Spatial Properties of Forest Clutter Measured by Wavelet Frames in Polarimetric PALSAR Imagery

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Abstract
The paper reports on experimental analysis of the spatial statistics (texture), as measured by wavelet frames in L-band SAR observations of tropical forest. Signatures are used to characterize the dependences of the texture measures on scale and polarization state. For detected data, experiments performed using a full resolution (12.5 m) JERS-1 image confirm that textural features provide good separability for two forest classes of interest (swamp and lowland rain forest). However, spatial resolution turns out to be a key factor influencing separability in the texture feature space. Indeed simulation of a PALSAR strip image at 50 m pixel spacing indicates that this product does provide textural information only at coarse resolution (800 m). Concerning polarimetry, analysis of a fully polarimetric PALSAR scene reveals that thematic classes such as primary forest, swamp (flooded) forest, degraded forest are uniquely characterized by texture signatures in the scale-polarization plane.

Keywords: texture, SAR, polarimetry, wavelet frames.

1. INTRODUCTION

Structural properties are fingerprints of natural targets, such as forests. The following questions need then to be addressed to assess whether radar remote sensing could provide a vehicle to exploit these properties for forest mapping and monitoring: are these fingerprints reflected into the SAR backscatter spatial statistics? In this case, can we derive measures of the backscatter statistics that could be helpful in characterizing different species and development patterns within the forest? Can polarimetry add value to this pursuit?

Within this broad context, the present paper proposes some answers to those questions based on experimental observations derived from L-band space-borne synthetic aperture radar (SAR) in a specific thematic context - forest mapping in the Congo River floodplain.

The experimental analysis presented here is based on a method for retrieving local measures of the SAR backscatter spatial statistics (texture) using wavelet frames, which was proposed in [1] from the theoretical point of view. One novel aspect of this method is the introduction of the concept of polarimetric texture, which is related to the dependences of the texture measures on the antenna polarization states. A formalism, called the Wavelet Polarization Signature (WASP), is also used for analyzing experimentally these dependences.

Main objective and focal point of this analysis is to set the ground for adding information layers extracted from PALSAR data in large scale tropical forest mapping projects, such as those foreseen in the JAXA K&C initiative. However, these future pursuits will have to rely on past experience, such as the one gained in the GRFM project, a K&C precursor. Therefore, in an historical perspective, also JERS-1 data will be taken into account for documenting the benefits (and losses) in the passage to the ALOS era.

2. TEXTURE MESAURES FROM WAVELET FRAMES

We summarize briefly in this section the ideas that underpin the method [1] for retrieving texture measures using wavelet frames and the related WASP analysis. In our approach texture measures related to spatial statistics (e.g. two point statistics) are afforded by the variance of the wavelet coefficients in a discrete transform, implemented using an à trous algorithm. The variance is estimated locally at several dyadic scales by convolution with a smoothing kernel. The wavelet of choice is a frame that acts as a differential operator.

In more detail, let S_{2^j} be the image at the output of the à trous low-pass filter (smooth image), $W^{xy}_{2^j}$ the wavelet coefficients in the x and y direction (output of the à trous high pass filters) at scale 2^j. The wavelet coefficients are normalized by the smooth image at the same scale. This step is necessary to make the wavelet variance independent from multiplicative noise (speckle) in homogenous areas. The normalized wavelet coefficients are then squared and averaged by convolution with a separable discrete cubic B-spline kernel enlarged by a factor m. This factor specifies the amount of averaging used for the local estimates, and dictates the resolution of the final texture images. Finally a feature vector is constructed as follows:

$$v_1 = \frac{\left\langle \left(S^p_{j-1}\right)^2 \right\rangle}{\left\langle S^p_{j-1} \right\rangle^2} \quad v_2 = \left\langle \left(\frac{W^x_j}{S_j} \right)^2 \right\rangle \quad v_3 = \left\langle \left(\frac{W^y_j}{S_j} \right)^2 \right\rangle \qquad (1)$$

Although the feature vector holds estimate of a one-point statistics, we will focus attention in the following on the two-point statistics given by the wavelet variance.

