The use of Laguerre-Gauss transform in 2D reverse time migration imaging

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Abstract

Zero-Lag Cross-Correlation Imaging condition (ZL-CC-IC) is widely used in Reverse Time Migration (RTM) for the recovery of structural images of the subsurface. The presence of spatial low frequency noise so called artifacts, is one of the challenges of post processing in certain complex velocity field models with special features. Paniagua and Sierra-Sosa (2016) proposed a new post processing technique for the edge enhancement and reduction of low frequency artifacts; now our aim is to demonstrate the good performance of this technique and establish quantitative features and relations between the numerical results and the physical phenomenon. We present a comparative spectral study of the zero-lag cross-correlation imaging condition (ZL-CC-IC), zero-lag cross-correlation plus Laplacian filtering (ZL-CC-LP) and zero-lag cross-correlation plus Laguerre-Gauss filtering (ZL-CC-LG) showing their frequency features, also we show some results of the Laguerre-Gauss filtering applied in complex synthetic datasets and finally, using a smoothed velocity model in order to simulate the uncertainties of a real application, we show the good results obtained by using the Laguerre-Gauss Filtering posterior to RTM.

Introduction

The imaging condition in reverse time migration (RTM) has been conventionally obtained by the zero lag cross-correlation (ZL-CC) by examining the double summation of products of seismic amplitudes between the source and the receiver wavefields. One of them, summed in time domain and the other one, summed in the source domain. (Claerbout, 1971, 1985). This imaging condition is kinematically accurate at the reflectors due to the fact that incident and reflected wavefields are coincident in space and time (Liu, et al., 2011), but the migrated amplitudes no longer hold any physical meaning. It produces kinematically correct images of the geometry of the subsurface structure (Chattopadhay and McMechan, 2008).

However, the image is contaminated with low spatial frequency noise (Artifacts) due to the unwanted cross-correlation of diving waves, head waves and backscattered waves (Suh and Cai, 2009).

For small impedance contrasts the cross correlation is a good approximation for the imaging condition. However, for large impedance contrasts the low frequency artifact becomes stronger and distorts the image (Kaelin, 2006, Tary et al., 2016). In presence of strong velocity changes, strong amplitude changes occur and the appearance of artifacts is greater than in smooth velocity changes (Loewenthal et al, 1987).

Different techniques have been proposed to eliminate or reduce the low frequency noise, which can be classified in: i) wavefield propagation approaches (wave equation is modified), ii) imaging condition approaches (reflection energy is kept in the final image) and iii) post-imaging condition approaches (image is filtered) (Guitton et al., 2007).

In regard to the latter, the Laplacian filtering is the post-processing technique frequently used to attenuate the low frequency artifacts present in the structural image obtained through ZL-CC-IC but it increases the high frequency noise in the image (Guitton et al., 2007). Looking for a new technique that allows for the enhancement of the structural images obtained in RTM, Paniagua and Sierra-Sosa (2016) proposed the use of the Laguerre-Gauss transform in the post-processing of the image obtained by zero-lag cross-correlation imaging condition (ZL-CC-IC). The kernel of this transformation is called the Laguerre-gauss filter and it consists in a pure-phase function that is composed by a heavy-side function with a π gap when crossing the origin in every angular direction and in the amplitude is a Gaussian toroid. With this spatial bandpass filter, the low-frequency noise (artifacts) is reduced and the subsurface structures are more defined. This filter enhances the edges without resolution loss.

It is important to demonstrate that as post processing strategy, the Laguerre-Gauss filtering (ZL-CC-LG) improves the images obtained even in complex structures and the high frequency noise is also removed, enhancing the capability of interpretation. Also, by featuring the frequency spectrum allows for the quantification of the advantages to be used in a future research.

In this paper, we show some spectral features of the Laguerre-Gauss filtering in the post-processing of seismic images obtained by the conventional zero-lag cross-correlation imaging condition and the good performance of this filter in the edge enhancement and reduction of low frequency artifacts.

