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Border extrapolation using fractal attributes in remote sensing images

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ABSTRACT

In management, monitoring and rational use of natural resources the knowledge of precise and updated information is essential. Satellite images have become an attractive option for quantitative data extraction and morphologic studies, assuring a wide coverage without exerting negative environmental influence over the study area. However, the precision of such practice is limited by the spatial resolution of the sensors and the additional processing algorithms. The use of high resolution imagery (i.e., Ikonos) is very expensive for studies involving large geographic areas or requiring long term monitoring, while the use of less expensive or freely available imagery poses a limit in the geographic accuracy and physical precision that may be obtained.

We developed a methodology for accurate border estimation that can be used for establishing high quality measurements with low resolution imagery. The method is based on the original theory by Richardson, taking advantage of the fractal nature of geographic features. The area of interest is downsampled at different scales and, at each scale, the border is segmented and measured. Finally, a regression of the dependence of the measured length with respect to scale is computed, which then allows for a precise extrapolation of the expected length at scales much finer than the originally available. The method is tested with both synthetic and satellite imagery, producing accurate results in both cases.

1. Introduction

Geomorphologic and oceanographic studies based on the use of physical-numerical models require a precise knowledge of geographic magnitudes in order to be applied (areas, coastline lengths, etc.). These quantities are not always available because the geographic features in study are located in difficult access areas, involve large extensions or direct measuring itself generates a negative environmental effect or introduces modifications in the evolution of the observed system. In these cases, the analysis of morphologic features from satellite images is an advantageous alternative (Schowengerdt, 1997; Lillesand and Kiefer, 2000; Chen and Ho, 2008). While the use of coarse spatial resolution images limits the precision, the use of fine spatial resolution images implies an excessive cost to cover large areas. Such situation motivates the development of reliable data-approximation techniques from coarse spatial resolution images.

Fractal geometry offers an ideal theoretical background to develop estimation algorithms. Its concepts and applications extend to all fields of human experience (Russ, 1993; Falconer, 2003) including natural sciences (Mandelbrot, 1983; Siu and Lam, 2002; Lopes and Betrouni, 2009). In digital image processing (DIP), fractal theory is the basis of several techniques for purposes such as segmentation, measurement, pattern recognition, etc. (Zhende and Yuwen, 2003; Lopes and Betrouni, 2009; García et al., 2010).

Richardson (1961), in his mathematical analysis of war, was the first to notice the relationship between geographic measurement and scale. In his work, measurement of borders between countries is performed by approximating the contour using a polygonal path composed of constant module segments ε and, as $\varepsilon \to 0$, Richardson infers that the result approaches to a limit. In the case of coastlines, which are continuous but not necessarily derivable curves, an increment in resolution implies the appearance of finer and finer details in a way such that the total magnitude appears to diverge $L(\varepsilon) \to \infty$ (Fig. 1). As a consequence, the measured length of

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the border depends on the precision employed in the calculation and the final result increases for a higher level of detail. However, Richardson (1961) developed a function to estimate borders among countries, which is defined as

$$L(\varepsilon) = F\varepsilon^{1-D} \tag{1}$$

where F and D are characteristic constants of each contour. Mandelbrot (1967) followed the studies by Richardson and proposed to use the exponent D as a natural dimension, also called fractional dimension or fractal dimension (FD) which, in certain cases, coincides with the Hausdorff–Besicovitch dimension (Mandelbrot, 1983; Falconer, 2003).

The standard fractal analysis method is formulated by Richardson (Richardson, 1961; Mandelbrot, 1967; Dutch, 1993) where the invariance to scale is established in the $\log(\mathit{Length}) - \log(\mathit{Scale})$ plane. Nevertheless, different authors present FD measurement algorithms and analyze their performance (Allen et al., 1995; Soille and Rivest, 1996; Schlueter et al., 1997; Dillon et al., 2001; Lopes and Betrouni, 2009). In particular, for feature and texture characterization, the approaches are mainly concerned with the accuracy of the algorithms (Allen et al., 1995; Soille and Rivest, 1996), the conditions to validate the results (Goodchild, 1980; Shelberg et al., 1982; Wu, 2004; Wu et al., 2006) or the description of pattern distribution (Korčák, 1938; Mandelbrot, 1983; Lipiec et al., 1998; Zuo et al., 2009; Imre et al., 2011). Also, simpler techniques like the one proposed by Håkanson (1978) are only focusing on feature estimation.

