LIDAR-Aided SAR Interferometry Studies in Boreal Forest: Scattering Phase Center and Extinction Coefficient at X- and L-Band

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Abstract—Scattering phase center (SPC) location in boreal forests was studied in order to assist forest inventory with single- and quad-pol synthetic aperture radar (SAR) interferometry. Airborne X- and L-band interferometric SAR data collected by the DLR E-SAR instrument in southern Finland during the FINSAR campaign was used in the study. A simple Random Volume over Ground (RVoG) model was employed as the theoretical framework for inversion of forest parameters and interpretation of the obtained results. LIDAR measurements of the canopy height and terrain elevation were used as reference and auxiliary data. The RVoG model was found to satisfactorily explain the SPC location inside the canopy in boreal forests. We show that when using X-band, the height of the SPC is typically about 75% of the canopy height, as predicted by the RVoG model; however, the retrieved extinction was found to be rather low. The feasibility of highly accurate tree height inversion using single-polarization X-band interferometry (with RMSE approaching 1.5 m) is demonstrated using a digital terrain model. For this purpose, the traditional polarimetric interferometry SAR technique for phase center retrieval is modified to include a complementary LIDAR measured terrain model. At L-band, the phase center height was determined to be around 50% of the canopy height and even lower, indicating that the ground contribution is significant. Moreover, several simplified inversion approaches for tree height and extinction coefficient retrieval were considered based on several boundary cases of the RVoG model, describing the canopy frequently encountered in boreal forest environments. These analyses allowed developing a combined approach for simultaneous estimation of both forest height and extinction in the boreal zone when an accurate elevation model of the terrain is available.

Index Terms—Boreal forest, phase center, polarimetric interferometry, synthetic aperture radar (SAR), tree height.

I. INTRODUCTION

NECESSITY of reliable all-weather monitoring of forest covered areas fosters further development and use of advanced synthetic aperture radar (SAR) remote sensing techniques. By far, the most important forest parameter for retrieval is forest height, potentially allowing radar observations to be related to forest biomass through allometry equations [1]. A number of established forest height retrieval techniques rely on model-based interferometric SAR (InSAR) analysis. While traditional coherent forward models [2]–[7] provide a good insight into the expected behavior of the forest canopies, they require many input parameters and can seldom be inverted in practice due to the lack of interferometric observables. Common methods to overcome this difficulty include increasing the number of independent observations through multipolarization, multifrequency, multi-incidence angle, and multibaseline acquisitions [8], [9], as well as adding supplementary topographic information. Another option is to use more simple models for data interpretation, however, these models still need to be capable of providing some essential information about canopy properties. For instance, inversion of polarimetric SAR interferometry (Pol-InSAR) data using the Random Volume over Ground (RVoG) model [10]–[14] provides estimates of forest height, extinction, as well as the ground-to-volume scattering ratio under some assumptions concerning the dominating scattering mechanism. The RVoG model performance was assessed through theoretical studies and extensively demonstrated in various airborne SAR experiments in different forest environments ranging from tropical rainforest [9], [14], [15] and temperate broad-leaved forests [16] to boreal forests [17]–[20], mostly at the X, C, and L frequency bands, as well as at longer wavelengths [21], [22].

Inversion of the RVoG model is applicable only to Pol-InSAR data since for single-pol InSAR the inversion problem becomes underdetermined. However, our earlier results from the FINSAR campaign [20], [25] showed that X-band single polarization interferometric coherence can be successfully used to retrieve forest height under certain conditions. Common simplifications to make the RVoG model invertible include the use of external ground digital elevation model (DEM), fixing the forest extinction coefficient to a certain value [15], [20] and, at higher frequencies, even discarding the ground scattering contribution [15] due to high attenuation in the vegetation layer. In this paper, we continue our previous study [20], [23], [24] on forest height retrieval in the boreal zone and focus on simultaneous estimation of scattering phase center (SPC) height and the extinction coefficient [25]. Once these two parameters are successfully recovered, the tree height estimation becomes feasible with accuracies approaching conventional stand-wise field inventory. This scenario is of particular interest for forest
parameter retrieval using the unique space-borne SAR imaging capabilities of the recently commenced TanDEM-X mission [26]. While some Pol-InSAR data are expected to be collected in experimental mode for the selected test sites [27], single-pol InSAR data still seem to be the general means for environmental and forest mapping on a global scale for this SAR mission. It leads to the necessity of using single-baseline single-pol InSAR data, the utility of which—for the purpose of forest mapping—can be assessed to some extent with airborne SAR instruments.

