Wave Inversion Technology Consortium

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established 1996 in Karlsruhe, Germany

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Preface

In search for a theme for the foreword I took a look into the very first WIT report that dates back to 1997. True amplitude image transformations and macro-model independent zero-offset simulations were hot topics at that time. You can also find papers on asymptotic methods, full waveform modeling, and artificial intelligence. None of these topics turned out to be obsolete in 2018 although the emphasis has changed. Time processing is an all time evergreen and the benefits of wavefront attributes are not yet fully exploited; full waveform modeling evolved into full waveform inversion accompanied by reverse time migration, and artificial intelligence has now the new tag of deep learning.

For WIT the marriage of time processing and ray/asymptotic approaches with full waveform methods within a single consortium has been complementary since the beginning. Pre-processing, time and depth velocity model building, time migration as well as other processing and imaging steps contribute to waveform methods like reverse time migration and full waveform inversion. During the last year the Karlsruhe group made continuous progress in further developing the technology of full waveform inversion, such as software development (C++ code modularization), higher-order optimization and pre-conditioning, inversion for second-order model parameters such as attenuation and anisotropy, and various successful applications of FWI to land and marine field data.

Passive seismic methods were added to the WIT portfolio more than 10 years ago and are now totally merged into the processing flow of wavefront attributes for reflection (active) seismic data. The kinematic processing and model building of passive seismic data is established and builds the foundation of the waveform based imaging and inversion. Full waveform inversion for diffractions as secondary sources in active seismic data may fill an existing illumination gap between transmitted wave fields of the diving waves with large angles of emergence and reflections with its steep emergence angles. The diffraction is the linking element between active and passive seismic data. In fact, locating a seismic source like a diffraction or a natural event in the subsurface and establishing a velocity model is *the* classical seismological problem and is exposed to the very same challenges caused by the location-velocity ambiguity.

The above mentioned topic was also the theme of one of the 2017 EAGE Workshops at the Annual Meeting in Paris entitled "Linking Active and Passive Seismics". Former WIT student Benjamin Schwarz, now a Postdoc at Oxford University, Dirk Gajewski and Ulrich Zimmer from Shell served as conveners of this workshop. It comprised twelve papers by scientists from academia and industry in four sessions on "Passive Sources on Large Scales", "Merging Aspects", "Unlocking the Potential of Ambient Noise", and "Instrumentation and Data Integration". Next to the workshop with the contributions by Benjamin Schwarz and WIT MSc student Leon Diekmann, there were four WIT presentations in the technical program. The WIT appearance at the 2017 Annual SEG Meeting in Houston included four WIT presentations.

Martin Tygel was SEG's 2017 Honorary Lecturer Latin America. Martin presented his lecture on "Multiparametric traveltimes: Concepts and applications" 25 times at 20 locations in Brazil, Argentina, Mexico, Colombia, and Bolivia.

Since a few words by former WIT director Peter Hubral from the 1997 WIT report equally apply today I cite them here: "We are glad to put this Annual Report of the WIT Consortium into your hands. We hope it will please you as we have made all attempts to be as professional in compiling this report as we have always been in our research." In the light of the difficult times we are currently going through in our profession I finish with a hearty "Live long and prosper" and thank you for your continuous support on behalf of the WIT teams, researchers and students.

Hamburg, 2018/20/02, Dirk Gajewski

Summary: WIT report 2017

IMAGING

Bauer et al. introduce a fully unsupervised scheme for the global identification and tagging of diffractions and passive events with a common origin in depth by analyzing the local similarity of zero-offset wavefront attributes.

Camargo and Santos present a FWI analysis formulated as nonlinear programming with constraints. We used the Algencan optimization package that presents robust methods for such types problems.

Costa et al. discuss new imaging conditions for RTM based on the phase coherence between the forward and backward propagated wavefields. These imaging conditions, which can be calculated simultaneously to conventional conditions at little or no extra cost, make use of the instantaneous phase and envelope of the analytical signals of the source and receiver wavefields. Numerical experiments with synthetic and field data show that these new imaging conditions can highlight weak reflectors by locally improving the resolution of RTM images.

Glöckner et al. generally discuss kinematic time migration/demigration duality and show how to use this in an advanced time imaging.

