

Analysis and Classification of SAR Textures using Information Theory

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Abstract—We propose a new technique texture analysis and classification based on the Bandt-Pompe symbolization, and we apply it to SAR data. It consists of (i) linearize a 2-D patch of the image using the Hilbert-Peano curve, (ii) build an Ordinal Pattern Transition Graph that considers the data amplitude encoded into the weight of the edges; (iii) obtain a probability distribution function derived from this graph; (iv) compute Information Theory descriptors (Permutation Entropy and Statistical Complexity) from this distribution, and use them as features to feed a classifier. The ordinal pattern graph we propose considers that the weight of the edges is related to the absolute difference of observations, which encodes the information about the data amplitude. This modification takes into account the scattering properties of the target and leads to the characterization of several types of textures. Experiments with data from Munich urban areas, Guatemala forest regions, and Cape Canaveral ocean samples show the effectiveness of our technique, which achieves satisfactory levels of separability. The two descriptors chosen in this work are easy and quick to calculate and are used as input for a k-nearest neighbor classifier. Experiments show that this technique presents results similar to state-of-the-art techniques that employ a much larger number of features and, consequently, require a higher computational cost.

Index Terms—Synthetic Aperture Radar (SAR), Time-series, Texture, Classification, Ordinal Patterns Transition Graphs.

I. INTRODUCTION

TEXTURE is an elusive trait. When dealing with remotely sensed images, the texture of different patches carries relevant information that, more often than not, is hard to quantify and to transform into useful and parsimonious features. This may be due to the fact that texture, in this context, is a synesthesia phenomenon that triggers tactile responses from visual inputs. This paper presents a new way of extracting features from textures, both natural and resulting from anthropic processes, in SAR (Synthetic Aperture Radar) imagery.

SAR systems are a vital source of data because they provide high-resolution images in almost all weather and day-night conditions. They provide basilar information, complementary to that offered by sensors that operate in other regions of the electromagnetic spectrum, for a variety of Earth Observation applications.

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SAR data are rich in information, although with challenging characteristics. Most notably, they do not follow the usual Gaussian additive model, and the signal-to-noise ratio is usually low.

Yue et al [1] provide a comprehensive account of how the physical properties of the target are translated into first- and second-order statistical properties of SAR intensity data.

There is general agreement that non-deterministic textures are encoded in the second-order features, i.e., in the spatial correlation structure. This notion often leads to using the covariance matrix and other measures that assume that a linear dependence, namely the Pearson correlation coefficient, suffices to characterize natural textures.

For the aforementioned reasons, this might not be the case when dealing with SAR imagery. Texture, in these images, is often visible only over large areas, and the multiplicative and non-Gaussian nature of speckle antagonizes with the additive assumption that underlies classical approaches.

SAR textures can be studied following two complementary approaches, namely analyzing the marginal properties of the data (first-order statistics), and observing their spatial structure [1], [2]. In this work, we focus on the second.

The most widely used approach to obtain textural features from SAR imagery is through co-occurrence matrices and Haralick's descriptors [3]. Radford et al. [4] used textural information derived from gray-level co-occurrence matrices, along with Random Forests, for geological mapping of remote and inaccessible localities; the authors obtained a classification accuracy of $\approx 90\%$, even when using limited training data ($\approx 0.15\%$ of the total data).

Hagensieker and Waske [5] evaluated the synergistic contribution of multi-temporal L-, C-, and X-band data to tropical land cover mapping, comparing classification outcomes of ALOS-2 [6], RADARSAT-2 [7], and TerraSAR-X [8] datasets for a study site in the Brazilian Amazon using a wrapper approach. The wrapper utilizes the gray-level co-occurrence matrix (GLCM) texture information and a Random Forest classifier to estimate scene importance.

Storie [9] proposed an open-source workflow for detecting and delineating the urban-rural boundary using Sentinel-1a SAR data. The author used a combination of GLCM information and a k-means classifier to produce a three-category map that distinguishes urban from rural areas. Other approaches include the Fourier power spectrum [10], and random fields [11].

In our approach, we opt to analyze the 1-D signals resulting from the linearization of the image samples, using non-parametric time series analysis techniques. With this approach, we reduce the dimensionality of the data and map the spatial

dependence of the pixels onto the temporal correlation of a time series. Next, we extract a probability distribution from the ordinal patterns of a new transition graph, herein proposed, which can discriminate different levels of amplitude, and we use well-known features borrowed from the Information Theory field to classify texture patches.

The main contribution of this work is the proposal of a new set of features for characterization and classification of SAR textures, based on a modification of the current ordinal patterns transition graph, incorporating relevant time-series information. Our proposal, hereinafter referred to as Weighted Amplitude Transition Graph (WATG), incorporates the absolute difference between the observations, weighting them in the calculation of the final value of their probabilities. Experiments performed on SAR image textures indicate that this approach preserves essential information about the dynamics of the system, presenting excellent results in the classification of regions, where it has reached satisfactory levels of separability.

The paper is structured as follows: Section II describes our proposed methodology. Section II-A presents the patch linearization process of the images. Section II-D shows our technique of ordinal amplitude transition graph weighting by amplitudes. In Section II-E we report the Information Theory descriptors used throughout this work. Section III describe the SAR image datasets, the analysis of ordinal pattern methods, experiments of sliding window selection, and a quantitative assessment. Finally, Section IV concludes the paper.

II. METHODOLOGY

The methodology applied in this work is shown in Alg. 1. The main idea of the technique is as follows. After receiving the P texture patch, the algorithm linearizes the image using Hilbert-Peano curves, thus acquiring a time series. Then, the procedure calls the WATG subroutine over the time series and the ordinal pattern parameters to calculate the probability distribution. Finally, shannon permutation entropy and statistical complexity are calculated. This features obtained in the last step can be used either for characterization or classification.

The WATG function basically consists of three steps: (i) we use the embedding dimension D and time delay τ in `BPSymbolization` subroutine for generate the ordinal patterns of the given time series using Bandt-Pompe, (ii) with the symbols in hand, the `transitions` function calculates the sequence of alternations of the ordinal patterns, and in (iii) `weighGraph` generates the desired incidence matrix of the graph using the weights of the amplitude differences between the time series elements. Finally, the probability distribution obtained by the proposed method is achieved by vectoring the final transition matrix. These steps are also depicted in Fig. 1, and are detailed in the following sections.

