# POLARIMETRIC RESPONSES PATTERNS AND SCATTERING MECHANISMS OF FOREST TARGETS FROM L-BAND RADAR

*Padrões de Respostas Polarimétricas SAR e Mecanismos de Espalhamento de Alvos Florestais Derivados de Radar de Banda L*

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## ABSTRACT

The objective of this study is to analyze the polarization responses derived from the airborne sensor SAR R99-B data (L-band) in areas of primary forest, secondary successions and forest with timber exploitation and those under recovery after a burning. In addition, we perform an exploratory analysis of the scattering mechanisms of each forest typology using an alternative procedure for SAR image classification based on target decomposition. The study site is located in the Tapajós region, Pará State (Brazil). Polarization response graphs were obtained by plotting the normalized cross-section of the forest targets, on a three-dimensional surface plot as a function of the orientation and ellipticity angles. The resulting surfaces were visually compared and the configuration of each plot was analyzed with support of physiognomic-structural information collected during forest inventories. The distinction between single and multiple scattering mechanisms was done by the association of entropy and alpha angle values derived from target decomposition for each sample area. Some results can be mentioned: (a) compared to areas of secondary succession, primary forests tend to present polarization responses with a higher pedestal, indicating greater variability in terms of scattering mechanisms; (b) for all thematic classes investigated, the distribution of pixels in the entropy-alpha angle classification space was more frequent at zones 4, 5 and 6, indicating the predominance of scattering processes with medium entropy. This study improves the understanding of the interaction mechanisms between L-band SAR signals and structural parameters of tropical rainforest, supporting inventory and the monitoring of forest in the Amazon region.

**Keywords:** tropical forest, SAR, scattering mechanism, inventory, monitoring, Amazon.

## RESUMO

O objetivo desse estudo é analisar as respostas de polarização, derivadas do sensor aerotransportado SAR R99-B (banda L), em áreas de floresta primária, sucessão secundária, floresta sob exploração madeireira e aquelas sob processo de regeneração após ação do fogo. Adicionalmente, é feita também uma análise exploratória dos mecanismos de espalhamento de cada tipo florestal, usando um procedimento alternativo de classificação de imagens SAR baseada em decomposição de alvos. A área de estudo está localizada na região do Tapajós, Estado do Pará (Brasil). Para a representação das respostas de polarização uma secção transversal normalizada dos alvos florestais foi plotada num gráfico tridimensional, como função dos ângulos de orientação e elipticidade. As superfícies resultantes foram visualmente comparadas e a configuração de cada amostra foi analisada com suporte de informações fisionômico-estruturais coletadas em inventários florestais. Por outro lado, a distinção de mecanismos de espalhamento simples e múltiplo derivados da decomposição de alvos foi feita pela associação de valores de entropia e ângulo alfa médio, derivados por decomposição de alvos para cada área amostral. Alguns resultados podem ser mencionados: (a) comparadas às áreas de sucessão secundária, verifica-se que as florestas primárias tendem a apresentar respostas de polarização com pedestais mais altos, sugerindo a ocorrência de maior variabilidade em termos de mecanismos de espalhamento; (b) para todas as classes temáticas investigadas, a distribuição de pixels no espaço bi-dimensional entropia-ângulo alfa concentra-se nas zonas 4, 5 e 6, indicando a predominância de processos de espalhamento de média

entropia. Esse estudo impulsiona as investigações acerca dos mecanismos de espalhamento que regem a interação do sinal de radar (banda L) com parâmetros estruturais da floresta tropical, subsidiando o inventário e o monitoramento da cobertura vegetal da região Amazônica.