First, we compare and analyze the Fourier spectra obtained by the spatial 2D fast Fourier transform of the images obtained by the zero-lag cross-correlation (ZL-CC-IC), zero-lag cross-correlation plus Laplacian filtering (ZL-CC-LP) and zero-lag cross-correlation plus Laguerre-Gauss filtering (ZL-CC-LG). Second, we show some results of the Laguerre-Gauss filtering applied in synthetic datasets and finally, using some smoothed velocity models, we present a good results obtained by using the Laguerre-Gauss Filtering in complex synthetic models.

Effects of the Laguerre-Gauss filter in the magnitude spectrum

In order to illustrate our purpose, we consider a synthetic two-layer model with a horizontal and vertical distance of 1.5 km as shown in Figure 1. We used 21 shot points. The first source is located at 0.25 km and the last one at 1.25 km from the beginning of the model; the source interval is 25 m; each shot contains 301 receivers and the receiver interval is 5 m.

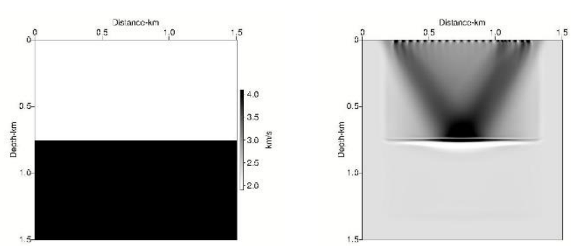
We use a reverse time migration (RTM) algorithm with a second and eighth order finite difference scheme in time and space, respectively to migrate this model and the seismic image is obtained by zero lag cross-correlation imaging condition given by equation 1:

$$I_{cc}(x,z) = \sum_{j=1}^{s_{max}} \sum_{i=1}^{t_{max}} S(x,z;t_i;s_j)R(x,z;t_i;s_j) \qquad (1)$$

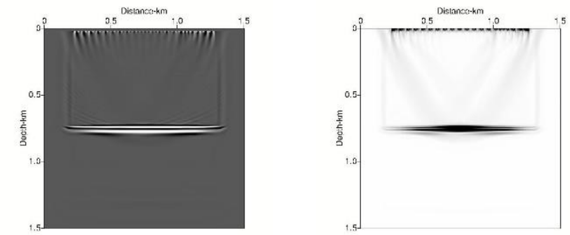
where $S(x,z,t)$ and $R(x,z,t)$ are the source and receiver wavefield, respectively; z denote depth and x is the horizontal axis, t is time, t_{max} is the total time, s_{max} is the total number of sources, and I_{cc} is the cross-correlation image.

This image is post-processed by using the Laplacian filtering (Youn and Zhou, 2001) and Laguerre-Gauss filtering (Paniagua and Sierra-Sosa, 2016). In order to compare, the resulting images are showed in Figure 1.

Figure 1b corresponds to the RTM image obtained by cross-correlation imaging condition (ZL-CC-IC), it can be seen that image is contaminated with low frequency artifacts (Dark shadows) above and near the reflective event and in the shallow parts. In Figure 1c we show the RTM result by using the Laplacian filtering (ZL-CC-LP). The artifacts are reduced, but some high frequency noise remains in the image close to the surface. On the other hand, the result obtained by applying the Laguerre-Gauss filtering (ZL-CC-LG) is shown in Figure 1d. The artifacts in shallow parts and near the reflective event are significantly reduced and the subsurface structure focalized by the gather shots is more defined and enhanced (Left and right spaces are due to the absorbent boundaries).



(a) (b)



(c) (d)

Figure 1. Two-layer model RTM using: a) Velocity model b) ZL-CC-IC c) ZL-CC-LP d) ZL-CC-LG.

In order to describe properly the L-G filter, the magnitude of the spatial Fourier spectrum of the images presented above is shown in Figure 2 (Left column). It is interesting to find out a way to properly compare the results of the post processing procedure so we perform the line profile of the Fourier Spectrum in order to extract features (Sierra- Sosa et al, 2016) and compare the intensity profiles and related them to the enhancement of the edges in the structural image.

