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Fractal Filtering Applied to SAR Images of Urban Areas

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Abstract—**In this paper a fractal filtering technique is described and applied to Synthetic Aperture Radar (SAR) images of urban areas. The considered technique has been originally developed for application to SAR amplitude images relevant to natural areas. In the present paper its behavior in presence of man-made objects and buildings is tested, both on simulated and actual SAR data.**

I. INTRODUCTION

New generation high resolution sensors (e.g., TerraSAR-X, COSMO-SkyMed) significantly changed the level of detail which can be appreciated in SAR images, in particular with reference to urban areas. A new set of previously masked features has emerged on these images: in fact, due to the metric resolution, many objects characterizing typical urban scenes present a strong radar return and appear on the images as strong intensity contributions. Hence, in order to retrieve value-added information from these data, it is very important to extract and analyze these contributions, using, if possible, automatic unsupervised techniques. In this context, the filtering of urban SAR data has a key role.

Natural surfaces can be effectively described using fractal models, which take into account in a simple way the irregularity and auto-affinity of this kind of surfaces [1], [2]. Conversely, man-made objects does not show a fractal behavior, at least at scales ranging from the sensor resolution one and that of the microwave electromagnetic field wavelenght. Thus, a geometric description in the context of Euclidean geometry is in order [3]. From a fractal point of view this means that they show a non-fractional dimension and, hence, at least in principle, they should be clearly separable from fractal objects in SAR images.

In this paper the behavior of urban elements in fractal filtered SAR images is investigated. The filter of interest has been introduced by the authors for the estimation of the fractal dimension of natural surfaces from their amplitude SAR image [4]. The fractal dimension D is a physical parameter of the observed surface and brings key information about its composition and morphology, being a good candidate for image segmentation and classification purposes. The filter is based on a complete analytical model of the SAR imaging process and has been positively tested on simulated data relevant to canonical fractal surfaces [3]. The rationale of the model and the implementation of the filter is summarized in Section II. Significant applications on canonical fractal cases are also shown.

In this paper the fractal filter is tested on simulated and actual SAR images relevant to urban areas, in order to assess its behavior in presence of man-made objects on the observed scene. This kind of structures determine the appearance on the image of very bright features, determining strong discontinuities in the radar signal. In fact, this is due to the presence of multiple scattering contributions, mainly generated by the dihedral configuration of soil and building walls [3]. The presence of discontinuities affects strongly the behavior of the fractal filter, whose rationale is based on the evaluation of the image spectrum. To analyze the behavior of the filter in this context, we apply it on simulated and actual SAR images .

The simulated images are obtained by means of the SAR raw signal simulator SARAS [5], [3]. In the simulated scenario the presence of buildings is accounted for by means of bright points and lines playing the role of the multiple scattering contributions, which are typical signatures of the buildings on SAR images [3]. Thus, the analysis of the simulated case is the base for the interpretation of the behavior of the filter on a COSMO-SkyMed SAR image relevant to L'Aquila, Italy. The description of the simulation setup, along with significant obtained results, is presented in Section III.

Finally, in Section IV some concluding remarks are drawn and possible applications of the proposed filter in the context of classification of urban areas are outlined.

II. FILTERING RATIONALE

A. Theoretical Framework

It is widely recognized that fractal models represent the best way to describe the irregularity of natural scenes [1], [2]. Among this kind of models, the regular stochastic fBm (fractional Brownian motion) process completely describes natural surfaces by means of two independent parameters: the Hurst coefficient, H (which is linked to the fractal dimension by the simple relation D=3-H) and the standard deviation of surface increments at unitary distance, s [m^{1-H}]. The power density spectrum of the isotropic two dimensional fBm process exhibits a power-law behavior:

$$S(k) = S_0 k^{-\alpha} \tag{1}$$

wherein S_0 and α are functions of the fractal parameters [1].

Besides the surface model, in order to retrieve the fractal dimension of a natural scene starting from its SAR image we need a direct model relating the surface to its amplitude image.

In [4] the authors presented a complete imaging model based on the assumption of a small slope regime for the observed surface: if this is the case, the image intensity comes out to be a linear function of the partial derivative of the surface evaluated along the range direction.

