FOREST STAND STRUCTURE FROM AIRBORNE POLARIMETRIC INSAR

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ABSTRACT

Interferometric SAR at short wavelengths can be used to retrieve stand height of forests. We evaluate the precision of tree height estimation from airborne single-pass interferometric E-SAR data at X-band VV polarisation and repeat-pass L-band polarimetric data.
General yield class curves were used to estimate tree height from planting year, tree species and yield class data provided by the Forest Enterprise. The data were compared to tree height estimates from X-VV single-pass InSAR and repeat-pass polarimetric InSAR at L-band acquired by DLR's E-SAR during the SHAC campaign 2000. The effect of gap structure and incidence angle on retrieval precision of tree height from interferometric SAR is analysed. Appropriate correction methods to improve tree height retrieval are proposed. The coherent microwave model CASM is used with a Lindenmayer system tree model to simulate the observed underestimation of stand height in the presence of gaps.

INTRODUCTION

Increasingly throughout Europe Forest Enterprises are using remote sensing to provide spatial information on the condition of forests that would not otherwise be available. In the UK, the Forestry Commission maintains a very comprehensive GIS database with data on tree species, planting year, soil type, and other ecological factors for all managed forest stands. However, because of the cost of forest mensuration, only stands mature enough for harvesting are being surveyed thoroughly. Young stands are inspected visually after 5 years to replant trees to fill gaps in areas of high tree mortality if required. The UK Forestry Commission manages large mainly coniferous plantations at Thetford, East Anglia. To improve timber production forecasts, monitoring the proportion of surviving trees following the planting is important. A sufficient stand density ensures timber quality and biomass allocation to the stem rather than to branches. The gap structure is very difficult to survey from the ground in dense forest stands, and interpretation of airphotos is labour intensive. Gap structure is also vital to rare ground-nesting bird species (night jar and wood lark) and plays a crucial role in conservation management. Besides gap fraction, mean top height of a stand is useful to improve the accuracy of long-term timber production forecasts. Top height together with basal area and a species-specific "form height" factor is used to estimate standing timber volume. Top height can be estimated from the GIS using a simple yield class model and data on stand age, species and yield class. The yield class estimates the expected incremental growth of a stand given the particular ecological conditions, mainly soil type, nutrient content, pH, slope and aspect.
SAR polarimetry and interferometry can potentially provide the required biophysical variables (Balzter 2001, Cloude and Papathanassiou 1998, Saich et al. 2001). We use airborne E-SAR data acquired during the SAR and Hyperspectral Airborne Campaign (SHAC) 2000, which was funded by the Natural Environment Research Council and the British National Space Centre, to evaluate the precision of tree height retrieval from X-band single-pass InSAR and L-band polarimetric repeat-pass interferometric data.

E-SAR POLARIMETRIC INTERFEROMETRY

During the SHAC 2000 campaign polarimetric and interferometric L-band imagery and interferometric X-band images were acquired by the German DLR aircraft. The E-SAR acquisition characteristics are given by Table 1.

Table 1: E-SAR acquisitions over Thetford forest during the SHAC campaign 2000.

Date	Band	Polarisation	InSAR Mode	Baseline
	X	VV	Single-pass	1.5 m
	L	quad-pol	Repeat-pass	~10 m

The X-band InSAR processing was carried out by DLR including the DEM product. The L-band data were delivered as coregistered single-look complex images with a motion compensation algorithm applied. Interferometric processing was done at CEH using the Gamma Interferometric SAR Processor. The SLC images were filtered in range and azimuth direction by common spectral band filtering. Then SLC1 was multiplied by the conjugate complex of SLC2, and normalised. The interferogram was multi-looked in range (2 looks) and azimuth (6 looks). Coherence estimation was carried out using an adaptive window size. The phase difference was flattened, filtered by an adaptive filter (6 pixel window) and unwrapped by a

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region growing algorithm. After a refined baseline estimation topographic height was derived using a least-squares method and 12 ground control points. The height images were transformed from slant to ground range and reprojected to the British National Grid. This processing chain was repeated for L-band HH, HV and VV polarisations.

