Article B

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ON THE RETRIEVING OF FOREST STEM VOLUME FROM VHF SAR DATA : OBSERVATION AND MODELLING

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ABSTRACT

VHF data were acquired by the Airborne Imaging Radar CARABAS over two different pine forests in the southern France. Data are analyzed using detailed ground truth measurements available on both sites including forest parameters as trunks height and diameter, stand stems density and stem volume. The experimental analysis is supported by theoretical modelling using a coherent backscatter model coupled with a tree growth model giving a fine and precise description of the trees on both sites.

The backscattering coefficient is strongly correlated to characteristics of the tree trunk. Signal saturation is not observed up to 900 m3/ha, however the sensitivity to the volume is high (e.g. 1 to 1.5 dB for 50 m3/ha) in the range of 0-500 m3/ha, whereas it is reduced beyond 500 m3/ha (<0.5 dB for 50 m3/ha).

The coherent model, based on the distorted born approximation, is used to analyze the effect of tree architectures. The modelling results show that the trunk is the main scatterer, but when the branches dimensions are not insignificant compared to trunk dimension, branch scattering have to be accounted for. However, since the two species under study are both coniferous, branch dimensions are relatively small compared to trunk dimension. Therefore no significant differences in the backscatter behavior between both sites is observed. For other species, in particular deciduous species, the branch contributions are expected to alter the sensitivity of the backscatter signal to the increase of trunk volume.

Finally, the effect of topography is investigated both experimentally, using a digital elevation model, and theoretically with the coherent model. The loss of sensitivity to stem volume due to slope is clearly demonstrated and explained by the decrease of the dihedral trunk-ground interaction as the slope increases. The possibility to include a correction for the slope-induced effect is indicated.

INTRODUCTION

In the last 10 years, forest biomass retrieval using radar data has been the subject of many studies. The works made use of operational satellite data (ERS, JERS, RADARSAT) as well as spaceborne or airborne experimental multi-frequency and multi-polarization SAR data. From these studies, the following conclusions have be drawn 1) the radar backscatter results from scattering and/or attenuation of vegetation scattering elements, which can be leaves, branches and trunk, leading to indirect relationship between the radar measurements and the forest biomass parameters; 2) the relationships depend on the radar frequency, polarization and incidence, and depend upon the forest types, species, site conditions; 3) the radar measurements are no longer sensitive to biomass variation after an amount of biomass is reached. This biomass saturation level increases with the wavelength, respectively at about 50, 100, 150 tons per hectare at C, L and P bands [1, 2, 3].

Since a significant part of the world forest biomass lies in a higher dynamic range, there is an interest to explore new sensors capable of retrieval high biomass values. Among new sensors, systems working at very long wavelengths (> 1m) appear the most promising. In recent years, several studies conducted using the CARABAS SAR airborne system (Coherent All Radio Band Sensing) operating in the HF-VHF band [4] have shown that no saturation observed for forest volume reaching up to 600 m^3/ha [5, 6, 7, 8]. To assess the possibility to use such airborne VHF SAR for operational biomass retrieval, there is a need to study the generality of the experimental results, especially concerning the influence of tree species, effect of sylvicultural practices (tree density, row direction..), and the effect of terrain relief.

For this purpose, an experiment has been conducted over two forest sites in France, taking the opportunity of the French Swedish RAMCAR campaign organized in May 1998.

The two testsites have been selected because they present various topographic conditions and two different pine species (Maritime pine and Austrian pine), grown in plantations with different forestry practices. One of the forest presents very high biomass values (> 700 tons/ha).

The choice of plantation forests was driven by the possibility to have ground data with reduced uncertainties, necessary for the interpretation of experimental results in terms of scattering phenomena.

In view of theoretical modelling, an architectural tree growth model is available for the two pine species and has been validated at the two testsites.

This paper presents the experimental results and their interpretation using a theoretical model. The first section of the paper will introduce the testsites and the CARABAS system. In the second part, the observed relations between the backscatter coefficient and some forest parameters of interest are presented. The third part of the paper describes the modelling work, coupling the tree growth model to a coherent backscatter model. The interpretation of the results leads to conclusions and perspectives of using VHF SAR for forest biomass mapping.

TEST SITE AND SAR DATA

Test Site Description

Two testsites were overflown : the Landes and the Lozère forests. The Landes forest in southwestern France is almost entirely formed of quasi-uniform large stands of maritime pine (*Pinus Pinaster* (Ait.)) over sandy terrain and is managed in a consistent fashion which ensures that the canopy is homogeneous. Most of the stands are artificially sown, generally in row of 4m spacing; the rows follow an east-west direction on the test sites. This flat plantation includes clear-cuts and a range of age classes from seedlings to stands over 46 years old, corresponding to a stem volume of about 215 m^3/ha (150 tons/ha).

The second test site is the Lozère forest in southern France, which differs from the previous site in topographic conditions and tree species. The area is characterized by large and gently rolling limestone plateaus of altitude around 1200m, which are intersected by gorges of 300-500m in depth and with steep slopes (up to 50°). In this paper we will focus on Austrian pine stands (*Pinus nigra nigrae)* made of even-aged trees ranging from 0 to 130 years old, covering 5400 ha. For these stands, of 10 ha mean area, part of a reforestation program in the area since the last century, volume can reach 900 m^3/ha (or biomass of 700 tons/ha).

For both sites, detailed forest parameters were available, including tree height, diameter and stem density, allowing the computation of stand basal area and stem volume (see Table I). Growth conditions and thinning practices are radically different between both sites. Lozère stands are characterized by higher stem density and slower tree growth than the Landes (Table I). These differences are highlighted when considering that for a given stem volume, the growth stage of the two pine species is different : a volume of 200 m^3/ha corresponds to the mature 46 year old stands at the Landes (Height = 20 m; DBH = 30 cm; Stem density = 200) but only to young 30 year old stands in Lozère (height = 12 m; DBH = 10 cm; stem density = 1600). General differences are highlighted by figures 1a) and 1b), which present the variations of tree mean height and stem volume against stand age. In addition, the two sites are different with respect to soil moisture condition (vertical distribution) since standing water was found half a meter below the surface in the Landes site whereas the Lozère forest is hilly, better drained and with ground water level much further below the surface.

Forest data (stand characteristics) have been collected at the Lozère testsite during the period of 1996-1998 [9] The accuracy associated to stem volume is estimated to be of the order of 15 % .Ground data, stand limits and radar images were included in a Geographic Information

System (GIS) along with a Digital Elevation Model (DEM) of the area with a 25 m cell size and a vertical accuracy of 5 m.

The data from .the Landes forest were updated from measurements performed during seseval campaigns since 1990 [Letoan..92, Andre 94] . Regression analysis on the ground data set was then used to derive relations linking the age to the different stands characteristics (stem density, trunk height and diameter) [10]. We estimated a relative error on the estimation on the stem volume of the order of 25%.