The wavelet variance is a proxy of the following two-point spatial statistics, also known in geo-science as "structure function":

$$\left\langle \left(f(x) - f(x+\tau)\right)^2 \right\rangle \approx \left\langle w^2_{2^j} \right\rangle \qquad (2)$$

The structure function is effective in characterizing the signal regularity in discontinuities, like edges and point targets, correlations in stationary random processes, and the scaling properties (e.g. fractal dimension) in non-stationary processes with stationary increments, like fractional Brown. We are here in particular concerned with spatial correlation in stationary targets.

3. EXTENSION TO POLARIMERY

Concerning polarimetry, the crucial question is: will the measures afforded by the wavelet variance depend on polarization state? In this case, could we find optimal polarimetric states with respect to the textural separability of regions of interest?

From a purely observational standpoint, these questions are addressed by an analytical tool called the Wavelet Polarimetric Signature (WASP). The tool captures the dependences on scale and polarization and encapsulates them in graphical form.

It is computed as follows. A vector of covariance matrix elements is extracted from the polarimetric data set along a linear transect defined interactively by visual inspection of the SAR image. From this vector, power is synthesized in the cross-polarized linear configuration at a number of orientation angles ranging from 0^0 to 180^0 with discrete increments. A discrete wavelet transform is applied to each of these vectors, and the variance of the wavelet coefficients computed at a number of dyadic scales (typically four). Finally, the signature consists of a family of graphs, each mapping the normalized wavelet variance against the orientation angle φ at a given dyadic scale.

4. SIGNATURES FOR SINGLE-POLARIZATION DETECTED DATA

For detected data, we define a signature that captures the scaling behavior of the wavelet variance for a single polarization state. The signature, dubbed Wavelet Scaling Signature (WASS), consists of a graph of wavelet variance versus dyadic scales in base 2 logarithmic scale (which linearizes a power law in scales and variance). This type of signature can give us clues about the type of stationary or non-stationary regime associated with the underlying random process. For example, a structure function that follows a power law with scale with a constant exponent gives evidence of the presence of a non-stationary process with stationary increments (e.g. a mono-affine fractal process).

Both signatures, the WASP and WASS, are based on a two-point statistics estimated over a linear transect. In the case of a texturally homogeneous extended target, this measure characterizes well the textural properties in the neighborhood of the transect, but does not bear information on the variance of this statistics as we move away from the transect within the region of interest. In other words, this analysis does not give information on the separability of two homogeneous regions, a fact which makes it less suitable for bridging over to a segmentation problem. Therefore an area extended version of the signatures is conceived. Here, given two regions defined in a supervised way, the criterion function of the Fischer linear discriminant (ratio of the between-region to within-region scatter matrices of the wavelet variance) is computed for a number of scales. For comparison, also the Fischer separability related to backscatter data, and to the one-point statistics (first component of the feature vector) are also computed.

5. EXPERIMENTAL OBSERVATIONS

5.1 Texture in detected single polarization SAR data

The thematic area of interest is located in Central Africa around the Congo River floodplain. The Congo floodplain hosts the world largest formations of swamp forests, and it is an important ecosystem for climate studies because it harbors bio-chemical processes that generate greenhouse gases, such as methane. In this experiment we are concerned with the possibility of delineating the extent of the swamp forest with respect to the surrounding lowland rain forest exploiting structural diversity of the two canopies, which, in turn, is reflected into difference of spatial statistics as seen by the radar. Indeed, the upper canopy layer of the swamp forest (up to 45 m in some cases), is composed of a small number of species, and is quite homogenous compared to the lowland rain forest.

