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Envelope of signal and bandwidth : the key parameters for vertical seismic resolution

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At many stages of the interpretation and exploration life cycles, seismics is impacted by resolution. By definition, resolution is the ability to distinguish separate features. Improving resolution is the key problem to see thinner stratigraphic units, smaller details, lateral changes in rock properties... Whereas horizontal resolution is known to be linked to the size of the Interface Fresnel Zone, vertical resolution is usually considered as being enhanced by both high frequencies and broadband signals. This common belief comes from the fact that zero-phase signals, and particularly Ricker wavelets for which frequency and bandwidth are linearly linked, are used in seismic signal processing and modeling, as they provide easier interpretation of images, thanks to the direct link between the peaks/troughs and the reflection arrival times. Nevertheless, this belief is incorrect for mixed-phase signals (i.e., non zero-phase signals) or for signals with many oscillations. For this type of signals, we show by using the ambiguity function that, besides the bandwidth, the envelope of the signal is a fundamental tool to separate closed events and to provide reliable measurements of reflection arrival times. Bandwidth and envelope are therefore the key parameters for the analysis of seismic resolution.

1 Introduction

At many stages of the interpretation and exploration life cycles, seismics is impacted by resolution. By definition, resolution is the ability to distinguish separate features [1]. Improving resolution to see thinner stratigraphic units, smaller details, or lateral changes in rock properties is still a topic of investigation and many papers are devoted to this problem.

Horizontal resolution is characterized by the minimum distance between two features along a single interface such that these two features can be defined rather than one. It is well-known that Fresnel Zone considerations are the essence of horizontal resolution. Indeed, the size of the Interface Fresnel zone (IFZ) determines the spatial resolution with which important changes in the interface properties may be observed. Following Lindsey [2], "two events are visually independent at the same reflection level if they are separated laterally by approximately the Fresnel radius or more". Depending on the shape of the interface, the diameter of the IFZ may be considerably great [3]. The process of migration however significantly improves the spatial (horizontal) resolution [2].

Vertical resolution is characterized by the minimum distance between two interfaces such that we can tell that there are two interfaces rather than a single. It is frequently stated that the seismic wavelength limits the resolving power. Following the Widess model, the resolution limit is about a quarter of the dominant wavelength of the signal. Following Sheriff [1], vertical resolution can be improved if higher frequencies and a broader band of frequencies can be recorded. We argue that this statement is correct for zero phase signals and incorrect for mixed phase signals. Conventional seismic analysis is based on a description of the real seismic trace. Event picks on the top and bottom of a thin layer and subsequent calculation of time shift and amplitude may be inaccurate due to interference. This resolution limit could lead to misinterpretation. As phase shifts affect the time resolution and side lobe effects affect the amplitude dramatically, we prefer to consider complex trace analysis because amplitude can be separated from phase in a natural way. Indeed, a single lobe is associated to a single wavelet, which avoids many problems usually encountered.

2 Seismic resolution and the ambiguity function

In radar and sonar signal processing, the major tool for defining the resolution is the ambiguity function [4]. This function represents the time response of a filter matched to a given finite energy signal when the signal is received with a delay τ and a Doppler shift ν relative to the nominal values (zeros) expected by the filter. It is given by :

$$\left\|\chi(\tau,\nu)\right\| = \left\|\int_{-\infty}^{+\infty} u(t)\, u^*(t+\tau)\exp(j\,2\pi\nu t)\,dt\right\|, \qquad (1)$$

where u is the complex envelope of the signal. Since Doppler shift is not always of interest to seismic applications, we only need to consider the cut along the delay axis. Setting ν = 0 then leads to the autocorrelation function of the envelope of the signal R(τ) :

$$\left\|\chi(\tau,0)\right\| = \left\|\int_{-\infty}^{+\infty} u(t)\, u^*(t+\tau)\;dt\right\| = \left\|R(\tau)\right\|. \qquad (2)$$

In the same way as it is defined for real signals, Rayleigh's criterion can be used for the quantification of the separation of resolved from unresolved domains for the signal envelopes. It is well-known in radar and sonar signal processing that the time resolution for the envelope is connected to the bandwidth B of the signal. We clearly show in Figure 1 that the key parameter for the separation of the envelopes of two seismic events is also the frequency bandwidth of the signal and not the central frequency. In Figure 1, we consider signals with the same central frequency, but with a different bandwidth. The separation in time of two events only appears when the bandwidth value is large enough. As a consequence, it is equivalent to extend the lower or the upper end of the spectrum to improve the separability. The central frequency only indicates the amount of low frequencies it is possible to include into the signal.