A. Linearization of image patches

In this step, we perform a data dimensionality reduction by turning the 2-D patch into a times series, i.e., a 1-D signal. This could be accomplished by reading the data by lines, columns, or any transformation of 2-D indexes into a sequence

Algorithm 1 $H \times C$ point from a patch using WATG

Input: Patch of texture P , dimension D and time delay τ

Output: $H \times C$ feature

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1: time.series  $\leftarrow$  hilbertCurve( $P$ )
2: Probs  $\leftarrow$  WATG(time.series,  $D$ ,  $\tau$ )
3:  $H \leftarrow$  ShannonEntropy(Probs)
4:  $C \leftarrow$  StatisticalComplexity(Probs)

5: function WATG(time.series,  $D$ ,  $\tau$ )
6:   patterns  $\leftarrow$  BPSymbolization(time.series,  $D$ ,  $\tau$ )
7:   transitions  $\leftarrow$  transitions(patterns)
8:   graph  $\leftarrow$  weighGraph(time.series, transitions)
9:   Probs  $\leftarrow$  as.vector(graph)
10:  return Probs
11: end function

```

of integers. In this work, we choose to use the Hilbert-Peano curve [12].

Nguyen et al. [13] firstly employed Space-filling curves, to map texture into a one-dimensional signal. When used as scanning methods of an image, such functions preserve relevant properties of pixel spatial correlation [12].

Carincotte et al. [14] used the Hilbert-Peano curve in the problem of change detection in pairs of SAR images. The authors noted that this transformation exploits the spatial locality and that its pseudo-randomness of direction changes works well for a large family of images, especially natural ones.

Assuming an image patch is supported by an $M \times N$ grid, we have the following definition.

Definition 1: An image scan is a bijective function $f: \mathbb{N} \times \mathbb{N} \rightarrow \mathbb{N}$ in the ordered pair set $\{(i, j) : 1 \leq i \leq M, 1 \leq j \leq N\}$, which denotes the points in the domain, for the closed range of integers $\{1, \dots, M \times N\}$. A scan rule is $\{f^{-1}(1), \dots, f^{-1}(M \times N)\}$.

This Definition imposes that each pixel is visited only once, and that all pixels are visited.

Space-filling curves, such as raster-1, raster-2, and Hilbert-Peano scanning techniques, stipulate a proper function f . Traditional Hilbert-Peano curves scan an array of pixels of dimension $2^k \times 2^k$, $k \in \mathbb{N}$, never keeping the same direction for more than three consecutive points, as shown in Fig. 2. Using the Hilbert-Peano curve, we reduce the data dimensionality by maintaining the spatial dependence information of the patch. In this work, we use patches of size 128×128 .

B. Bandt-Pompe Symbolization

The representation of time series by ordinal patterns was introduced by Bandt and Pompe [15] as a transformation resistant to noise, and invariant to nonlinear monotonic transformations. Therefore, the first step of the WATG subroutine is to calculate the ordinal patterns of time series by Band-Pompe symbolization.

Consider $\mathcal{X} \equiv \{x_t\}_{t=1}^T$ a real valued time series of length T .

Let \mathfrak{A}_D (with $D \geq 2$ and $D \in \mathbb{N}$) be the symmetric group of order $D!$ formed by all possible permutation of order D ,

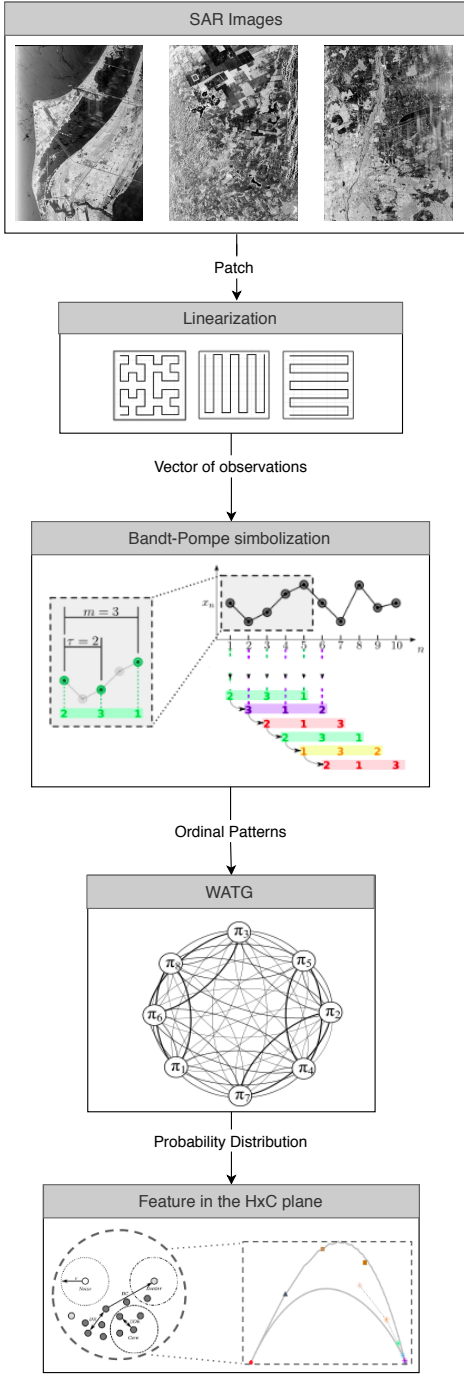


Figure 1. Outline of the methodology used for the classification of textures.

and the symbol component vector $\pi^{(D)} = (\pi_1, \pi_2, \dots, \pi_D)$ so every element $\pi^{(D)}$ is unique ($\pi_j \neq \pi_k$ for every $j \neq k$). Consider for the time series $\mathcal{X} \equiv \{x_t\}_{t=1}^T$ its time delay embedding representation, with embedding dimension $D \geq 2$ and time delay $\tau \geq 1$ ($\tau \in \mathbb{N}$, also called “embedding time”, “time delay”, or “delay”):

$$\mathbf{X}_t^{(D,\tau)} = (x_t, x_{t+\tau}, \dots, x_{t+(D-1)\tau}), \quad (1)$$

for $t = 1, 2, \dots, N$ with $N = T - (D-1)\tau$. Then the vector $\mathbf{X}_t^{(D,\tau)}$ can be mapped to a symbol vector $\pi_t^D \in \mathcal{A}_D$. This

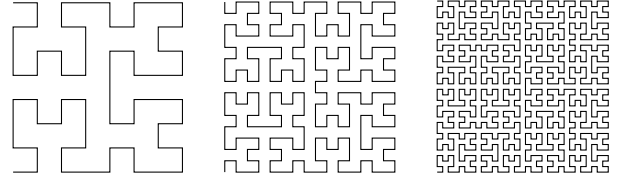


Figure 2. Visual representation of Hilbert-Peano curve in areas of: (a) 8×8 , (b) 16×16 and (c) 32×32 .

mapping is such that preserves the desired relation between the elements $x_t \in \mathbf{X}_t^{(D,\tau)}$, and all $t \in \{1, \dots, T - (D-1)\tau\}$ that share this pattern (also called “motif”) have to be mapped to the same π_t^D .

We define the mapping $\mathbf{X}_t^{(D,\tau)} \mapsto \pi_t^D$ by ordering the observations $x_t \in \mathbf{X}_t^{(D,\tau)}$ in increasing order. Consider the time series $\mathcal{X} = (1.8, 1.2, 3.2, 4.8, 4.2, 4.5, 2.3, 3.7, 1.2, .5)$ depicted in Fig. 3. Assume we are using patterns of length $D = 5$ with unitary time lag $\tau = 1$. The code associated to $\mathbf{X}_3^{(5,1)} = (x_3, \dots, x_7) = (3.2, 4.8, 4.2, 4.5, 2.3)$, shown in black, is formed by the indexes in $\pi_3^5 = (1, 2, 3, 4, 5)$ which sort the elements of $\mathbf{X}_3^{(5,1)}$ in increasing order: 51342. With this, $\tilde{\pi}_3^5 = 51342$, and we increase the counting related to this motif in the histogram of all possible patterns of size $D = 5$.