The SAR data

For each testsite, about 20 scenes with a wide range of incidence angle (40° to 70°) have been acquired during 4 days. The flight directions were chosen to acquire data at different azimuth directions, including cases of radar perpendicular and parallel to row directions. CARABAS is an ultra wideband SAR developed by the Swedish Defense Research Establishment (FOA). This imaging radar operates in the lower part of the VHF band, i.e. 20-90 MHz, corresponding to wavelengths between 3 and 15m. The resolution of full bandwidth CARABAS-II data is about 3 m in range [4]. The same resolution in azimuth is obtained by the use of a wide angle aperture, which is around 90°. Two biconical wideband antennas are housed in a dual push-broom configuration, giving essentially horizontal polarization within the processed aperture. However vertically polarised field components are present in the antenna pattern away from the broadside direction and horizontal plane. The images were processed and calibrated by the FOA, using methodology described in [11]. A narrow-band filtering of strong radio frequency interference (RFI) due to communications has to be conducted after the range compression. For calibration, 5-m trihedral radar reflectors were deployed on both testsites. A numerical electromagnetic method (FDTD) was used to obtain knowledge of the scattering diagram of this trihedral reflector is used to achieve a final precision which is of 1 dB. The backscattering coefficient was obtained after a projection of the image from the range to ground geometry. A flat ground surface was assumed at the Landes testsite, whereas for the Lozère site, the projection angle takes into account the local topography, by use of the DEM.

Figures 2a) and 2b) present images acquired over the Landes and the Lozère sites. Differences between sites appear clearly on these images : the Landes scene shows a graduation in grey tones from clear-cuts (dark) to the 46 years old stands (bright), whereas the Lozère scene is visually more difficult to interpret, mainly because of the distortions created by the topographic variations.

DATA ANALYSIS

General backscatter behavior

Five scenes of the Lozere and seven of the Landes, with a wide range of incidence angle (40° to 70°) were analyzed. The first analysis focused on the row effect at different azimuth and incidence angles in the Landes site. At narrow frequency band, the row spacing can introduce interference effects in particular conditions (Bragg resonance has been observed on Landes scene, with the frequency band of 38-53 MHz, at incidence angle around 40° and mean row spacing of 4m), as described in [12]. However, when analyzed at the full 20-90 MHz bandwidth, the data show no significant row effect. Previous study on CARABAS images[6] has shown that the backscatter was independent on the incidence angle in the gap of 45°-65° for forest horizontal ground. Same results have been found on the Landes and Lozère scene, with incidence angle varying from 40° to 70°. In the following analysis, the data have been analyzed in a range of incidence of 40°-60°, independently on the azimuth angle. Relationship between backscattering coefficient and forest parameters have been established using homogeneous stands over flat terrain for both sites. The influence of the topographic conditions will be address in the last part of the paper.

Figure 3 displays the backscattering coefficient (in dB) extracted from pine stands from both sites versus stem volume. For the Lozère site we observe a 12 dB dynamic range for the range of volume from 0 to 900 m^3/ha. The rate of increase is high until 500 m^3/ha (~1 dB for 50 m^3/ha), and is reduced from 500 m^3/ha to 900 m^3/ha (~0.5 dB for 50 m^3/ha). The Landes dataset has a dynamic range of 6 dB for a reduced range of volume, 7 to 215 m^3/ha, corresponding to a higher rate of increase (~1.5 dB for 50 m^3/ha). To study in details the differences and similarity of the two datasets, the backscattering coefficients in m^2/m^2 are plotted against tree parameters over the range of volume where the two datasets can be compared. In figure 4 (stem volume), both regression lines are statistically close at 95% of confidence, leading to the first interpretation that the relationship between the backscattering coefficient and the stem volume could be species independent. When the backscatter is plotted against stand mean diameter (figure 5) and height (figure 6), remarkably strong correlations are observed for both sites but the relationships depend on the site. The denser Lozère stands (600 to 800 stems/ha) exhibit much higher backscatter values than the Landes stands (200 to 300 stems/ha) even if they are all formed by trees with the same diameters (figure 5). For a DBH of 30 cm at both sites, the backscatter coefficients are respectively 0.08 m^2/m^2 and 0.025 m^2/m^2 .

Table II presents the correlations between the backscattering coefficients and the forest parameters of interest (height, trunk diameter, stem density, basal area, stem volume) at the two sites. At the Lozère forest, high correlation is obtained for height, trunk diameter and stem volume but lower correlation are observed for basal area and stem density. For the Landes, high correlation is obtained for all the parameters. For this latter site, as the forest parameters were obtained trough regression analysis based on the stand age it is difficult to conclude on a different behavior between the sites.

To understand the effect of tree species, sylvicultural practices and growth conditions on the radar backscatter , a modelling approach is developed to interpret the observations in terms of scattering mechanisms and to determine the relative importance of the vegetation scattering elements.

MODELLING

For VHF modelling in forest studies, several models have been developed. Smith and Ulander [13] represented the tree by a vertical cylinder for the trunk, and considers only one tree per resolution cell. The assumption was considered realistic for volume above 200 m^3/ha. Applied on a boreal test site, the study has shown that the main scattering mechanism is dihedral reflection between the trunk and the ground. This model results in the backscattering coefficient being proportional to stem volume squared and inverse proportional to stem number density. Alternatively, they suggested to use the averaged scattering amplitude which was shown to be directly proportional to stem volume. The modelling presented in [13] is computationally efficient, and can provide general trend for sensitivity studies. However, it does not indicate the role played by different elements of the trees nor by the interaction between different trees. Israelsson et al. [14] used an approach based on the FDTD method and showed that coherent interactions need to be taken into account, in particular the interactions between scatterers and the ground. The calculations are more exact from an electromagnetic point of view, especially concerning interactions between trunk and branches, but cannot be applied on a realistic fine description of a forest.

The modelling presented here is driven by the need to take into account, a)the realistic description of the forest, b) the coherent interactions between scatterers, and c) the specificity of the CARABAS SAR .

A. DESCRIPTION OF THE FOREST

The general method used to describe a forest is to consider a coniferous tree as a collection of cylinders whose dimensions and orientations are derived statistically from available ground data. To account for the detailed tree structure, a new approach has recently been developed [15, 16] which is based on tree growth models. This approach is used in this paper, where the tree description is provided by the AMAP tree growth model, developed by the CIRAD in France[17]. For both testsites, the AMAP model was validated through botanical calibration measurements, allowing the 3D tree architecture at different ages to be reconstructed. The AMAP model also provides different realistic trees at a given biological age, allowing the natural variability of the forest to be reproduced. Ground data have also been used to complete the forest description, e.g. to define the tree density per stand, to measure soil and vegetation moisture

B. BACKSCATTER THEORY

Concerning electromagnetic modelling of forest in the VHF band, the coherent effects have to be taken into account. However, exact methods can only be efficiently applied on a simplified description of the forested medium, which may induce erroneous results especially concerning the relative role of each scatterer type. Our approach was based on the capability of the AMAP growth model to provide detailed descriptions of the tree[18], then on the use of the Distorted Born approximation [19, 20], which is able to consider, in the first order, the coherent interactions.

