

## Upcoming events

### 5<sup>th</sup> CeGP Workshop

KFUPM  
Dhahran, Saudi Arabia  
March 27-30, 2016



### ICASSP 2016

The 41<sup>th</sup> IEEE International Conference on Acoustics, Speech and Signal Processing.

Shanghai, China  
March 20-25, 2016

### SIAM IS 2016

Society for Industrial and Applied Mathematics Conference on Imaging Science.

Albuquerque, NM, USA  
May 23-26, 2016

### EAGE 2016

78<sup>th</sup> European Association of Geoscientists and Engineers Conference and Exhibition

Vienna, Austria  
May 30-June 2, 2016

### ICIP 2016

IEEE International Conference on Image Processing

Phoenix, AZ, USA  
September 25-28, 2016

### SEG Annual Meeting 2016

Society of Exploration Geophysicists Annual Meeting

Dallas, TX, USA  
October 16-21, 2016



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## Foreword by Directors

This is the second issue of the CeGP newsletter and several exciting developments have taken place since the publication of the first issue. This issue has several components on the excellent progress we have made in research, education, and outreach activities. As in any global operation, the beginnings are the hardest part and we believe we have passed that phase. This is evident from the number of joint publications and the activities that have taken place in the past eighteen months. We leave the details on the research progress to the several research summaries in the newsletter and to the impressive list of publications at the end of the document. Besides publication, CeGP has been working hard to build and share products that could be used by other researchers in both industry and academia. We are very proud of the number of downloads the S3I package has received over the past two years with researchers from five continents have downloaded the package. Also, we have created a fully labeled post-migration dataset for researchers to use when they apply learning algorithms to interpretation. Finally, we have created a software tool that is a benchmark to all salt dome delineation works. All those products are available to the public and they have been heavily downloaded by both industry and academia over the past few months.

Besides the excellent work in research, we have progressed well on the education front. CeGP planned, organized, and executed the first ever KFUPM Senior Design Expo in May 2015. We are using that collaboration to create a joint senior design experience in 2016 and beyond. Similarly, CeGP has designed and planned the first undergraduate research experience at KFUPM. This is taking place in spring 2016 and the plans to develop a joint global research experience for undergraduate students starting Fall 2016 are to follow. The long experience Georgia Tech has in this domain and the experience KFUPM will gain in Spring 2016 will be instrumental for this global effort.

Furthermore, in the outreach activity, we have had excellent visitations in 2015/2016 and the outcomes are very fruitful and impactful on the joint efforts. The visits by Dr. Ali Muqiabel and Dr. Suhail Al-Dharrab have been very productive and instrumental as you will read in this newsletter. We look forward to a new very productive year and perhaps it is a year that takes the products from papers and software packages to patents and joint ventures.

Finally, we thank the unmatched support from the administrations of KFUPM and Georgia Tech. We also thank everyone who contributed to this newsletter with special thanks to Motaz Alfarraj for all the great efforts in putting this newsletter together.



Dr. Ali Al-Shaikhi  
Director, CeGP @ KFUPM



Prof. Ghassan AlRegib  
PI & Director, CeGP @ Georgia Tech

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# SalSi: A New Seismic Attribute for Salt Dome Detection

Muhammad Amir Shafiq, Tariq Alshawi, Zhiling Long, Ghassan AlRegib, and Suhail Al-Dharrab

Saliency detection aims to highlight the salient regions in images and videos by taking into consideration the biological structure of the human vision system (HVS). As a great deal of research in computational cognitive science suggests, HVS has evolved to reduce the amount of the sensory data information gathering stage, also known as the task-free visual search, by focusing on the perceptually salient segments of visual data that convey the most useful information about the scene.

We proposed a saliency-based attribute, SalSi, to detect salt dome bodies within seismic volumes. Using SalSi, we highlight the parts of the seismic volume that receive highest attention from the human interpreter, and based on the salient features of a seismic image, we detect the salt domes. The saliency maps of two seismic section inlines are shown in Figure 1, which demonstrates that the proposed method highlights the salt dome boundaries.

Experimental results show the effectiveness of SalSi on the real seismic dataset acquired from the North Sea, F3 block. Subjectively, we have used the

ground truth and the output of different salt dome delineation algorithms to validate the results of SalSi. The output of different delineation algorithms and regions highlighted by SalSi in green are shown in Figure 2. SalSi, originally designed to detect salt domes, can be modified to capture chaotic horizons and faults as well from seismic volumes. SalSi can be used to initialize algorithms, tracking salt domes in seismic volume, salt dome delineation and to reduce computational complexity of algorithms. The results of salt domes delineation using SalSi are shown in Figure 3.

For the objective evaluation of results, we have used the receiver operating characteristics (ROC) curves and area under the curves (AUC) to demonstrate that SalSi is a promising and an effective attribute for seismic interpretation. The experimental results show that the proposed framework is very fast and achieves salt dome delineation comparable to the state of the art methods. The initial results show a promising future of the proposed framework for salt dome delineation and very good potential in seismic interpretation.

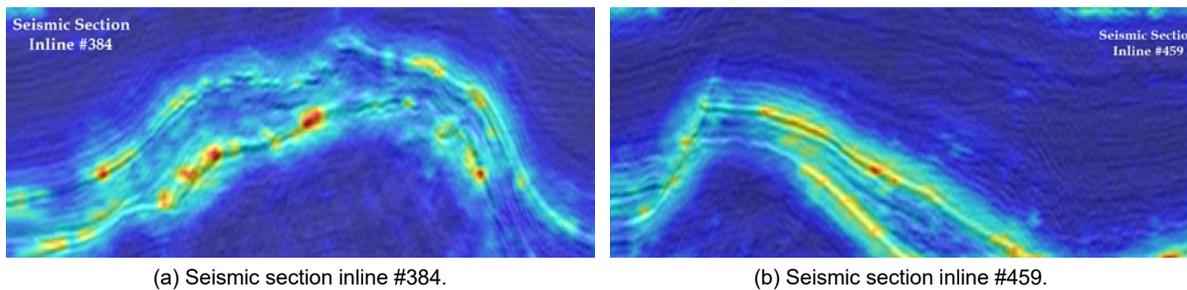


Figure 1. Saliency maps superimposed on the seismic sections.

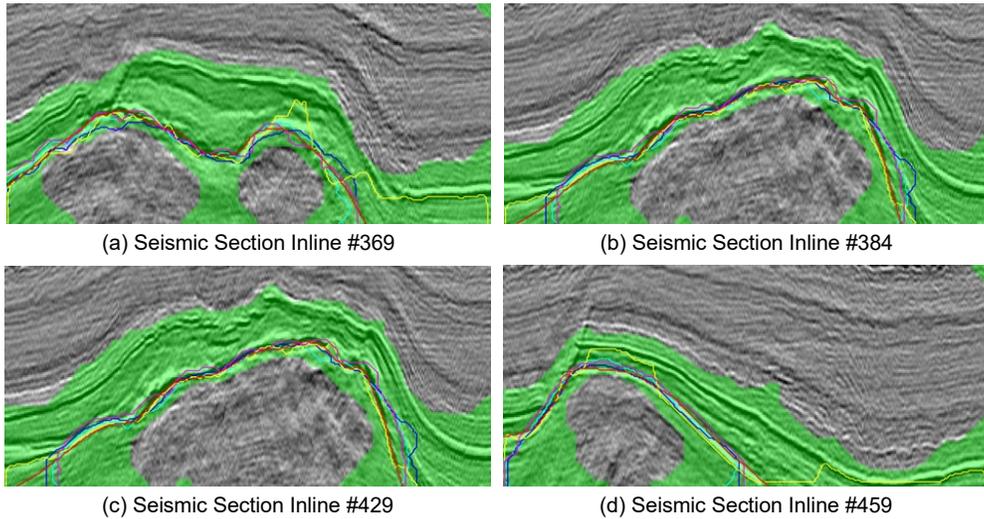


Figure 2. SalSi output superimposed on different seismic sections. Magenta: Aqrabi et al. [1], Yellow: Berthelot et al. [2], Cyan: Wang et al. [3], Blue: Shafiq et al. [4], Green: SalSi Output, Red: Ground Truth.

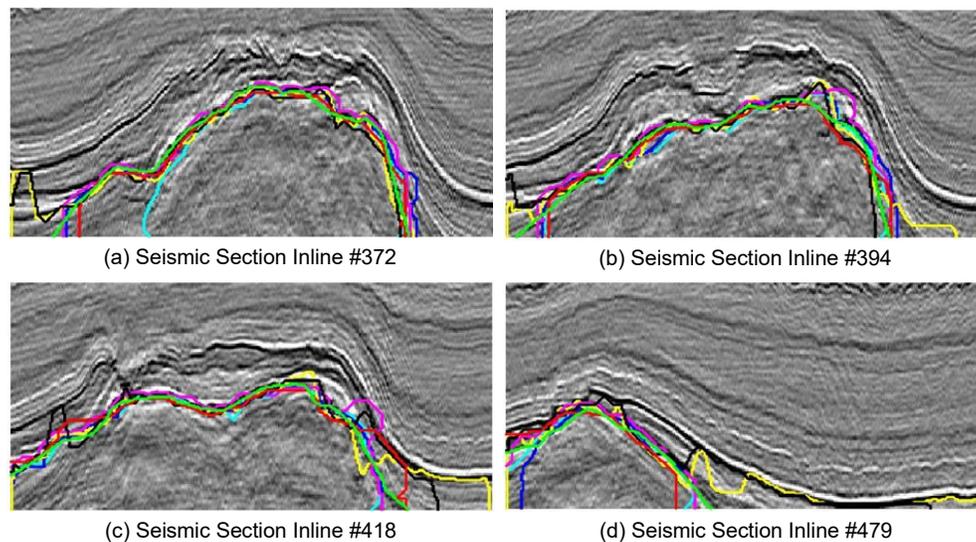


Figure 3. The experimental results of salt dome delineation on different seismic sections. Green: Ground Truth, Magenta: Aqrabi et al. [1], Yellow: Berthelot et al. [2], Cyan: Wang et al. [3], Blue: Shafiq et al. [4], Black: Amin et al. [5], Red: Proposed Saliency Method.

## References:

- [1] A. A. Aqrabi, T. H. Boe, and S. Barros, "Detecting salt domes using a dip guided 3D Sobel seismic attribute," in Expanded Abstracts of the SEG 81st Annual Meeting, 2011.
- [2] A. Berthelot, A. HS Solberg, and L. J. Gelius, "Texture attributes for detection of salt," *Journal of Applied Geophysics*, vol. 88, pp. 52–69, 2013.
- [3] Z. Wang, T. Hegazy, Z. Long, and G. AlRegib, "Noise-robust detection and tracking of salt domes in post-migrated volumes using texture, tensors, and subspace learning," *Geophysics*, November 2015, v. 80, p. WD101-WD116.
- [4] M. Shafiq, Z. Wang, A. Amin, T. Hegazy, M. Deriche, and G. AlRegib, "Detection of salt-dome boundary surfaces in migrated seismic volumes using gradient of textures," Expanded Abstracts of the SEG 85th Annual Meeting, pp. 1811-1815, New Orleans, Louisiana, Oct. 18-23, 2015.
- [5] M. Shafiq, T. Alshawi, Z. Long, and G. AlRegib, "SalSi: A new seismic attribute for salt dome detection," to be presented at IEEE Intl. Conf. on Acoustics, Speech and Signal Processing (ICASSP), Shanghai, China, Mar. 20-25, 2016.
- [6] A. Amin and M. Deriche, "Salt dome detection using a codebook based learning model", in preparation.

# Extending the Seismic Coherence Attribute To New Dimensions

Yazeed Alaudah and Ghassan AlRegib

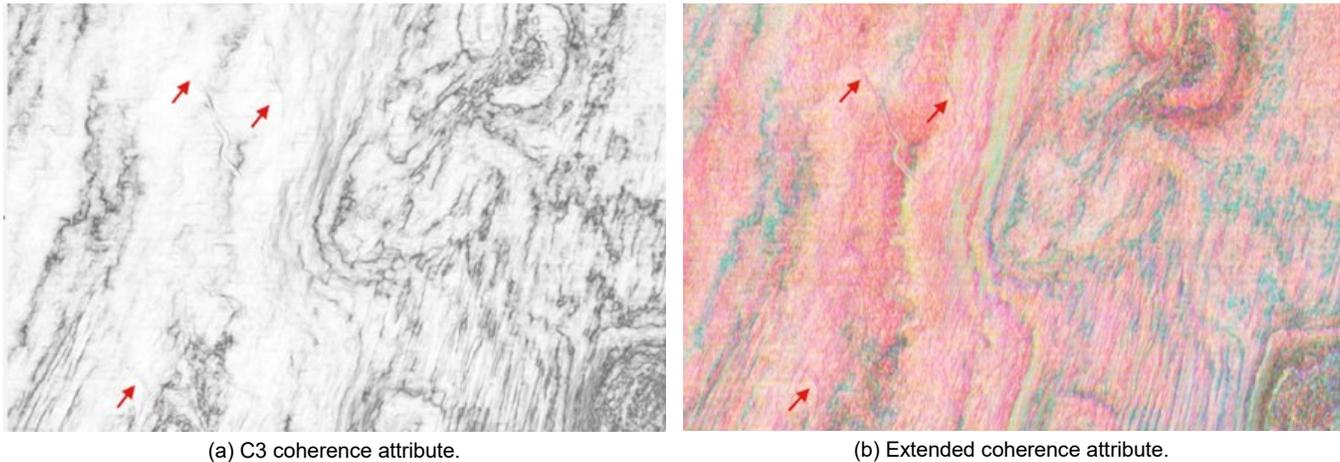


Figure 1. Coherence attribute for time section 952 ms from F3 block.

The coherence attribute has proven to be a very useful attribute for highlighting structural and stratigraphic discontinuities such as faults, fractures and channels in 3-D seismic volumes. While it has been widely used in academia and industry, few advances have been made to how the coherence attribute is computed since its inception two decade ago. The coherence attribute is commonly calculated by extracting an eigenstructure-based attribute from the covariance matrix of seismic traces within a small analysis window. This can be viewed as unfolding a small analysis tensor along the time direction. In a recent paper [1] we will present at the EAGE 2016 conference, we show that unfolding the tensor along all three directions (time, crossline, and inline) gives a much richer coherence attribute that can help interpreters highlight more intricate geological structures. We also proposed a preprocessing stage based on a normal-

ized multivariate Gaussian kernel that can help weigh traces by their relative proximity to the analysis trace. We show that this greatly enhances the results, and gives the seismic interpreters more flexibility at the same time. The figures above show the original coherence attribute and the proposed generalized coherence attribute. The generalized attribute offers a higher level of detail as well as colored features. The reader can notice that the channels highlighted in the figures appear much more clearly in the generalized attribute.

