Title:

A noise robust approach for delineating subsurface structures within migrated seismic volumes

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Summary:

In this paper, we propose and demonstrate the robustness of a three dimensional texture-based method, Gradient of Texture (GoT), for salt dome delineation in the presence of various types of random and non coherent noise. The noise robustness of GoT is inherent from the perceptual dissimilarity measure function that evaluates the dissimilarity between neighboring cubes in GoT along inline, crossline and time directions. The noise causes a shift in dissimilarity and hence the GoT map which is countered by the adaptive global threshold in the GoT post-processing. The experimental results of the synthetically induced noise on the real dataset from the North Sea, F3 block show the effectiveness of 3D-GoT to various types of noise. The majority of edge-based and texture-based algorithms fail to yield any results in current experimental setup, whereas GoT successfully delineates the salt domes with a minimal degradation in its performance.

Introduction

Salt domes are an important diapir shaped geophysical structures in the Earth's subsurface that are impermeable and contain hints about petroleum and gas reservoirs. Therefore, determining the accurate location of the salt domes within migrated seismic volumes in one of the key steps in the exploration projects. Over the last few years, researchers have proposed several methods, which include edge-based detection methods by Zhou et al. (2007), Aqrawi et al. (2011) and Amin and Deriche (2015b), texture-based methods by Berthelot et al. (2013), Hegazy and AlRegib (2014), Shafiq et al. (2015b) and Wang et al. (2015), graph theory based methods by Shi and Malik (2000) and Felzenszwalb and Huttenlocher (2004), active contours by Haukas et al. (2013) and Shafiq et al. (2015a), saliency based methods by Drissi et al. (2008) and Shafiq et al. (2016), and different image processing techniques by Lomask et al. (2007), Guillen et al. (2015) and Amin and Deriche (2015a) to delineate different structures within seismic volume. Guitton (2005) showed that the coherent noise can be attenuated using seismic inversion, which is driven by the covariance operator obtained by probability density function and pattern statistics of the noise, whereas Chopra and Marfurt (2014) mentioned that the noise such as ground roll, multiples, pump-jacks action and acquisition footprint create more coherent energy and however still remains as one of the challenging problems in seismic processing to date because they can be misinterpreted as a true signal. The presence of noise and amplitude variations in seismic data poses significant detection and delineation problems, whereas the vast majority of algorithms proposed in the past are sensitive to noise. These algorithms usually assume either data is noiseless or pre-processed using various noise removal techniques such as structured oriented filtering, principal component filtering, mean/median filtering, dip filtering or random noise removal. Furthermore, many assumptions are made on noise types and acquisition processing pipeline to simplify the noise removal process which are not always true. Although pre-processing removes a good amount of random noise, yet their remains in data after pre-processing coherent and random noise, which could seriously effect seismic interpretation. The noise within a seismic volume is contributed by various sources, which may vary across different crossline and inline directions as well. Furthermore, the noise from drilling rigs, outside activity, wind motion and cable vibrations effect the seismic traces that make noise space-time dependent. The complex space-time dependence makes the noise removal task for interpreters and computer aided models more challenging. The majority of the proposed algorithms for salt dome delineation don't address the noise problem directly and rather rely on the pre-processing of the seismic data. In this paper, we present one of the texture-based methods, three dimensional Gradient of Texture (3D-GoT) by Shafiq et al. (2015b), and demonstrate its robustness to various types of random noise.

Theory

The 3D-GoT highlight the changes between salt and non-salt regions by evaluating the perceptual dissimilarity between the two neighboring cubes that share a square face centered around the given voxel within a migrated seismic volume. The highest value in the GoT map indicates the maximum dissimilarity when the center point falls exactly on the texture boundary along the inline, crossline and time direction. An adaptive global threshold by Otsu (1979) is used to threshold the GoT map to yield a binary map, which is later used in region growing to form a 3D salt body. The 3D-GoT can perform robustly in

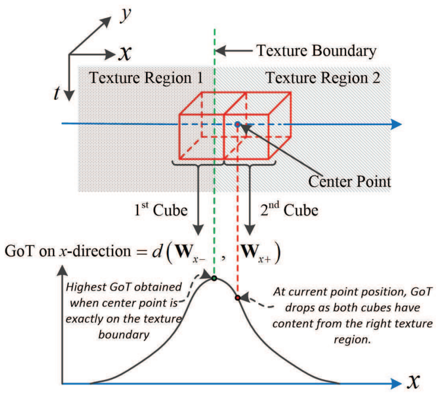


Figure 1: Illustration of GoT along x-direction

Table 1: *SalSIM* indices for different inlines

Noise Type	Inline	No.		
	#372	#382	#386	#401
None	0.9491	0.9249	0.9340	0.9082
Gaussian	0.9470	0.9187	0.9157	0.8959
Poisson	0.9489	0.9184	0.9231	0.9033
Speckle	0.9411	0.9044	0.9247	0.9025
Salt&Pepper	0.9343	0.9064	0.7513	0.8988
Combination	0.9205	0.9168	0.9067	0.9013