The Distorted Born Approximation (DBA) is used to simulate the backscattered field. DBA based modelling computes the first order interactions of scatterers in a simulated scene by adding coherently the contribution of each independent scatterer excited by the effective incident field.

In the Distorted Born Approximation, the scattered field from a collection of N cylinders is written as (Eq. 1),

(Eq. 1) $$\overline{E^S} = \frac{e^{jk_0 r}}{r} \sum_{n=1}^{N} e^{j\phi_n} . \overline{\overline{S_n}} . \overline{E^i_{eff}}$$

where r is the distance between the sensor and the observed area, S_n is the scattering matrix of the scatterer, N the number of scatterers interacting, and E_{eff} is the effective field exciting the cylinder considered. E_{eff} is computed by the use of the Foldy-Lax approximation and allows for the attenuation along the path to be considered. The model includes three layers : a crown layer, a trunk layer and the ground surface. The crown layer is used to evaluate the effective field reaching the trunk and the ground. For each scatterer located in the layers, the first order model considers four contributions : direct backscattering, scatterer-ground, ground-scatterer and ground-scatterer-ground interaction. For each cylinder, the scattered field is computed by using the finite cylinder approximation [21, 22]. The Rayleigh approximation may seem more suitable, but previous results have shown that this causes a bias which induce errors in the simulated field, especially concerning bistatic cases which appears in the interaction between the scatterer and the ground. The Fresnel reflection coefficient of the underlying ground is evaluated by the IEM [23]. In order to add the scattered field coherently a phase reference is arbitrarily fixed in the center of the illuminated scene, at the ground level.

Estimation of the backscattering coefficient then proceeds as follows : a forest is generated through the AMAP model and soil description (dielectric constant, tilting and orientation), Firstly, the attenuation is evaluated through the Foldy-Lax approximation. For this step, complete AMAP models have been used : trunk, all branches order and needles. Values obtained have been then introduced as input data in the simulation. As needles have a non negligible contribution only for the attenuation, they have not been considered in the computation of the backscattered field with the Distorted Born approximations. Unless specified, simulations are based on simplified tree model with trunk, first order and second order branches. The complex sum of the contributions of each scatterers provides the simulated field for a given pixel. In order to obtain a good estimate of the backscattered intensity of a homogeneous forest stand, a Monte Carlo method is applied, with a number of realizations generally of the order of 200. Each results has been obtained with a number of trees per resolution cell over 10, in order to consider interactions between different trees. This process may be applied at different frequency bands. However, for data provided by the CARABAS sensor, the wide bandwidth and wide beamwidth induce strong influences on the electromagnetic modelling.

C. SPECIFICITY OF THE CARABAS SAR SYSTEM

The CARABAS SAR provides on the full bandwidth processed images a resolution of 3 by 3 m, with a pixel size of 1 by 1 m. It is a stepped frequency system with pulse bandwidth of 2MHz of frequency band, in the 26-86 MHz. Once the raw data have been range compressed, the final resolution in range is around 3m. However, the illuminated target will have a slightly different response as a function of the incident frequency. To simulate the range compression is time consuming, and may not be of particular interest in forest applications. Nevertheless, the choice of the incident frequency in the modelling process is important when dealing with comparison between experimental data and theory. Specific bandwidths can provide particularities such as the Bragg resonance observed on CARABAS images over the Landes site [12].

To compare the modelling output with the experimental results, the approach chosen is to define an equivalent frequency for the whole spectrum. For forests a first approach must account for the fact that the trunk is in the Rayleigh region with respect to the frequency. In this case, the magnitude of the backscattered field is proportional to the square of the trunk volume and to the wave number :

(Eq. 2) $|E_{Scat}| \propto k^2.V$

Considering the whole spectrum used by the CARABAS system (26-86 MHz) in N separated pulse, the mean magnitude scattered by a trunk is then

(Eq. 3) $P_{Mean} \propto \frac{1}{N}\sum_{f=26MHz}^{86MHz}(k^2(f).V)^2 = k^4(f_{eq}).V^2$

Which correspond to the magnitude obtained for the equivalent incident frequency :

(Eq. 4) $f_{eq} = \sqrt{\langle f_{inc}^2 \rangle} \approx 60MHz$

This simple approach shows that for forests, a single frequency that provides the same backscattered field than the range 20-90 MHz is around 60 MHz.

To obtain a resolution of about 3m in the azimuth direction, a wide aperture angle is used. Each target is illuminated during the acquisition process with an aperture angle varying from -45° to 45°. This has no particular effect for flat areas such as the Landes plantation. For sloping terrain, the local incidence angle changes during the acquisition, in a manner depending on the slope's orientation with regard to the flight direction. A previous analysis of the CARABAS data over the Lozere site has underlined the large reduction of backscattering coefficient for tilted areas, even with a small local slope. For modelling of these topographic effects, a realistic definition of the local incidence angle is needed. The variation of the local incidence angle as a function of the relative position of the sensor with regard to the phase reference may been included for the study of topographic effects. The backscattering coefficient will then simulated, for a given forest stand with defined topographic angle, by averaging the results for each effective incidence angle obtained during the acquisition.

COMPARISON BETWEEN THEORETICAL AND EXPERIMENTAL RESULTS

The modelling results are compared to experimental measurements. For all the simulations conducted, the ground dielectric constant was chosen accordingly to the commonly used values , Er = 10 +i*3.6 [24], corresponding to the soil moisture of about 0.20 m3/m3 measured for the 0-10 cm surface layer on the two sites during the experiments. Soil composition and soil moisture 0-1 m vertical profile differs between sites, but lack of precise measurements prevent to realistically simulate these differences. Moreover, choosing the same soil characteristics allows to directly assess by modelling the effect of thinning practice and species, independently on the soil moisture.

A. BACKSCATTERING COEFFICIENT AS A FUNCTION OF STEM VOLUME.

The figure **7** shows the modelling results obtained at 60 MHz compared to CARABAS measurements at the Landes and Lozere sites. The backscattering coefficient is expressed as a function of the stem volume. A good agreement is observed between the model and the data. The rates of increase estimated by the model decreases with the stem volume, similarly to the experimental data. However, at very low biomass, modelling suggests lower backscatter values than the observations. This may be related to the noise level of the system. For the youngest stands, only the power received for the highest transmitted frequencies is significant. Since the simulated backscattering coefficient for these young stands is close or below the noise level, the equivalent frequency should be higher than the one chosen for older stands. Instead of adapting the incident frequency to the growth stage, the solution chosen was to add to the simulation results the noise level measured on the experimental data, which was about -21 dB during the experiments. The results obtained after adding the noise level in figure **8** show clearly better agreement. Finally, differences between the both site have been simulated by the model. The most interesting results are obtained for stem volume around 200 m^3/ha at the Landes testsite and 300 m^3/ha at the Lozere testsite. Both model and experiment show the same backscattering coefficients, whereas the both sites significantly differs, and present strong differences in stem volume. At these different stages of growth of the both species, the maritime pine are sparse (around 200 stems per hectare) but have high and large trunk. On the other hand, the austrian pine stand includes smaller trunk with a relative high density (800 stems per hectare). For low stem density (Landes), backscattering coefficient appear to be more sensitive to trunk dimension than to number density, whereas for high density (Lozère), backscatter is sensitive to both dimension and density. The differences between the two sites could be interpreted by differences in geometrical properties of trees (stem dimension and density). The effect of soil moisture profile, which was not simulated by the model, can be considered in a first approach as less significant.

