Article D

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soumis à *Tree Physiology*.

RETRIEVING VERTICAL FOLIAGE DISTRIBUTION USING HIGH RESOLUTION AIRBORNE SCATTEROMETER DATA

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ABSTRACT

This paper presents the comparison between vertical backscatter profiles of forest measured by an airborne ranging scatterometer radar and in-situ measurements of foliar biomass in a pine forest. Radar ranging scatterometer allows to study, with a vertical resolution inferior to the meter, the radar backscatter vertical distribution into the canopy which is known to be physically related to the vegetation biophysical properties. The objective is to explore a new method to assess the vertical distribution of foliar biomass inside tree canopy using remotely sensed data.

In a recent work, simulations of the backscatter profiles using a multi-layer radiative transfer (RT) model have shown that the needles are by far the main scatters at short wavelength (2.1 cm) and that the microwave interacts with all the canopy allowing to retrieve the tree foliar characteristics. Based on these results, a simple relation between the measured backscatter and the foliar biomass is derived using the RT model. Experimental backscatter profiles are then inverted into the vertical foliar biomass distribution. For validation, 7 and 9 trees have been destructively sampled in respectively 40 and 100-year old Austrian pine stands. Good agreement is found for different ages, both qualitatively and quantitatively, between the retrieved and measured vertical distribution of the foliar biomass as well as the total foliar biomass. Finally, advantages and limitations of the method are discussed.

I. INTRODUCTION

Vertical distribution of forest foliar biomass is an important structural characteristic for quantifying energy and mass exchange inside forest canopies. A better characterisation of the foliar biomass distribution would allow a better modelling of the light transmittance inside tree canopies, which is an important regulator of canopy carbon gain (Russel et al. 1989). Several studies have shown that foliar vertical distribution plays a major role in different vegetation processes such as trunk cross sectional increment (Kershaw et al. 1999), partitioning of nutrient resources and photosynthetic activity (Ellsworth and Reich 1993), and that the nature of the leaf area profile as well as the canopy geometry control the amount and pattern of the light at the forest floor (Cowan 1968). It has interest for process-based forest growth models in which canopy characteristics are often required. Vegetation distribution is also an indication of the growth competition between trees (Vose et al. 1995) and of the impact of the sylvicultural practices.

Some studies have provided information on the vertical distribution (Aber 1979, Ellsworth and Reich 1993, Hollinger 1989, Hutchison et al. 1986, Kruijt 1989, Parker et al. 1989, Vose et al. 1995, Yang et al. 1999). However, in comparison to other forestry research subjects, the architecture of forest canopies is not much studied, in particular due to the difficulty to work throughout forest canopies. In particular, it is difficult to extend the experimental results due to the diversity in ground measurements techniques and the specificity of the forest type under study (monospecific/mixed stands, even aged/uneven aged forests).

The objective of this paper is to present a new method to assess foliar vegetation distribution using remotely sensed data from a ranging radar scatterometer. Radar data are well known to be physically related to the vegetation characteristics allowing to retrieved forest biomass and other correlated parameters (Dobson et al. 1992, Le Toan et al. 1992, Beaudoin et al. 1994). For forestry radar airborne scatterometers combines three interesting properties: a) the possibility to vertically sound tree canopies with a high resolution (< 1 m); b) the possibility to retrieve the biophysical characteristics of the vegetation from the radar backscatter coefficient; c) the potentiality to cover large areas with an aircraft instead of *in situ* measurements located on reduce sets of sample plots.

Several studies dealt with ranging scatterometer applications for forestry concerning tree height retrieval, stem volume or species discrimination (Bernard et al. 1987, Hallikainen et al. 1993, Martinez et al. 2000a) giving excellent results. In this paper, we propose to explore another potentiality of vertical backscatter profiles within tree canopies, by assessing the foliar biomass vertical distribution inside a pine forest.

The study is driven by past experimental and theoretical results (Martinez et al. 2000a, Martinez et al. 2000b) based on an experiment performed in November 1997 (Martinez et al. 1998), using the helicopter-borne scatterometer HUTSCAT (Helsinki University of Technology SCATterometer), over the Lozère forest in France.

In the first part of the paper, we present the test-site, the radar data and the ground data used for validation which consist in destructive sampling of 16 trees in two stands of 40 and 100 years old. In the second part, a short summary of the previous theoretical work introduces the foliar distribution retrieval algorithm. Then, comparisons between radar derived foliar biomass distribution and ground based measurements are presented. Finally, a discussion on the results and on the potential of the method is presented.

TEST-SITE AND DATA

Test-site

The Lozère forest is located in the South of France over limestone plateaus at an altitude of about 1000 m above sea level. The plateaus are intersected by deep gorges of about 300 m depth. This forest is a plantation made of even-aged and relatively homogeneous stands of Austrian Pine (*Pinus nigra Arnold ssp Nigricans Host.*) with age from 0 to 130 years old, covering 5400 ha. The first seedlings date from the last century in the framework of a program aiming at limiting the erosion of the plateaus. The forest was not managed until the 1960's when the forest began to be also used for wood production. Nowadays the majority of the stands are aged of 100 to 130 years old but a part of the forest has been renewed and a new generation between 0 and 40 years old is present. Figure 1 presents examples of 15 and 100 year-old stands. The stands are of about 10 ha each and are managed by the French Forestry Board. The stands limits and ages are included in a Geographic Information System (GIS) (Figure 2).

