

# Simultaneous estimations of anelastic attenuation and outliers of propagated wavelet for adaptive least-squares Gabor deconvolution

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## Summary

The successes in seismic interpretation and reservoir characterizations rely heavily on the quality and bandwidth of the seismic data used regardless of if the seismic data acquired from new or legacy seismic surveys. Gabor deconvolution of seismic data is an effective method to enhance resolution of seismic section by mitigating the effects of nonstationary propagated wavelet due to anelastic attenuation. This paper presents a new method for enhancing resolutions of post migrated seismic data. In this work, we simultaneously estimate both anelastic attenuation and outliers of smoothed Gabor spectrogram of the deconvolution operator. Furthermore, the deconvolution of the seismic trace is obtained using adaptive Least square Gabor deconvolution to optimize time computations, reduce noise effects and broaden amplitude spectra. The proposed algorithms were applied to both synthetic and field seismic data and have proved their effectiveness and proposed theory. The adaptivity step in this method leverages the advantages of using a single propagated wavelet for a group of traces in poststack seismic section/ volume based on certain criterion of input seismic data. Thus, it reduces time computations and noise effects compared to trace-by-trace Gabor deconvolution method, yet it broadened amplitude spectra. The application of adaptive least-squares Gabor deconvolution to field data has improved lateral continuity of seismic reflectors, delineated thin channels and revealed many hidden stratigraphic features. Moreover, the proposed method has also proven to be AVO compliances by applying the method in ensemble mode, such as CDP- or CIG- gathers to preserve relative amplitude. The method also can work as trace-by-trace mode.

## Theory of Gabor Deconvolution

In seismic data processing, the dispersive characters of evolved propagated wavelet, due to anelastic attenuation (Kjartansson, 1979), of nonstationary seismic trace is tackled by Gabor deconvolution. Eliminating these effects improves resolutions of seismic imaging.

The non-stationary seismic trace (Margrave, 1998) is written as

$$\hat{S}(f) = \hat{W}(f) \int_{-\infty}^{\infty} \alpha(t, f) r(t) e^{-2\pi i f t} dt \quad (1)$$

where  $\widehat{W}$ ,  $\alpha(t, f)$  and  $r(t)$ , respectively are source wavelet, anelastic attenuation and reflectivity.

As Margrave et al. (2011), indicated, attenuation  $\alpha(t, f)$  is related to non-separable contributions of nonstationary dissipations described by Q factor and short path interbed-multiples.

The Gabor transform of seismic trace in the non-stationary Gabor deconvolution (Margrave and Lamoureux, 2001) is written as

$$\widehat{S}_g(t, f) \approx \widehat{W}(f)\alpha(t, f)\widehat{r}_g(t, f) \quad (2)$$

The product of  $\widehat{W}(f)\alpha(t, f)$  represents propagated wavelet, and seismic reflectivity is recovered by

$$\widehat{r}_g(t, f) = \widehat{S}_g(t, f)D(t, f) \quad (3)$$

where  $D(t, f) = \frac{1}{|\widehat{W}\alpha|_{est}(t, f) + \mu A_{max}} e^{-i\theta(t, f)}$

$D(t, f)$  is a time-frequency dependant Gabor deconvolution operator formed from  $|\widehat{S}_g(t, f)|$  by smoothing process. The reflectivity  $\widehat{r}_g(t, f)$  is obtained as point-wise division. The following section introduces a new method for smoothing propagating operator  $D(t, f)$ . This followed by an introduction to another technique to estimate reflectivity of seismic trace through Adaptive least-squares Gabor deconvolution.

### Joint estimations of $\alpha(t, f)$ and outliers of propagated operator $D(t, f)$

The magnitude spectrum of the propagating wavelet is estimated by smoothing the Gabor spectrogram of the seismic trace. In Margrave et al., (2011), the smoothing of the Gabor spectrogram is performed using a hyperbolic smoothing filter. While this method enjoys stable and smooth spectrogram of the propagated operator  $D(t, f)$ , however, it also attenuates the low frequency end of spectra slightly more than the high frequency of the deconvolved trace. Therefore, a new smoothing process is devised and implemented as an inverse problem and solved accordingly.