The dash-dot line in Fig. 3 illustrates $\mathbf{X}_1^{(5,2)}$, i.e. the sequence of length $D = 5$ starting at x_1 with lag $\tau = 2$. In this case, $\mathbf{X}_1^{(5,2)} = (1.8, 3.2, 4.2, 2.3, 1.2)$, and the corresponding motif is $\tilde{\pi}_1^5 = 51423$.

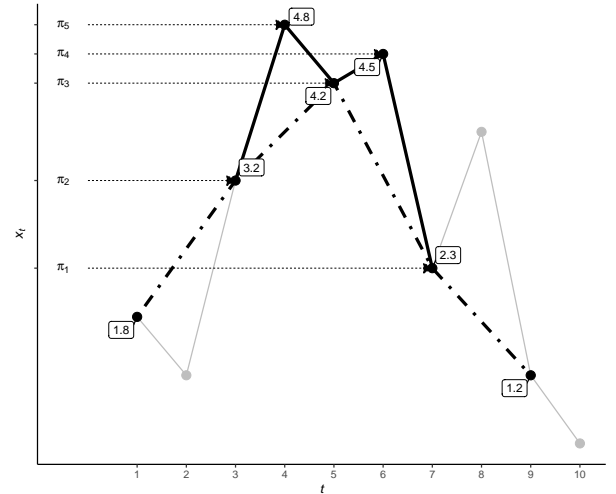


Figure 3. Illustration of the Bandt and Pompe coding

The classic approach to calculating the probability distribution using ordinal patterns is through the frequency histogram. So, denote Π the sequence of symbols obtained by a given series $\mathbf{X}_t^{(D,\tau)}$. The Bandt-Pompe probability distribution is the relative frequency of symbols in the series against $D!$ possible permutations of patterns $\{\tilde{\pi}_t^D\}_{t=1}^{D!}$:

$$p(\tilde{\pi}_t^D) = \frac{\#\{\mathbf{X}_t^{(D,\tau)} \text{ is of type } \tilde{\pi}_t^D\}}{T - (D-1)\tau}, \quad (2)$$

where $t \in \{1, \dots, T - (D-1)\tau\}$. These probabilities meet

the conditions $p(\tilde{\pi}_t^D) \geq 0$ and $\sum_{i=1}^{D!} p(\tilde{\pi}_t^D) = 1$.

Recent works propose a weighting in the calculation of relative frequencies for ordinal patterns with different amplitude variances, making them contribute differently to the final value of the permutation entropy (PE) and thus incorporating amplitude change information within a given set [16]. However, these methods do not consider the amplitude difference present in different time series, weighing them similarly when calculating the final value of their probabilities. Therefore, data with different amplitudes but with similar variance dynamics are not discriminated, losing important information about the system dynamics.

C. Ordinal Pattern Transition Graph

Alternatively, one may form an oriented graph with the transitions from $\tilde{\pi}_t^D$ to $\tilde{\pi}_{t+1}^D$. The Ordinal Pattern Transition Graph $G = (V, E)$ represents the transitions between two consecutive ordinal patterns over time t . The vertices are the patterns, and the edges the transitions between them: $V = \{\tilde{\pi}_t^D\}$, and $E = \{(\tilde{\pi}_t^D, \tilde{\pi}_{t+1}^D) : \tilde{\pi}_t^D, \tilde{\pi}_{t+1}^D \in V\}$ [17].

The literature reports two approaches to compute the weight of edges. Some authors employ unweighted edges [18], [19] which represent only the existence of transitions, while others apply the frequency of transitions [20], [21]. The weights $\mathbb{W} = \{w_{\tilde{\pi}_t^D, \tilde{\pi}_j^D} : \tilde{\pi}_t^D, \tilde{\pi}_j^D \in V\}$ assigned to each edge describe the chance of transitions between the patterns $(\tilde{\pi}_t^D, \tilde{\pi}_j^D)$. The weights are calculated as the relative frequency of each transition, i.e., as:

$$w_{\tilde{\pi}_t^D, \tilde{\pi}_j^D} = \frac{|\Pi_{\tilde{\pi}_t^D, \tilde{\pi}_j^D}|}{T - (D - 1)\tau - 1}, \quad (3)$$

where $|\Pi_{\tilde{\pi}_t^D, \tilde{\pi}_j^D}|$ is the number of transitions from pattern $\tilde{\pi}_t^D$ to pattern $\tilde{\pi}_j^D$ and $\sum_{\tilde{\pi}_j^D} w_{\tilde{\pi}_t^D, \tilde{\pi}_j^D} = 1$, and the denominator is the number of transitions between sequential patterns in the series of motifs of length $T - (D - 1)\tau$.

D. Weighted Ordinal Patterns Transition Graph

For the probability distribution, our proposal is henceforth referred to as Weighted Amplitude Transition Graph (WATG) and takes into account the scattering properties of the target, leading to a good characterization of the textures of interest. We propose a modification of the current ordinal pattern transition graph, incorporating the absolute difference between the observations that produced the patterns, change the traditional distribution of the weight of the edges.

First, each \mathcal{X} time series is scaled to $[0, 1]$, since we are interested in a metric able to compare datasets:

$$\frac{x_i - x_{\min}}{x_{\max} - x_{\min}} \mapsto x_i, \quad (4)$$

where x_{\min} and x_{\max} are, respectively, the minimum and maximum values of the series. This transformation is relatively stable before contamination, e.g., if instead of x_{\max} we observe kx_{\max} with $k \geq 1$, the relative values are not altered. Nevertheless, other more resistant transformations as, for instance, z scores, might be considered.

Each $\mathbf{X}_t^{(D, \tau)}$ vector is associated with a weight β_t that measures the largest difference between its elements:

$$\beta_t = \max\{x_i - x_j\}, \quad (5)$$

where $x_i, x_j \in \mathbf{X}_t^{(D, \tau)}$.

In our proposal, the weights assigned to each edge depict the amplitude difference observed in the transition. So we have that:

$$w_{\tilde{\pi}_t^D, \tilde{\pi}_j^D} = \sum_{i: \{\mathbf{X}_t^{(D, \tau)} \mapsto \tilde{\pi}_t^D\}} \sum_{j: \{\mathbf{X}_t^{(D, \tau)} \mapsto \tilde{\pi}_j^D\}} |\beta_i - \beta_j|. \quad (6)$$

Thus, the probability distribution taken from the weighted amplitude transition graph is given as follows:

$$\begin{cases} \lambda_{\tilde{\pi}_t^D, \tilde{\pi}_j^D} = 1, & \text{if } (\tilde{\pi}_t^D, \tilde{\pi}_j^D) \in E, \\ \lambda_{\tilde{\pi}_t^D, \tilde{\pi}_j^D} = 0, & \text{otherwise.} \end{cases} \quad (7)$$

$$p(\tilde{\pi}_t^D, \tilde{\pi}_j^D) = \frac{\lambda_{\tilde{\pi}_t^D, \tilde{\pi}_j^D} \cdot w_{\tilde{\pi}_t^D, \tilde{\pi}_j^D}}{\sum_{\tilde{\pi}_a^D, \tilde{\pi}_b^D} \lambda_{\tilde{\pi}_a^D, \tilde{\pi}_b^D} w_{\tilde{\pi}_a^D, \tilde{\pi}_b^D}}. \quad (8)$$

Note that the conditions $p(\tilde{\pi}_t^D, \tilde{\pi}_j^D) \geq 0$ and $\sum_{\tilde{\pi}_t^D, \tilde{\pi}_j^D} p(\tilde{\pi}_t^D, \tilde{\pi}_j^D) = 1$ are satisfied.

Thus, series with uniform amplitudes have edges with probability of occurrence well distributed along the graph, while those with large peaks have edges with probability of occurrence much higher than the others.

E. Information-Theoretic Descriptors

How discriminating features we choose the application of two descriptors of Information Theory: shannon entropy and statistical complexity. This consists of the last step of the algorithm, the calculate the $H \times C$ point.

Entropy measures the disorder or unpredictability of a system characterized by a probability measure \mathbb{P} .

Let $\mathbb{P} = \{p(\tilde{\pi}_1^D, \tilde{\pi}_1^D), p(\tilde{\pi}_1^D, \tilde{\pi}_2^D), \dots, p(\tilde{\pi}_{D!}^D, \tilde{\pi}_{D!}^D)\} = \{p_1, \dots, p_{D!2}\}$ be the probability distribution taken from the time series weighted amplitude transition graph \mathbb{X} . The normalized Shannon entropy is given by:

$$H(\mathbb{P}) = -\frac{1}{2 \log D!} \sum_{\ell=1}^{D!2} p_\ell \log p_\ell. \quad (9)$$

The ability of the entropy to capture system properties is limited, so it is necessary to use it in conjunction with other descriptors to perform a more complete analysis. Other interesting measures are distances between the \mathbb{P} probability function and a probability measure that describes a non-informative process, typically the uniform distribution.

The Jensen-Shannon distance to the uniform distribution $\mathbb{U} = (\frac{1}{D!2}, \dots, \frac{1}{D!2})$ is a measure of how similar the underlying dynamics are to a process without information; it is calculated as:

$$Q'(\mathbb{P}, \mathbb{U}) = \sum_{\ell=1}^{D!2} \left(p_\ell \log \frac{p_\ell}{u_\ell} + u_\ell \log \frac{u_\ell}{p_\ell} \right). \quad (10)$$

This quantity is also called “disequilibrium.” The normalized disequilibrium is $Q = Q' / \max\{Q'\}$.

Conversely to entropy, statistical complexity seeks to find interaction and dependence structures among the elements of a given series, being an extremely important factor in the study of dynamic systems.

The Statistical Complexity is then defined as [22]:

$$C(\mathbb{P}, \mathbb{U}) = H(\mathbb{P})Q(\mathbb{P}, \mathbb{U}). \quad (11)$$

In our analysis, each time series can then be described by a point $(H(\mathbb{P}), C(\mathbb{P}, \mathbb{U}))$. The set of all pairs $(H(\mathbb{P}), C(\mathbb{P}, \mathbb{U}))$ for any time series described by patterns of length D lies in a compact subset of \mathbb{R}^2 : the Entropy-Complexity plane.

Through such a tool it is possible to discover the nature of the series, determining if it corresponds to a chaotic (or other deterministic dynamics) or stochastic sequences.

III. EXPERIMENTAL RESULTS AND ANALYSIS

In this section, we describe the dataset, the classification process and the results of the experiments. To assess the performance of the developed technique, we first analyze the impact of its parameters and then compare its results generated in the classification with other methods.

A. Image Dataset

The proposed method was evaluated based on the HHHH backscatter magnitudes of three different quad-polarimetric L-band SAR images from the NASA Jet Propulsion Laboratory's (JPL's) uninhabited aerial vehicle synthetic aperture radar (UAVSAR):

- Sierra del Lacandon National Park, forest region in Guatemala (acquired on April 10, 2015)¹;
- Cape Canaveral Ocean Regions (acquired on September 22, 2016);
- Urban area of the city of Munich, Germany (acquired on June 5, 2015)².

A total of 160 uniform samples with size 128×128 were manually extracted from the images to compose the dataset used in the experiments, is organized as follows: 40 samples from Guatemalan forest regions; 80 samples from the oceanic regions of Cape Canaveral, where they were divided into two types that have distinct contrast information; and 40 samples of urban regions of the city of Munich. Fig. 4 a) shows examples of each of them.

Since the symbolization process is invariant to monotonous transformations and resistant to contamination effects, contrast changes are not capable of causing changes in the final results obtained by the descriptors. Thus, the different types of oceanic regions considered in this work were studied as a single more general class.