TREE HEIGHT ESTIMATION

Tree height was estimated by subtracting a ground DEM from a surface DEM. As gound DEM an Ordnance Survey (OS) DEM derived from digitised contour lines (10 m pixel spacing) was used initially. An alternative, which may be more accurate, would be to interpolate a ground DEM from the imagery itself using unvegetated areas as control points. Surface DEMs were the X-VV, L-HH, L-HV and L-VV InSAR DEMs. Figure 1 shows a 3D representation of tree height estimated from the X-VV and OS DEMs. Boundaries between even-aged stands and a line of trees along a bridleway are clearly visible.
The precision of the estimated tree height was assessed using tree height values derived from stand age and yield class given by the Forestry Commission GIS database and published general yield class curves (Figure 2). The yield class is a rough indicator of expected incremental growth based on stand conditions, and its relation to maximum stand height h can be approximated by

$$h = \frac{1.1 \cdot a^4 - 199 \cdot a^3 + 9032 \cdot a^2 + (28032 \cdot yc - 41001) \cdot a}{10^{-6}}$$

where a is the stand age in years. Stand height estimated by the above equation is strongly correlated to stand height measured in the field using a SUUNTO clinometer with r^2=0.97.

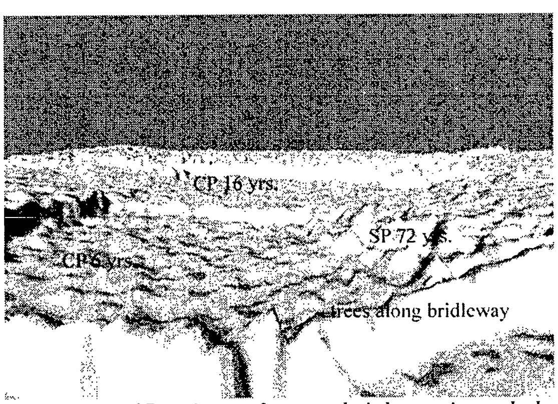


Figure 1: 3D view of tree height estimated by subtraction of X-VV InSAR DEM and OS DEM. CP = Corsican Pine, SP = Scots Pine. Stand age in years is indicated.

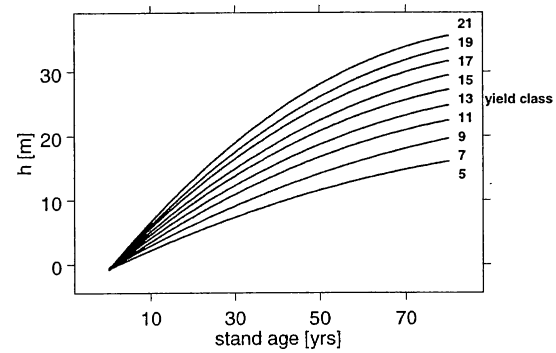


Figure 2: General yield class curves for Corsican Pine used by the Forestry Commission for production forecasts. h = maximum stand height.

Figure 3 shows the results of subtracting the OS ground DEM from the X-VV InSAR DEM compared to stand height estimates from the yield class model. The SAR method systematically underestimates height due to a partial penetration into the crown layer. For tall stands the underestimation increases nonlinearly, because of gaps in the stand increasing the soil contribution to the received signal. The InSAR height is a spatially averaged height, and not the maximum top height. Similar results were observed using the L-band DEMs and a LIDAR DEM.

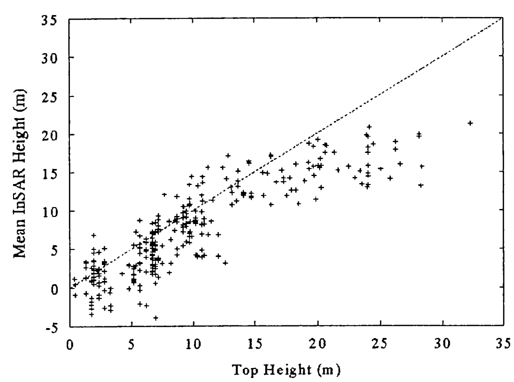


Figure 3: Mean stand height estimated from X-VV InSAR DEM and OS DEM compared to top height from the yield class model. For tall stands the InSAR DEM underestimates stand height.

Similar results are found at L-band, but with a much greater variation of InSAR height values and a greater number of points with high top height values that have been underestimated by the InSAR method. The scatterer geometry at L-band is very different from that at X-band. Different height variations within forest stands has been observed (Figure 4). This phenomenon remains to be explored in more detail.