A backscatter JERS-1 (L-band) image acquired over the area of interest (JAXA GRFM project, 1997) is shown in Fig. 1. The pixel spacing of the ground-range product is 12.5 m. Two transects are marked in the image corresponding to areas known to belong to the swamp (SF) and rain forest (RF) from auxiliary data (airborne video imagery). The associated backscatter one-point statistics is: SF σ^0= -7.21 dB, RF σ^0= -7.10 dB. Being the difference of the two values within the speckle noise variance, it would therefore be impossible to discriminate the classes based on this statistics.

A WASS signature was computed for the two transects (see Fig. 2). Clearly the signature indicates that the two classes (SF diamond symbol, RF star symbol) feature different spatial statistics at all scales. What is also interesting to notice is the highly linear trend of the wavelet variance with scale. This trend is typical of a mono-affine fractal (a statistical self-similar process, like fractional Brownian motion). Separation of the two classes in the texture feature space of the GRFM products indeed allowed us to segment them with good accuracy. However, future large scale mosaics of PALSAR imagery over Africa will be compiled in the K&C project starting from strip data at 50 m pixel spacing. The question then arises as to what extent we will still be able to exploit texture for mapping the swamp forest. Since at the time of writing no strip image of the area of interest was available, we have investigated the problem by degrading the JERS-1 image resolution to 50 m.

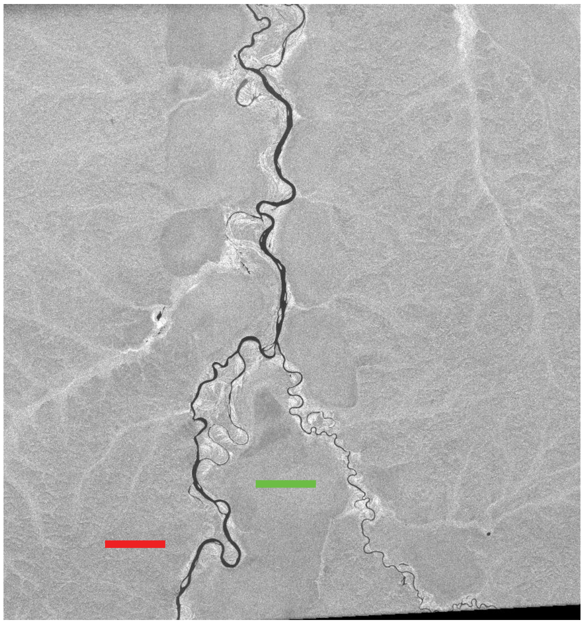

Figure 1. JERS-1 Level 2.1 image(12.5 m pixel spacing)

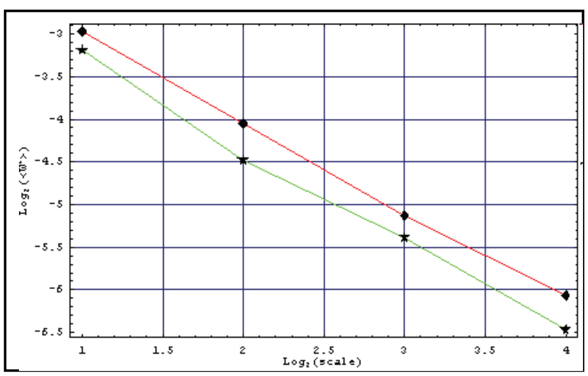

Figure 2. WASS signature related to the two transects of the JERS-1 data set shown in Fig. 1.

We did not use the available full polarization image (see Fig. 4) because of the substantial difference in incidence angle.

The WASS signature of the simulated K&C image is reported in Fig. 3. Still separation in wavelet variance for the two classes can be observed. However, in absolute terms, the separation is by far less than in the case of the full resolution image. At scales 2 and 4 differences are 0.02, 0.017 for the full resolution, and 0.00077, 0.00083 for the 50 m image.

