{m}$ forest plots, for which stem diameter has been measured for all trees, and height for a subset of trees [5]. For quantitative performance analysis, biomass and forest height maps derived from lidar data and species stratification information are used as input to the FM.

3. FORWARD MODEL

The model is designed to compute the extended covariance matrix for a polarimetric-interferometric pair. First, it is assumed that the backscatter signature is equal for both the master and slave images, which gives the following extended covariance matrix:

$$\hat{C}_6 = \begin{bmatrix} \hat{V} & \hat{K}_{12} \\ \hat{K}_{12}^H & \hat{V} \end{bmatrix}, \quad (1)$$

where ^{H} is the Hermitian (conjugate transpose) operator. $\hat{V}$ is the polarimetric covariance matrix, formulated as:

$$\hat{V} = \begin{bmatrix} \sigma^0_{\mathrm{HH}} & 0 & \tilde{\rho}\sqrt{\sigma^0_{\mathrm{HH}}\sigma^0_{\mathrm{VV}}} \\ 0 & 2\sigma^0_{\mathrm{HV}} & 0 \\ \tilde{\rho}^*\sqrt{\sigma^0_{\mathrm{HH}}\sigma^0_{\mathrm{VV}}} & 0 & \sigma^0_{\mathrm{VV}} \end{bmatrix}, \quad (2)$$

where the correlation between co- and cross-polarized channels has been shown to be zero for monostatic acquisitions [6]. The polarimetric-interferometric covariance matrix $\hat{K}_{12}$ can be formulated as:

$$\hat{K}_{12} = \begin{bmatrix} \tilde{\gamma}_{\mathrm{HH}}\sigma^0_{\mathrm{HH}} & 0 & \tilde{\rho}D \\ 0 & 2\tilde{\gamma}_{\mathrm{HV}}\sigma^0_{\mathrm{HV}} & 0 \\ (\tilde{\rho}D)^* & 0 & \tilde{\gamma}_{\mathrm{VV}}\sigma^0_{\mathrm{VV}} \end{bmatrix}, \qquad (3)$$

where

$$D = \frac{\tilde{\gamma}_{\mathrm{HH}} + \tilde{\gamma}_{\mathrm{VV}}}{2}\sqrt{\sigma^0_{\mathrm{HH}}\sigma^0_{\mathrm{VV}}}. \qquad (4)$$

Backscattering coefficient (σ^0) for polarization PQ is modelled in dB using a linear model with an additive error:

$$[\sigma^0_{\mathrm{PQ}}]_{\mathrm{dB}} = a_{\mathrm{PQ}} + b_{\mathrm{PQ}}\log_{10} B + 10\log_{10}(\cos\theta_i) + N(0, s^2_{\mathrm{PQ}}) \qquad (5)$$

where θ_i is the local angle of incidence, B is the biomass in tons (Mg) per hectare (100 m x 100 m), and the last term is a normally distributed, zero-mean error, with standard deviation estimated using the 10 field plots. The parameter values estimated for the boreal data can be found in Table 1.

Table 1. Parameter values for backscatter model.

Polarization	a_{PQ}	b_{PQ}	s_{PQ}
HH	-20.1	8.1	1.3
HV	-20.7	4.2	0.7
VV	-6.7	0.6	1.2

The complex correlation coefficient between the HH and VV channels $\tilde{\rho}$ is for the boreal scenario modelled as:

$$\tilde{\rho} = (0.39 + N(0, 0.07^2)) \cdot e^{i(-41.5^\circ - 0.27B + N(0,(11.6^\circ)^2))} \qquad (6)$$

where the last term in both magnitude and phase are normally distributed, zero-mean errors. The standard deviations have been estimated from the same field plots.