Figure 9 shows an example of the contribution of the main scatterers, i.e. trunk and branches, to the signal at different stage of growth of the Landes forest. The results show that as expected, the trunk ground interaction is the dominant scattering source. More generally, for every type of scatterers, main mechanisms are the scatterer-ground and ground -scatterer interactions, well over the direct contributions. However, for young stands (<100 m3/ha), the contribution of the primary branches becomes significant, the branch and trunk radii being of the same order. The same result was observed at the Lozere site for young stands. For species with larger branch dimensions, e.g. compared to the trunk dimension, such as deciduous species, the importance of the branches contribution could degrade the direct correlation between the backscatter signal and the stem volume.

ANALYSIS OF THE TOPOGRAPHIC INFLUENCE

Slope effects on CARABAS data over forests have been addressed by Smith and Ulander [25], focusing on the azimuthal effect. In this paper, we analyse the slope effect on the relationship between the radar backscatter and stem volume at the Lozere site. The analysis was as follows : we consider several homogeneous areas with approximately the same stand volume and tree growth stage in different topographic conditions with regard to the radar flight direction, and we evaluate the ratio of the backscattering coefficient measured in flat area to the one measured for the local slope. Two cases were considered here : slope facing and opposed to the flight direction. Unfortunately, the case of an arbitrary orientation of the slope could not have been analyzed due to the lack of radar data on the same types of forest stands. In order to preserve a sufficient dynamic, only high volume stands were considered in this study (over 500 m^3/ha). Figure 10 presents the loss of backscattering coefficient (in natural values) against the local slope. For both cases, a strong and continuous loss of backscatter against the slope is observed, up to the noise level reached for local slope of about 20°. This loss of backscatter prevent from simple potential inversion algorithm when terrain is not flat. In order to explain this phenomenon and overcome this limitation, a theoretical analysis have been conducted. The first results have shown that as expected, this loss of sensitivity is directly linked to the vanishing dihedral reflection when the trunk is no more perpendicular to the ground. However, the simulated trend does not fit the measurements, especially for low local slopes where the model does not correctly estimate the rapid decrease of the backscatter (see the raw simulation curve on the figure 11). Estimation of the backscatter have been firstly improved by introducing the large aperture effect, which lead to a variation of the incidence angle during the acquisition, then to a variation of the dihedral reflection. Considering this wide beamwidth effect allows to correctly predict the backscatter behavior for slow slope ("aperture corrected" curve on figure 11), and taking into account the noise level in the modelling ensures a more valid prediction. For the derivation of retrieval algorithm, these results indicate the need of an a posteriori correction, that should be applied using a DEM. However, forest stands of backscatter below the noise level could not be inverted, and the species effect (i.e. impact of larger branches) should be first investigated.

CONCLUSION

This study aimed at assessing the sensitivity of VHF SAR data to forest stem volume. The work developed through an experimental analysis using CARABAS VHF SAR data acquired over two coniferous forests, and theoretical modelling to interpret the observations. The analysis results show that the signal is strongly correlated to stem characteristics (trunk diameter, length and stand stem volume). Relations between the backscattering coefficients with trunk diameter and trunk length were found to be different at the two sites. On the opposite, relations linking the radar backscatter versus the stand stem volume were found very close for both sites. This because stand stem volume integrates all the variability of the sites (stem density, trunks diameter and length). The saturation was not observed up to 900 m3/ha, far beyond the saturation level of P to C band SARs. For inversion purpose, it is to be noted that the sensitivity to volume is high (e.g. 1 to 1.5 dB for 50 m3/ha) in the range of 0-500 m3/ha, whereas it is reduced beyond 500 m3/ha (<0.5 dB for 50 m3/ha).

The observations were interpreted by a theoretical model based on Distorted Born Approximation coupled with the AMAP tree growth model. A good agreement between simulations and the experimental observations is found. Simulations show that for coniferous species when the trunk diameter are much larger than the branches, the trunk-ground reflection is largely the dominant mechanism. For species presenting more complicated structure such as deciduous species, the radar response is expected to result from trunk and branches contributions.

The dominant trunk ground interaction induces a strong sensitivity of the signal to the local slope. This effect was confirmed by the analysis, and well simulated by the DBA model. The variation of about 10 dB between flat terrain and slopes of 15 degrees, must be taken into account for derivation of robust stem volume retrieval algorithms.