In classification, to avoid overlap between training and validation samples, the data were divided into classes (regions of analysis) based on percentiles and random sampling occurs in each subgroup, preserving the general class distribution of the data. Using this dataset, we have trained a K-nearest

neighbor classifier algorithm with 85% of all images and used tenfold cross-validation. The remaining 15% of the images (that were never exposed to the learning algorithm) are used for testing the predictions.

B. Analysis of ordinal patterns methods

Fig. 4 b) shows examples of the ocean, forest and urban samples as sequences values, after the linearization process. Data resulting from remote sensing have a peculiar feature that justifies the application in this article: The variation in the magnitude of the targets' backscatter and, consequently, in the intensity of the image pixels, depends on the intrinsic properties of the regions under analysis. Thus, urban targets are those that usually give the highest peaks, followed by forests, and finally, water bodies.

By adding information related to amplitude, the proposed method is able to increase, compared to traditional methods, the granularity of information captured by ordinal patterns. In Fig. 4 d), we can see the evolution of the descriptive power of these techniques.

As the first method in the literature for ordinal pattern analysis, the distribution of Bandt-Pompe calculated from the histogram of pattern frequencies manages to capture little information about the spatial structure of the textures, obtaining the worst result among the analyzed symbolization techniques. When considering the dynamics of alternating between consecutive patterns in a sequence, the transition graphs provide more information about the reference target and, consequently, this method is able to differentiate most of these dynamics, but there are challenging situations without a clear separation between them, causing misclassifications.

On the other hand, as discussed in the section II-D, the weighted graph provides greater weight for transitions between ordinal patterns that have a wide range of amplitude. While in the traditional graph, the weight of the edges was obtained only by the frequency of the transitions, in the proposed method the symbols that appear with the same frequency gain different importance. In this way, we were able to obtain, for this experiment, a perfect characterization and, consequently, the high descriptive power of the regions. In addition, some edges may disappear if the variation in amplitude between ordinal patterns is zero.

Among the classes of patches analyzed, the one that had the greatest impact with the redistribution of weights in the graph were urban regions. As can be seen in Fig. 4 b) a patch from the Munich region when linearized gives rise to a time series characterized by a low amplitude variation and the presence of peaks. In the example analyzed in Fig. 4 c) we can see that the addition of the amplitude information changed the distribution of weights in the graph increasing the weight of some edges, as occurred in $v_{\pi_{123}}^3, v_{\pi_{123}}^3$) and causing the disappearance of others, as was the case with $(v_{\pi_{312}}^3, v_{\pi_{231}}^3) \rightarrow (v_{\pi_{213}}^3, v_{\pi_{132}}^3)$.

With the reallocation of weights caused by the proposed weighting technique, we can highlight the impact on the probability distribution in the two extreme cases observed:

- If the time series presents a low amplitude variation and intensity peaks between its elements, the transitions

¹https://uavsar.jpl.nasa.gov/cgi-bin/product.pl?jobName=Lacand_30202_15043_006_150410_L090_CX_01#dados

²https://uavsar.jpl.nasa.gov/cgi-bin/product.pl?jobName=munich_19417_15088_002_150605_L090_CX_01#data

of ordinal patterns that represent the latter have greater weights. Therefore, this contributes so that the probability distribution becomes less uniform among the symbols, since it will be more concentrated in these respective edges. This behavior of the graph will also cause a drop in the entropy value, when compared to the traditional method.

- In time series that show a uniform amplitude variation, we managed to generate graphs with weights well distributed between their edges, giving rise to a more random probability distribution, thus obtaining a greater entropy value.

C. Experiments on sliding window selection

In this section, we analyze the parameters of the proposed method and its impact on the performance of the recognition of regions in textures, since inadequate values can hide important characteristics of the phenomenon under analysis [23]. The two parameters of the transition graph modeling are: the dimension D , and the delay τ . In the experiments below, we present the results in the classification using different values of these parameters.