For the interferometric part, correlation coefficients ($\tilde{\gamma}_{\mathrm{PQ}}$) are modeled using the random volume over ground (RVoG) model with two different profile functions. Here, the exponential profile will be used, yielding:

$$\tilde{\gamma}_{vol} = \frac{\int_0^{h_{top}} f(z)e^{ik_z z}\mathrm{d}z}{\int_0^{h_{top}} f(z)\mathrm{d}z} = \frac{1}{1+\frac{ik_z\cos\theta_i}{2\sigma}} \cdot \frac{e^{\left(\frac{2\sigma}{\cos\theta_i}+ik_z\right)h_{top}} - 1}{e^{\frac{2\sigma h_{top}}{\cos\theta_i}} - 1} \qquad (7)$$

where σ is the extinction coefficient, h_{top} is top forest height, and k_z is the vertical wave number. This is inserted in the general RVoG expression giving:

$$\tilde{\gamma}_{\mathrm{PQ}} = e^{ih_0 k_z} \cdot \frac{\tilde{\gamma}_{vol} \cdot \gamma_{temp} + \mu_{\mathrm{PQ}}}{1 + \mu_{\mathrm{PQ}}}, \qquad (8)$$

where $\gamma_{temp} = e^{-B_T/\tau_D}$ is a temporal decorrelation term, B_T is the temporal baseline, τ_D is decorrelation time, h_0 is ground height, and μ_{PQ} are ground-to-volume ratios.

In the boreal forest model, $\sigma = N(0.1, 0.1^2)$ dB/m has been chosen, based on results from PolInSAR height inversion, and $\mu_{\mathrm{HH}} = N(6.4, 1.3^2)$ dB, $\mu_{\mathrm{HV}} = N(-2.1, 0.7^2)$ dB, and $\mu_{\mathrm{VV}} = N(2.2, 0.7^2)$ dB were estimated from the data using polarimetric decomposition. h_0, h_{top}, k_z, B_T, and θ_i are known input parameters. τ_D is set through the choice of temporal decorrelation scenario.

4. RESULTS

The forward model is evaluated qualitatively for 2D mapping. Predictions of σ^0_{PQ}, $\tilde{\rho}$, and $\tilde{\gamma}_{\mathrm{PQ}}$ are made from biomass map, forest height map, and DTM, and compared to E-SAR data. Temporal decorrelation is neglected. The results are shown in Figures 1-4. The results are in general good, but in the case of VV-backscatter, HH-VV coherence, and interferometric coherences, the model does not predict some spatial changes, probably due to insufficient description of the scene with the input data. Information on, e.g., forest density or forest type would probably improve modeling.