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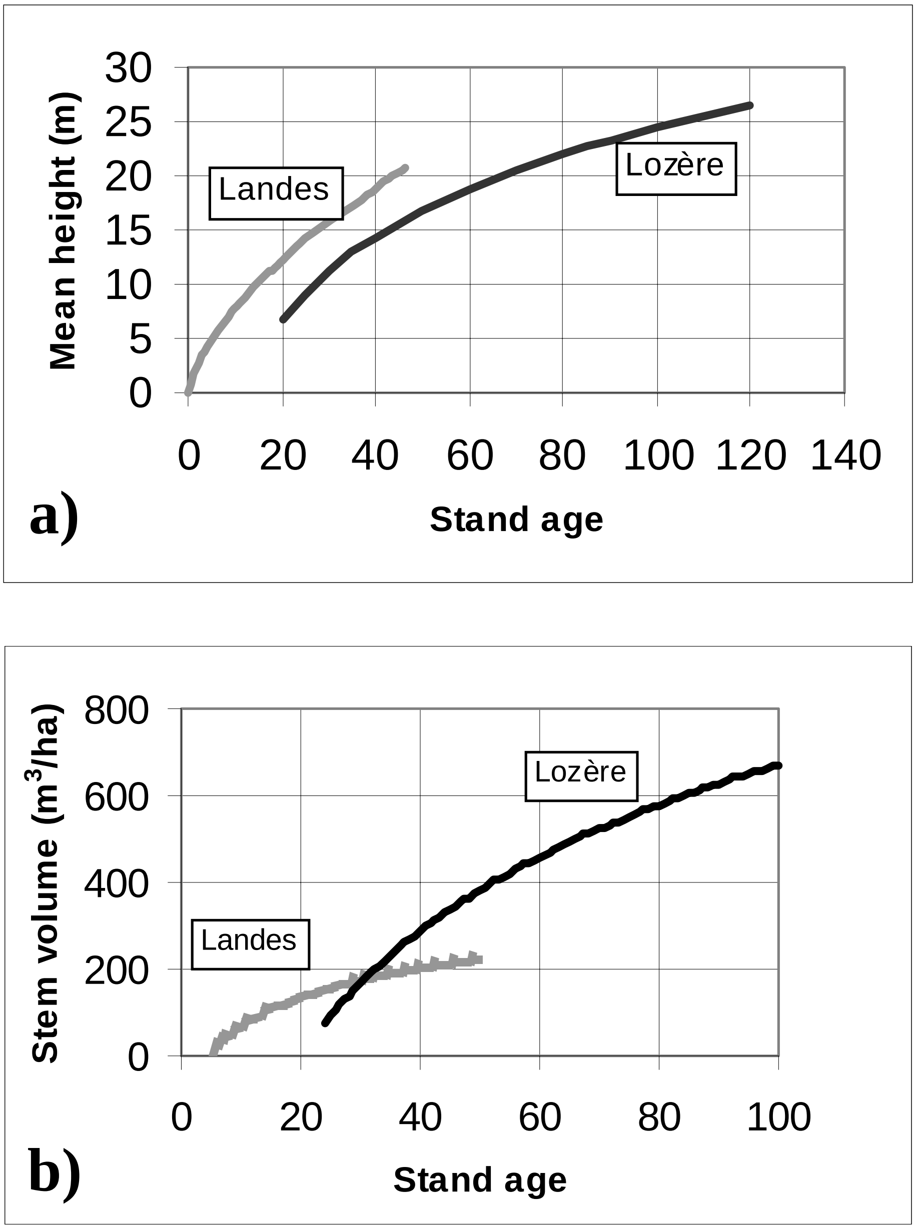
	Lozère Forest (Austrian Pine) *Min-Max*	Landes Forest (Maritime pine) *Min-Max*
Number of stands	15	19
Age (years)	6 - 100	0 – 46
Mean-Diameter (cm)	6.0 – 35.6	0 – 40.4
Mean-Height (m)	1.5 – 26.2	0 – 20.6
Stem volume (m^3/ha)	10 - 903	0 – 217
Density (stems/ha)	573 – 2907	240 - 1443
Slope (°)	0 - 50	0

Table I : General characteristics of Lozère and Landes forests stands

	Stem volume	Trunk Height	Trunk diameter	Stem density	Basal area
Lozère	**0.99**	**0.95**	**0.98**	-0.74	0.48
Landes	**0.94**	**0.93**	**0.93**	-0.92	0.86
Lozère + Landes	**0.99**	0.83	0.62	-0.43	0.61

Table II: Correlation r^2 between forest parameters and backscatter coefficient for Lozère and Landes forests.



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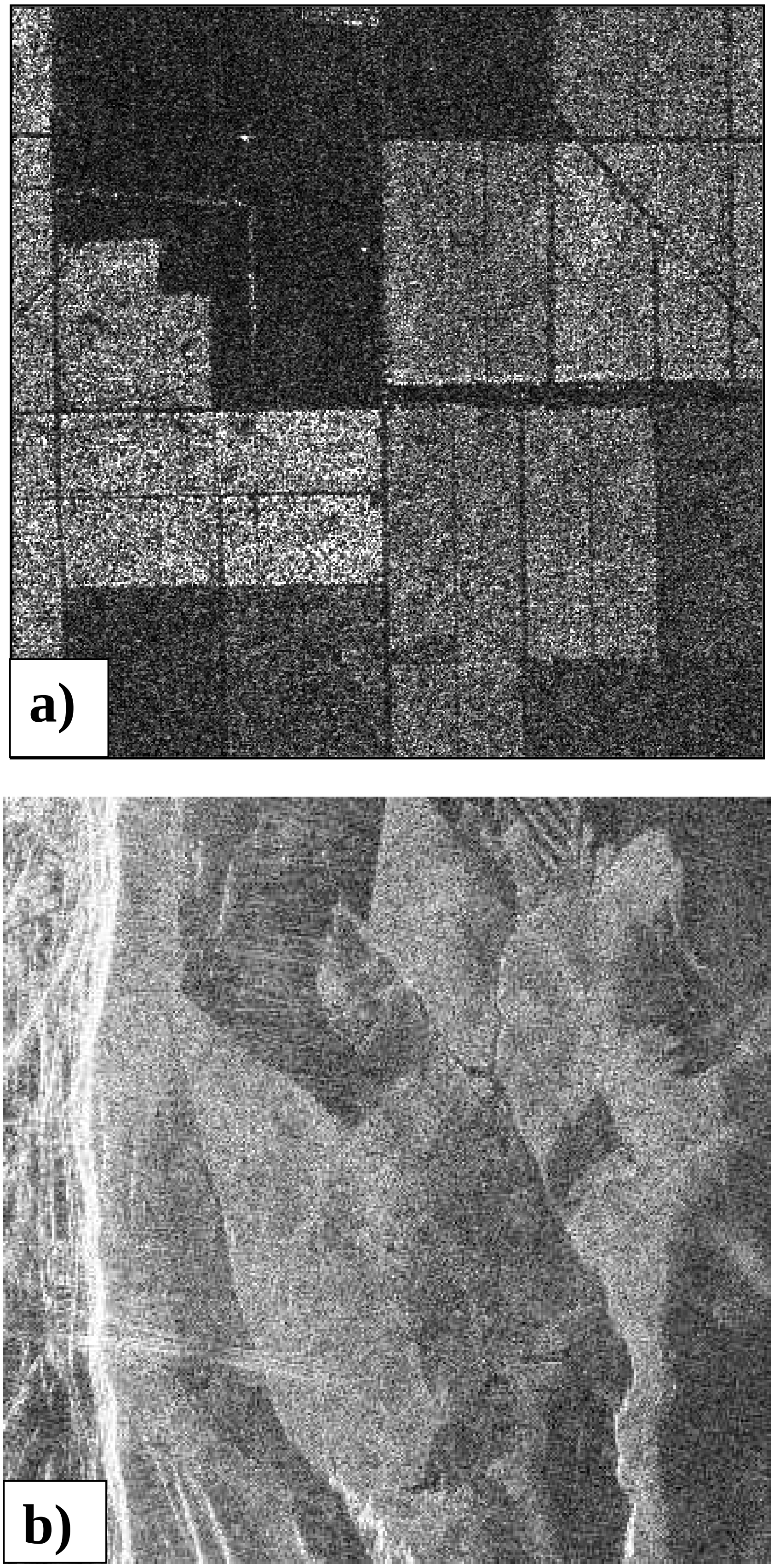

