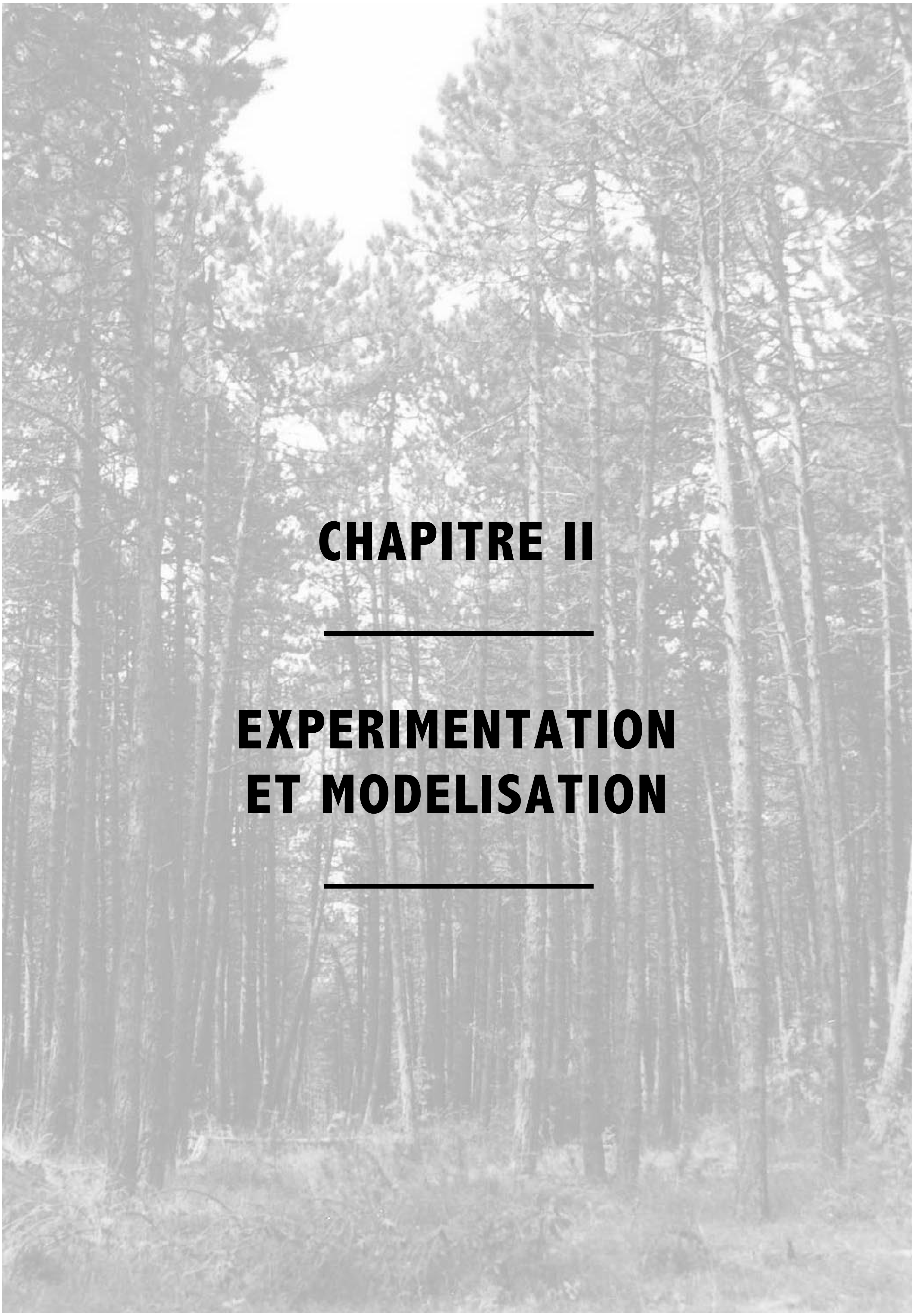

CHAPITRE II

EXPERIMENTATION ET MODELISATION

Article A

« Measurements and modeling of vertical backscatter distribution in forest canopy »

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MEASUREMENTS AND MODELING OF VERTICAL BACKSCATTER DISTRIBUTION IN FOREST CANOPY

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ABSTRACT

This paper presents the results of analysis and modeling of the airborne ranging scatterometer HUTSCAT data obtained over an Austrian pine forest in Southern France. The objective is to use high vertical resolution backscatter profiles to validate a model which is subsequently used to determine the scattering sources within a canopy and to understand the wave/tree interaction mechanisms.

The backscatter coefficients derived from HUTSCAT measurements at X band at near normal incidence, and polarizations HH, VV, VH are analyzed. The tree crown backscatter separated from the ground backscattering shows a sensitivity of about 3 dB between 0 and 200 m^3/ha.The estimation of tree height using HUTSCAT profiles gives very good results, with a mean precision of 1 meter.

The vertical backscatter profiles are compared with the output from the MIT/CESBIO radiative transfer (RT) model coupled with a tree growth architectural model, AMAP, which recreates tree architecture using botanical bases. An *a posteriori* modification to the RT model is introduced, taking into account the vertical and horizontal variability of the scattering area, in order to estimate correctly the backscatter attenuation. The results show good agreement between both simulated and HUTSCAT derived vertical backscatter distribution within the canopy.

The penetration depth at near normal incidence is studied. Both simulated and experimental penetration depth are compared and appears to be of several meters, varying with the stand's age.

I. INTRODUCTION

In recent years, the use of radars to estimate forest resources has been subject of numerous works, carried out using either empirical or theoretical approaches in order to understand the information content of the spaceborne SARs for their best use in forest resource estimation.

The empirical approaches have shown their limits, mainly because the derived relations often appear to be strongly site and time dependent. The theoretical approach completes the observations by formulating models based on knowledge of the interactions between the electromagnetic waves and the media, to interpret the link between the measured signal and the parameters of interest. The first "historical" models used the water cloud approach [1, 2] in which the vegetation is represented by a homogeneous droplet cloud. They have been used successfully to interpret measurements over simple canopies but cannot take into account the complex canopy structure. Since then, numerous studies specified the importance of both the canopy architecture and its microstructure in the forest backscatter [3, 4, 5], especially when advanced multifrequency polarimetric radar systems were used. Consequently, the models became more complex both in the description of forest media and in the application of scattering theories. In particular, the description of the forest media becomes more and more improved, from a single layer medium in which the vegetation was characterized using *in-situ* measurements, to a multi layer medium in which the vegetation is characterized using mathematical models or a botanical approach. This latter approach, by providing detailed and realistic information on the canopy, appears to be very interesting to analyze in detail the interaction between the microwave and the vegetation elements..

The coupling of a radiative transfer (RT) model to the architectural tree growth model AMAP [6, 7] has been recently applied to SAR data such as SIR-C/X-SAR data [8, 9, 10] leading to improvement in the understanding of backscatter mechanisms.

In order to complete the validation of such a backscatter model, it appeared interesting to use ranging backscatter measurements to asses the capability of the model to correctly determine the scattering sources within the tree canopy.

In the past, high range resolution airborne scatterometer providing vertical backscatter profiles have been used to study the interaction of the microwaves into the canopy, using experimental approach [11] or semi-theoretical approach with the simple water cloud model [12].

The objective of this paper is to use airborne scatterometer measurements to validate and improve an electromagnetic model.

In the framework of the EUFORA project (European Forest Observations by Radar), we organized an experiment was performed in November 1997 using the helicopter borne ranging scatterometer HUTSCAT developed by the Helsinki University of Technology (HUT) [13]. The campaign was carried out on the Lozère forest in France, for which the coupling between the RT model and the AMAP architectural tree growth model was previously developed [10].

The first part of the paper presents the experimental results : the HUTSCAT scatterometer is described in the first section followed by test site and data description. In this paper only data acquired in the near normal incidence mode at X band were used. The last section summarizes the data analysis and provides also a study of the sensitivity of HUTSCAT data to forest parameters such as stem volume and tree height. This latter section aims at completing previous studies using HUTSCAT over boreal forests [14, 15] with observations on another type of forest (temperate, plantation forest).

