X-band Extinction in Boreal Forest: Estimation by Using E-SAR POLInSAR and HUTSCAT

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***Abstract*—In this paper we study the extinction coefficient of boreal forest by utilizing airborne E-SAR X-band POLInSAR and HUTSCAT X-band profiling scatterometer measurements. By combining E-SAR VV-pol coherency with HUTSCAT tree height measurements we calculate forest extinction coefficients by RVoG model inversion and compare the results with extinction values obtained from HUTSCAT measurements. For retrieval of the extinction coefficient we propose robust RVoG model inversion procedure and discuss the model inversion conditions. Our results show, that extinction coefficient for boreal forest is quite low even for X-band, especially from nadir looking instruments. The extinction coefficient of forest canopy retrieved from HUTSCAT measurements is 0.15 dB/m and retrieved from E-SAR and HUTSCAT measurements is 0.9 dB/m.**

I. INTRODUCTION

SAR polarimetric interferometry (POLInSAR) has introduced a branch of applications utilizing Random Volume over Ground (RVoG) model [1] as the theoretical toolbox. Inversion of the RVoG model can provide for example a good estimate of forest height [1] which has been shown in several studies for different forest types [2], [3], [4]. The model inversion allows to study also extinction and ground-to-volume scattering ratio. The RVoG model inversion has been utilized mostly for fully polarimetric data, because for single-pol data the inversion problem is under-determined. However, restricted model inversion have been applied successfully also to single polarization data [5]. As our results from FINSAR campaign showed [6], X-band single polarization interferometric coherence can be successfully used to invert the RVoG model for forest height. This is an important application prospect for future Tandem-X mission. In this work we continue our study of the RVoG model inversion for single channel data. With help of complementary HUTSCAT measurements, we invert RVoG model for extinction, which is one of key parameters in RVoG model restricted inversion. The paper is structured as follows. First, we give a short overview of the campaign and the data, then we obtain extinction estimates by using only HUTSCAT scatterometer measurement. After that we discuss RVoG model inversion and conditioning in order to retrieve the extinction and propose inversion procedure for parameter estimation. At the end we present the extinction coefficients retrieved from E-SAR coherence and discuss the results.

II. MATERIAL

The FINSAR campaign [6] was carried out in autumn 2003 in Finland. Main instruments of the campaign were E-SAR [7] and HUTSCAT ranging scatterometer [10]. On 29 September the E-SAR collected from 3 km altitude four L-band (1.3 GHz) repeat pass fully polarimetric interferometric images and a single-pass single-pol (VV) interferometric image pair at X-band (9.6 GHz). Images are processed to a 2×2 m (range and azimuth) resolution grid.

The helicopter-borne HUTSCAT scatterometer measurement was carried out two days later. The HUTSCAT collected a vertical backscattering profile along the 36 km flight track at C-band (5.4 GHz) and X-band (9.8 GHz). The incidence angle was vertical and the helicopter location was measured by a GPS receiver. Most of the HUTSCAT measurements were concentrated on a 2×2 km area covering the E-SAR near and mid range. The HUTSCAT range resolution is 0.65 m, antenna beam width is 3.8^0, the system along-track sampling distance is 1.25 m when helicopter moves with ideal speed 25 m/s. The HUTSCAT and E-SAR slant range images are co-registered according to the pixel coordinates.

The test site in southern Finland (N 60^0 $11'$, E 24^0 $29'$) comprises forest, fields and lakes. The forest in the area is heterogeneous and consists of rather small stands. The dominant tree species are Scotch pine, Norwegian spruce, birch and alder. Ground measurements comprised soil moisture, temperature and leaf area index measurements. Forest inventory data were made available by the local forest authority for 76 stands, covering a 136 ha area. The forest stand information was gathered in April 2001.