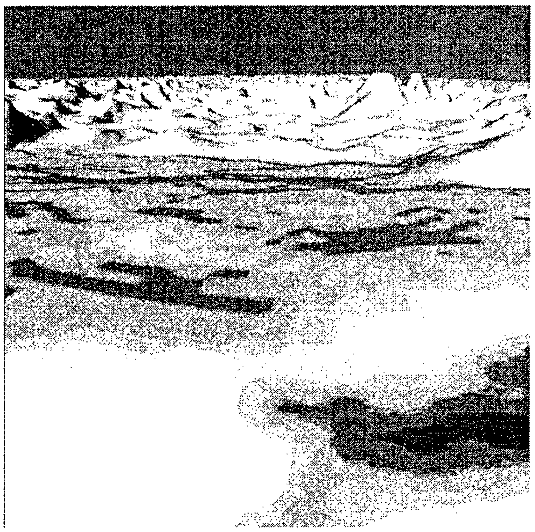


Figure 4: 3D view of L-HV InSAR DEM showing the6 year old CP stand from Figure 1 in the front and the 16 year old at the back. The height variation is much stronger than at X-band.

GAP EFFECTS

The observed underestimation of height by the InSAR DEMs can be explained by the decreasing fractional cover of older stands (Figure 5).

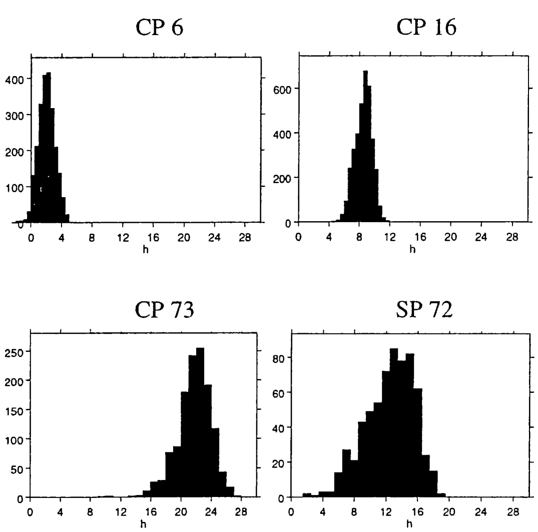


Figure 5: Histograms of tree height estimated by subtracting X-VV InSAR DEM and OS DEM for the stands shown in Figure 1 and an additional 73 year old CP stand. Gap fraction increases with stand age.

To improve the height estimation, a simple gap fraction model was developed using the ground data from the SHAC 2000 field campaign (Figure 6).

$$G = 1 - N \cdot A \cdot 10^{-4}$$

with G = gap fraction at nadir, N = number of trees [ha^{-1}], and A = mean area coverage of an individual tree crown [m^2].

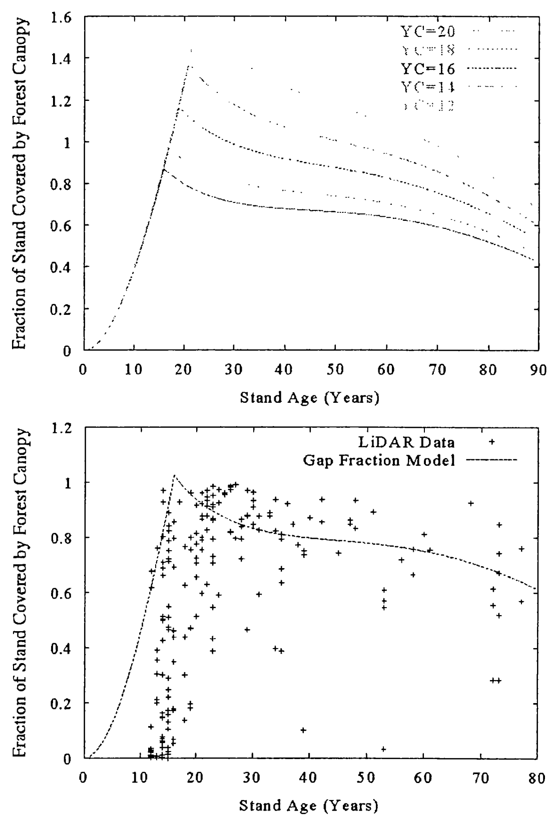


Figure 6: Gap fraction model for increasing stand age and different yield classes (top). Model fit compared to gap estimates from LIDAR image acquired by the Environment Agency (bottom). © Laine Skinner, Swansea.