## References:

- [1] Y. Alaudah and G. AlRegib, "A Generalized tensor-based coherence attribute," at the 78th EAGE Annual Conference & Exhibition, Vienna, Austria, May 30-June 2, 2016.
- [2] Y. Alaudah, M. Shafiq, and G. AlRegib, "A hybrid spatio-frequency approach for delineating subsurface structures in seismic volumes," SIAM conference on Imaging Science, New Mexico, USA, May 23-26, 2016.

# Phase Congruency in Computational Seismic Interpretation

Muhammad Amir Shafiq, Yazeed Alaudah, and Ghassan AlRegib

Phase Congruency (PC) highlights the discontinuities in images with varying illumination and contrast using the congruency of phase in Fourier components. PC does not only detect subtle variations in the image intensity but can also highlight the anomalous values to develop a deeper understanding of the image's content and context. Figure 1 shows a typical grayscale image and its PC map.

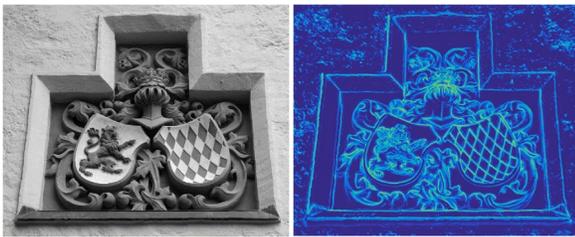


Figure 1. A typical grayscale image and its PC map.

We proposed a new method based on PC for computational seismic interpretation with an application to subsurface structures delineation within migrated seismic volumes. The proposed method is suitable for segmenting seismic volumes having weak seismic reflections, varying illumination and contrast. This proposed workflow for salt dome delineation can be modified to capture other geological structures such as chaotic horizons and faults. We show the effectiveness of the proposed method as compared to the edge and texture-based methods for salt dome boundary detection. A sample result on a real dataset from the North Sea, F3 is shown in Figure 2. The experimental results show that the proposed method is not only compu-

tationally very efficient but also outperforms the state of the art methods for salt dome delineation. The proposed method is expected to reduce the time for seismic interpretation and become a handy tool in the interpreter's toolbox for delineating geological structures within migrated seismic volumes.

## References:

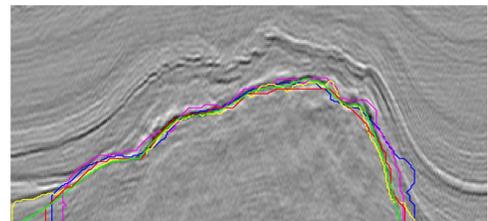


Figure 2. Experimental results on seismic section Inline #384. Green: Ground truth, Magenta: Aqrabi et al [1], Yellow: Berthelot et al [2], Blue: Shafiq et al [3], Red: PC.

- [1] A. A. Aqrabi, T. H. Boe, and S. Barros, "Detecting salt domes using a dip guided 3D Sobel seismic attribute," in Expanded Abstracts of the SEG 81st Annual Meeting, 2011.
- [2] A. Berthelot, A. HS Solberg, and L. J. Gelius, "Texture attributes for detection of salt," *Journal of Applied Geophysics*, vol. 88, pp. 52–69, 2013.
- [3] M. Shafiq, Z. Wang, A. Amin, T. Hegazy, M. Deriche, and G. AlRegib, "Detection of salt-dome boundary surfaces in migrated seismic volumes using gradient of textures," Expanded Abstracts of the SEG 85th Annual Meeting, pp. 1811-1815, New Orleans, Louisiana, Oct. 18-23, 2015.
- [4] M. Shafiq, Y. Alaudah, and G. AlRegib, "Phase Congruency for image understanding with applications in computational seismic interpretation," submitted to IEEE Intl. Conference on Image Processing (ICIP), Phoenix, Arizona, USA, Sep. 25-28, 2016.
- [5] M. Shafiq, Y. Alaudah, and G. AlRegib, "A hybrid approach for salt dome delineation within migrated seismic volumes," at the 78th EAGE Annual Conference & Exhibition, Vienna, Austria, May 30-June 2, 2016.
- [6] M. Shafiq and G. AlRegib, "A noise robust approach for delineating subsurface structures within migrated seismic volumes," at the 78th EAGE Annual Conference & Exhibition, Vienna, Austria, May 30-June 2, 2016.

# A Texture-based Interpretation of Salt Domes

Muhammad Amir Shafiq, Ghassan AlRegib, and Mohamed Deriche

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 is one of the key steps in the exploration projects.

We proposed a novel seismic attribute, three-dimensional gradient of textures (3D-GoT), for delineating geophysical structures such as salt domes within migrated seismic volumes. The 3D-GoT computes an attribute map by measuring the dissimilarity between the neighboring cubes around each voxel in seismic volume across crossline, inline and time directions. The experimental results on real seismic data from the North Sea demonstrate that the 3D-GoT delineates salt domes with

high accuracy and precision and outperforms the state of the arts methods of salt dome delineation. A 3D view of seismic volume containing a salt dome with three different slices is shown in Figure 1. The detected salt dome volume is illustrated in Figure 2.

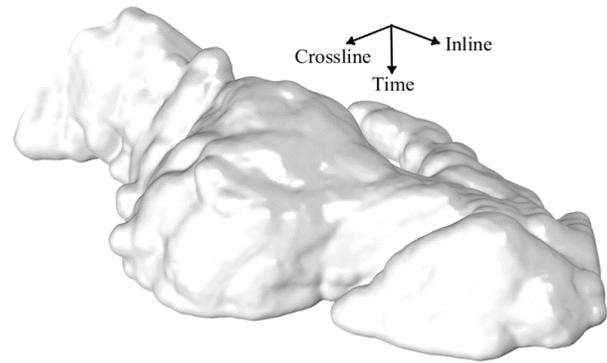


Figure 2. Detected salt dome.

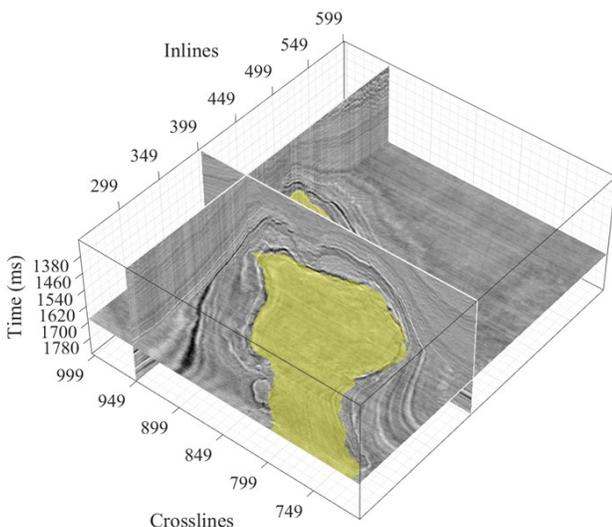


Figure 1. A 3D presentation of a slice of a detected salt dome.

## References:

- [1] M. Shafiq, Z. Wang, G. AlRegib, A. Amin, and M. Deriche, "A texture-based interpretation workflow with application to delineating salt domes," submitted to Interpretation, March, 2016.
- [2] Z. Wang, T. Hegazy, Z. Long, and G. AlRegib, "Noise-robust detection and tracking of salt domes in post-migrated volumes using texture, tensors, and subspace learning," Geophysics, 80(6), WD101-WD116.
- [3] M. Shafiq, Y. Alaudah, and G. AlRegib, "A hybrid approach for salt dome delineation within migrated seismic volumes," at the 78th EAGE Annual Conference & Exhibition, Vienna, Austria, May 30-June 2, 2016.
- [4] M. Shafiq and G. AlRegib, "A noise robust approach for delineating subsurface structures within migrated seismic volumes," at the 78th EAGE Annual Conference & Exhibition, Vienna, Austria, May 30-June 2, 2016.
- [5] M. Shafiq, T. Alshawi, Z. Long, and G. AlRegib, "The role of visual saliency in seismic interpretation with an application to salt dome delineation," SIAM conference on Imaging Science, New Mexico, USA, May 23-26, 2016.

# Learning from a Dictionary: The Case of Detecting Salt Domes

Asjad Amin, Mohamed Deriche, and Ghassan AlRegib

One of the most important tasks in seismic data interpretation is the detection of salt bodies as most of the important reservoirs are trapped around such bodies. Salt domes are largely subsurface geologic structures that consist of cylinder-like salt bodies. Major accumulations of oil and Gas are associated with salt domes. Unfortunately, salt dome detection is a difficult and a time consuming task especially in the case of 3D seismic volumes.

In this work, we developed a patch-based approach for salt dome detection using a dictionary-based classifier. The algorithm overcomes the drawbacks of existing texture-based salt dome detection techniques; which are heavily dependent upon the relevance of attributes to the geological nature of salt domes and the number of attributes used for classification. This dictionary-based method uses the attributes derived from the Gray Level Co-occurrence Matrix (GLCM), the Gabor filter, and the Higher Order Singular Value Decomposition (HOSVD). An information theoretic-based frame-

work is used to rank the attributes; the top ranked attributes are then selected for training and classification.

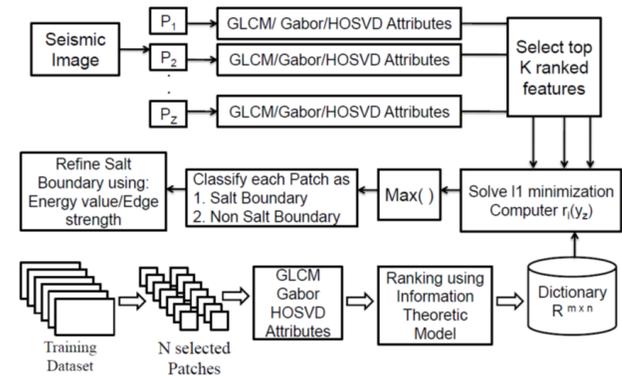


Figure 1. The Proposed Dictionary-based Salt Dome Detection Algorithm.

Contrary to other texture attributes-based salt dome detection techniques, our algorithm works with a minimum set of features and is shown to be independent of the amplitude variations in seismic data. We tested the proposed algorithm on the Netherlands offshore F3 block. Our experiments show excellent detection results of salt bodies with high accuracy superior to existing gradient-based

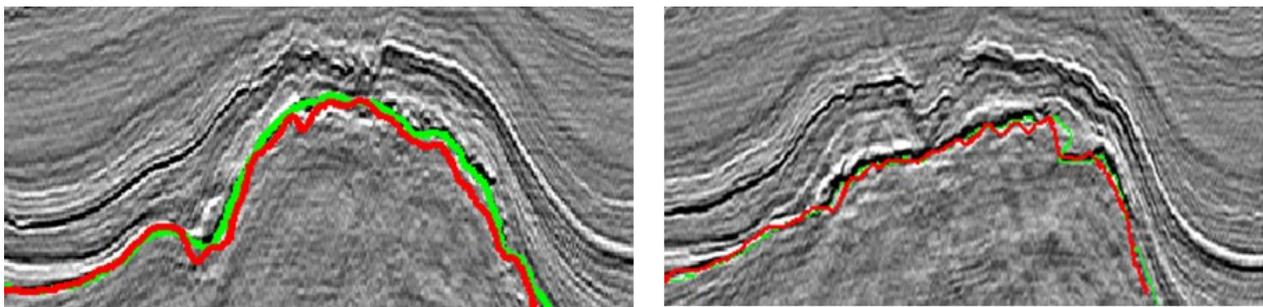


Figure 2. Salt boundary detected for inlines 105 (left) and 140 (right).

(Ground Truth = Green, Detected boundary = Red).

<b>Salt Dome Detection Method</b>	<b>Precision</b>	<b>Recall</b>	<b>F-measure</b>
Proposed method	98.97	94.24	96.55
Edge detector method	97.75	91.25	94.37
Texture attributes method	95.82	92.12	93.92
Hybrid edge and texture method	97.93	91.63	94.67
Dictionary method without refining	98.84	90.08	94.26

Table 1: Precision, Recall & F-Measure

and texture-based techniques. The overall structure of the proposed algorithm is shown in Figure 1.

We show in Figure 2 the boundary detected for Inline # 105 using the proposed method. Table-1 compares the performance of the proposed algorithm with other state-of-the-art salt dome detection methods. The average F-measure shows 3.6% improvement compared to the traditional texture-based attributes methods.

#### References:

- [1] A. Amin, M. Deriche, Z. Wang, and G. AlRegib, "A Novel approach for salt dome detection using a dictionary-based classifier", submitted to IEEE Transactions on Image Processing, March, 2016.
- [2] A. Amin and M. Deriche. " New attributes for salt dome detection in 3D seismic data using higher order SVD." submitted to IEEE Intl. Conference on Image Processing (ICIP), Phoenix, Arizona, USA, Sep. 25-28, 2016.
- [3] A. Amin, M. Deriche, T. Hegazy, Z. Wang, and Ghassan AlRegib, "A novel approach for salt dome detection using a dictionary-based classifier," Expanded Abstracts of the SEG 85th Annual Meeting, pp. 1816-1820, New Orleans, Louisiana, Oct. 18-23, 2015.
- [4] A. Amin and M. Deriche. "A hybrid approach for salt dome detection in 2D and 3D seismic data." Proc. IEEE ICIP 2015, Québec City, Canada, Sept. 27-30, 2015.

# DTSIM: A Directional Texture Similarity Metric

Motaz Alfarraj, Yazeed Alaudah, and Ghassan AlRegib

Image characterization is an essential tool to aid the process of image analysis and retrieval especially with the exponential growth of visual and pictorial content. Texture is an important feature of a broad spectrum of images. Such a feature has been widely utilized in various applications such as image classification and segmentation. For example, texture attributes have been widely used in salt body segmentation in seismic volumes.

In a recent paper we submitted to the International Conference on Image Processing (ICIP 2016), we proposed a directional texture similarity metric (DTSIM) based on the singular value decomposition (SVD) of the curvelet coefficients in which the singular values are trimmed adaptively via effective rank approximation. DTSIM is designed for images that have repeating structures and directional content such as texture, fingerprint, and seismic images. The block diagram of the proposed metric is depicted in Figure 1.