III. EXTINCTION ESTIMATION BY USING HUTSCAT MEASUREMENTS

The ground scattering amplitude and the tree height can be directly estimated from the HUTSCAT measured scattering profile. By using those values, the forest mean extinction coefficient can be calculated under certain assumptions. The two-way transmissivity t^2 of the canopy layer is defined by

$$t^2 = \frac{\beta_{gc}}{\beta_{g0}}, \tag{1}$$

TABLE I

EXTINCTION VALUES RETRIEVED FROM HUTSCAT MEASUREMENT

HUTSCAT POL	**HH**	**HV**	**VV**
$\sigma\left(\frac{dB}{m}\right)$	0.14	0.09	0.13

where β_{gc} is the ground scattering coefficient measured in presence of canopy attenuation and β_{g0} is the ground scattering coefficient measured without attenuating layer [8]. The two-way transmissivity t^2 is related to the extinction coefficient σ as

$$t^2 = e^{\frac{-2h\sigma}{\cos\theta}}, \tag{2}$$

where h is the canopy height and θ is the incidence angle ($\theta = 0$ in present case). β_{gc} can be directly measured from HUTSCAT profile. For transimissivity calculations, one needs also backscattering of the forest floor without the canopy. The reference ground scattering cannot be measured in the open areas, because of the different ground roughness and therefore possibly different scattering. Another problem is the large spatial variability of the ground floor backscattering in the HUTSCAT profile. To overcome these problems we use the following technique for average extinction value retrieval from HUTSCAT measurements. We can rewrite (1) and (2) as

$$\frac{-2\sigma}{\cos\theta}h + \log\beta_{g0} = \log\beta_{gc}. \tag{3}$$

It can be seen, that when σ is constant, we should obtain a linear relationship between $\log\beta_{gc}$ and forest height h. σ and $\log\beta_{g0}$ parameters can be determined as a parameters of a linear fit. In reality the extinction is not constant. It is shown in [8] that σ diminishes toward smaller canopy height. However for canopy heights above 7 m and more, σ value more or less saturates. By assuming that for high enough forest the extinction is nearly constant average extinction can be estimated by using (3). We calculated the extinction values by applying a least square linear fit to ground scattering against tree height values, including only tree height h >7 m. The values are presented in Table I.

IV. EXTINCTION ESTIMATION USING E-SAR X-BAND VV COHERENCY MEASUREMENTS

In order to calculate extinction estimates from single channel E-SAR X-band VV-pol coherency using RVoG model inversion, additional information is needed, otherwise the model inversion is under-determined. The polarization dependent complex coherence $\gamma(\vec{w})$ for a volume above the ground can be modeled as [2]

$$\tilde{\gamma}(\vec{w}) = e^{(i\phi_0)}\left[(\gamma_V - 1)(1 + M(\vec{w})e^{h\sigma_m})^{-1} + 1\right], \tag{4}$$

where h is height of volume layer, ϕ_0 is ground phase, M is ground-to-volume amplitude ratio and γ_V is volume only caused coherence, defined as

$$\gamma_V = \frac{e^{h(\sigma_m + i\kappa_z)} - 1}{(1 + i\kappa_z\sigma_m^{-1})(e^{h\sigma_m} - 1)}. \tag{5}$$

where κ_z is the vertical wavenumber, depending on imaging parameters. $\sigma_m = 2\sigma/\cos\theta$ is defined by mean extinction σ and local incidence angle θ. As we can see from (4), the RVoG model depends strongly on ϕ_0 and therefore accurate estimate of ϕ_0 is required along with the forest height estimate to make RVoG model inversion for σ, using single channel coherence, possible. The forest height can be obtained from HUTSCAT measurement. An estimate for ground phase ϕ_0 can be retrieved from the coherence values, when the forest height is known. By assuming ground-to-volume ratio $M = 0$ and extinction $\sigma = 0$ we can simplify (4) to

$$(\phi_\gamma - \phi_0) = sinc^{-1}|\gamma|, \tag{6}$$

obtaining (6) called "sinc" ϕ_0 equation, similarly to "sinc" height equation, retrieved by similar conditioning from the RVoG model. The smoothed ϕ_{0sinc} obtained by using (6) is presented in Fig. 3. Additionally we estimated the ground phase also from HUTSCAT ground line measurements. Because the HUTSCAT absolute height measurement is unreliable, ϕ_{0HUT} is estimated by tying the ground line on open areas to ϕ_γ values, because the phase center on the open area should lay on the ground.

