VOLCANO MONITORING VIA FRACTAL MODELING OF LAVA FLOWS

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***Abstract*—In this paper use is made of fractal models for the development of a processing chain devoted to volcano monitoring. In particular, we present new models for the characterization of microwave images of fractal surfaces and we show how these models can account for the presence of different types of lava flows on these images.**

The imaged surfaces are modeled as fractional Brownian motion (fBm) stochastic processes. First of all, we show how the radar image relevant to an fBm can be linked to an associated fractional Gaussian noise (fGn) process. Different types of lava flow surfaces are simulated and their image spectra are analyzed and compared.

Finally, a case study is presented. The area of interest is the Vesuvio volcano close to Naples, Italy. Simulated results, showing the possibility to discriminate different types of lava, are provided.

I. Introduction

New generation SAR sensors are providing huge amount of high resolution images, whose increasingly rich texture allows the identification of a great number of previously unavailable geophysical information. Unfortunately, their use is still very limited and their interpretation is often performed only by expert analysts. This is due to the peculiarity of radar images, whose interpretation is not straightforward and frequently needs to be strongly model-based.

When a disaster occurs, the observed scene dramatically changes: the natural disasters modify the surface profile from scales smaller than the sensor coverage but comparable to the sensor resolution, up to scales comparable to the electromagnetic wavelength. In particular, in the case of lava flows, which is of interest in this paper, the scales smaller than the resolution are subject to the main roughness modifications. However, this is no longer completely true when we deal with new generation high resolution sensors: in this case, also the scales larger than the resolution begin to be affected by the presence of lava, determining a significant textural modification in the final SAR images. In this paper the first steps in modeling this effect are reported.

The possibility to use radar data for the monitoring of natural disasters is strongly dependent on the availability of efficient, possibly unsupervised, data analysis techniques. In order to develop this kind of techniques, sound models are required for the description of the involved surfaces and their interaction with the impinging electromagnetic field. When natural surfaces are of interest the fractal geometry [1] is recognized to provide the better description with a minimum number of parameters. In this paper use is made of fractal models to describe natural surfaces and, in particular, lava flows presenting different physical characteristics. The direct models used in this paper are summarized in Section II.

Recently, the authors developed a fractal framework for the elaboration and analysis of SAR images relevant to scenes hit by natural disasters [2]. In particular, in [3] the proposed chain was used to study the case of volcano eruption and lava flow detection and discrimination.

Meanwhile, the authors developed a novel imaging model [4], which can be used to evaluate the spectral behavior of images relevant to fractal surfaces. This new model can be used to support the fractal analysis performed in the abovementioned papers. In particular, in Section III we perform a first simple generalization of the numerical setup in [4] in order to cope with the two-dimensional case and we show the results of simulated lava flows of different geophysical nature. This generalization consists basically in the synthesis of a two-dimensional fractal surface, in the following evaluation of the two-dimensional backscattered signal from the surface and in the valuation of the spectra of the surface and of its image along one-dimensional range and azimuth cuts. The possibilities and limits of spectral-based techniques to discriminate these kinds of lava are also stressed.

Finally, in Section IV a case study is presented. The area of interest is the Vesuvio volcano close to Naples, Italy. Simulated SAR images are presented: in particular, the simulations parameters are relevant to the German high resolution sensor TerraSAR-X. Images of simulated eruptions, presenting different types of lava (aa and pahoehoe), are shown. The possibility to develop efficient change detection techniques is highlighted.

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II. Direct Models

A. SAR simulation

In past years, a SAR raw signal simulator was developed and tested [5]. In the following we describe briefly the key issues for SAR raw signal simulation.

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 [5]:

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

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]. Evaluation of the reflectivity pattern requires a description of the observed surface as well as a model for its interaction with the electromagnetic fields radiated by the SAR antenna [5]. In this paper we use the models presented in the next two paragraphs.

B. Surface model

As mentioned in the previous section, use is made of fractal models to describe natural surfaces. In particular, we describe the imaged surfaces as fractional Brownian motion (fBm) processes [1]. The fBm is defined in terms of the probability density function of its height increments. A stochastic process $z(x, y)$ is an fBm surface if, for every x, y, x', y', it satisfies the following relation:

$$\Pr\left\{z(x,y)-z(x',y')<\bar{\zeta}\right\} = \frac{1}{\sqrt{2\pi}s\tau^{H}}\int_{-\infty}^{\bar{\zeta}}\exp\left(-\frac{\zeta^2}{2s^2\tau^{2H}}\right)d\zeta \quad , \qquad (2)$$

where τ is the distance between the points (x,y) and (x',y'), and the two parameters that control the fBm behaviour are:

H : the *Hurst coefficient* ($0<H<1$), related to the fractal dimension D by means of the relation $D=3-H$.

s : the standard deviation of surface increments at unitary distance; it is measured in [$m^{(1-H)}$].

