FOREST HEIGHT ESTIMATES FOR BOREAL FOREST USING L- AND X-BAND POLINSAR AND HUTSCAT SCATTEROMETER

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ABSTRACT

In this paper we present a airborne polarimetric interferometric SAR measurement campaign, carried out in Finland in 2003. The main aim of the FinSAR campaign was to validate POLinSAR tree height retrieval algorithms for boreal forest and it was arranged jointly by Helsinki University of Technology (TKK) and German Aerospace Center (DLR) Microwaves and Radar Institute. During the campaign airborne DLR's E-SAR radar (operating at L- and X-band) and TKK's HUTSCAT scatterometer (operating at X- and C-band) were operated over a boreal forest test site to retrieve tree height. The tree height from fully polarimetric L-band SAR data was retrieved by Random Volume over Ground inversion and it was compared with scatterometer measurements and forest stand wise inventory tree height values. Additionally we calculated tree height from X-band single polarisation interferometric images by means of restricted RVoG model inversion and compared the results with other data. Our results show that the tree height values, estimated by means of two different radar instruments, are in good agreement. We also found that single band X-band data allows to calculate the mean tree height with surprisingly good accuracy.

1. INTRODUCTION

Forest height estimation by model based inversion of polarimetric interferometric synthetic aperture radar (POLInSAR) measurements [1] [2] has been proven to be feasible. The estimation performance has been validated for a large variety of forests and terrain conditions, including tropical rainforest [3] and tempered broad-leaved forests [4]. Also several other approaches have given good SAR interferometry based techniques have successfully applied to retrieve boreal forest vertical profile [5] and biomass [6], [7], [8]. In our study we evaluete the tree height retrieval algorithms based on Random Volume over Ground (RVoG) model inversion in the case of boreal forest. The FinSAR measurement campaign was conducted at the end of September and the beginning of October 2003. The POLInSAR data were collected by German Aerospace Center's (DLR) E-SAR airborne radar [9]. Five repeat pass interferometric baselines were acquired in a quad-pol mode at L-band and one single-pass single-pol (VV) interferometric baseline in (VV) X-band. The data acquisition covered approximately a 3 km x 15 km forested area. Additionally, 11 C- and X-band backscattering profiles of the test site forest were measured with the helicopter-mounted HUTSCAT profiling scatterometer [10] [11]. Ground measurements were performed during the campaign and a large database of supporting material was established. In the paper we describe the test site and the collected dataset, then we present methodology we used to retrieve the tree height an present results and a comparison between treeheight estimates retrieved by various means. We aslo introduce a novel approach to invert the RVoG model without iteration and ground-to-volume amplitude ratio estimation. Finally, we discuss the results and draw the conclusions.

2. TEST SITE

The test site is located in southern Finland (N 60^0 $11'$, E 24^0 $29'$), near Helsinki. In the area T agricultural fields alternate with forest patches and lakes. The forest in the test area is very heterogeneous and consists of rather small stands. The main species are Scots pine, Norwegian spruce and birch and other deciduous species. Test area incorporates stands with variable species composition and development stage, also some clear cuts and mires are in the area. For part of the area we have available a forest inventory information, gathered in 2001. In this area the concentrated field campaign and HUTSCAT measurements were conducted. According to inventory information the median stand size in the area is 1 ha, median age 46 years, median stand mean height only $6.3\ m$, however highest stand mean height is $22\ m$, median stem volume of a stand is $160\ m^3/ha$. Ground elevation varies from $15\ m - 80\ m$ over sea level. The campaign was carried out in autumn when the deciduous forest was still in full leaf, but discoloration had already. The backscattering properties of tree crowns were presumably very close to those under summer conditions.