The second part of the paper presents the modeling work carried out to interpret the backscatter profiles. The first section summarizes the backscatter model which consists of a coupling between the MIT/CESBIO RT model [16] and the tree growth model AMAP. The second section compares the backscatter model to the HUTSCAT profiles, and includes the improvement of the backscatter model to fit with the observations. In the last section the estimation of penetration depth using the RT model and experimental data is discussed.

II. HUTSCAT SCATTEROMETER

HUTSCAT is a helicopter-borne non-imaging FM-CW scatterometer operating simultaneously at frequencies 5.4 GHz (C-band) and 9.8 GHz (X-band) and polarizations HH, VV, HV and VH [13]. HUTSCAT was designed and constructed during 1987-1990 by the Laboratory of Space Technology of the Helsinki University of Technology (HUT). The main parameters of HUTSCAT are presented in Table I. HUTSCAT measures about 20 backscattered power spectra at each channel per second. Simultaneously with the backscattering measurements, the target is observed by a video camera, and Differential Global Positioning System(DGPS)-coordinates of the flight track, with an absolute precision of 1 meter, are stored in a laptop computer. The typical flight altitude is 100 m and the flight speed is around 25 m/s. HUTSCAT is calibrated both internally and externally to eliminate short-term and long-term variations in the backscattered power level. Internal calibration is conducted by a delay line, which connects transmitted power to the receiver. External calibration is conducted with active radar calibrators (ARC) and corner reflectors [17].

III. TEST-SITE AND DATA

The HUTSCAT campaign took place on 22-23 November 1997 over Austrian pine (*Pinus nigra nigrae*) forests located in Lozère, Southern France. These forests are plantations made of even-aged trees ranging from 0 to 130 hundred years old, covering 5400 ha. The stands are of about 10 ha each and are exploited by the French Forestry Board. One interesting point is the large range of stem volume encountered, up to 1000 m3/ha for some stands of one hundred years old. Two examples of stands of 15 and 100 years old are presented in Fig. 1.

A total of 13 flights, all of 4 km long, acquired at 3° or 23° incidence along 3 main flight paths were analysed. The flight paths were included in a Geographic Information System (GIS) of the site defined to include various stand conditions in age and density.

The ground measurements were carried out in the forest stands under study on 20 meters spaced sample plots of 14 meters diameter along the flight track. The plot diameter has been chosen to have sufficient samples of HUTSCAT measurements of 7 meter of horizontal resolution. The 20-meter space between the sample plots ensures a statistical independence between consecutive HUTSCAT samples. In each sample plot, diameter, height and crown depth were measured for all the trees. In cases where the stem density was higher than 1500 stems per hectare all tree diameters were measured but only 10 heights were sampled. Then the basal area, stem volume, tree density and mean tree height were calculated for each sample plots. The mean height refers to the averaged height of all measured trees. A total of 66 plots were used, with a range of biomass going from 70 up to 1000 m^3/ha. The stem volume for each stand was obtained by averaging the values measured at the sample plot level. Table III presents the statistical properties of these 66 samples. Finally, we extracted the HUTSCAT profiles corresponding to each sample plot and stand for the analysis, using the GIS.

IV. DATA ANALYSIS

The calibrated radar data provide the ground and tree crown backscattering coefficients, along each measurement transect, with a 0.68 meter vertical resolution. The forest backscattering profile was calculated only when returns from ground and tree crown were reasonably well separated from each other. Otherwise, only the total backscattering coefficients were provided. For more details on the profiles computation and extraction the reader can refer to [13]. Fig. 2 shows a succession of profiles along a transect over stands of different ages.

Finally, for a total of 15 stands ranging from 20 to 100 years old, the detailed crown backscattering coefficients have been extracted at X band. We selected profiles for which 90 % of the total above ground backscattered energy came from the crown layer, removing the cases where understory layer contributes significantly to the signal. For this calculation, the bottom limits of the crown were determined using the *in-situ* measurements of the crown height presented in the previous section. Three examples of vertical backscatter profiles are shown in Fig. 3, extracted from profile sequences over 30, 40 and 90 years old Austrian pine stands at X band for VV and VH polarizations in the near normal incidence mode. These profiles averaged from more than 30 individual profiles, suggest that the penetration depth is of the order of several meters even for old stands.

A. *Sensitivity to stem volume*

The vertical and horizontal resolution of HUTSCAT profiles at near normal incidence are of 0.68 m and 7 meters respectively. In order to have a reliable estimate of backscatter coefficients, it is necessary to average measurements over a sufficient number of independent samples (70 to 120 samples).

For each of the stands under study, the crown backscatter σ^0_{crown}, the ground contribution σ^0_{ground}, and the total backscatter σ^0_{total}, sum of the two previous coefficients, were derived from HUTSCAT profiles. The crown backscatter is obtained by vertically summing the canopy backscattering coefficients for each profile and then by averaging over all the profiles along the transect. The backscatter values were analysed as a function of stem volume. As expected, σ^0_{total} exhibits almost no sensitivity to stem volume in the range of stem volume considered (100 to 900 m^3/ha).

The sensitivity of the backscatter to biomass parameters is expected to be higher when the crown contribution can be isolated [15]. Fig. 4 shows σ^0_{crown}, versus the stem volume. The data show a dynamic range of about 3 dB between 150 and 300 m^3/ha and saturates beyond. However the lack of data between 150 and 300 m^3/ha makes it difficult to clearly determine where the saturation level is reached.

B. *Sensitivity to tree height*

The parameter of interest that can be directly derived from HUTSCAT vertical backscatter profiles is the tree height. The tree height is determined by the first return, above noise level, coming from the crown. Reliable estimation of tree height can be derived from a small number of profiles [9]. As a result, the height can be estimated for each sample plot from the ground truth (Section III), from a 7 profile sequence. The corresponding HUTSCAT sequence of profiles over each sample plot has been determined using the DGPS data included in the GIS. Similar results were obtained at HH, VV and VH, therefore only the estimations using the HH polarization are presented. Fig. 5 presents the measured mean height versus the radar derived mean height, averaged height over a 7 profile sequence. The correlation coefficient between estimated height and measured mean height is 0.96 and the residual standard deviation is of 1 m for the 66 sample plots. The relative precision of about 6 %, can be considered equivalent to the in-situ measurement precision.

These results appear very promising in terms of tree height retrieval and confirm previous studies [8,9] on boreal forests with mixed deciduous/coniferous species : in [9] the mean precision is of 1.2 meter for all species and 1 meter when the data are stratified by species.

V. MODELING

HUTSCAT data are further used for validation of a backscattering model. In the first step the vertical backscatter distribution within crowns provided by HUTSCAT is used to validate a scattering model, and in the second step the model is used to interpret the experimental profiles. Finally both experimental and simulated backscatter vertical distributions will be used to study the penetration depth of the waves into the forest medium.

A. *The backscatter model*

In this study, we used the MIT/CESBIO backscatter model [16], which is a first order radiative transfer model. It describes the medium as a superposition of horizontal layers containing multi-scale clusters of dielectric cylinders. The phase matrix and the extinction matrix are formulated in terms of scattering coefficients of the various scattering elements of the medium. As far as the scattering coefficient computation is concerned, trunks, branches and needles are modelled as dielectric cylinders where finite cylinder approximation is used [18, 19]. The coherent interactions between the responses of the various elements of a cluster are taken into account by using the branching model [20]. The multiple scattering is expected to be significant at X-band. In [21] the importance of multi-scattering in a cypress cover is addressed. It appears that at X band, the second order solution differs from the first order solution of about 1.5-2 dB at cross polarization. From the tables characterising the vegetation given in [21] it is possible to compute the cypress leaflet volume fraction, proved to be the main scatterers at X band. The volume fraction is of 0.073 %. In the Austrian pine case, the volume fraction of needles, third and second order branches (the main scatterers) varies from 0.02% (24 years old) to 0.05 % (40 years old). When needles are considered alone, the volume fraction fells down 0.01 %. These values indicate that the volume fraction of our pine stands is low and that in a first approximation we can use only the first order solution.

The geometric description of the vegetation relies on the AMAP (Atelier de Modélisation de l'Architecture des Plantes) tree growth model developed at the CIRAD (Centre de Coopération Internationale en Recherche Agronomique et Développement) [6, 7].

