

## Full-waveform inversion: From near surface to deep

TARIQ ALKHALIFAH, KAUST

WILLIAM W. SYMES, Rice University

The ancient Persian Gulf port city of Muscat provided a spectacular setting for the SEG's 2013 Workshop on Full-waveform Inversion (FWI). This active R&D topic attracted about 36 oral presentations and 20 or so posters, which added up to three intense days of ideas, images, and discussion. FWI has progressed from academic research topic to commercial workflow component in roughly 10 years, with many case studies documenting improved imaging and business value and others documenting a definite need for improved understanding of algorithms and applicability. Along with fundamental research issues of worldwide importance, the meeting provided an opportunity to showcase implications of the Middle East's particular exploration challenges for the further development of FWI.

The opening keynote address by Salim Rawahi, manager of GeoSolutions for Petroleum Development Oman LLC (PDO), set the geologic and economic stage. Rawahi described the severe demands that both conventional geophysical imaging and innovative technologies such as FWI must meet in order to add value to the exploration in the Omani setting.

FWI in its current form dates from work in the early 1980s by Patrick Lailly, Albert Tarantola, and many others. Jean Virieux of Université Joseph Fourier Grenoble I and CNRS opened the first technical session "FWI: From Practice to Theory" with an overview of FWI fundamentals. He mentioned and illustrated several obstacles which blunted the practical impact of this early work and remain key research issues. They include the following:

- the "cycle-skipping" problem, leading optimization formulations of FWI to stall far from geologically informative models
- the high computational cost of FWI in any form
- the challenge (and importance) of including accurate wave physics, in the form of multiple model parameters, and of accounting for both reflected and refracted energy in the same model

These themes surfaced repeatedly in various ways throughout the meeting. Virieux, recipient of this year's Desiderius Erasmus Award from EAGE, outlined the solutions underlying current industrial FWI practice (many pioneered by Gerhard Pratt and coworkers): emphasis on low-frequency data, diving waves recorded at long offsets, and low-to-high-frequency continuation, often implemented explicitly in the frequency domain. QC to detect cycle skipping is important because FWI velocity-update algorithms themselves do not yield any direct evidence. Andrew Ratcliffe (CGG) illustrated a couple of solutions to this problem, as well as the use of PSDM image gathers to assess the accuracy of FWI velocity estimates (another idea to surface

repeatedly throughout the meeting). He also mentioned that data fit may function as a QC element—an idea which has not yet featured prominently in practice, even though FWI is based fundamentally on data fitting. Laurent Sirgue (Total) emphasized integrating FWI into a comprehensive workflow, in particular the importance of ray-based tomography for construction of initial velocity models to be updated by FWI. His examples of near-surface lateral velocity heterogeneity clearly illustrated one of the major limitations of current workflows.

Having established that FWI has both great potential value and considerable pitfalls as currently formulated, the program turned to alternative theoretical visions. In his keynote address, Ru-Shan Wu (University of California, Santa Cruz) took the inverse scattering series approach pioneered by Art Weglein (University of Houston) in a novel direction via renormalization techniques motivated by quantum electrodynamics. Morten Jacobsen (University of Bergen) also presented a series approach, using T-matrix field updates. Hongbo Zhou (Statoil) ended the morning session by introducing a completely different set of ideas, namely, waveform inversion in the image domain (also called waveform tomography), and showed a promising reformulation in the data domain. These ideas, deriving from migration velocity analysis, formed another recurring theme of this conference.

The first afternoon session ("Elasticity and Near-Surface Inversion") focused on the implications of complex near-surface physics for effective FWI. Dries Gisolf (Delft University of Technology) gave the opening keynote talk on a Neumann-series approach to fully elastic inverse scattering, illustrated by several complex synthetic and field data examples. Fabian Ernst (Shell) showed how the classic least-squares data-fitting approach can be adapted to various forms of near-surface guided waves, such as ground roll, to produce highly resolved maps of shallow subsurface properties. Derecke Palmer (University of New South Wales) used an accurate approximation of head-wave amplitudes to invert the near surface for both P-wave velocity and density, showing that the latter quantity may be an important contributor to resolution of near-surface geology.

After an excellent poster session, the oral presentations resumed with a keynote by Yu Zhang of CGG, who showed how reverse time migration can be modified to produce accurate impedance maps rather than merely structural images. His examples illustrated the importance of careful preprocessing for ghost compensation, among other effects, required by these true-amplitude techniques. Denes Vigh (WesternGeco) gave an overview of contemporary field application of FWI, emphasizing the importance of recently developed very long-offset acquisition techniques to provide adequate quality and quantity of the diving-wave data. The day's program closed with a lively discussion session.