Radar data

HUTSCAT is a helicopter-borne non-imaging FM-CW scatterometer (Hallikainen et al. 1993) designed and constructed by the Laboratory of Space Technology of the Helsinki University of Technology (HUT). The system provides the vertical distribution of backscatter within the tree canopy with a 68-cm vertical resolution. In this paper we will focus on profiles obtained at X band (wavelength of 2,1 cm) and at 3° of incidence (near normal to the ground).

Fig. 3 shows the basic principle of an HUTSCAT acquisition. An antenna, located under the helicopter flying at an altitude of 100 m above the ground, emits pulses with a regular frequency toward the ground and measures the backscattered echoes. The system gives the backscatter coefficient which represents the ratio of the backscattered energy to the emitted energy, normalised by the backscattering area (circular area of 7 to 9 meters depending on the flight altitude which is the intersection of the beam with the ground). The signal is frequency modulated, which allows by measuring the frequency shifts, to assess the different distances between the targets and the antenna in the frequency spectrum. It is then possible to obtain the backscatter variation as a function of the height. The height of a resolution cell in the radar return spectrum is estimated relatively to the ground echo, meaning that the height measurements are independent to the local topography.

Data were collected during a campaign in November 1997. A total of 6 flights of 4 km long, aligned along 3 transects (see figure 2), acquired at 3° incidence was used. The calibrated data provide the ground and tree canopy backscattering coefficients along each measurement transect. The forest backscattering profile was calculated only when returns from ground and tree canopy were reasonably well separated from each other.

At near vertical incidence, the understory layer and other vegetation elements above the ground (dead branches) contribute significantly to the total backscatter. We selected profiles in which 90 % of the total above ground backscattered energy comes from the canopy layer. The bottom limits of the canopy were determined with in situ measurements of the canopy depth (Martinez et al. 1998). One example of vertical backscatter profiles is shown in Fig. 4, for a 40-year old Austrian pine stand at X band and for cross-polarisation. The backscatter distribution seems clearly correlated with the canopy characteristic, suggesting that the microwave interacts with all the canopy layers.

Foliar biomass in-situ measurements

Two stands of 40 and 100-year old were chosen for biomass measurements, in which respectively 9 and 7 trees were cut down for destructive sampling (Deshayes et al. 1999). The trees were chosen with respect to the class frequency of DBH and the social status (dominant, codominant and dominated) in the stands. The stand characteristics are summarised in Table 1.

Measurements were first performed for 40 years old trees for protocol validation. For all the primary branches of 2 trees, total needle biomass (fresh and dry weight), branch length and diameter were measured. For the other 7 trees, all the primary branches diameter were measured but needle biomass (fresh weight) simply measured every 2 whorls. To interpolate the missing foliar biomass in between the measured whorls, we used relations linking the diameter of the primary branches to their foliar biomass weight (Deshayes et al. 1999). This undersampling method was validated on the two firsts 40-year old pines sampled. By comparing the measurements and the interpolated results, the error introduced on the estimation of the tree foliar biomass by the under-sampling was found to be less than 10%. The same protocol was used for the 100 years old stand, except that only one tree was fully sampled for foliar biomass measurements.

Needle samples were ovendried (at 105°C during 72 hours). These samples were in majority collected on the fully sampled trees (the two 40 year old pines and the one 100 year old pine). Some other samples were collected on the others trees. The total projected area of a sample is then measured with a planimeter and weighted in order to establish the specific area (area per unit of weight). In the results section we will use needle number density and total foliar area instead of needle biomass for the comparisons with the scatterometer data. Needle density and foliar area were determined from mean needle weight and mean needle specific area.

Finally, for comparison with the radar data, the vertical distribution of foliar biomass for each tree was averaged into 68-cm vertical layers. The experimental vertical distribution profile of the mean foliar biomass at the stand level was established according to the weight contribution of each tree, following its DBH class occurrence in the stand. Fig. 5 shows the derived vertical distribution at the stand level for the 40-year old stand.

EXTRACTION OF FOLIAR PARAMETERS FROM RADAR BACKSCATTER

In a previous work (Martinez et al. 2000b), the vertical backscatter profiles acquired over the Lozère forest were interpreted using a multi-layer first order radiative transfer (RT) model (Hsu et al 1994, Floury et al. 1997). The model describes the medium as a combination of horizontal layers containing multi-scale clusters of dielectric cylinders. The description of the canopy which provides inputs to the backscatter model is given by the AMAP tree growth model developed at the French institute CIRAD (De Reffye et al. 1995), which recreates trees on the basis of realistic botanic criteria. Main results showed : 1) the microwave penetrates deeply into the canopy at near normal incidence angle, 2) the needles are by far the main scatterers at X band cross-polarization (VH), with a contribution higher than 10 dB comparing to the other vegetation scatters (branches of order 2 and 3). Visual comparison of fig. 4 and fig. 5 suggests the similarity of the vertical distributions of the backscatter and the foliar biomass. This result indicates the possibility to retrieve the foliar biomass distribution from the radar backscatter profiles.