the presence of noise and requires very few parameters as compared to other algorithms. The details of theory and processing framework of 3D-GoT can be found in Shafiq et al. (2015b), whereas a brief description to outline the noise robustness is given in this paper. Given a 3D seismic data volume $\mathbf{V}$ of size $X \times Y \times T$, where X represents crosslines, Y represents inlines and T represents time depth, we evaluate GoT along crossline, inline and time directions, respectively. To evaluate the GoT in the x-direction (crossline), we calculate GoT at each voxel $[x,y,t]$ in x-direction. As we move the center point as shown in Fig. 1, and its two neighboring cubes, denoted W_x and W_{x+}, in the x-direction along the blue line, the texture dissimilarity along the blue line using the function $d(\cdot)$, we yield the GoT profile as the curve shown at the bottom of Fig. 1. Theoretically, the highest dissimilarity, and hence the highest GoT value is obtained when the center point falls exactly on the texture boundary. Similarly, GoT is also calculated along y and t directions. To improve the delineation efficiency and robustness, 3D-GoT employs a multi-scale gradient, which is the weighted average of GoT values calculated based on various cubes. The multi-scale 3D-GoT is mathematically expressed as

$$\mathbf{G}[x,y,t] = \left(\sum_{i \in \{x,y,t\}} \left(\sum_{n=1}^{N} \omega_n \cdot d\left(\mathbf{W}_{i-}^n, \mathbf{W}_{i+}^n\right) \right)^2 \right)^{\frac{1}{2}}, \tag{1}$$

$$d\left(\mathbf{W}_{i-}, \mathbf{W}_{i+}\right) = E\left(|\mathscr{F}\{|\mathscr{F}\{|\mathbf{W}_{i-} - \mathbf{W}_{i+}|\}|\}|\right), \quad i \in \{x,y,t\}, \tag{2}$$

$$\mathscr{F}[u,v,w] = \frac{1}{L^3} \sum_{x=0}^{L-1} \sum_{y=0}^{L-1} \sum_{t=0}^{L-1} f[x,y,t] e^{-2\pi i (xu+yv+tw)/L}, \tag{3}$$

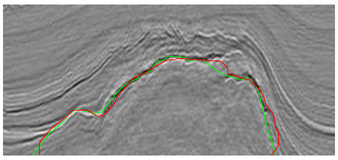
where $d(\cdot)$ is the dissimilarity function, which computes the perceptual dissimilarity between two cubes by applying two concatenated 3D-FFT magnitude operations to the absolute difference of neighboring cubes and averages the results using expectation operation E. $\mathscr{F}\{\cdot\}$ represents the 3D-FFT and $\mathbf{W}_-^n$ and $\mathbf{W}_+^n$ represent the two cubes of size n in negative and positive directions, respectively, with respect to the voxel at which GoT is calculated. $[x,y,t]$ and $[u,v,w]$ represent the coordinates of the spatial and frequency domains, respectively, and L defines the edge length of a cube-shaped data volume. If the migrated seismic data is contaminated by the random noise n, which may include gaussian, poisson, speckle, salt and pepper or combination of the aforementioned noise types, then the neighboring cubes at voxel $[x,y,t]$, denoted $\widehat{\mathbf{W}}_-$ and $\widehat{\mathbf{W}}_+$ are contaminated by the additive random noise. Therefore, (2) can be re-written as

$$d\left(\widehat{\mathbf{W}}_{i-}, \widehat{\mathbf{W}}_{i+}\right) = E\left(|\mathscr{F}\{|\mathscr{F}\{|\Delta W + \Delta n|\}|\}|\right), \quad i \in \{x,y,t\}, \tag{4}$$

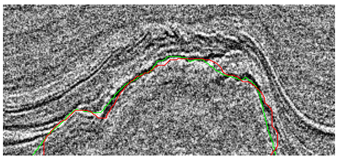
where $\Delta W = (\mathbf{W}_{i-} - \mathbf{W}_{i+})$ and Δn is the difference of additive noises in the two neighboring cubes. Using the linearity property, it can be shown that the dissimilarity function $d(\cdot)$ is same as that of noiseless volume, except they are contaminated with $\mathscr{F}\{\Delta n\}$. According to Wang et al. (2015) and Schoukens and Renneboog (1986), the noise can expressed as a complex signal over the cube of size $(2n+1) \times (2n+1) \times (2n+1)$ as

$$\mathscr{F}\{\Delta n\} = \sum_{x=0}^{2n-1} \sum_{y=0}^{2n-1} \sum_{t=0}^{2n-1} a[x,y,t] + i \sum_{x=0}^{2n-1} \sum_{y=0}^{2n-1} \sum_{t=0}^{2n-1} b[x,y,t], \tag{5}$$