The AMAP model relies on detailed botanical observations which allowed to develop an architectural typology used to simulate trees growths. Specific botanical measurements are necessary to calibrate the model for a given species in its environmental conditions. Then, tree architecture simulation for a given age is realized through a Monte-Carlo technique and a Markov process in order to reproduce the buds activity, the branching process and the associated geometry (angle, length, diameter) of the tree shoots (called growth units). Finally, the crown natural variability is reproduced through successive random AMAP simulations. Fig. 6 presents different simulations results of Austrian pine (without needles) from 16 to 40 years old Austrian pine .

In recent studies [8, 9, 10], the coupling between this architectural model and the MIT/CESBIO radiative transfer model was presented, including an interface which adapts the AMAP description of trees to the specific MIT/CESBIO RT model. The interface [22], AMAP2SAR, transforms the 3D trees into a collection of cylinders characterized for each cluster scale (branch order 1 to 3) by its mean length, diameter, linear density and branching angle, after averaging over 20 simulated trees.

The AMAP model has been calibrated for Austrian pine, from 0 to 45-year old, and for the Lozère test-site. For validation purposes, AMAP-derived parameters such as tree height, diameter and length of primary branches were compared to in-situ measurements with a satisfactory agreement [5].

AMAP simulates primarily the tree architecture and still requires botanical measurements on needles to be complete. Furthermore, simulations with a complete needle description are very time consuming : for a 40 year old pine, 24 hours on Sun Ultra Station with needles and 2 hours without needles. The alternative we adopted is as follows : a mean needle cluster is used with needle diameter, length, density and insertion angle of 1 mm, 8 cm, 16/cm and 33°. The length of the cluster, equal to the branch length covered by needles, is assumed to be a constant depending on the branch order. First order branches are covered by needle clusters of 20 cm long and upper orders of 10 cm long. The total needles distribution is then obtained using the linear densities of the branches (given by AMAP) supporting the needles.

For validation we used measurements of needles distribution, carried out by the Laboratoire Commun de Télédétection (LCT), within the crown of one 40 years old pine [23]. The in situ measurements were carried out on one single tree, the amount of work (300000 needles for one tree) preventing from more. The needles were weighted for each growth unit and branch order. Then, it was possible to compare directly as a function of height both experimental and simulated needles distributions with a good agreement.

B. *Comparison between backscatter model and HUTSCAT profiles*

We will focus on two stands of 30 and 40 years old, with a stem volume of 120 and 330 m^3/ha, for which we have HUTSCAT profiles, in-situ measurements and AMAP simulations. The height of each layer defined into the RT model is set to 0.68 m, the vertical resolution of HUTSCAT. The first simulations are conducted using the RT model, with the branching model, coupled with AMAP considering the canopy as horizontally infinite homogeneous layers. The simulation predicted that the principal backscattering sources are localized in the first top layers of the trees showing a shallow penetration depth. On the opposite, the HUTSCAT profiles suggest that a significant proportion of the energy backscattered comes from lower parts of the crown. The disagreement can be interpreted as follows : at near normal incidence, the external part of the largest branches at the lower part of the crown can be seen without attenuation by the upper layers. But when the crown is considered as infinite homogeneous horizontal layers, the contribution of the lower part is always attenuated by the uppermost and therefore is reduced. We propose to correct the infinite horizontal layers assumption in order to take into account the real interception paths within the canopy.

In most existing models [24, 25, 26], the crown is modeled as a unique layer composed of homogeneous randomly placed ellipsoids or parallelepipeds, of scattering elements. These models compute the backscatter for different scattering paths, weighted by the probability of each path. The sum of all the components constitutes, then, the total backscatter. In the experimental configuration under study, we assume that the wave interacts only with a single tree, provided that the forests under study are plantations with disconnected canopies. Consequently, instead of computing interception probabilities, we propose a simple *a posteriori* correction to the backscattering coefficients of each layer in the RT model by taking into account the vertical variability of the scattering area of each layer and then the real path of the microwaves within each layer.

In the infinite layer hypothesis the scattering area A is the same for all the layers. In the correction we propose, the scattering area of the n-th layer, A_n, is defined as a disk whose radius is the horizontal projection of the mean length of the primary branches in the n-th layer. The two-way attenuation of the j-th layer in the actual scattering area approach and the infinite layer hypothesis are respectively K_j' and K_j. The number of vegetation elements in a layer is the same using the two approaches, however the vegetation elements are spread over the surface A_j instead of A in the approach taking into account the actual scattering area. The attenuation being proportional at the first order to the scatterers density, we have $K_j' = K_j / F_j$ where $F_j = A_j / A$.

Fig. 7 illustrates the difference in the description using the infinite layer and the actual scattering area hypothesis. In this illustration, the crown is composed of 3 horizontal layers. In the first hypothesis the backscatter from the bottom layer (Fig. 7) is attenuated by all upper layers. When the actual scattering area is taken into account, the corrected backscatter $\sigma_1^{0}{}'$ from the bottom layer is the sum of 3 contributions : 1) direct backscatter from the part of this layer directly seen by the radar, 2) backscatter from the rest of the bottom layer, attenuated only by the second layer and 3) backscatter from the rest of the bottom layer, attenuated by the second and third layers:

$$\sigma_1^0{}' = \sigma_1^0\left((1-f_1) + f_1(1-f_2)e^{-K'_2} + f_1.f_2.(1-f_3)e^{-(K'_2+K_3')}\right) \tag{1}$$

where $f_j = A_{j+1} / A_j$, and at the top of the crown $f_3 = 0$. The backscatter of each layer, σ_j^0, is calculated using the RT model with infinite layers and no attenuation. Iterating on a N layer crown, the modified total backscatter $\sigma_{Tot}^0{}'$ is :

$$\sigma_{Tot}^0{}' = \sum_{j=1}^{N}\left((1-f_j)\,\sigma_j^0 + \sigma_j^0\left(\sum_{i=j+1}^{N}(1-f_i)\left(\prod_{k=j}^{i-1} f_k\; e^{-K'_{k+1}}\right)\right)\right) \tag{2}$$

where $f_j = A_{j+1} / A_j$. The first term in the brackets represents the non attenuated backscattering of the j-th layer and the second term the backscatter contributions of the layer j attenuated by all the i-th layers between the radar and the j-th layer ($j < i < N$). Simulations show that error on the primary branches length An induces error of the same order on the backscatter (for a given layer) : a 10% percent error on An will result in a 0.4 dB error on the backscatter.

The correction results in a decrease of the contribution of the upper layers and in an increase of the contribution of the lower layers (Fig. 8). Comparisons of experimental and simulated profiles for 30 and 40 years old Austrian pines are shown respectively in Fig. 9 and Fig. 10 for VV and VH polarizations. The vertical resolution if of 0.68 m, so that 14 and 22 layers were used to calculate the crown backscatter respectively for the 30 and 40 years old pines. The experimental profiles consist in an average of more than 30 profiles over a given stand, as described in the analysis section. A good agreement is found, in particular at 30 years old concerning the shape of the profile and the value of the maximum energy at cross polarization whereas the simulated backscatter at co-polarization is lightly overestimated, of about 1.5 dB (Table III). At 40 years old a more significant difference is found in the lower part of the profiles, and the backscatter is underestimated. The experimental crown backscatter increases between 30 and 40 years (Table III) unlike the simulations exhibiting a slight decrease.

The model is then used to specify the contribution of each vegetation element within the tree crown. Fig. 11 shows the contributions as a function of height for a 40-year old stand of needles, branches order 1, 2, 3 and the coherent interactions between the multi-scale clusters. The needles are by far the main contributors, followed by the second and third order branches.

These results can be interpreted as follows :

- The slight decrease of the simulated backscatter (table III) between 30 and 40 years old, indicates that the backscatter saturates, due to the high number of scatterers and that the signal is no longer sensitive to an increase of needle biomass, but rather to variations of needles geometry (diameter, insertion angle, length) not taken into account by AMAP;
- The differences in experimental and simulated profiles in the lower parts of the profiles of 40 years old can be explained by the presence of dead old branches along the bottom part of the trunk under the crown in the 40 year old stand which does not appear in the AMAP simulated trees. The water retained by these dead branches from rain which occurred on previous days increases probably their backscatter. However, despite the differences in the profile shape, the total backscatter is not affected significantly by the low backscatter values of dead branches.
- The 3 dB underestimation (Table III) at 40 years old and for cross–polarization is probably due to multiple scattering within the crown which are not simulated by the first-order model.