**Palavras-chave:** floresta tropical, SAR, mecanismos de espalhamento, inventário, monitoramento, Amazônia.

## 1. INTRODUCTION

Due to the advancement of economic activities in the domain of the Amazon forest, remote sensing is becoming a fundamental tool to characterize the causes of degradation (conversion of natural vegetation to agriculture and cattle raising, selective logging, charcoal production, etc.) and also to monitor the impact of human activities (fragmentation of habitats, loss of biodiversity, reduction of hydrological and edaphic potentials) over these large ecosystems. Because in tropical regions there is a high percentage of cloud all year round, which impedes forest inventory and monitoring by optical data, it is important to use sensor systems that operate at microwave wavelengths.

RAUSTE et al. (1994), KASISCHKE et al. (1997) and HENDERSEN and LEWIS (1998) studied polarimetric SAR backscatter for the discrimination of forest types, discussing aspects of scattering and attenuation of the SAR signal at different frequencies. Furthermore, KUGLER et al. (2006) and TREUHAFT et al. (2006) discussed the contribution of the interferometric SAR mode to estimate biophysical parameters in forest areas. Power spectrum analysis was used for the study of spatial features of forests (canopy structure and distances between major tree individuals) from airborne SAR data in the Amazonia (NEEFF et al. 2005). SAATCHI et al. (1997), LUCKMAN et al. (1997), HOEKMAN and QUIÑONES (2000), SANTOS et al. (2002), SANTOS et al. (2003) and GONÇALVES et al. (*in press*) estimated specifically the forest biomass from polarimetric and/or interferometric SAR data, discussing the backscatter saturation due to the high density of tropical forests.

The above mentioned experiments indicate the potential of SAR systems for thematic mapping, taking into account the restrictions of frequency and polarization of each sensor system. These restrictions are a function of the sensitivity of the radar to the forest structure and the possibility of interaction with trunks and branches, where most of the aboveground biomass is concentrated.

Within this framework, the objective of this study is to analyze the polarimetric response patterns derived from SAR data (L-band) in areas of primary forest, secondary succession, forests with timber exploitation and those under recovery after burning. Additionally, we perform an exploratory analysis of scattering mechanisms of each forest typology using an alternative procedure of SAR image classification based on target decomposition.

The interaction mechanisms between the radar signal and the structural aspects of forests has been the objects of several studies (ZEBKER et al. 1991; CLOUDE and POTTIER, 1997; CHAMPION et al. 1998; WATANABE et al. 2006). There are several interaction mechanisms (FREEMAN and DURDEN, 1998), such as: multiple backscatter within the canopy (volumetric scattering), direct scattering from the tree trunks, scattering from the interaction canopy-soil, scattering from the interaction trunk-soil (double bounce), whose intensities depend on the SAR wavelengths, on the polarization, on the angle of incidence and on terrain parameters.

## 2. STUDY SITE

The area under study is located in the Tapajós region (NW Pará State, Brazil), delimited by the geographical coordinates S 3º01’59.85” - S 3º10’39.33” and WGr 54º 59’53.08” - WGr 54º52’44.96” (Figure 1). This region is characterized by a low rolling relief, constituting the lower Amazon plateau and the upper Xingu-Tapajós Plateau. It is dominated by a continuous cover of primary tropical rainforest characterized by the presence of emergent trees and an uniform vegetation cover (Dense Ombrophilous Forest), as well as sections of low to dissected plateaus with few emerging individuals and a high density of palm trees (Open Ombrophilous Forest). The land use is related to subsistence agriculture, few cash crops, cattle raise and selective logging activities.

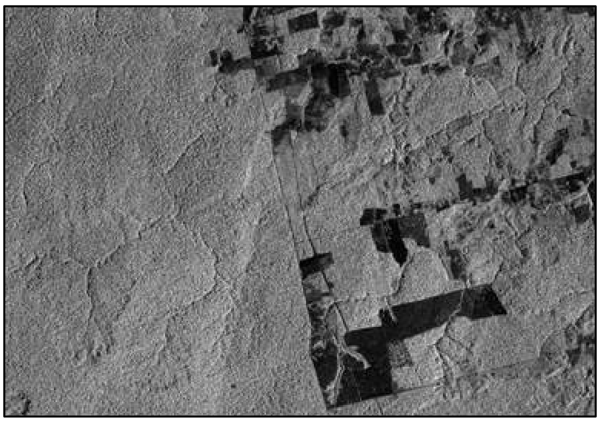

Fig. 1 - SAR R99-B image of the Tapajós region.

