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Review

Classification of radar echoes using fractal geometry

Nafissa Azzaz*, Boualem Haddad

University of Science and Technology Houari Boumediene, Faculty of Electronic and Computer Science, Department of Telecommunication, BP N 32 El Alia, Bab Ezzouar, Algiers, Algeria

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ABSTRACT

This paper deals with the discrimination between the precipitation echoes and the ground echoes in meteorological radar images using fractal geometry. This study aims to improve the measurement of precipitations by weather radars. For this, we considered three radar sites: Bordeaux (France), Dakar (Senegal) and Me lbourne (USA). We showed that the fractal dimension based on contourlet and the fractal lacunarity are pertinent to discriminate between ground and precipitation echoes. We also demonstrated that the ground echoes have a multifractal structure but the precipitations are more homogeneous than ground echoes whatever the prevailing climate. Thereby, we developed an automatic classification system of radar using a graphic interface. This interface, based on the fractal geometry makes possible the identification of radar echoes type in real time. This system can be inserted in weather radar for the improvement of precipitation estimations.

1. Introduction

Radar imaging is currently the most used technique for rainfall estimation by weather forecasters. However, by using electromagnetic waves, radars often receive echoes backscattered by the Earth's surface. These echoes called ground echoes or fixed echoes are a source of noise and they reduce consequently the radar ability to estimate efficiently the precipitations [1]. The other kind of undesirable echoes is due to abnormal meteorological conditions, caused by gradients of refraction indices less than $-157 \times 10^{-6}\,\text{km}^{-1}$. In this case, the electromagnetic waves coming from the radar are affected; as a result, they are propagated through atmospheric ducts and backscattered by the earth surface. These unwanted echoes are called Anomalous Propagations (APs) or anaprops. Also, the parameterization of precipitation fields in meteorological radars requires a prior knowledge of their structure and density at different scales [2,3].

Fractal geometry is of great interest for the analysis and processing of digital images for a very large number of applications. It is used in meteorology to study cells structure in radar and satellite images [4–6], in medicine [7–9], in geology [10], as well as in various other fields. Fractal geometry is used to describe self-similar sets called fractals and characterizes natural objects that cannot be described by classical geometry [11].

Fractals may be described by their dimension [12,13], and their lacunarity [7,14]. These two fractal properties are used to discriminate between different types of structures with a fractal appearance, and also for classification and segmentation, due to their scale invariance, their rotation and their translation [9,15,16].

The major problem of weather radar measurement is related to the clutter coming from the Earth's surface. These significantly reduce instrument performance by inducing significant errors in the estimation of precipitation, making the hydrological measurement very difficult [17,18].

The aim of this study is to identify the ground echoes in meteorological radar images. Several techniques are proposed in the literature for identifying and removing fixed echoes, for example Doppler filtering [19], or dual polarization filtering [20,21]. In order to eliminate clutters, the authors in [22] compare the statistical properties of the ground echoes to those of precipitation echoes, such as textural features clutter can also be removed by analyzing in real time the coefficient of the autocorrelation function of the radar signal [23]. Others applied the fuzzy logic technique, to classify the Doppler radar echoes types [24] or for identifying non-precipitating echoes in radar scans [25,26]. We can also undertake the classification of radar echoes with a textural–fuzzy approach for the removal of ground clutter [17], and the technique of neuro-fuzzy to eliminate noise in Doppler radar signals [27].

Our work will carry on the implementation of two concepts of fractal geometry to classify two types of echoes, and this by using the Box-counting method to calculate the fractal dimension [11], and the method of Allain and Cloitre to determine the fractal lacunarity [29].

* Corresponding author.
E-mail address: nafissa_an1@yahoo.fr (N. Azzaz).

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In the recent past, it has been shown that the fractal dimension in single scale can't be used as a discriminating parameter between precipitations and the fixed echoes [1,30]. The questions are: Does the fractal dimension provide a solution to discriminate between the two types of echoes? Can the lacunarity fractal be used as a parameter for identifying the ground echoes? To answer these questions, we propose a new approach, called a fractal dimension based on contourlets. This method consists in decomposing all images by the contourlets transform, to calculate the fractal dimension of the resultant contourlets coefficients through various scales and directions.

The Contourlet Transform is a thorough representation for 2-D and 3-D images. It is applied in various fields [31,32]. Using a rich set of images with oriented base at different directions and scales, the contourlets can actually capture the intrinsic contours in images and offer better anisotropy, multi-resolution, directivity and localization properties of the images than obtained with mono scales representation tools already existing [33]. The application of the fractal dimension on the resulting coefficients of the contourlets decomposition using the Box Counting method allows the extraction of the fractal characteristics with greater accuracy on different scales and orientations [33].

The purpose of our paper is to test that the fractal geometry can be successfully applied in discrimination between the fixed echoes and rain echoes. In addition, we propose an automatic system for real time identification of the two types of echoes. We considered in our analysis a database obtained from three radar sites with different climates and topographies, namely, Bordeaux (France), Dakar (Senegal) and Melbourne (United States).