David Lumley (University of Western Australia) opened the second day with a discussion of 4D imaging as a full-wavefield inverse problem. Lumley illustrated the potential and pitfalls of 4D inversion with a variety of interesting field data examples, both from petroleum applications and from carbon dioxide sequestration and monitoring. His examples included both data-domain FWI and image-domain approaches. Image-domain techniques are particularly appropriate in the case of highly compressible rock/fluid reservoir changes that lead to significant traveltime changes. Mamoru Takanishi (Japan Oil, Gas, and Metals National Corporation) exploited the nonattenuative nature of guided waves to image fluid intrusions in low-velocity zones between boreholes. Dmitry Borisov (Institute of Earth Physics–Paris) demonstrated the use of the Chapman–Robertsson grid injection technique to dramatically speed up the modeling steps in 4D FWI. Thierry Tonellot (Saudi Aramco) returned to a theme of the morning session, with several near-surface FWI case studies.

FWI in the Laplace and Fourier-Laplace domains provides a convenient and effective way to stress first-arrival and low-frequency parts of the data, which play a critical role in diving-wave inversion. This technique has been emphasized particularly in the work of Changsoo Shin (Seoul National University). Phil Bording (Shin Geophysical) presented many examples in two presentations (one of them standing in for Shin) of field data inversions using Shin's methodology, including some remarkable examples from the Canadian Foothills. Felix Herrmann (University of British Columbia) uses ideas from compressive sensing and machine learning to accelerate FWI via random shot synthesis and sparsity in various domains, with application to

the Chevron Gulf of Mexico synthetic from last year's SEG workshop.

The afternoon session of the second day focused on inversion for multiple parameter fields, particularly anisotropy parameters. René-Édouard Plessix (Shell) opened the session with a keynote presentation on multiparameter inversion. He emphasized that inversion for anisotropy must take into consideration the potential null space introduced by the additional degrees of freedom. Application of this inversion to real data demonstrated the specific and precise role that these parameters may play, based on their radiation patterns, in such an inversion. Christos Saragiotis (KAUST) followed by introducing a novel approach in dealing with multiple first-arrival traveltime picks for wave-equation tomography. The multiple travletime picks can result from using various



*Daniel Macedo (left) and Christos Saragiotis during the poster session.*



*The field trip on which Bushra Al Touqi and Zainab Al Rawahi described the region's geology.*

automatic first-arrival picking algorithms with varying degrees of accuracy. He relied on the inversion-fitting process to help guide us to the proper picks by updating these measured picks based on the fitting criteria. Tariq Alkhalifah (KAUST) followed by introducing a new attribute to represent the model space that is capable of mitigating the nonlinearity induced by the complex reflectivity of the earth. Referred to as the instantaneous depth, this model representation spreads the classical long-wavelength components of the model to all frequencies, which will allow us to invert for these components at high frequencies.

The attendees then enjoyed a poster session dominated by student participants in the workshop, after which the oral presentations resumed with keynote speaker Said Al Abri (Petroleum Development Oman). Al Abri showed a case study conducted by his firm of wide-azimuth land data containing usable frequencies down to 1.5 Hz. He focused on the pre-processing needed to make the data FWI friendly and usable. The resulting model demonstrated the importance of low frequencies to bridge the gap in the model wavelength/resolution dilemma. Chris Cunnell (WesternGeco) concluded the oral presentations for the day with another case study of shallow water in the North Sea. This work showed that FWI could resolve fine-scale anomalies in the reservoir region and obtain models with better well ties.

The afternoon session closed with a discussion period that lasted beyond the 30 minutes devoted to it as attendees and presenters exchanged thoughts on issues ranging from multiparameter inversion to the role of anisotropy and our capabilities to invert field data.

The final day of the conference began with a session on novel mathematical ideas with implications for inversion. The keynote talk by Marteen de Hoop (Purdue University) described one of the first mathematically rigorous guarantees for successful inversion in certain circumstances. This complex of ideas incorporates in a natural but precise way some well-established practical features of successful inversion, such as continuation from low to high frequencies but adds hypotheses on the target model that permit a mathematical proof of success. The most important of these is that the model contains a finite number of interfaces, and the sensitivity of the inversion is predicted to degrade exponentially with the number of interfaces. Anatoly Baumstein (ExxonMobil) described a practical algorithmic approach to enforcement of geometric constraints (such as position-dependent parameter bounds) via projection on convex sets. The ability to account properly for multiple reflection is one of the hallmarks of FWI; Vladimir Kazei (Saint Petersburg State University) gave an analysis of sensitivity in the presence of multiples. Yi Luo (Saudi Aramco) tackled reflection inversion in the absence of low frequencies via a combination of FWI and wave-equation tomography.