When inverting multidimensional nonlinear equation, one should make sure that the function is determined under given conditions. We developed a simple test for γ values to assure that σ is feasible to obtain. By rearranging (4) and taking the argument of both sides, M parameter can be eliminated,

$$arg\left(|\gamma|\, e^{i(\phi_\gamma - \phi_0)} - 1\right) = arg\left(\gamma_V - 1\right). \tag{7}$$

(7) has two knowns $|\gamma|$, and ϕ_γ and three unknowns h, ϕ_0, σ_m. By knowing one parameter, inversion for the rest of the two parameters should be possible using one complex value, if γ value fulfills the boundary conditions. In Fig. 1 the boundary conditions for the γ amplitude and phase are shown. Only the γ values which lie above blue line and below red line are in the region where σ and M are determined.

For inversion of the RVoG model (4) with respect to σ and M we propose a following procedure: first, ϕ_0 is estimated by using the known tree height and (6) and smoothed, then γ and obtained ϕ_{0sinc} values are checked against boundary conditions in order to eliminate non-determined solutions. After that we can use (7) to invert σ without worrying about M values and in the last step the equation (4) is inverted for a single parameter, namely M. In this way it is possible to divide the inversion process into separate steps where only one parameter is estimated at the time. This avoids problems with multi-parameter inversion instability and lead to accurate results. (7) can be successfully applied also to forest height retrieval [9] using fully polarimetric data.

V. DISCUSSION

The extinction values obtained from HUTSCAT measurements, presented in TableI are quite low, which is in good agreement with results obtained previously with HUTSCAT [8]. The extinction is low probably because the HUTSCAT

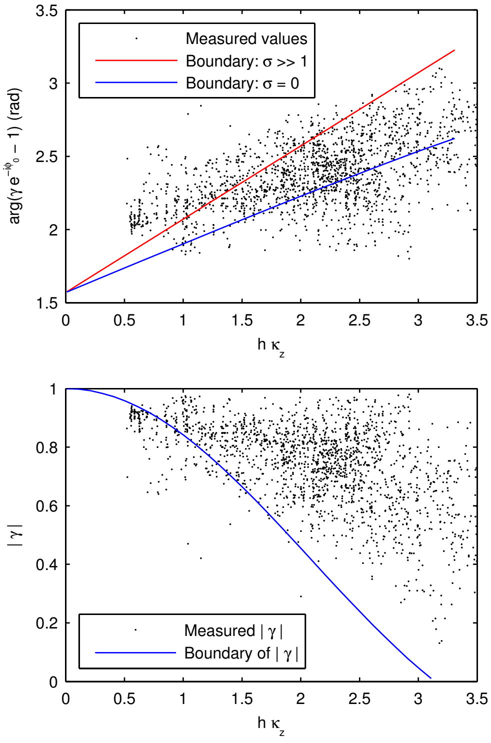

Fig. 1. Boundary conditions for RVoG model inversion. On the x-axis is height h multiplied by vertical wave number κ_z. On the y-axis are functions of invertible coherence γ values. The dots represent measured γ values.

nadir viewing geometry and relatively wide beam, it sees the ground between the trees almost continuously. The values for the linear polarizations are very similar, because the nadir measurement setup is symmetrical for both polarizations. Cross polarization gives even lower extinction, probably due to contribution from branches. In Fig. 2 the HUTSCAT measurement is presented and in Fig. 3 two different reconstructed ground phases and scattering center phases are presented. The HUTSCAT aided estimation ϕ_{0HUT} has produced tightly to open areas connected line, whereas the “sinc” estimation ϕ_{0sinc} gives a estimate which is much further away from the scattering center phase. The true ϕ_0 is most probably between these two extreme values. The inversion results are presented in Fig. 4 and in Fig. 5. M and σ are presented for both ground phase estimates presented in Fig. 3. M is presented in logarithmic scale, in order to see clearly the dominant scattering contribution, ground (positive values) or volume contribution (negative values). In most cases the volume contribution is clearly dominant. It seems that opposite to the HUTSCAT, the E-SAR does not see much of the ground scattering. This can be due the much higher incidence angle. Both initial ground phases produce very similar ground-to-volume ratio estimates. In Fig. 4 the obtained extinction values are presented. Again the difference between two used ground phase estimates is very small. The nonlinearity of the model produces some high values, probably where agreement between E-SAR and HUTSCAT co-registration is poor. This does not necessarily reflect the real extinction. The distribution of extinction values is exponential and therefore the median value is appropriate measure for prevailing conditions. Median value is 0.9 dB/m for both estimates. The small difference between parameter values obtained for different ground phase lines, suggest that presented inversion procedure is rather robust and the extinction has small influence on height inversion.