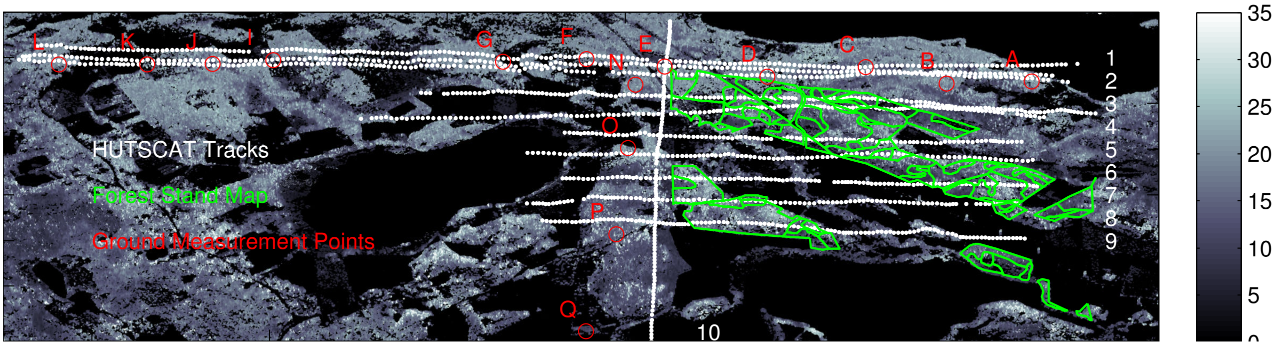

Figure 1. Forest height map, generated by model inversion using L-band POLInSAR, combined with ancillary data. Slant range geometry. Top - near range, bottom - far range. Dotted lines are the HUTSCAT measurement tracks identified by numbers. Part of tracks 1 and 5 are highlighted and presented in detail in Fig. 2. Solid lines show available forest stand map. Circles marked with letters denote ground sample plots. Height (m) scale on the left.

3. AIRBORNE CAMPAIGN

The E-SAR flight took place on 29 September 2003 between eight and nine o'clock in the morning. The instrument flew in 3 km altitude along five parallel tracks, each separated by a spatial baseline about 5 , and collected quad-pol images at L-band and along a single track in a single-pass single-pol (VV) interferometric mode at X-band. The temporal baseline between subsequent tracks was approximately 12 - 14 minutes. The initial pixel size for E-SAR products is 2 x 2 m. The weather during the image acquisition was, according to our weather station in the area, mostly calm with an average wind from WSW from 0 to 1.8 m/s. The wind was measured at 2 m altitude from ground in the field. Air temperature in the forest was around 10^0C. Reference tree height data were collected by the helicopter-borne HUTSCAT scatterometer [10]. The scatterometer is able to collect a vertical backscattering profile along the flight track at C- and X-band. Due the fog the HUTSCAT measurement was carried out two days later under similar weather conditions. The incidence angle was 0 degrees (vertical), the helicopter location was measured by differential GPS (the attitude was not acquired). HUTSCAT measured 11 transects, altogether 36 km. Most of the HUTSCAT measurements are concentrated on a 2 x 2 km area (see Fig. 1), covering well the E-SAR near and mid range. Accuracy of HUTSCAT tree height measurement capability has been determined to be 1.6 m [12]. The HUTSCAT range resolution is 0.65 m and antenna beam width is 3.8 $\deg$ resulting 6.6 m footprint on the ground from 100 m altitude. However the system along-track sampling distance is 1.25 m when helicopter moves with ideal speed of 25 m/s. Ground measurements were made both during the E-SAR and during the HUTSCAT flight day. The test plots were located along the HUTSCAT flight lines. Soil moisture, temperature and leaf area index (with LAI2000) were measured and digital photographs were taken. Weather information was collected by two portable weather stations. Forest inventory data were made available by the local forest authority for 77 stands, covering a 136-ha area. The forest stand information was gathered in April 2001 and, unfortunately, it may not be sufficiently up to date for some rapidly growing stands however. Aerial image mosaic and maps are available for the whole test site.