Provided that the forest backscatter is dominated by the needles contribution, the RT model is used to simulate backscatter σ and attenuation L as a function of needle parameters. Fig. 6 presents simulated backscatter and two-way attenuation as a function of needle number density. A linear relationship is found for the values of needle density usually encountered in a 68-cm layer (between 0 and 4000 needles/m^3). The relations depend implicitly on the needle characteristics (moisture, diameter, length) meaning that at this stage the inversion process presented here needs an *a priori* knowledge of the needles properties. If σ_H (i) is the backscatter coefficient of the i-th layer in the scatterometer profile, the non attenuated backscatter coefficient σ (i) of the layer is :

$$\sigma(i) = \sigma_H(i) \bullet \prod_{j=i+1}^{N} L(j) \qquad for\ i = 1 \ldots N-1 \quad (1)$$

where the second term on the right hand side represents the attenuation of all the layers above the i-th layer. Hence, iterating from the top of the tree (for which σ (N) = σ_H (N)) to the bottom of the tree, we can derive the non-attenuated backscatter contribution for each layer in the scatterometer profile and, therefore, the corresponding foliar density using the relations derived from simulations.

RESULTS

Fig. 7 and Fig. 8 present the comparison between measured and radar-derived needle density vertical profiles, for the 40- and 100-year old stands. The associated error bars denotes, respectively for the inverted profiles and for the ground measurements, 1) the uncertainty coming from the measured backscatter 2) the error introduced by the conversion from needle weight to needle density.

A good agreement is found for both needle density vertical profiles. The thickness of the canopy is well determined, and some details in the canopy itself can be observed in both profiles. In particular, at mid-height a “gap” in the foliar distribution (present at both ages) is exactly retrieved. Quantitative comparison is also satisfying : the retrieved foliar biomass differs from the ground measurements only of 10 %, see Table 2. Some discrepancies appear in the lower part of the profiles which can be attributed to the assumption that the attenuation is predominantly caused by the needles. Although the assumption is correct for the largest part of the tree, simulations of the RT model show that in the lowest part of the living crown, the attenuation caused by the thickest primary branches at the bottom of the tree is as much as that of the needles. This effect induces an overestimation of the needle biomass in the lower part of the profile, particularly in the 100-year old pines.

To illustrate the interest of having both accurate and a rapid coverage over a whole forest, let have a look of how the foliage vertical distribution varies with the age. We extracted backscatter profiles over 4 Austrian pine stands, including the two previous 40- and 100-year old stands, and two other stands of 30 and 70 years old. The distance from a stand to its nearest is at least 1.5 km. We used the same retrieved algorithm presented in the previous section. We used also the same foliar characteristics for all the stands (8 cm length, 0.5 mm diameter and 60 % of gravimetric moisture).

For each age, we computed a normalised height h_n expressed as $h_n=(z-H_{lc})/(H_{tot}-H_{lc})$ where z is the true height, H_{lc} the height of the living crown and H_{tot} the total height of the tree. The normalised height, which varies from 0 to 1, allows to directly compare the different stands without considering the relative crowns thickness. Figure 9 exhibits the leaf area distribution as a function of the normalised height for the four stands. The 30-year old stand shows a classical vertical distribution close to a bell shape as related by other studies (Baldwin et al. 1997, Yang et al. 1999). In this stand, the stem density is rather high (> 1500 stems/ha) and the tree crowns do not freely develop. The 3 others stands show a systematic gap at mid height of the tree. From there, several hypothesis can be put forward. The gap may be related to a reduced growth during one year due to a local dryness. It may be also due to growth competition between trees in these very dense stands.

However, the gap width, is of at least 1 meter, which represents a minimum of three years of a "normal" growing period, and no such long dryness was recorded during the last 20 years in this area. In our opinion, the most likely hypothesis is that the gap is related to sudden regrowths associated to forest management and thinning practices in which a fifth to a fourth of the trees are removed from the stands. These cuttings (starting after 30 years old and repeated every 10 years) may allow the tree crowns to freely develop using the newly available space and the better access to the light, leading to a quick and sudden acceleration of the growth during the following two or three years.

These results demonstrate the interest of the method to derive, both qualitatively and quantitatively, the vertical distribution of the foliar biomass without time and manpower costly destructive measurements on the trees. However, for generalisation purpose, more work is necessary to determine if the method can be applied to other forest types. In particular, it will be necessary to test the sensitivity of the retrieval algorithm to foliar characteristics, especially over deciduous forests for which the foliar geometric characteristics are more complex.

ACKNOWLEDGMENTS

This work was performed within the EUFORA and MARIE-F European projects, both funded by European Union. The authors want to thank Mr. Martti Hallikainen and his team at the Helsinki University of Technology for the processing of the HUTSCAT data and for their help during the analysis. We want also to acknowledge Y. Caraglio from the CIRAD for his assistance during the interpretation of the data. Special thanks to the UMR-3S Cemagref-ENGREF, the CIRAD AMAP and the French Forestry board (ONF) teams for their contribution to the ground measurements.

REFERENCES

Aber, J.D. 1979. A method for estimating foliage-height profiles in broad-leaved forests. Journal of Ecology 67:35-40.

Baldwin V.C., Jr., K.D. Peterson, H.E. Burkhart, R.L. Amateis and P.M. Dougherty. 1997. Equations for estimating loblolly pine branch and foliage weight and surface area distributions. Canadian Journal of Forest Research 27:918-927.

Beaudoin A., T. Le Toan, S. Goze, E. Nezry, A. Lopes, E. Mougin, C.C. Hsu, H.C. Han, J.A. Kong, and R.T. Shin. 1994. Retrieval of forest biomass from SAR data. International Journal of Remote Sensing 15(14):2777-2796.

