The Borga transform and some applications in seismic data analysis

Todor Todorov and Gary Margrave, The CREWES Project, University of Calgary*

Summary

Signal transforms form the bases for many seismic data processing and analysis algorithms. We present the adjoint of the Gabor transform, which we call the Borga transform. The Gabor transform uses the operations of first windowing and then Fourier transform while the Borga transform reverses the order so that the window is applied in the frequency domain. The result is a real-valued time-frequency decomposition that is essentially a complete set of frequency slices. When summed, the frequency slices exactly recreate the original signal.

The Borga transform can be used in various processing steps. Since ground roll noise is predominantly low-frequency and high-amplitude, one can separate it from the signal in a raw shot gather. Other types of noise can have a band-limited nature and anomalous amplitudes as well. By assuming local predictable behavior of the amplitudes in a CMP NMO-corrected gather, we can design a noise attenuation algorithm, based on the Borga frequency slices. The process can lead to better results in AVO analysis and inversion. The transform is a natural choice for time-variant spectral whitening. By applying an amplitude gain function for each frequency slice, one can compensate for time and frequency dependent amplitude attenuation.

Introduction

Signal transforms form the bases for many seismic data processing and analysis algorithms. Examples include the Fourier transform, the Radon transform, the Gabor transform (Margrave et al., 2011) and so on. The basic idea is that in a different domain various physical events (primaries, multiples, surface waves) and noises a better separable.

In this publication we present a new type of transform, the Borga transform, which can be viewed as adjoint of the Gabor transform. We believe it can be implemented in various seismic processing and analysis algorithms. Three examples are presented: CMP NMO-corrected gather noise attenuation, high-amplitude data separation and time-variant spectral whitening.

The Borga transform

In recent years the Gabor transform (short-time Fourier transform) has seen an increase application in seismic data processing and analysis. Examples include the spectral decomposition and the Gabor deconvolution (Margrave et al., 2011). In this publication we present the adjoint of the Gabor transform, which we call the Borga transform. The Gabor transform uses the operations of first windowing in time domain and then Fourier transform while the Borga transform reverses the order so that the window is applied in frequency domain. The result is a real-valued time-frequency decomposition that is essentially a complete set of frequency slices. When summed, the frequency slices exactly recreate the original signal.

The Fourier spectrum *S(f)* of a seismic trace *s(t)* is:

$$S(f) = \int_{-\infty}^{\infty} s(t) e^{-i2\pi ft} df \qquad (1)$$

Then we define the Borga transform as:

$$B(t, f') = \int_{-\infty}^{\infty} S(f) w(f - f') e^{i2\pi ft} df \qquad (2)$$

where *w(f)* is a Gaussian window, centered at frequency *f'*.

Figure 1 is a flow chart describing the Borga transform algorithm:

- Compute the complex Fourier spectrum of the input signal (seismic trace) via DFT.
- For each frequency:
- Multiply (window) the complex Fourier spectrum with a Gaussian window, centered at the frequency.
- IDFT of the windowed spectrum.

After repeating for all frequencies we compute a series of frequency slices of the seismic trace. Each one of them contains narrow band-pass information of the signal, such as amplitude strength and location in time.

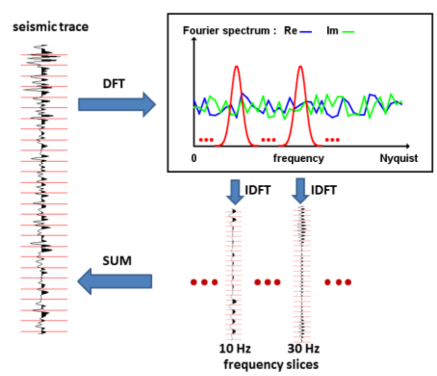

Figure 1: Flow chart of the Borga Transform. A seismic trace can be decomposed into frequency slices by performing DFT, windowing the complex Fourier spectrum and applying IDFT.