At X-band, ground is usually not visible, and a simple model representing a single layer of randomly oriented volume can be inverted for tree height estimation with single-pol InSAR data when ground topography is known. A similar approach was envisaged in, e.g., [28]–[30], where the availability of stand-wise canopy height model (CHM) allowed for a direct comparison between the estimated SPC locations and averaged tree heights. Moreover, the inversion for extinction might also be possible in several cases where ground is not visible. If the extinction coefficient information is available, it can be further used for improving the accuracy of tree height estimation. In [31], an advanced extinction coefficient model with fractal trees was used for more accurate recovery of the tree heights; however, this required some additional reference information. Also, if extinction can be retrieved from InSAR data, then an obvious benefit is the possibility of producing extinction coefficient lookup tables for selected forest species, with respect to density and structure orientation. Following the idea in, e.g., [32] such a lookup table can be further used for more accurate height estimation through model-based inversion.

At L-band, ground is usually visible [20], [33] and thus does not allow one to neglect the ground contribution in a typical inversion scenario. Polarimetric diversity of the polarization-dependent ground response is usually further employed for extraction of the model’s parameters from Pol-InSAR data. However, using a ground phase estimate from an external ground DEM can still improve the reliability and stability of the inversion process, as well as to provide a means for estimating the mean extinction value for areas with very high and dense forests, where ground may not be visible.

The objective of this paper is to study phase center location and canopy extinction retrieval at X- and L-bands in boreal forests in order to assist forest inventory, using the RVoG model as the theoretical framework. It is obvious that knowledge regarding both of these parameters will enable straightforward forest height estimation at a pixel-based level. While in our previous study [20], the value for the boreal forest extinction coefficient was fixed, particularly during the height estimation using X-band single-pol single-pass InSAR data, here we attempt to estimate both parameters simultaneously, taking advantage of several specific cases of the RVoG model.

II. MEASUREMENT DATA

A. Test Site and SAR Data

SAR data were collected in Finland during the autumn of 2003 within the FINSAR campaign. It was jointly carried out by the Helsinki University of Technology (now part of Aalto University) and the German Aerospace Center (DLR) Mi-

crowaves and Radar Institute. The main instruments used were the DLR E-SAR and the HUTSCAT ranging scatterometer [19]. A majority of the measurements took place on September 29, 2003 over a test site in southern Finland (60° 11’ N, 24° 29’ E) in the vicinity of Helsinki. The DLR E-SAR collected five L-band (1.3 GHz) repeat-pass fully polarimetric images with 5 m, 10 m, 12 m, and 0 m baselines from a 3 km altitude. Additionally, an X-band (9.6 GHz) single-pass VV-polarization interferometric image pair was acquired.

The forest in the area is heterogeneous and consists of small stands, alternating with fields and lakes. Forested areas are mostly located on the top of small hills. The dominant tree species are Scots pine, Norway spruce, birch, and alder. According to forest inventory information, the stem volume is up to 250 m3/ha, with tree heights up to 30 m.

B. LIDAR Measurements

Laser scanning over part of the FINSAR test site was performed on July 25, 2005 using a laser scanner Optech ALTM 3100 unit with 100 kHz PRF at a 1-km flight altitude. This provided a target point density of 3–4 pts/m².

The strip adjustment (matching adjacent flight strip data) was produced using TerraMatch software. Ground hits were classified using TerraScan [34]. A digital surface model (DSM) relevant to treetops was obtained by taking the highest point within a 1-m grid, with missing points interpolated by Delaunay triangulation. Furthermore, the CHM was obtained by simply subtracting the ground DEM from the corresponding treetop DSM.