4. TREE HEIGHT ESTIMATION FROM E-SAR DATA

The estimation of forest height from interferometric coherence measurements at L-band is based on the inversion of the Random Volume over Ground (RVoG) scattering model by using a novel inversion technique described here. Our method does not use iteration and leaves ground-to-volume amplitude ratio undetermined. Here we present the basic steps of the procedure we use. The RVoG model gives the interferometric coherence $\tilde{\gamma}_m$ of homogeneous attenuating layer with height h and extinction coefficient σ_h over impenetrable surface as a function of polarization $\vec{w}$ for given interferometric system:

$$\tilde{\gamma}_m(\vec{w}) = e^{(i\phi_0)}\frac{\tilde{\gamma}_V + m(\vec{w})}{1+m(\vec{w})}, \quad (1)$$

where $\phi_0 = \kappa_z z_0$ is the phase related to the ground topography z_0 and κ_z is the effective vertical interferometric wavenumber after range spectral filtering that depends on the imaging geometry and the radar wavelength. $\tilde{\gamma}_V$ is the volume-only coherence (i.e. the volume decorrelation caused in the absence of the ground layer) and $m(\vec{w})$ is the effective ground-to-volume amplitude ratio accounting for the attenuation through the volume given by

$$m(\vec{w}) = \frac{m_G(\vec{w})}{m_V(\vec{w})}e^{(-\sigma h)}, \quad (2)$$

where m_G and m_V are ground and volume scattering amplitudes, $\sigma = 2\sigma_h \cos\theta^{-1}$ where σ_h is the mean extinction coefficient of the volume layer, h is thickness of the volume layer and θ_0 is mean incidence angle [1], [2]. Volume decorrelation for the vegetation layer alone is given by:

$$\gamma_V = \frac{\int_0^h e^{(\sigma z)} e^{(i\kappa_z z)} dz}{\int_0^h e^{(\sigma z)} dz} \quad (3)$$

It has been shown in [1] that the (2) describes a straight line at complex plane with $m(\vec{w})$ as a parameter. To show this more clearly, we make a variable substitution, by defining new variable $a(\vec{w}) = m(\vec{w}) + 1$ and substituting this to 2 we get:

$$\tilde{\gamma}_m(\vec{w}) = e^{(i\phi_0)} \left[(\gamma_V - 1) a(\vec{w})^{-1} + 1 \right], \quad (4)$$

It can be seen that (4) describes a line with slope $(\gamma_V - 1)$, offset 1 from the origo and has rotated around the origo by the angle ϕ_0 on the complex plane. It is also seen that the coherence is non-leariliy dependent on ground-to-volume ratio but depends almost linearly on volume-to-ground ratio. It is also clear that the slope of the line $(\gamma_V - 1)$ is not dependent on the polarization. By using (:4) and studying the line slope $(\gamma_V - 1)$ more closely we can write it in the form

$$\gamma_V - 1 = Ae^{\left(\frac{i\kappa_z h}{N}\right)}. \quad (5)$$

The magnitude of the vector is a function of $A(\sigma, \kappa_z, h)$ but its argument is dependent mainly on forest height h. However, the parameter is also function of $N(\sigma, \kappa_z, H])$ but depends mainly on σ. It is possible to show, that when $\kappa_z H < \pi$ then $2 < N < \pi$ and

$$\begin{cases} \lim_{\sigma \to 0} N \cong \pi \\ \lim_{\sigma >> 0} N = 2 \end{cases} \quad (6)$$

