Foliage penetration effect on polarimetric SAR interferometry observation of forest.

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Abstract

The capability of electromagnetic waves to penetrate trough foliage (FOLPEN), combined with the potentialities of the polarimetric SAR interferometry (POL-InSAR) are demonstrated to be valid instruments for the investigation of forest characteristics and the detection of camouflaged targets. However, the complexity of the interactions of different forest elements can lead to unexpected results. Some of these effects are explained by means of a simulator (PRIS).

1 Introduction

One advantage of SAR technology in the observation of forest is related to the ability of microwaves to penetrate through the foliage. A deep understanding of this phenomenon can enhance our ability to provide information regarding forest structures or understorey and to detect the presence of targets hidden by the canopy. The two main effects related with foliage penetration of the electromagnetic (EM) wave are attenuation and depolarisation.

In the radar community, the attenuation trend of the signal trough a forest layer is usually modelled as an exponential decay [1]. This is reasonable decay for a forest represented as a random homogeneous leaky medium (e.g. RVoG Random Volume over Ground or OVoG Oriented Volume over Ground) [2]. Here, the forest particles are located randomly in one or more forest layers in such a way that the layer is statistically homogeneous. In this way the attenuation of the wave is characterized with an extinction coefficient. In this context, a model (e.g. a fractal model [3]) can be accommodated to define a complete profile for the extinction coefficient, because we can interpret it as an infinite sum of very thin layers. However, some authors (mainly engaged in the transmission of signals trough the forest environment [4, 5]) have introduced the idea that the heterogeneity of the forest structures can initiate some preferential propagation mechanism that makes the attenuation deviate from (less strong than) exponential.

As mentioned previously, the second effect is related to the EM field depolarisation. For this reason, a system that can detect the field polarisation (POL-InSAR) can be very powerful. POL-InSAR is able to investigate the depolarisation effect that is related to the presence of distributed scatterers. The forest is composed of different particles (e.g. branches, leaves, trunks), each having a different backscattering behaviour (mainly anisotropic). When the backscatter of all these particles is coherently combined, the SAR return generally loses its initial polarisation, becoming a depolarised wave. RVoG assumes that the particles are randomly oriented and all the polarisation have the same attenuation trough the canopy, whilst OVoG assumes the presence of some oriented forest structure which makes some polarisations more attenuated than others [2]. The ground return is always polarisation dependent (as for a rough surface [6]).

In case of penetration in the target (volume), the interferometric phase (now called the phase centre) is not located on top of the volume, but inside. Its location is determined by the averaging of all the elements inside the same slant range cell (clearly weighted by the visibility due to the wave penetration). The most used bands for interferometry are X- (typically, 3 cm wavelength), C- (5.6 cm), L- (23.5 cm) and P-band (75 cm). Considering that the attenuation of the forest volume increases with the frequency because the elements in the cell start to be bigger electrically (i.e. the particles dimensions are bigger than the wavelength), it is understandable why the X-band phase centre occurs higher within the volume than for P-band.

One important feature of POL-InSAR is the possibility to discriminate among different scattering mechanisms by the use of a target decomposition theorem [7]. In this way, it is theoretically possible to distinguish between ground (single bounce) and canopy (volume) returns. This leads to a series of possible technique for parameter retrieval [8].

The complexity of the interactions among different forest components makes the field behaviour prediction (e.g. location of phase centre, strongest polarisation) a challenge. This paper will present some particular occasion where the real data result seems to contradict the theory. Theoretical explanations for these effects are proposed. Moreover, the scenario is simulated with the PRIS (Polarimetric Radar Interferometry Simulator) model. PRIS is being developed in the University of Edinburgh since 2004 [9], and is able to simulate the interferometric and polarimetric backscattering of a forest stand. The model for the forest is RVoG, and the radiative transfer equation is applied to compute the received field.

2 Foliage penetration effect

2.1 Trend of the attenuation

As mentioned before, the attenuation experienced by the electromagnetic wave penetrating the canopy is generally modelled with an exponential trend. However, especially in high frequencies (C- and X-band), the forest heterogeneity can not be neglected. In this context, some preferential propagation mechanism can be introduced, e.g. the incoherent scattering related with the forest particles that become electrically long. Figure 1 shows the result of an experiment with a bistatic system (transmitter and receiver are separated by a forest stand) [5].

