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Subsurface Exploration: Recent Advances in Geo-Signal Processing, Interpretation, and Learning

For centuries, humans have been exploring the subsurface structure of planet Earth. Several Earth geophysical applications, such as mining, earthquake studies, and oil and gas exploration, have driven research that produced, over the years, ground-breaking theories and innovative technologies that image Earth's subsurface. The pursuit is ongoing with an increasing desire to have higher-resolution subsurface models and images. Signal processing, data interpretation, and modeling have been the cornerstones of such innovations.

In recent years, there have been advances in technologies and requirements that demand the utilization of advanced signal processing and machine-learning theories and algorithms. For example, the wide- and full-azimuth acquisition technologies have proven to be instrumental in providing high-resolution subsurface images. Similarly, geophones and hydrophones are becoming smaller, cableless, wireless, and mobile and, soon, with processing capabilities. Further, recent experiments to deploy autonomous nodes have proven the viability of automating part of or the entire acquisition process. This becomes necessary when the number of sensors increases rapidly to be in the range of hundreds of thousands per survey.

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Deployment requires these sensors to be wireless and more intelligent with limited processing in the field. Besides such advances in sensing, the target reservoirs are getting deeper with complex wave propagation effects and poor target illumination. With all of these added complexities, the interpretation task becomes more challenging. Recent advances in machine learning have proven effective in automating part of the interpretation process. This special issue of *IEEE Signal Processing Magazine* (*SPM*) provides an introduction to the role of signal processing in areas where automation and learning are being deployed in Earth exploration. We envision that such technologies will also be essential for the exploration of other planets including Mars.

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In this issue

The signal processing community has been making important contributions to the most diverse fields, and Earth geophysics and exploration is no exception. Much of the interest in subsurface exploration was sparked by a 2012 special issue of *SPM* on geophysical signal processing [1]. We believe, however, that the community has come a long way since then, and the diversity of research areas has increased dramatically. The current special issue was created from this belief, and it addresses new, timely topics such as machine learning and full-waveform inversion (FWI) in light of the new advances in exploration geophysics such as wide azimuth, wireless geophones and hydrophones, robotics for acquisition, ambient seismic noise, and broadband imaging. The articles in this issue summarize the current state of the art and will hopefully trigger the interest of the larger signal processing community to work on such an exciting and challenging mission of studying Earth's subsurface and, eventually, other planets' subsurface.

The articles are diverse in their coverage and discuss a wide range of problems in geophysics. Some of these problems range from near-surface monitoring to well-log data estimation and from compression of seismic data to interpretation of seismic volumes using machine learning.

The first article by Malfante et al., "Machine Learning for Volcano-Seismic Signals," presents an overview of the challenging task of monitoring, mitigating, and preventing risks related to volcanic hazards. The authors focus on the optical representation of volcanic-seismic signals, the detection of such events, and, finally, the classification of the detected events. They utilize a data set that contains six years of recordings with more than 100,000 volcano-seismic events acquired from Ubinas volcano, the most active volcano in Peru.

In the article "A Seismic Shift in Scalable Acquisition Demands New Processing," Martin et al. address a crucial development in the field of near-surface monitoring in urban areas, triggered by optical seismic acquisition systems. The article uses data from a fiber-optic array in existing telecommunications conduits underneath the Stanford University campus in California. The authors focus on the automation of ambient noise processing.

Next, approaches to seismic deconvolution are discussed in "Improving Sparse Multichannel Blind Deconvolution with Correlated Seismic Data" by Nose-Filho et al. Specifically, the authors discuss multichannel blind deconvolution methods where the underlying assumption is that the wavelets that affect some subsets of the seismic data are approximately the same. The authors highlight a method that exploits the high correlation of seismic data to both reduce the computational complexity of multichannel deconvolution and improve the quality of the solution.

Payani et al. address the challenge of reducing the size of the sensed data in seismic surveys in their article, "Advances in Seismic Data Compression via Learning from Data." Specifically, they show that, by placing some intelligence at the sensors in the field, they can achieve good lossless compression ratios. They discuss both dictionary domain methods and predictive methods.

In Santos de Oliveira's article, "An Approximate Representation of the Fourier Spectra of Irregularly Sampled Multidimensional Functions," a common challenge in inverse problems is discussed where the Fourier spectra of irregularly sampled multidimensional is estimated in an approximate fashion.