In order to estimate the tree height, we have to estimate the argument of the $(\gamma_V - 1)$ and the parameter N. In our proposed inversion procedure, the first step is estimation of the ϕ_0 by line fitting. After line fitting we get two ϕ_0 values. In this case it is not important which one we choose, one produces positive, another negative tree height estimate and it is easy to use absolute value. After calculation of ϕ_0 it is possible to calculate ancillary parameter γ_n as

$$\tilde{\gamma}_n(\vec{w}) = \gamma(\vec{w}) e^{(-i\phi_0)} - 1, \quad (7)$$

where γ is measured coherence value and ϕ_0 is estimated ground topography related angle. The arguments of γ_n and $(\gamma_V - 1)$ are equal. That means that the argument of γ_n is practically linear function of $\kappa_z H$ when $\kappa_z H < \pi$ with some dependance on σ. Parameter N can be estimated by using the absolute value of the coherence. In described procedure we assume that all decorrelation is caused by volume decorrelation and other decorrelation sources are negligible. In our study a single-baseline quad-pol L-band (10m nominal spatial baseline, average $\kappa_z = 0.11$) acquisition is used for the inversion of Eq.1. For the coherence estimation we have used 7 x 7 pixel averages.

In addition, also the single-pass single-pol X-band acquisition is used for tree height inversion, as proposed in [13]. As the number of observations is not sufficient, straight inversion of Eq.1 by means of X-band single-pol interferometric SAR measurement is not possible. In order to obtain a determined inversion problem the ground scattering component can be neglected and the extinction coefficient is fixed. The reasoning behind this is as follows. Compared to L-band, X-band extinction in forest canopy is higher, attenuating strongly the ground scattering. In this case, with increasing extinction the interferometric coherence increases as the effective phase center moves toward the top of the trees. In this high extinction, low ground scattering domain the dependency of the interferometric coherence on polarization is rather limited. Fixing also the extinction coefficient σ value ($\sigma_0 = 0.01$ in this study) and assuming $m = 0$ for all polarizations, the inversion problem for polarization $\vec{w}$ takes form

$$\min_{h,\phi_0} \|\tilde{\gamma}(\vec{w}) - \tilde{\gamma}_m(h, \phi_0 | \sigma = \sigma_0)\| \quad (8)$$

that can be further reduced to a single parameter (real) problem if the ground phase ϕ_0 is ignored

$$\min_{h} \| \quad |\tilde{\gamma}(\vec{w})| - |\tilde{\gamma}_m(h, \phi_0 | \sigma = \sigma_0)| \quad \| \quad (9)$$

As a part of the tree height estimation, the forest mask is generated by using SNR decorrelation [14] for L-band. By using forest mask, all height estimates for non-forested areas are set to zero.

4.1. Tree height estimation by using HUTSCAT

The HUTSCAT instrument measures vertical forest backscattering profile. In most cases, ground reflection and last reflections from tree crown top are possible to identify on the profile and thus tree height can be calculated by knowing the instruments range resolution and incidence angle as a difference between ground reflection ant treetop reflection. HUTSCAT's resolution in range direction is $0.6m$. An automatic algorithm was developed to detect the ground backscattering peak and the backscattering minimum corresponding to tree tops. The algorithm was applied for both, X-band- and C-band-profiles and the treeheight profile was created and connected to GPS measurements by using the instruments time stamp. Derived tree height profiles were slightly different for X-band and C-band, because C-band penetration depth is slightly greater. C-band measurement has also slightly more noise and therefore we use here only X-band derived profile. HUTSCAT data collection provided $\approx$ 32000 samples along 11 transects, comprising $\approx$ 24000 height estimates. The estimate accuracy is influenced by pixel location accuracy. The the helicopter's X and Y coordinates were used for antenna footprint coordinates, because the HUTSCAT system does not have attitude measurement system. This causes a localization error when measurement system is tilted from the nadir. We assume that the beam localization error is in most cases to be less than 15 m; this was checked by using orthophotos.