Applications

The Blackfoot seismic survey

A 3C-3D, 3C-2D seismic surveys were acquired over the Blackfoot field (Alberta, Canada) in 1995 (Stewart et all., 1995). The survey was sponsored by a group of Calgary based exploration companies and was planned and conducted by the CREWES Project, University of Calgary.

CMP gather noise attenuation

Figure 2 shows migrated NMO-corrected gathers from the Blackfoot survey and two Borga frequency slices at 10 Hz and 40 Hz. The gather in the middle contains a noisy trace. From the frequency slices we can see that the noise is mainly present at the 10 Hz frequency slice, while the 40 Hz looks relatively clean. It is obvious that noise can be band-limited in nature and have abnormal amplitudes at particular Borga frequency slices. For example, ground roll is relatively low frequency, while the power line noise has a very narrow, mid-range bandwidth.

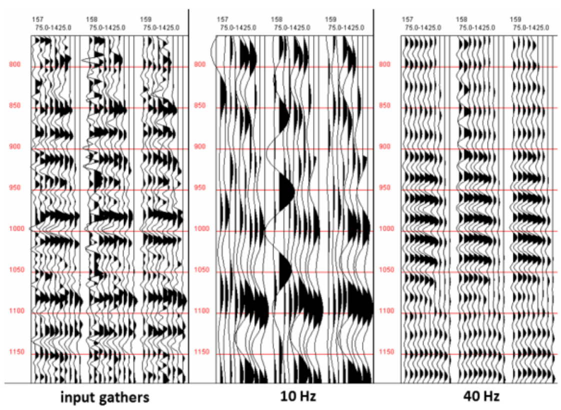

Figure 2: Blackfoot CMP NMO-corrected gathers and two Borga frequency slices at 10 Hz and 40 Hz. The gather in the middle contains a relatively noisy trace. The noise is present at 10 Hz frequency slice but not in the 40 Hz one.

Aki and Richards (1980) have shown us that within reasonable assumptions the amplitudes for a particular time change in a linear fashion with incidence angle. AVO intercept and gradient analysis are based on the linear assumption.

Based on the above assumptions we can design a noise attenuation algorithm:

- Start with a CMP NMO-corrected gather.
- Using the Borga transform, generate frequency sliced gathers.
- For each frequency slice:
- For each time:
- Estimate the amplitude of all samples, based on a linear-least squares fit of nearby samples (the predicted sample is not used in the least-squares).
- Compute the absolute error between the actual and estimated amplitudes.
- Correct the amplitude of the sample with the largest error.
- Repeat until the error is small.
- Sum all noise attenuated frequency sliced gathers to obtain the final result.

Figure 3 is an example of the process. The input data are CMP NMO-corrected gathers from the Blackfoot survey. The noise attenuated gathers show better signal-to-noise ratio and they are better suited for AVO analysis, inversion, and interpretation.

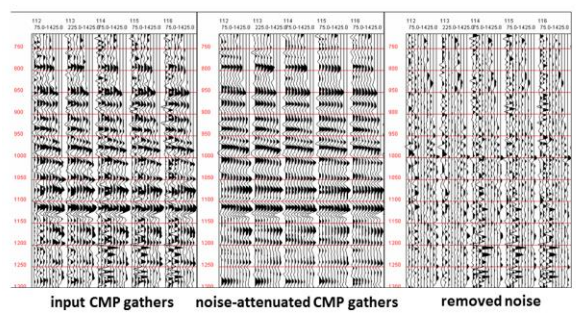

Figure 3: CMP NMO-corrected gather noise attenuation example from the Blackfoot survey. The noise attenuated gathers show better signal-to-noise ration and they are better suited for AVO analysis, inversion, and interpretation.

In order to investigate the amplitude preserving property of the described algorithm, we have generated an angle gather synthetics, 0-45 degree, based on the Zoeptitz equations. The model contains type II and type III AVO amplitude response. Figure 4 shows the model, model plus added noise, and the result of the noise attenuation on the noisy gather. The method has removed the noise successfully. Figure 5 is an amplitude plot, model verses model plus noise, of the type III AVO response. Figure 6 is a amplitude plot, model verses noise attenuated noisy gather, of the type III AVO response. The result and the plots clearly confirm the amplitude preserving property of the described algorithm.