Bernard, R., M.E. Frezal, D. Vidal-Madjar, D. Guyon, J. Riom. 1987. Nadir looking Airborne Radar and Possible Applications to Forestry. Remote Sensing of Environment 21:297-309.

Cowan I.R. 1968. The interception and absorption of radiation in plant stands. Journal of Applied Ecology 8:367-379.

De Reffye, P., F. Houllier, F. Blaise, D. Barthelemy, J. Dauzat, and D. Auclair 1995. A model simulating above- and below-ground tree architecture with agroforestry applications, Agroforestry Systems 30:175-197.

Deshayes, M., E. Mushinzima and N. Stach 1999. Assessment of FLIM reflectance model : case study Lozère, France. In, MARIE-F (Monitoring and Assesment of Resources in Europe – Forest) project final report, contract ENV4-CT96-0316, 5.1-5.56.

Dobson, M. C., F.T. Ulaby, T. Le Toan, A. Beaudoin, E.S. Kasischke, and N.L. Christensen Jr. 1992. Dependence of radar backscatter on coniferous forest biomass. IEEE Transactions on Geoscience and Remote Sensing 30(2):412-415.

Ellsworth, D.S., P.B. Reich. 1993. Canopy structure and vertical patterns of photosynthesis and related leaf straits in a deciduous forest. Oecologia 96:169-178.

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

Hallikainen, M., J. Hyyppä, J. Haapanen, T. Tares, P. Ahola, J. Pulliainen, and M. Toikka. 1993. A helicopter-borne eight-channel ranging scatterometer for remote sensing - Part I: system description, IEEE Transactions on Geoscience and Remote Sensing 31(1):161-169.

Hollinger, D.Y. 1989. Canopy organization and foliage photo-synthetic capacity in a broad-leaved evergreen montane forest. Funct. Ecol. 3:53-62.

Hsu C.C., H.C. Han, R.T. Shin, J.A. Kong, A. Beaudoin, T. Le Toan. 1994. Radiative Transfer theory for polarimetric remote sensing of forest at P band. Int. Journal of Remote Sensing 15(14):2943-2954.

Hutchison, B.A. et al. 1986. The architecture of a deciduous forest canopy in eastern Tennessee. Journal of ecology 74:635-646.

Kershaw, J.A. Jr and D.A. Maguire 2000. Influence of vertical foliage structure on the distribution of stem cross-sectionnal area increment area increment in western hemlock and balsam fir. Forest Science 46(1):86-94.

Kruijt, B. 1989. Estimating canopy structure of an oak forest at several scales. Forestry 62:269-284.

Martinez, J.M., A. Beaudoin, N. Floury, M. Makynen T. Le Toan, M. Hallikainen, and J. Uusitalo 1998. First results and analysis of HUTSCAT data over Austrian Pine plantations. Proceedings of the 2nd International Workshop on Retrieval of Bio- & Geo-physical parameters from SAR data, ESTEC, 317-324.

Martinez, J.M., A. Beaudoin, P. Durand, T. Le Toan, N. Stach 2000a. Une nouvelle méthode pour l'estimation de la hauteur des peuplements, Canadian Journal of Forest Research, p 1983-1991, Décembre 2000.

Martinez, J.M., N. Floury, T. Le Toan, A. Beaudoin, M. Hallikainen, M. Makinen 2000b. Understanding of backscatter mechanisms inside tree canopy for penetration depth estimation, IEEE Trans. Geosci. Remote Sensing 38(2):710-719.

Le Toan T., A. Beaudoin, J.Riom, D. Guyon. 1992. Relating forest biomass to SAR data. IEEE Transactions on Geoscience and Remote Sensing 30(2):403-411.

Parker, G.G., J.P. O'Neill, and D. Higman. 1989. Vertical profile and canopy organization in a mixed deciduous forest. Vegetatio 89:1-12.

Vose, J.M., N.H. Sullivan, B.D. Clinton and P.V. Bolstad. 1995. Vertical leaf area distribution, light transmittance, and application of the Beer-Lambert law in four mature hardwood stands in the southern Appalachians. Canadian Journal of Forest Research 25:1036-1043.

Yang, X., J.J. Witcosky, and D.R. Miller. 1999. Vertical overstory canopy architecture of temperate deciduous hardwood forests in the eastern United States. Forest Science 45(3):349-358.