The horizontal (x- axis) and vertical (z- axis) line profile is evaluated in each spectrum (center and right column, respectively). The top row corresponds to the zero lag cross-correlation image ZL-CC-IC crossing the origin of the Fourier spectrum, the center row to the cross-correlation image plus Laplacian filtering ZL-CC-LP and the bottom row to the cross-correlation image plus Laguerre-Gauss filtering ZL-CC-LG**.**

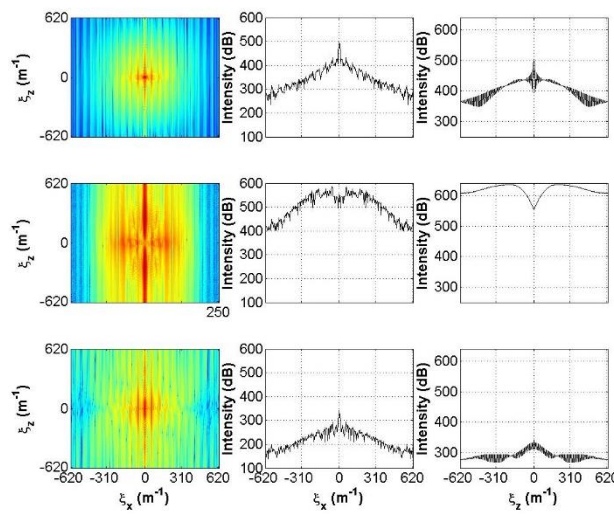


Figure 2. Magnitude of the spatial Fourier spectrum and horizontal and vertical line profiles from images presented in Figure 1.

From vertical profile, we can note that the Laplacian filtering modifies the intensity of low frequencies abruptly and increases the intensity in high frequencies. In horizontal profile, the intensity of the line profile was increased in all frequency values. These modifications are evidenced in the strong changes in the shape of the line profiles from the Fourier spectrum of the Laplacian image respect to the Fourier spectrum of cross-correlation image.

On the other hand, the Laguerre-Gauss filtering shows a good behavior due to its isotropic feature. In addition to the advantage of spatial isotropic common to the Riesz transform stemming from the spiral phase function, the Laguerre-Gauss transform has the favorable characteristics to automatically exclude any DC component of the original input function (Wang et al., 2006).

The intensity at low and high frequencies are distributed smoothly and homogeneously. The shape of the horizontal line profile of Laguerre-Gauus spectrum is similar to the horizontal line profile of the cross-correlation spectrum. In vertical profile the variations in intensity at high and low frequencies are attenuated and smoothed.

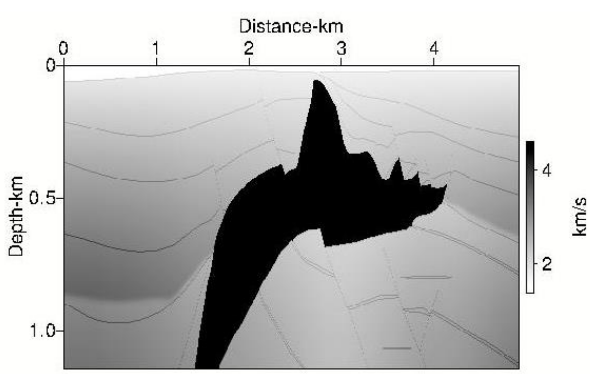
Numerical examples

To show the major effects of the Laguerre-Gauss filtering, we apply the same strategy to the 2D SEG-EAGE salt model. The length of the model is 4.91 km; the depth of model is 1.14 km. we lay out 32 shot points. The first source is located at 0.19 km and the last one at 4.72 km. Each shot contains 1290 receivers and the receiver interval is 3.81 m.

