RESEARCH CENTRE

Inria Center at the University of Bordeaux

IN PARTNERSHIP WITH:

Institut Polytechnique de Bordeaux, Université de Pau et des Pays de l'Adour, CNRS, TotalEnergies

2022

ACTIVITY REPORT

Project-Team

MAKUTU

Experimental-based modeling and simulation of wave propagation to characterize geophysical and heliophysical media and to design complex objects

IN COLLABORATION WITH: Laboratoire de mathématiques et de leurs applications (LMAP)

DOMAIN

Digital Health, Biology and Earth

THEME

Earth, Environmental and Energy Sciences

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Project-Team MAKUTU

Creation of the Project-Team: 2021 February 01

Keywords

Computer sciences and digital sciences

A6.1. – Methods in mathematical modeling

A6.1.1. – Continuous Modeling (PDE, ODE)

A6.1.4. – Multiscale modeling

A6.1.5. – Multiphysics modeling

A6.2. – Scientific computing, Numerical Analysis & Optimization

A6.2.1. – Numerical analysis of PDE and ODE

A6.2.7. – High performance computing

A6.3.1. – Inverse problems

A6.5. – Mathematical modeling for physical sciences

A6.5.1. – Solid mechanics

A6.5.4. – Waves

Other research topics and application domains

B3. – Environment and planet

B3.3. – Geosciences

B3.3.1. – Earth and subsoil

B4. – Energy

B9.2.1. – Music, sound

B9.5.2. – Mathematics

B9.5.3. – Physics

B9.5.5. – Mechanics

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2 Overall objectives

Imagine trying to describe a place with exactness from more or less numerous and precise memories, or guessing the content and internal structures of an object after having observed it only partially, without ever touching it because it is inaccessible or very fragile? These are the objectives of Makutu team, where recordings of reflected waves correspond to the memories. Waves can be seismic, electromagnetic or acoustic and Makutu focuses its research on the characterization of Earth's subsurface, of the Sun, and of musical instruments. An important component of Makutu's work is the improvement of the resolution methods for direct problems, in order to simulate the propagation of waves in complex media. The characterization and reconstruction of objects using non-invasive approaches then need the resolution of an inverse problem, with efficient forward modeling at the center.

Makutu is an industrial Inria project-team joint with TotalEnergies, in partnership with University of Pau and Pays de l'Adour, Institut Polytechnique de Bordeaux and CNRS. The team is bi-located, one part is hosted by UPPA and the other is hosted by Inria on the University of Bordeaux campus. It is a follow-up of Magique-3D (Advanced Modeling in 3D Geophysics) and its research topics have expanded are summarized as "*Experimental-based modeling and simulation of wave propagation to characterize geophysical and heliophysical media and to design complex objects*" with the new name Makutu (magicians in Maori).

The numerical simulation of waves propagating in complex media (the direct problems solved by Makutu) requires the development of advanced numerical methods but the research does not stop there. Indeed, to probe a medium or reconstruct an object from reflected waves measurements (the inverse problems addressed by Makutu), it is important to accurately solve systems of partial differential equations that model all the waves that can be measured. As the complexity of the physical models goes hand in hand with the complexity of the calculations, Makutu is particularly committed in the development and analysis of appropriate mathematical models as well as in the design and study of advanced numerical methods taking into account the characteristics of the physics considered.

Makutu's research has many facets, with final goals ranging from the development of open-source prototype codes written to assess new ideas, to software packages to be ported to an industrial environment. Makutu's research activities are inspired by a strong interdisciplinary industrial and academic partnership. The team's contributions are at the interface of applied analysis, numerical analysis, and scientific computing. The size of some of our problems projects us into the High Performance Computing (HPC) environment and dictates the choices we make for certain approximation spaces that are conducive to massive parallelism.