We would also like to draw the attention on the use of the Ricker wavelet for resolution studies since this particular wavelet is only a one-parameter function that exhibits a linear relation between its central frequency and its bandwidth. The existence of this linear relation may lead to misinterpretation of the role of the key parameters that affect resolution. It would be interesting to analyze the resolution limits with a two-parameter function, which would allow the understanding of the role of the central frequency and the role of the bandwidth independently.

3 Detectability, resolvability and thin bed

In order to illustrate the significance of the bandwidth parameter and its usefulness, the response from a progressively thicker bed is examined in the case of two interfaces with the same polarity and in the case of two interfaces with opposite polarities.

First, consider the case of two interfaces with the same polarity. Figure 2 shows the seismic traces associated to the real signal and to the envelope. For each trace collection, the value of the maximum of the trace as a function of the increasing thickness d of the bed is drawn. The left curve corresponds to the maximum of the real signal and the right curve to the maximum of the envelope. By the analysis of the trace collections, it is possible to determine when the separation between two events occurs. Note that this is a measure of the detectability, but not a measure of the resolvablity that occurs when the trace is free from interference, i.e., when the maximum value is equal to the value of the individual wavelet (i.e., 1). Inspection of Figure 2 shows that for two closed events having the same polarity, the detectability occurs for approximately $d = \lambda/5$ ($\lambda = c/f_0$, f_0 being the wavelength associated to the dominant frequency and c the wave velocity), while the resolvability occurs for approximately $d = \mu/2$ where μ is a characteristic length defined by $\mu = c/B$, a quantity we choose to call the "wavewidth". This confirms that the envelope contains the amplitude information and that consequently, the key parameter to obtain this information is the bandwidth, as stated in the previous section. It also can be noted that a trough occurs for approximately $d = \mu/4$ that corresponds to the detectability of the two events.

Now consider the case of two interfaces with opposite polarities. From the inspection of Figure 3 we can see that it is more difficult to identify the detectability limit from the analysis of real traces, while it still remains easy from the analysis of the envelopes. This is particularly true when the signal is a Gaussian modulated function with oscillations. This confirms that the envelope is not sensitive to phase shifts. The value for which the resolvability is obtained is the same as in the case of two interfaces with the same polarity. Note that no trough occurs for this configuration.

A new question then arises: once separated, how to resolve events (i.e., to obtain reliable measurements of reflection arrival times)? Figure 4 illustrates the error on the time arrival of the wave reflected at the top interface of the thin bed layer and the error on the bed thickness, as a function of a dimensionless parameter defined by the ratio of the "true" bed thicknes to the dominant wavelength of the signal. The signal recorded is composed of two Ricker wavelets (each one reflected, respectively, at the top interface and the bottom interface of the thin bed layer) with a different phase shift ($-\pi/6$, $-\pi/8$), which means that the thin bed layer has a significant influence. We can note that even the bed thickness is evaluated reliably by the envelope or the primary lobe of the signal, reliable estimation of the reflection arrival time is provided only by the envelope.

4 Conclusion

The bandwidth of the signal is the key parameter that controls the vertical resolution. The larger the bandwidth, the better the resolution. This statement is particularly true for mixed-phase signals (i.e., non zero-phase signals) for which the envelope must be taken into account for the analysis of resolution. Criterions based on the wavelength do not ensure that the true amplitude of the events to be identify is obtained. The only way to ensure that the amplitude of the event is correct is to use a criterion based on the "wavewidth". As a sequel, more works remain to be done to investigate in more details the influence of the properties of the wavelets on the seismic resolution power, which will provide a better understanding of how it is possible to improve the seismic resolution.