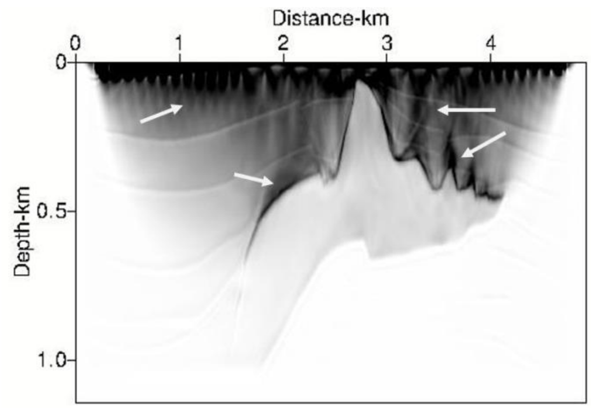
We applied RTM using the ZL-CC-IC, ZL-CC-LP and ZL-CC-LG. Similarly, the results obtained in the Fourier spectrum of each image and line profiles is analyzed.

In Figure 3a the velocity model of 2D SEG-EAGE salt model is presented. Figure 3b shows the image obtained by applied RTM using the ZL-CC-IC. The image is contaminated with low frequency artifacts in the shallow parts and close to the salt body. We can note that these artifacts are located near at sharp interfaces and the shallow structures above the salt body are almost invisible. Some artifacts are marked with white arrows.

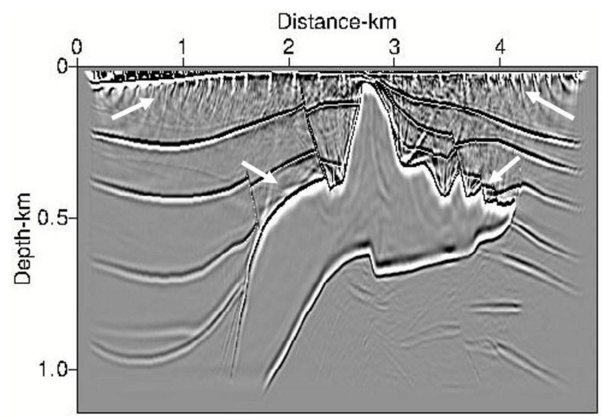
Applying the Laplacian filter, the artifacts are reduced but in different parts there are some high frequency noise (Marked with arrows) (Figure 3c). The seismic image is improved to applying the Laguerre-gauss filtering (Figure 3d). The artifacts are significantly reduced, the subsurface structures are more defined and the flanks of the salt body are enhanced.



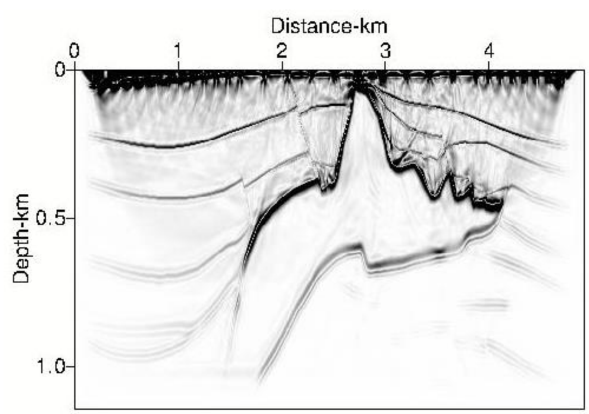
(a)



(b)



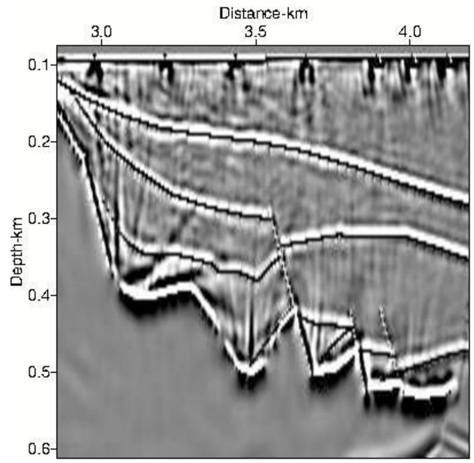
(c)