5. REFERENCES

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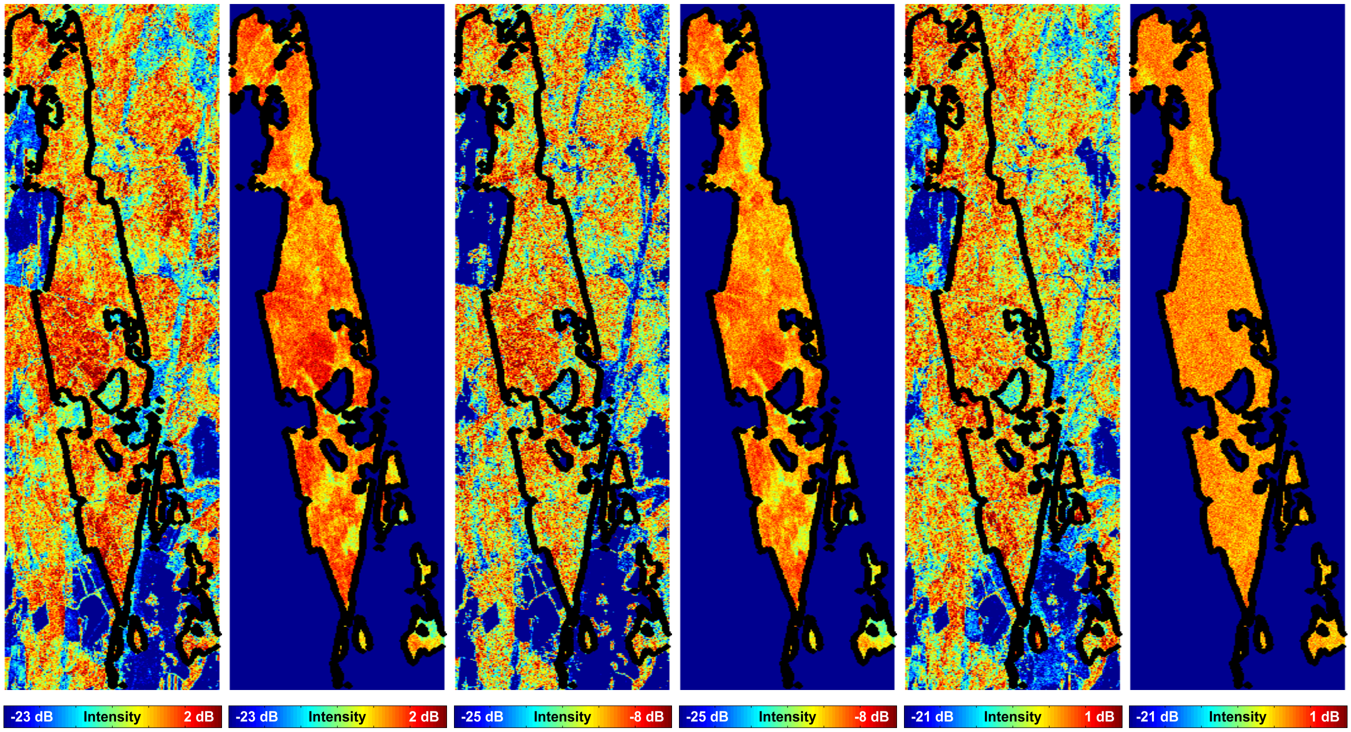
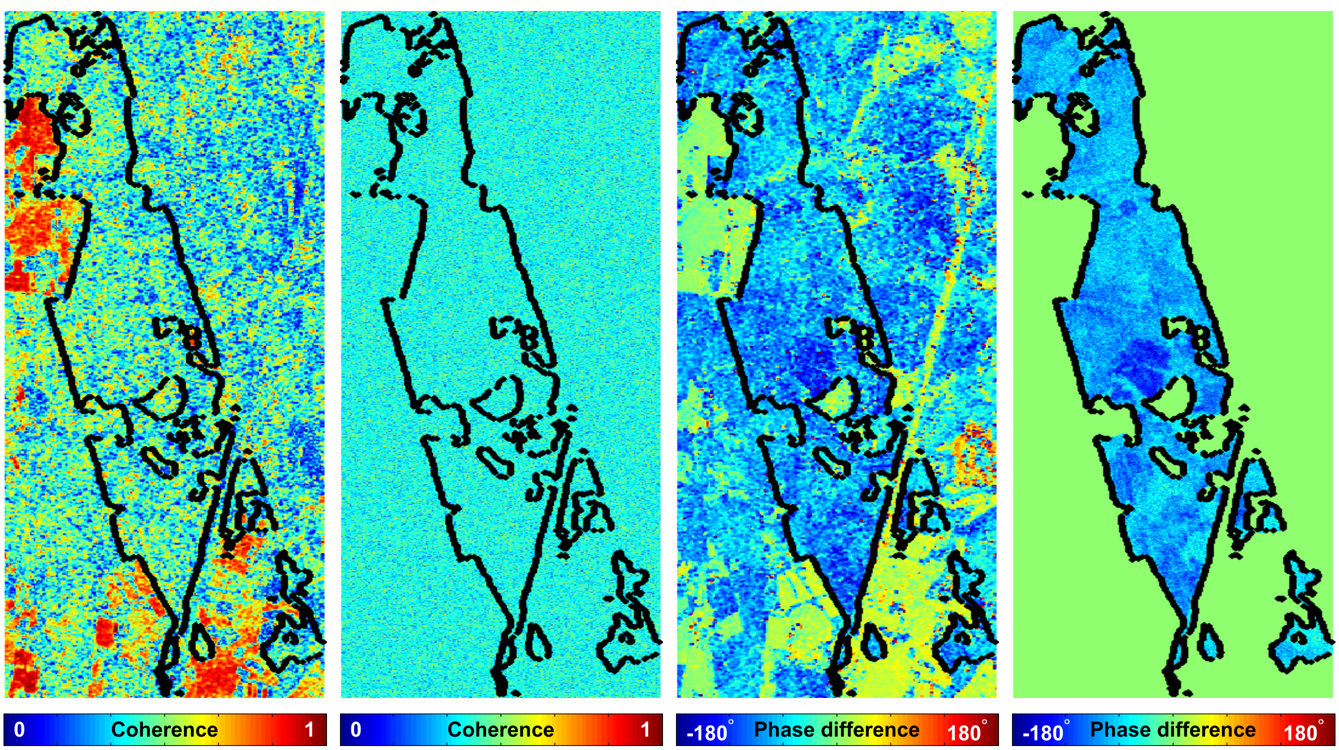