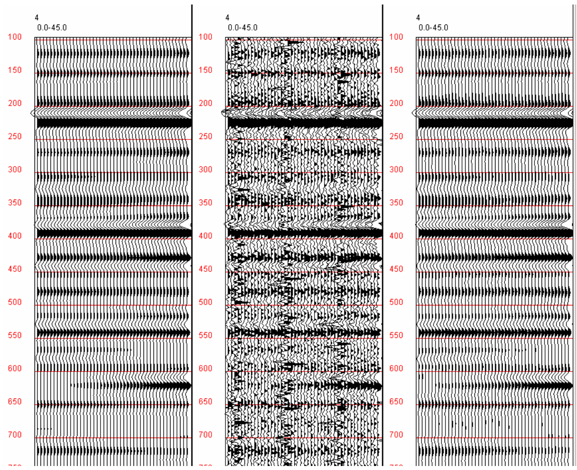

Figure 4: Synthetic data example of the CMP gather noise attenuation. Gather on the left is synthetic gather generated using the Zoepritz equation, angle range 0-45 degree. Gather in the middle is the synthtetics plus added noise and on the right is the noise attenuated result.

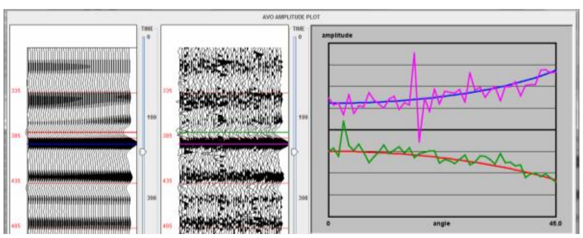

Figure 5: Amplitude plot of the type III AVO responce. Red – synthetics top, green – synthetics plus noise top, blue-synthetics base, magenta-synthetics plus noise base.

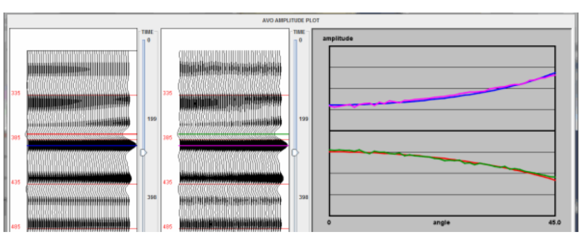

Figure 6: Amplitude plot of the type III AVO responce. Red – synthetics top, green – noise attenuated top, blue-synthetics base, magenta-noise attenuated base.

Frequency-dependent high-amplitude data separation

The Borga transform decomposes the single sample seismic amplitude into frequency dependent amplitudes. The ground roll will be present as band-limited high amplitudes. One can separate the data into anomalously high amplitudes and reasonable amplitudes, based on the following process:

- Apply the Borga transform to the seismic trace.
- For each sample, sort the frequency-dependent amplitudes in decreasing order. Anomalously high amplitudes will be in front of the array.
- Define a cutoff value: pick a reference amplitude value at the sample index that is, let say, 10 % from the start of the array and multiply it by a scaler, let say 2.
- Sum all the amplitudes, if amplitude is above the cut-off value, replace it with the cut-off value, the difference is defined as high-amplitude data.

Figure 7 is an example of the process. The input raw shot gather has been separated into two shot gathers: one with reasonable amplitudes and one with very high amplitudes, mostly ground roll and guided waves.