The crown DSM was calculated by means of the first pulse echo while the DEM used the last pulse echo. The accuracy of the obtained DEM was noted to be better than 20 cm for forested terrain. The CHM had a −70 cm bias in the obtained tree heights and an RMSE of 0.5 m. Information regarding individual tree heights can be derived from CHM using methods discussed in [35].

III. FOREST PARAMETER RETRIEVAL ALGORITHM

A. Producing Ground Phase Estimate From DEM

In order to analyze LIDAR material together with SAR measurements, the DEM and CHM were transferred to slant range coordinates by using E-SAR range and azimuth geocoding tables. The missing pixels in slant range maps were recovered by 2-D interpolation. In order to obtain an estimate of the true ground phase, we wrapped the LIDAR measured DEM to inSAR phase for every interferogram individually. The ground phase $\phi_0$ can be represented in terms of the SAR vertical wavenumber $k_z$ and terrain elevation $h_{DEM}$ as

$$\phi_0 = k_z(h_{DEM} + h_f) + \phi_f$$

where $h_f$ and $\phi_f$ are unknown constants, and unique for every interferogram. The vertical wavenumber $k_z$ is a parameter describing the interferometric measurement. It depends on the radar wavelength $\lambda$, incidence angle $\theta$ and incidence difference between interferometric measurements $\Delta \theta$ as $k_z = 4\pi\Delta \theta/(\lambda \sin(\theta))^{-1}$. Note that this parameter varies along the range and depends on the actual flight tracks. The two unknown
constants $h_f$ and $\phi_f$ were recovered by fitting the DEM-generated ground phase $\phi_0$ with the SAR-measured ground phase $\phi_i$ in open areas. This is where LIDAR-estimated ground phase and SAR-measured ground phase should coincide. The open areas were chosen by a simple coherence value threshold (e.g., $\gamma > 0.97$), and appropriate parameters were obtained as a solution to the optimization problem

$$
\hat{h}_f, \hat{\phi}_f = \arg \min_{h_f, \phi_f} \sum \left\| e^{i(k_z(h_{DEM} + h_f) + \phi_f)} - e^{i\phi_i} \right\|^2.
$$

The obtained values were further used to produce a ground phase estimate for the entire test site using (1). The derived ground phase estimate was in good agreement with InSAR phase in open areas, and we assume that it also produces a good estimate for theoretical ground phase inside the forest canopy where radar signals do not reach ground level.

**B. Scattering Phase Center Height and Extinction According to the RVoG Model**

RVoG is a simple model for describing interferometric coherence as a function of the following random volume layer parameters: layer height or thickness, topographic phase, extinction coefficient, and ground reflection contribution. It assumes the presence of a uniformly dense layer that is characterized by a mean wave extinction in the canopy ignores the coherence drop due to independent double-bounce (ground-volume reflection) contributions, and neglects higher order ground-volume interactions. Stated simply, the model calculates the balance between the polarized ground reflection and random canopy reflection as a function of random volume parameters. The RVoG model states that the polarization-dependent complex coherence $\tilde{\gamma}(\omega)$ for a volume above the ground can be modeled as in [13] and is presented here as found in [23]

$$
\tilde{\gamma}(\omega) = e^{i\phi_0} \left[ (\gamma_V - 1) (1 + M(\omega)e^{h_0\sigma_m})^{-1} + 1 \right]
$$

where $h$ is the height of the volume layer, $\phi_0$ is the ground phase, $M$ is the ground-to-volume amplitude ratio parameter, and $\gamma_V$ is the volume decorrelation, i.e., the complex coherence affected exclusively by decorrelation of the random volume. The ground-to-volume amplitude ratio $M$ is related to the ground contribution parameter $m$, and is often used in the RVoG model as $m(\omega) = M(\omega)e^{h_0\sigma_m}$. The volume decorrelation $\gamma_V$ can be calculated as