C. *Penetration depth estimation*

The penetration depth δ_p may be defined as the depth at which $I(\delta_p)/I(0)=1/e$, where I(0) is the transmitted intensity of the incident wave at the top of the crown. Fig. 12 presents the penetration depth estimated from HUTSCAT data at normal incidence compared to simulated values using the

RT model. The simulations were performed using AMAP models on even-aged stands between 24 and 45 years old with a 4 year step. The experimental profiles were selected over stands of 30, 34, 40, 70 and 90 years old. The error bars denote the layer thickness (± 0.68 m) and do not account for other sources of error.

Features to be noted are the following :

- the penetration depths appear more important (from 4 to 7.5 m) than what is known qualitatively in general for X band [27], although the profiles corresponding to gaps in between the trees were removed;
- the penetration depth increases with age. This can be explained by the decrease of the density of scattering elements on the top layers of the trees, and the variation in scatterer geometry as the age increases;
- the model simulates the same range of penetration depth than the experimental data (4-6 m) in the range of age for which we have both tree growth model and the radar measurements. However the penetration seems to increase more rapidly in the experimental data than in the simulation.

The penetration depth could be a key information for many applications using radar, such as DEM generation over forested areas using interferometry [28]. However the above results are applicable to high resolution measurements and only when gaps in the forest are excluded. At current satellite spatial resolution, the impact of the gaps in between the trees is important and needs to be studied. The results presented are only valid for near normal incidence angles. In addition, extension to larger incidence angles should be performed.

VI. CONCLUSION

Analysis and interpretation of HUTSCAT data acquired at X band and near vertical incidence over temperate Austrian pine plantations were presented. The analysis results confirm the previous results obtained in more natural northern boreal forests on the sensitivity of the radar data to biophysical parameters. In particular, the tree mean height derived from vertical backscattering profiles shows very good agreement with in-situ measurements. The precision of the derived heights (of about 1 meter) is of the same order as that of the *in-situ* measurements.

The measured vertical backscatter profiles were used to validate a radiative transfer model coupled with an architectural tree growth model (AMAP). The RT model simulates the vertical backscatter distribution with the same vertical resolution than HUSTCAT (0.68 cm). A correction to the existing RT model has been carried out, taking into account the real path of the wave into the medium and the vertical variation of the scattering area. A good agreement is found between simulated and experimental profiles. The model was used subsequently to interpret the scattering mechanisms. The results confirm that at X band the needles are by far the main scatterers. Both the experimental measurements and the model suggest that the penetration depth within the canopy is of several meters. The results indicates that a precise description of the vertical and horizontal structure of the forest and, measurements provided by a ranging scatterometer, can contribute to refine our understanding of the interactions mechanisms.

VII. ACKNOWLEDGMENTS

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REFERENCES

[1] E. P. W. Attema and F. T. Ulaby, "Vegetation modeled as a water cloud", *Radio Science*, vol. 13(2), pp. 357-364, 1978.

[2] F. T. Ulaby, C. T. Allen, G. III Eger, and E. Kanemazu, "Relating the microwave backscattering coefficient to leaf area index", *Remote Sensing of Environment*, vol. 14, pp.113-133, 1984.

[3] R. Zoughi, L. K. Wu and R. K. Moore, "Identification of major backscattering sources in trees and shrubs at 10 Ghz", *Remote Sensing of Environment*, vol. 19, pp.269-292, 1986.

[4] H. Hirosawa, Y. Matsuzaka, M. Daito and H. Nakamura, "Measurements of backscatter from coniferous in the C and X bands" *International Journal of Remote Sensing*, vol. 8, no. 11, pp.1687-1694, 1987.

[5] E. Mougin, A. Lopes, M. A. Karam and A. K. Fung, Effect of tree structure on X-band microwave signature of conifers, *IEEE Transactions on Geoscience and Remote Sensing*, vol. 31, No. 3, pp. 655 - 667, May 1993.

[6] M. Jaeger and P. de Reffye,. "Basic concepts of computer simulation of plant growth", *J. Bioscience*., No 17, pp. 275-291, 1992.

[7] P. de Reffye, F. Houllier, F. Blaise, D. Barthelemy, J. Dauzat, and D. Auclair, "A model simulating above- and below-ground tree architecture with agroforestry applications", *Agroforestry systems*; vol. 30, pp.175-197, 1995.

[8] T. Castel, A. Beaudoin, J.F. Barczi, Y. Caraglio, N. Floury, T. Le Toan: "On the coupling of backscatter models with tree growth models: 1) A realistic description of the canopy using the AMAP tree growth model", *Proceedings of IGARSS'97 Symposium*, Singapore, August 1997, pp. 784-786.

[9] T. Castel, A. Beaudoin, N. Floury, T. Le Toan, J.F. Barczi, Y. Caraglio: «Coupling backscatter models with a generic architectural tree growth model.1) A realistic description of the canopy using the AMAP model ». Submitted to IEEE Transaction on Geoscience and Remote Sensing.

[10] N. Floury, G. Picard, T. Le Toan, J. A. Kong, T. Castel, A. Beaudoin, J. F. Barczi : « On the coupling of backscatter models with tree growth models: 2) RT modelling of forest backscatter ». , *Proceedings of IGARSS'97 Symposium*, Singapore, August 1997, pp. 787-789.

[11] M. Hallikainen, T. Tares, J. Hyyppa, E. Somersalo, P. Ahola, M. Toikka and J. Pulliainen, "Helicopter-borne measurements of radar backscatter from forests", *International Journal of Remote Sensing*, vol. 11, no 7, pp. 1179-1191, 1990.

[12] R. Bernard, M. E. Frezal, D. Vidal-Madjar, D. Guyon, J. Riom, "Nadir looking Airborne Radar and Possible Applications to Forestry", *Remote Sensing of Environment*, vol. 21, pp. 297-309, 1987.

[13] M. Hallikainen, J. Hyyppä, J. Haapanen, T. Tares, P. Ahola, J. Pulliainen, and M. Toikka, "A helicopter-borne eight-channel ranging scatterometer for remote sensing - Part I: system description", *IEEE Transactions on Geoscience and Remote Sensing*, vol. 31, No. 1, pp. 161 - 169, January 1993.

[14] J. Hyyppä and M. Hallikainen, "A helicopter-borne eight-channel ranging scatterometer for remote sensing - Part II: Forest Inventory", *IEEE Transactions on Geoscience and Remote Sensing*, vol. 31, pp. 170-179, No. 1, January 1993.

[15] J. Hyyppä and M. Hallikainen, "Applicability of airborne profiling radar to forest inventory", *Remote Sensing Environment*, vol. 57, pp.39-57, 1996.

[16] C.C. Hsu, H.C. Han, R.T. Shin, J.A. Kong, A. Beaudoin and T. Le Toan, "Radiative transfer theory for polarimetric remote sensing of pine forest at P band ", *International Journal of remote Sensing*, vol. 15, No. 14, pp. 2943-2954, September 1994.

[17] M. Mäkynen, “Calibration and accuracy of an airborne scatterometer”, *M.Sc. thesis* (in Finnish), Helsinki University of Technology, Department of Electrical Engineering, 1994, pp.183.

[18] H. C., Vande Hulst, “Light Scattering by Small Particles”, Wiley, New York, 1957.

[19] M.A. Karam, A. K. Fung, “Electromagnetic scattering from a layer of finite length, randomly oriented, dielectric, circular cylinders over a rough interface with application to vegetation”, *International Journal of remote Sensing,* vol. 9, No. 6, pp. 1109-1134, 1988.

[20] S. H. Yueh, J.A. Kong, J. K. Jao, R.T. Shin, and T. Le Toan, “Branching model for vegetation”, *IEEE Trans. Geosci. and. Remote Sensing* ,vol. 30, No 2, pp. 390-402, 1992.

[21] M. A. Karam, A. K. Fung, R. H. Lang and N. Chauchan, “A microwave Scattering model for layered vegetation”. ”, *IEEE Transactions on Geoscience and Remote Sensing*, vol. 30, No. 4, pp. 767 - 784, July 1992.