Acknowledgments

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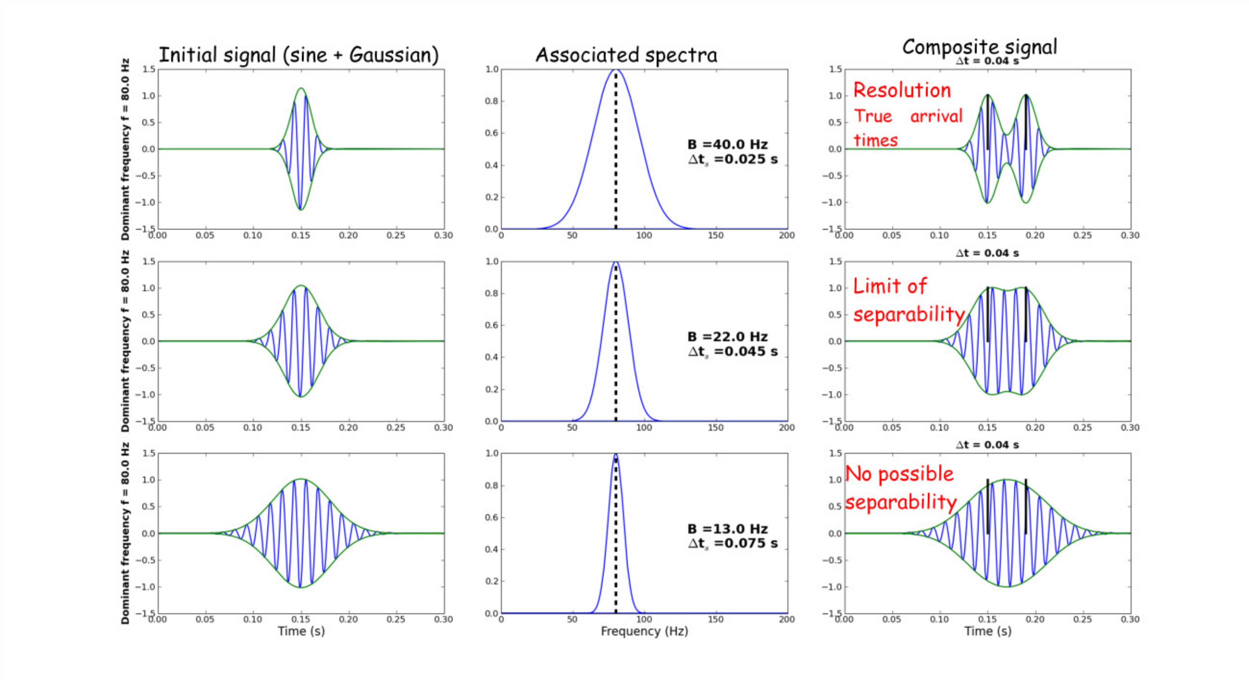

Figure 1: Resolution for mixed-phase signals with different bandwidths. Left column: three signals, together with their envelope, that are composed of the same sinusoidal signal with frequency f = 80Hz and mixed (non zero) phase multiplied by different Gaussian windows whose width defines the frequency bandwidth B. Central column: associated spectra. Right column: signals, with their envelopes, composed of the sum of the signal (in the left column) and the same signal time-delayed of Δt = 0.04s. The black bold lines indicate the time arrival of the two signals supposed to be reflected by two interfaces.