Glöckner et al. present a diffraction separation based on migration apertures. Apertures in the range of the first Fresnel zone favour reflections whereas large apertures enhance diffractions. Differences are visible in the migrated coherence section and can be used for a masking and final demigration to obtain diffraction only pre stack data. The proposed method is applied to synthetic data. It shows good separation results for simple data but also the limitations when data is more complex.

Gomes et al. analyse how seismic denoising using the curvelet transform as a conditioning step affects acoustic poststack seismic inversion. Their experiments involve both white and coloured noise with a standard hard thresholding technique for denoising and a Bayesian approach to constructing the objective function for inversion. Even though the minimum converges to solutions with reduced noise, curvelet filtering helps to reduce the misfit error considerably. However, they find that for high levels of white noise, and even for rather low levels of coloured noise, curvelet filtering by the tested method fails. In these situations, a more robust filtering technique is required.

Vanelle et al. present an extension of the Common Reflection Surface operator to account for arbitrary anisotropy in the 3D finite-offset situation. The derivation is based on geometry and ray theory. The resulting expressions have the same shape and number of coefficients as their isotropic counterparts as long as they are expressed by traveltime derivatives. However, the expressions for the coefficients in terms of wavefront attributes differ from the isotropic case and additional parameters need to be introduced to account for the anisotropy, e.g., the zero-offset operator in 2D requires four attributes instead of three in the isotropic case. Numerical examples in 2D and 3D demonstrate the accuracy of the new operator.

Walda and Gajewski introduce an alternative method of detecting intersecting events in the common-reflection-surface method. The CRS method enhances the signal-to-noise ratio of stacked data significantly.

Furthermore, its wavefront attributes can be used in appealing subsequent processing steps, in particular diffraction imaging and velocity model building. Increasing computational facilities research in recent years showed, that a simultaneous parameter estimation is nowadays feasible. Furthermore, it leads to more accurate CRS parameters compared to the pragmatic approach, introduced when CRS was published. This also made alternative methods of detecting intersecting events possible. Nevertheless are modern methods still expensive, in particular for 3D acquisitions since the search space was divided into smaller spaces where CRS has to be performed in each of the smaller spaces. In this paper, we use one application of CRS over the full search space and detect clustering at each iteration based on the dip angle or slowness. The application to 2D synthetic and field data shows promising results. The 3D case indicates issues with the acquisition footprint which needs further investigation.

Znak et al. propose a novel wavefront curvature based post-stack tomography method valid for reflection, diffraction and passive seismic data inversion. The basis of the new approach is minimizing of geometrical spreading at diffractor position, which they call dynamic focusing. The natural parametrization of the inverse problem by velocity model as the only unknown leads to significantly decreased tomographic matrix dimension and higher data-unknowns ratio. Since deriving and coding the conventional wavefront tomography is cumbersome even in the isotropic case, the reduction of the Fréchet derivatives number is an attractive feature if generalization to anisotropy is desired. The authors provide both Fréchet derivatives and adjoint-state method formulae for computing the gradient of the new functional and perform a field data test.

MODELING

Wittkamp et al. present a matrix-vector formalism for time-domain finite-difference seimic modelling. Matrix-vector products can be parallelized on multiple computing systems using an HPC library. We implemented the open-source framework LAMA to develop hardware-independent code. Benchmarks of a 3D elastic forward problem show promising scaling results of the code on CPUs as well as GPUs.

FULL WAVEFORM INVERSION

Athanasopoulos givs an introduction to a modified workflow of applying full-waveform inversion to shallow seismics. He demonstrates how, with a two-stage procedure, the contribution of the P-wave velocity is properly incorporated in the convergence of the FWI algorithm and no longer ignored due to the high-amplitude Rayleigh waves.

Pan et al. give a short introduction on how to sequentially invert surface-wave phase velocity and the full waveform for shallow seismic imaging of near-surface materials. A synthetic case demonstrates the advantages of this strategy, and a real-world case proves its validity.

Thiel et al. compare the results of acoustic and elastic FWI applied to a marine towed-streamer field data set. They show in this report that even for marine data, it is necessary for complex salt environments to use elastic FWI instead of acoustic FWI.