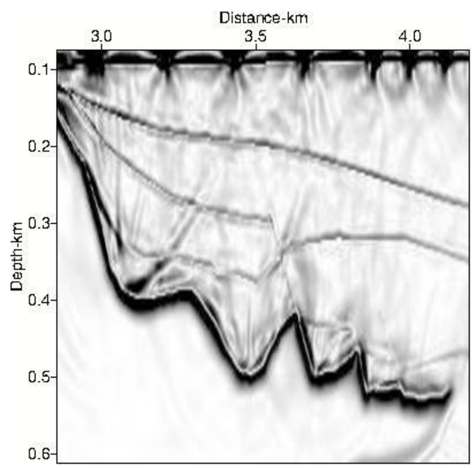
(d)

Figure 3. 2D SEG-EAGE salt model: a) Velocity model; RTM result with: b) Cross-correlation imaging condition c) Cross-correlation imaging condition plus Laplacian filter d) Cross-correlation imaging condition plus Laguerre-Gauss filter.

Figure 4 shows a close-up view of the images obtained by ZL-CC-LP and ZL-CC-LG. These images correspond to an enlargement of the upper right hand corner of the salt body in Figure 3.



(a)



(b)

Figure 4. Detail of 2D SEG-EAGE RTM image with: a) ZL-CC-LP and b) ZL-CC-LG.

We can note that the artifacts are largely reduced, the image is improved and the edges are enhanced, especially the salt flanks of the salt body.

As presented in previous section for the two-layer model, the Fourier spectra and the horizontal and vertical line profiles are analyzed in order to quantify the effect of the Laplacian and Laguerre-Gauss filtering in the Fourier spectrum of the cross-correlation image.

In Figure 5, the top row corresponds to the magnitude spectrum and the horizontal and vertical lines profiles of the cross-correlation image, respectively, the center row to the cross-correlation image plus Laplacian filtering and the bottom row to the cross-correlation image plus Laguerre-Gauss filtering**.** Similarly, horizontal and vertical line profiles cross the origin of the Fourier spectrum.

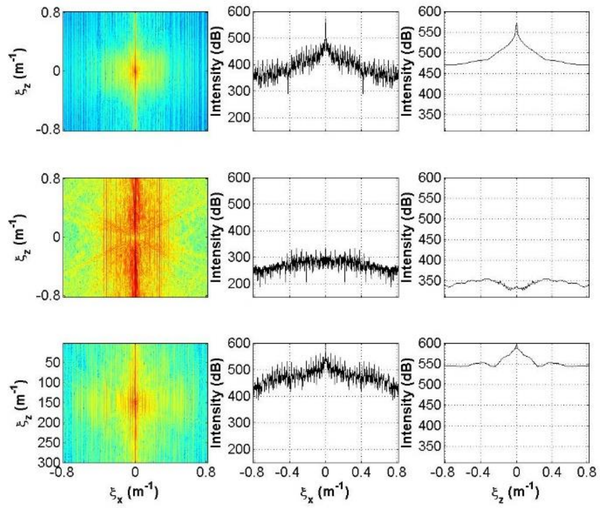


Figure 5. Magnitude spectra and horizontal and vertical line profiles from images of 2D SEG-EAGE RTM.

The Laplacian filtering shows a strong attenuation of the intensity at high and low frequency noise, modifying the shape of the line profiles, and changing the intensity in each spatial frequency value. We can note this effect in the shape of the horizontal and vertical line profiles. In the vertical line profile, the reduction is more evident in the intensity at low frequencies values.

Laguerre-Gauss filtering shows that the intensity in all frequency values are modified homogeneously and smoothly. The shape of the horizontal line profile is similar to the shape of the horizontal line profile of the cross-correlation spectrum. From vertical line profile, we can note that the variations of the intensity are smoother and evenly distributed.