[22] J. F. Barczi, T. Castel, Y. Caraglio, A. Beaudoin, H. Rey, S. Chetaille, and L. Castagnas, *“AMAP2SAR, AMAP sorter V1.0, user manual.”*, ESA/ESTEC contract n° 163014/96/NL, 73 p, 1997.

[23] M. Deshayes and N. Stach, “*MARIE-F final report” - Workpackage 3b, Lozère test site investigations*, Commission of the European Communities, Contract ENV4-CT96-0316, 1999.

[24] K. C. Mcdonald and F. T. Ulaby, “Radiative transfer modeling of discontinuous tree canopies at microwave frequencies”, *Int. Journal Radio Science,* vol. 14, No 11, pp. 2097-2128, 1993.

[25] Y. Wang, J. Day, G. Sun, “Santa barbara microwave backscaterring model for woodlands”, *International Journal of Remote Sensing*, vol. 14, No.8, pp. 1477-1493, 1993.

[23] G. Sun, D. S. Simonett and A. H. Strahler, “A radar backscatter model for discontinuous coniferous forests”, *IEEE Trans. Geosci. Remote Sensing,* vol. 29, No 4, pp. 639-650, 1991.

[27] F. T. Ulaby, R. K. Moore and A. K. Fung, Microwave Remote Sensing : *Active and Passive. Vol. II Radar Remote Sensing and Surface Scattering and Emission theory.* Addison-Wesley Publishing Company, 1982.

[28] N. Floury, T. Le Toan, J. C. Souyris, K. Singh, N. Stussi, C. C. Hsu, J. A. Kong, "Interferometry for forest studies", *Proceedings of FRINGE'96*, Zurich, Switzerland, December 97, vol. II, pp. 57-70.

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Parameter	Value
Center frequencies	5.4 and 9.8 GHz
Modulation	FM-CW
Sweep bandwidth	230 MHz
Polarization	HH, VV, HV, VH
Measurement range	8 to 167 m
Range resolution	0.68 m
Incidence angle	0 to 45°
Antenna effective two-way 3 dB beamwidth	4.7° (5.4 GHz) 4.4° (9.8 GHz)
Antenna sidelobe level	< -16.5 dB (5.4 GHz) < -16.5 dB (9.8 GHz)
Antenna polarization isolation	26.0 dB (5.4 GHz) 28.5 dB (9.8 GHz)
Relative accuracy of σ^0 90% confidence interval	±0.3 dB (5.4 GHz) ±0.3 dB (9.8 GHz)
Absolute accuracy of σ^0 68% confidence interval [1)]	±1.2 dB (5.4 GHz, VV-pol)
Mean noise equivalent tree crown coefficients [2)] (measured during the Lozère campaign)	<-40 dB (5.4 GHz HH-pol) <-43 dB (5.4 GHz VV-pol) <-60 dB (5.4 GHz cross-pol) <-30 dB (9.8 GHz HH-pol) <-35 dB (9.8 GHz VV-pol) <-60 dB (9.8 GHz cross-pol)

1) Accuracy was estimated by comparing HUTSCAT and ERS-1 SAR mean backscattering coefficients of different land-use classes from the Sodankylä test area in northern Finland. The data sets were obtained in 1991-1993.

2) Noise equivalent tree crown and total backscattering coefficients depend on the height of the tree crown. These values represent only an average along the range distance.

Table I : The main parameters of HUTSCAT scatterometer [13, 17]. In the Lozère campaign incidence angles 3° and 23° were used.

	Basal area (m^2/ha)	***Stem volume (m^3/ha)***	***Stem density (stems / ha)***	***Mean height (m)***	***Crown depth (m)***
Mean	49.5	492.1	788.1	18.4	7.0
Std	17.4	266.7	405.5	5.7	1.1
Max	91.1	1023.1	2216.1	27.8	9.8
Min	19.7	71.0	288.1	7.2	4.5

Table II : Statistics of main derived parameters from the 66 sample plots.

	30 years old		**40 years old**	
	Model	**HUTSCAT**	**Model**	**HUTSCAT**
HH	-10.3 dB	-12 dB	-11.8 dB	-10.1 dB
VV	-10.3 dB	-13.1 dB	-11.8 dB	-11.1 dB
VH	-18.3 dB	-18.6 dB	-20.1 dB	-16.7 dB

Table III : Comparisons between the modeled and experimental crown backscatter coefficients of two stands of Austrian pine for HH,VV and VH polarizations for the near incidence mode of HUTSCAT.

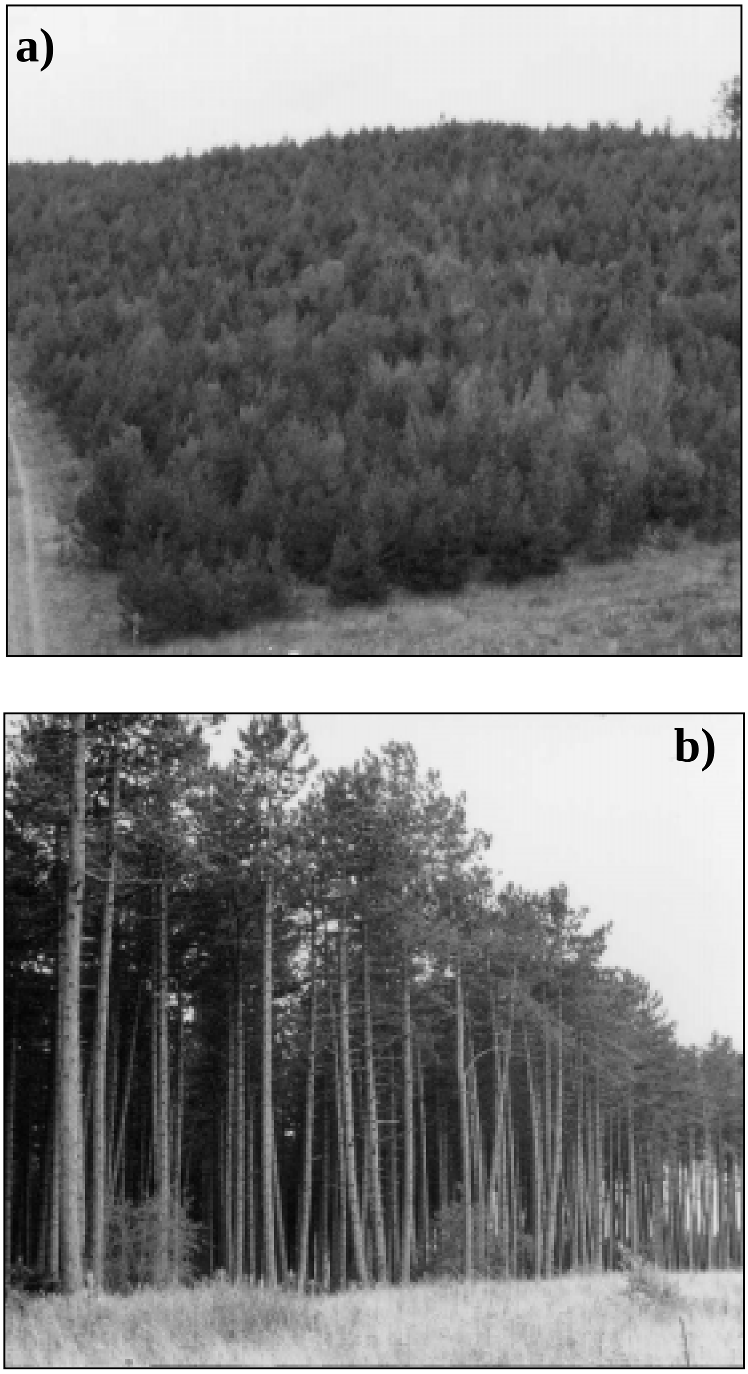


Fig. 1 : Austrian pine stands (Pinus nigra nigrae) of the Lozère forest (France) of a) 15 years old and b) 100 years old.