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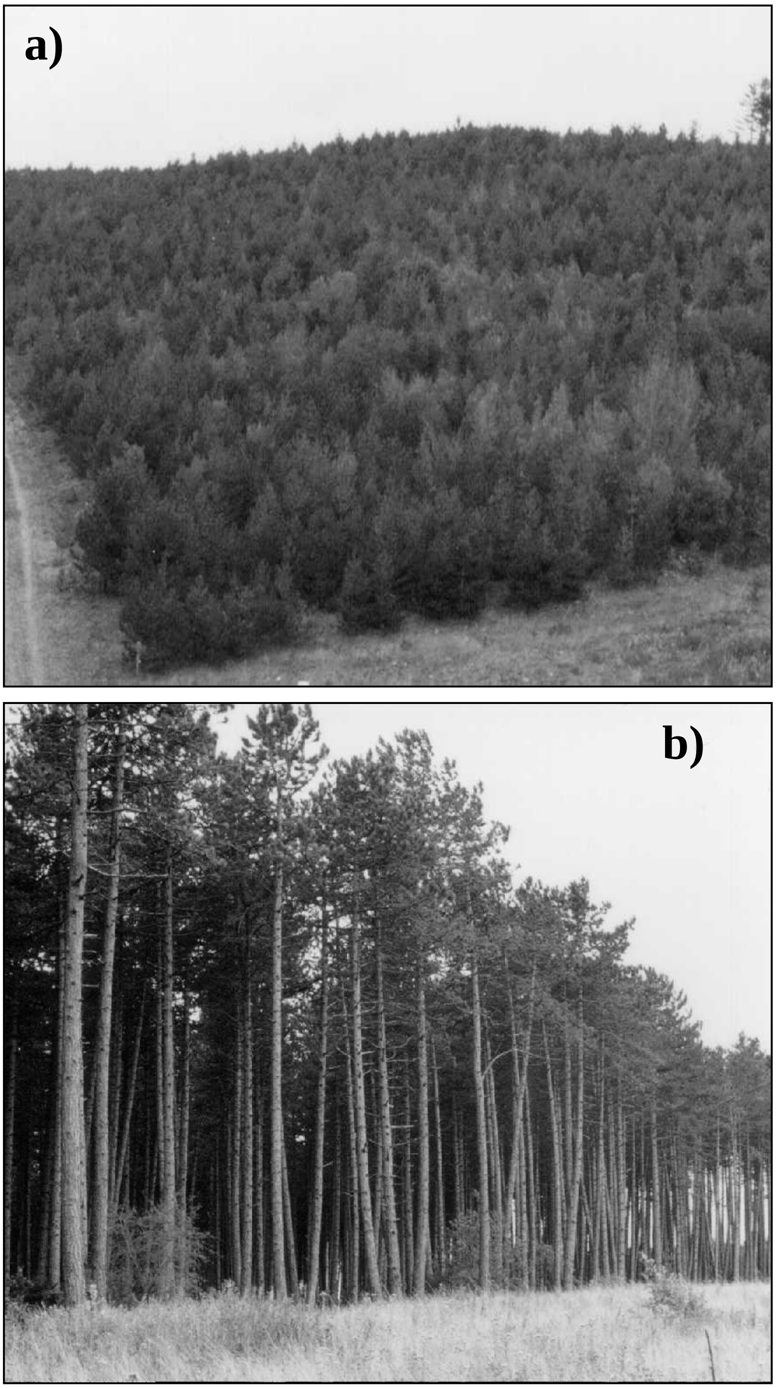
	40-year old Austrian Pine	100-year old Austrian Pine
Number of trees sampled	9	7
Stem volume (m^3/ha)	334.6	483.3
Mean tree height (m)	15.3	19.5
Stem density (pc/ha)	871,8	586.6
Mean Needle weight (g)	0.148 ± 0.058	0.128 ± 0.043

Table 1 : General characteristics of the 2 stands studied in this paper.

	40 years old pine			100 years old pine		
	Measured	Retrieved	Relative error	Measured	Retrieved	Relative error
Total density of needles (Nb/m^3)	13638	12525	8.2 %	12305	14241	13.6 %
Total LAI (m^2/m^2)	5.3	4.8	7.7 %	4.1	4.7	12.8 %

Table 2 : Comparisons of measured and retrieved total foliar biomass.



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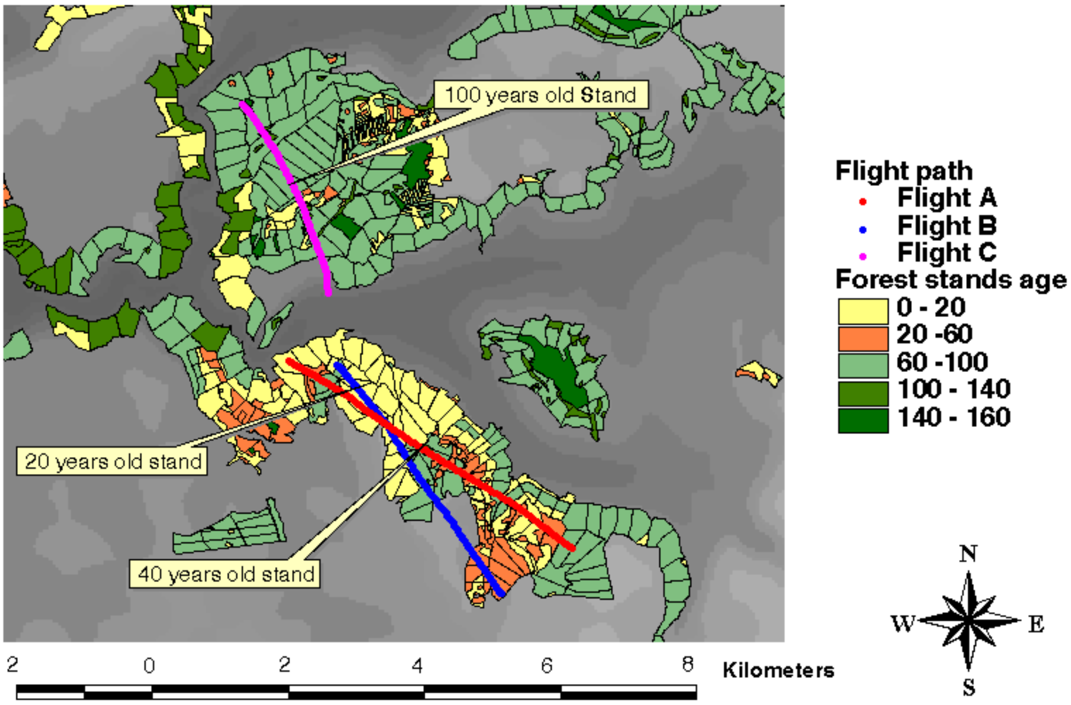