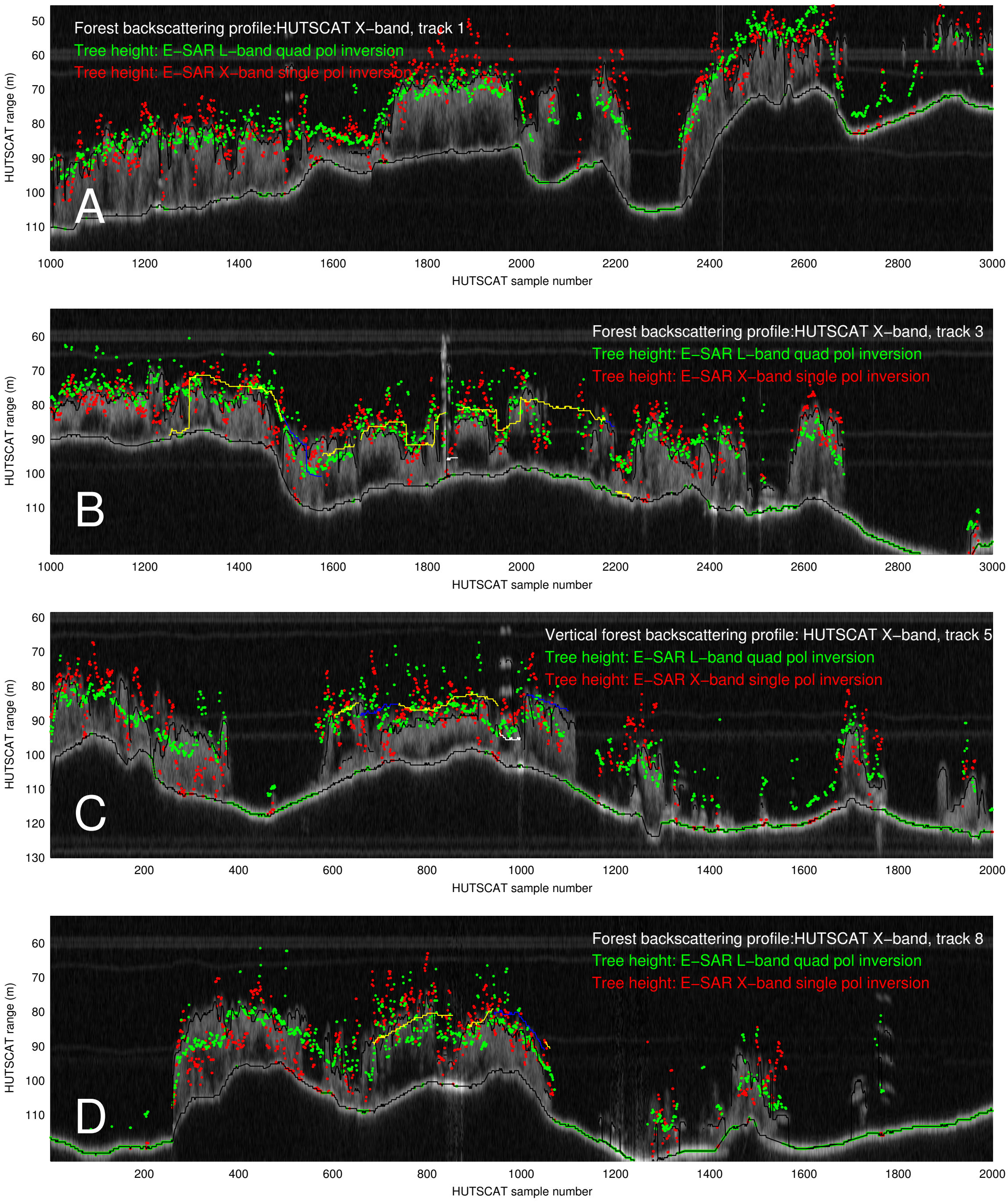

Figure 2. E-SAR L- and X-band forest height estimates on top of HUTSCAT X-band vertical forest backscattering profile. Panels A represent HUTSCAT track 1 (E-SAR near range), B track 3, C track 5 (E-SAR mid range) and D track 8. Green dots represent the POLInSAR forest height estimates for L-band 10 m baseline and red dots forest height estimates derived by using X-band 0.8 m baseline data. The x-axis is HUTSCAT sample number, corresponding to helicopter movement. One sample corresponds approximately to 1.25 m. The y-axis is HUTSCAT vertical range and tree height in meters. Lighter areas correspond to backscattering (dB) from trees and ground. The black line corresponds to the automatically detected ground and treetop level for HUTSCAT profile. The colored line shows the stand mean height from forest inventory where available (yellow = pine dominated, blue = spruce dominated and white birch domianted) . The length of track in the image is ≈ 2.5 km.