Makutu has important contributions in the field of high-order discretization methods along with high-order time schemes. Whatever the application is, numerical schemes are all designed with a view to reduce computational time or limit memory consumption, while maintaining a high level of accuracy. Sometimes, it is also necessary to work on the mathematical models themselves whose brute complexity can be a source of difficulty or even blockage for the numerical simulations. One of the originality of the team is to collaborate with experimenters to compare measurements and numerical data in order to calibrate the models. All these contributions are significant steps to reach the final team's objectives which are expressed as the resolution of complex inverse problems. Large-scale computing is then an important part of our activity, which we carry out taking into account the three pillars that make up HPC, i.e. computing time, storage and precision. Recently, the team has started to work on the use of machine learning to assist the numerical schemes they develop in order to control the numerical pollution (or dispersion) which becomes very strong in large-scale computations. This is particularly the case in geophysics where several hundred wavelengths can be propagated. It is worth noting that we take particular care in developing our numerical methods so that they can be used for a wide range of applications, whether the calculations are done in an HPC environment or on a simple laptop.

3 Research program

Makutu's research program decomposes itself into four axes that are: (1) Methodological contributions to the simulation of mechanical and electromagnetic waves in complex media; (2) Seismic imaging; (3) Helioseismology; (4) Musical Acoustics. Each axis shares the same objective to realize simulations of real phénomena. To achieve this, one needs real data and advanced mathematical models and high-order numerical schemes that are compatible with high-performance computing architectures.

To obtain real data, in addition to its current collaborations with scientists both from Academia and Industry, Makutu is developing a new branch of research activities by carrying out its own laboratory measurements. For instance, in order to take into account porosity, parameters such as viscosity, attenuation, thermodynamic effects, etc., must be integrated, and their impact must be properly analyzed before considering using them to characterize the propagation media. This constitutes a clear step ahead for Makutu, and opens up new prospects of contributing to the characterization of very complex media based on wave field measurements.

Regarding the development of numerical schemes, Makutu is developing high-order Discontinuous Galerkin (DG) methods and high-order time schemes. The coupling of DG methods with other techniques of discretization is also under consideration. Trefftz-DG and Hybridizable DG methods have been developed both for poro-elastic waves and electromagnetic waves. HDG and HDG+ formulations are also under study for helioseismology.

The research activities of members of Makutu share a common theme of using numerically computed wavefield measurements to reconstruct the propagation medium they passed through before recording. The medium can be reconstructed by identifying either the physical parameters or the geometrical parameters that characterize it. In each case, the next step is to solve an inverse problem that is nonlinear and ill-posed. To solve it, Makutu is focusing on the Full Waveform Inversion (FWI), which is a high-definition imaging method widely used in the field of geophysics.

4 Application domains

Makutu research program is organized around three principal domains of applications: geophysical exploration, solar imaging, and music. Each of them requires a relevant panel of significant contributions requiring achievements in laboratory measurements, modeling, mathematical analysis, advanced numerical schemes and massively parallel software development. Recently, the team has added experimental contributions to feed simulations with real data and also improve modeling through better calibration. Makutu's application domains can be regrouped into a long-standing activity dedicated to subsurface imaging, and two more recent activities dedicated to solar imaging and the development of numerical wind instruments. Each field of application is not compartmentalized in the methodological sense of the term: equations, numerical schemes and programming practices are shared and possibly adapted to the underlying application.

4.1 Geophysical exploration

Geophysical exploration is a historical field for the team (see e.g [64, 68, 69, 71].Geophysical exploration has been driven for a very long time by the goal of finding hydrocarbons. Today, it is evolving towards a very proactive direction in favor of renewable energies and Makutu commits part of its research activities in this direction, in the framework of industrial and international collaborations. Industrial partnership with TotalEnergies has evolved to the transformation of Makutu into an industrial project-team since January 2022. The dedicated research project targets monitoring of CO2 storage through the development of a new numerical branch in GEOSX for seismic propagation and inversion. As far as geothermical energy is concerned, Makutu is member of the international project SEE4GEO lead by C. Morency from Lawrence Livermore National Laboratory. The project combines experimental research in the field and in laboratory with numerical developements in the continuity of CHICkPEA project previously funded by UPPA (2018-2021).
Inversion is central for geophysical exploration and Makutu focuses on Full Waveform Inversion (FWI) as a high-fidelity solution methodology for reconstructing the physical parameters from observed data. FWI can be carried out in time-domain [67, 87, 98, 97] or in frequency domain [91, 92, 90]. Its main feature is to avoid the formation of the large Jacobian matrix by computing the gradient of the misfit functional using the adjoint-state method [72]. A detailed review of FWI for geophysical applications can be found in [89].