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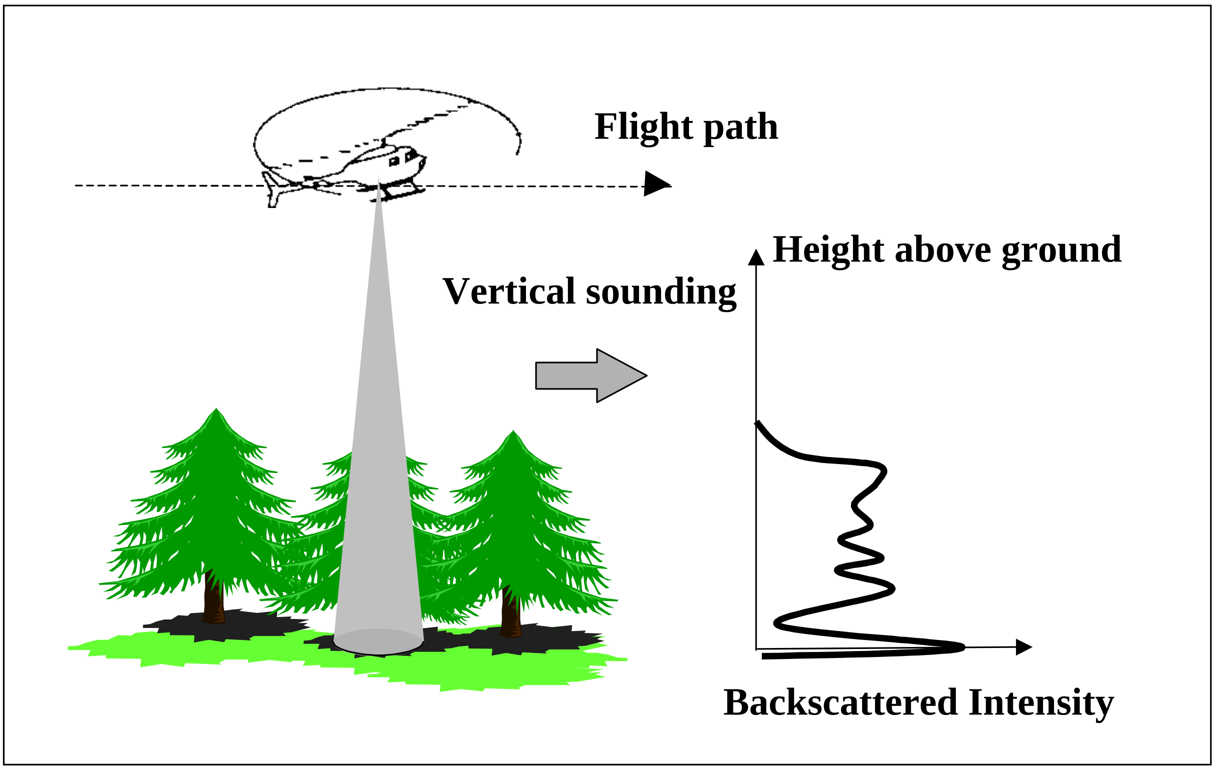

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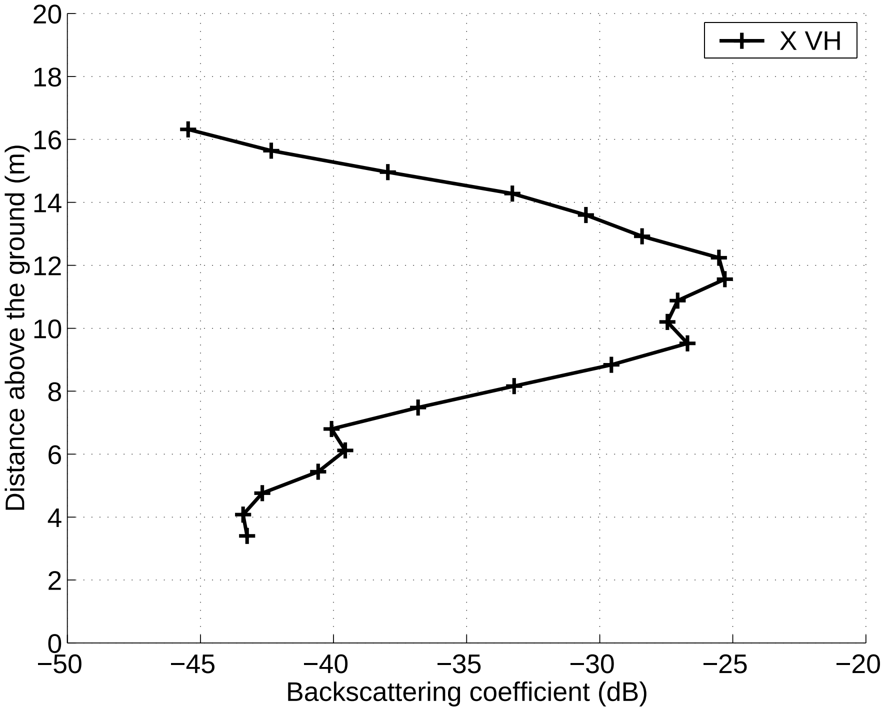