In the Gabor domain (time-frequency), the fussed Lasso (Tibshirani et al., 2005) equation for estimating smooth magnitude of propagated operator  $\widehat{\beta}$  is written as

$$\widehat{\beta} = \operatorname{argmin} \frac{1}{2} \|y - \beta\|_2^2 + \lambda_1 \|D\beta\|_1 + \lambda_2 \|\beta\|_1 \quad (4)$$

where  $y$  is the Gabor spectrogram of input trace (or group of traces), and  $D$  is a derivative operator of 1st or 2nd order. Moreover,  $\lambda_1$  and  $\lambda_2$  are regularizations parameters. Equation (4) promotes both sparsity and smoothness for estimated model parameters  $\widehat{\beta}$ .

In order to handle outliers in the magnitude of Gabor spectrogram used in estimating propagating operator, we use simultaneous estimations of smoothing  $D(t, f)$  and outliers  $v$  as

$$(\hat{\beta}, v) = \operatorname{argmin} \frac{1}{2} \|y - \beta - v\|_2^2 + \lambda_1 \|D\beta\|_1 + \lambda_2 \|v\|_1 \quad (5)$$

Equations (4) and (5) are linear inverse problems and are solved based on L1-minimization optimization methods. Several advanced techniques are experimented and have shown their robustness in solving fused Lasso inverse problems given in equations (4 and 5). The smoothing algorithms can be iterated, and the regularization parameters can be adjusted to ensure a smooth magnitude of  $D(t, f)$  is achieved accordingly.

### Adaptive Least squares Gabor Deconvolution

In this section, we estimate seismic reflectivity using Least-squares inverse problems rather than using point-wise division method. The proposed method has advantages by iteratively refining estimated reflectivity solutions. The adaptive least-squares Gabor deconvolution of seismic trace is also a linear inverse problem based on L1-minimization and is written as

$$\hat{r}_g = \operatorname{argmin} \frac{1}{2} \|\hat{S} - \hat{W}r_g\|_2^2 + \lambda_1 \|D r_g\|_1 \quad (6)$$

The obtained reflectivity  $\hat{r}_g$  from equation (6) is in time-frequency domain. Therefore, an inverse Gabor transform is performed to the deconvolved trace to obtain reflectivity in time domain. The Gabor deconvolution method is a spike deconvolution method and does not differentiate between good signal and noise. Therefore, and depends on the seismic data used in the algorithm for noise attenuation, a dip-guided filter (Fehmers and Hocker, 2003) should be applied. A robust Cadzow filter has also been developed to handle random noise that might appear after applying the proposed algorithm.

### Results

A synthetic non-stationary seismic trace is generated using a minimum phase source wavelet with a dominate frequency of 25Hz and Q value of 25. The trace length is set to 2 second and sampling interval,  $dt = 0.002$ . The objective is to simulate aseismic trace from a deep reservoir in highly attenuated media, where thin reservoirs often encounter. The adaptive least-squares Gabor deconvolution algorithms are applied to examine their ability to recover signal (or reflectivity) of deep section of input attenuated trace. Figure (1a) shows the result after applying the proposed methods. Notice the deconvolved trace (green color) managed to recover reflectivity of deep attenuated signal below one second in time-axis. Figure (1b) shows associated amplitude spectra, where spectrum of deconvolved trace has substantially whitened and fairly matches the amplitude spectra of true reflectivity.

Figure (2) shows a seismic stack section (Saeed, 2013) from Pikes-peak Heavy oil field. New details inside Waseca channels have further been revealed in figure (3) as well as another

interesting target (both circled) after applying proposed algorithms in this paper. Figure (4) shows that the amplitude spectrum has flattened and expanded in both low- and -high frequency ends.

## Conclusions

We show the effectiveness of the joint estimate of anelastic attenuation and outliers for smoothing the Gabor spectrogram to estimate propagated operator. The adaptive least-squares Gabor deconvolution has been applied to CIG gathers and stack sections and demonstrated to be a robust tool in preserving AVO signature and providing high resolution seismic image, as it improves spatial continuity of seismic reflectors and broadens seismic amplitude spectra.