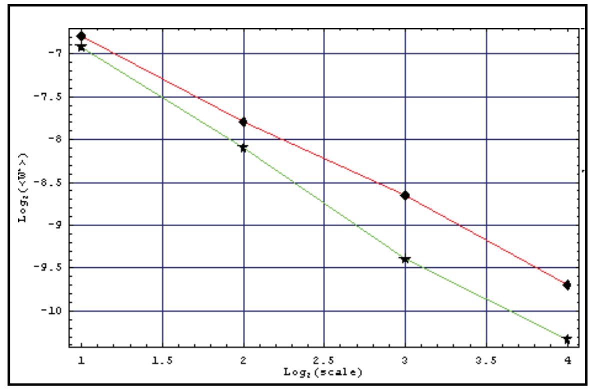

Figure 3. WASS signature related to the simulated PALSAR strip image (50 m pixel spacing).

To investigate further the issue, the Fischer separability of the two classes in the wavelet variance feature space was computed using wavelet decompositions scales 2 and 4, and averaging kernel dilation factors of 4, 8, 16. The resolution of the texture image is proportional to the support of this kernel, resulting in texture resolutions for the 12.5 m images of 50 m, 100 m and 200m and 200 m, 400 m and 800 m for the simulated PALSAR image. Comparison is also made with the separability afforded by one-point second order (variance) and first order statistics of backscatter, and with texture measures extracted from an ESA ERS-1 PRI image (12.5 pixel spacing) acquired over the same area. Results are summarized in Table I.

Table 1. Fischer Separability Criterion

	wavelet	bck CV	bck mean	all
JERS (200 m)	1.05	1.66	0.006	4.54
ERS (200 m)	1.31	1.9	0.001	6.86
PALSAR (200 m)	0.16	0.33	0.15	0.16
PALSAR (800 m)	1.15	2.8	0.15	4.58

Two main observations can be made. The ERS separability is slightly better than the JERS, due to the fact that at C-band canopy penetration is less, and therefore the upper layers "roughness" is better sensed. However resolution of the original image is the dominating factor, since, although texture related to the lowland forest develops at several scales, the limitation of useful samples for the local estimates jeopardizes the ability to separate regions, because the within-regions variance increases. Indeed reasonable separability for the simulated PALSAR image can be achieved only degrading the texture resolution to 800 m.

5.2 Texture in fully polarimetric PALSAR data

In this experiment we make the passage to polarimetry, and investigate by WASP analysis the spatial statistics of targets in the same thematic context as in the previous experiment, but using a slant range full resolution and fully polarimetric ALOS-PALSAR data set.