VI. CONCLUSION

In this paper we calculated X-band extinction values for boreal forest by using E-SAR VV-pol X-band interferometric coherence image and the RVoG model inversion. To make single-pol inversion possible, the forest height from HUTSCAT measurements was used as initial condition. For the inversion we present a inversion procedure where only one parameter is estimated at the time, complete with the boundary conditions. The extinction coefficients obtained from model inversion were compared with extinction coefficients retrieved from HUTSCAT scattering profiles. For both instruments obtained extinction coefficients were low. Retrieved ground-to-volume estimates show that volume scattering is prevailing for E-SAR X-band measurement. This can explain why simplified RVoG model inversions, where zero extinction is assumed, give good height estimates.

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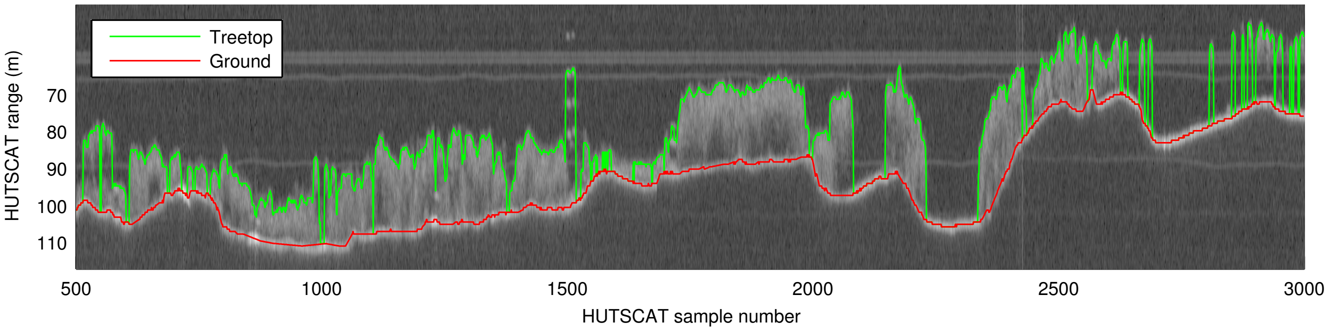

Fig. 2. HUTSCAT X-band vertical scattering profile (dB) with estimated ground and treetop locations. On the x-axis is the HUTSCAT sample number, one sample corresponds approximately to 1.3 m. The profile presented in the figure is approximately 3.5 km long.

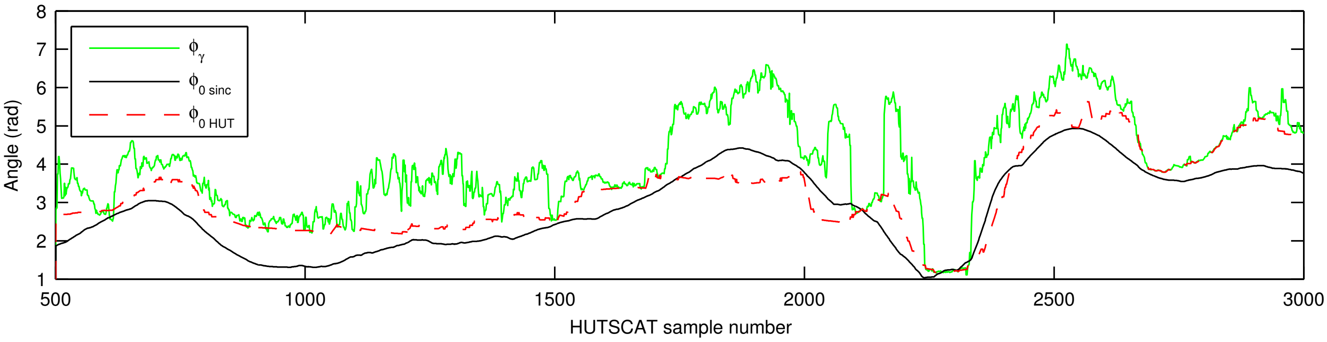

Fig. 3. E-SAR X-band unwrapped coherence phase ϕ_γ and two ground phase estimaetes: ϕ_{0sinc} and ϕ_{0sinc} along the HUTSCAT flight line. ϕ_{0sinc} is estimated from coherence amplitude and ϕ_{0HUT} is estimated by using HUTSCAT detected ground level.