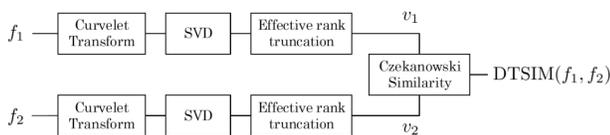


Figure 1. Block diagram of the proposed metric.

A retrieval experiment was set up to evaluate the performance of the metric. DTSIM outperforms state-of-the-art texture similarity metrics by 11% and 9% in terms of retrieval accuracy on CURET

and PerTex texture databases, respectively. In addition, DTSIM achieved 91% retrieval accuracy on the seismic image database LANDMASS-2 outperforming other seismic similarity metrics. Figure 2 shows a retrieval example using DTSIM showing its ability to retrieve images with similar structures.

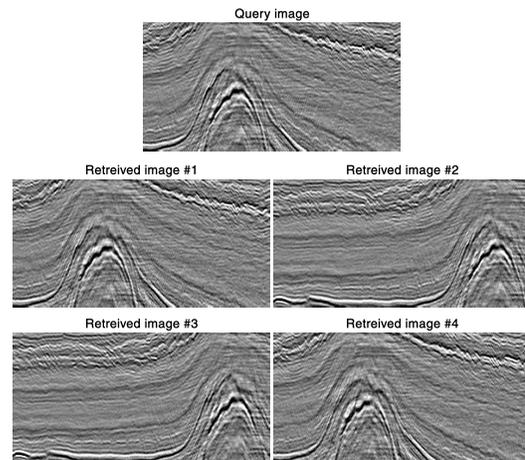


Figure 2. A salt dome query image and the top 4 retrieved images ranked according to their DTSIM scores.

## References:

- [1] H. Al-Marzouqi and G. AlRegib, "Curvelet transform with learning-based tiling," submitted to the Elsevier Signal Processing: Image Communication Journal, February 2016.
- [2] M. Alfarraj, Y. Alaudah, and G. AlRegib, "DTSIM: A directional texture similarity metric," submitted to IEEE Intl. Conference on Image Processing (ICIP), Phoenix, Arizona, USA, Sep. 25-28, 2016.
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- [4] Z. Long, Y. Alaudah, M. Qureshi, M. Farraj, Z. Wang, A. Amin, M. Deriche, and G. AlRegib, "Characterization of migrated seismic volumes using texture attributes: a comparative study," Expanded Abstracts of the SEG 85th Annual Meeting, pp. 1744-1748, New Orleans, Louisiana, Oct. 18-23, 2015.

# Characterization of Migrated Seismic Volumes Using Texture Attributes: A Comparative Study

Zhiling Long, Yazeed Alaudah, Muhammad Ali Qureshi, Motaz Alfarraj, Zhen Wang, Asjad Amin, Mohamed

*Deriche, and Ghassan AlRegib*

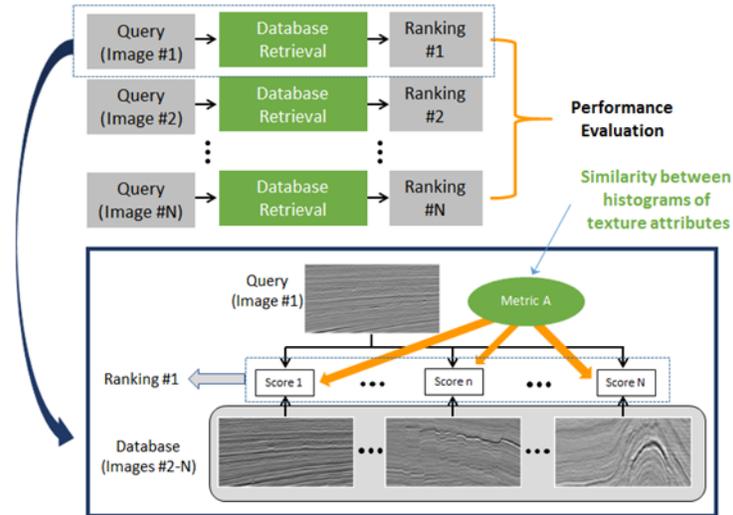


Figure 1. An illustration of the structure-based retrieval process.

In image processing, texture attributes are quantities generated from a texture pattern that capture the unique spatial distribution of the pixel intensities. Although texture attributes such as GLCM and Gabor features have been employed in some seismic interpretation applications with success, many more powerful texture analysis techniques developed in the image processing community have not yet been exposed adequately to exploration geophysicists. Therefore, in this work, we conduct a comparative study examining several typical texture attributes with respect to their capability of characterizing a seismic volume. We hope this study will help provide more alternative attributes for seismic exploration.

The attributes we examine here can be categorized into frequency or space domain techniques. For the

frequency domain, we explore the steerable pyramid (SP) [1], and the curvelet transform (CT) [2]. These are two typical extensions of the standard wavelet transform (WT) [3], which is probably the most popular technique for spectral content-based image and texture analysis. For the space domain, we study the local binary pattern (LBP) [4] and the local radius index (LRI) [5]. LBP has been widely used for very successful texture analysis due to its robustness and computational efficiency, while LRI is one of the newer variants of the LBP.

The attributes are examined in the context of image retrieval based on structural similarity, as illustrated in Figure 1. Figure 2 shows examples of the dataset we use. The retrieval results are given in Table 1, where SeiSIM [6] is used as a benchmark. According to the results, we conclude that all these

attributes demonstrate great potential to effectively capture the characteristics of different geological structures, with CT and LRI being the most promising ones. In addition, CT is the most computationally efficient among all the techniques.

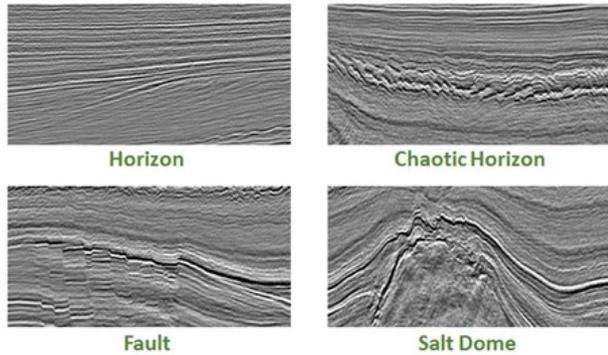


Figure 2. An illustration of the dataset used for the retrieval experiment.

Attribute	P@20	P@50	MAP	RA	AUC	Comp. Time (s)
Steerable Pyramid	1.000	0.965	0.928	0.866	0.965	0.2137
Curvelet	1.000	0.968	0.954	0.914	0.988	0.1201
LBP	0.999	0.953	0.932	0.871	0.967	0.1638
LRI	0.997	0.977	0.953	0.896	0.968	2.3946
SeiSIM	1.000	0.992	0.974	0.943	0.990	1.1872

Table 1. Comparison of the retrieval performances.

## References:

- [1] Simoncelli, E., W. Freeman, E. Adelson, and D. Heeger, 1992, Shiftable multiscale transforms: Information Theory, IEEE Transactions on, 38, 587–607.
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- [3] Chui, C. K., 2014, An introduction to wavelets: Academic press, 1.
- [4] Ojala, T., M. Pietikainen, and T. Maenpaa, 2002, Multiresolution gray-scale and rotation invariant texture classification with local binary patterns: IEEE Transactions on Pattern Analysis and Machine Intelligence, 24, 971–987.
- [5] Zhai, Y., D. L. Neuhoff, and T. N. Pappas, 2013, Local radius index—a new texture similarity feature: International Conference on Acoustics, Speech and Signal Processing (ICASSP), IEEE, 1434–1438.
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# Weakly-supervised Labeling of Seismic Volumes Using Reference Exemplars

Yazeed Alaudah and Ghassan AlRegib

Localizing seismic structures that can form traps for hydrocarbon reservoirs within large seismic volumes is a very challenging task. Due to the lack of large amount of accurately labeled data, it becomes difficult to use powerful machine learning approaches (such as Convolutional Neural Networks) to achieve this task. In a recent paper submitted to the International Conference on Image Processing (ICIP 2016) we proposed using a directional similarity metric to extract data having similar geological structures to several hand-labeled ‘exemplars’. This process produces a large number of images that can be assigned the same classes as the hand-labeled exemplars. Features based on the singular values of curvelet coefficients are extracted and used to train a Support Vector Machine (SVM). This SVM is then used to label seismic sections segmented using superpixels. The overall diagram of the proposed method is shown in Figure 1. Experiments on reference seismic sections in

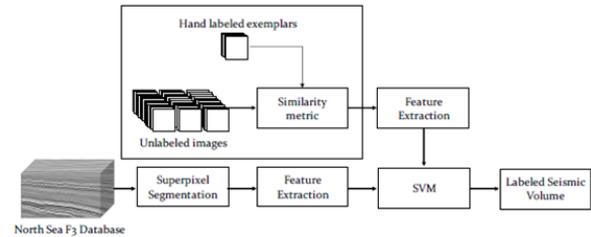


Figure 1. Main diagram of proposed method .

the Netherlands North Sea seismic dataset result in 73.8% mean pixel accuracy and 75.5% mean class accuracy, with an average labeling time of 5.2 seconds per section. A sample labeled section from Crossline #281 of the North Sea F3 Block is shown in Figure 2.

## References:

- [1] Y. Alaudah and G. AlRegib, “Weakly-supervised labeling of seismic volumes using reference exemplars,” submitted to IEEE Intl. Conference on Image Processing (ICIP), Phoenix, Arizona, USA, Sep. 25-28, 2016.

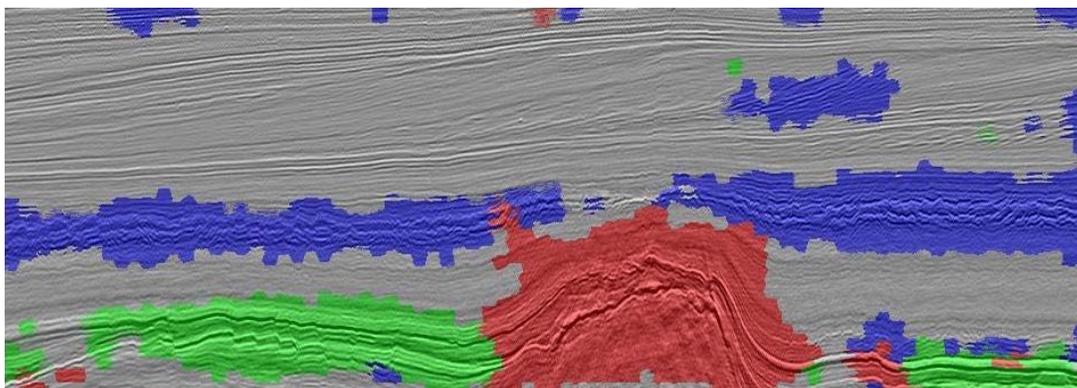


Figure 2. Example labeled section from Crossline #281 of the North Sea F3 Block .

# Tensor-based Subspace Learning for Tracking Salt-dome Boundaries Constrained by Seismic Attributes

Zhen Wang, Zhiling long, and Ghassan AlRegib

In the past year, we proposed a method to delineate salt dome structures by tracking manually labeled boundaries through seismic volumes. We first extract texture features from boundary regions using the tensor-based subspace learning method. Then, we utilize one seismic attribute, the gradient of texture (GoT), as a constraint on the tracking process. Using texture features and GoT maps, we can identify tracked points and optimally connect them to synthesize the boundaries. The proposed method is evaluated using real-world seismic data and experimental results show that it outperforms the state of the art in accuracy, robustness, and computational efficiency.

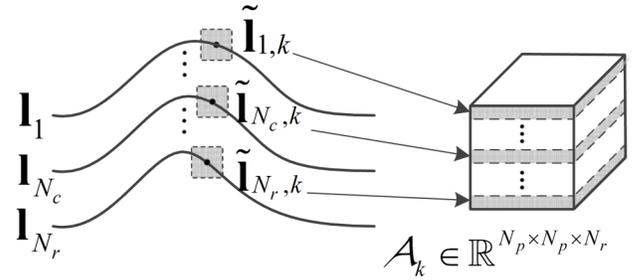
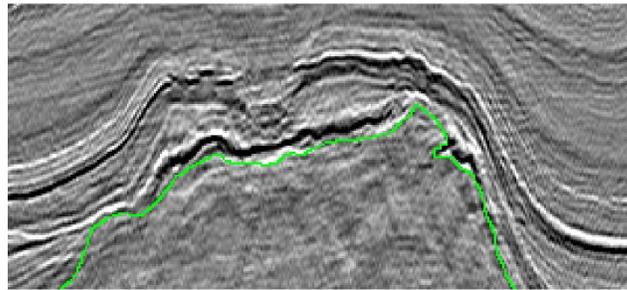
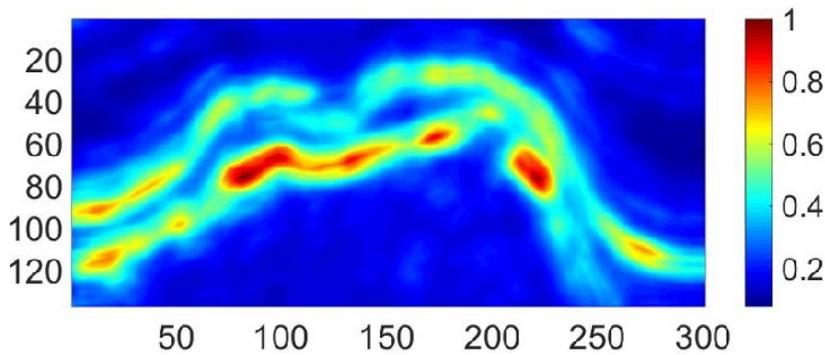


Figure 1. Building a texture tensor.

Figure 1 illustrates the process that builds texture tensors from the boundaries of reference sections. We define  $N_r$  neighboring seismic sections as reference sections, in which the corresponding boundaries, denoted  $l_b, b=1, \dots, N_r$ , are manually labeled. To fully capture texture information along all reference boundaries, we focus on texture patches cen-



(a) Reference image. Ground truth is highlighted in green.



(b) Corresponding GoT map of the reference image.

Figure 2. A typical seismic inline containing a salt dome body and its GoT map.

tered at boundary points with a size of  $N_p \times N_p$ . Therefore, third-order texture tensors with a size of  $N_p \times N_p \times N_p$  can be built from these patches.