The Wave Inversion Technology (WIT) Consortium

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The Wave Inversion Technology Consortium (WIT) was established in 1996 and is organized by the Institute of Geophysics of the University of Hamburg. It consists of three integrated working groups, one at the University of Hamburg and two at other universities, being the Mathematical Geophysics Group at Campinas University (UNICAMP), Brazil, and the Geophysical Institute of the Karlsruhe University. In 2007, NORSAR joined WIT as research affiliate, and in 2010, Fraunhofer ITWM joined WIT, also as research affiliate.

The WIT Consortium offers the following services to its sponsors:

a.) research as described below;

b.) deliverables;

c.) technology transfer and training.

The ultimate goal of the WIT Consortium is a most accurate and efficient target-oriented seismic modelling, imaging, and inversion using elastic and acoustic methods. Within this scientific context it is our aim to educate the next generations of exploration geophysicists.

Exploration and reservoir seismics aims at the delineation of geological structures that constrain and confine reservoirs. It involves true-amplitude imaging and the extrapolation of the coarse structural features of logs into space. The goals on seismic resolution are constantly increasing which requires a complementary use of kinematic and wave equation based techniques in the processing work flow. At WIT we use a cascaded system of kinematic and full wave form model building and imaging techniques. Since our data and inversions are never perfect it is the challenge to find those techniques which produce the best images for erroneous velocities and faulty wave forms.

RESEARCH TOPICS

The WIT consortium has the following main research directions, which aim at characterizing structural and stratigraphic subsurface properties. Some of the topics are studied by more than one team, applying different approaches. The WIT research is divided into five subgroups:

Processing and Imaging

The Common Reflection Surface (CRS) concept plays a key role in the WIT research on processing and imaging. The WIT hyperbolic CRS and non-hyperbolic i-CRS stacking operators are based on this concept and represent the backbone of many research topics.

- global (ZO CRS) vs. local (CO CRS) approximations
- estimation of CO CRS attributes from ZO attributes
- amplitude-friendly CRS processing
- improved conflicting dip processing
- 3-D i-CRS operator
- wavefield decomposition using stacking attributes (multiples, reflections, diffractions)
- utilizing super resolution
- pre-stack diffraction/reflection separation
- 5-D CRS and i-CRS interpolation and pre-stack data enhancement
- improved coherence measures (MUSIC, cross-correlation, analytical trace, etc.)
- optimization of multi-dimensional coherence analysis
- data driven isotropic and anisotropic time migration
- wavefield decomposition and filtering in the CSP domain
- inverse CSP mapping
- CRS and diffraction processing of 3-D hard rock data
- angle domain migration
- beam migration
- image wave re-migration
- migrated-domain CRS methods

Model Building

Most of our model building approaches also exploit the CRS concept, which may be applied in the data or time migrated domain.

- diffraction focusing velocity analysis
- diffraction stereotomography
- passive seismic data velocity model update
- CRS based time to depth conversion
- tomographic inversion of stacking attributes

Full Waveform Inversion

Research on Full Waveform Inversion (FWI) is moving toward applications to marine reflection seismic data and near surface seismic data (surface waves) and three-component Vibroseis data acquired in crystalline rocks.

- development of robust preprocessing of seismic data for FWI
- multi-parameter FWI
- source wavelet inversion
- accurate methods for geometrical spreading correction
- implementation of 3-D acoustic/elastic/viscoelastic FWI on HPC machines
- FWI in viscoelastic media
- optimization of Finite-Difference forward solvers used in FWI with respect to MPI communication, higher order time integration, variable spatial discretization and smooth free surface topography
- application of pseudo spectral methods in FWI

Modeling and RTM

In modeling and RTM we use FD, FE, and pseudo spectral approaches. Optimizations of the computational effort is highest on the agenda.

- 2-D and 3-D RTM for VTI and TTI media (spectral methods)
- 2-D and 3-D acoustic and elastic RTM (FD methods)
- finite element (FE) elastic wavefield modeling
- computational optimizations of FD and spectral method approaches for acoustic, elastic, and anisotropic media, including benchmarking
- improved one-way wave equation
- reflection impedance description of reflection coefficients
- tuning effects in AVO and AVA

Passive Seismics

Passive seismic signals as a diffraction event provide the link to reflection seismics. Located diffractions or micro-earthquakes provide natural Green's functions for reflection imaging.