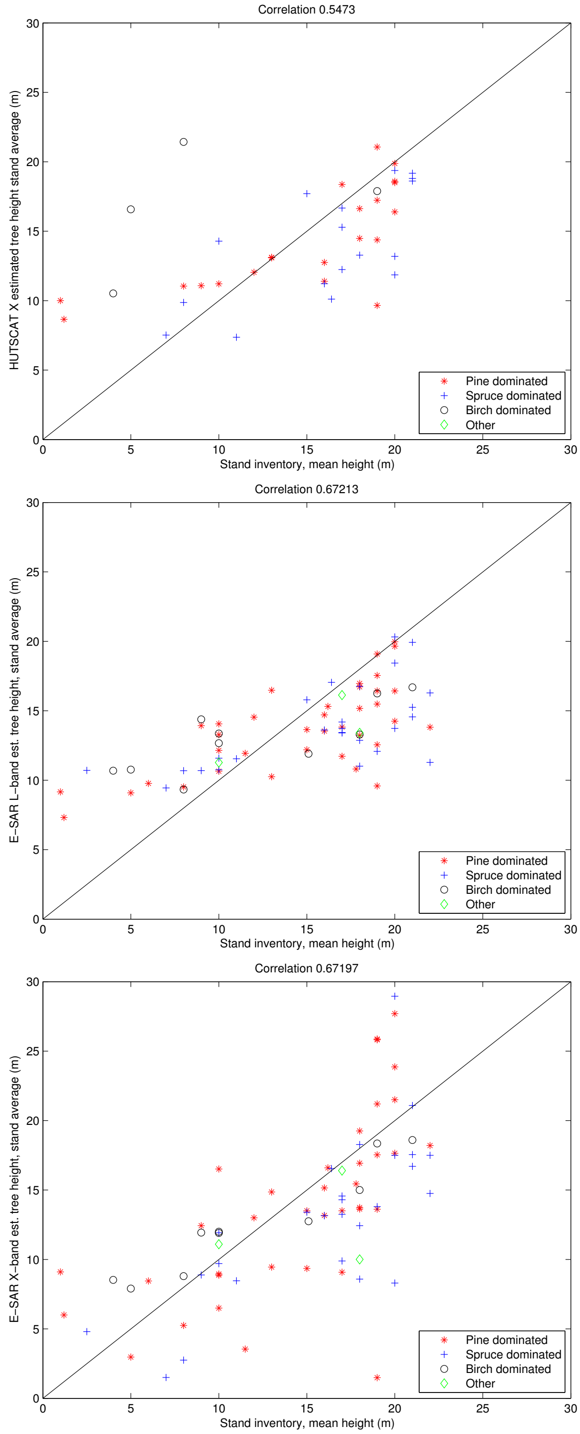

Figure 3. Tree height estimate cross comparison by stand averages. Stand averages for E-SAR and HUTSCAT estimates are calculated according to forest inventory stand borders and compared with inventory data. Dominating species of the stand is marked with different colors.

