Inversion of wave parameters to perform spectral recomposition of GPR data

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Abstract

To perform a better characterization of stratigraphic sequences, it is fundamental obtain the geophysical attributes associated to frequencies. The technique known by spectral recomposition is based on the extraction of the wave parameters, as the amplitudes and the frequencies, of the components of a seismic spectrum. This technique even being created to be applied to the reflection seismic method, it has the potential of also be used in the GPR (Ground-Penetrating Radar) method.

Due to the similarities of the methods during the data processing, the spectral recomposition technique can provides good results and be an efficient way to obtain frequency and amplitude informations of a GPR signal spectrum.

To recover the frequency and its associated amplitude informations, the spectral recomposition was treated as an inverse problem according to an optimization criterion. It was also performed the sensibility analysis to understand which parameter would be more difficult to be recovered.

The sensibility analysis showed that the frequency is a little more difficult to be recovered than the amplitude during the inversion

After recover the frequency and amplitude informations the spectral recomposition presented to be an efficient technique to reach a better characterization of a stratigraphic model using the GPR method.

Introduction

The possibility of have a better resolution in the seismic imaging resides in the reception of the seismic signal composed by each set of frequencies. The fact of know each frequency which composes a spectrum is essential to a better stratigraphic characterization for a near-surface analysis and for a hydrocarbon reservoir characterization (Castagna *et al*., 2003; Li *et al*., 2011).

Differently than the seismic method, the GPR (Ground-Penetrating Radar) is used only for the shallow geophysical surveys, and uses electromagnetic radiation in a high frequency (Bevan and Kenyon, 1975; Voughan, 1986; Davis and Annan, 1989; Beres and Haeni, 1991; Conyers, 1995; Conyers and Goodman, 1997). As the frequencies used are much higher than the seismic wave frequencies, it is better applied to near-surface analysis. However, even the GPR being an electromagnetic method, it is strongly similar to the seismic method concerning the processing (Fisher *et al*., 1992; Conyers and Lucius, 1996; Cardimona *et al.*, 1997). For this reason, many techniques used in seismic method can be applied to the GPR method.

The spectral decomposition was a technique which was much studied since its creation when it was used for the stratigraphic characterization with the seismic method (Dilay and Eastwood, 1995; Chakraborty and Okaya, 1995; Partyka *et al*., 1999; Liu, 2006; Chen *et al*., 2008; Liu *et al*., 2011).

This kind of technique used to be performed by a time-frequency analysis. However Tomasso *et al*. (2010) tried a different approach proposing a method that can recomposes single frequencies into a multi-frequencies model, differently than the previous techniques based on decomposing the frequencies.

This approach has a significant restriction, the necessity of execute a manual pick of each pair of amplitudes and frequencies. Aiming to overcome this limitation, Cai *et al*. (2013) proposed an estimation of linear and nonlinear parts of the Ricker wavelet spectrum performed in an automatic form. The nonlinear estimation was based on the proposition of Golub and Pereyra (1973).

Due to the fact of the GPR signal has some similarities to the seismic signal, as the hyperbolic reflection events or the similarities between the wavelet spectra, the spectral recomposition is an important technique that can be applied to the GPR method.

The sum of different Ricker components is used as a representation of a seismic spectrum, and here it was used to represent the GPR signal spectrum.

As the optimization criterion, it was used the algorithm proposed by Nelder and Mead (1965), and the minimization method was the Least Squares. The spectral recomposition was treated as an inversion, with the objective of estimate the peak frequency and its associated amplitude of the component of a GPR signal spectrum.

Method

The seismic spectrum was described by Tomasso *et al*. (2010) as a sum of different Ricker components (Equation 1).

$$d(f) \approx \sum_{i=1}^{n} a_i \psi_i (m_i, f) \qquad (1)$$

Where $d(f)$ is the spectrum of a seismic, f is the vector of frequency, m_i is the peak frequency of a determined Ricker spectrum component and a_i is the amplitude of each determined component (Equation 2 and 3).

$$R(f) = a\psi(m, f) \qquad (2)$$

$$R(f) = a\frac{f^2}{m^2}\exp\left(-\frac{f^2}{m^2}\right) \qquad (3)$$

This is a linear combination of the Ricker wavelet spectra composed by nonlinear functions which are function of two vectors of parameters, the vector of frequencies and the vector of correspondent amplitudes. As the GPR signal has a strong and evident peak frequency, therefore it was treated as though it had only one frequency and its associated amplitude.

As the problem has two variables, it shall be treated as an inverse problem by an optimization criterion (Bokhonok, 2010; Zuniga *et al*., 2015). The Nelder-Mead (Nelder and Mead, 1965) optimization algorithm was used as the optimization criterion, and the minimization method was the least squares.