- optimization of model domain stacking and time domain localization approaches
- high resolution full waveform relative event localization
- microtremor localization
- interferometric re-localization
- development of fast time-domain localization technique
- localization uncertainties (apertures, velocities, bandwidth, acquisition footprint)
- real time processing methodology

WIT STEERING COMMITTEES

Internal Steering Committee

Name	WIT team
Thomas Bohlen	Karlsruhe
Norman Ettrich	ITWM
Dirk Gajewski	Hamburg
Thomas Hertweck	Karlsruhe
Tina Kaschwich	NORSAR
Jörg Schleicher	Campinas
Martin Tygel	Campinas
Claudia Vanelle	Hamburg

External Steering Committee

Name	Sponsor
Shinichi Itoh	Hanshin Consultants
Dan Grygier	Landmark Graphics Corporation
Henning Trappe	TEEC

COMPUTING FACILITIES

The Hamburg group has access to a 3.000 nodes (100.000 cores in total) bullx B700 DLC sytem at the German Computer Center for Climate Research (Deutsches Klimarechenzentrum, DKRZ) for numerically intensive calculations. It is equipped with 240 TeraByte of memory and its peak performance is 3.14 PetaFlops. For medium sized problems there are several IBM Xeon-based 64 cores login nodes with 1 GB memory each and four compute nodes for batch processing accessible. Additional computer facilities consist of several Linux workstations and Linux PCs.

The research activities of the Campinas Group are carried out in the Computational Geophysics Laboratory. The Lab has 15 Linux PC workstations connected by a dedicated high-speed network, suitable for parallel processing. Educational grants provide seismic packages from leading companies such as Landmark and Paradigm. Besides State Government funds, substantial support both for equipment and also scholarships are provided by the Brazilian Oil Company Petrobras. An extension of the Lab with substantial increase of computer power and space in the new facilities of the Center of Petroleum Studies went fully operational in 2012. The new Lab extension counts on another 30 Linux PC workstations that rely on resources shared by a high-performance server and provide access to a 3Tflops cluster with 2TB RAM. The LGC also has remote access to the computing facilities of the Petrobras Research Center in Rio de Janeiro.

The computing facilities of the WIT group in Karlsruhe consist of several local and external clusters, Linux workstations and Linux PCs. For large-scale computational tasks, the WIT group in Karlsruhe co-funded and has exclusive access to the SCC Institutscluster 2 (IC2) with 480 nodes, each consisting of 16 cores. The performance is 135.5 TFlops and 28 TeraByte of memory are available. About 300 Terabyte disk space are available via a Lustre file system and an InfiniBand interconnect. The group has also access to one of the most powerful cluster at the KIT, the ForHLR (522 nodes, each with 20 cores, 216 TFlops in total and 41 TB memory), funded by the state of Baden-Wuerttemberg and the German research foundation (DFS). We have now access to the second phase of the ForHLR, the ForHLR II, which was launched in 2016. It is composed of 1152 nodes with 20 cores each. Together with several fat nodes this cluster obtains a perfomance of 1 PetaFlops. Furthermore, successful project proposals at the Jülich Supercomputing Centre (JSC) have granted access to a large volume of computing hours for one of the newest and best supercomputers in Europe, the JURECA Clustercomputer. This supercomputer consists of 1872 nodes, each with 24 cores with a theoretical computational power of 1.8 PetaFlops. In 2015 the WIT group in Karlsruhe also acquired an SGI UV20. With its 96 cores and 512 GB shared memory it is ideal for small test computations and code development. The cluster is used extensively by our Master and PhD students.

Fraunhofer ITWM builds up new compute clusters early 2014. The largest machine consists of 192 dual Intel Xeon E5-2670 ("Sandy Bridge") (i.e. 16 CPU cores per node) with 64 GB RAMeach, 300 GB HDD, 2x Gigabit Ethernet and FDR Infiniband interconnect. In total, 3072 CPU cores, 12 TB main memory, and 57 TB disk space. Estimated peak performance is 56 TFlops. In addition, 4 quad Intel Xeon E5-4650L ("Sandy Bridge") (i.e. 32 CPU cores per node) with 256 GB RAM, 2x 500 GB HDD will be available. The storage system consists of 12 storage servers, connected via FDR Infiniband an 10 Gigabit Ethernet with a total capacity of 200 TB via the Fraunhofer file system. In addition, the HPC department of ITWM runs a cluster with 92 compute nodes, among them 60 Intel Xeon E5-2680 IvyBridge nodes. Disk capacity will be 270 TBytes.