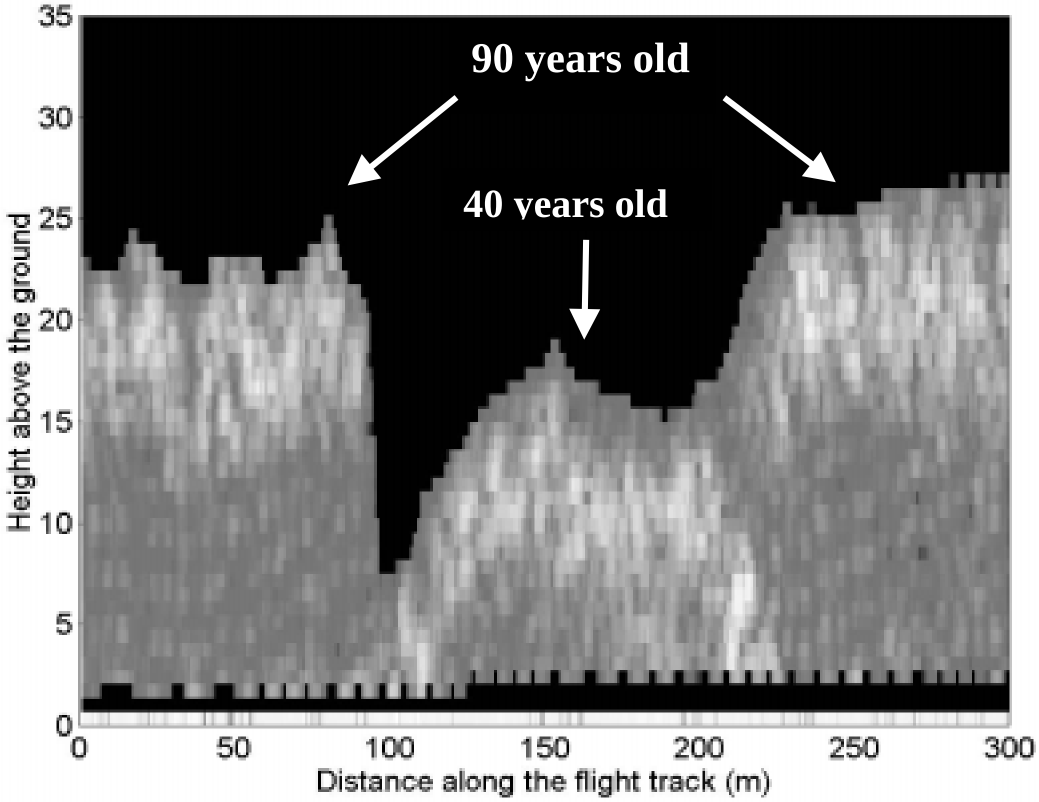


Fig. 2 : Succession of 300 vertical backscatter profiles measured by HUTSCAT at X band and HH polarization, along a transect over 3 Austrian pine stands of (from left to right) 90, 40 and 90 years old. A profile is measured at each meter, and the vertical resolution is of 0.68 cm. The different tones denote the backscatter intensity of each resolution cell.

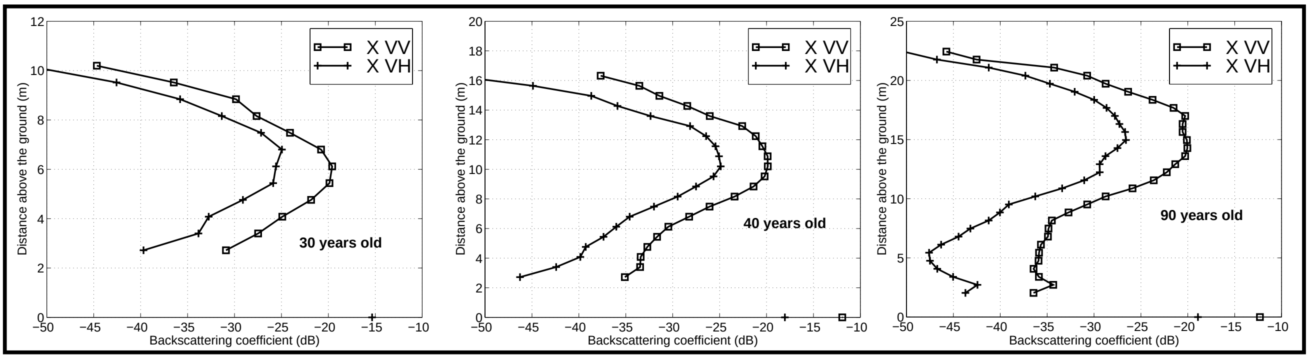


Fig. 3 : Vertical backscatter profiles measured at VV and VH polarizations by HUTSCAT over Austrian Pine Stands of (from left to right) 30, 40 and 90 years old.

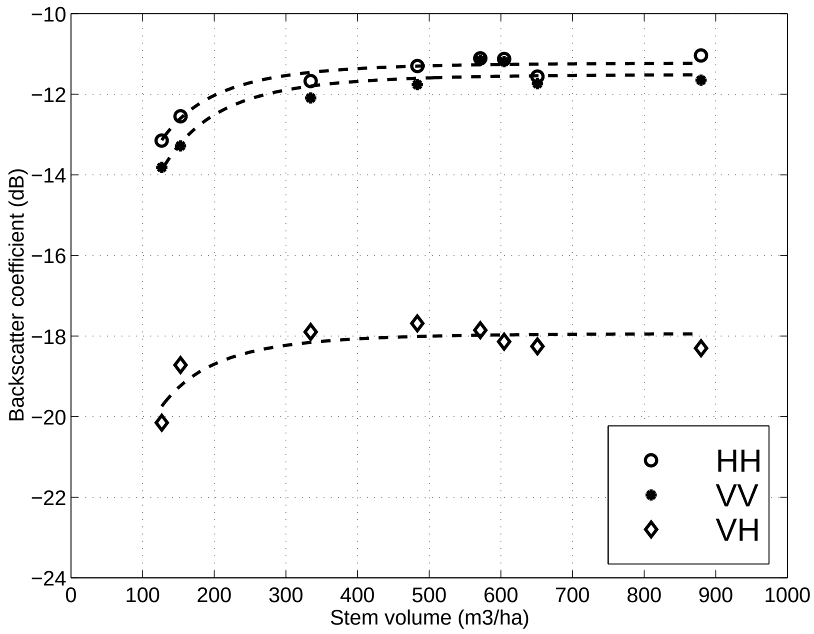


Fig. 4 : Crown backscatter of Austrian pine stands, for the near-normal incidence mode, and for the 3 polarizations at X band versus the stem volume. The crown backscatter is the sum of all the contributions coming from all the resolution cells in the radar backscatter profiles within the crown.

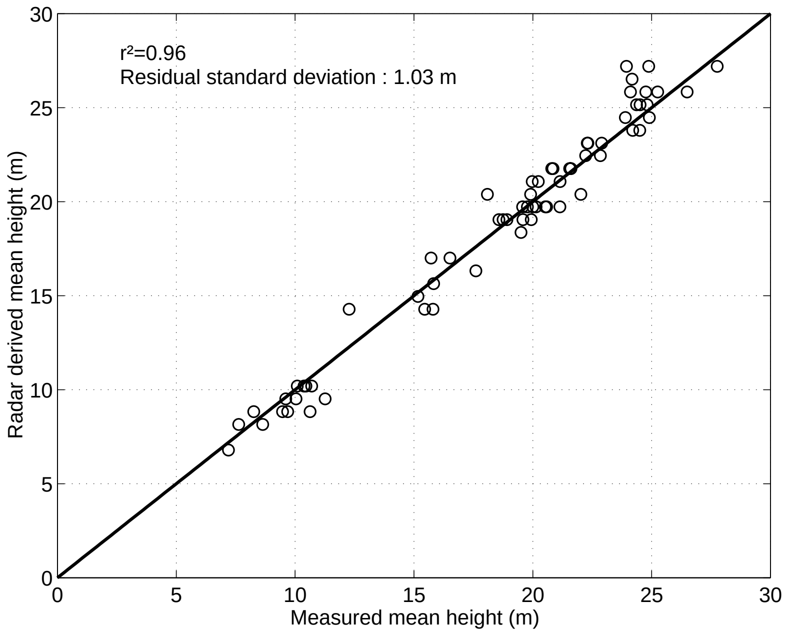


Fig. 5 : Radar derived mean height versus the in-situ measurements for 66 samples plots of Austrian Pine. Results are presented for the X band HH channel.