For higher yield classes, the thinning regime is more rigorous, leading to a larger gap fraction despite thicker stems for old stands. The crowns do not seem to form a closed canopy anymore.

INCIDENCE ANGLE EFFECTS

Older stands with a larger gap fraction are more prone to incidence angle effects. In the near range a larger proportion of the radar signal penetrates the forest canopy through gaps right to the soil. This effect results in an increased underestimation of stand height in the near range for older stands (Figure 7). In the far range this effect is much weaker, as larger gaps are required for the radiation to pass through to the ground.

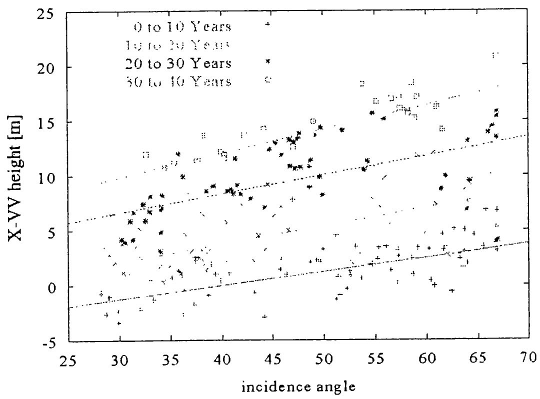


Figure 7: Dependence of estimated tree height on E-SAR incidence angle and stand age.

Using the mean slope from Figure 7 the following correction model was derived:

$$h_{i,corr} = h_i - 0.171 \cdot \theta_i$$

where $h_{i,corr}$ is the corrected mean stand height of stand i, h_i is the mean stand height of stand i before incidence angle correction, and θ_i is the incidence angle at the centre of stand i.

IMPROVEMENTS IN PRECISION

Mean stand height was calculated from the X-VV InSAR DEM applying the gap fraction and incidence angle corrections described in the previous sections. The results of the correction methods are shown in Figure 8. Both the gap model (Figure 8a) and the incidence angle correction (Figure 8b) reduce the bias of stand height estimation for older stands. A combination of both methods (Figure 8c) gives the best results.

Table 2: Root mean square error [m] and r^2 between top height estimated from X-VV InSAR DEM and OS DEM and from the yield class model. The gap fraction model was applied to all stands taller than 15 m.

Correction method	rmse	r^2
none	4.1	0.77
gap fraction	3.1	0.75
incidence angle	3.2	0.84
gap+angle	4.0	0.89
gap+angle+bias	2.9	0.89

Table 2 shows improvements in precision achieved by combinations of the correction methods. The rmse is improved by both correction methods, but a bias of 2.7 m is introduced. The rmse contains the bias as well as the random error σ_e,

$$rmse = \sqrt{bias^2 + \sigma_e^2}$$

so that removal of the bias reduces the rmse further (Table 2 last row).