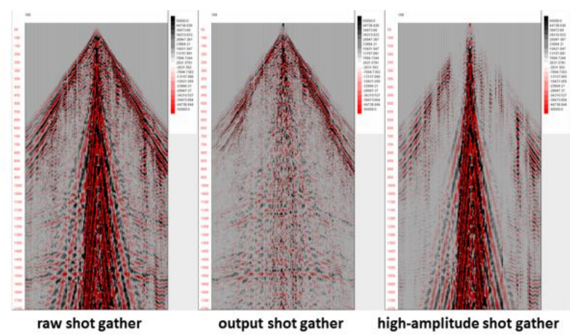

Figure 7: High-amplitude data separation: input shot gather has been separated into two gathers, one with reasunable amplitudes and one with very high amplitudes, mostly ground roll.

After separation one may apply a ground roll attenuation process, like f-k filter, on the high-amplitude shot gather and add back the result to the reasonable amplitude shot gather. This process will ensure that most of the signal has been preserved by the ground roll attenuation

Time-variant spectral whitening (TVSW)

Time-variant spectral whitening (Yilmaz, 2001) is a common seismic processing technique used to compensate for frequency dependent time amplitude decay. It is commonly applied after spiking deconvolution (Yilmaz, 2001) to improve the flatness of the amplitude spectrum.

The process is performed as follows:

- Pick a desired frequency bandwidth to be whitened, for example 8 – 70 Hz.
- Apple a series of narrow band-pass filters covering the desired bandwidth (frequency panels).

- Compute a time-dependent gain function, $g_f(n)$, for each frequency panel:

$$g_f(n) = \frac{A}{\frac{1}{M}\sum_{n-M/2}^{n+M/2} |a_i|} \qquad (3)$$

where:
A – desired output amplitude level
n – trace sample index
M - widow, usually 600-1000 ms

- Apply the gain function to the frequency panel
- Sum all frequency panels to form the whitened seismic section

The design of the narrow bandpass filters and their number is up to the processor. The Borga transform properties make it a natural candidate to perform TVSW on a seismic trace *s(t)*, by computing a gain function for each frequency slice $s_f(t)$:

$$s(t)_{TVSW} = \sum_f g_f(t) s_f(t) \qquad (4)$$

One may wish to restore the amplitude scaling of the original seismic trace in amplitude-friendly processing. Then the process is defined by:

$$s(t)_{TVSW} = \left[\sum_f g_f(t) s_f(t) \right] \sum_f \frac{1}{g_f(t)} \qquad (5)$$

Amplitude spectrum color can be introduced by using a frequency dependent desired output amplitude level *A(f)*, usually based on synthetics.

Figure 8 is an example of the TVSW with the Borga frequency slices in the range of 8-60 Hz on a raw shot gather from the Blackfoot survey.

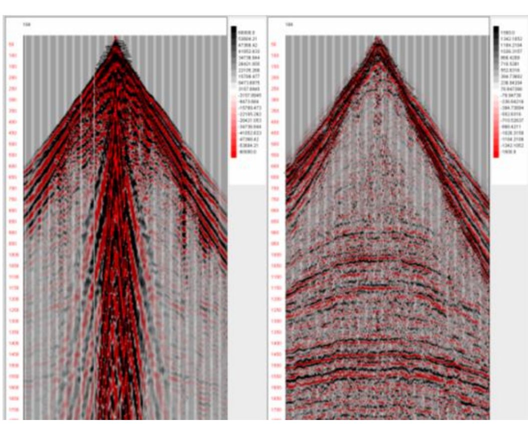

Figure 8: Blackfoot raw shot gather before and after TVSW.

Conclusions

The Borga transform decomposes the seismic signal into a complete set of frequency slices. This property makes the transform a useful tool for designing seismic data processing and analysis algorithms. The CMP NMO-corrected gather noise attenuation is an effective and AVO amplitude preserving method. The high-amplitude seismic data separation can be incorporated in a ground roll attenuation workflow and lead to better preservation of the underlying signal. The Borga transform allows as designing an effective TVSW algorithm and introducing color in the amplitude spectrum. We believe that more algorithms for seismic data processing and analysis, based on the Borga transform, can be developed.

Acknowledgments

The authors would like to thank the sponsors of the CREWES project, University of Calgary, for their continued support.