To recover the aimed wave parameters (amplitude and frequency), it must be analyzed the complexity of reach reliable values of the parameters obtained with the inversion routine.

The sensibility analysis was necessary here to understand the complexity of obtain each parameter during the inversion routine. The objective of this kind of analysis here was to perform the decomposition in singular values to analyze the eigenvector in data space and in parameters space.

The situation studied here was a GPR signal spectrum with a peak frequency of 0.9 GHz and amplitude of 2.7, and it was represented by a Ricker wavelet spectrum with noise (Figure 1) and after the Fourier transform as a frequencies spectrum (Figure 2).

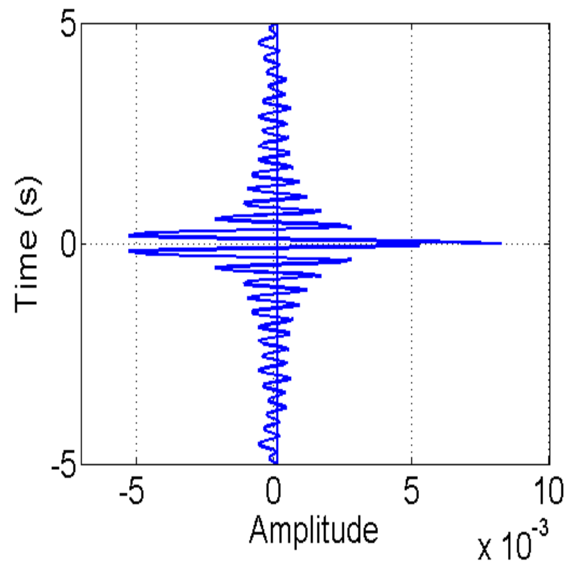

Figure 1: Ricker wavelet spectrum of the model on time domain with noise of the GPR data.

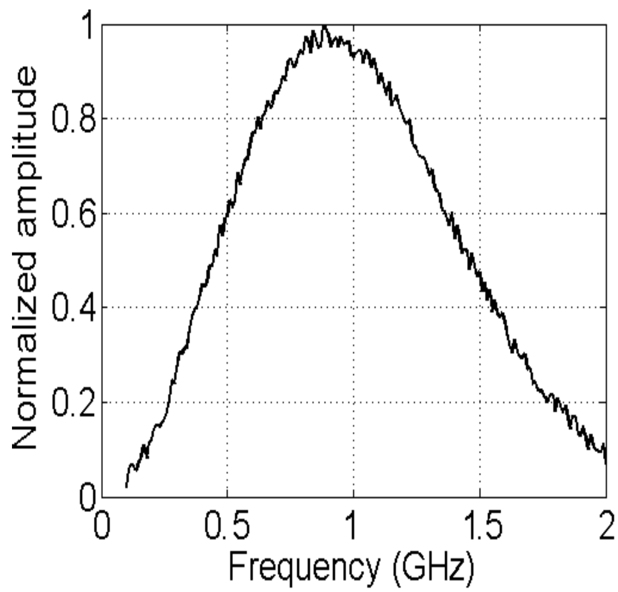

Figure 2: Frequencies spectrum of the model with noise of the GPR data.

Results

As it can be observed in Figure 3, focusing the sensibility analysis of the eigenvector in data space, the amplitude is less complicated of be recovered than the peak frequency during the inversion routine. Therefore the value of amplitude obtained can be more precise than the frequency value.

The Figure 4 showed a good curve fitting after the inversion routine, and it can be seen that even with the noise, the parameters were recovered very precisely, once the frequency and amplitude recovered were, respectively, 9.0031 GHZ and 2.6981, an error with order of 10^{-3}.