Smoothed velocity model

In order to show the capability of the post processing strategy proposed, the original velocity model of 2D SEG-EAGE model (analyzed in previous section) was smoothed by using a 2D spatial Gaussian filter with an arbitrarily chosen standard deviation of 10 to simulate uncertainties. The velocity model obtained is shown in Figure 6.

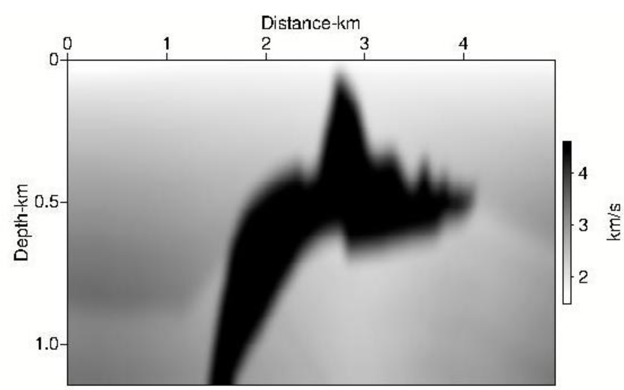
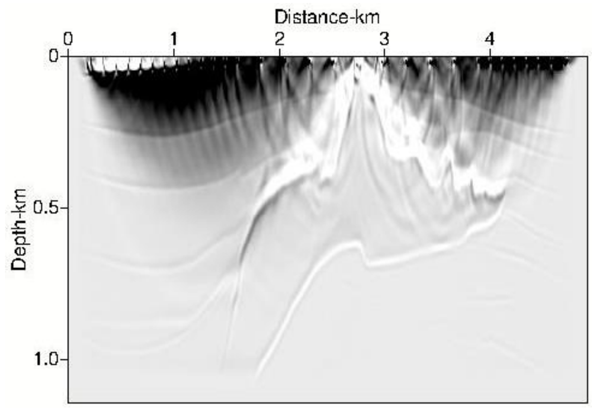


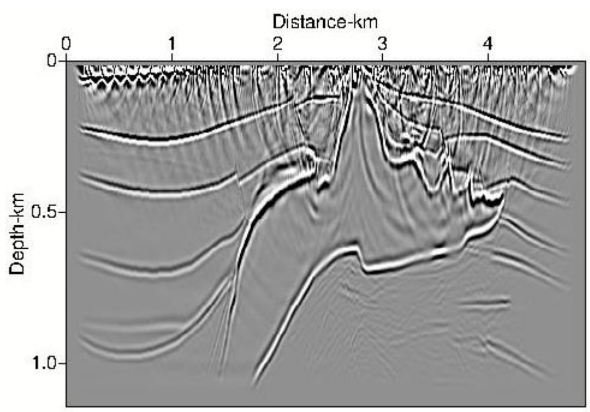
Figure 6. Smoothed velocity model of 2D SEG-EAGE model

To simulate a real scenario, Figure 7 shows the migrated smoothed (uncertain) velocity model via RTM presented in Figure 6 but using the data recorded in the surface obtained migrating the original velocity model showed in Figure 3a.

Figure 7a shows the image obtained by cross-correlation imaging condition. We can note the strong low frequency artifacts in the shallow parts above the salt body and close to the flanks of the salt body. The artifacts almost completely cover the shallow structures. The ZL-CC-LP image is shown in Figure 7b. The Laplacian filtering shows a good reduction of artifacts; the subsurface structures are enhanced but the high frequency noise is increased.



(a)



(b)

Figure 7. 2D SEG-EAGE RTM with the smoothed velocity model using: a) ZL-CC-IC b) ZL-CC-LP

Applying the ZL-CC-LG, the image is improved. Due to its characteristic of being bandpass filter, the low and high frequency noises are attenuated. The artifacts in shallow parts and near the salt dome are significantly reduced. The edges are enhanced, especially the salt flanks of the salt body. Despite the smoothed velocity model, the Laguerre-Gauss filtering has a good behavior by enhancing the structures and flanks of the salt body and the reduction of low spatial artifacts (Figure 8).