To increase the robustness of tracking, we select the GoT attribute as a constraint because of its capability of describing texture differences between the salt dome and its neighboring rock strata.

Figure 2 illustrates the reference image and its corresponding GoT map. By building texture tensors from reference images and GoT maps, we can synthesize the tracked boundaries as Figure 3 shows.

## References:

- [1] Z. Wang, Z. Long, and G. AlRegib, "Tensor-based subspace learning for tracking salt-dome boundaries constrained by seismic attributes," to be presented at IEEE Intl. Conf. on Acoustics, Speech and Signal Processing (ICASSP), Shanghai, China, Mar. 20-25, 2016.
- [2] Z. Wang, Z. Long, and G. AlRegib, "Tensor-based subspace learning for tracking salt-dome boundaries," Proc. IEEE ICIP 2015, Québec City, Canada, Sept. 27-30, 2015.
- [3] M. Shafiq, Z. Wang, and G. AlRegib, "Seismic interpretation of migrated data Using edge-based geodesic active contours," Proc. IEEE Global Conf. on Signal and Information Processing (GlobalSIP), Orlando, Florida, Dec. 14-16, 2015.

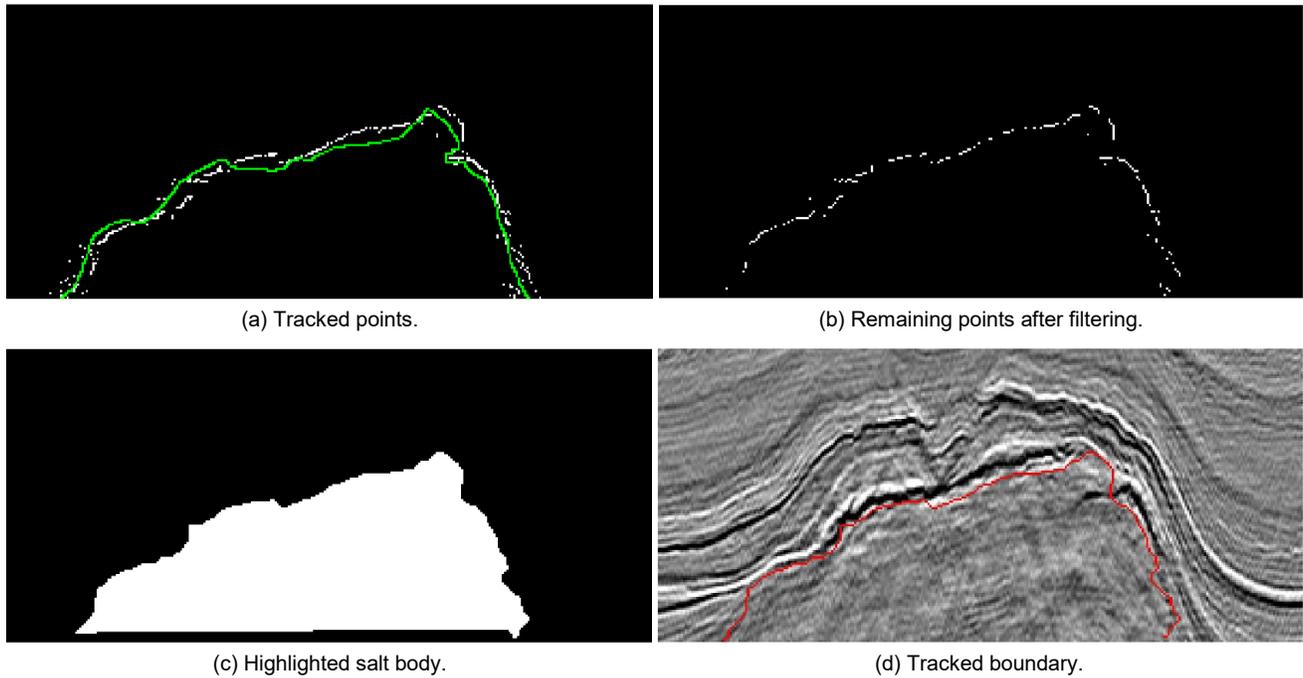


Figure 3. Salt dome boundary tracking steps.

# Assessing the Performance of Signal Compression in Seismic Data Acquisition

*Hamood Khan and Salam A. Zummo*

The amount of data generated during seismic data acquisition is huge. Typical modern surveys produce data in the order of 4-10 TB on a daily basis. In the future, this size is expected to grow by an order of magnitude to the tune of 100 TB. This blow up in gathered data is due to the fact that industry is now moving away from the best possible shot acquisition (through optimal placement of geophones) to increased data density (in space and time) through, high sampling rates, higher node density, or higher number of shots. The emphasis is to enable statistical sampling where more data is acquired than is needed. Already fiber optic cables are being used as the backhaul link to move the huge amount of generated data from the survey field to the recording unit. It is obvious that to support future node densities and data rates, some kind of compression of the acquired seismic signal is needed, so that storage and transmission costs are manageable.

One question that we sought to answer was: What is the best/worst that can be achieved in terms of compression performance for a 2D seismic shot gathers. The question is key to assessing and benchmarking the performance of actual compression algorithms that work on seismic data. The seismic wave field gathered through acquisition is the result of a physical process. The physics imposes a certain temporal and spatial structure on the resulting signal, which dictates the design of the geophone network used to acquire it. We modelled the physics of the acquisition process through standard acoustic wave equation in geophysics. In this model, the energy from the seismic source is modelled as wave motion governed by a hyperbolic PDE, called the wave equation. The medium is assumed to be compressible and with no shear taking place. The solution to the wave equation gives the seismic wave field in the subsurface. Figure 1 shows two parallel layers in which the wave ener-

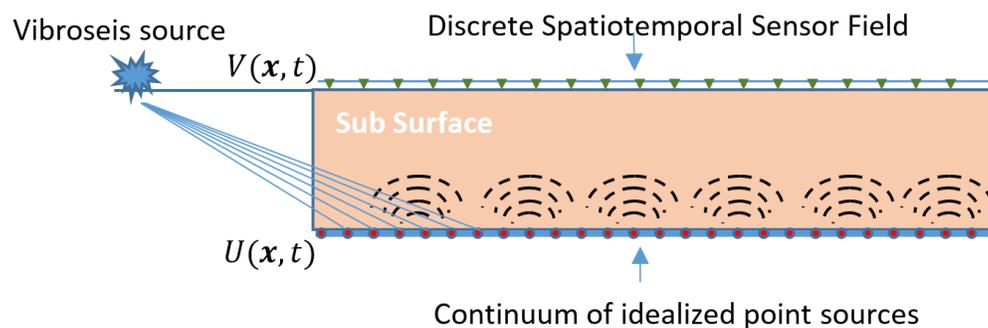


Figure 1. Two-layer physical model for seismic acquisition.

gy from the subsurface layer to the surface that is sampled by in discrete time and discrete space through sensors. Zero initial conditions are assumed to obtain a unique solution for the wave equation. The equation possesses what is called a fundamental solution or “Green functions”. The Green functions are the solution  $V(x,t)$  when the source field is a Dirac distribution at the origin. The spectrum of the Green’s function was computed in closed form and plotted in Figure 2. Note that it has a bow-tie shape that has an exponential decay (as can be inferred from closed formed approximations). From the spectrum of the Green function the rate distortion performance of any compression algorithm for seismic field can be computed using standard reverse water-filling methods of infor-

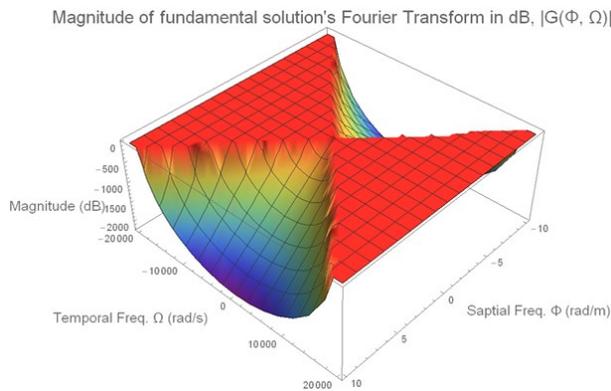


Figure 2. Magnitude Spectrum of the Green function as a function of spatial and temporal frequency.

mation theory.

Three source coding schemes were considered and the corresponding rate distortion curves were computed for them. The first scheme is where there is no communication cost between geophone sensors,

i.e., each sensor can see the data of every other sensor perfectly so that in effect we have all the data located at a single spatial location available to a single “super” sensor. This is the ideal situation and is the baseline that serves as a lower bound for the rate distortion performance. The second scheme is an upper bound for the rate distortion. Here all sensors code their data independently without regard to any correlation among neighboring sensors. Hence the rate performance is an upper bound. The third scheme is a tighter lower bound that results when multi-terminal source coding is performed where the sensors do not communicate with each other but the recorder unit exploits the correlation between data streams of neighboring sensor nodes. Figure 3 compares the rate distortion performance of the three schemes.

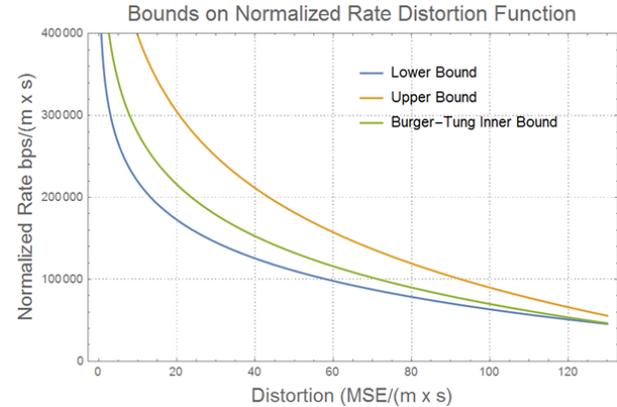


Figure 3. Bounds on the Rate Distortion performance of the three coding schemes.

# Sparse-promoting Full Waveform Inversion Based on Online Orthonormal Dictionary Learning

Lingchen Zhu, Entao Liu, and James H. McClellan

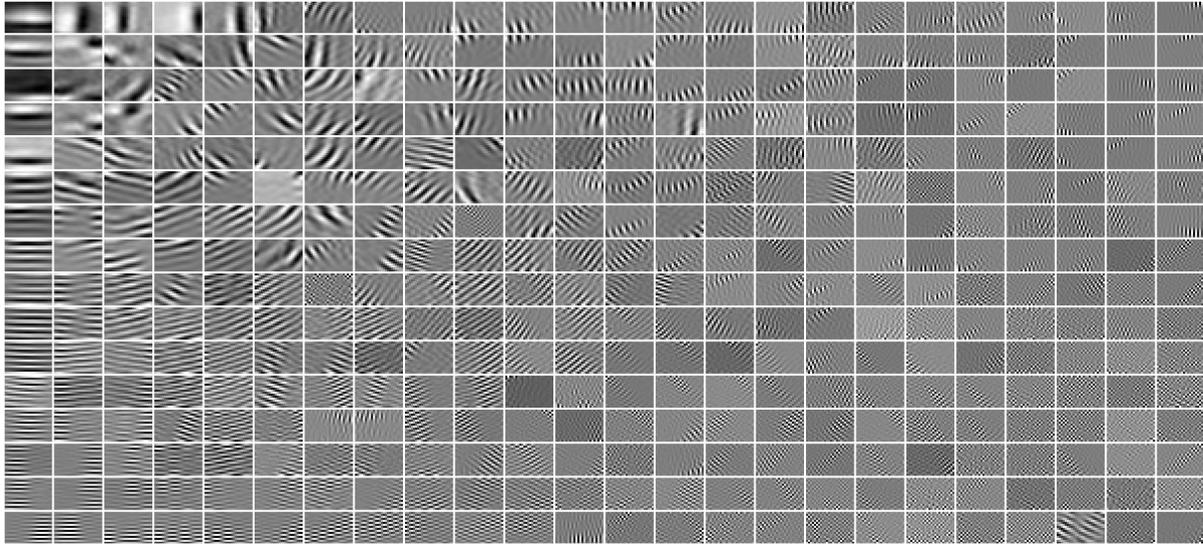


Figure 1. Learned dictionaries to represent model perturbation in the velocity model.

During the latter half of 2015, we proposed a new Full Waveform Inversion (FWI) method based on the dictionary-learning method and submitted two papers. One is accepted by *International Conference on Acoustics, Speech and Signal Processing (ICASSP) 2016* in Shanghai, China and another one is pending review in *Geophysics*.

FWI delivers high-resolution subsurface geophysical models by iteratively minimizing the least-squares misfit between the observed and simulated seismic data. Due to the limited accuracy of the starting model and the inconsistency of the seismic waveform data, the FWI problem is inherently ill-posed, so that regularization techniques are typi-

cally applied to obtain better models. FWI is also a computationally expensive problem because modern seismic surveys cover very large areas of interest and collect massive volumes of data. The dimensionality of the problem and the heterogeneity of the medium both stress the need for faster algorithms and sparse regularization techniques to accelerate and improve imaging results.

Our method reaches these goals by developing a compressive sensing approach for the FWI problem, where the sparsity of model perturbations is exploited within learned dictionaries. Dictionaries are updated iteratively to adapt to dynamic model perturbations. Meanwhile, the dictionaries are kept

orthonormal in order to maintain the corresponding transform in a fast and compact manner without introducing extra computational overhead to FWI. Such a sparsity regularization on model perturbations enables us to take randomly subsampled data for computation and thus significantly reduce the cost.