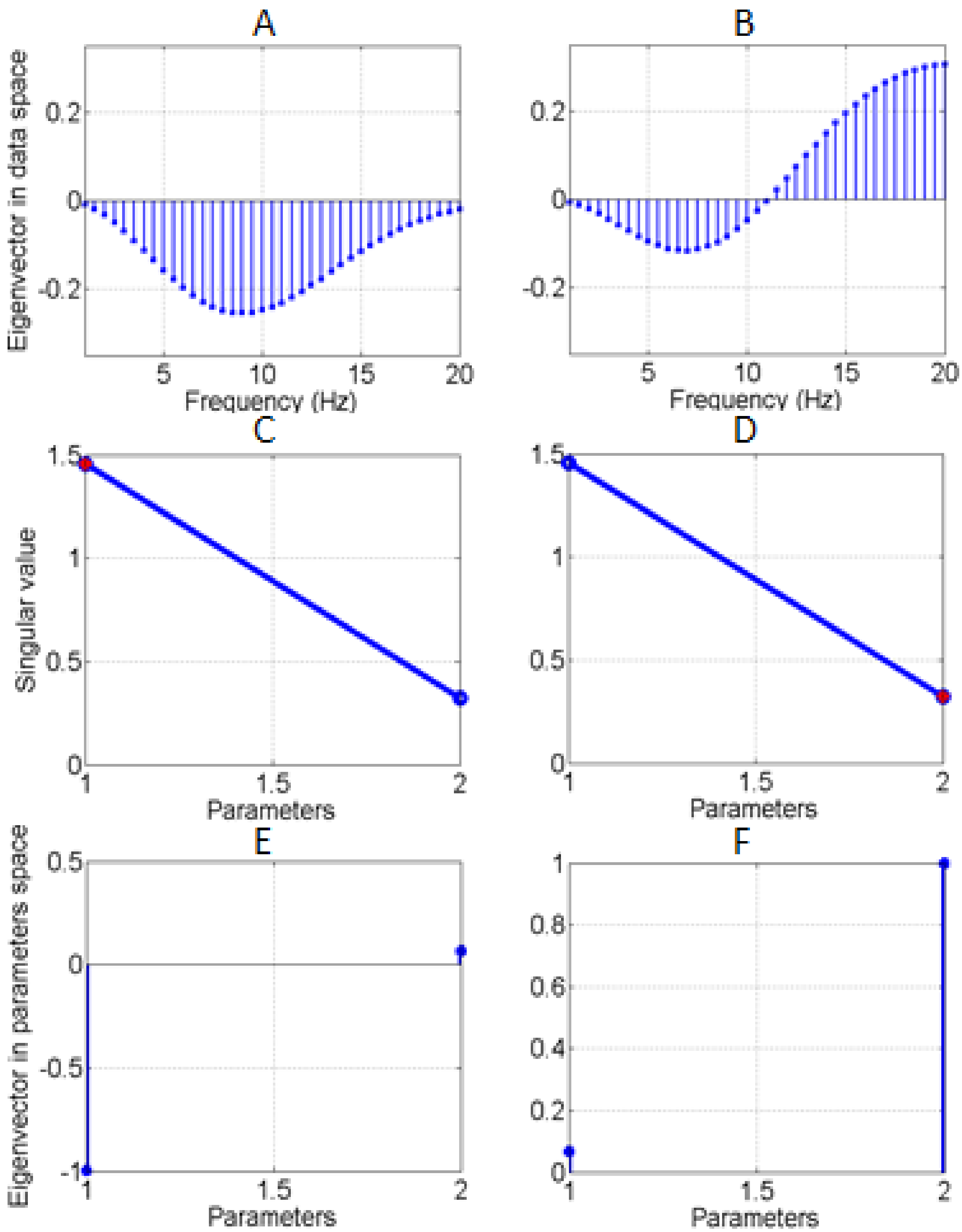

Figure 3: Sensibility analysis using decomposition in singular values. The eigenvector in the data space of the (A) amplitude and (B) peak frequency, the singular value of the (C) amplitude and (D) peak frequency, and the eigenvector in the parameters space of the (E) amplitude and (F) peak frequency.

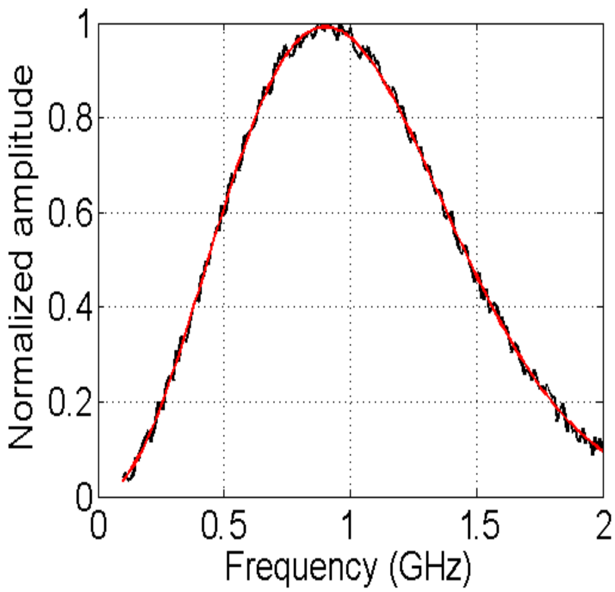

Figure 4: Curve fitting between the observed curve and the calculated curve with the inversion routine.

Conclusions

The wave parameters (amplitude and frequency) were very well recovered during the inversion routine with the method used in this work.

The method has proved to be very efficient when it is applied to GPR signal spectrum. It could be clearly observed with the precise results obtained in this study.

It is important in future works, to test some situations using the GPR method with different frequencies aiming to understand in which applications this method can bring better results.

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