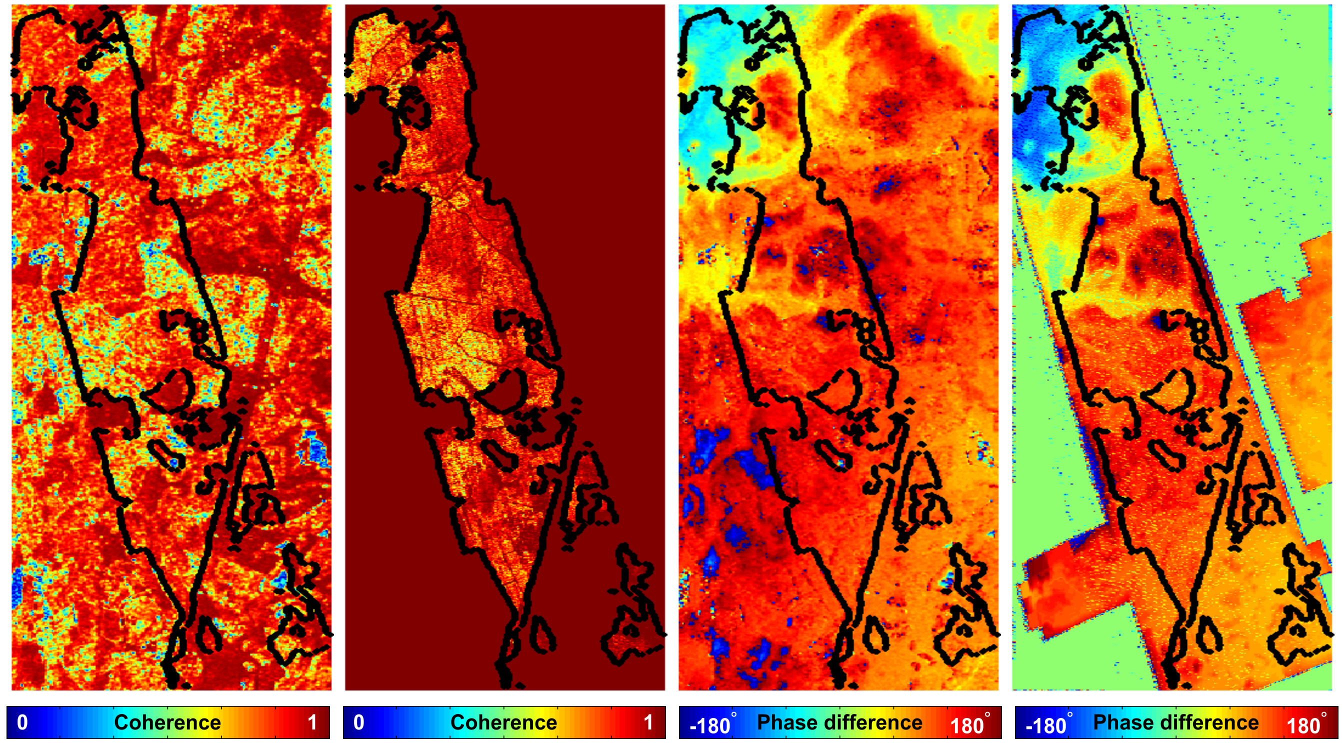
(a) E-SAR, HH (b) Model, HH (c) E-SAR, HV (d) Model, HV (e) E-SAR, VV (f) Model, VV

Fig. 1. Modeling results for backscattering coefficient compared to E-SAR data. All three polarizations are shown. The black outline marks the largest region covered by all required input data.