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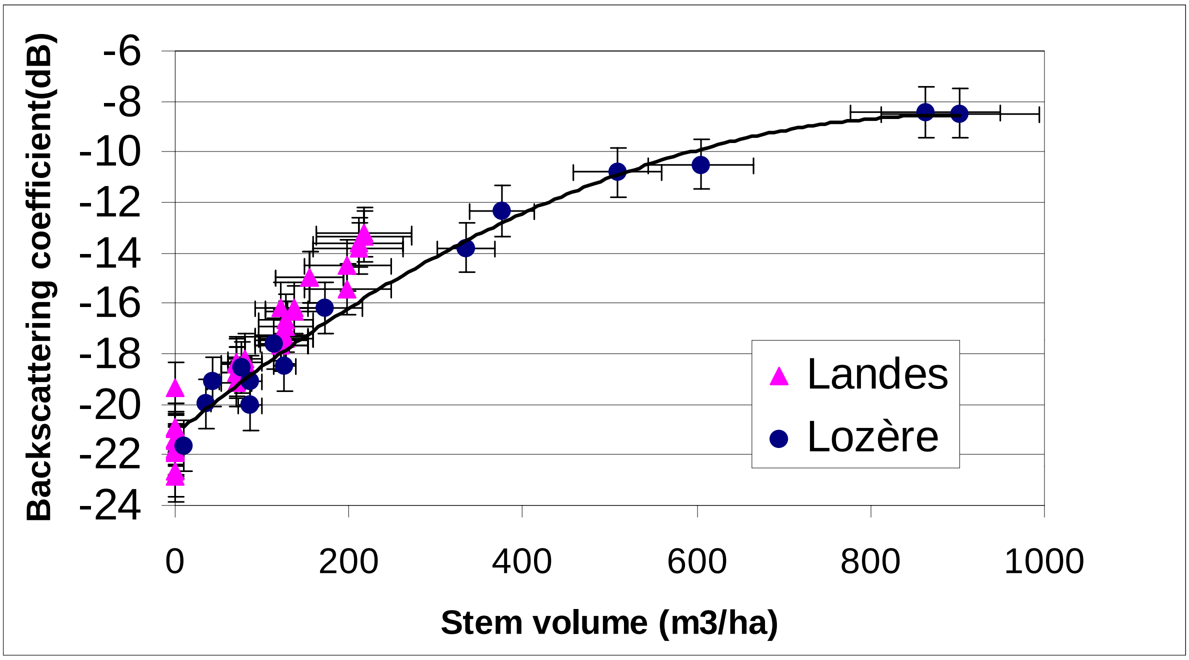

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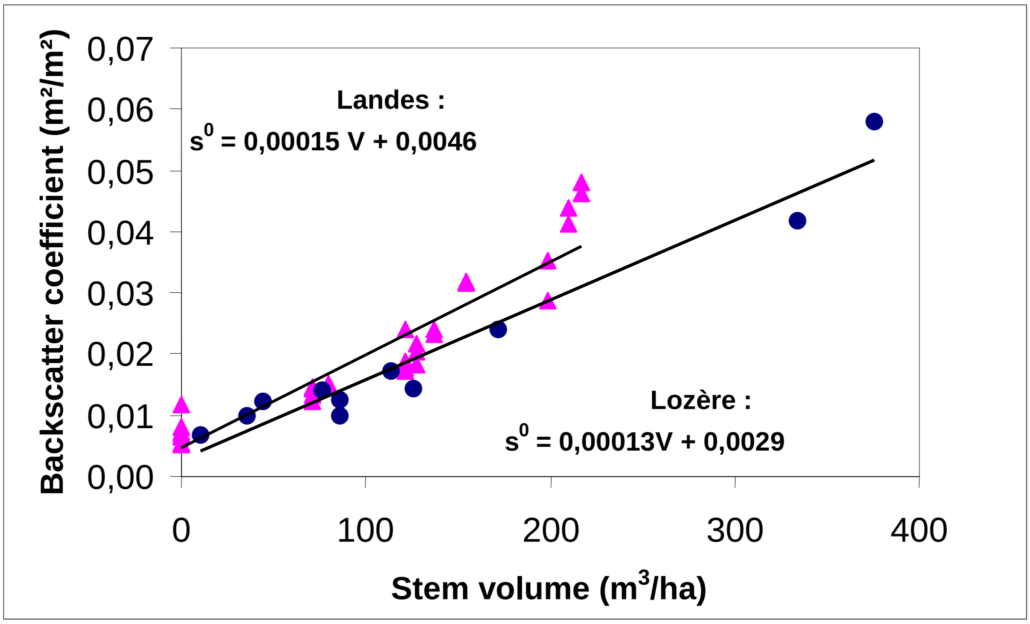

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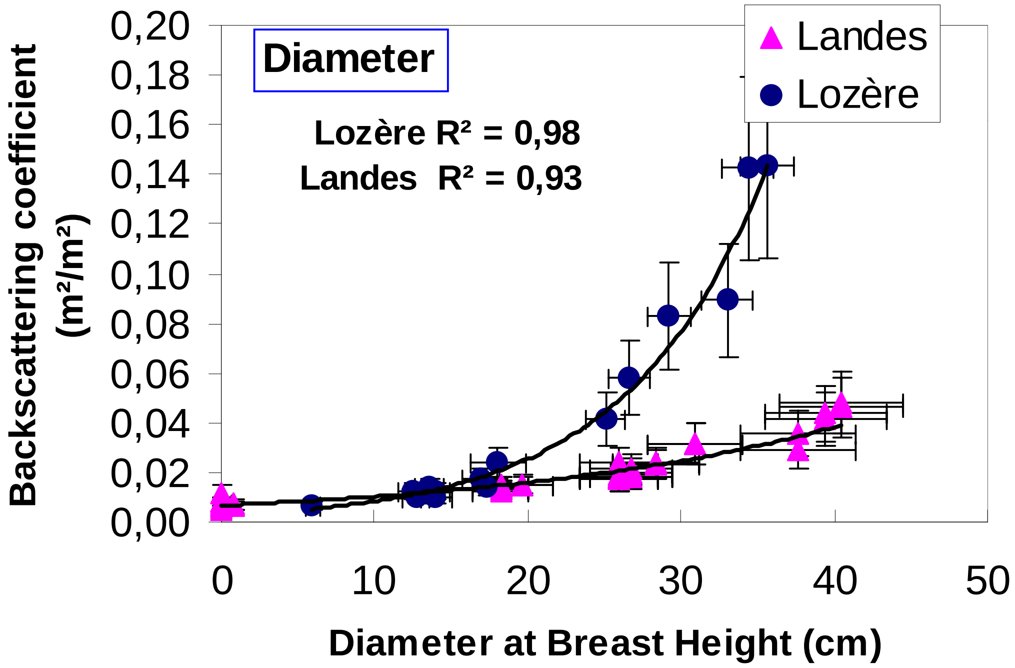