The paper is structured as follows: after an introduction, we present a theoretical study on the fractal dimension and the fractal lacunarity. The database is presented in the third section. In section four, we present the results and interpretations, and finally we end with a conclusion.

2. Theoretical concept

In the real world, the Euclidean geometry does not characterize all forms of existing objects. Thus was born a new discipline called fractal geometry, which is actually complementary to the Euclidean geometry.

The word “fractal” is a term proposed by Mandelbrot in 1974 from the Latin root “fractus” which is synonymous of irregular and fragmented [11]. The fractal objects are the result of an iterative process that presents a character of self-similarity and can be defined recursively [11,34].

In the field of image analysis and processing, fractal study provides rich information in content and represents a necessary element for the knowledge of their structure [34]. In the literature, there are several concepts used to characterize fractals. We mention as an example, the concept of fractal dimension [11,28,35–37], and the technique of fractal lacunarity [28]. In our case, we applied the box-counting method for calculating the fractal dimension [38], and the approach of Allain and Cloitre to estimate lacunarity [29].

The Lacunarity and Fractal dimension are two physical quantities using fractal geometry, and they must be complementary [39,40]. Indeed, Przemyslaw Borys [39] has mentioned that the Lacunarity is a measure designated to accompany the fractal analysis in case where the images have similar fractal dimensions. Lacunarity corresponds to the measurement of the distribution of the holes, whereas the fractal dimension is a measure of the masses distribution. These two measures should be inversely proportional, i.e., when the one decreases, the other increases [40].

In the literature, some articles suggest an equation for the relationship between the fractal dimension and lacunarity [41]:

$$D_f = 2,47 - 1,4\Lambda \tag{1}$$

Where:

D_f: is the fractal dimension.
Λ: is the fractal lacunarity

In [42], they have also demonstrated that the lacunarity varies in the same sense with the fractal dimension, but they said that the first relation is the most used in the literature.

2.1. Fractal dimension

The Box Counting method is based on the recovery of all analyzed image space, by a grid of squares (or "boxes") of side ε. The number $N(\varepsilon)$ is the number of boxes that are used to pave the cells presented in the analyzed image. The fractal dimension D_f is then defined by [38]:

$$D_f = \lim_{\varepsilon \to 0} \frac{\ln[N(\varepsilon)]}{\ln(1/\varepsilon)} \tag{2}$$

The number of boxes $N(\varepsilon)$ containing the pixels of rainfall support are counted. This operation is repeated for different values of ε ($\varepsilon = 2, 4, 8, \ldots, 2^P$). The ($2^P$) value represents the maximum size of our images. By tracing for different values of ε, $ln(N(\varepsilon))$ versus $ln(1/\varepsilon)$, we get a points cloud $\{\ln(N(\varepsilon)), \ln(1/\varepsilon)\}$. The slope of the line that fits the points cloud gives us an estimation of the fractal dimension D_f.

2.2. Fractal dimension based on contourlets

2.2.1. Contourlets transform

In the literature, it is stated that the conventional multi-resolution decompositions make a restricted and limited category of possibilities for multiscale image representations [43]. Recently, studies have shown that is possible to define new theoretical methods more appropriate for multi-scale representations, creating a new transform more suited to the extraction of cells geometric structures present in the images such as the objects contours [43,44]. We mention the new family of wavelet derivatives, namely: the Ridgelet transform, the Wedgelet transform, the Curvelet transform and the Contourlet transform [45,46]. The Contourlet transform which will be applied in our case, is a discrete version adapted to the digital images, and based on the use of directional pyramidal filters banks. It is a multi-scale decomposition, which operate in a multitude of directions and frequencies that offer a good compromise between the representation of the decomposed image characteristics and the perceptual quality of this latter reconstructed [43].

Contourlet transform was introduced by Minh Do and Martin Vetterli [45,47]. This is an image decomposition method, designed directly into the discrete domain, which provides a sparse representation of the data contained in the image, both in spatial and frequency resolutions.

Contourlet transform is constructed by combining two distinct successive decomposition steps: a multi-scale decomposition followed by an oriented directional decomposition [43].

The first step uses a Laplacian pyramid (LP) [48] to transform the image into a series of bandpass LP levels and a single lowpass level (low frequency approximation of the image) [49]. The second step applies appropriate bidimensional filters and a sampling, in order to decompose each bandpass LP level into a number of directional strips, thus capturing the frequency information of the image [49,50]. The filters used in our contourlets decomposition are the 9/7 filters and the *PKVA* filters [51].

Finally, the image is represented by a set of multi-scales and oriented sub-bands [52]. These sets present the multi-scale and time-frequency characteristics of a decomposed image. Each scale can be divided into an arbitrary number of directions that is a power of 2 [52].