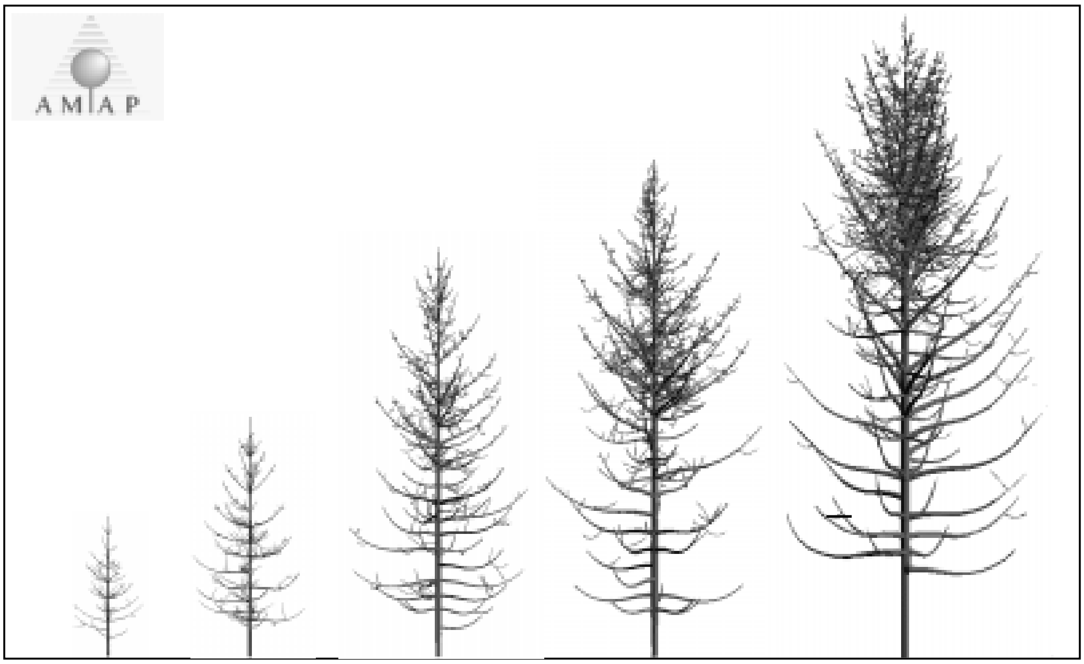


Fig. 6 : 3D AMAP simulations of 6 Austrian pines of (from left to right) 16,24,32,36,45 years old .

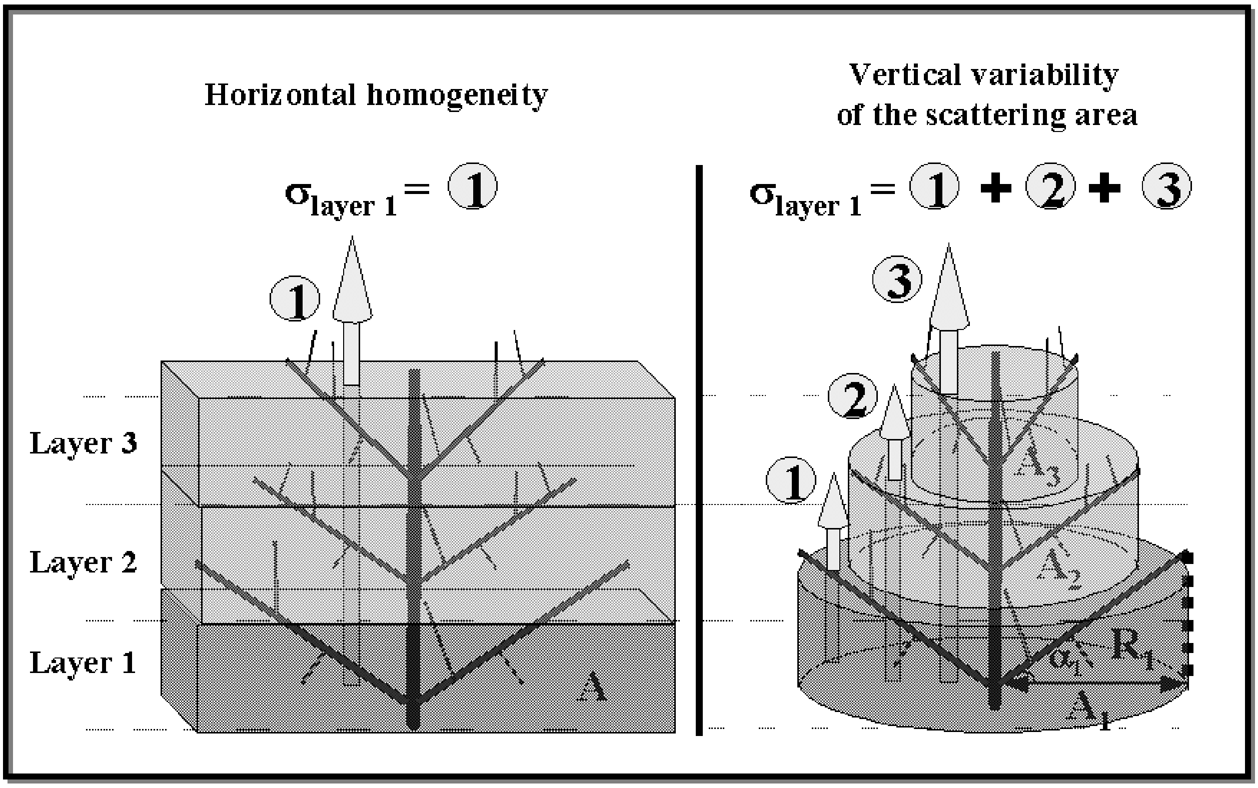


Fig. 7 : 3- layer medium describing a crown using two approaches : (left) the scattering area is an infinite homogeneous layer, (right) the scattering area is defined as the disk for which the radius depends on the mean length of the primary branches belonging to the layer.

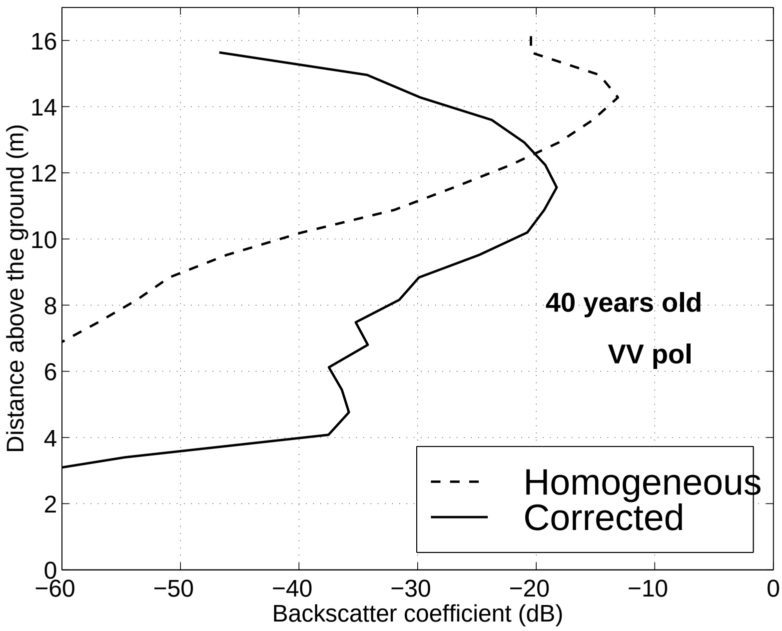


Fig. 8 : Vertical backscatter profiles using the actual scattering area correction ("corrected") and the infinite layer hypothesis ("homogeneous"). Results are presented for X band at VV polarization for a 40-year old Austrian pine at 3° incidence.