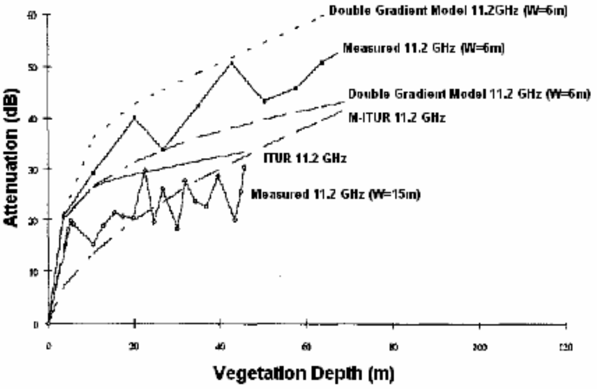

Figure 1 Attenuation trend in X-band in a bistatic geometry trough forest (source: [5])

The vegetation depth (path length in the forest) is changed moving the receiver further. The illumination width W is the maximum effective coupling width between the transmit and receive antennas, that lies within the vegetation medium. As shown in the measured data, the trend of the attenuation changes dramatically after 15-20 m.

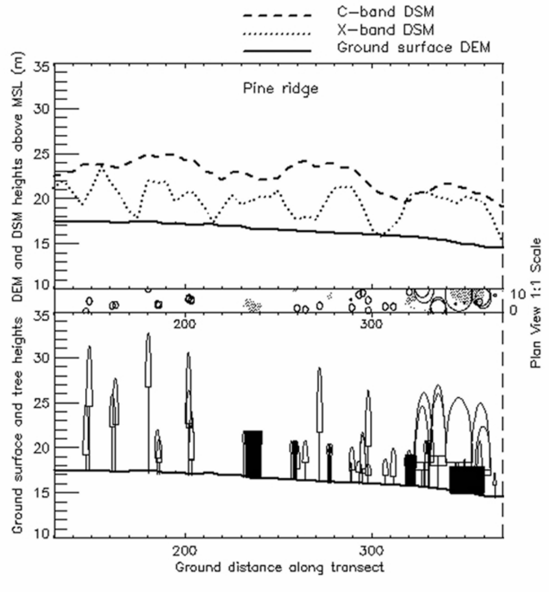

Figure 2 X and C-band DSM above mean sea level (MSL) mapped against measured tree heights and interpolated ground surface DEM for a sparse savanna woodland in Belize. The middle graph shows the plan view at 1:1 scale, which indicates the vegetation density. The dense groupings of similarly sized trees in the graph represent palmetto clumps

The electromagnetic wave going trough the forest can be decomposed into two components: a direct wave (fed directly by the antenna) and an incoherent scattering component (due to the incoherent sum of the fields from all the forest particles electrically long). The direct wave decay, is exponential as expected, but the incoherent one is generally geometrical (or exponential with a lower time constant)[10]. For this reason, after some meters from the source (in our case the top of the canopy) the direct wave is strongly attenuated, hence the incoherent component (that on the canopy top was lower then the direct one) becomes dominant. In Figure 1, this effect is particularly confirmed by the attenuation measured with a narrower antenna beam width. In free space, when the same power is concentrated in a narrower antenna beam, the field received is higher (clearly the two antennas are supposed to be in line of sight). However, in this case the larger the beam width, the higher the incoherent scattering effect, and therefore the higher the field received.

In conclusion, when the frequency is high enough to render the forest particles electrically long, the penetration capability is slightly longer. Consequently, very bright targets under the canopy could be visible even with very tall forests.

2.2 Sparse tree effect

Forest tree height can be retrieved by means of the interferometric phase centre using InSAR. The location of the phase centre is determined by the interaction of all the elements inside the same slant range cell (from the canopy top down to the ground) [11]. Consequently, it is strongly related to the signal penetration in the canopy; the lower the penetration, the higher the phase centre. The retrieval is facilitated by forest density (denser forest reduces the penetration), and disturbed by the ground return (if visible, the ground averages with the tree crowns, pulling the phase centre down). Consequently, interferometric height retrieval for sparse trees becomes a challenge. A recent study of InSAR tree height retrieval [12] in a sparse tropical savanna woodland in Belize has shown an unexpected result.