4.1.1 Deep geothermal energy

Obtaining accurate images of natural reservoirs is critical for their management and exploitation and seismic imaging is an efficient tool (see [86, 85] and their references therein. One example is with deep geothermal energy which requires precise imaging of deep fractured reservoirs filled with geothermal fluids. Standard seismic imaging is based upon inverting mechanical waves which have difficulties to detect them, whereas electromagnetic waves are more sensitive. We see here a clear interest of coupling seismic with electromagnetic methods and this is what Makutu began developing with CHICkPEA project ended in 2021. The team is now involved in project **SEE4GEO** funded by ADEME, in the framework of Geothermica call.

4.1.2 Shallow geothermal energy

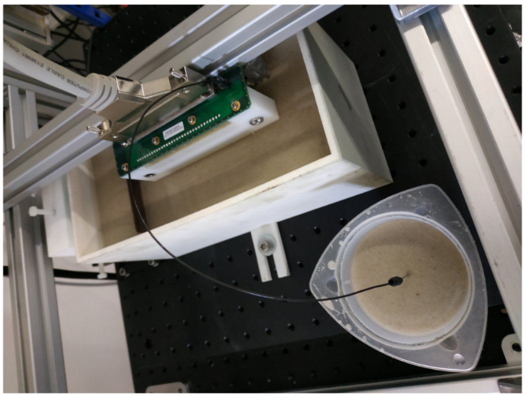
Regarding shallow geothermal energy, Makutu worked until May 2022 with **RealTimeSeismic** SME in the framework of the FEDER-Poctefa **Pixil** project in order to use surface waves for a better imaging of shallow reservoirs. Surface waves have long been considered as noise in seismograms because they were used to study the subsurface at depths. In shallow geothermal energy, surface waves contain interesting information on the first layers of the subsurface. Inverting them is challenging because the surface waves are of high amplitude while propagating slowly. They therefore pose difficulties for multi-frequency optimization methods.

4.1.3 CO2 injection monitoring

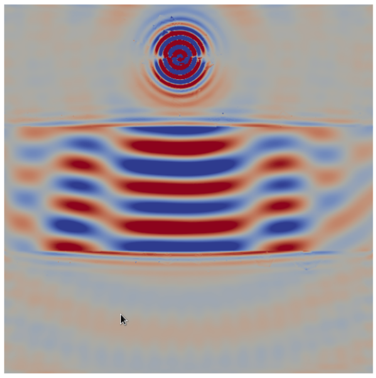
The reduction of greenhouse gases in the atmosphere is a societal topic of the utmost importance, with the Paris Agreement setting ambitious goals for many countries. One fundamental pillar of greenhouse emission management is Carbon Capture Utilisation and Storage (CCUS) [99]. With this strategy, carbon dioxide produced on- or off-site is sequestered and injected into depleted reservoirs, thus offsetting an important portion of current CO2 emissions. The successful and safe implementation of this strategy requires the prediction, monitoring and surveillance of stored CO2 over long periods, which presents significant challenges in terms of seismic acquisition, seismic inversion and numerical simulation. These tools, coupled with state-of-the-art flow simulations, are vital in order to support the injection operations with vital real-time and long-term information. Moreover, specific challenges related to the physics of injected CO2, such as viscosity, temperature and multi-phase fluid conditions push to the limits our current numerical models, and require ambitious new multi-physics simulations to support safe and cost-effective CO2 injection operations. For example, some recent publications like [96, 102] have shown that the combination of CO2-brine flow with wave propagation provides efficient simulations for the monitoring of sequestered CO2. Makutu is currently developing numerical methods for this new application, in collaboration with TotalEnergies, as a new computational branch of the open-source multiphysics simulator GEOSX.