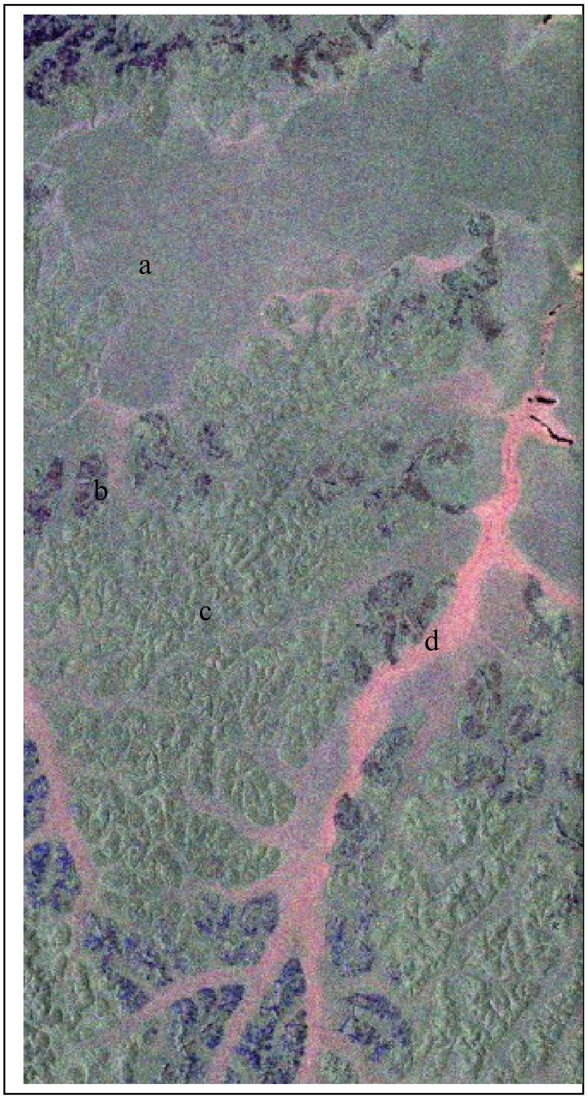

Figure 4. PALSAR FB fully polarimetric image (Pauli decomposition: R=double bounce, G=volume, B=surface)

A Pauli decomposition of the data set over the area of interest is shown in Fig. 4. WASP signatures are computed for the transects marked in the image, and corresponding to the swamp forest, the primary rain forest, the flooded swamp forest and the secondary forest. The related WASP signatures are shown in Fig. 5. The swamp forest features a very homogeneous canopy, and therefore low texture (a) and little dependence on polarization. Also notice that there is a sharp decay of the wavelet variance from the shortest scale to the second and onward. This trend is apparent in all signatures, and it is due to the sensor's resolution with respect to the scale of analysis. The degraded forest, on the other hand, presents quite a distinctive signature (b), with much more texture, and polarimetric diversity with maxima near HV.

The primary forest (c) features some texture, somehow in between the more homogeneous swamp forest and the rugged secondary forest. However notice how polarimetrically this signature differs from the one related to the secondary forest, because now the maxima occur at 45^0.

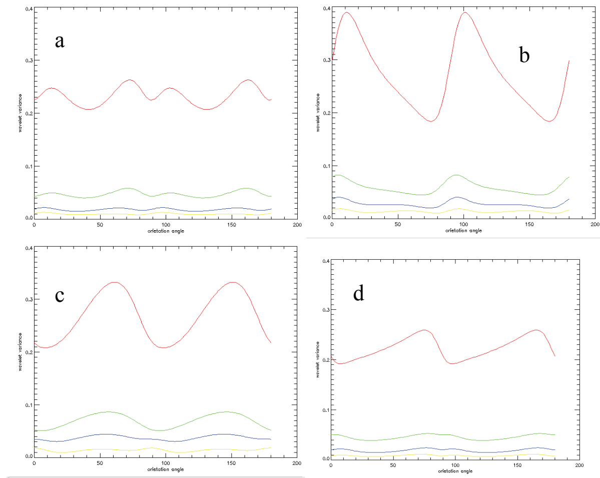

Figure 5. WASP signatures related to the transects in Fig. 4..

Finally the flooded swamp forest (d) presents a signature similar to the swamp forest but with a more marked dependence on polarization, and maxima tending to HV. We can tentatively conclude that the different thematic classes considered in this analysis are characterized by different combinations of texture strength and dependency on polarization state.

6. CONCLUSIONS

Experiments reported in this paper indicate that texture measures based on wavelet frames (possibly augmented by polarimetric textural information) can be an effective vehicle to characterize forest structural properties which are reflected in the spatial statistics of SAR observations. However, resolution of the backscatter data set, wherefrom texture is estimated, is the dominating factor to make the passage from target characterization to the scene segmentation problem. In this respect, it is foreseen that the PALSAR strip imagery used in the compilation of the K&C project mosaics will not be suitable for exploiting texture measures, at least in some specific thematic contexts, such as the ones studied in this paper.

Acknowledgement
This research is carried out under the JAXA Research Announcement (PI: JAXA-1970001).

References
[1] De Grandi G., Lee J.S., Schuler D.L., "Target Detection and Texture Segmentation in Polarimetric SAR Images Using a Wavelet Frame: Theoretical Aspects", IEEE Transactions on Geoscience and Remote Sensing, vol. 45, no. 11, pp. 3437-3453, November 2007.