$$
\gamma_V = \frac{e^{h_0\sigma + ik_z\gamma}}{(1 + ik_z\gamma e^{-1}) (e^{h_0\sigma_m} - 1)}
$$

where $k_z$ is the vertical wavenumber, describing the measurement system. $\sigma_m = 2\sigma/\cos \theta$ is defined by the mean extinction $\sigma$ and local incidence angle $\theta$. The model (3) clearly consists of two main parts: volume decorrelation and ground contribution. If we assume that the ground phase $\phi_0$ and the measured coherence phase $\phi_i$ are known, we can calculate the phase $\Delta \phi = \phi_i - \phi_0$ that is introduced solely by the canopy. This phase difference defines a virtual scattering point inside the canopy which is called the SPC. Note that the temporal decorrelation is not accounted for in (3) and (4). We assume that in the absence of strong winds, temporal decorrelation effects can be neglected at L-band, and in the case of the X-band single-pass acquisition, temporal decorrelation is not applicable.

Apparently, the RVoG model is a highly simplified description of the actual scattering phenomena occurring in a real forest canopy. However, when only a limited amount of measured variables are available, usage of such a simple model is justified. In the following section, we discuss how the model could be utilized for the retrieval of forest parameters. First, let us investigate SPC height when compared to volume height. Three special boundary cases can be identified where it is possible to radically simplify the model for easier understanding.

**Case 1** The ground contribution is missing ($M \to 0$) and extinction is very large ($\sigma_m \to \infty$). In this case, the model for phase height simply becomes $\Delta \phi = k_z h$, see Appendix A. It means that the scattering center is located at the top of the volume layer, i.e., the backscattered signal arrives from the top of the canopy and is independent of polarization. This particular case is related to the random volume model used in [36], where the tree crown was described as a random volume with no waves penetrating into the trunk and ground layers, and with all polarizations having the same penetration depth.

**Case 2** The second boundary case appears when we assume that ground reflection is negligible ($M \to 0$) and the canopy extinction is very small ($\sigma_m \to 0$). While this is merely a hypothetical case, it does provide some useful insight to the expected behavior of the model. In this case, the expression for the phase center height becomes $\Delta \phi = 0.5k_z h$, see Appendix B; SPC is situated halfway within the random volume.

**Case 3** The third distinguishable case is characterized by a significant ground contribution ($M \gg 0$). In this scenario, the phase height is $\Delta \phi = 0$ regardless of height and extinction values. This means that when the phase center is located close to ground, interferometric coherence does not contain significant information anymore about the volume layer, which is also easy to understand intuitively.

It should be noted that according to the first two cases where $M = 0$, the scattering center cannot be lower than 1/2 of the canopy height when the ground contribution is completely missing, regardless of the extinction value. Then, provided the ground phase $\phi_0$ is known, both the volume height and the extinction coefficient can be calculated directly even with single-pol complex coherence using the volume decorrelation (4). Also, the coherence amplitude has a special interpretation when the canopy is lossless ($\sigma_m \to 0$). The RVoG model when void of extinction is a non-normalized sinc-function (however, with only half of the argument), see Appendix B. It is equivalent to the polarization-coherence-tomography approach by Cloude [37], provided that ground phase is accounted for. The so-called sinc-approximation can be used to calculate a rough tree height estimate using only coherence amplitude; however, this usually leads to height overestimation [38].
The three aforementioned boundary cases provide theoretical limits. However, in practical situations, SPC can be located anywhere inside the canopy being only limited by a certain range of coherence values. Nevertheless, these boundary cases provide some useful interpretation tools. For example, if the SPC is located at lower than half of the actual tree height, it could indicate the presence of a ground reflection contribution according to the RV oG model. Generally, one can expect the first described case of the RV oG model to be applicable to densely forested areas at X-band (significant extinction, ground contribution practically absent), and the third case could describe sparse forest at L-band (insignificant extinction along with strong ground contribution). When processing experimental data, it is realistic to expect that the observed backscatter will follow some intermediate scenario. Finally, the second case can be expected to provide a rough initial height estimate, primarily for a very high canopy.