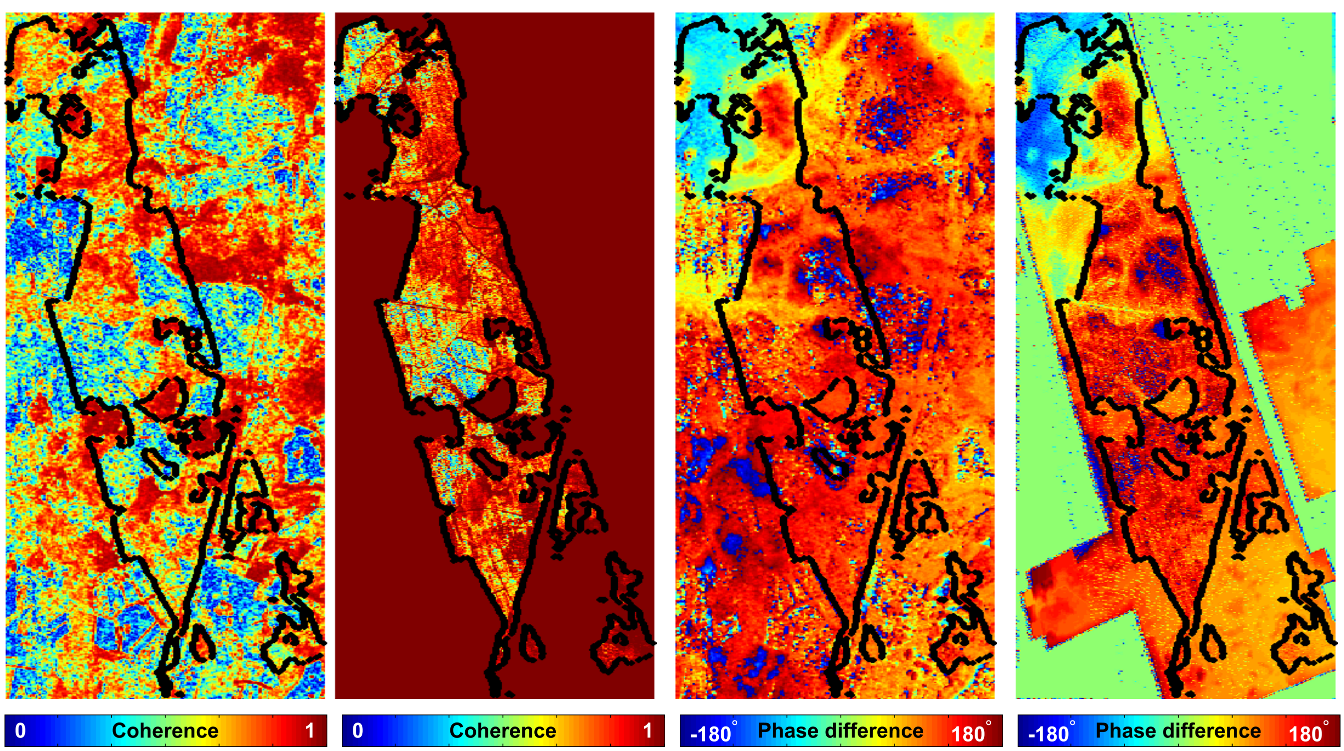
(a) E-SAR (b) Model (c) E-SAR (d) Model

Fig. 2. Modeling results for polarimetric coherence and phase compared to ESAR data. The black outline marks the largest region covered by all required input data.



(a) E-SAR, VV (b) Model, VV (c) E-SAR, VV (d) Model, VV

Fig. 3. Modeling results for interferometric coherence and phase compared to ESAR data. VV-polarization is shown here. The black outline marks the largest region covered by all required input data.



(a) E-SAR, HV (b) Model, HV (c) E-SAR, HV (d) Model, HV

Fig. 4. Modeling results for interferometric coherence and phase compared to ESAR data. HV-polarization is shown here. The black outline marks the largest region covered by all required input data.