C. Scattering model

In order to effectively describe the formation of SAR signals, adequate models of the interaction between the incident electromagnetic field and the surface have to be introduced. In particular, the choice of the model used to compute the backscattered field from a given surface should strongly depend on the geometrical characteristics of the surface itself.

In fact, theoretical and experimental studies [6], [7] suggest that use of fractal models improve the scattering method results. A complete discussion on the choice and the characteristics of the scattering method is beyond the goal of this paper. Here, we use the fBm fractal model for describing the surface roughness and the small perturbation method (SPM) as scattering model for evaluating the reflectivity pattern [6].

D. Simulation results

In order to show the ability of the presented simulator in providing likely simulated images, we present here a simulated SAR image relevant to the Vesuvio volcano.

The DEM provided as input to the simulator is shown in Fig.1. It was interpolated so that its dimension and resolution could match the specifications required by the considered sensor acquisition geometry. As mentioned before, the sensor parameters given to the simulator are those relevant to the TerraSAR-X sensor. Accordingly, the obtained resolution is 1.69 x 3.99 m^2, in azimuth - ground range. The dielectric constant ε of the scene is set to $\varepsilon=4\varepsilon_0$, and the conductivity σ is set to $\sigma=0.001$ S/m, while the fractal parameters are $H=0.8$ and $s=0.16\ m^{0.2}$.

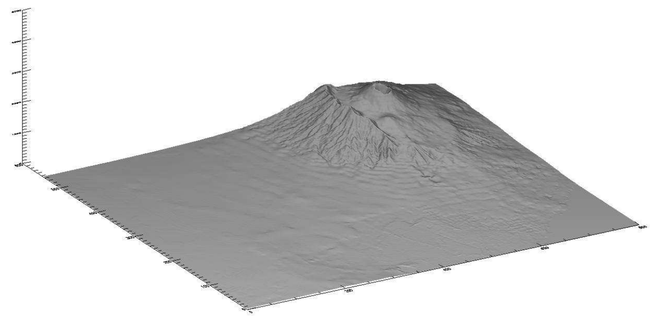

Figure 1 3D representation of the Vesuvio volcano area.

The simulation result is presented in Fig. 2, where an 8 x 4 multi-look is applied in order to obtain an approximately square pixel. Note that for better simulation results a DEM with a resolution closer to the one of the sensor would be necessary, to preserve the details and avoid the appearance of features related to DEM interpolation. Furthermore, an adequate statistical characterization of the speckle noise on high resolution SAR images is in order if stochastic analysis methods are used on the simulated images. In fact, for high resolution sensors the full developed speckle hypothesis could be questionable.

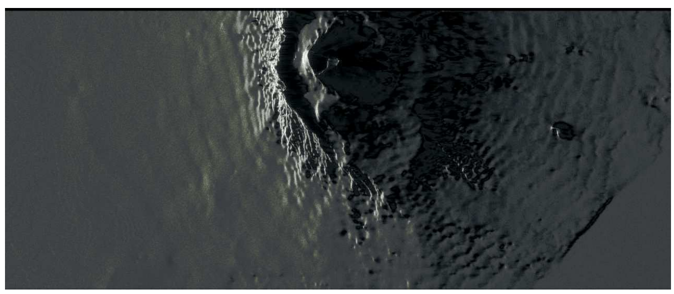

Figure 2 Simulated SAR image relevant to the DEM of Fig. 1.

III. FRACTAL IMAGING OF LAVA FLOWS

A sound interpretation of SAR amplitude data requires a deep knowledge of the mechanisms underlying the image formation process. The results shown in this section generalize to a two-dimensional surface those presented in [4] with respect to a fractal one-dimensional profile.

In [4] the authors obtained a closed form expression for the spectrum of the radar image relevant to a fractal profile. However, the proposed model is valid only in the hypothesis of a small slope regime for the observed profile. Furthermore, a numerical setup was introduced to analyze fractal profiles and to test the range of validity of the proposed model. Here we modify the numerical setup in order to show a possible two-dimensional fractal model for the lava flows. The performed modifications allow for the synthesis of a two-dimensional multi-fractal surface, for the computation of the backscattered signal and for the evaluation of the spectra of the surface and of its image on one-dimensional range and azimuth cuts.