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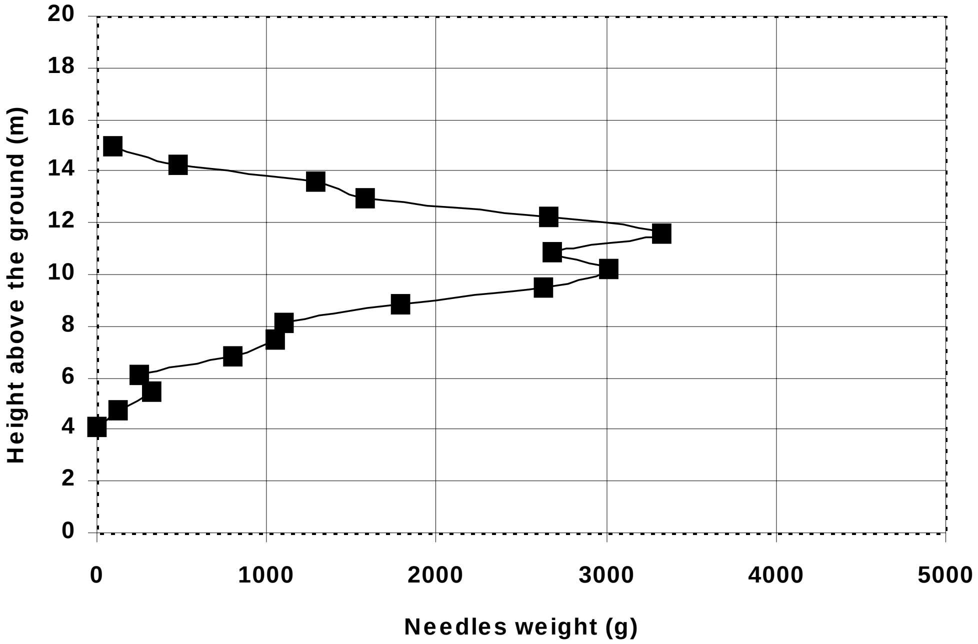

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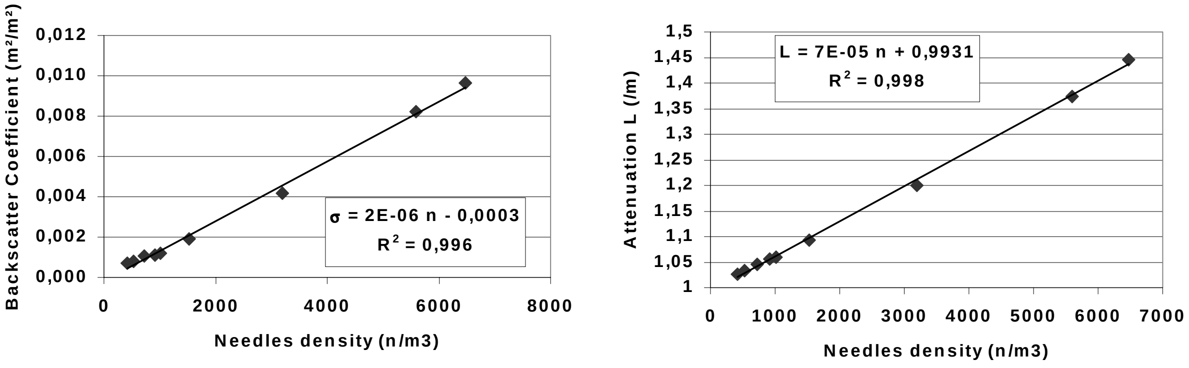

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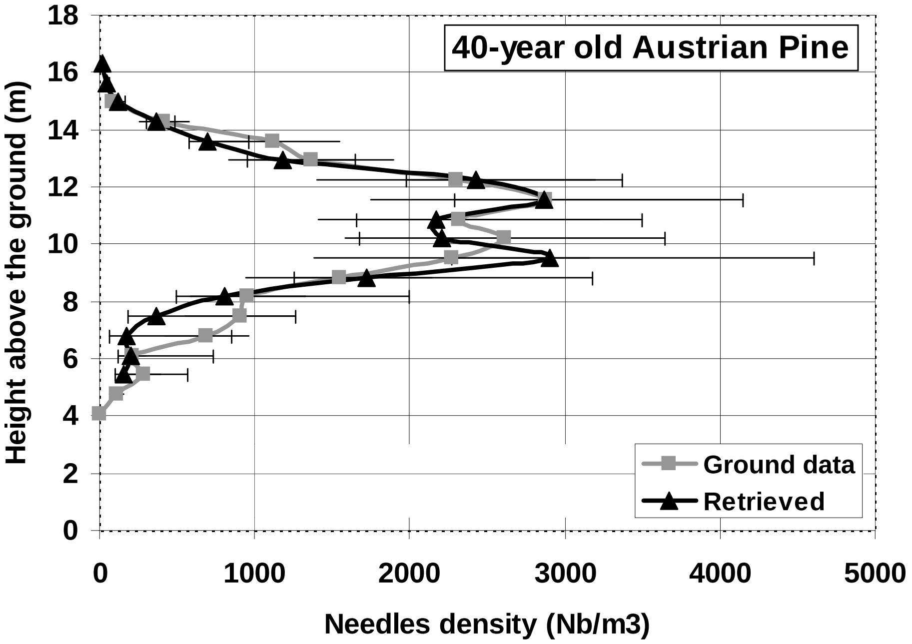