## 3. METHODOLOGICAL PROCEDURE

### *3.1. SAR data acquisition*

The MAPSAR Project (Multi-Application Purpose SAR) is a Brazil-Germany scientific cooperation program, whose initial objective was to perform a feasibility study focussing on an L-band SAR satellite with fine spatial resolution, polarimetry and interferometry (SCHRÖDER et al. 2005). An experiment was conducted in the Tapajós region to simulate the MAPSAR satellite data (MURA et al. 2007; SANTOS et al. 2008), using the airborne SAR R99-B sensor operated by the Amazon Surveillance System (SIVAM). The SAR data were collected in September 2005, at HH, VV and HV polarizations (descending mode), with a spatial resolution of 5 m, and incidence angle varying from 52.7º to 70.1º.

The SAR data were calibrated as follows: first, antenna pattern correction was performed to remove gain variations in the range direction by applying a polynomial function applied to the sum of the amplitude values; then, absolute calibration was achieved by using the peak estimation method to transform the amplitude data into backscatter values. This was accomplished by using the radiometric responses of 12 corner reflectors that were placed in the field, during the imaging campaign. The average calibration error was estimated at 0.84 dB ± 0.18 dB.

### *3.2. Field survey and data analysis*

Interaction mechanisms between SAR data and structural properties (e.g. density, shape, dielectric constant, height, biomass, etc) of the land cover have been the focus of several studies, where the polarimetric signatures are used as an analysis tool (HENDERSON and LEWIS, 1998). According to VAN ZYL et al. (1987), the polarimetric response of targets allows a detailed knowledge of the scattering mechanisms that determine the radiation response to the SAR antenna. The scattering mechanisms, in turn, can be used to predict backscattering coefficient, not only as a function of the incidence angle and electric properties but also considering the polarization. It is important to note that polarization responses are not the unique for a certain type of forest cover. Different combinations of distinct scattering mechanisms can result in the same response.

In this context, an exploratory analysis was conducted to evaluate the sensitivity of two polarimetric techniques in the assessment of structural variations of some classes of forest cover. The following classes were chosen for this analysis, which was based on a field survey, conducted in September 2005 simultaneously with the SAR imaging: primary forest (PF); selectively-logged forest (SL refers to low-impact logging in legally managed forests); advanced secondary succession (ASS); intermediate secondary succession (IntSS); initial secondary succession (ISS); degraded forest (DF), related to severe impacted areas due to excessive harvesting of wood, poor management, repeated fire (~10 years ago) and/or overgrazing, with small degree of natural regrowth. Forest inventories were conducted for the physiognomic-structural characterization of all classes.

The first polarimetric technique involved the generation of graphic representations of the co-polarized response of each forest type (six samples in total), as described by VAN ZYL et al. (1987). In these plots, the cross-section (σ) of a certain type of forest cover was plotted on a three-dimensional space, as a function of all possible combinations of orientation (ψ) and ellipticity (χ) angles. In order to derive the polarization response for a given region of interest (ROI) – sample area including a sufficient number of representative pixels of a given forest type, reducing statistical uncertainties and the influence of speckle noise –, we used the average complex value of all pixels within that ROI. The resulting surfaces were compared by visual inspection, using information on structural characteristics derived from field data.