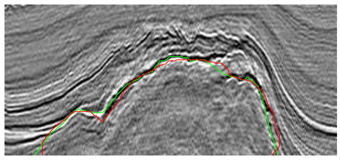
where a and b are two random variables, which subject the fourier coefficients of 3D-FFT to the summation of several random variables. The complex analysis of $\mathscr{F}\{\Delta n\}$ show that the amplitude spectrum of both 3D-FFTs in (4) will cause the dissimilarity measure $d(\cdot)$ to shift by a constant value equal to the mean of random noise. Therefore, theoretically the random noise in migrated seismic volume will cause the dissimilarity measure and hence the GoT to change by some constant value. The processing framework on 3D-GoT includes the adaptive global thresholding on GoT map which will counter the effects of noise on dissimilarity function and therefore the overall results of 3D-GoT will not be effected by noise.



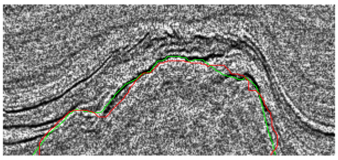
(a) Original seismic section



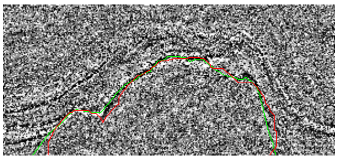
(b) Gaussian(0, 0.05) noise



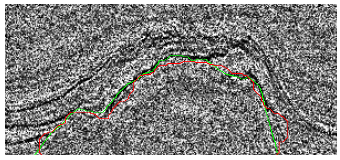
(c) Poisson noise



(d) Speckle noise



(e) Salt and pepper niose



(f) Combination of random noises

Figure 2: Experimental results of 3D-GoT on section section inline #372. Green: Ground Truth, Red: 3D-GoT by Shafiq et al. (2015b).

Experimental Results

In this section, we show the robustness of 3D-GoT to the synthetically induced noise on the real seismic dataset acquired from the Netherlands offshore, F3 block in the North Sea by dGB Earth Sciences (1987). The seismic volume that contains the salt dome structure has an inline number ranging from #151 to #501, a crossline number ranging from #401 to #701, and a time direction ranging from 1,300ms to 1,848ms sampled every 4ms. The original seismic section inline #372 and the results of 3D-GoT with different noise types are shown in Fig. 2. Fig. 2b–Fig. 2f show the seismic sections contaminated by gaussian noise having zero mean and 0.05 variance, poisson noise, additive speckle noise having multiplicative gaussian variance of 0.4, salt and pepper noise having density of 0.2 and mixture of different noise types, respectively. The output of 3D-GoT is labelled in red color, whereas the ground truth is manually labeled in green. Subjectively, it can be observed that the boundaries detected by 3D-GoT in all seismic sections contaminated by noise are very close to ground truth. The results show that the 3D-GoT performs very well in the presence of noise. To objectively evaluate the similarity between the detected boundaries and the ground truth, we have used the Fréchet distance based similarity index, *SalSIM* by Wang et al. (2015). The *SalSIM* index varies between 0 and 1, indicating minimum and maximum similarity between the two curves, respectively. The *SalSIM* indices of the detected salt dome boundaries for different seismic section inlines are shown in Table. 1, which show that the noise has a minimal effect on the 3D-GoT performance. It is worth mentioning that all other methods for salt dome delineation fail to yield any results for noise contaminated inlines, whereas the 3D-GoT performs very well even in the mixture of various noise types as shown in Fig. 2f.

Conclusions

In this paper, we have shown the robustness of 3D-GoT to various types of random noise. The noise in 3D-GoT shifts the perceptual dissimilarity function by a constant value which is countered by the adaptive global thresholding in the post-processing step thereby giving 3D-GoT robustness to various types of random and non coherent noises. The experimental results of synthetically induced noise on real seismic dataset demonstrates the noise robustness of 3D-GoT in migrated seismic volumes. The subjective and objective evaluation of the results show that 3D-GoT performs very well even in the mixture of various noise types, whereas other edge-based and texture-based algorithms fail to yield results for any type of such noise.

Acknowledgements

This work is supported by the Center for Energy and Geo Processing (CeGP) at the Georgia Institute of Technology and King Fahd University of Petroleum and Minerals.

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