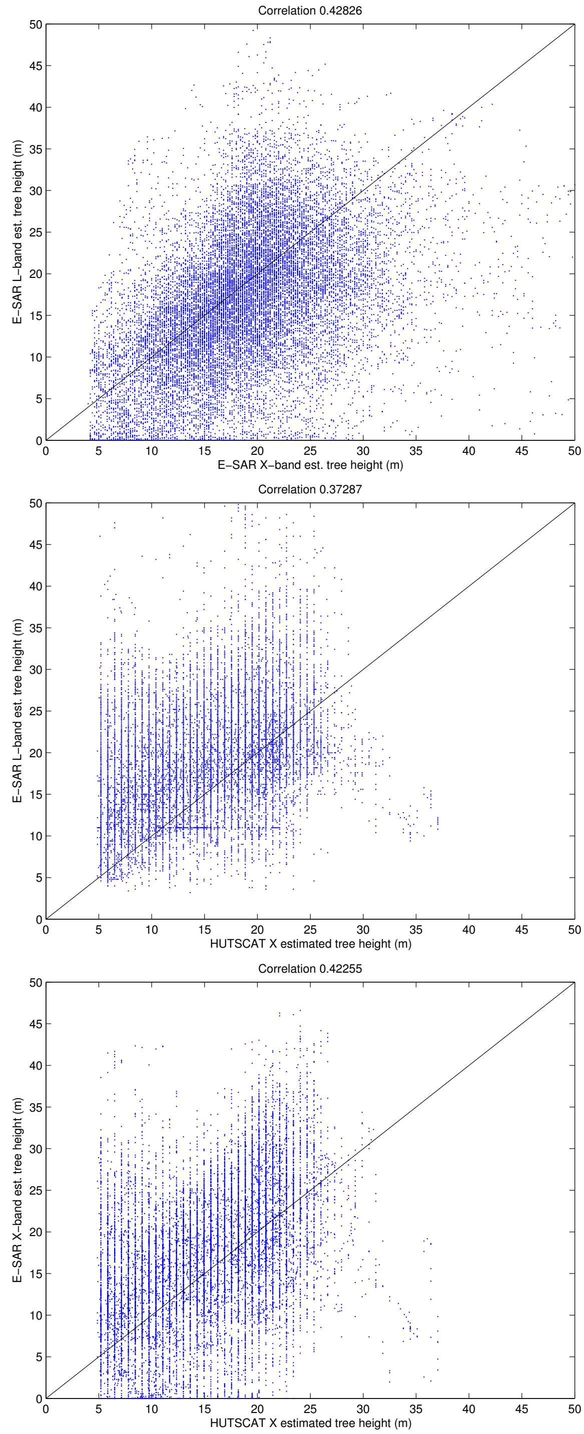

Figure 4. Tree height estimate cross comparison pixel by pixel. Comparison scatterplot between E-SAR L- and X-band estimates is made pixel by pixel for whole image in slant range. For comparison between HUTSCAT and E-SAR estimates all HUTSCAT estimates are transformed to E-SAR L-band image slant range coordinates.

4.2. Validation

For cross validation and comparison of derived tree height estimates we used several approaches, trying to find most suitable for different data types. We compared the forest height estimates from model inversion with HUTSCAT measurements and forest inventory data. In order to preserve most of the information from inversion we converted all ancillary data to the slant range geometry of L-band. Fig. 1 shows POLInSAR generated forest height map in slant range geometry combined with HUTSCAT measurement tracks and stand inventory vector map. In order to compare the SAR and HUTSCAT tree height estimates, the estimates were converted to SAR slant range coordinates. The E-SAR estimates were also converted to the HUTSCAT range profile coordinates. The comparison was done in slant range on pixel basis. However, this pixel-based comparison approach was found difficult: problems were caused especially due to the localization errors in the HUTSCAT data. The tree height in mixed forest can have very rapid fluctuations with a large amplitude and, therefore, localization error may cause large errors. In order to better understand the error sources and scattering process we decided to concentrate the comparison mainly on HUTSCAT backscattering profile coordinates.