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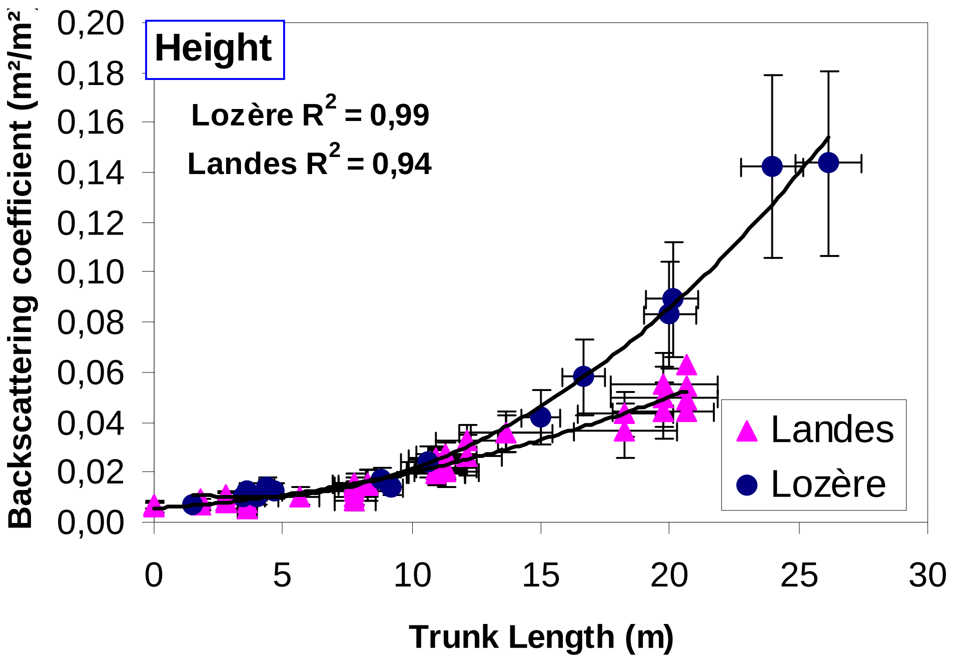

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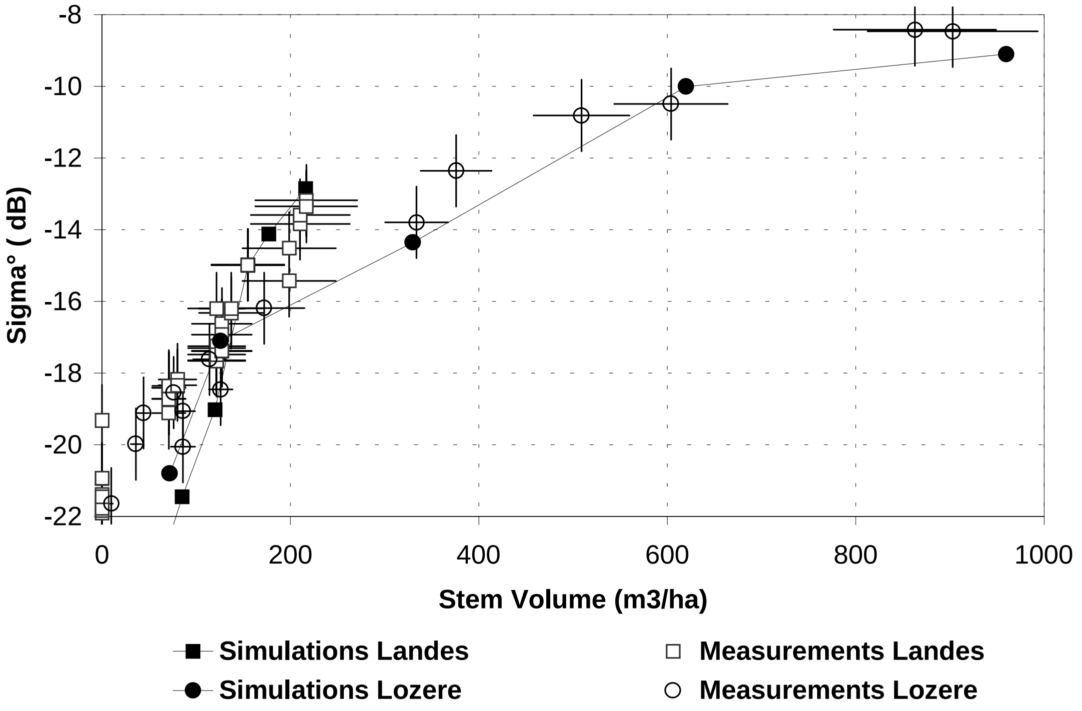

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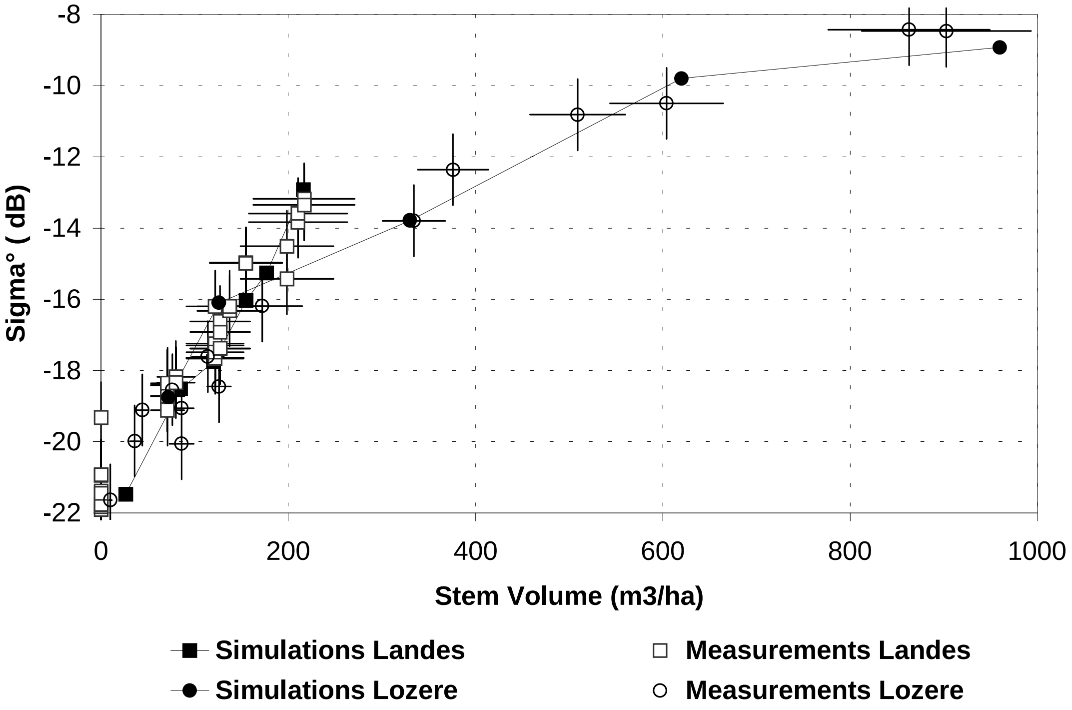