WIT research personnel

Ivan Abakumov received his MSc from St. Petersburg University in 2013 and defended his Ph.D. thesis at the University of Hamburg in 2017. His research interests are time imaging, converted waves, time-lapse seismic, full waveform inversion, geophysical data processing and computer programming. Ivan is a student member of EAGE, SGE and SPE.

Nikolaos Athanasopoulos, M.Sc. (IDEA LEAGUE Joint Master in Applied Geophysics, 2015), started his Ph.D. studies at the Karlsruhe Institute of Technology (KIT) in 2015. He is working in the field of Full Waveform Inversion (FWI). His research focus is the elastic FWI of shallow seismic surface waves and its application in field data. He is member of the EAGE.

Alexander Bauer received an M.Sc. in Geophysics from Hamburg University in 2014 and is currently a PhD student in the Hamburg WIT group. His research interests focus on seismic diffraction imaging and velocity model building. He is a member of DGG, EAGE and SEG.

Ricardo Biloti received his B.Sc.(1995), M.Sc. (1998) as well as Ph.D. (2001) in Applied Mathematics from the State University of Campinas (UNICAMP), Brazil. He worked at Federal University of Paraná (UFPR), Brazil, as an Adjoint Professor, at the Department of Mathematics, from May 2002 to September 2005, when he joined Unicamp as an Assistant Professor. He has been a collaborator of the Campinas Group since his Ph.D. His research areas are multiparametric imaging methods, like CRS for instance. He has been working on estimating kinematic traveltime attributes and on inverting them to construct velocity models. He is also interested in Numerical Analysis, Numerical Linear Algebra, and Fractals. He is a member of SBMAC (Brazilian Society of Applied Mathematics), SIAM and SEG.

Thomas Bohlen received a Diploma of Geophysics (1994) and a Ph.D. (1998) from the University of Kiel, Germany. From 2006 to 2009 he was Professor of Geophysics at the Institute of Geophysics at the Technical University Freiberg where he was the head of the seismics and seismology working groups. Since 2009, he has been Professor of Geophysics at the Geophysical Institute of the Karlsruhe Institute of Technology. He is the head of the applied geophysics group. His research interests and experience include: seismic modelling, full waveform inversion, surface wave inversion and tomography, reflection seismic imaging. He is a member of SEG, EAGE, and DGG.

Alexandre William Camargo received his BS (2011) in Applied Mathematics from the State University of Campinas (UNICAMP), Brazil. He is currently about to finish the Master Science in Applied Mathematics in the same university. His professional interests include seismic modeling and numerical methods for differential equations. He is member of SEG (Society of Exploration Geophysicists).

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Jessé Carvalho Costa received his diploma in Physics in 1983 from the Physics Department, Federal

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Sergius Dell received his diploma (2009) and a Ph.D. (2012) in geophysics from the University of Hamburg. In 2012-2015, he worked at Fugro and CGG (UK). Since 2016 he has been self-employed. His key interests are least-squares seismic migration, multiple migration, travel-time tomography, diffraction processing, ray tracing, and dual-semblance analysis. He is a member of EAGE and SEG.

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Mario Rubén Fernandez received his M.Sc. at the Institut de Physique du Globe de Paris and started his Ph.D studies at the Karlsruhe Institute of Technologies (KIT) in 2015. He is working for the CRC 1173 "Wave phenomena" on the implementation of full waveform inversion of seismic wave attenuation.

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Dirk Gajewski holds the chair of Applied Seismics at the University of Hamburg. Until 2006 he worked at the same institution as associate professor. He received a diploma in geophysics in 1981 from Clausthal Technical University and a Ph.D from Karlsruhe University in 1987. After his Ph.D, he spent two years at Stanford University and at the Center for Computational Seismology at the Lawrence Berkeley Lab in Berkeley, California. From 1990 until 1992, he worked as an assistant professor at Clausthal Technical University. His research interests include high-frequency asymptotic, seismic modeling, and processing of seismic data from isotropic and anisotropic media. Together with Ivan Psencík, he developed the ANRAY program package. He is a member of AGU, DGG, EAGE, and SEG, and served as Associate Editor for Geophysical Prospecting (section anisotropy). Since 2009 he is a member of the research committee of the EAGE. Besides his activities in WIT he is vice director of the Centre for Marine and Climate Research.