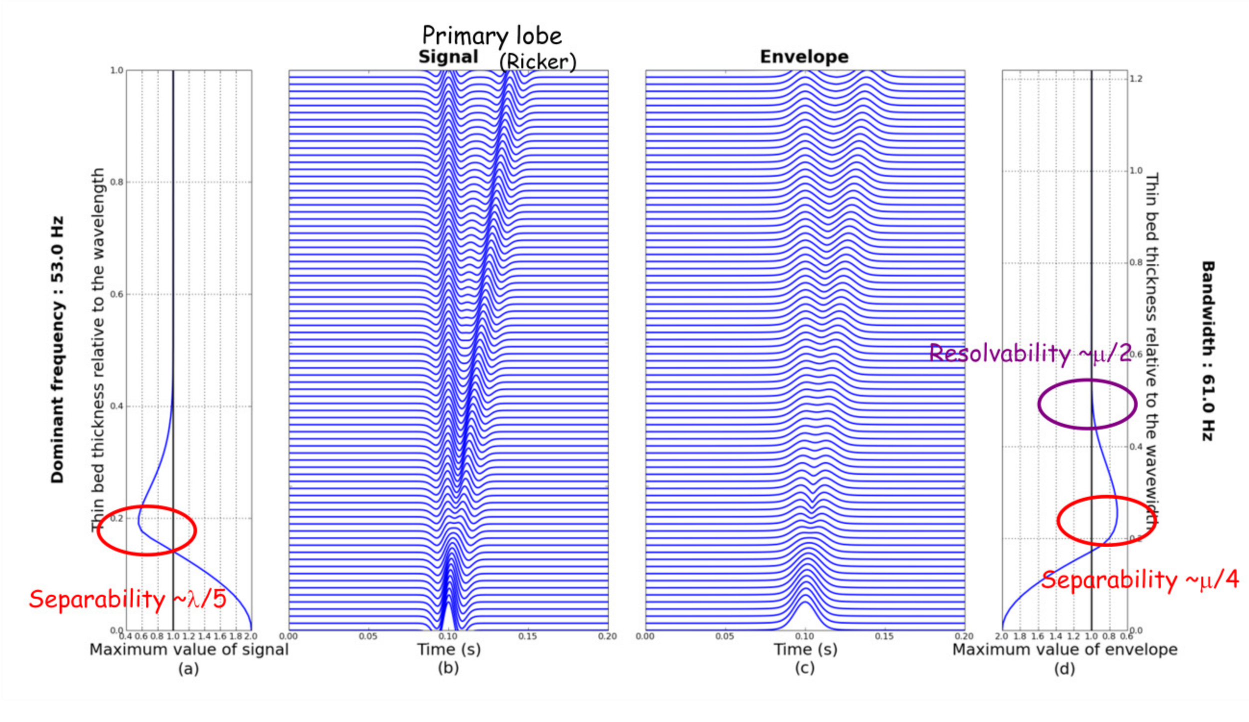

Figure 2: Thin bed response with identical-polarity reflections. (b) the seismic traces associated to the real signal. (c) the seismic traces associated to the envelopes of the signal. (a) the variation of the maximum value of the real signal as a function of a dimensionless parameter defined by the ratio of the bed thicknes to the wavelength.(d) the variation of the maximum value of the envelope as a function of a dimensionless parameter defined by the ratio of the bed thicknes to the "wavewidth". The signal is a 50Hz Ricker wavelet.