4.2 Solar imaging

Helioseismology studies the interior and dynamics of the Sun based on the observation of wave oscillation in the solar photosphere. These movements can be observed at the surface by the Dopplergrams given by ground-based or satellite-borne observatories. In recent years, methods for understanding Earth subsurfaces have opened up new ways to study the interior of the Sun as in the case with helioseismology and the interior of stars with aesteroseismology from oscillation observed at their surface. Techniques in helioseisomolgy is generally divided into global and local helioseismology. The first approach studies frequencies of oscillations modes, cf. [73]. On the other hand, local helioseimology, which adapts techniques of geophysical seismic interferometry studies, measures local wave propagation and works with the full 3D observed wavefield, and is thus more adapted to study additional features such large-scale flows in active region, sun spots and plage, cf. [82, 81].



(a) Experimental device for measuring co-seismic and converted waves in a conducting porous medium



(b) Numerical wave in a porous medium with Hou1Oni

Figure 1: Experimental device and numerical simulation of waves in porous media, CHICkPEA, E2S

Makutu extends its activity on terrestrial seismology to studying the Sun, for the latter offers a vast wealth of problems to be explored both for direct modeling as well as inversion. The collaboration between Makutu and the solar group at the Max Planck institute for Solar research MPS at MPS brings together the expertise of MPS in solar physics and seismology and that of Makutu in numerical simulation of wave propagation and large-scale inversion in geophysics. This ongoing collaboration dating from 2016 obtains its official mark with the creation of associated team ANTS which started in 2019 and ended in 2022. The main goal of the collaboration is the creation of a computational framework for accurate and efficient simulation of solar oscillation to be used in full wave-form inversion, e.g. for 3D solar flow.

The stochastic nature of solar oscillation is described by random right-hand source term, and in using statistical analysis, under appropriate assumptions (e.g. the convenient source assumption), power spectrums and time-distance diagrams can obtained from the deterministic Green kernel of modeling wave equation, cf. [80]. In this way, the Green kernel becomes a crucial object in local helioseismology, and its accurate and efficient computation is the main goal of forward modeling. In addition to appropriate numerical schemes, investigation of radiation boundary conditions is required in order to describe accurately waves above cut-off frequencies.

Up until 2021, the focus has been put on acoustic waves which are identified with p-ridges in observed solar power spectrum. Acoustic waves at low frequencies can be adequately described by a scalar equation. The thesis of Rouxelin 2021 studied convected Helmholtz which allows for a simplified description of the effect of convection on acoustic waves. Recent and ongoing works extend the investigation to vector wave equation to include gravity and differential rotation. The latter is particularly of interest due to the recent discovery of inertial waves in the Sun. This is subject of the thesis of Chatbat which starts in October 2022, and the goal of which is to create an in-house software to compare accurately eigenvalues for the solar wave equation with differential rotation. The remaining challenge is to include full 3d flow to the vector equation, which is the goal for the next year.

The above works lay the necessary foundation for inversion of solar parameters such as flow and active region sound speed. Current state-of-the art tools in these references is linear inversion using Born approximation [78]. In additional they are carried out in 1D or 2D. It is thus interesting to apply nonlinear inversion such as Full Waveform Inversion in 3D cf. [76] to these problems.

4.3 Musical acoustics

This field of application is a subject of study for which the team is willing to take risks. We propose using a mix of experimental and numerical approach in order to study and design musical instruments. Makers have designed wind musical instruments (as flutes, trumpets, clarinets, bassoons. . .) in the past through “trial and error” procedures by performing a geometrical calibration of musical instruments in order to improve their accuracy, tone, homogeneity and even their sound volume, ergonomics, and robustness. During the past few decades, musical acoustics has been in a process of rationalizing the empiric understanding of instrument makers in order to formulate a scientific approach to future evolution. Our research proposal is along this axis of research by proposing new mathematical models based on our solid experience in terms of wave propagation in media with interfaces that can significantly change the sound. As was done in geophysical exploration, we propose to assist the modelling process with laboratory experiments. Direct comparison between simulations and experiments will allow to assess the model error. For this purpose, an experimental device has been developed in collaboration with I2M, Mechanics Laboratory of the University of Bordeaux and Humeau Factory, Montpon- Ménestérol, and is currently in use.