The performance of the classification method based on ordinal patterns is sensitive to the parameters of the sliding window used. In techniques based in Bandt-Pompe symbolization, as the size of the delay decreases, more ordinal patterns are produced. Therefore, we acquire a greater granularity of information about the dynamics of the system and, consequently, we capture more spatial dependencies between the elements.

To choose the most appropriate configuration of the sliding window parameters, we use the ROC curve shown in Fig. 5 for different values of $D \in \{3, 4, 5, 6\}$ and $\tau \in \{1, 2, 3, 4, 5\}$. As we can see in the plot above, the model that presented the best results in the experiments and consequently managed to extract more information from the time series was formed with the smallest parameter settings (that is, $D = 3$ and $\tau = 1$). Such an analysis also informs us that the best performance is acquired in the choice of parameters with the lowest computational cost.

We can see in Fig. 6 that the spatial distribution of the points changes in relation to the parameters, allowing different types of regions to become differentiable in determined configurations. When we apply small values of delay and dimension in WATG to data from the urban region (for example, as with $D = 3$ and $\tau = 1$), we obtain the lowest entropy values and the highest statistical complexities values of the dataset, which is justified by the peak values present in their sequences, as seen in Fig 4 b). On the other hand, oceanic and forest regions have as their main discriminating descriptor the statistical complexity that portrays the degree of temporal dependence structure between the symbols and consequently between the pixel intensity values.

Fig. 6 shows the characterizations for several dimension values D and delays τ . Since such values inform us of intrinsic characteristics of the dynamics of the series in their specific domains, inadequate values may hide this kind of knowledge about the data, and this analysis step is crucial.

As shown in Fig. 6, class discrimination decreases with increasing τ because the special dependency structure of patches

is lost, as neighboring points in the sample tend to be more distant in the image, thus making a better distinction between classes when we have $\tau = 1$. As WATG captures amplitude differences between different time series, when the values of the τ scale increase, well-distributed weight plots are formed, thus obtaining increasing entropy values. On the other hand, as we increase D , the granularity of the information increases, capturing more spatial dependence structures in the data and, consequently, acquiring greater statistical complexity. There is a relationship between the dimension variable of ordinal patterns and the discrimination between the analyzed regions that presents its best result for $D = 3$. On the other hand, when we have $D = 6$, textures acquire a lower entropy value and become harder to distinguish.

D. Quantitative Evaluation

Several experiments were carried out to validate the features extracted from the information theory descriptors in the characterization and classification of regions. In this subsection, we present a comparison between the proposed method and other methods present in the literature for characterization with ordinal patterns and texture classification. In the comparisons, we use the following four methods: gray level co-occurrence matrices [24], Gabor filters [25], Bandt-Pompe probability distribution [15], and ordinal patterns transition graph [26]. As applied in [27], for each co-occurrence matrix, four statistics are selected: contrast, correlation, energy, and homogeneity. Likewise, the Gabor filters are implemented in five scales and eight orientations. The energy was used and an 80-dimensional feature vector is obtained for each patch.

To evidence the importance of features in the classification process, we chose the algorithm of the k-nearest neighbors, due to its simplicity. In all experiments, we used Euclidean distance and 10 resampling interactions and a 10-fold cross-validation method to evaluate our proposal. More details about the classifier and the sampling scheme can be seen in [28].

In addition, the automatic grid search method of the Caret R package is applied to estimate the k parameter of the k-nearest neighbors algorithm [29]. This can be done by configuring the tuneLength parameter of the train function to sample a certain number of candidates from a hyper-parameter. The following results demonstrate the automatic grid search of the KNN attribute k with 20 (tuneLength = 20) attempts of values (20 total models).

The experimental results of the 160 samples of the dataset used are presented in the Table I. We assess the effectiveness of each approach using the following metrics: recall or true positive rate (TPR), precision or positive predictive value (PPV), overall accuracy (OA), and F1-score.