**References:**

- [1] L. Zhu, E. Liu, and J. McClellan, "Sparse-promoting full waveform inversion based on online orthonormal dictionary learning," submitted to Geophysics.
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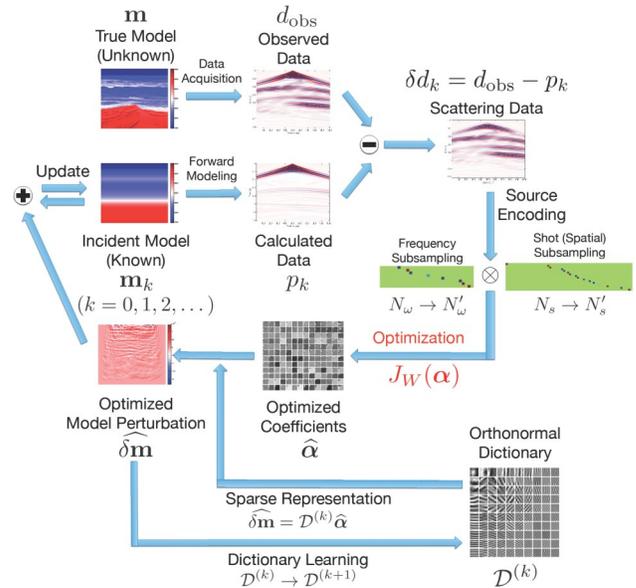
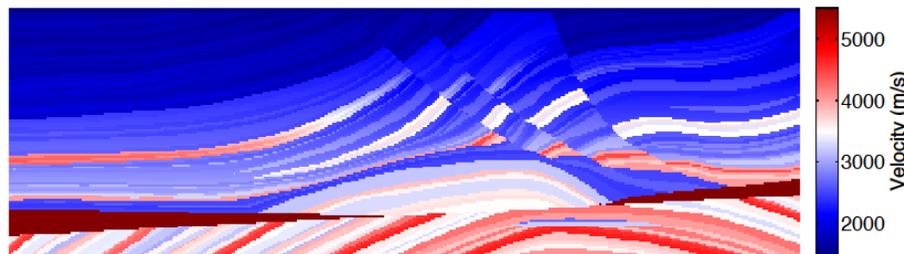
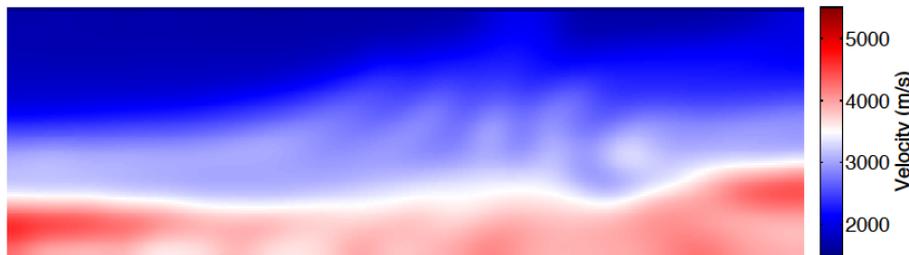


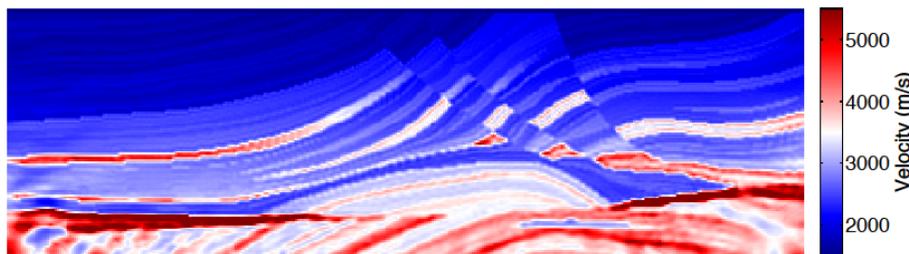
Figure 2. Overall workflow of the proposed FWI method based on online orthonormal dictionary learning.



(a) True velocity model "Marmousi" for reference.



(b) Initial smooth velocity model.



(c) FWI after 100 iterations using Online Orthonormal Dictionary Learning.

Figure 3. FWI using the proposed method.

# Microseismic Events Enhancement and Detection in Sensor Arrays

Entao Liu, Lijun Zhu, Anupama Govinda Raj, James H. McClellan, Abdullatif Al-Shuhail, and SanLinn I. Kaka.

Passive microseismic data are commonly buried in noise, which presents a significant challenge in microseismic data analysis and event detection. One of the ongoing topics is to provide efficient and robust algorithms for the microseismic event detection and denoising. Practically, we consider the situation where a sensor array (downhole or on the surface) provides multiple traces that each contain an arrival from the event. We have proposed an autocorrelation-based method that designs a denoising filter in the frequency domain which is then applied to all the traces to make the event detection easier. This approach uses stacking of the

autocorrelation functions, which works well because the autocorrelations of all the traces are centered at zero in the lag domain. Thus, it does not suffer the usual drawback of stacking where the time offsets among traces must be known. The performance of the method is studied with respect to the number of traces, the noise level, as well as the spectra of the wavelet and the noise.

The simplicity and robustness of this method is validated with synthetic and field datasets. In Figure 1 (a) to (c), we show the original data (only showing 14 traces out of 200), noisy data after adding Gaussian noise, and the denoised results. The interested reader is referred to the CeGP publica-

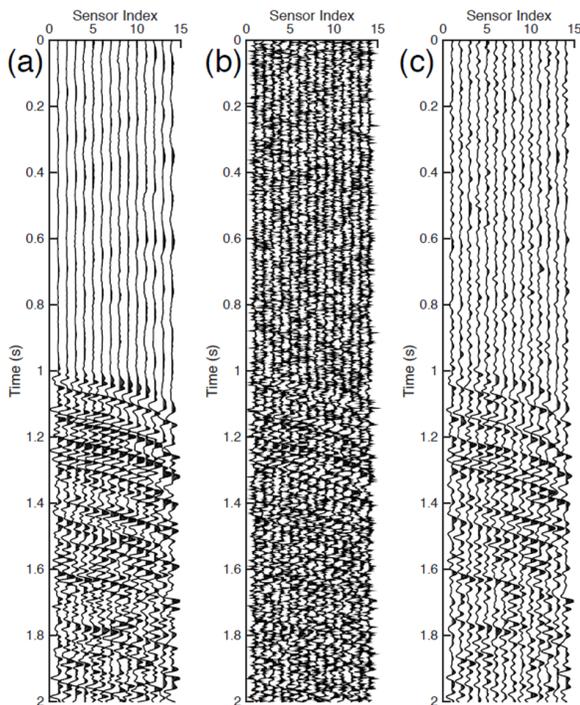


Figure 1. (a) Original data. (b) Noisy data. (c) Denoised data using the proposed method.

## References:

- [1] E. Liu, L. Zhu, and J. H. McClellan, A. Al-Shuhail, S. I. Kaka, "Microseismic events enhancement in sensor arrays using autocorrelation based filtering," submitted to the 78th EAGE Annual Conference & Exhibition, Vienna, Austria, May 30-June 2, 2016.
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# EE Senior Design Expo at KFUPM

*Amit S. Jariwala*



At the expo: (from left to right) Dr. Mohammad Al-Homoud, KFUPM Vice-Rector for Academic Affairs, Dr. Suhail Al-Dharrab, Dr. Omar Al-Swailem, Dean of College of Engineering Sciences at KFUPM, Dr. Amit Jariwala, and students presenting their project.



Best project winners at the Expo

The EE Department of KFUPM hosted its first Senior Design Expo on the 9th of May, 2015 with collaboration and support from Georgia Tech faculty. The Expo was a celebration of all the incredible hard work and dedication put in by the senior graduating students of the EE Department of KFUPM. 97 students in 30 teams from the EE Department participated at the expo and prizes worth over 6000 Saudi Riyals were given out to the top three winning teams. The event marked a historic beginning of an annual tradition of organizing the Expo for the EE Department. The Expo was graced by the presence of Dr. Mohammad Al-Homoud, KFUPM Vice-Rector for Academic Affairs and Dr. Omar Al-Swailem, Dean of College of Engineering Sciences. Over 20 industry experts attended the event and served as judges for the Expo, and they were absolutely thrilled with the level of creativity and talent of the students. The Expo has paved a

path for industry to further collaborate with KFUPM and engage more closely with the students and faculty of the EE department of KFUPM.

There were numerous factors that led to the successful launch of the Expo and the CeGP collaboration between GT and KFUPM was the cornerstone for all of this. Georgia Tech has had a long standing success in organizing the largest (in the US) bi-annual institute wide Capstone Design Expo with participation of around 150 teams per expo (around 750 students), with over 3000 visitors and numerous corporate partners. Dr. Jariwala, who oversees the planning and execution of the Georgia Tech Capstone Design Expo, was invited by Dr. Ali Al-Shaikhi, the chairman of the EE Department at KFUPM, to present technical talks and provide guidance for organizing the Senior Design Expo. The planning for the expo started several months

prior to the event with online discussions between KFUPM faculty and Dr. Jariwala. Throughout the duration of the visit to KFUPM (a few days prior to the expo), Dr. Jariwala met with faculty, students and staff of KFUPM's EE Department, The Dhahran Techno-Valley Company, and the Dhahran FabLab to share insights about the Expo and industry participation. He attended the KFUPM Career Day to solicit industry sponsors and judges for the Senior Design Expo. The EE Student Club of KFUPM played a pivotal role in the execution of the event under the leadership of their faculty advisor, Mohammad AlMuhaini. Several faculty and staff members within the EE department of KFUPM under the leadership of Dr. Ali Al-Shaikhi worked tirelessly to put the event together. The CeGP leadership thanks the support and coordination provided by Mohammad Tamim Alkhodary for his selfless service to the collaboration in helping to enable creative educational experiments through the CeGP project. The Expo has sent a message within KFUPM to celebrate student success and inspire more creative industry engagement with the university. This foundation will be built upon further with the development of a joint Design Education Project under CeGP which would be mutually beneficial to both Georgia Tech and KFUPM students and faculty.



Dr. Jariwala giving a talk on "Preparation for Senior Design Expo" for student in EE411 Capstone Design Projects.



Dr. Ali Al-Shaikhi and Dr. Amit Jariwala in a seminar on "Industry Engagement Through Senior Design".



Dr. Jariwala briefing the judges at the Expo.



Photos from the first EE senior design Expo at KFUPM.

# Global Research Experience for the Undergraduate Students (GREU)

*Ghassan AlRegib and Ali Muqaiabel*

In summer 2015, Professor Ali Muqaiabel spent two months on the Georgia Tech campus. One of the activities he focused on was to learn how Georgia Tech organizes activities on research for undergraduate students. He met with several UG students who are doing research and he met with their graduate students mentors and faculty advisors. As an outcome of the visit, Professor Muqaiabel and Professor AlRegib put together a plan to create a global research experience for UG students. This plan works in multiple phases. In the first phase (2016), KFUPM develops a course on UG research, where a small group of students enroll and experience this for the first time at

KFUPM. In the process, faculty, graduate students, and undergraduate students provide suggestions, guidelines and feedback on the process. This transfer of knowledge has been very helpful to the KFUPM team as they start the experience in early 2016. In the second phase, the plan is to engage students from both campuses (~5 or less from each side) to conduct research collaboratively on problems that are of a global scale.

Below are some photos from the activities that have taken place so far and we are very excited about the prospect to take this to a global scale in late 2016 and in 2017.



Some activities that took place in the first phase of GREU.

# Design of an ACL-Based Course Introduction to EE

*Maan Kousa, Ali Muqaibel, and Doug Williams*

The widespread and growing adoption of active and cooperative learning (ACL) techniques is changing education. Rather than simply attending lectures and taking notes, students spend much of the class period interacting with each other and with the instructor to solve problems relevant to the course's subject matter. The Electrical Engineering Department at KFUPM has seized the opportunity of the joint collaboration program with Georgia Institute of Technology (GT), and decided to start an ACL-based educational project jointly with GT. The project was to develop and to run one of the EE basic courses, Introduction to Electrical Systems and Computation (EE 206), in ACL format as a pilot for other courses.

The teams have surveyed and examined several alternatives and flavors of running ACL, in an attempt to customize a platform that best achieves KFUPM and GT goals at large and the course objectives in specific. A complete set of documents has been developed to run the course in a productive and engaging manner. Every effort has been made to provide detailed guidance for both students and instructors of the course in all aspects (preparation, delivery, management, and assessment). Part of this material will be used to deliver a training workshop for the course instructors in particular, and for faculty members at large in order to

promote transformation to ACL for few other courses.



Students group in ACL-Based course.

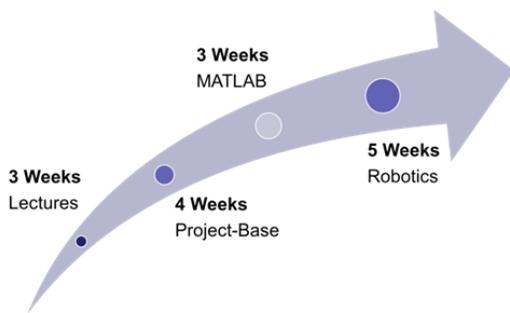
Working in teams is unquestionably the most effective form of collaboration. Three processes are crucial for the success or failure of teams: Team Formation, Team Management, and Team Assessment. The best practices in these processes have been reviewed and discussed. Jigsaw, a well-structured cooperative learning techniques that is receiving an increasing attention and is proving to be exceptionally effective for learning, has been presented.

The objectives of the developed course were:

1. Emphasize the role of engineering in society.
2. Introduce the various disciplines of electrical engineering.
3. Motivate students towards the profession.

4. Demonstrate basic concept in the context of some widely encountered electrical engineering systems and devices.
5. Introduce skills that are important to industry.
6. Getting hands-on experience with MATLAB.

The course will be divided into four modules: Introducing EE fields, Project I: Research Activity, MATLAB, and Project II: Robotics. The first module of the course is mainly lecture-based and is meant to introduce the student to the different sub-fields under electrical engineering. This helps the student to comprehend the scope of electrical engineering. The subfields cover Communication, Electromagnetic, Signal Processing, Power, Control, Electronics and Instrumentation.



Structure of the developed ACL-based course.

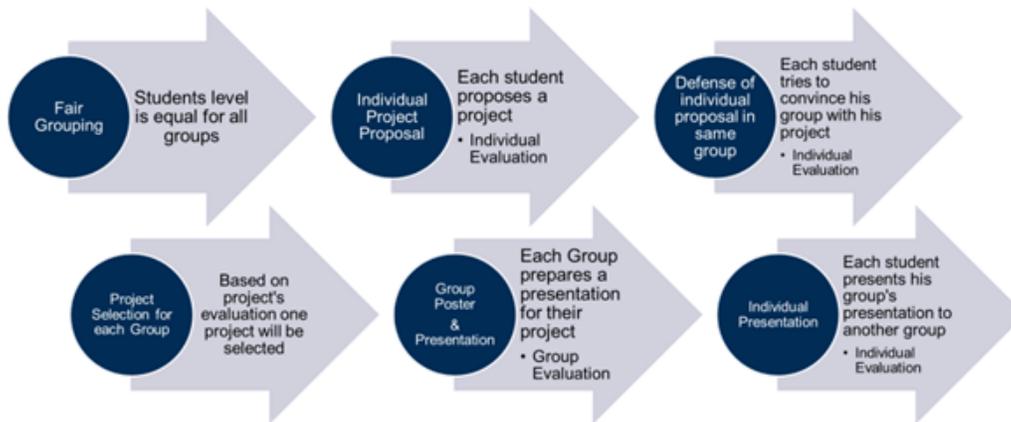
In the second module students work in teams to conduct simple search. This module aims to develop students' abilities in the following:

- Learn independently.
- Work effectively in teams.
- Communicate technical information in both written and oral form.
- Plan and execute short term projects.
- Teach others.
- Assess peers professionally and objectively.