In the second exploratory analysis, the entropy and average alpha angle values of each ROI, derived from the coherence matrix, were plotted in the bi-dimensional classification space $\left(H,\overline{\alpha}\right)$, following the procedure introduced by CLOUDE and POTTIER (1997). In this procedure of classification by target decomposition, the scattering mechanisms are defined in 9 distinct zones, namely: Z1 – High entropy multiple scattering; Z2 – High entropy vegetation scattering; Z3 – High entropy surface scatter; Z4 – Medium entropy multiple scattering; Z5 – Medium entropy vegetation scattering; Z6 – Medium entropy surface scatter; Z7 – Low entropy multiple scattering events; Z-8 – Low entropy dipole scattering; and Z9 – Low entropy surface scatter.

After including the SAR response of each forest type in the $\left(H,\overline{\alpha}\right)$ bi-dimensional space, the resulting classifications were pair-wise compared using regression analysis techniques. First, a linear model was fit for each classification pair by regressing the percentage number of pixels classified in each zone of the plane. The estimated regression coefficients were then tested to check whether the fitted line was a 45-degree line through the origin (i.e. F-test of $b_1 = 0$ vs. $b_1 \neq 0$; t-test of $b_0 = 0$ vs. $b_0 \neq 0$; and t-test of $b_1 = 1$ vs. $b_1 \neq 1$, where $b_0$ and $b_1$ are regression coefficients). This result would indicate no significant difference between the two tested classifications at the 5% significance level, and therefore no success of the technique in discriminating between the two forest types.

## 4. RESULTS AND DISCUSSION

At Figure 2 the co-polarized responses derived from the SAR R99-B data are presented. In order to characterize the diversity of forests in the Tapajós region, we selected a total of six representative ROIs. The polarization responses of classes ISS, IntSS and ASS show a strong similarity to the theoretical responses of short and thin conducting cylinders (i.e. with radius and length much shorter than the wavelength). This suggests that the scattering produced by twigs and small branches has an important contribution to the total backscattering in areas of regrowth. The co-polarized response of ASS and IntSS shows that the maximum measured scattering cross section occurs for HH polarization, consistent with increased double-bounce and predominance of horizontally oriented scatterers (ψ = ± 90º). The response of the ISS area, on the other hand, indicates the predominance of branches oriented at ±45º in relation to the horizontal plane, possibly due to more homogeneous canopies, characteristic of younger forests with low species diversity and uniform growth rate.

As the successional stage advances, the vertical structure and the species diversity become more complex, resulting in an increase of the pedestal height, which represent the non-polarized component of the received signal (LECKIE and RANSON 1998).