## References

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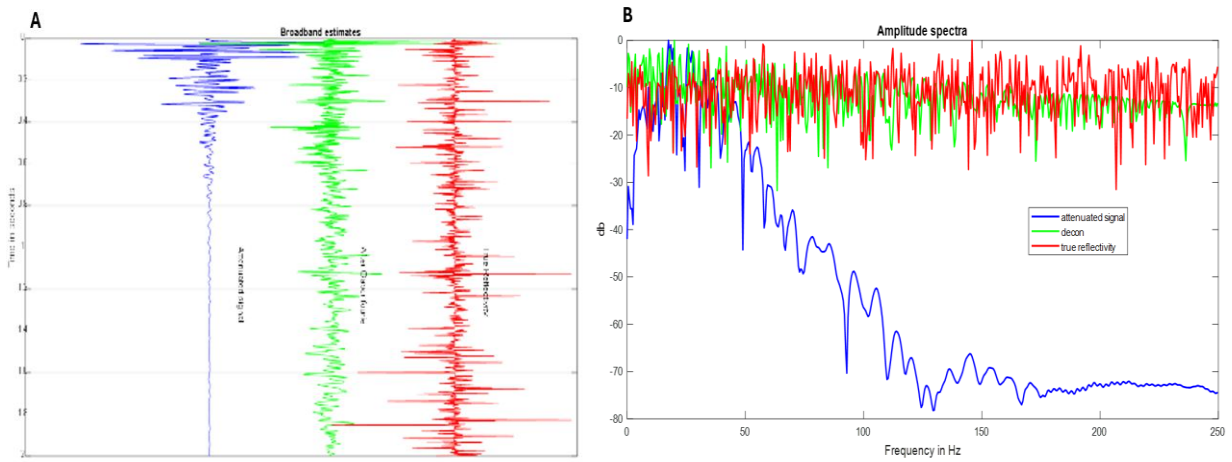


Figure 1: (A) Application of adaptive least-squares Gabor deconvolution to attenuated synthetic trace. Attenuated signal (blue), deconvolved signal (green) and true reflectivity (red). (B) amplitude spectra.

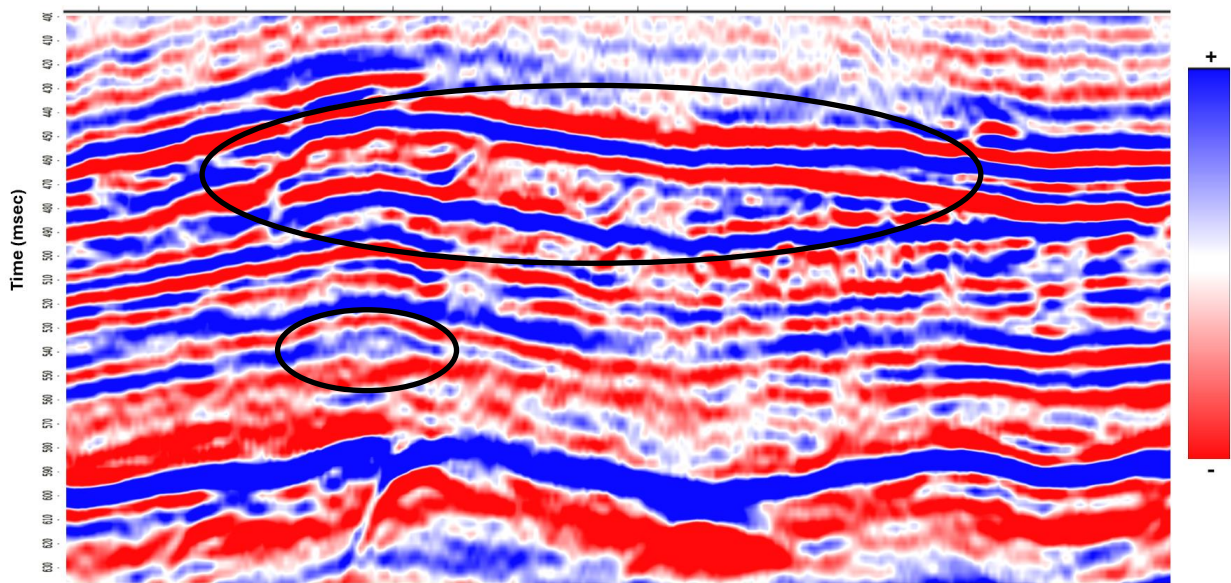


Figure (2). Seismic stack section, Pikes-Peak Heavy oil. Circles to highlight features of interest that will be shown in next figure

