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Improving the analysis of well-logs by wavelet cross-correlation

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HIGHLIGHTS

- We use wavelet cross-correlation to identify similar patterns in physical data sets.
- We compare measures of physical quantities collected from two neighboring oil wells.
- We also compare measures of different physical quantities taken on the same oil well.
- Well-localized correlations among logs of an oil exploration field have been found.

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ABSTRACT

The concept of wavelet cross-correlation is used to provide a new approach to identify similar patterns in related data sets, which largely improves the confidence of the results. The method amounts to decompose the data sets in the wavelet space so that correlations between wavelet coefficients can be analyzed in every scale. Besides the identification of the scales in which two independent measures are correlated, the method makes it possible to find patches of data sets where correlations exist simultaneously in all scales. This allows to extend the information of a small number of spots to larger regions. Well-log data sets from two neighboring oil wells are used. We compare similar measures at different probe sites, and also measurements of different physical quantities taken on the same place. Although this is a typical scenario for the application of classical geostatistical methods, it is well known that such methods erase out local differences in favor of smoother variability. In contraposition, this wavelet cross-correlation takes advantage of the fluctuations to give information about the continuity of the geological structures in space. It works even better if no filtering procedure has been applied to the original raw data.

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1. Introduction

Randomness, be apparent or actual, is a common element of typical natural and social complex systems related to climate, geology, economics, elections, and so on [1,2]. Most because of this, there has been a great effort to set up efficient tools to characterize randomness in a more precise way, which amounts to identify and quantify proper correlations within temporal and spatial outputs obtained from measurements performed on such systems [3–6]. Severe burdens appear when we try to accomplish such an identification program either when the correlations are weak or when they are expressed only in given scales, or in limited ranges of the measured data. In the current case, we have to deal with spatial patches, but the same kind of problems appear when temporal dependence is involved.

Although a general solution for this broad problem is still far from being achieved, concepts and methods of statistical physics have been very useful in the analysis of time series, allowing for the identification of hidden scales in which similarities can be easily detected [5,7–11]. In this work, we discuss an approach that increases the confidence in the identification of correlations between well logs. For the sake of simplicity, we fix our discussion on spatial data sets, but all conclusions we derive here can be extended to temporal series as well. A good way to unveil hidden organized relationships related to spatial structures is to make a very careful analysis of the correlations between the same physical properties measured at different locations, comparing these data at every scale. This can be accomplished by the wavelet coherence [12], a new correlation tool based on the wavelet transform. This tool is able to analyze the correlations in all scales, scanning all spatial locations. It allows us to improve the degree of confidence in finding analogous spatial patterns. This wavelet correlation approach, which has been applied to several problems, with promising results [13–18], has a strong advantage over the standard cross-correlation method, that gives only a global measure of the correlation. This standard cross-correlation can lead to low confidence results because it integrates the product of two data and, then, spurious coincidences and compensations can occur.

In order to test the reliability of this method, we provide a case analysis of data sets of geological structures, a system where the presence of correlations is well documented. Indeed, geological structures result from a complex dynamical process of the Earth crust solidification followed by tectonic migration, which give rise to long range correlations due to continuous repetitive processes occurred during long periods, punctuated by a burst of extreme events. These assumptions have been introduced in models for rock formation, leading to the emergence of structures quite similar to those observed in nature [19].

The rest of this work is organized as follows. In Section 2 we present the basic tools for wavelet cross-correlation analysis, characterizing the mother wavelet used throughout the work and main evaluation steps. In Section 3 we characterize the used data records, a set of two well logs obtained from an actual oil exploration field. We also include a brief discussion on the relevance of the correct interpretation of well-logs for the oil exploration industry. Results are presented and discussed in Section 4. We make an effort to bring into evidence the internal consistency of the method and to compare its results with those provided by the standard cross-correlation. We then present two different ways the technique can be used to treat the data. Finally, Section 5 closes the paper with concluding remarks and possible ways to extend the method to analyze further aspects of the records.

2. Methodology

Suppose we are given a set of M related records $\{f_m(x_i)\}$, where $m = 1, \ldots, M$ identifies the record and $i = 1, \ldots, N_m$ runs over the number of locations where the m-measurements were performed. Note that the length N_m of each series may be different from each other. Although not specifically indicated, actual data series analysis must take into account for missing records. For the sake of a simpler notation, let us assume that the records $f_m(x_i)$ are expressed as continuous functions $f_m(x)$, although the actual data sets consist of discrete measurements.

The wavelet cross-correlation [13] amounts to evaluate the cross-correlation among two components ($f_m(x)$ and $f_n(x)$) of non-stationary signals in different scales. The scale-space decomposition is performed by a continuous wavelet transform (WT), indicated by

$$Wf(s,a) = \langle f, \psi_{s,a} \rangle = \int_{-\infty}^{\infty} f(x)\psi_{s,a}^{*}(x)\,\mathrm{d}x \tag{1}$$

where * denotes complex conjugation, and

$$\psi_{s,a}(x) = \frac{1}{\sqrt{s}}\psi\left(\frac{x-a}{s}\right) \tag{2}$$

is the wavelet (or basis) function with scale s in the position a. $Wf(s,a)$ represents the projection of $f(x)$ into the "basis vector" $\psi_{s,a}$ that has position a and scale s. The function ψ, called mother wavelet, is chosen in order to satisfy the conditions

$$\int_{-\infty}^{\infty} \psi(x)\,\mathrm{d}x = 0, \qquad \int_{-\infty}^{\infty} |\psi(x)|^2\,\mathrm{d}x = 1 \tag{3}$$

which ensure that ψ is a wave-like function with compact support and finite energy. In this work, we use the complex Morlet wavelet, consisting of a Gaussian-modulated wave [14,20]:

$$\psi(x) = \pi^{-1/4}\,\mathrm{e}^{i\omega_0 x}\,\mathrm{e}^{-x^2/2} \tag{4}$$