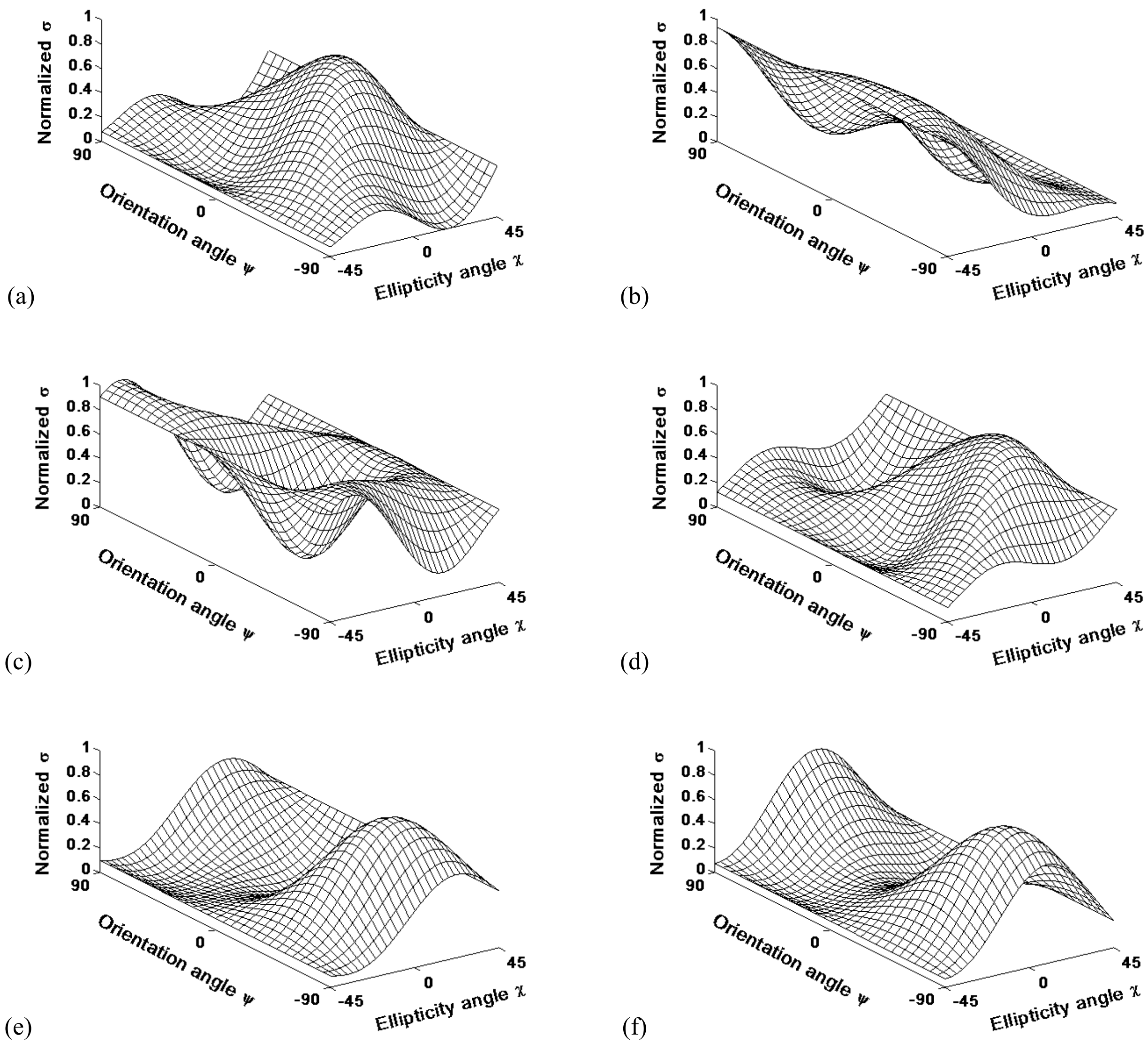


Fig. 2 – L-band polarimetric response patterns of (a) degraded forest, (b) primary forest, (c) selectively-logged forest, (d) advanced secondary succession, (e) intermediate succession, and (f) initial succession.

Figure 2 shows that the L-band polarimetric response of primary forest (PF) stand is similar to the theoretical response of a helix oriented to the right. The highest values of σ occur at circular polarization (RR), which a certain independence of orientation angle. In the DF stand, the scattering by branches represents an important contribution at the total backscattered, as it is the case in areas of secondary succession. In this forest stand which was burnt about 10 years ago, the lower stratum is composed by thin bamboos and a number of recovery species that compete for light with more vertically oriented branches. The polarization response is similar to the theoretical response of short and thin conducting cylinders, but in this case, most scatterers are vertically orientated.

The polarization response of the selectively-logged forest (Figure 2) is similar to that of a trihedral corner reflector, which has a double bounce scattering geometry when one of the reflector sides is aligned with the direction of wave propagation (ZEBKER and NORIKANE 1987). In areas affected by timber exploitation, it is reasonable to expect the dominance of double-bounce scattering due to the large number of gaps resulting from removal of trees with commercial value. This type of mature forest also has a well-defined vertical structure, which contributes to the increase of double-bounce scattering. It is important to note that the polarization response of this stand presents a relatively high pedestal, suggesting the existence of considerable variation in the scattering mechanisms of adjacent resolution elements. This is most likely caused by the presence of gaps, a consequence of selective logging, which are generally associated with an increase of the structural heterogeneity.