4.3.1 Modeling

Although the playing context should always be the final reference, some aspects of the behavior of a wind instrument can be firstly characterized by its entry impedance which quantifies the Dirichlet-to-Neumann map of the wave propagation in the pipe in the harmonic domain. This impedance can be both measured [79, 74] and computed with simulations based on accurate and concise models of the pipe [94, 70] [100],[62]. A more realistic approach accounts for the embouchure [83, 70, 65, 66, 101], which is modeled as a nonlinear oscillator coupled with the pressure and acoustic velocity at the entry of the pipe, allowing to predict the sound qualities. Mathematical properties of the underlying models are not yet totally understood, and adequate models still need to be developed. This is particularly true when accounting for dissipation phenomena, junctions of pipes, pipe porosity and rugosity, embouchures...
To reproduce the sound of instruments, time-dependent models are more suitable. Here, nonlinear lumped elements induce an “auto-oscillatory” behavior of the instrument. The models currently available in the literature are meant to reproduce viscothermal effects, pipe junctions, pipe radiation, lips oscillation, etc. They do not necessarily possess adequate mathematical properties to ensure stable simulations and they should be improved using asymptotic analysis methods or Lagrangian formalism.

4.3.2 Numerical methods

As far as numerical developments are concerned, the accuracy of the calculations is essential. Indeed, for some aspects like the sounding frequency, a deviation of 1% between the predictions and the observations is unacceptable. Moreover, contrary to what the team is used to do for geophysics or astrophysics thanks to HPC, numerical methods for acoustical musics must be frugal to be run on personal computers by acousticians and makers. Makutu has a wide range of numerical methods that have been implemented in its codes for linear problems. New numerical schemes will have to be implemented to take into account the non-linearities of time-dependent models.

4.3.3 Virtual workshop

Beyond the idea of mathematically modeling musical instruments, Makutu wishes to develop a virtual workshop whose vocation will be twofold: (i) support the manufacturers to design new instruments; (ii) recreate the sound of old and historical instruments. To implement this idea, we propose to elaborate optimization techniques that are well-known in the team to define optimal geometries to meet given specifications. This can be used to reconstruct existing instruments from acoustic measurement or to design new instruments by fixing relevant quantitative objective which is a research activity by its own [63]. Behind the idea of the virtual workshop is also the intention to hear the instruments, from the knowledge of their shape and playing regime. For that purpose, time-domain models are essential.

5 Social and environmental responsibility

Makutu recognizes the importance of conducting research in a responsible and sustainable way. We are committed to ensuring that our work has a positive impact on society and the environment.

In terms of social responsibility, Makutu members ensure that their research is inclusive and accessible to all members of society. The team prides itself on bringing together researchers from diverse social and cultural backgrounds. It makes its results and publications available to the general public and is involved in scientific dissemination activities.

In terms of environmental responsibility, Makutu strives to minimize the environmental impact of its research. Wherever possible, the team works to reduce its carbon footprint by implementing environmentally friendly practices and maintaining remote collaborations to limit international travel. It is also engaged in a research program dedicated to sustainable energy. In particular, it is contributing to the development of advanced software for monitoring CO2 storage and is studying complex models that can assist in the development of geothermal drilling by avoiding the devastating creation of micro-earthquakes.

Overall, Makutu is committed to conducting research in a responsible and sustainable manner and is committed to having a positive impact on society and the environment.

6 Highlights of the year

6.1 Transformation into an industrial project team

After many years of collaboration with Total, Makutu has become a joint team with TotalEnergies, now hosting 4 researchers from the company. This transformation was made around a research program on CO2 storage monitoring, in collaboration with Lawrence Livermore National Laboratory and Stanford University. Two theses have been started, a post-doctoral fellow has been recruited as well as two research engineers.

7 New software and platforms

7.1 New software

7.1.1 OpenWind

Name: Open Wind Instrument Design

Keywords: Wave propagation, Inverse problem, Experimental mechanics, Time Domain, Physical simulation

Scientific Description: Implementation of first order finite elements for wind musical instrument simulation. Implementation of the Full Waveform inversion method for wind musical instrument inversion. Implementation of energy consistent numerical schemes for time domain simulation of reed-type wind musical instrument.