As expected, we can see that the result obtained by the Bandt-Pompe distribution reached the lowest results with OA = 70.8% and F1-score = 22.2%. Then, we followed the improvement in the descriptive power of ordinal patterns with the transition graph that obtained OA = 83.3% and F1-score = 60.0%. We can also observe that GLCM is not able to have high descriptive power in the proposed dataset, obtaining OA = 66.6% and F1-score = 80.0%. In addition, it is observed

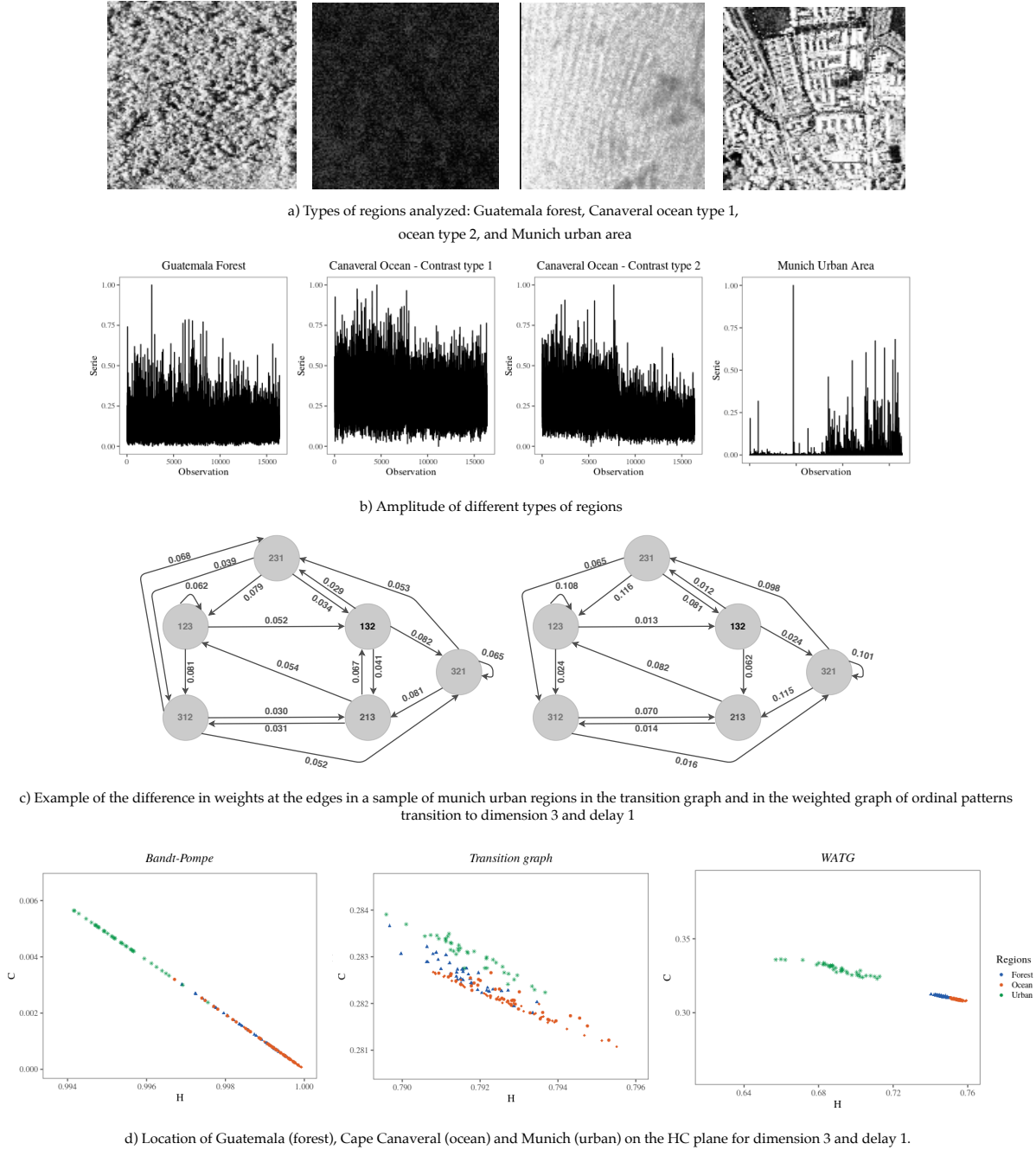


Figure 4. Main steps of the proposed method: (1) Get samples of SAR texture images from different regions, (2) transform 2D image into a time series by linearization, (3) build the ordinal pattern transition graph to extract the distribution and (4) computing entropy and statistical complexity.

that the highest success rate was obtained by the proposed method, which provided results comparable to the Gabor filters that acquired $OA = 100\%$ and $F1\text{-score} = 100\%$. Thus, when applying WATG we managed to maintain the success rate using fewer features and, consequently, less computational power since only two descriptors were used in the characterization.

IV. CONCLUSION

In the study presented, a new method of analysis and classification of SAR images was presented. This method consists

of three steps, the linearization of the SAR image texture, the weighted ordinal pattern transition graph technique, based on the Bandt-Pompe symbolization method, and the information theory descriptors.

The main objective of the proposed method is to find a probability distribution of ordinal patterns sensitive to amplitude information and that, due to the backscattering properties of the SAR image sensors, classifies different regions of analysis. Detection and classification were performed using the k-nearest neighbors algorithm of supervised learning. Experi-

Table I. Experimental results using KNN

Method	N. of features	TPR			PPV			OA	F1-Score
		Urban	Forest	Ocean	Urban	Forest	Ocean		
Bandt-Pompe HC	2	0.833	0.666	0.833	1.000	0.571	0.833	0.792	0.615
Transition Graph HC	2	1.000	0.666	0.916	0.857	1.000	0.846	0.875	0.800
WATG HC	2	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Gabor	80	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
GLCM	4	1.000	0.833	1.000	1.000	1.000	0.923	0.666	0.800

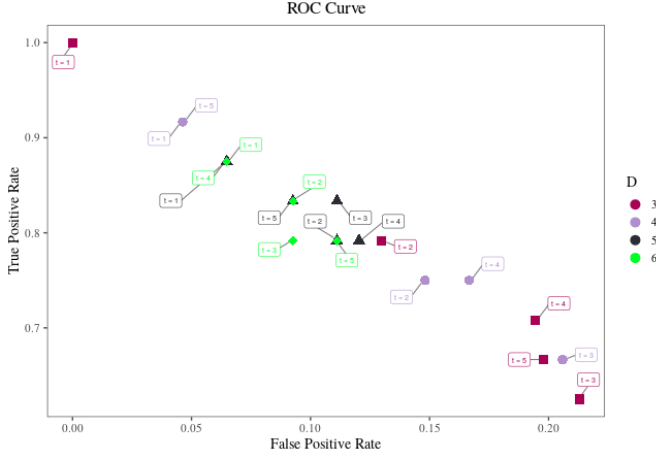


Figure 5. Evaluation of the sliding window parameters

ments with UAVSAR images demonstrated that the proposal meets a performance superior to that of competing methods and similar to the Gabor filter. However, when applied, it overcomes some disadvantages of the Gabor filter, managing to maintain its effectiveness in classifying different regions in SAR image textures. For example, it does not need a large number of features and therefore a high computational power.

As a result, in addition to perfectly separating urban areas from the others analyzed by entropy values, we are still able to differentiate oceanic and forest areas through their different values of statistical complexity, which informs us of the degree of spatial dependence between their elements. The proposed method is also invariant to monotonous transformations and resistant to the effects of contamination, even changes, in contrast, do not cause changes in the descriptors of the images. In the future, we hope to continue to refine the extraction of texture features, proposing an extension of the algorithm for the segmentation of regions and investigate the effects of their use in other applications e.g., erosion monitoring and urban activities.

V. SOURCE CODE AVAILABILITY

The source code generated during the current study are available in the SAR-WATG repository, <https://github.com/EduardaChagas/SAR-WATG>.

REFERENCES

- [1] D.-X. Yue, F. Xu, A. C. Frery, and Y.-Q. Jin, "A generalized Gaussian coherent scatterer model for correlated SAR texture," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 58, no. 4, pp. 2947–2964, Apr. 2020.
- [2] F. N. Numbisi, F. Van Coillie, and R. De Wulf, "Multi-date Sentinel SAR image textures discriminate perennial agroforests in a tropical forest-savannah transition landscape," *International Archives of the Photogrammetry, Remote Sensing & Spatial Information Sciences*, vol. 42, no. 1, 2018.
- [3] Q. Yu, M. Xing, X. Liu, L. Wang, K. Luo, and X. Quan, "Detection of land use type using multitemporal SAR images," in *IGARSS 2019 – IEEE International Geoscience and Remote Sensing Symposium*. IEEE, 2019, pp. 1534–1537.
- [4] D. D. Radford, M. J. Cracknell, M. J. Roach, and G. V. Cumming, "Geological mapping in western tasmania using radar and random forests," *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, vol. 11, no. 9, pp. 3075–3087, 2018.
- [5] R. Hagenseiker and B. Waske, "Evaluation of multi-frequency SAR images for tropical land cover mapping," *Remote Sensing*, vol. 10, no. 2, p. 257, 2018.
- [6] Y. Kankaku, S. Suzuki, and Y. Osawa, "Alos-2 mission and development status," in *2013 IEEE International Geoscience and Remote Sensing Symposium-IGARSS*. IEEE, 2013, pp. 2396–2399.