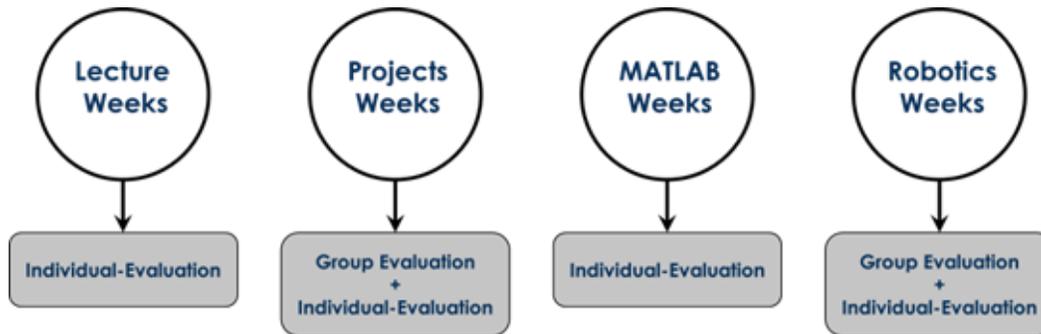
The objective of the third module, the programming module, is to introduce EE student to different EE software packages, with emphasize on MATLAB. Students are introduced to the interface environment, language syntax, basic linear algebra operation, and plotting commands with basic application to signal processing.

The fourth module on robotics aims at achieving the following objectives:

- Demonstrate the multidisciplinary nature of real life systems and problems.
- Highlight the engineering approach for problem analysis and solution
- Enhance students' ability for self-learning.



Process of the project-based learning.



Overall Assessments Scenarios.

- Work effectively in teams.
- Plan and execute short term projects.

The following list summarizes what can be achieved with the use of robots:

- Mathematical skills and concepts, such as proportions and ratios, graphing data, and multi-digit computation.
- Apply knowledge of science concepts, such as speed and power, motion and stability, and forces and interactions
- Understand cross-cutting concepts, such as systems, patterns, structure and function, and logical thinking.
- Understand the core concepts of technology.
- Understand the role of troubleshooting, invention and innovation, and experimentation in problem solving.
- Plan and manage activities to develop a solution or complete a project.

In drafting the pilot course material, the teams did every effort to provide the fine details so that instructors feel comfortable with the approach.

# Visiting Georgia Institute of Technology: A Personal Perspective

*Suhail Al-Dharab*



4th annual STEM Education Research Expo, Klaus Advanced Computing Building, Georgia Tech.



Invention Studio, Manufacturing Related Disciplines Complex (MRDC) Building, Georgia Tech.

Upon my arrival to the culturally vibrant city of Atlanta, I received a cordial welcome in the Center for energy and Geo-Processing (CeGP) at Georgia Institute of Technology. The center is located in Centergy One Building in Tech Square, surrounded by several academic buildings, restaurants, and retail shops. During the visit, I had the privilege to meet the Director of CeGP at Georgia Tech (GT), Professor Ghassan AlRegib, Professors, post-docs, and PhD students in the joint projects with King Fahd University of Petroleum and Minerals (KFUPM). The GT visit has enriched me in numerous aspects, specifically, in terms of research, education and learning methodologies, and administration.

As of research experience, I attended joint video-conferencing meetings with KFUPM, where they

discuss their progress and future contributions in the areas of micro-seismic detection, seismic interpretation, and in-field seismic data compression. These video-conferencing meetings engage open discussions between the teams at KFUPM and GT. I am currently involved in the "Interactive Computer-Aided Seismic Interpretation" joint CeGP research project. There are several topics under this joint research project; but, I am specifically interested in investigating the detection of seismic faults based on multi-attribute approach and visual saliency. I was also involved in administrative duties to facilitate potential joint CeGP educational projects. In addition to those meetings, Schools and Departments at GT offer research seminars covering a wide range of interesting technical topics. I attended some of these seminars, and even ad-

vanced graduate courses on digital image processing and statistical digital signal processing in the school of Electrical and Computer Engineering at GT. Thanks to the center at GT, I attended the 85th annual meeting of Society of Exploration Geophysicists (SEG) in New Orleans, Louisiana, on 18-22 October 2015. It is one of the largest global geoscience exhibitions with more than 8500 attendees from over 70 countries.

My experience in education and learning has enhanced by joining the discussions on effective pedagogical practices organized at GT, and participating in student activities. One of the main events at GT is the “Capstone Design Expo” that was held in McCamish Pavilion on December 3, 2015. I participated in this well-organized event as a judge. I met Dr. Amit Jariwala, Director of Design and Innovation, and had a tour in the Invention Studio. A similar contest is the “2016 InVenture Prize” competition. I participated as a judge in the preliminary round. Students showed enthusiasm to compete for the 1st prize of \$20,000. I participated in informative and engaging workshops offered by the Center for the Enhancement of Teaching and Learning (CETL), and discussed our practices at KFUPM with faculty members at GT. I also attended the 4th Annual Science, Technology, Engineering, and Mathematics (STEM) Education Research Expo. During the poster session, attendees exchanged ideas on current education and learning research.



The team at SEG 2015 Annual Meeting, New Orleans, LA: (from left to right) Motaz Alfarraj, Amir Shafiq, Prof. Ghassan AlRegib, Yazeed Alaudah, Zhen Wang, and Dr. Suhail Al-Dharrab.

All in all, the visit has been a rich experience with new perspectives in research, education, and administration. I had valuable discussions with Professors and graduate students. Finally yet importantly, I am grateful for the support of King Fahd University of Petroleum and Minerals. My thanks extend to the Electrical Engineering Department at KFUPM and all members in the Center for energy and Geo-Processing at KFUPM and GT.



2016 InVenture Prize competition, preliminary round, Klaus Advanced Computing Building, Georgia Tech.

# Computational Seismic Interpretation (CSI): Salt domes

*Muhammad Amir Shafiq and Ghassan AlRegib*

At CeGP, we are conducting research on the automation of seismic interpretation for post-migrated seismic volumes using advanced pattern recognition, machine learning, and human vision system models. The Graphical User Interface (GUI) of Computational Seismic Interpretation (CSI): Salt domes version 1.0 for visualizing, testing, and benchmarking various algorithms for salt dome delineation is now available to download. This version (v1.0) of the GUI compares different salt dome delineation algorithms.

We seek your feedback and suggestions. You are also welcome to send your salt dome delineation algorithms to include in the GUI for benchmarking, and comparison with other algorithms.

## Dataset:

We have used the real seismic dataset acquired from the Netherland's offshore, F3 block in the North Sea, whose size is 24 x 16 km<sup>2</sup> [1]. The seis-

mic 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.

## Salient Features of the GUI

- Comparison of different salt dome delineation algorithms, which include
  - 2D GoT by Wang et al.
  - 3D GoT by Shafiq et al.
  - 3D Sobel filter by Aqrawi et al.
  - Texture attributes by Berthelot et al.
  - Codebook by Amin et al.
  - Active Contour by Shafiq et al.
- Visualization of 3D Salt domes.
- Objective evaluation of the results of different salt dome delineation algorithms.
- Interactive salt dome boundary correction.

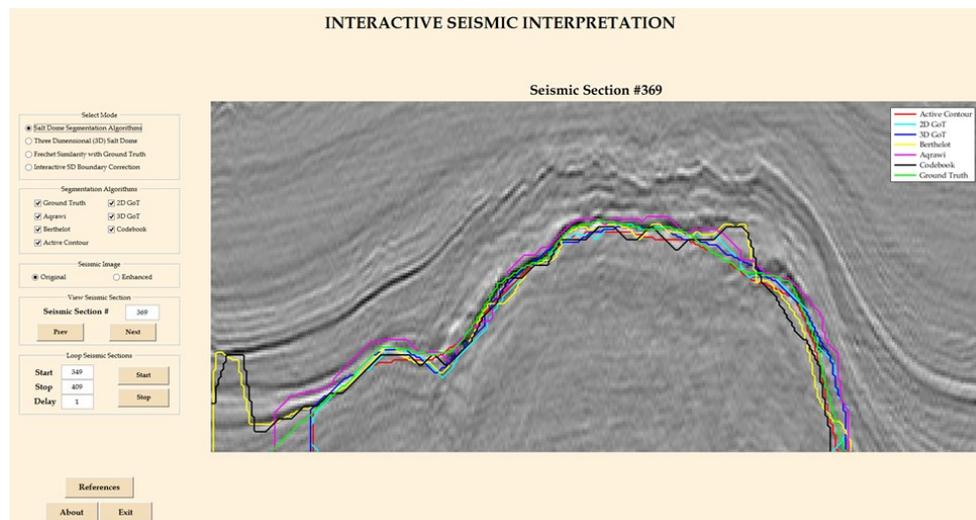


Figure 1. A snapshot of the GUI of CSI: Salt domes version 1.0.

## How to download the GUI?

In order to receive an email with the download link, please fill out the form available at the following link (<http://cegp.ece.gatech.edu/codedata/salt/>) to submit your information and agree the conditions of use. These information will be kept confidential and will not be released to anybody outside the CeGP administration team.

## References:

- [1] dGB Earth Sciences, The Netherlands Offshore, The North Sea, F3 Block - Complete, available at <https://opendtect.org/osr/pmwiki.php/Main/Netherlands/OffshoreF3BlockComplete4GB,1987>
- [2] Z. Wang, T. Hegazy, Z. Long, and G. AlRegib, "Noise-robust Detection and Tracking of Salt Domes in Post-migrated Volumes Using Texture, Tensors, and Subspace Learning," *Geophysics*, 80(6), WD101-WD116
- [3] M. Shafiq, Z. Wang, A. Amin, T. Hegazy, M. Deriche, and G. AlRegib, "Detection of salt-dome boundary surfaces in migrated seismic volumes using gradient of textures," *Expanded Abstracts of the SEG 85th Annual Meeting*, pp. 1811-1815, New Orleans, Louisiana, Oct. 18-23, 2015.
- [4] A. A. Aqrawi, T. H. Boe, and S. Barros, "Detecting salt domes using a dip guided 3D Sobel seismic attribute," in *Expanded Abstracts of the SEG 81st Annual Meeting*, 2011.
- [5] A. Berthelot, A. HS Solberg, and L. J. Gelius, "Texture attributes for detection of salt," *Journal of Applied Geophysics*, vol. 88, pp. 52-69, 2013
- [6] M. Shafiq, Z. Wang, and G. AlRegib, "Seismic interpretation of migrated data Using edge-based geodesic active contours," in *Proc. IEEE Global Conf. on Signal and Information Processing (GlobalSIP)*, Orlando, Florida, Dec. 14-16, 2015.

## CeGP at KFUPM acquires a High Performance Computing Cluster (HPC)

The HPC has the following specifications:

- Number of Nodes: 14 nodes
- Number of total physical processors: 24
- Total Logical cores: 336
- Total RAM Memory: 1536 GB
- GPU: 2x NVIDIA Tesla K40M, 12GB GDDR5,288GB
- Total Storage: 14.4 TB +(12TB external storage)
- Node Connection: InfiniBand 40GB
- OS: Linux Redhat

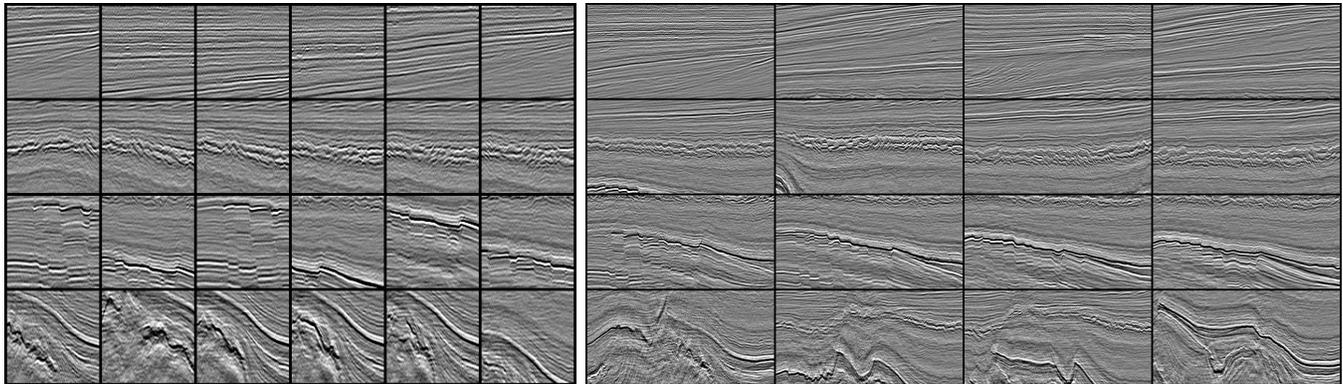
The following software are install on all nodes:

- MATLAB 2015b (latest version) with all toolboxes including parallel computing toolbox and it is GPU-compatible.
- VNC server to allow graphical interface access through SSH protocol
- Cluster management tools.



# Large North-Sea Dataset of Migrated Aggregated Seismic Structures (LANDMASS)

Yazeed Alaudah, Motaz Alfarraj, Zhiling Long, Muhammad Amir Shafiq, Zhen Wang, and Ghassan AlRegib



(a) LANDMASS-1.

(b) LANDMASS-2.

Samples from LANDMASS dataset.

At CeGP, we have been working on creating big datasets for post-migrated seismic volumes. The LANDMASS dataset is now available for development, testing, and benchmarking of various techniques aimed towards seismic applications such as retrieval, classification, and machine learning.