Luo's talk telegraphed the theme of the second morning session, as captured in Paul Sava's keynote titled "Do we really need low frequencies in waveform inversion?" Sava (Colorado School of Mines) examined the central idea of image-domain inversion methods, the extraction of kinematic information



Workshop conveners (left to right) Yi Luo, William Symes, Tariq Alkhalifah, and Said Mahrooqi.

about the model from the geometry of image volumes. He illustrated the well-known vulnerability of data-domain waveform inversion (or waveform tomography) to capture by spurious local minima in the absence of very low-frequency signal and the apparent absence of such traps in image-domain methods based on focusing criteria. Sava emphasized that the image-domain methods use the same wavefields and optimization methods as data-domain FWI. Jeff Schragge (University of Western Australia) presented joint work with Sava, carrying the image-domain theme forward into 4D inversion. Schragge emphasized the peculiarly 4D possibility of estimating relative slowness perturbations based on successive surveys. Sanzhong Zhang (KAUST) explained how to transfer the concept of Luo-Schuster wave-equation tomography to the image domain.

The image-domain tomography theme continued into the final session of the conference with the keynote talk of William W. Symes (Rice University) on fusing FWI and migration velocity analysis. The link between the two is the concept of extended or nonphysical modeling, implicit in velocity analysis, which had been mentioned repeatedly in other talks on image-domain methods. Symes proposed that the image volume of MVA should really be regarded as a model volume, to be inverted via extended modeling operators, and showed some simple examples in which global FWI without extremely low-frequency data was successfully achieved, even in the presence of strong multiple reflections. Another approach to integration of kinematic and dynamic inversion was presented by Haiyang Wang (Institute of the Earth-Paris): in contrast to the sequential approach favored by others who have combined wave-equation tomography with full-waveform inversion, Wang constructs a hybrid objective function with a weighted sum of waveform and traveltime data misfits. Ali Aldawood (KAUST) showed how sparsity enhancement can stabilize least-squares migration (that is, linearized inversion) implemented with Kirchhoff modeling.

As suggested by the session title, “FWI: from Theory to Practice”, the session ended with a pair of talks on FWI in exploration practice. Jerry Kapoor (WesternGeco) gave a grand survey of FWI case studies taken from land and marine projects around the world. Kapoor emphasized the critical importance of good tomographic control of long-scale velocities to give an adequate starting model for FWI iteration. His extensive discussion of examples, along with those previously presented in other talks, cemented the sense that FWI is having a measurable impact on practice. Closing out the talks, Chu-Ong Ting of CGG described a practical workflow for salt-delineation FWI. The needs for careful denoising and data prep to enhance low-frequency P-wave data, good tomographic initial model building, and geometric intervention in the iteration process, were illustrated via an inversion of the Chevron GoM synthetic data.

The discussion session at conference end was particularly lively, with strong opinions expressed both pro and con regarding the proposition that “low frequencies are essential for inversion.” Some observed that no convincing field data trials have been demonstrated without high S/N at exceptionally low frequency (and reliance on diving-wave data). Others countered that the mere feasibility of traveltime tomography, both reflection and refraction, is ipso facto proof that such exceptional low frequencies cannot possibly be essential. It was mentioned that CGG’s recently developed high-resolution tomography may even provide sufficiently short scale-model resolution to fill the gap between tomographic and waveform inversion. The resolution of this and other questions, raised

in Jean Virieux’s opening presentation and reiterated throughout the workshop proceedings, remains a work in progress—with this workshop firmly establishing that there is currently much of both work and progress.

Many participants stayed on an extra day to take part in the field trip to Jebel Al-Akhdar, organized by Said Mahrooqi and others and led by Bushra Al Touqi and Zainab Al Rawahi, geology students at Sultan Qaboos University in Muscat. Over the course of the day and several hundred kilometers of travel, Al Touqi and Al Rawahi gave the audience a fascinating account of regional geology, including stops to inspect the well-known Samail Ophiolite, the Hajar carbonate sequence, some interesting Precambrian diamictite-carbonate outcrops, and a “coral garden” (fossil-rich carbonate outcrop). This well-organized, informative, and pleasant tour ended in a desert rainstorm, but only after the group was well on the road back into Muscat. **TLE**

*Acknowledgments: The conveners of the Oman FWI workshop (Tariq Alkablifab, KAUST; Yi Luo, Saudi Aramco; Said Mahrooqi, Petroleum Development Oman; and William W. Symes, Rice University) thank Cassidy Coleman, SEG meeting planner, and Yogaani Bhatia and Hyra Dalisay of SEG’s Middle East office for their expert management of the meeting. Their untiring efforts and constant attention to detail ensured a smoothly running and intellectually productive event.*

*Corresponding author: symes@caam.rice.edu*



*Attendees of the Oman FWI Workshop.*