Figure 3 shows the distribution of pixels extracted from the six ROIs in the bi-dimensional classification space $(H,\overline{\alpha})$, while the numerical results (i.e. the percentage of pixels in each scattering zone) are presented in Table 1. In Figure 3 it is possible to observe that all 6 ROIs show a concentrated pixel distribution (average value of 91.6%) at zones Z4, Z5 and Z6. This indicates that at the plots sampled, those scattering processes of medium entropy predominate and at an overview, it is independent of the floristic composition and structural characteristics of each forest typology studied. Only in the primary forest and degraded forest stands, the amount of pixels classified, in the three zones mentioned, was below 90%. It is also important to mention that the proportion of pixels in each zone was similar for most classes, except at those plots of degraded forest and at initial secondary succession. At these two cases, zone Z5 surpasses ~1.7 times more pixels than Z4, indicating that in these two vegetation typologies there is less multiple scattering, if compared to the other classes under study.

Table 1. Percent pixel distribution of each ROI at zones of bi-dimensional classification scheme $\left(H,\overline{\alpha}\right)$.

| Zones* | Forest types | | | | | |
|---|---|---|---|---|---|---|
| | **DF** | **PF** | **SL** | **ASS** | **IntSS** | **ISS** |
| Z1 | 1.0 | 0.7 | 1.0 | 1.1 | 1.8 | 0.9 |
| Z2 | 1.7 | 2.8 | 2.5 | 1.8 | 2.6 | 1.8 |
| Z3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Z4 | 26.2 | 37.2 | 32.1 | 34.4 | 40.5 | 28.7 |
| Z5 | 49.1 | 32.5 | 46.6 | 43.8 | 40.7 | 46.4 |
| Z6 | 11.9 | 19.8 | 13.3 | 14.8 | 10.4 | 21.1 |
| Z7 | 1.3 | 1.3 | 0.4 | 0.0 | 1.0 | 0.0 |
| Z8 | 0.9 | 0.0 | 0.9 | 1.4 | 1.0 | 0.0 |
| Z9 | 7.7 | 5.7 | 3.2 | 2.6 | 2.1 | 1.0 |

The statistical tests used to detect variations among classifications of pairs of ROIs, at 5% significance values, indicate that there are no significant differences. We observed larger ***p*** values at the comparison DF/PF, ISS/SL and IntSS/SL, with values of 0.964, 0.909 and 0.816 respectively, while the other ROIs were classified in equivalent mode, presenting low ***p*** values. Since physiognomic-structural differences clearly exist among forest types, one can infer that this classification scheme $\left(H,\overline{\alpha}\right)$ based on target decomposition is not robust enough to detect such variability when using L-band data.

## 5. CONCLUSIONS

The analysis of the airborne SAR R99-B data (L-band) based on decomposition of scattering mechanisms allows the following conclusions: (a) at types of landscapes investigated here there is a predominance of scattering processes with medium entropy. The three main scattering mechanisms observed at the experiment, in decreasing order of occurrence are: dipole, double bounce and surface type; (b) the classification method based on entropy and mean alpha angle values was not robust enough to detect the floristic-structural variability existing among forest types; (c) the co-polarized responses derived from the SAR data showed different configurations, indicating that the backscattering of certain forest types was dominated by distinct physical mechanisms. A more detailed analysis of species composition and its associated effects on vertical stand structure should be performed in order to improve the understanding of polarization responses and scattering mechanisms in tropical forests. Cross-polarized responses derived from PALSAR data are currently being analyzed to gain further insights into the mechanisms controlling the radar response. This information can improve the performance of classification methods, leading to improved biomass determination in the Amazon region