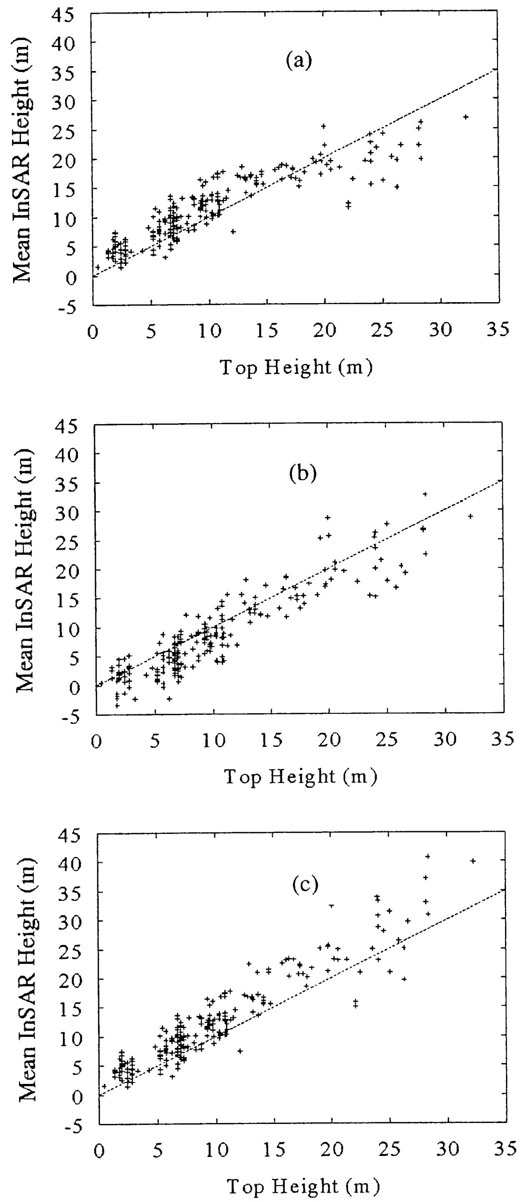


Figure 8: Mean stand height from X-VV InSAR DEM and OS DEM compared to top height from yield class model. Results of gap model (a), incidence angle correction (b) and both corrections (c).

COHERENT MODELLING

The microwave scattering model is described elsewhere (Saich et al. 2001). It is based on the coherent addition of single scattering from vegetation elements, along with double-bounce scattering between the vegetation and ground. The scattering amplitudes (weighted by a term incorporating the phase change due to the propagation path) for all the elements in a simulation cell are summed and the intensity is calculated.. Backscattering and interferometric signatures are obtained by averaging over a large number of independently generated simulation cells. As such, the model allows for prediction of both the backscattering coefficient and complex interferometric coherence.

Our model for the trees is based on a Lindenmayer system (Prusinkiewicz and Lindenmayer 1990) and is shown in Figure 9. We have not yet attempted to tune these L-system trees to match those at Thetford forest, and therefore our simulation results will be indicative of the effects we expect to see, rather than a quantitative match.

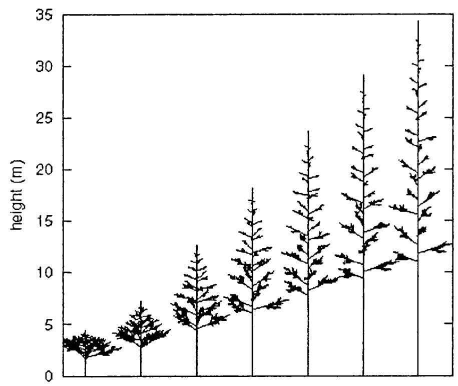


Figure 9: Simplified Lindenmayer system model of pine trees used by the coherent microwave model CASM.

Figure 10 shows the modelled effective height at X-VV for a range of tree densities. As expected the tree height is underestimated by the InSAR height for increasing tree height (see also observed response in Figure 3). This effect is stronger for stands with lower tree density, i.e. larger gap fraction because of the ground contribution to the phase signal.

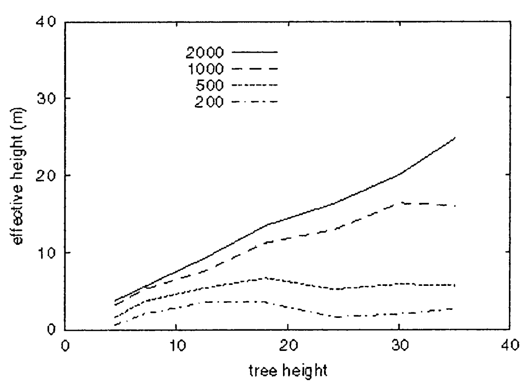


Figure 10: Effective interferometric height at X-band VV polarisation modelled by the coherent microwave model CASM for tree densities between 200 and 2000 ha^{-1}. 45° incidence angle.

Compared to the interferometric heights at L-band (Figure 11), the X-band height is more representative of the overall tree height. For L-HH, the retrieved InSAR height is usually very small as these signatures are dominated by ground scattering effects. Figure 11 also shows the effect of polarisation on the interferometric height. This information could potentially be useful to retrieve forest structural parameters other than top height.