C. Algorithm Development

As mentioned in the previous section, the assumption that the ground contribution is not significant practically reduces the RV oG model to the random volume decorrelation model (4), with the exception that the ground phase is accounted for in this representation. Then, when the ground phase is known (e.g., from an auxiliary ground DEM), we can use the random volume decorrelation model to retrieve both the tree height and extinction coefficient from single-pol InSAR measurements.

However, in order to use this simplified approach, one should develop criteria to determine areas where ground contribution is so small that it can be neglected.

Let us first assume that both the ground phase and the forest tree heights are known. Then, for a given complex coherence, we propose the following criteria to determine whether ground contribution is insignificant.

— SPC is located above half of the tree height. As discussed above according to the RV oG model, the SPC is always located in the upper half of the canopy volume when the ground contribution is missing.

— The magnitude of the coherence is larger than the “sinc-approximated” value for identical tree heights. According to the previous discussion, the “sinc-approximated” height overestimation is caused by canopy extinction.

Obviously, the above proposed criteria for selecting areas with insignificant ground contribution cannot be applied when independent tree height measurements are not available. In this paper, the available reference tree height observations from LIDAR measurements helped to circumvent this problem by using a further semi-empirical approach. In fact, it was possible to select areas with negligible ground contribution based only on the SPC height and the coherence amplitude. For example, in this study for X-band we found that when: 1) $|\gamma| > 0.9$; and 2) (phase center height) > (12 m above the ground DEM); then, the respective areas with no ground contribution were similar to those obtained using Criteria 1 and 2.

Finally, we utilize a simple combined approach, detailed below, for forest parameter retrieval based on single-pol InSAR complex coherence when a ground DEM is available. For areas with negligible ground contribution, a simple volume decorrelation model (4) inversion is used to provide tree height and extinction estimates. The obtained average extinction can then be used for the rest of the test site for inverting the complete
RVoG model while retrieving height and ground contribution, or, the RVoG model inversion can be performed with a fixed small ground-to-volume ratio. Generally, inversion that utilizes a fixed ground-to-volume ratio is expected to provide more stable results since shadowed areas and forest borders introduce large errors during the complete RVoG model inversion. The RVoG inversion for tree height is quite insensitive to small values of M, but estimates for extinction using the same assumptions become unreliable. As for the fixed but small ground contribution, in the algorithm we let M span from 0.01 to 0.1. However, it should be noted that the numerical values of the inversion process parameters selected for this study might vary for different SAR measurements, as well as for different forest type and density configurations.

The flowchart of the proposed forest parameter retrieval algorithm is shown in Fig. 1.

Fig. 2. X-band VV polarization coherence amplitude (a) and phase (b), ground phase estimate based on LIDAR measured DEM (c), and LIDAR-measured CHM (d). The dashed line indicates the transect depicted in Fig. 3.
IV. EXPERIMENTAL RESULTS AND DISCUSSION

A. X-Band Data Processing

A part of the X-band coherence amplitude and phase image, as well as the ground phase and laser-based tree height map, are shown in Fig. 2. The ground phase was calculated according to (1) and (2) using the LIDAR-based DEM and the LIDAR-based canopy height map for the same region. The dashed line in each image corresponds to the transect which is presented in more detail in Fig. 3.

Fig. 3 shows the X-band VV polarization coherence phase across the range, a LIDAR-based ground phase estimate, and a tree height estimate. The range index on the x-axis refers to the E-SAR range coordinate for the slant range image. The ground phase fit is good and follows the X-band coherence phase well for open areas. Visual inspection indicates that the X-band coherence phase is located in the upper quarter of the forest canopy. For the highest canopies, the ground contribution insignificance conditions are satisfied; these coherence values are marked with blue circles. The LIDAR measured forest height is not filtered in any manner and therefore exhibits high dynamics. However, the X-band coherence phase follows this line rather well, although more smoothly due to coherence window averaging. The relationship between the scattering center height and the LIDAR measured tree height is presented in more detail in a 2-D histogram in Fig. 4. The figure shows that the phase center height correlates with LIDAR measured tree height very well; however, it is located approximately 25% lower than the tree top (solid green line). However, for canopies lower than 10 m in height the scattering center loses its good correlation with the LIDAR-based tree height being often less than half of the measured tree height. This indicates that for tree stands with height below 10 m, X-band coherence typically already contains a significant ground contribution for boreal forests.