In "Well-Log and Seismic Data Integration for Reservoir Characterization," Chaki, Routray, and Mohanty provide an overview of existing signal processing and machine-learning algorithms that explore the relationship between well-log data and seismic data. In particular, the signal processing tools are primarily required for information matching, preprocessing for noise and artifacts, and postprocessing for removing irregularities.

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AlRegib et al. focus on the challenge of interpretation in their article, "Subsurface Structure Analysis Using Computational Interpretation and Learning," where they provide a detailed overview of existing image processing methods that have been developed for interpretation. They further discuss recent advances in machine learning and human vision system modeling and their effectiveness in the seismic interpretation process. The authors propose a new application of labeling seismic volumes that contributes to the automation of the overall interpretation workflow.

In the article "Array Processing in Microseismic Monitoring," McClellan et al. discuss a process that has become popular in recent years—hydraulic fracturing, where fluid is injected at high pressure into a subsurface reservoir. Such injection results in failure of the rocks and that produces a seismic wave. This article discusses advanced signal processing methods that estimates the location as well as the character of the failure events.

In the "Wireless Digital Communication Technologies for Drilling" Jarrot, Gelman, and Kusuma provide an overview of monitoring the drilling process with the goal of achieving a safe operating envelope, guiding the drilling system into the most productive zones, and providing information for further stages in the completion of the well. The article addresses recent advances in digital channel models and geological models to achieve data rates higher than existing technologies such as mud-pulse telemetry and electromagnetic telemetry.

Al-Marzouqi's article, "Digital Rock Physics," presents recent advances and major challenges in using CT scan to extract rock properties. The key open problems are highlighted as well.

Hu et al., in "Retrieving Low Wavenumber Information in FWI," address one of the FWI challenges that takes place when low-frequency seismic data are not available. In this case, FWI suffers from the cycle-skipping issue caused by the severe nonlinearity nature of the standard L2 norm objective function and results in severe artifacts.

In the final article, "Complex Autoregressive Time–Frequency Analysis," Andrade, Porsani, and Ursin discuss the effectiveness of time-frequency representations of nonstationary signals in geophysical applications. They specifically address the challenge of estimating the individual components of the signal.

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Meet the guest editors

Ghassan AlRegib (alregib@gatech.edu) received his B.S. degree in electrical engineering from King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia, in 1997 and his Ph.D. degree in electrical and computer engineering from the Georgia Institute of Technology (Georgia Tech) in 2003, where he is a professor in the School of Electrical and Computer Engineering. In 2012, he was named the director of Georgia Tech's Center for Energy and Geo

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Renato Lopes (rlopes@decom.fee.unicamp.br) received his B.S. and M.Sc. degrees in electrical engineering from the University of Campinas (UNICAMP), Brazil, in 1995 and 1997, respectively. He received an M.Sc. degree in mathematics and a Ph.D. degree in electrical engineering from the Georgia Institute of Technology in 2001 and 2003, respectively. He is an associate professor at the School of Electrical and Computer Engineering at UNICAMP. His main research interest is in digital signal processing, especially its application to communication systems and to seismic data analysis.

Reference

[1] *IEEE Signal Process. Mag.*, vol. 29, no. 4, July 2012.

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FROM THE EDITOR *(continued from page 4)*

Internships also facilitate the transfer of information between academia and industry through the students. Internships, of course, are great for companies. In this example, as my interest and appreciation in the work grew, I devoted a lot of resources to work in millimeter-wave communication, including looking for funding from a number of companies. This led to a substantial amount of return in terms of research dollars spent, versus salary paid during the internship.

Third, practical ideas lead to more research opportunities. Doing research on practical problems attracts the attention of others in industry. As a result, it leads to more discussions about practical challenges, which, in turn, provides more problems to solve. This creates even more opportunities for research funding and makes the students even more marketable. In essence, solving practical and relevant problems makes our research more attractive to industry, leading to further industry involvement.

I am fully supportive of industry involvement in *SPM*. I hope authors will continue to make their content available to a wide audience. I would like to encourage our industry colleagues to get involved with special issue proposals, articles for special issues, and feature articles. The signal processing community is actively listening or, in this case, reading.

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