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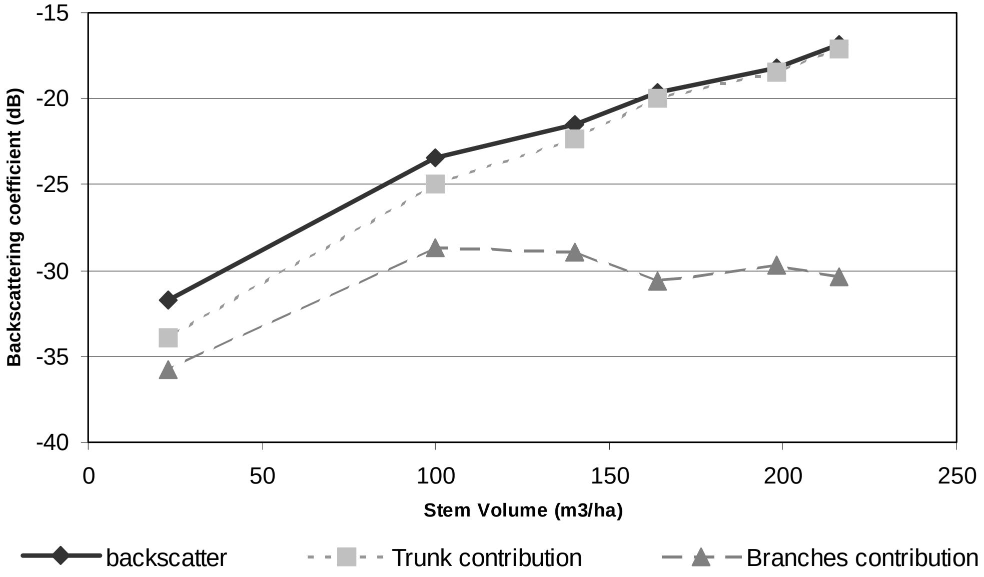

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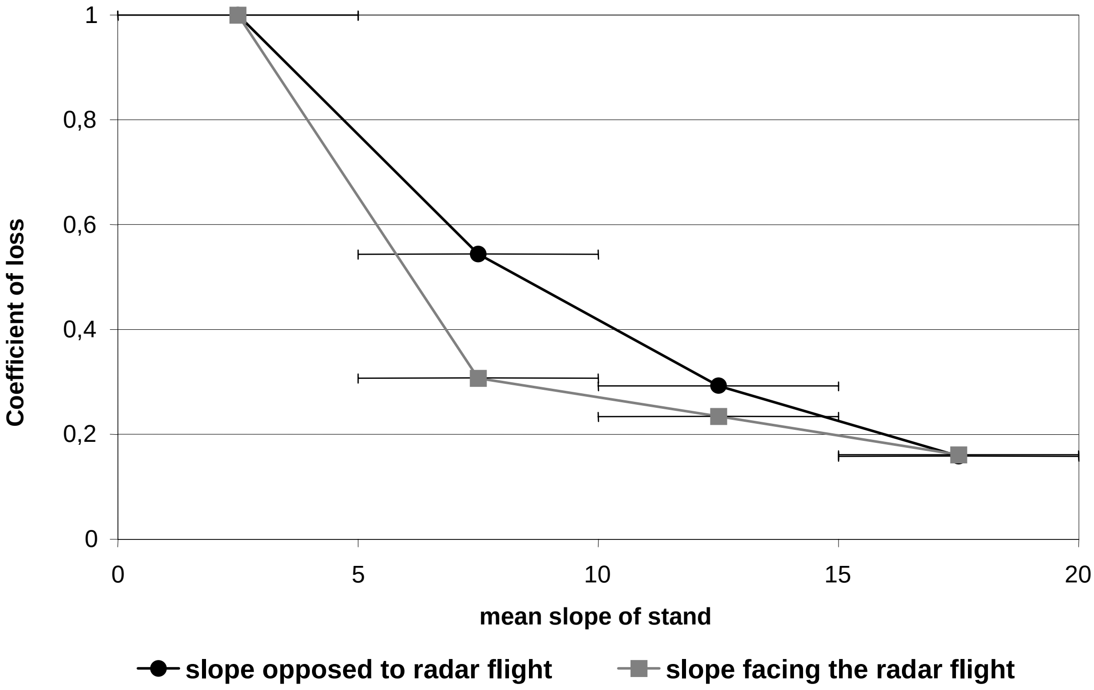

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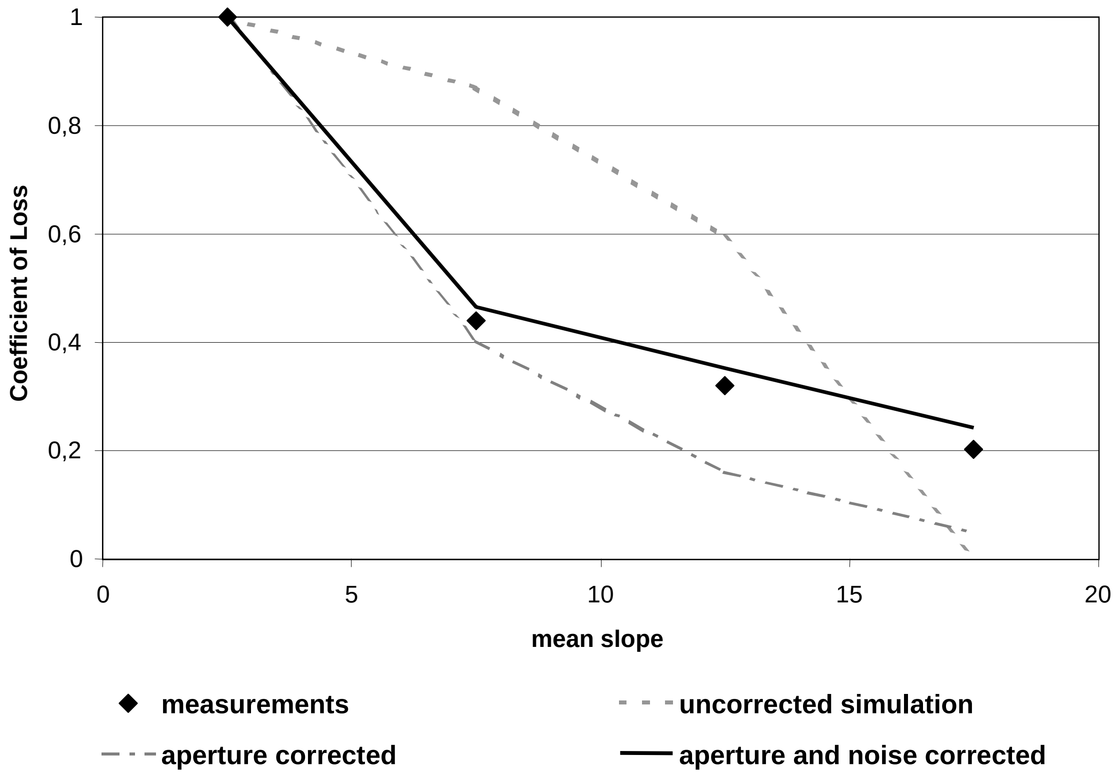

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