According to the presented boundary cases of the RVoG model, the phase center for a higher forest is located apparently in the region where ground contribution could be insignificant. A further detailed study of the measurements, by also taking into account the coherence amplitude, indicated that the insignificant ground contribution assumption for the RVoG model is fulfilled for several regions.

For those regions, random volume decorrelation model inversion was performed both for forest height and extinction coefficient. The obtained results are restricted by the validity of the adopted model and the simplifying assumptions. However, this approach gives possibility to estimate the extinction coefficient at X-band for selected regions. Fig. 5(a) shows
Fig. 5. RV inversion results at X-band for areas with no ground contribution. (a) Retrieved extinction values and (b) retrieved tree heights.

the distribution of extinction values retrieved by the described volume decorrelation model inversion approach. The histogram shows an almost normal distribution with the mean value close to 0.4 dB/m with the highest values approaching 0.8 dB/m. The variability of corresponding height values is shown in Fig. 5(b), indicating that the forest canopies, for which we can assume insignificant ground contribution, tend to be over 20 m in height while being practically void of trees with heights less than 10 m.

Fig. 6 shows a pixel-by-pixel scatter plot between the tree heights retrieved by the volume decorrelation model (4) inversion and the corresponding unfiltered LIDAR measured tree heights. The correlation is quite good (Pearson’s correlation coefficient $R = 0.83$), and no systematic error between these two measurements was noted. This indicates that the insignificant ground contribution assumption for selected areas at X-band is in good agreement with the observations.

Encouraged by this good correlation, we implemented a simple two stage inversion scheme for single channel X-band data when the ground DEM is known. The first stage of the inversion was performed with the volume decorrelation model (4) for areas where the ground contribution was negligible. For the rest of the forested areas, we applied the restricted RVoG model inversion, where the value of $M$ was set to a very small number ($M = 0.01$ in this particular case). Generated in such a manner, the forest height map is presented in Fig. 7 and includes LIDAR canopy height measurements along with the calculated extinction coefficient estimates (only for areas where $M = 0$) for comparison purposes.

An accuracy analysis was performed between the LIDAR measured CHM and the tree height estimates obtained from the proposed combined model inversion approach. The mean extinction coefficient at X-band was estimated to be around 0.4 dB/m, with RMSE = 2.6 m between the obtained InSAR estimates of treetop height and the reference LIDAR measurements. As the processed area represents typical mixed boreal forestland with varying density, an additional analysis was performed on selected homogeneous forest stands, with RMSE approaching 1.5 m. These results are significantly better than the direct interferometric phase height estimates in, e.g., [29], indicating a high potential of quality for the model-based inversion method.

B. L-Band Data Processing

Fig. 8 shows part of an L-band HV polarization coherence amplitude image and phase image together with the ground phase, calculated with the help of the LIDAR-measured DEM and LIDAR-measured canopy height map. More detailed information along the dashed transect is presented in Fig. 9. In particular, the interferometric coherence phase calculated for different combinations of polarizations is shown together with LIDAR-based ground phase and tree height estimates. The ground phase fit was not as good as for X-band data; this was probably due to the repeat-pass configuration of the L-band measurement and some penetration into soil, but was sufficient for the phase height study. The SPC height differences between polarizations are surprisingly small and indicate the significant domination of the volume scattering component.

The relation between the interferometric scattering center heights and the LIDAR-measured tree heights is presented in more detail in the 2-D histograms of Fig. 10. Here, the HV and HH-VV polarization combinations are shown. Optimum correlation between SPC heights and LIDAR-measured tree heights was obtained using HV polarization. Variability of the scattering center height inside the canopy at L-band is clearly larger than at X-band, indicating the more significant influence of ground contribution. The phase center height is typically around 50% of the tree height level or just below that.
Fig. 7. (Left) Canopy height model measured by LIDAR. (Middle) Tree height estimate by VV-polarization interferometry with reference ground phase from LIDAR measured DEM. (Right) Estimated values for extinction coefficient.