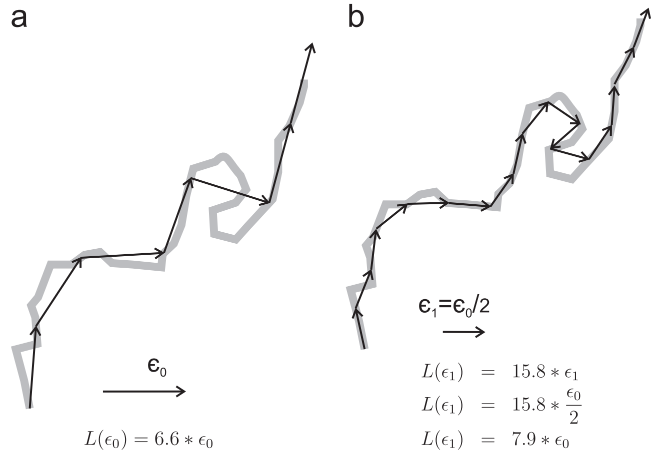

Fig. 1. Length approximation scheme of the coast line from a polygonal with constant modulus segments ε. (a) Scale $= \varepsilon_0$ and (b) scale $= \varepsilon_1 = \varepsilon_0/2$.

Håkanson (1978) uses fractal analysis to estimate the perimeter of twelve lakes in Sweden. In his work, he claims that it is not possible to evaluate the precision of a measurement results without specifying the method used and establishing rules for selecting an adequate scale. He also develops an empiric expression of the length variation which allows to compare the different scales among the lakes. However, some authors question the reliability of his work due to the information incongruence in the calculations when using heterogeneous cartography (Mark and Aronson, 1984; Lam and Quattrochi, 1992). In DIP, the standard measurement algorithms or “chain codes” (Freeman, 1961, 1970; Dunkelberger and Mitchell, 1985) present a high degree of systematic associated error (Kulpa, 1983; Dorst and Smeulders, 1987; Yang et al., 1994; Imre, 2006; Cipolletti et al., 2012).

The purpose of this work is to further develop the fractal estimation techniques using consistent data sources and more accurate length measurement algorithms to apply them in satellite imagery. In this way, we are able to perform high quality border measurements with low resolution imagery. The proposed methodology is based on measuring the border at different scales and, then, computing a regression of the dependence of the measured length with respect to scale. This enables the extrapolation of precise length measures using imagery of coarse spatial resolution without the information incongruence problems present in Håkanson algorithm. The method was tested on synthetic images and on Landsat images of Buenos Aires Province (Argentina). In the latter case, the work focuses in coastal areas of the Bahía Blanca Estuary. In all the experiments, we were able to extract border measurements from coarse resolution images that are significantly similar to the values measured at much finer resolution.

2. Methodology

In satellite imagery, each pixel has color or radiance information divided into n-bands and an associated spatial-resolution value S corresponding to the pixel side length. Fig. 2 shows the length estimation process: segmentation + downsampling + border measurement + fractal regression. This method lets to predict the value of a measurement in a finer scale than that of the original image avoiding information incongruence problems caused by the use of heterogeneous cartography (Håkanson, 1978; Mark and Aronson, 1984; Lam and Quattrochi, 1992).

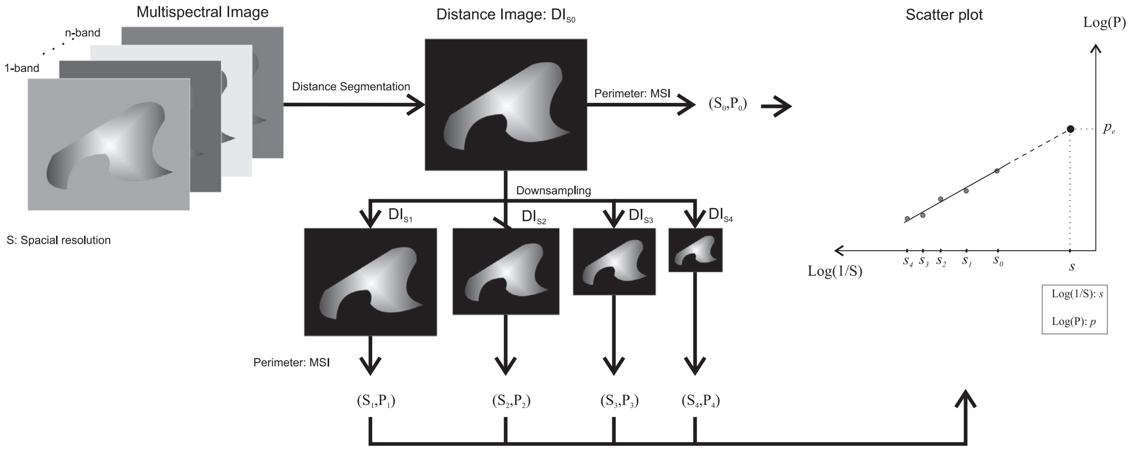

Fig. 2. Complete processing pipeline to perimeter estimation: segmentation + downsampling + measurement + fractal analysis.