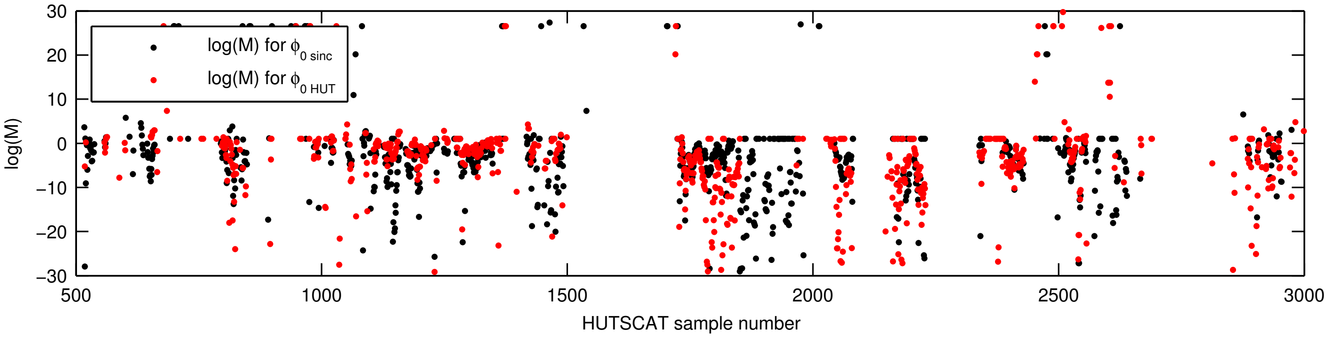

Fig. 4. The logarithm of ground-to-volume ratio M for E-SAR X-band VV-pol coherence, retrieved by RVoG model inversion, for two different ground phase estimates. Positive values indicate dominating ground scattering and negative values dominating volume scattering.

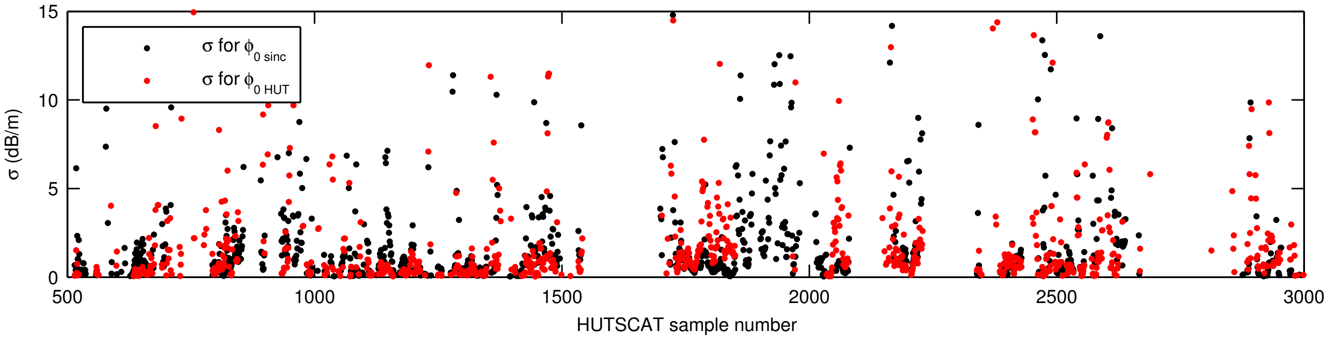

Fig. 5. The forest extinction coefficient σ for E-SAR X-band VV-pol coherence, retrieved by RVoG model inversion, for two different ground phase estimates.