According to the proposed interpretation based on the RVoG model, this cannot occur without a ground contribution. This is supported by a more detailed inspection that also takes into account the coherence amplitude. However, by applying the insignificant ground contribution criterion, some small areas with a high and dense forest on steep slopes in the direction of the incident SAR pulse were found to satisfy the conditions of no-ground contribution. Only few of these pixels happened to be on a transect shown in Fig. 9. Although it is unlikely that L-band SAR cannot see the ground, we applied to these areas the same volume decorrelation model inversion as for X-band. We did this in order to obtain some information about the extinction coefficient also at L-band, however, with some expected bias as only dense forests were selected.

Using HV and HH-VV based coherences, Fig. 11(a) and (c) indicate the histograms of extinction values retrieved by the volume decorrelation model inversion for a small area on the slopes with no ground contribution. The histogram is almost normally distributed, indicating a stable inversion, with a mean value of 0.18 dB/m for HV polarization (0.21 dB/m for HH-VV) and the highest attainable values near 0.6 dB/m. Corresponding height values for the same inversion are presented in Fig. 11(b) and (d). The histogram median is closer to the higher values than that for X-band.

Fig. 12 shows the pixel-by-pixel scatter plots between tree height retrieved by the volume decorrelation model inversion and LIDAR measured tree height for the aforementioned polarization combinations. Note the small amount of pixels when compared to the X-band measurement case. The correlation coefficient is at the 0.77 level for HV (0.79 for HH-VV), and there is no systematic error between these two measurements. This indicates that the insignificant ground contribution assumption for the RVoG model appears to be in agreement with these relatively few measurements.

The same simple two-stage inversion scheme was implemented for the L-band HV-polarized measurement. The ground contribution was fixed to a slightly higher value \( M = 0.04 \) than at X-band. An example of resulting tree height profiles can be seen in Fig. 9 (black dots). The overall height estimation accuracy of this combined approach is 3.4 m when compared to LIDAR measurements, with accuracy better than 2.7 m over selected homogeneous regions.

When compared to X-band, the extinction at L-band is relatively low. Therefore, we also performed a simple inversion from the interferometric phase, assuming that the phase center height is fixed to 50% of tree height, being equivalent to the volume decorrelation model with zero extinction (sinc-model). The results were not as good as those with restricted RVoG inversion, with an overall RMSE of 3.7 m and some obvious bias for height overestimation. It indicates that the ground contribution should be taken into account at L-band, thus supporting our previous argument. However, the interferometric phase height at L-band contains tree height information and could be used for a very rough estimate of tree height due to its robustness.

V. CONCLUSION

In this paper, single-pol X-band and quad-pol L-band InSAR measurements were combined with LIDAR measured DEM and CHM for the development of the RVoG inversion algorithm for simultaneous retrieval of forest tree height and extinction.

We showed that at X-band, the SPC height was approximately 75% of the forest tree height, thus resulting in a systematic error if SPC is used directly for forest height estimation. A comparison of measurements with the RVoG model suggests that at X-band, the ground contribution can be assumed to be insignificant only for forest canopies where tree heights exceed 10 m. By using the ground phase and tree height estimates from the LIDAR measurements, several areas with negligible ground contribution in X-band signals were selected and the volume decorrelation model was inverted to estimate extinction and tree height. The inversion results appeared to be stable and consistent, confirming the validity of the assumed insignificant ground contribution at X-band for the selected areas. For areas where the ground contribution could not be neglected, a restricted RVoG inversion scheme with a fixed ground-to-volume ratio was implemented for forest height and extinction retrieval.