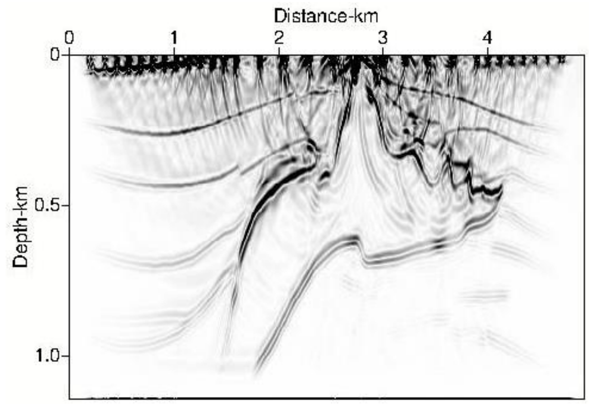


Figure 8. 2D SEG-EAGE RTM with the smoothed velocity model using ZL-CC-LG.

In Figure 9, the Fourier spectra and the horizontal and vertical line profiles are shown. The top row corresponds to the magnitude spectrum and the horizontal and vertical lines profiles of the cross-correlation image, respectively, the center row to the cross-correlation image plus Laplacian filtering and the bottom row to the cross-correlation image plus Laguerre-Gauss filtering**.** Similarly, horizontal and vertical line profiles cross the origin of the Fourier spectrum.

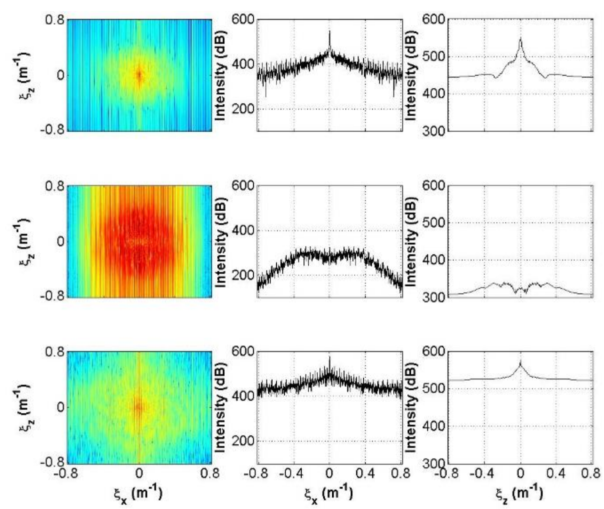


Figure 9. Magnitude spectra and horizontal and vertical line profiles from images of 2D SEG-EAGE RTM with smoothed velocity model.

Comparing the horizontal line profile of three spectra, the Laplacian filtering significantly modifies the intensity values at each frequency and the shape of the line profile. Similarly, from the vertical profile, we can observe that the variations in intensity in high and low frequency are strong in Laplacian filtering spectrum.

The magnitude of the spatial spectrum of Laguerre-Gauss image presents a spatial distribution of the intensity homogeneously compared with the other spectra. The line profiles of the Laguerre-Gauss spectrum show that the shape of these are preserved and the intensity in both line profiles are smoother.

This post-processing technique was used in other complex models, such as 2D Sigsbee2A, Marmoussi, among others, with the original and smoothed velocity models, achieving good results and improved images.

Conclusions

The conventional zero-lag cross-correlation imaging condition (ZL-CC-IC) used in reverse time migration produces low frequency artifacts because the incident and reflected wavefields are in phase at locations that are not the reflection points. The Laplacian filter is an easy technique for the post-processing of the cross-correlation image. This filter reduces the artifacts but increases the high frequency noise.