LANDMASS includes two datasets:

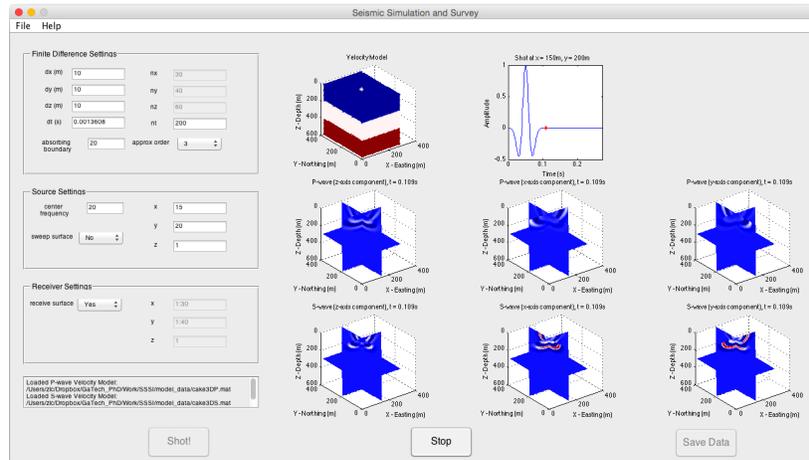
- LANDMASS-1, contains 17667 small “patches” of size 99x99 pixels. It includes 9385 Horizon patches, 5140 chaotic patches, 1251 Fault patches, and 1891 Salt Dome patches. The images in this database have values in the range [-1,1]
- LANDMASS-2, contains 4000 images. Each image is of size 150x300 pixels and normalized to values in the range [0,1]. Each one of the four classes has 1000 images.

## How to download the dataset ?

In order to receive an email with the download link, please fill out the form available at the following link ( <http://cegp.ece.gatech.edu/codedata/LANDMASS> ) to submit your information and agree the conditions of use. These information will be kept confidential and will not be released to anybody outside the CeGP administration team.

# S3I: Seismic Survey and Seismic Imaging

Lingchen Zhu, Lijun Zhu, Entao Liu, James McClellan, and Ghassan AlRegib



A snapshot of S3I GUI in the process of generating 3D (isotropic) elastic waves.

SSSI is a toolbox that was developed at CeGP. It can be used as a simulation and tutorial platform of seismic survey, data acquisition, and seismic imaging process such as pre-stack Kirchhoff migration, reverse time migration (RTM), least -square RTM (LSRTM), full waveform inversion (FWI), etc.

The SSSI numerically simulates the physical process for acoustic/elastic waves by solving the wave equation in given model using finite difference method on staggered-grid methods with arbitrarily high order of approximation. Moreover, the open boundary of the simulated region is taken care of by a perfectly matched layer (PML). For the readability of the codes and the tutorial purpose, MATLAB is chosen to be the coding platform of SSSI. In order to enhance its computational performance, several basic functions like acoustic wave simulation in SSSI is implemented with C MEX-file. There are a number of imaging conditions to form

a migrated image from the received data on the receiver array. Commonly used Kirchhoff and reverse time migration are implemented. FWI is also implemented so that high-resolution quantitative imaging of subsurface can be supported.

In order to accelerate seismic wave simulation, RTM and FWI, parallel computing based on the distributed memory model (implemented by OpenMPI) is supported in SSSI. One can run our code on a computing cluster across multiple computing nodes. Each node has its own independent processor(s) and memory, takes charge of its own imaging process for a local partition on the velocity model and communicates the required boundary cell values with its direct neighboring nodes. The final global result will be gathered after all nodes finish calculations of their own partitions. More technical details can be found at the following link (<http://cegp.ece.gatech.edu/s3i>).

## Dr. Steven McLaughlin and Dr. Douglas Williams visited KFUPM



A meeting with His Excellency Dr. Khalid Al-Sultan, Rector of KFUPM: (from left to right) Dr. Khalid Al-Sultan, Dr. Steven McLaughlin, Dr. Doug Williams, Dr. Ali Al-Shaikh, and Mr. Mohamed Alkhodary.



A meeting with Dr. Sahel Abduljawwad, The Vice Rector for Applied Research at KFUPM and Dr. Omar Al-Swailem, Dean of College of Engineering Sciences at KFUPM: (from left to right) Dr. Omar Al-Swailem, Dr. Sahel Abduljawwad, Dr. Steven McLaughlin, Dr. Doug Williams, and Dr. Ali Al-Shaikh.



At CeGP @ KFUPM: (from left to right) Dr. Mohamed Deriche, Mr. Mohammed Alkhodary, Dr. Doug Williams, Dr. SanLinn Kaka, Dr. Steven Mclaughlin, and Dr. Ali Al-Shaikhi.



A tour of CeGP @ KFUPM

## Georgia Tech President Participated in the IAB of KFUPM

Dr. G.P. "Bud" Peterson participated in the 17th (7-8 January, 2015) and 18th (8 September, 2015) International Advisory Board (IAB) meetings of KFUPM in Dhahran, Saudi Arabia.



IAB members at KFUPM, Dhahran, Saudi Arabia.

## Dr. Omar Al-Swailem at Georgia Tech

Dr. Omar Al-Swailem, Dean of College of Engineering Sciences at KFUPM, visited Georgia Tech in Summer 2015. During his visit, Dr. Al-Swailem met with Dr. Gary S. May, Dean of College of Engineering at Georgia Tech. He also toured CeGP and campus and met with visiting professor Dr. Ali Muqaibel.



A tour of the CeGP lab @ Georgia Tech during Dr. Al-Swailem's visit.

## Dr. Ali Muqaibel Spent Summer 2015 at Georgia Tech

Dr. Ali Muqaibel joined CeGP @ Georgia Tech in Summer 2015. During his visit, Dr. Muqaibel participated in research activities and educational collaboration between KFUPM and Georgia Tech.



Dr. Ali Muqaibel at the Campus Recreation Leadership Challenge Course at Georgia Tech.



Dr. Ali's office at Georgia Tech.

## Establishment of CeGP Center at KFUPM

The center consists of two research labs, a meeting room and a lounge.



The entrance of the center .



One of CeGP 's research LABs at KFUPM.

## CeGP team at SEG 85th Annual Meeting, New Orleans, LA

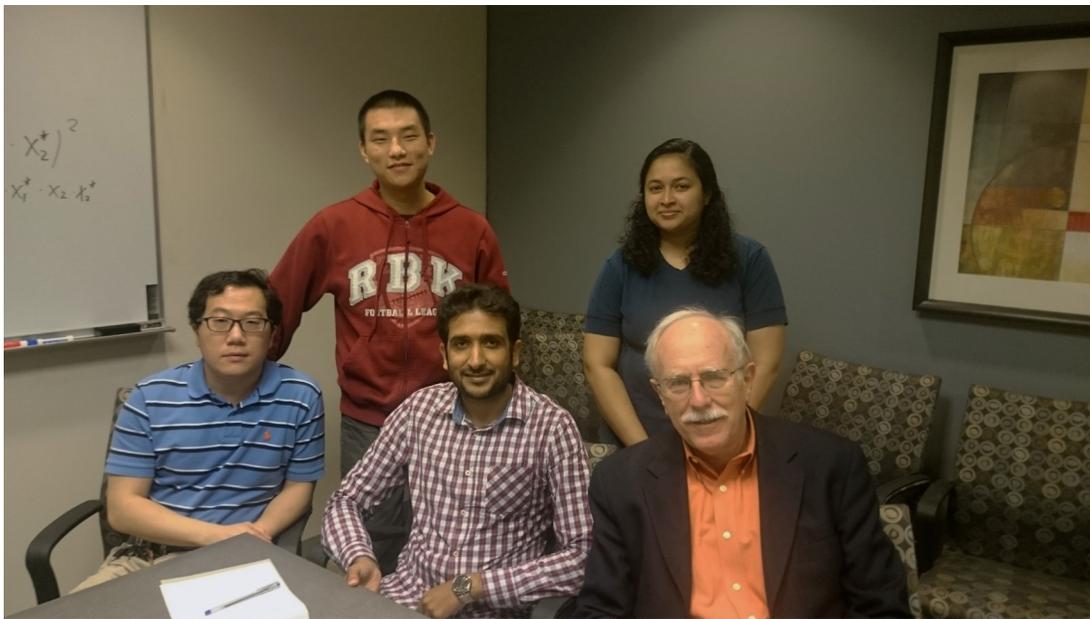
CeGP team participated and presented 3 papers at the Society of Exploration Geophysicist (SEG) 85th annual meeting that took place in New Orleans, LA, October 18-23, 2015.



CeGP team at SEG 2015: (from left to right) Motaz Alfarraj, Prof. Ghassan AlRegib, Yazeed Alaudah, Muhammad Amir Shafiq, Zhen Wang, and Dr. Zhiling long.

## Dr. Naveed Iqbal Visited Georgia Tech in March 2016

Dr. Naveed Iqbal, a postdoctoral researcher at KFUPM and a CeGP member spent the month of March 2016 at Georgia Tech.



(From left to right) Dr. Entao Liu, Lijun Zhu, Dr. Naveed Iqbal, Anupama Govinda, and Prof. James McClellan.

## 4th CeGP Workshop Held at Georgia Tech, Atlanta, GA

The 4th CeGP workshop took place on March 23-26, 2015 in Atlanta, GA. The list of participants included executives and researchers from the industry as well as faculty members and researcher from KFUPM and Georgia Tech.



A Group photo at the 4th CeGP workshop.



4th CeGP workshop reception.



Prof. Ghassan AlRegib presenting at the 4th CeGP workshop.



CeGP members at dinner after the workshop.

## CeGP Visits ExxonMobil in Houston, TX

The CeGP team visited the main campus of ExxonMobil in late spring 2015. The team presented CeGP work and met with researchers and teams from ExxonMobil. The feedback, the suggestion and the experience was invaluable. Many of the outcomes from CeGP in the months that followed were a result of such rich interaction with ExxonMobil and their researchers, scientists, and engineers. We look forward to strengthen this relationship.



## CeGP Graduate Student Interns with Saudi Aramco

أرامكو السعودية  
Saudi Aramco



In Fall 2015, Lijun Zhu, a graduate student at CeGP, went to Houston, TX on an internship with Saudi Aramco. Working his mentor, Dr. Weichang Li, the team was processing a microseismic monitoring dataset with the help from the geophysics team, particularly from their team member Dr. Yang Zhao. Together, they uncovered the myth behind the dataset which was previous seen as too noisy to extract valuable information. This study helps improve the knowledge of passive surface land data and offers good testing data for future denoising and localization works. The collaboration between CeGP and Aramco HRC continues after Lijun's internship and an abstract has been planned to submit to SEG annual meeting 2016.

## Nine KFUPM Undergraduate Students Spent Fall 2015 at Georgia Tech



The group is pictured here at the peak of Stone Mountain during another off-campus learning activity. The students climbed the 1 mile trail to reach 1,686 feet above sea level and viewed downtown Atlanta, and the adjacent mountains, and beautiful scenery. They also visited the Confederate Hall Historical & Environmental Education Center, a space that allows for learning about the geology and ecology of Stone Mountain and gives historical context about the famous carving on the mountain side.



The group attended an excursion at Sweet Water Creek that included a guided kayak trip and hike on a trail that leads to a historical site, a textile mill that was burned during the Civil War.



The group visited the Center for Civil and Human rights in Atlanta, an opportunity to explore and learn about US history and discuss the American Civil Rights Movement and Atlanta's historic role in the movement.

In addition to the activities and excursions pictured, the KFUPM exchange group were engaged in on-campus activities designed to make the most of their academic and cross-cultural experience, including a leadership obstacle course that uniquely looked at teamwork, collaboration, and communication. During the Fall 2015 semester, the group also engaged with other Georgia Tech students and staff through intercultural activities, such as International Coffee Hour.

“We have been hosting KFUPM undergraduate students for 6 years on our campus in Atlanta. I have been personally involved in the process of their application, admission, hosting, and on-campus activities. It has been a great pleasure to work with these students. Not only they perform well in their classes but also act as ambassadors to KFUPM and later on to Georgia Tech and Atlanta. Some of them come back to Georgia Tech as PhD students and what a great experience to work with such bright individuals. I got to learn the students’ individual experiences. They embrace the vibrant daily college life we have here and they go back to Dhahran full of energy with many ideas to contribute to KFUPM culture. They leave Atlanta with a lasting impression on many of us at Georgia Tech. With the demand on such a program at Tech, our Office of International Education (OIE) has a new program *TECHsplore* for all such students. Fall 2015 was the first time KFUPM students enroll in the program and what a difference it makes to have Susannah McFaul as the students’ guide in their experience. Thanks to KFUPM, Georgia Tech, Susannah, and the students for such an impactful program. “

Ghassan AlRegib

## List of CeGP Seminars

**Title:** Sparse-promoting Full Waveform Inversion based on Online Orthonormal Dictionary Learning.

**Speaker:** Mr. Lingchen Zhu.

**Date:** Wednesday, December 9, 2015.

**Time:** 11:00 am (Atlanta), 7:00 pm (Dhahran).

**Title:** Microseismic Denoising and Detection using Autocorrelation.

**Speaker:** Dr. Entao Liu, Georgia Institute of Technology.

**Date:** Wednesday, September 16, 2015.

**Time:** 11:00 am (Atlanta), 6:00 pm (Dhahran).

**Title:** SOC in Microearthquakes and Hydraulic Fracturing Microseisms.

**Speaker:** Dr. Tim Long, Professor Emeritus, School of Earth and Atmospheric Sciences, Georgia Institute of Technology.