The mean extinction coefficient at X-band for the selected boreal forest areas was found to be around 0.4 dB/m, with the
RMSE (between the obtained InSAR estimates of treetop height and the reference LIDAR measurements) approaching 1.5 m over homogeneous regions. We demonstrated that the proposed approach can be successfully utilized for highly accurate forest height retrieval in the boreal forest zone using single-pol X-band InSAR data combined with the ground phase estimate from external DEM. This obviously leads to an important application for the TanDEM-X mission if an accurate digital model of underlying terrain is available. We plan to address this issue in our future research.

The application of the developed combined inversion technique to multipolarization L-band InSAR data revealed that at L-band, the SPC height is approximately 50% of the canopy height. According to our RVoG model interpretation, this suggests that at L-band ground is visible for most types of boreal forest; the only exceptions being some very dense forests on hilly slopes in the incident direction. By applying the volume decorrelation model inversion for these isolated and limited areas, we calculated the mean extinction coefficient at L-band as well. The retrieved mean extinction coefficient value at
L-band HV polarization for the studied boreal forest case was around 0.18 dB/m, with the highest values being around 0.7 dB/m. These values generally agree with the reference values available in the literature [39]. The forest height estimates at L-band differed from the LIDAR measurements more strongly than at X-band, with an RMSE of around 2.7 m.

When topographic phase is available from an external ground DEM, the proposed inversion procedures provide more exact tree height estimates than estimates based solely on the interferometric coherence magnitude or SPC location. We also found that as a theoretical framework, the RVoG model provides a satisfactory explanation for the observed complex interferometric coherence over boreal forests at X- and L-bands.

**APPENDIX A**

Starting from (4)

\[
\gamma_V = \frac{\exp(h\sigma_m)\exp(ik_z h) - 1}{(1 + ik_z\sigma_m^{-1})}\left(\exp(h\sigma_m) - 1\right)
= \left(\frac{1}{1 + ik_z\sigma_m^{-1}}\right)\left(\frac{\exp(h\sigma_m)}{\exp(h\sigma_m)}\right)
\times \left(\frac{\exp(ik_z h)}{1 - 1/\exp(h\sigma_m)}\right)
\]

Under \(\sigma_m \to \infty\), one easily obtains \(\gamma_V = \exp(ik_z h)\).
Fig. 11. Volume decorrelation inversion results at L-band for areas with no ground contribution for (a), (b) HV polarization and (c), (d) HH-VV component. Shown in (a) and (c) are the estimated extinction values while (b) and (d) indicate the estimated tree heights.

Fig. 12. Relationship between LIDAR measured tree height and tree height estimates from volume decorrelation model inversion at L-band for areas assuming no ground contribution. (a) HV polarization. (b) HH-VV component.

APPENDIX B

The interferometric coherency over a random volume vegetation layer is given by

\[
\gamma_V = \frac{\exp(h\sigma_m)\exp(ik_z h) - 1}{(\sigma + ik_z)\left(\frac{\exp(h\sigma_m) - 1}{\sigma_m}\right)}
\]

\[
= \left(\frac{h\sigma_m}{\exp(h\sigma_m) - 1}\right)\left(\frac{\exp(h(\sigma + ik_z)) - 1}{h(\sigma + ik_z)}\right)
\]

\[
= \left(\frac{h\sigma_m}{\exp(h\sigma_m) - 1}\right)\left(\frac{\exp(i(k_z h - ih\sigma)) - 1}{i(k_z h - ih\sigma)}\right). \quad (6)
\]

Then, after some algebraic manipulation and using the relationship

\[
\exp(2ix) - 1 = \exp(ix)\frac{\sin(x)}{x} = \exp(ix)\text{sinc}(x) \quad (7)
\]

expression for (6) can be rewritten as

\[
\gamma_V = \left(\frac{h\sigma_m}{\exp(h\sigma_m) - 1}\right)\exp\left(\frac{ik_z h + h\sigma_m}{2}\right) \times \text{sinc}\left(\frac{k_z h - ih\sigma_m}{2}\right). \quad (8)
\]

Furthermore, if (the canopy is lossless), then we finally obtain

\[
\gamma_V = C \exp(ik_z h/2)\text{sinc}(k_z h/2). \quad (9)
\]
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REFERENCES


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