5. RESULTS AND DISCUSSION

Inversion of the RVoG model for tree height was done for L band for four baslines; 5m, 10m, 15m, 20m. Best results were achieved with 10 m baseline and reasonable results also with 5m banseline. Here we present only tree the results for L-band 10 m baseline and X-band 0.8 m single pass baseline. Other baselines gave very noisy height estimates. Fig. 2 show tree height estimates on vertical scattering profiles measured with the HUTSCA. The x-axis is HUTSCAT sample number, corresponding to helicopter forward velocity (one sample is approximately 1.25 m and the length of track on image is $\approx$ 2.5 km), and the y-axis is HUTSCAT vertical range. On the background image the lighter areas correspond to backscattering (dB) from trees and ground. The black line corresponds to the automatically detected ground level and colored lines correspond to tree height stand inventory values (where available), where the color of the line tells the main tree species; yellow - pine, blue - spruce, white - birch. Red and green dots correspond to POLInSAR X- and L-band tree height estimates relative to HUTSCAT detected ground line; therefore, zero tree height (open areas) dots appear on the HUTSCAT ground line. The results in Fig. 2A indicate that estimates derived from L-band 10-m baseline POLInSAR model inversion are in a agreement with HUTSCAT measurements. In the far range (panel D) the L-band tree height estimate is often underestimated, also estimate is more noisy. L-band estimate is less noisy than X-band estimate for throughout the range. However, L-band estimate tends overestimates the height of smaller stands systematically. For very sparse (open-canopy) forest on the right-hand side of the image the POLInSAR estimates at L-band underestimate tree heights. The X-band derived tree height estimate, shown as red dots in Fig. 2, is noisier than L-band estimate and tends also to underestimate the tree height in far range. As discussed in Section 4 and mentioned in [13], the technique is still under development and uses rather strong assumptions to make inversion possible. However, as seen in Fig 2B, the obtained X-band estimates perform rather well, although there is some overestimation and noise. Fig. 3 show comparison of E-SAR and HUTSCAT derived tree height with stand inventory information. The HUTSCAT estimate has lowest correlation with forest inventory data. This is caused probably by the limited sample from the stand, the HUTSCAT measurements also covered only half of inventoried stands. Several estimates for stand height are calculated on basis of only short section of transect happened to cross the stand area. Agreement between stand inventory and E-SAR derived estimates are better. L-band and X-band estimate perform on the average almost equally well. However, it can be seen that L-band estimate has systematic overestimation for lower stands. X-band estimate has clearly bigger variance than L-band estimate. We should also keep in mind that mean tree height measure used in stand-wise inventory is different. HUTSCAT and E-SAR inversion estimate the top-height, where inventory estimates the mean height [4]. Small stand size causes problems also to E-SAR inversion due to incidence angle. As shown in [15] the HUTSCAT-measured forest parameters can be more accurate than ordinary forest inventory. Fig. 3 show pixel by pixel scatterplots between E-SAR L- and C-band derived tree and HUTSCAT derived treeheight estimates. As it is seen, HUTSCAT estimate does not have pixels with high overestimation, but both E-SAR estimates tend to give high overestimation when coherence is low. The quantitative agreement between E-SAR and HUTSCAT measurements varies for different areas. Generally it is better when both, the HUTSCAT and POLinSAR estimates are filtered (correlations up to $R = 0.75$). It is also better for larger homogeneous stands and worse for smaller stands. For L-band POLinSAR estimate depends also on range, being better at near range.

6. CONCLUSIONS

In this study we have shown that tree height estimation by means of L-band interferometric polarimetry and inversion of the Random Volume over Ground model works well for boreal forest. POLInSAR-derived heigh agrees well with independent tree height measurements made with the HUTSCAT profiling scatterometer. We also conclude that X-band inversion for tree height has a potential at low density forest ecosystems (e.g. boreal region). This is important for future single-pol InSAR systems at X-band, such as the Tandem-X configuration. We also present here a simplified RVoG inversion procedure which significantly reduces inversion times and gives also less noisy estimate. A profiling scatterometer instrument, like HUTSCAT, can give valuable information to support validation of POLInSAR methods and helps to better understand backscattering processes in vertically distributed media like forests. The material collected for the study is extensive and gives many possibilities for further studies.

7. ACKNOWLEDGMENT

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