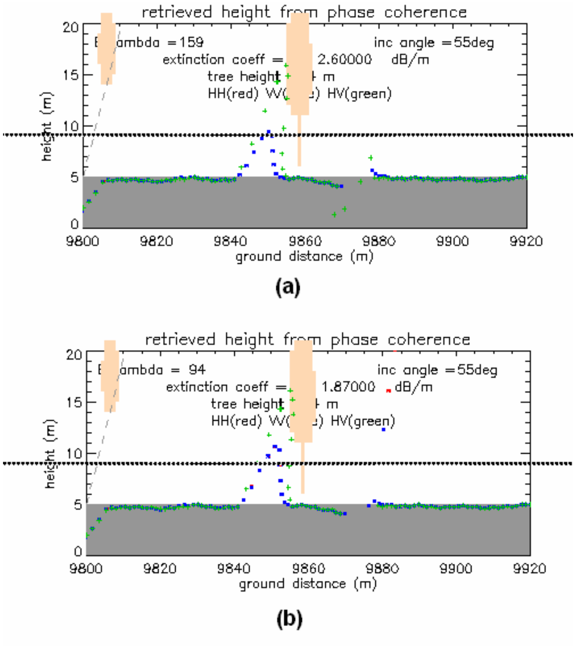

Figure 3 PRIS phase centre extraction for a sparse savanna woodland scenario. The C-band is able to retrieve better than X-band the sparse trees height. (a) X-band; (b) C-band

Figure 2 shows the C and X-band InSAR-derived Digital Surface Models (DSMs) plotted against trees as measured in the field. The C-band DSM estimates higher tree heights than the X-band DSM. As the X-band data (Intermap, 1999) was acquired 5 years prior to the C-band data (AIRSAR, 2004), the possibility that this difference was caused by tree growth was ruled out after a follow-up field campaign which re-measured a subset of the trees, confirming slow tree growth rates in the savannas. Although both DSM surfaces follow roughly similar trends, there is no consistent difference between the two surfaces and the X-band DSM values have a much greater range. Theoretically, the X-band ground contribution is stronger than for C-band, in that the grass blades of the ground cover fall well within the Rayleigh region for scattering for both the X (3.5 cm) and C-band (5.7 cm) as the circumference of these long thin cylinders is ≈ 0.3 cm (based on a 1 mm diameter). As the backscatter drops off as a function of $1/\lambda^4$ in the Rayleigh region [13], the X-band backscatter from the grass undergrowth is theoretically a factor of ~7.4 higher than for the C-band backscatter. This causes a larger ground-level contribution, lowering the scattering phase centre for the X-band. We simulated this situation based on Belize ground data using PRIS. The results (Figure 3) show the difference between the maximum of the two phase centres to be ~1.5 m for a tree of 21 m. It is also interesting to note that the HV polarisation almost does not present this effect (because of the low backscattering of the ground).

However, we believe that the difference in ground return is not the only reason for the trend inversion. A lower attenuation in the canopy makes the internal part of the crown more visible (Figure 4). Consequently, in C-band the inner crown part scatters more than in X-band. Here we assume that the same forest sample scatters similarly for both X- and C-band (this seems reasonable). Finally, considering the C-band, in the same slant range cell the ground contribution is lower and the crown return is higher. Those two effects combined generate the inversion between C- and X-band.

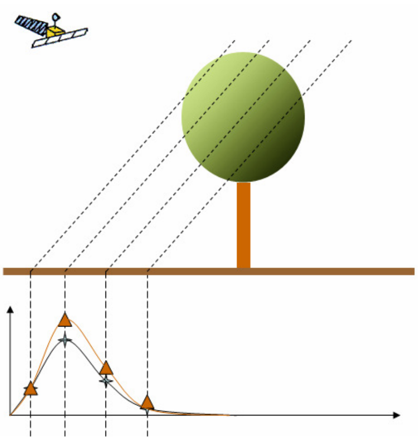

Figure 4 Scheme of the phase centre for C-band (triangles) and X-band (stars). The location is determined by the averaging of all the contribution in the same slant range cell (dashed lines)

In summary, the use of C-band and not X-band in case of sparse trees can be preferable for height retrieval.

2 Conclusion

It is complicated to predict the interaction of electromagnetic waves with a forest environment, especially due to the penetration capability of the target. Penetration complicates this interaction which, as shown in this paper, sometimes makes the interaction between EM waves and the forest difficult to explain.

Initially, it is shown that the penetration in the canopy can be slightly better than expected in case of high frequencies (C- and X-band) because the incoherent scattering of the forest particles is related to their electrical dimensions. In other words, if there is a very bright target under the canopy, the sensor could be able to detect it, as long as it is able to pass trough double of the distance where the incoherent component becomes dominant.

Finally, we presented an unexpected result for the phase centre of sparse woodland, whereby C-band showed a higher phase centre than X-band. The subsequent simulation carried out on experimental data, also showed a similar result. This is mainly due to the combination of lower C-band crown extinction and the higher X-band ground contribution.

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