The expressions of the autocorrelation functions of the SAR image and of the Power Spectral Densities (PSDs) of two cuts of the image in the range and azimuth directions respectively, have been evaluated by the authors in [4]. The PSDs of the azimuth and of the range cut of the SAR image show very different behaviors, thus highlighting an intrinsic asymmetry in the structure of SAR data, that is also intuitively referable to the particular acquisition geometry of a side looking mono-static radar. In particular, the spectrum of the image range cut, in an appropriate range of sufficiently low spatial frequencies, presents a power law behavior - thus showing on a log - log plane a linear behavior with a slope related to the Hurst coefficient H of the observed surface. In fact, the expression of the PSD of the range cut of a SAR image, for adequately low wavenumbers, turns out to be [4]:

$$S_p(k_y) = s^2\Gamma(1+2H)\sin(\pi H)\frac{1}{\left|k_y\right|^{2H-1}}, \qquad (2)$$

where k_y is the wavenumber of the range cut of the image and Γ is the Euler Gamma function.

Comparing (2) with the expression of the PSD of the surface in (1), it can be inferred that the slope of the spectrum relevant to a range cut of a SAR image is equal to that of the imaged surface, assuming that the Hurst coefficient is decreased by one.

B. Filter Description

In order to retrieve the fractal parameters starting from a SAR image, we can perform the analytical inversion of the presented theoretical model.

In particular, starting from (2), it is possible to implement linear regression algorithms on the spectrum of range cuts of the image in a log - log plane, thus retrieving the fractal dimension. Hence, a software was developed that, by means of a sliding window spanning the entire image, provides the corresponding fractal map, i.e. a matrix of the point by point fractal dimension relevant to the observed surface.

The implemented filter extracts the local fractal dimension of the imaged surface working on patches of the SAR image and iterating the procedure on the whole image, through a moving window, whose dimension can be set by the user according to its specific needs, resulting from a trade-off between accuracy and resolution of the output fractal dimension map. In particular, the algorithm performs this estimation selecting in each window range cuts that are sufficiently spaced from each other to be considered uncorrelated. Then the spectra of these cuts (whose number can be again chosen by the user, as a trade-off between accuracy, resolution and computation time) are evaluated using a Capon estimator [4]. Finally, these spectra are averaged and a linear regression is performed on this mean PSD.

As an example of the application of the filter on images relevant to canonical natural scenes, the algorithm is applied to simulated SAR data obtained by means of the SARAS simulator [5]: the input of the simulator is a Digital Elevation Model (DEM) of a fractal surface realized implementing a Weierstrass-Mandelbrot function [1]. The selected sensor is an ENVISAT sensor providing a SAR image - in presence of speckle - with an azimuth resolution Δx=3.986 m and a ground range resolution Δy=19.928 m. The algorithm, implemented with a sliding windows, whose size is set to 71x71 pixels, provides a fractal map of the imaged surface giving the point by point fractal dimension D.

In Fig. 1 and 2 we show the simulated SAR image and its fractal map, respectively. The surface fractal parameters are set to D=2.2, s=0.1 m$^{0.2}$ and the fractal map presents the following global statistics:

- mean: 2.26
- standard deviation: 0.05

Hence, the accuracy of the retrieved fractal dimension can be considered satisfactory.

Figure 1. Simulated SAR image

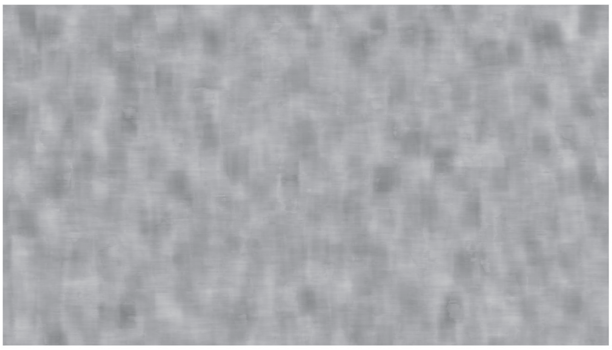

Figure 2. Fractal map relevant to the image in Fig. 1

III. RESULTS

A. Simulation Analysis

Let x and r be the independent space variables, standing respectively for azimuth and range. By using primed coordinates for the independent variables of the SAR raw signal, $s(x',r')$, this can be expressed as:

$$s(x',r') = \iint dxdr\gamma\left(x,r\right)g\left(x'-x,r'-r;r\right), \qquad (1)$$

where $\gamma(x,r)$ is the reflectivity pattern of the scene and $g(x'-x,r'-r;r)$ the unit impulse response of the SAR system [5]. The evaluation of the reflectivity function requires a description of the observed surface in terms of the topography, as well as a model for the interaction with the electromagnetic fields radiated by the SAR antenna [5]. Hence, the considered simulator requires as input a DEM relative to the scene of interest, sampled with a resolution coherent with the considered sensor parameters. When an electromagnetic field impinges on a scenario formed by a building on a rough ground, the electromagnetic return is formed by single, double and triple reflection mechanisms [3].