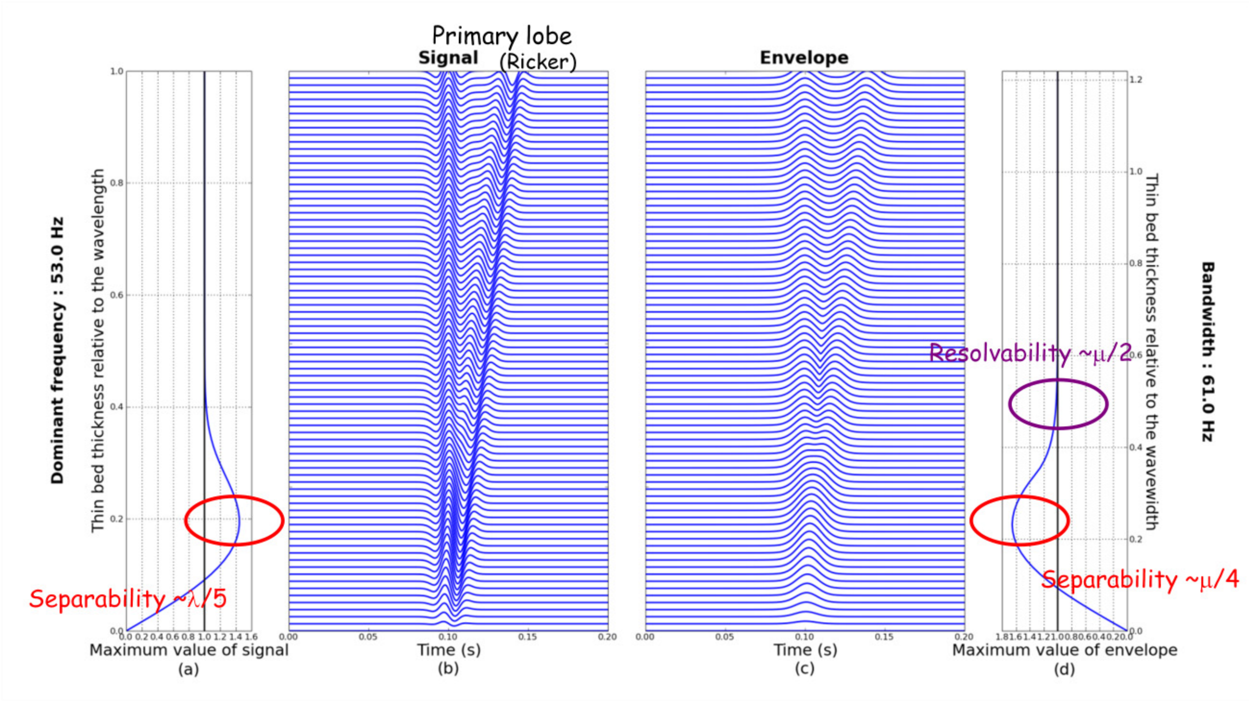

Figure 3: Thin bed response with opposite-polarity reflection. All plot characteristics are identical to Figure 2.

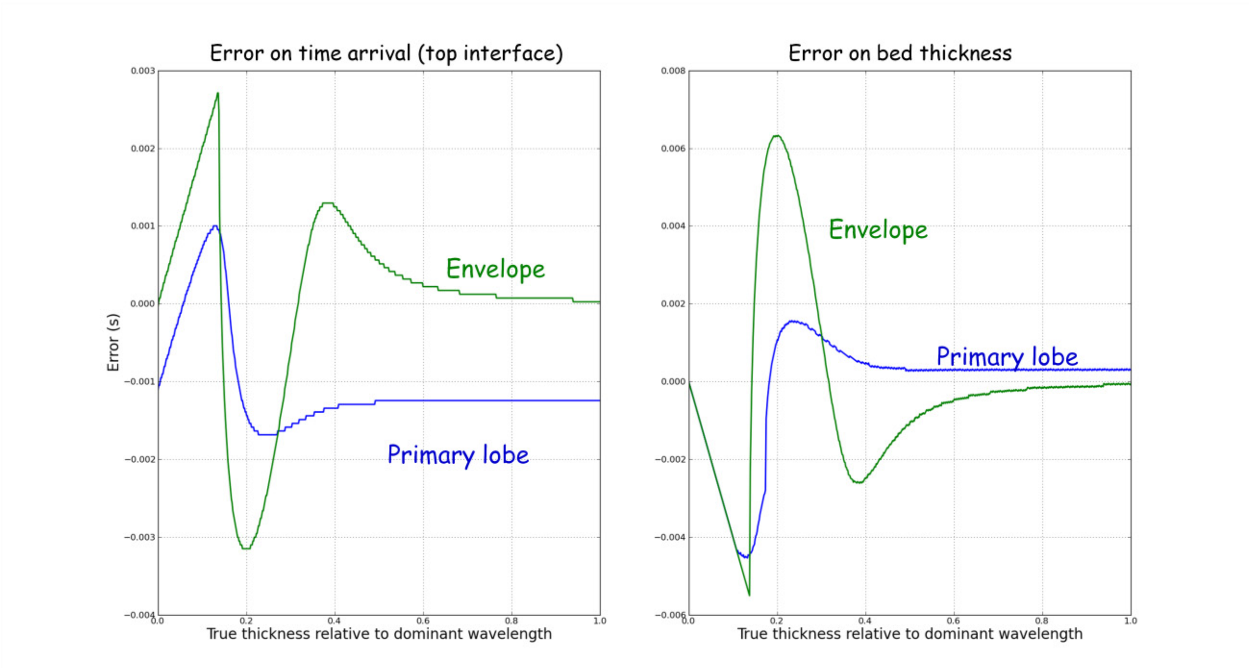

Figure 4: Error on the time arrival of the wave reflected at the top interface of the thin bed layer and error on the bed thickness, as a function of a dimensionless parameter defined by the ratio of the "true" bed thicknes to the dominant wavelength of the signal. The signal recorded is composed of two Ricker wavelets (each one reflected, respectively, at the top interface and the bottom interface of the thin bed layer) with different phase shift ($-\pi/6$, $-\pi/8$).