**Date:** Wednesday, May 20, 2015.

**Time:** 11:00 am (Atlanta), 6:00 pm (Dhahran).

**Title:** Microseismic Parameters Inversion without Arrival-Time Picking.

**Speaker:** Dr. Entao Liu, Georgia Institute of Technology.

**Date:** Wednesday, March 04, 2015.

**Time:** 11:00 am (Atlanta), 7:00 pm (Dhahran).

**Title:** Salt Dome Detection and Tracking Using Texture-Based Gradient and Tensor-Based Subspace Learning.

**Speaker:** Dr. Tamir Hegazy and Zhen Wang, Georgia Institute of Technology.

**Date:** Wednesday, February 18, 2015.

**Time:** 11:00 am (Atlanta), 7:00 pm (Dhahran).

**Title:** Seismic Denoising through Dictionary Learning.

**Speaker:** Lingchen Zhu, Georgia Institute of Technology.

**Date:** Wednesday, February 4, 2015.

**Time:** 11:00 am (Atlanta), 7:00 pm (Dhahran).

**Title:** Enhanced Reservoir Characterization and Uncertainty Quantification: A Multi-Data History Matching Approach.

**Speaker:** Dr. Ibrahim Hoteit, King Abdullah University of Science and Technology (KAUST).

**Date:** Monday, December 8, 2014.

**Time:** 10:00 am (Atlanta), 6:00 pm (Dhahran).

**Title:** Texture attributes for detecting salt bodies in seismic data.

**Speaker:** Dr. Tamir Hegazy, Georgia Institute of Technology.

**Date:** Wednesday, November 19, 2014.

**Time:** 11:00 am (Atlanta), 7:00 pm (Dhahran).

**Title:** Automatic fault surface detection by using 3D Hough transform.

**Speaker:** Zhen Wang, Georgia Institute of Technology.

**Date:** Wednesday, November 19, 2014.

**Time:** 11:00 am (Atlanta), 7:00 pm (Dhahran).

**Title:** Introduction to Marine Seismic Acquisition.

**Speaker:** Mr. Azizur Rahman Khan, Saudi Aramco.

**Date:** Monday, November 10, 2014.

**Time:** 9:30 am (Atlanta), 05:30 pm (Dhahran).

**Title:** Introduction to Field Acquisition.

**Speaker:** Dr. Abdullatif A. Al-Shuhail, King Fahd University of Petroleum and Minerals (KFUPM).

**Date:** Wednesday, October 15, 2014.

**Time:** 10:30 am (Atlanta), 5:30 pm (Dhahran).

**Title:** Parallel Computing Basics with a Case Study on the CeGP Cluster.

**Speakers:** Dr. Tamir Hegazy, Dr. Entao Liu, and Dr. Zhiling Long, Georgia Institute of Technology.

**Date:** Wednesday, September 17, 2014.

**Time:** 11:30 am (Atlanta), 6:30 pm (Dhahran).

**Title:** Numerical Simulation of Exploration Geophysics: Introduction to S3I.

**Speakers:** Dr. Entao Liu and Lingchen Zhu, Georgia Institute of Technology.

**Date:** Wednesday, September 10, 2014.

**Time:** 11:30 am (Atlanta), 6:30 pm (Dhahran).

# List of CeGP Scholarly Accomplishments

## Datasets

[Large North-Sea Dataset of Migrated Aggregated Seismic Structures \(LANDMASS\).](#)

## Software

[Seismic Simulation, Survey, and Imaging \(S3I\)](#)

[Salt Dome Interpretation Tool.](#)

## Journal Publications

### [2016]

- H. Al-Marzouqi and G. AlRegib, "Curvelet transform with learning-based tiling," submitted to the *Elsevier Signal Processing: Image Communication Journal*, February 2016.
- Z. Wang and G. AlRegib, "Fault detection in 3D seismic data using the Hough transform and tracking vectors," submitted to *IEEE Transactions on Computational Imaging*, 2016.
- M. Shafiq, Z. Wang, G. AlRegib, A. Amin, and M. Deriche, "A texture-based interpretation workflow with application to delineating salt domes," submitted to *Interpretation*, March, 2016.
- A. Amin, M. Deriche, Z. Wang, and G. AlRegib, "A novel approach for salt dome detection using a dictionary-based classifier", submitted to *IEEE Transactions on Image Processing*, March, 2016.
- Z. Long, Y. Alaudah, M. Qureshi, M. Alfarraj, Y. Hu, Z. Wang, A. Amin, M. Deriche, and G. AlRegib, "Describing migrated seismic volumes using texture attributes ", in preparation.
- A. Amin and M. Deriche, "Salt dome detection using a codebook based learning model", in preparation.

### [2015]

- L. Zhu, E. Liu, and J. McClellan, "Sparse-promoting full waveform inversion based on online orthonormal dictionary learning," submitted to *Geophysics*.
- Z. Wang, T. Hegazy, Z. Long, and G. AlRegib, "Noise-robust detection and tracking of salt domes in post-migrated volumes using texture, tensors, and subspace learning," *Geophysics*, November 2015, v. 80, p. WD101-WD116
- L. Zhu, E. Liu, and J. McClellan, "Seismic data denoising through multi-scale and sparsity-promoting dictionary learning," *Geophysics*, November 2015, v. 80, 80(6), WD45-WD57.
- A. Amin and M. Deriche. "A new approach for salt dome detection using a 3D multidirectional edge detector." *Applied Geophysics* 12.3 (2015): 334-342.

## Conference Publications

## [2016]

- Xin Tian, Entao Liu, Afshin Abdi, Song Li, Fekri Faramarz, "Seismic Data Compression by Dictionary Learning and Sparse Representation," The 17th IEEE International workshop on Signal Processing advances in Wireless Communications (SPAWC), 2016.(Submitted)
- A. Abdi and F. Fekri, "Mixture Source Identification in Non-Stationary Data Streams with Applications in Compression," , submitted to IEEE International Symposium on Information Theory, 2016.
- A. Payani, A. Abdi and F. Fekri, "Near Optimal Representative Subset Selection from Short Sequences Generated by a Stationary Source," , submitted to IEEE International Workshop on Signal Processing Advances in Wireless Communications, 2016
- M. Alfarraj, Y. Alaudah, and G. AlRegib, "DTSIM: A directional texture similarity metric," submitted to *IEEE Intl. Conference on Image Processing (ICIP)*, Phoenix, Arizona, USA, Sep. 25-28, 2016.
- Y. Alaudah and G. AlRegib, "Weakly-supervised labeling of seismic volumes using reference exemplars," submitted to *IEEE Intl. Conference on Image Processing (ICIP)*, Phoenix, Arizona, USA, Sep. 25-28, 2016.
- M. Shafiq, Y. Alaudah, and G. AlRegib, "Phase congruency for image understanding with applications in computational seismic interpretation," submitted to IEEE Intl. Conference on Image Processing (ICIP), Phoenix, Arizona, USA, Sep. 25-28, 2016.
- A. Amin and M. Deriche. " New attributes for salt dome detection in 3D seismic data using higher order SVD." submitted to IEEE Intl. Conference on Image Processing (ICIP), Phoenix, Arizona, USA, Sep. 25-28, 2016.
- Y. Alaudah and G. AlRegib, "A Generalized tensor-based coherence attribute," at the *78th EAGE Annual Conference & Exhibition*, Vienna, Austria, May 30-June 2, 2016.
- M. Shafiq, Y. Alaudah, and G. AlRegib, "A hybrid approach for salt dome delineation within migrated seismic volumes," at the *78th EAGE Annual Conference & Exhibition*, Vienna, Austria, May 30-June 2, 2016.
- M. Shafiq and G. AlRegib, "A noise robust approach for delineating subsurface structures within migrated seismic volumes," at the *78th EAGE Annual Conference & Exhibition*, Vienna, Austria, May 30-June 2, 2016.
- M. Shafiq and G. AlRegib, "Perceptual and non-perceptual dissimilarity measures for salt dome delineation," at the *78th EAGE Annual Conference & Exhibition*, Vienna, Austria, May 30-June 2, 2016.
- M. Shafiq and G. AlRegib, "Interpreter-assisted tracking of subsurface structures within migrated seismic volumes using active contour," at the *78th EAGE Annual Conference & Exhibition*, Vienna, Austria, May 30-June 2, 2016.
- Y. Alaudah, M. Shafiq, and G. AlRegib, "A Hybrid spatio-frequency approach for delineating subsurface structures in seismic volumes," *SIAM conference on Imaging Science*, New Mexico, USA, May 23-26, 2016.
- M. Shafiq, T. Alshawi, Z. Long, and G. AlRegib, "The role of visual saliency in seismic interpretation with an application to salt dome delineation," *SIAM conference on Imaging Science*, New Mexico, USA, May 23-26, 2016.
- L. Zhu, E. Liu, and J. H. McClellan, ""An automatic arrival time picking method based on RANSAC curve fitting," submitted to *78th EAGE Annual Conference & Exhibition*, Vienna, Austria, May 30-June 2, 2016.
- E. Liu, L. Zhu, and J. H. McClellan, A. Al-Shuhail, S. I. Kaka, "Microseismic events enhancement in sensor arrays using auto-correlation based filtering," submitted to *78th EAGE Annual Conference & Exhibition*, Vienna, Austria, May 30-June 2,

2016.

- L. Zhu, E. Liu, and J. H. McClellan, "Fast online orthonormal dictionary learning for efficient full waveform inversion," to be presented at *IEEE Intl. Conf. on Acoustics, Speech and Signal Processing (ICASSP)*, Shanghai, China, Mar. 20-25, 2016.
- M. Shafiq, T. Alshawi, Z. Long, and G. AlRegib, "SalSi: A new seismic attribute for salt dome detection," to be presented at *IEEE Intl. Conf. on Acoustics, Speech and Signal Processing (ICASSP)*, Shanghai, China, Mar. 20-25, 2016.
- Z. Wang, Z. Long, and G. AlRegib, "Tensor-based subspace learning for tracking salt-dome boundaries constrained by seismic attributes," to be presented at *IEEE Intl. Conf. on Acoustics, Speech and Signal Processing (ICASSP)*, Shanghai, China, Mar. 20-25, 2016.

## [2015]

- L. Zhu, E. Liu, and J. H. McClellan, "Full waveform microseismic inversion using differential evolution algorithm," *Proc. IEEE Global Conf. on Signal and Information Processing (GlobalSIP)*, Orlando, Florida, Dec. 14-16, 2015.
- M. Shafiq, Z. Wang, and G. AlRegib, "Seismic interpretation of migrated data Using edge-based geodesic active contours," *Proc. IEEE Global Conf. on Signal and Information Processing (GlobalSIP)*, Orlando, Florida, Dec. 14-16, 2015.
- T. Hegazy, Z. Wang, and G. AlRegib, "The role of perceptual texture dissimilarity in automating seismic data interpretation," *Proc. IEEE Global Conf. on Signal and Information Processing (GlobalSIP)*, Orlando, Florida, Dec. 14-16, 2015.
- A. Amin, M. Deriche, T. Hegazy, Z. Wang, and Ghassan AlRegib, "A novel approach for salt dome detection using a dictionary-based classifier," *Expanded Abstracts of the SEG 85th Annual Meeting*, pp. 1816-1820, New Orleans, Louisiana, Oct. 18-23, 2015.
- Z. Long, Y. Alaudah, M. Qureshi, M. Farraj, Z. Wang, A. Amin, M. Deriche, and G. AlRegib, "Characterization of migrated seismic volumes using texture attributes: a comparative study," *Expanded Abstracts of the SEG 85th Annual Meeting*, pp. 1744-1748, New Orleans, Louisiana, Oct. 18-23, 2015.
- M. Shafiq, Z. Wang, A. Amin, T. Hegazy, M. Deriche, and G. AlRegib, "Detection of salt-dome boundary surfaces in migrated seismic volumes using gradient of textures," *Expanded Abstracts of the SEG 85th Annual Meeting*, pp. 1811-1815, New Orleans, Louisiana, Oct. 18-23, 2015.
- Y. Alaudah and G. AlRegib, "A curvelet-based distance measure for seismic images," *Proc. IEEE ICIP 2015*, Québec City, Canada, Sept. 27-30, 2015.
- A. Amin and M. Deriche, "A hybrid approach for salt dome detection in 2D and 3D seismic data." *Proc. IEEE ICIP 2015*, Québec City, Canada, Sept. 27-30, 2015.
- Z. Wang, Z. Long, and G. AlRegib, "Tensor-based subspace learning for tracking salt-dome boundaries," *Proc. IEEE ICIP 2015*, Québec City, Canada, Sept. 27-30, 2015.
- Z. Long, Z. Wang, and G. AlRegib, "SeiSIM: structural similarity evaluation for seismic data retrieval," *Proc. IEEE Intl. Conf. on Communications, Signal Processing, and their Applications (ICCSPA)*, Sharjah, United Arab Emirates (UAE), Feb. 17-19, 2015.

## [2014]

- H. Al-Marzouqi and G. AlRegib, "Texture similarity using periodically extended and adaptive curvelets," *Proc. IEEE Global Conf. on Signal and Information Processing (GlobalSIP)*, pp. 1119-1123, Atlanta, Georgia, Dec. 3-5, 2014.
- Z. Wang, D. Temel and G. AlRegib, "Fault detection using color blending and color transformations," *Proc. IEEE Global Conf. on Signal and Information Processing (GlobalSIP)*, pp. 1171-1175, Atlanta, Georgia, Dec. 3-5, 2014.
- H. Al-Marzouqi and G. AlRegib, "Similarity index for seismic data sets using adaptive curvelets," in *Expanded Abstracts of the SEG 84th Annual Meeting*, pp. 1470-1474, Denver, Colorado, Oct. 26-31, 2014.
- T. Hegazy and G. AlRegib, "Texture attributes for detecting salt bodies in seismic data," in *Expanded Abstracts of the SEG 84th Annual Meeting*, pp. 1455-1459, Denver, Colorado, Oct. 26-31, 2014.
- Z. Wang and G. AlRegib, "Automatic fault surface detection using 3D Hough transform," in *Expanded Abstracts of the SEG 84th Annual Meeting*, pp. 1439-1444, Denver, Colorado, Oct. 26-31, 2014.
- Z. Wang, Z. Long, G. AlRegib, A. Asjad, and M. A. Deriche, "Automatic fault tracking across seismic volumes via tracking vectors," *Proc. IEEE Intl. Conf. on Image Processing (ICIP)*, pp. 5851-5855, Paris, France, Oct. 27-30, 2014.
- Z. Wang and G. AlRegib, "Fault detection in seismic datasets using Hough transform," *Proc. IEEE Intl. Conf. on Acoustics, Speech and Signal Processing (ICASSP)*, pp. 2372-2376, Florence, Italy, May 2014.

### [2013]

- H. Al Marzouqi and G. AlRegib, "Using the coefficient of variation to improve the sparsity of seismic data," *Proc. 1st IEEE Global Conference on Signal and Information Processing*, pp. 630-630, Austin, TX, December 2013.
- H. Al Marzouqi and G. AlRegib, "Searching for the optimal curvelet tiling," *Proc. IEEE Intl. Conf. on Acoustics, Speech and Signal Processing (ICASSP)*, pp. 1626-1630, Vancouver, Canada, May 2013.

### [2012]

- H. Al Marzouqi, G. AlRegib, "Curvelet transform with adaptive tiling," *Proc. IS&T/SPIE Electronic Imaging*, vol. 8259, pp. 825950F1-6, Burlingame, CA, January 2012.

***Center for Energy & Geo Processing***



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