Lingli Gao received her PhD from China University of Geosciences (Wuhan) in 2016. Now she is a Postdoc researcher at Zhejiang University. Currently, she is a visiting scholar at KIT working on high-frequency surface-wave methods.

Laura Gaßner studied geophysics at the Karlsruhe Institute of Technology (KIT) and received a B.Sc in 2011 and a M.Sc degree in 2014. She is now a Ph.D. student at the Geophysical Institute of KIT and works on the characterization of gas hydrate deposits with full waveform inversion within the project SUGAR (SUbmarine GAs hydrate Resources).

Martina Glöckner (née Bobsin) is a Ph.D. student at the University of Hamburg. Her research interests focus on time migration and demigration. She received her M.Sc. (2014) and B.Sc. (2012) in geophysics at the University of Hamburg. Topics of her work were the application of multiparameter stacking operators.

Håvar Gjøystdal is Research Manager of Seismic Modelling at NORSAR in Kjeller, near Oslo. He also holds an adjunct position of Professor of Geophysics at the Department of Earth Science, University of Bergen. In 1977 he joined NORSAR and started building up research activities within the field of seismic modelling, which to-day include both R&D projects and services and software products for the petroleum industry. Key topics are ray tracing, seismic tomography, and time lapse seismic modelling. He is a member of SEG and OSEG.

Peter Michael Habelitz studied mechanical engineering at the Duale Hochschule Baden-Württemberg Mannheim (DHBW) and received his B.Eng. in 2012. Thereafter he began to study geophysics at the Karlsruhe Institute of Technology (KIT) where he graduated with B.Sc with the quantification of the error in finite-difference simulation caused by staircase interfaces. Currently he is working on his Master thesis in the area of full wave form inversion.

Thomas Hertweck received a diploma in Geophysics (2000) and a doctor's degree of natural sciences (2004) from the University of Karlsruhe, Germany. He joined Fugro in September 2004 as researcher and software developer before becoming an R&D manager in 2007 and global head of R&D in 2011. In 2013 Thomas became an R&D manager for external research at CGG following the successful takeover of Fugro's Geoscience Division. At CGG he was also a member of the business line's R&D management team, the company's technology board, and its IP and HSE committees. After more than 12 years in the UK Thomas returned to Germany in January 2017 when he joined KIT's Geophysical Institute as senior research fellow and teaching assistant. Thomas' research interests include all aspects of seismic acquisition, processing and imaging as well as HPC software development. He serves as reviewer for various journals and is a member of SEG, EAGE, DGG and the Editorial Board of JSE.

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Martin Tygel received his B.Sc. in physics from Rio de Janeiro State University in 1969, his M.Sc. in 1976 and Ph.D. in 1979 from Stanford University, both in Mathematics. He was a visiting professor at the Federal University of Bahia (PPPG/UFBa), Brazil, from 1981 to 1983 and at the Geophysical Institute of Karlsruhe University, Germany, in 1990. In 1984, he joined Campinas State University (UNICAMP) as an associate professor and since 1992 as a full professor in Applied Mathematics. Professor Tygel has been an Alexander von Humboldt fellow from 1985 to 1987. In that period, he conducted research at the German Geological Survey (BGR) in Hannover. From 1995 to 1999, he was the president of the Brazilian Society of Applied Mathematics (SBMAC). In 2002, he received EAGE's Conrad Schlumberger Award, and in 2007 the Lifetime Achievement Award by the Brazilian Geophysical Society (SBGf). In 2014, he has been elected member of the Brazilian Academy of Sciences. Prof. Tygel's research interests are in seismic processing, imaging and inversion. Emphasis is aimed on methods and algorithms that have a sound wave-theoretical basis and also find significant practical application. These include, for example, the unified approach of seismic reflection imaging (problem-specific combinations of true-amplitude migration and demigration) and, more recently, data-driven seismic imaging approaches such as the Common Reflection Surface (CRS) method. Prof. Tygel is a member of SEG, EAGE, SBGf, and SBMAC.

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