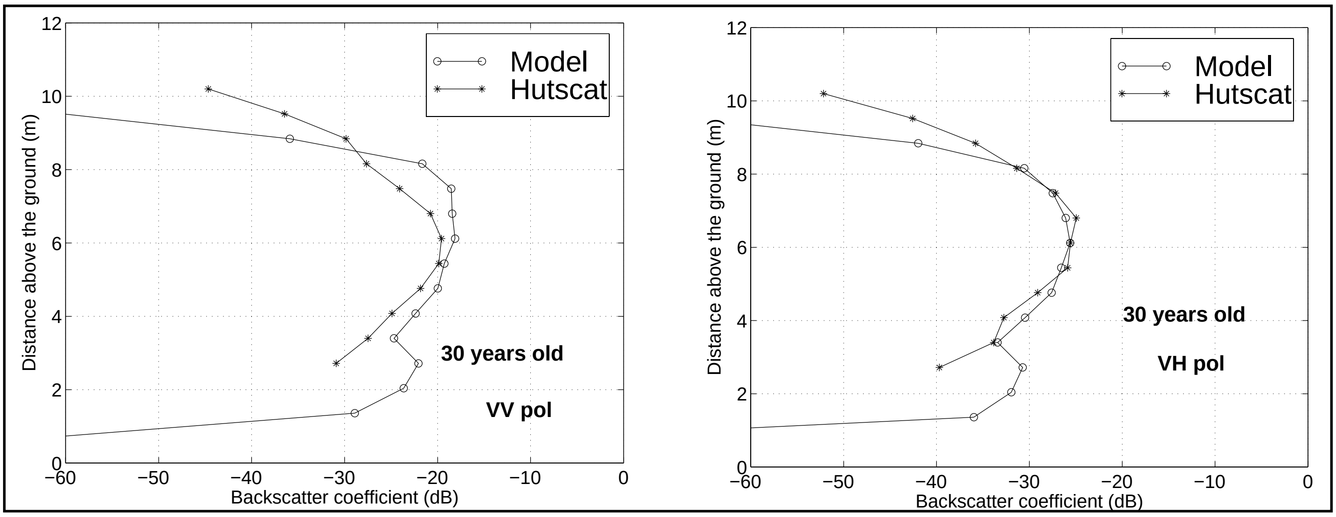


Fig. 9 :Comparisons between experimental and simulated profiles for a 30-year old stand at X band, VV and VH polarization in the near normal incidence.

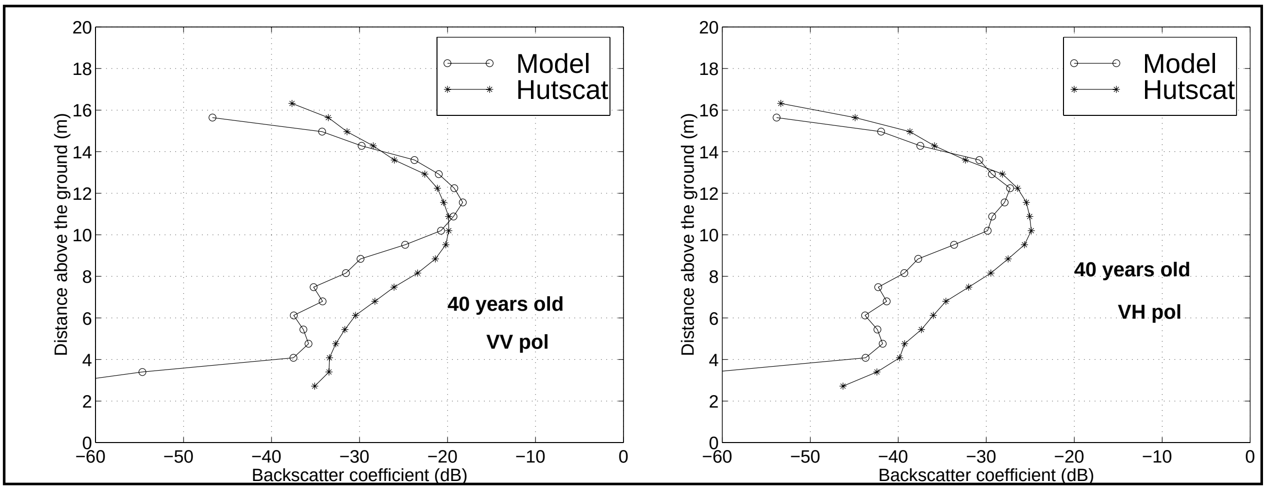
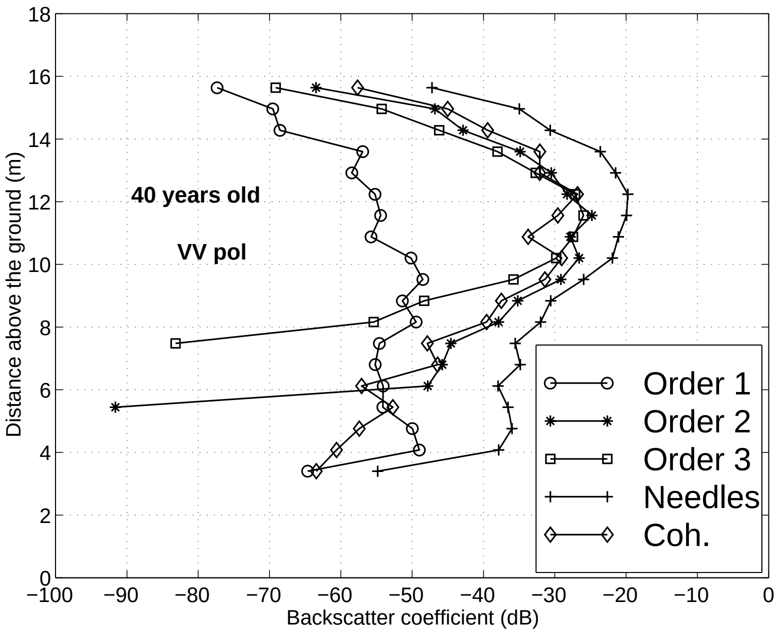


Fig. 10 : Comparisons between experimental and simulated profiles for a 40 years old stand at X band, VV and VH polarization in the near normal incidence mode.



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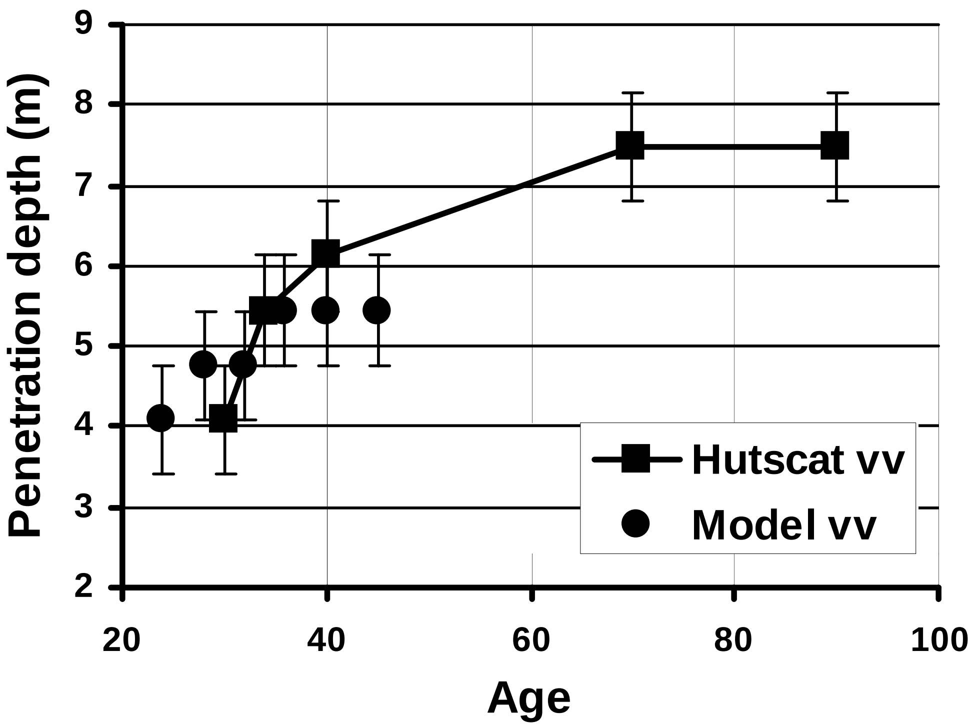

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