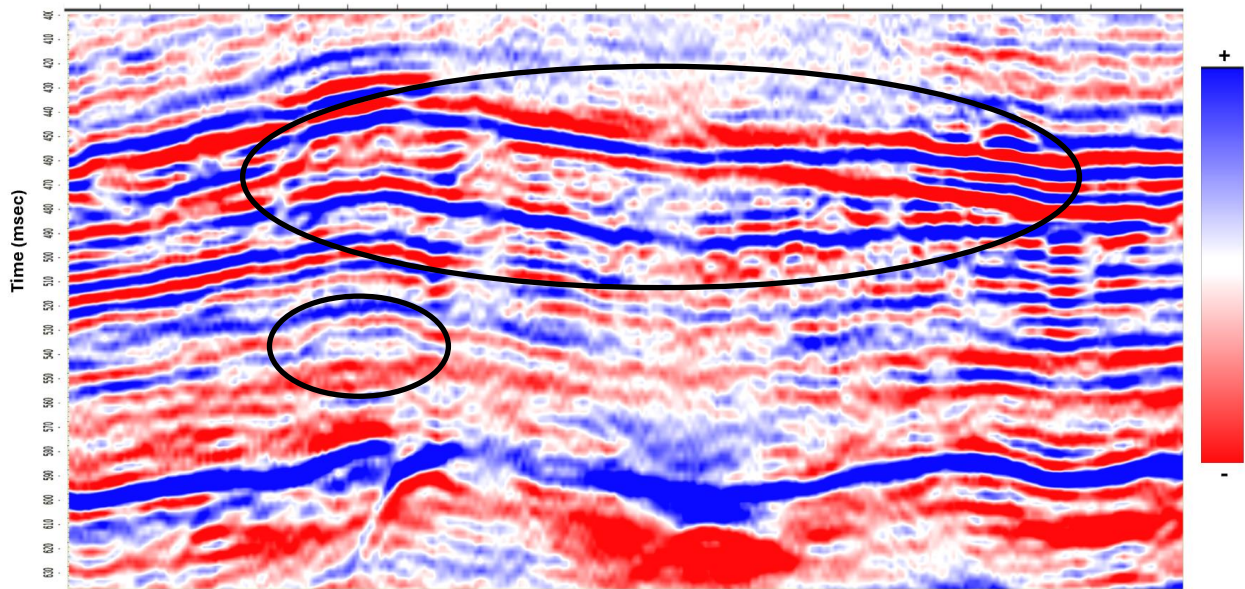


Figure (3). Seismic stack section, Pikes-Peak Heavy oil after applying Adaptive Least-squares Gabor deconvolution. Notice more details are now showing inside Waseca channel. Also, another interesting target now appears.

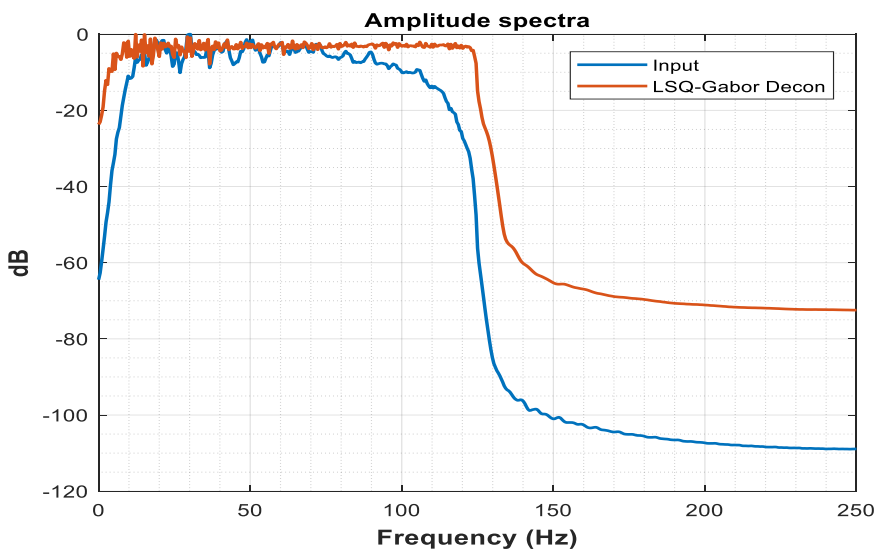


Figure (4). Seismic amplitude spectra before and after applying adaptive least-squares Gabor deconvolution to seismic stack section.