In the following we present a canonical study which takes into account most of the physical phenomena occurring in the formation of the SAR signal. The SAR images are obtained simulating an Envisat sensor. To investigate the behavior of the fractal filter in presence of multiple reflection contributions, we superimposed on the reflectivity relevant to a fractal DEM, with prescribed microscopic roughness, three fifty-pixels-long bright lines and one bright point, presenting all the same intensity (Fig. 3).

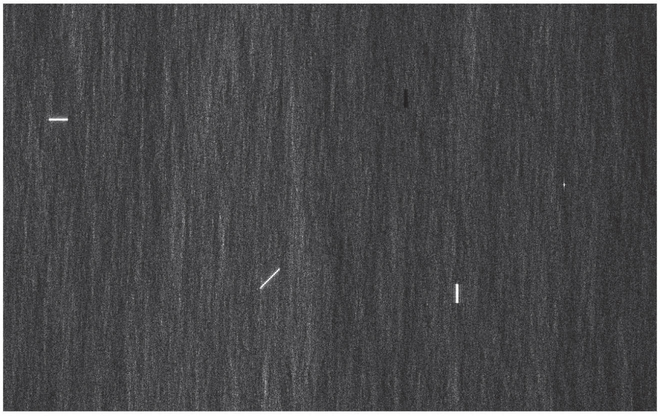

Figure 3. Simulated SAR image.

In Fig. 4 and 5 two filtered versions of the test image, obtained with elaboration windows of dimensions 35x35 pixels and 71x71pixels respectively, are shown. First of all, it is evident that the dimensions of the geometric features relevant to the bright objects depend on the sliding window dimension. Some quantitative considerations are in order. In both Fig. 4 and 5, the presence of the isolated bright point does not significantly affect the fractal map. At the right side of the figures there is a square window of the same dimension of the elaboration window presenting a constant fractal dimension. Such a phenomenon depends on the fact that the level of spectrum distortion due to the presence of a single non fractal point in a whole range line (whose length depends on the range-sliding window dimension) that is also averaged with a number of fractal spectra (the number of these spectra depending on the azimuth-sliding window dimension), does not significantly alter the fractality of the area covered by the window. The vertical bright line produces in both cases a rectangle showing a width equal to that of the used sliding window, and a length equal to that of the line summed to the length of the sliding window. The rectangle turns out to be dark with respect to the background, in fact it presents quite constant values of fractal dimension lower than 2: in this case a brilliant point is present in several range lines in the same sliding windows, so the averaged spectrum is finally non-fractal. As a matter of fact, the algorithm perfectly retrieves the non fractal object, and its length can be exactly deduced. A very similar effect is that produced by the oblique line. In both Fig. 4 and 5 we can see an hexagon due to the dragging of a window (whose dimensions are those of the elaboration window) for all the length of the starting oblique line The most evident difference between the two images is due to the processing of the horizontal bright line, which, anyway, cannot be related to double reflection contributions, but shows an interesting behavior of the filtering.. In Fig 4. the filtering produces two side by side square windows having the same dimension of the sliding window, spaced out 15 pixels. This phenomenon depends on the fact that a sliding window smaller than the line in the range direction has been used. This implies that, for a distance equal to the length of the horizontal bright line minus the range dimension of the sliding window, during the processing, there is a constant bright line spanning all the elaboration window extension, whose spectrum, averaged with those of the other range lines present in the windows, does not produce any distortion. This effect does not occur in Fig.5, where the size of the elaboration window is greater thanthat of the bright line. In this case, we have a 71 pixels-long and 121-pixels wide rectangle (the range dimension is given by the sum of the window size and of the bright line length).

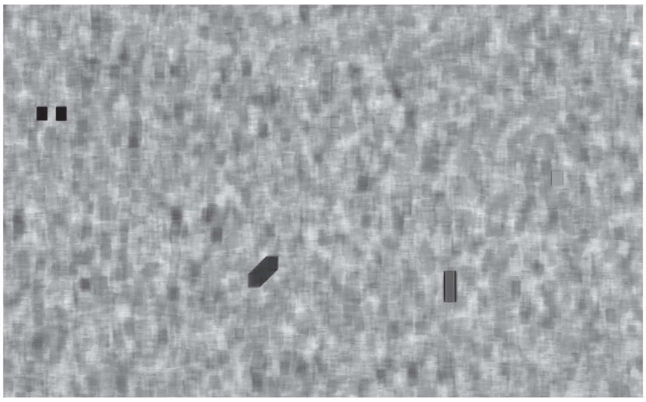

Figure 4. Filtered image with window 35x35.