- [7] L. Morena, K. James, and J. Beck, "An introduction to the radarsat-2 mission," *Canadian Journal of Remote Sensing*, vol. 30, no. 3, pp. 221–234, 2004.
- [8] H. Breit, T. Fritz, U. Balss, M. Lachaise, A. Niedermeier, and M. Vonnava, "TerraSAR-X SAR processing and products," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 48, no. 2, pp. 727–740, 2009.
- [9] C. D. Storie, "Urban boundary mapping using Sentinel-1A SAR data," in *IGARSS 2018-2018 IEEE International Geoscience and Remote Sensing Symposium*. IEEE, 2018, pp. 2960–2963.
- [10] J. B. Florindo and O. M. Bruno, "Fractal descriptors based on Fourier spectrum applied to texture analysis," *Physica A: Statistical Mechanics and its Applications*, vol. 391, no. 20, pp. 4909–4922, 2012.
- [11] T. Zhu, F. Li, G. Heygster, and S. Zhang, "Antarctic sea-ice classification based on conditional random fields from radarsat-2 dual-polarization satellite images," *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, vol. 9, no. 6, pp. 2451–2467, 2016.
- [12] J.-H. Lee and Y.-C. Hsueh, "Texture classification method using multiple space filling curves," *Pattern Recognition Letters*, vol. 15, no. 12, pp. 1241–1244, 1994.
- [13] P. Nguyen and J. Quinqueton, "Space filling curves and texture analysis," in *IEEE Intl. Conf. Pattern Recognition*, 1982, pp. 282–285.
- [14] C. Carincotte, S. Derrode, and S. Bourennane, "Unsupervised change detection on SAR images using fuzzy hidden Markov chains," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 44, no. 2, pp. 432–441, Feb 2006.
- [15] C. Bandt and B. Pompe, "Permutation entropy: A natural complexity measure for time series," *Physical review letters*, vol. 88, p. 174102, 2002.
- [16] B. H. Fadlallah, B. Chen, A. Keil, and J. C. Principe, "Weighted-permutation entropy: a complexity measure for time series incorporating amplitude information," *Physical review. E, Statistical, nonlinear, and soft matter physics*, vol. 87 2, p. 022911, 2013.
- [17] J. Borges, H. Ramos, R. Mini, O. A. Rosso, A. C. Frery, and A. A. F. Loureiro, "Learning and distinguishing time series dynamics via ordinal patterns transition graphs," *Applied Mathematics and Computation*, vol. 362, p. UNSP 124554, 2019.
- [18] M. McCullough, M. Small, T. Stemler, and H. H.-C. Iu, "Time lagged ordinal partition networks for capturing dynamics of continuous dynamical systems," *Chaos: An Interdisciplinary Journal of Nonlinear Science*, vol. 25, no. 5, p. 053101, 2015.
- [19] C. W. Kulp, J. M. Chobot, H. R. Freitas, and G. D. Sprechini, "Using ordinal partition transition networks to analyze ecg data," *Chaos: An Interdisciplinary Journal of Nonlinear Science*, vol. 26, no. 7, p. 073114, 2016.

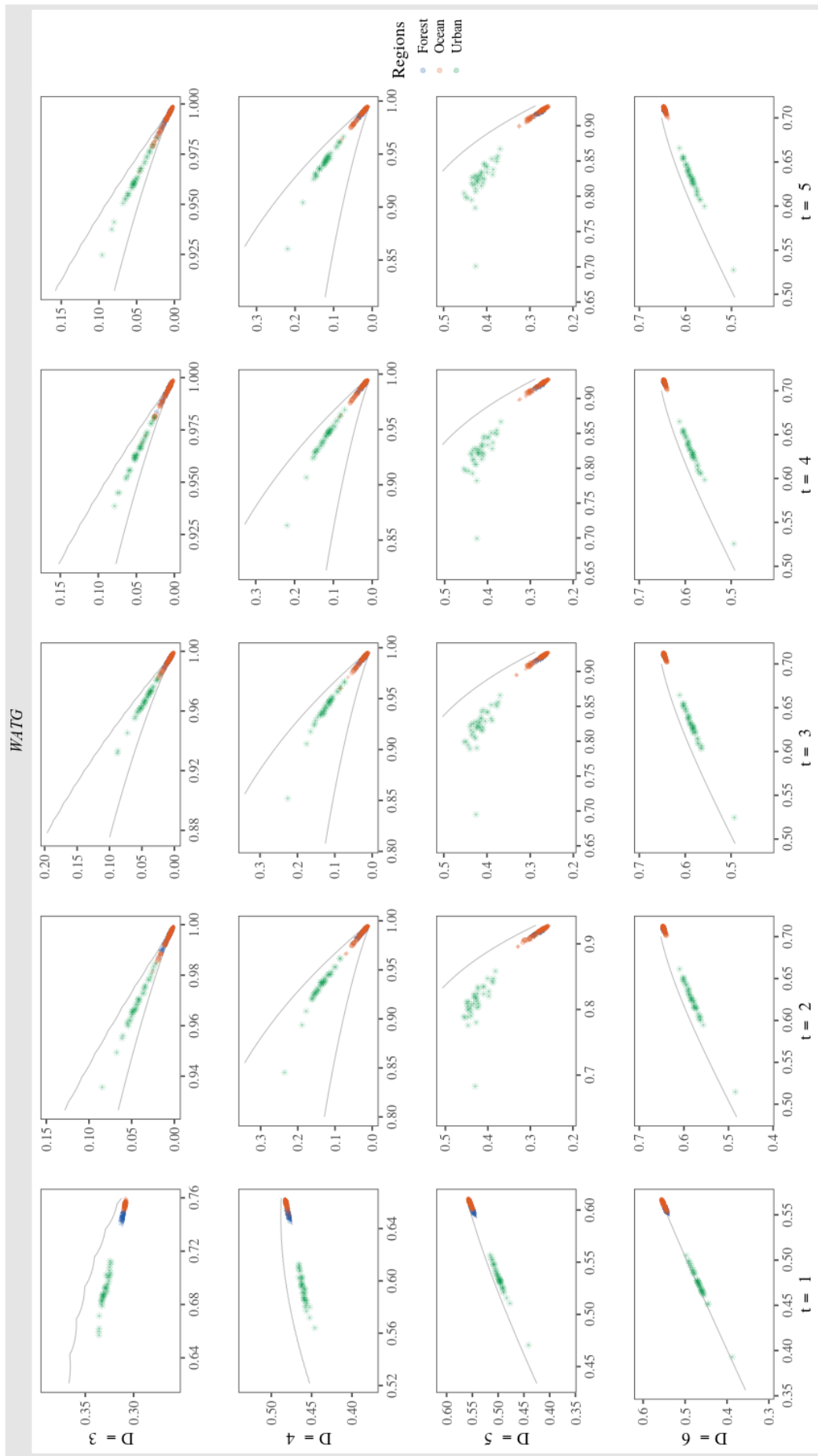


Figure 6. Characterization resulting in HC Plane from the application of the Hilbert-Peano curve in WATG on textures of different regions: Guatemala (forest), Cape Canaveral (ocean) and Munich (urban).

- [20] T. Sorrentino, C. Quintero-Quiroz, A. Aragonese, M. Torrent, and C. Masoller, "Effects of periodic forcing on the temporally correlated spikes of a semiconductor laser with feedback," *Optics Express*, vol. 23, 2015.
- [21] J. Zhang, J. Zhou, M. Tang, H. Guo, M. Small, and Y. Zou, "Constructing ordinal partition transition networks from multivariate time series," in *Scientific Reports*, 2017.
- [22] P. W. Lamberti, M. T. Martín, A. Plastino, and O. A. Rosso, "Intensive entropic non-triviality measure," *Physica A: Statistical Mechanics and its Applications*, vol. 334, no. 1–2, pp. 119–131, 2004. [Online]. Available: <http://www.sciencedirect.com/science/article/pii/S0378437103010963>
- [23] M. McCullough, M. Small, T. Stemler, and H. H.-C. Iu, "Time lagged ordinal partition networks for capturing dynamics of continuous dynamical systems," *Chaos: An Interdisciplinary Journal of Nonlinear Science*, vol. 25, no. 5, p. 053101, 2015.
- [24] A. Kourgli, M. Ouarzeddine, Y. Oukil, and A. Belhadj-Aissa, "Texture modelling for land cover classification of fully polarimetric SAR images," *International Journal of Image and Data Fusion*, vol. 3, no. 2, pp. 129–148, 2012.
- [25] T. P. Weldon, W. E. Higgins, and D. F. Dunn, "Efficient gabor filter design for texture segmentation," *Pattern recognition*, vol. 29, no. 12, pp. 2005–2015, 1996.
- [26] J. B. Borges, H. S. Ramos, R. A. Mini, O. A. Rosso, A. C. Frery, and A. A. Loureiro, "Learning and distinguishing time series dynamics via ordinal patterns transition graphs," *Applied Mathematics and Computation*, vol. 362, p. 124554, 2019.
- [27] D. Guan, D. Xiang, X. Tang, L. Wang, and G. Kuang, "Covariance of textural features: A new feature descriptor for SAR image classification," *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, vol. 12, no. 10, pp. 3932–3942, 2019.
- [28] T. M. Mitchell *et al.*, "Machine learning," 1997.
- [29] M. Kuhn *et al.*, "Building predictive models in r using the caret package," *Journal of statistical software*, vol. 28, no. 5, pp. 1–26, 2008.

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