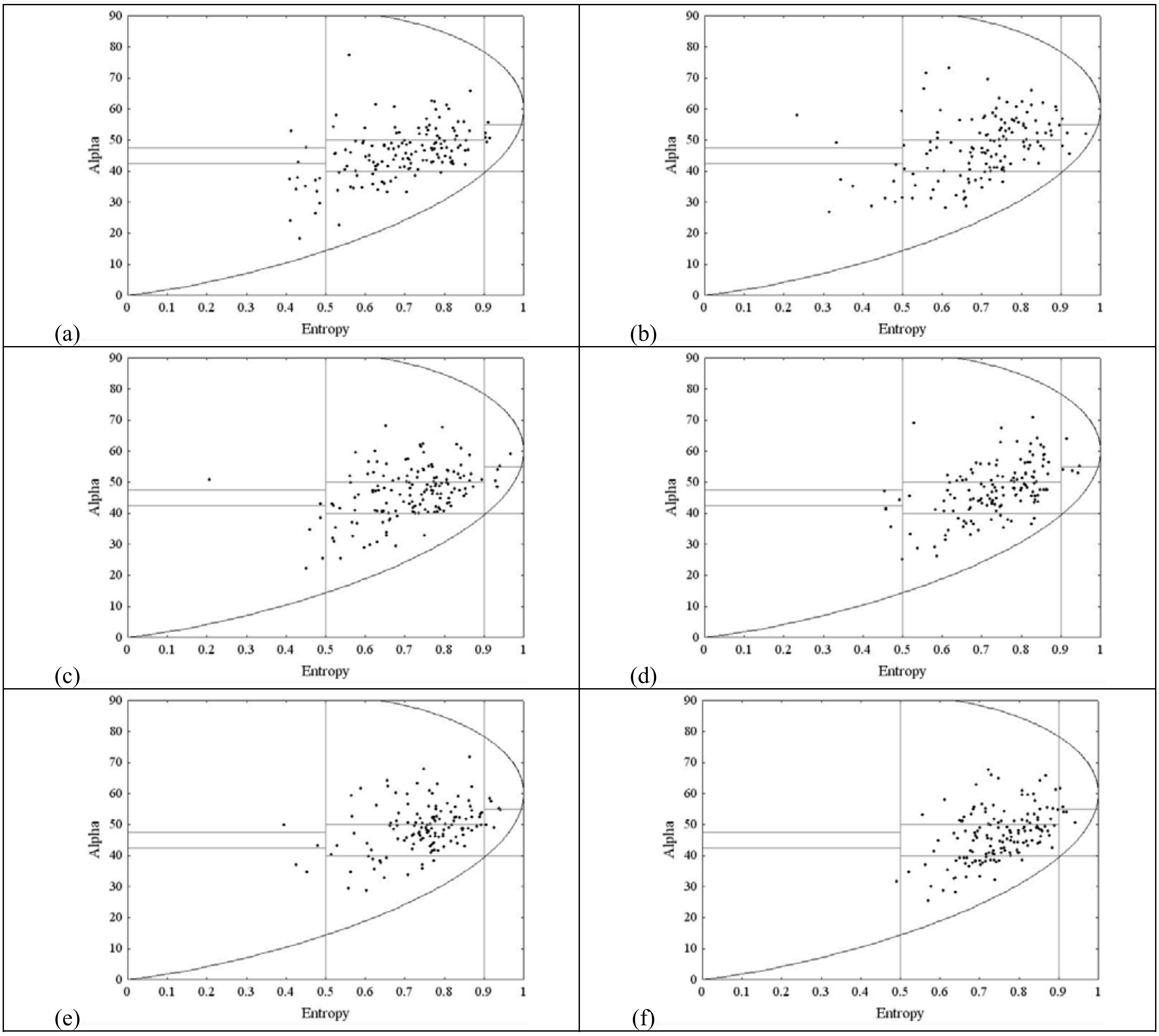


Fig. 3 – Distribution of pixels in the bi-dimensional classification scheme $(H,\overline{\alpha})$ at L-band of SAR R99-B: (a) degraded forest, (b) primary forest, (c) forest with old selective logging, (d) advanced secondary succession , (e) intermediate secondary succession, and (f) initial secondary succession.

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