The first step consists in the generation of the desired surface. This is performed via a synthesis algorithm based on the Weierstrass-Mandelbrot function, which is obtained via a superposition of adequately spaced sinusoidal tones [6]. However, the peculiarity of the lava flows lies in their multi-fractality, which is due to the fact that their behavior at scales above some meters is inherited from the surface on which they are located. This means that different types of lava (e.g. aa and pahoehoe) located on the same portion of surface present different fractal parameters only for scales lower than a threshold dependent, presumably, on the type of lava itself and on the roughness of the underlying surface. To the best of our knowledge there is no work in the open literature helping in the definition of such a threshold. Anyway, in the scenario of high resolution sensors the sensor resolution is comparable with the the threshold, meaning that much more textural information on lava flows will be available in SAR images of areas hit by this kind of natural disasters [3].

In Fig. 3 and 4 we show the simulated lava surfaces for an hypothetic aa and pahoehoe scenario, respectively.

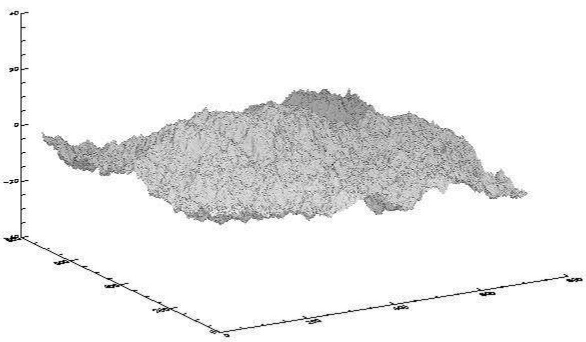

Figure 3 Simulated aa lava flow.

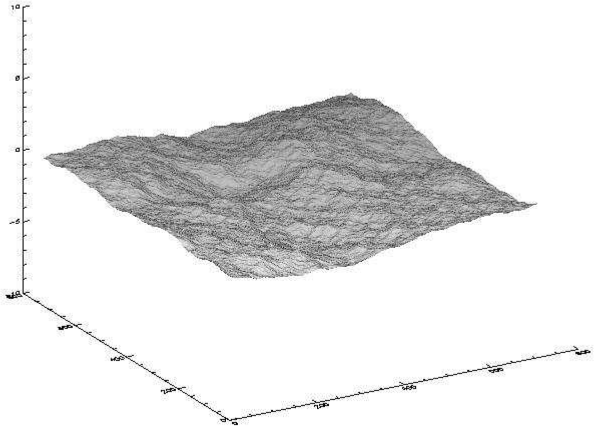

Figure 4 Simulated pahoehoe lava flow.

The dimension of the simulated surfaces is of about 700 x 700 m^2 and they are obtained modifying the fractal parameters of the same original Weierstrass-Mandelbrot surface (which presents an H=0.8 and an s=0.16 $m^{0.2}$) relevant to scales below 25 m: this results in a quite similar macroscopic profile, but in a very different microscopic roughness. In particular, for the aa lava H has been set to H=0.7 and s to s=0.25 $m^{0.3}$, while for the pahoehoe lava H=0.9 and s=0.05 $m^{0.1}$.

Once the surfaces were synthesized, their radar cross section was evaluated using the SPM model. Therefore, the spectra of the original surface and of its image could be evaluated via a Capon filtering technique [8] applied to one-dimensional range and azimuth cuts. This particular filtering is necessary to circumvent the leakage and high variance problems affecting classical spectral estimation techniques dealing with power-law spectra [8]. A comparison between numerical and theoretical results is presented in Fig. 5 for both the above mentioned types of lava flows.