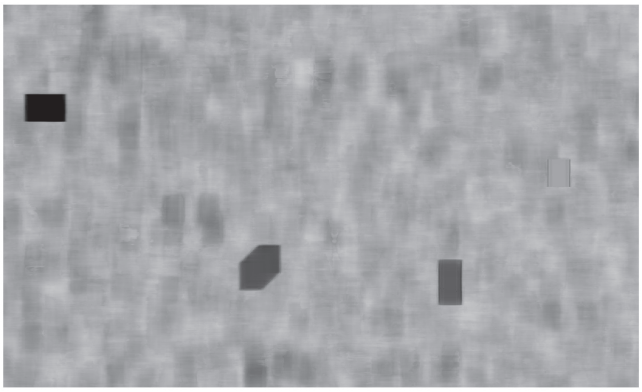

Figure 5. Filtered image with window 71x71.

In conclusion, the proposed test simulation shows how the fractal filtering recognizes non-fractal features and how it is possible to retrieve the dimension of such objects taking into account the sliding window dimensions.

B. *Actual SAR Image Analysis*

Figure 6. COSMO-SkyMed image relevant to L'Aquila, Italy.

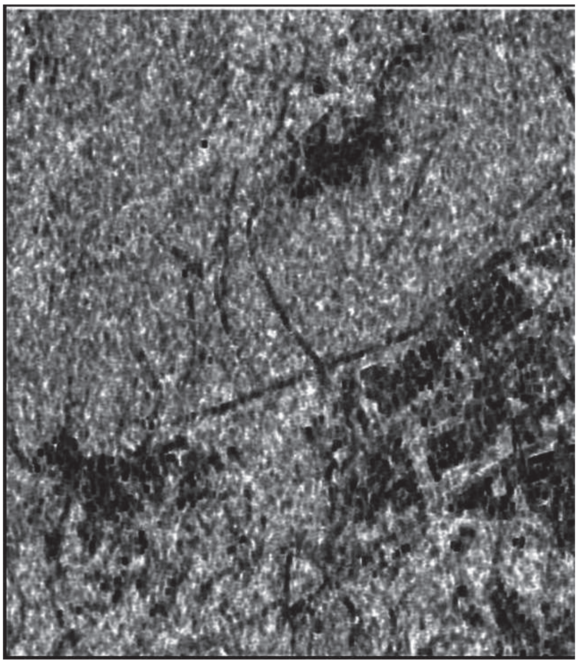

Figure 7. Fractal dimension map relevant to the image in Fig. 6.

In order to test the filter behavior on actual SAR images, we applied it on a COSMO-SkyMed image relevant to the zone of L'Aquila, which is a mix of rural and built-up areas. The image is acquired in spotlight mode and its original resolution is 1x1 m^2; on the original image a 2x2 multilook was applied, hence the final resolution is 2x2 m^2. The images before and after the filtering are shown in Fig. 6 and 7, respectively. The size of the elaboration window is 35x35 pixels.

Comparing the original image in Fig. 6 with its filtered version in Fig. 7 all the signatures discussed in the previous sub-section can be appreciated. The range of values of the recovered fractal dimension is $1.6 \le D \le 2.7$. The lower values correspond to the darker shade of grey, while the higher values of D are represented with lighter shade of grey. Actually, the D range of fractality of a natural surface is $2 < D < 2.5$; pixels with $D < 2$ represent non-fractal objects; pixels with $D > 2.5$ represent fractal scatterers whose fractal dimension does not match the range of fractality of a natural surface. Note that the obtained map allows the automatic identification of man-made objects (urban areas as well as the motorway in the centre and so on) that appear darker with respect to the brighter natural zones. In particular, due to the small size of the elaboration window and to the high density of the buildings in some zones of the observed scene, where they are not isolated from each other as was the case in the simulated images, the built-up areas can be distinguished as darker zones.

Such a type of filtering can be used as a support to image classification and segmentation. It turns out to be extremely simple, effective and reliable because it is enforceable to a single amplitude-only SAR image and it is unsupervised.

IV. CONCLUSIONS

In this paper a fractal filter, recently developed by the authors in order to retrieve fractal parameters that quantitatively describe a natural surface starting from its SAR image, has been applied to SAR images presenting man-made objects. The goal is, in fact, to test the behavior of such a processing when typical signatures of microwave images of urban centers, like bright points and lines, due to multiple scattering effects, occur.

Furthermore, the filter was applied to an actual SAR image relevant to L'Aquila, Italy. This result confirmed its ability to act as a classifier which can be used to identify the built-up areas present on the scene. In accordance with the results obtained for the simulated canonical case, its behavior and performances are determined by the size of the elaboration window.

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