Laguerre-Gauss filtering is a post-processing technique that avoids the high frequency noise and reduces the artifacts due to its feature of being a bandpass filter. The effect of the Laplacian filtering in the spatial Fourier spectrum is a strong modification of the intensity in high and low frequency values. The shape of the horizontal and vertical line profiles that cross the origin of the Fourier spectrum are significantly modified.

On the other hand, we showed that the Laguerre-Gauss filter has a good behavior and distributed homogeneously and smoothly the intensity of the magnitude of the Fourier spectrum. This effect is due to its isotropic feature. The shape of the horizontal and vertical line profiles is similar to the line profiles of the cross-correlation spectrum but the intensity in all frequency values are distributed smoothly.

When the Laguerre-Gauss filtering is applied in presence of smoothed velocity models, we obtain similar results, achieving the attenuation of the low frequency noise and the preservation of the reflections. It seems promising for real applications in which the velocity model is highly uncertain, allowing to obtain good images of the subsurface without having a closely related to reality velocity model. From the spatial Fourier spectrum of the Laguerre-Gauss filtering, we can note the same behavior presented when the original velocity model is used. In future work we are going to explore the increasing in the velocity models to demonstrate how accurate this strategy can be for artifacts removal in RTM.

Acknowledgments

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References

Chattopadhyay, S., and McMechan, G., 2008, Imaging conditions for prestack reverse time migration: Geophysics, 73, 3, S81 - S89.

Claerbout, J. F., 1971, Toward a unified theory of reflector mapping: Geophysics, 36, 467-481.

Claerbout, J. F., 1985, Imaging the Earth's interior: Blackwell Scientific Publications.

Debnath, L., and Bhatta, D., 2010, Integral transforms and their applications: CRC press.

Guitton, A., Kaelin, B., and Biondi, B., 2007, Least-square attenuation of reverse time migration: 76th International Annual Meeting, SEG, Expanded abstracts, 2348 – 2352.

He, B., Tang, D., He, Y., Xie, X. and Long, B., 2016, The imaging resolution analysis for complex models applied in seismic survey design: 86th International Annual Meeting, SEG, Expanded abstracts, 265 – 269

Kaelin, B., and A. Guitton, 2006, Imaging condition for reverse time migration: 76th International Annual Meeting and exposition, SEG, Expanded abstracts, 2594-2598.

Liu, F., Zhang, G., Morton, S., and Leveille, J., 2011, An effective imaging condition for reverse time migration using wavefield decomposition: Geophysics, 76, 10 - 29.

Loewenthal, D., Stoffa, P. and Faria, E., 1987, Suppressing the unwanted reflections of the full wave equation: Geophysics, 52, 7, 1007-1012.

Paniagua, J. G. and Sierra-Sosa, D., 2016, Laguerre Gaussian filters in reverse time migration image reconstruction: VII Simpósio Brasileiro de Geofísica, Resumos expandidos.

Sierra-Sosa, D., Bastidas, M., Quintero, O.L, 2016. Double Fourier analysis for emotion identification in voiced speech: Journal of Physics: Conference series, 705.

Suh, S. Y., and Cai, J., 2009, Reverse time migration fan filtering plus wavefield decomposition: International exposition and annual meeting, SEG, Expanded abstracts, 2804-2808.

Tary, J., van der Baan, M., and Herrera, R., 2016, Attenuation estimation using high resolution time-frequency transforms: Dig. Sig. Proc. August 2016. DOI: 10.1016/j.dsp.2016.08.007

Wang, Z., Ding, H., Lu, G., and Bi, X., 2016, Reverse time migration based optical imaging: IEEE Transactions on medical imaging, 35, 1, 273-281.

Wang, W., T. Yokozeki, R. Ishijima, M. Takeda, and S. G. Hanson, 2006, Optical vortex metrology based on the core structures of phase singularities in Laguerre-Gauss transform of a speckle pattern: Optics Express, 14, 10195-10206.

Youn, O., and H. Zhou, 2001, Depth imaging with multiples: Geophysics, 66, 246-255.