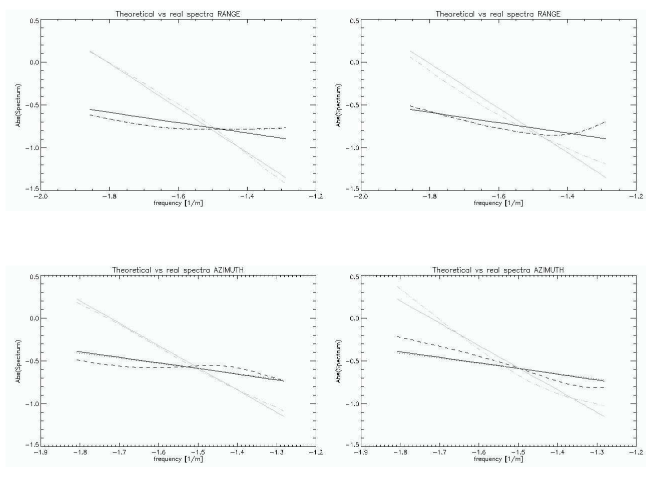

Figure 5 Spectra of the simulated lava flows and of their images: on top the range cuts are considered; the aa case is presented on the left, while the phaohoe is on the right. The full lines represent the theoretical results and the dashed ones represent the estimated spectra (black for the image and light grey for the surface).

As can be noted in Fig. 5, the spectral estimation technique, using very low spatial frequencies, is not the best technique for the identification of lava effects, which, as said above, are high frequency effects. Anyway, cooperative use of both azimuth and range information can be in this case useful for lava discrimination purposes. Obviously, both the multi-fractal model and these spectral behaviors need to be deeply investigated in order to be effectively exploited as lava flow discrimination tools. In particular, the use of spectral estimation techniques able to provide a larger range of estimated spatial frequencies would be of key importance in situations like this.

IV. The Case Study

In the following, the potentiality of the chain presented in Section II is tested on a case study, focused on the monitoring of volcanic areas. The simulator is set with the parameters of the TerraSAR-X sensor and the reference simulation (without lava flows) is the one presented in Fig. 2.

The region of interest is the area of the Vesuvio volcano, presented in Section II. In order to show the ability of the proposed chain, we simulated a lava eruption, by setting the simulation parameters of a given region (for the moment chosen with a simple distance-criterion from the volcano) to the typical values for aa and pahoehoe lava flows.

In order to appropriately account for the presence of lava, we gave the region parameters the values shown in Table I. Two kinds of lava are defined: a smoother one, recalling the properties of the pahoehoe lava flows and a rougher one, recalling the properties of the aa lava flows.

TABLE I. Lava Parameters

Lava parameters	*aa*	*Pahoehoe*
Dielectric Constant	8	20
Conductivity [S/m]	0.01	1
Hurst coefficient	0.7	0.9
s [m^(1-*H*))]	0.25	0.05

In Fig. 4 and Fig. 5 the two simulated SAR images are presented.

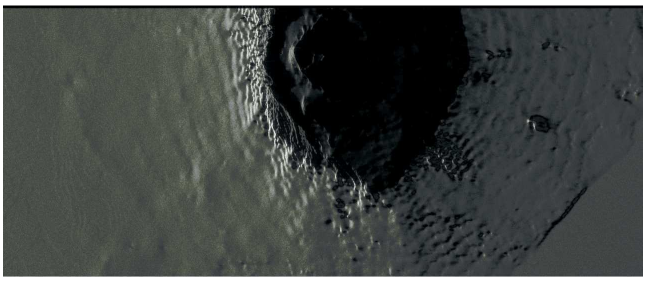

Figure 6 Simulated SAR image with pahoehoe lava flow.

Figure 7 Simulated SAR image with aa lava flow.

A simple visual comparison of the two simulated images allows for the identification of the lava zone and for the identification of the two different types of lava. Obviously, in the presented examples we reproduced two particularly favourable situations: in particular, the high contrast between the lava-covered zone and the surroundings and the steepness of the lava borders facilitate the retrieving of the region of interest. However, thanks to the proposed simulation chain and with the development of the more effective lava models presented in the previous section, a full set of simulations could be performed. Indeed, such a set, as the authors have stressed in [2] and [3], is fundamental for the development of change detection techniques particularly suited and adapted to cope with each type of disaster.

V. Conclusions

In this paper we presented a complete framework based on fractal models whose use allows to improve the comprehension, interpretation, and information extraction from SAR images. A lava surface model was presented, based on the novel imaging model recently presented in the open literature by the authors [4]. The use of spectral analysis techniques for the discrimination of different types of lava flows was considered and its advantages and drawbacks were highlighted.

A case study, based on simulated TerraSAR-X data of the Vesuvio volcano area, was also presented. The presence of lava flows was simulated, with the goal of assessing the ability of the presented framework to work as a support to the development of adequate change detection techniques particularly suited to disaster monitoring issues. The further steps to improve the high resolution simulation technique, both from the point of view of the geometrical (multi-fractal lava) and of the statistical models (non-full developed speckle noise), were also highlighted.

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