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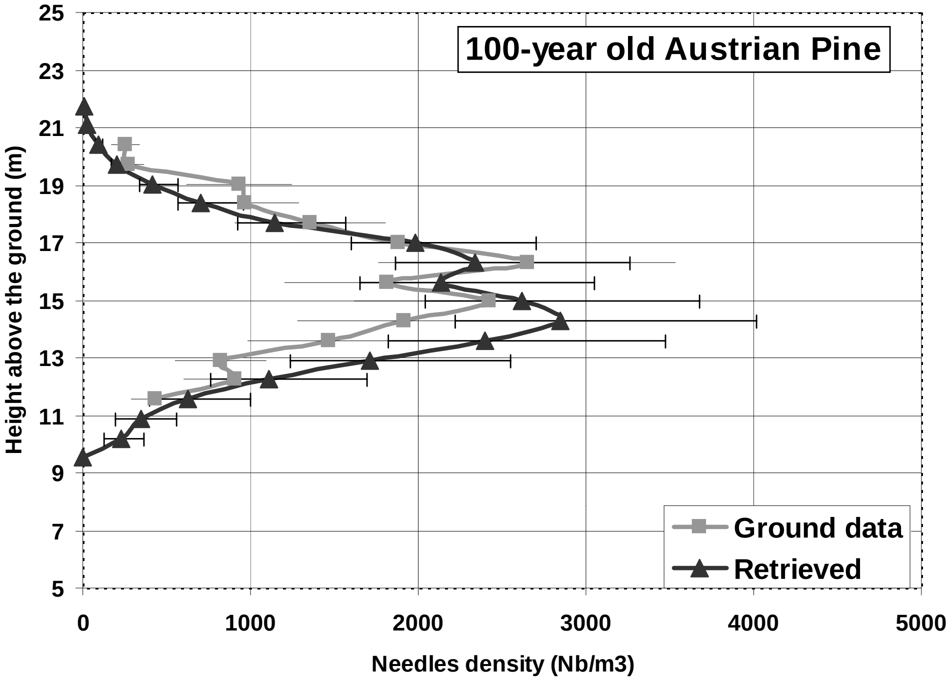

Figure 8 : Comparisons of retrieved and measured vertical distribution of needle density as a function of height above the ground for a 90-year old stand. The vertical resolution is 0.68 m

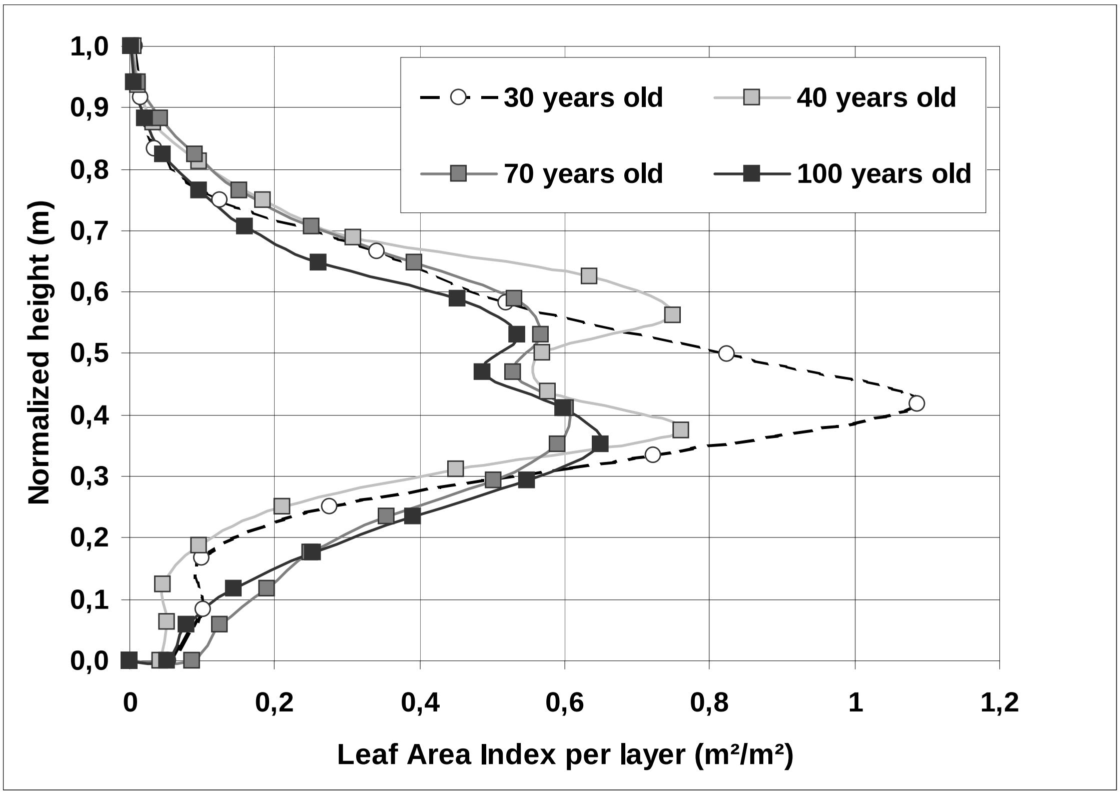

Figure 9 : Comparisons of retrieved vertical distribution of leaf area as a function of normalised height (see text).