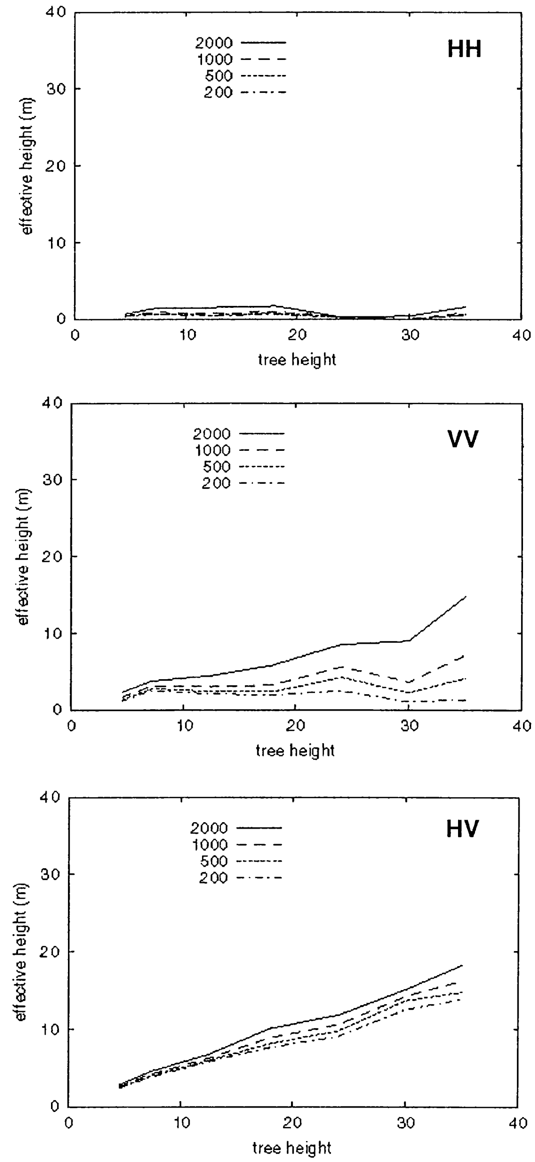
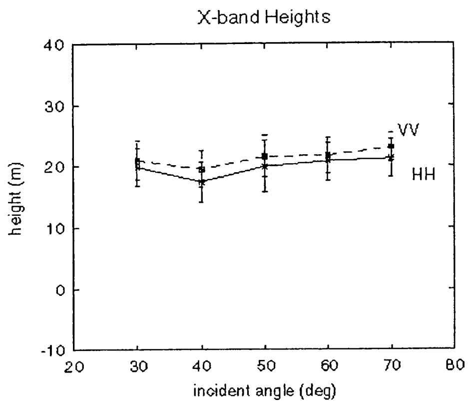


Figure 11: Effective interferometric height at all L-band polarisations modelled by the coherent microwave model CASM for tree densities from 200 to 2000 ha^{-1}. 45° incidence angle.

In Figure 12 we show the uncertainties in scattering height derived from the ensemble of simulations. These show that uncertainties can be quite large (even where the coherence is close to 1 as is the case for the L-HH simulations).



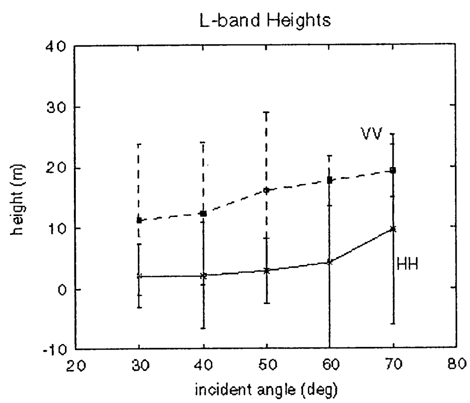


Figure 12: Mean and standard deviation of the effective interferometric height at X- and L-band modelled by CASM as a function of incidence angle. Assumed 100% ground cover.

FUTURE RESEARCH

The results of the microwave modelling suggest that effective interferometric height can be strongly affected by the tree density. This is likely to be the result of increased penetration into the forest canopy and through gaps to the forest floor. The effect is particularly marked at X-band.

We have demonstrated that simple gap and incidence angle corrections can improve tree height estimation, particularly for mature stands. This has great practical importance for forest managers who are mainly interested in retrieving tree height to determine the optimal time for harvest.

Better knowledge of gap fraction and the spatial distribution of gaps in a stand is required to be fed into a geometric model to jointly correct for ground contribution and incidence angle effect.

The coherent microwave model CASM has shown strong potential to underpin the observed radar reponse by theoretical model results. Particularly its ability to model the radar response to very complex vegetation structures (Figure 9) distinguish it from the past generation of models.

The challenge for the future will be to better model

- spatial distribution of trees,
- more 'natural' shape of Lindenmayer system trees,
- introduce natural variability into L-system stand models;
- and to understand and utilise the polarimetric interferometric response at L-band.

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