Functional Description: Simulation and inversion of wind musical instruments using one-dimensional finite element method with tonholes or valves and fingering chart. The software has three functionnalities. First, the software takes the shape of a wind instrument and computes the acoustical response (answer to a given frequential excitation). Second, the software takes the instrument shape and the control parameters of a musician, and computes the produced sound and the time evolution of many acoustical quantities. Last, the software takes a measured acoustical response and computes the corresponding instrument geometry (inner bore and tone holes parameters).

Release Contributions: - New input file formats (compatibility with other software, use of other units, unified file, etc) - Possibility to have conical side holes and pistons - Modal calculation of the frequency response

URL: `https://openwind.inria.fr`

Publications: hal-02984478, hal-02996142, hal-03132474, hal-02917351, hal-02432750, hal-02019515, hal-03231946, hal-03328715, hal-03794474, hal-01963674

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Participants: Juliette Chabassier, Augustin Ernoult, Alexis Thibault, Robin Tournemenne, Olivier Geber, Guillaume Castera, Tobias Van Baarsel

7.1.2 Hou10ni

Keywords: 2D, 3D, Elastodynamic equations, Acoustic equation, Elastoacoustic, Frequency Domain, Time Domain, Discontinuous Galerkin

Scientific Description: Hou10ni simulates acoustic and elastic wave propagation in time domain and in harmonic domain, in 2D and in 3D. It is also able to model elasto acoustic coupling. The time domain solver is based on the second order formulation of the wave equation and the space discretization is achieved using Interior Penalty Discontinuous Galerkin (IPDG) Method. Both IPDG and Hybridizable Discontinuous Galerkin (HDG) Methods are implemented in the frequency domain solver. Recently, the HDG version has been extender to poroelastic and conducting poroelastic (poroelastic+electromagnetic) media.

Functional Description: This software simulates the propagation of waves in heterogeneous 2D and 3D media in time-domain and in frequency domain. It is based on an Interior Penalty Discontinuous Galerkin Method (IPDGM) and allows for the use of meshes composed of cells of various order (p-adaptivity in space).

News of the Year: In 2022, we have focuses the 3D seismoelectomagnetic equations and compared various approximation of the frequency-dependent coupling coefficient.

URL: `https://team.inria.fr/magique3d/software/hou10ni/`

Publications: hal-01513597, hal-01957131, hal-01388195, hal-01972134, hal-01957147, hal-02152117, hal-02486942, hal-02408315, hal-02911686, hal-03464413, tel-03442300, tel-03014772, hal-01656440, hal-01662677, hal-01623953, hal-01623952, hal-01513597, hal-01519168, hal-01254194, hal-01400663, hal-01400656, hal-01400643, hal-01313013, hal-01303391, hal-01408981, tel-01304349, hal-01184090, hal-01223344, hal-01207897, hal-01184111, hal-01184110, hal-01184107, hal-01207906, hal-01184104, hal-01207886, hal-01176854, hal-01408705, hal-01408700, tel-01292824, hal-01656440, hal-00931852, hal-01096390, hal-01096392, hal-01096385, hal-01096324, hal-01096318, tel-01133713, tel-00880628

Contact: Julien Diaz

Participants: Conrad Hillairet, Elodie Estecahandy, Julien Diaz, Lionel Boillot, Marie Bonnasse, Marc Fuentes, Rose-Cloe Meyer, Vinduja Vasanthan, Arjeta Heta

7.1.3 haven

Name: time-HArmonic waVe modEling and INversion using Hybridizable Discontinuous Galerkin Discretization

Keywords: Inverse problem, Wave Equations, Geophysics, Helioseismology, Discontinuous Galerkin, MPI, Large scale, Wave propagation, 3D, 2D

Scientific Description: Many applications such as seismic and medical imaging, material sciences, or helioseismology and planetary science, aim to reconstruct properties of a non directly accessible or non-visible interior. For this purpose, they rely on waves whose propagation through a medium interrelates with the physical properties (density, sound speed, etc.) of this medium. Haven is a software designed to perform imaging with waves, following an algorithm that comprises of two main stages: In the data acquisition stage, the medium response to probing waves is recorded (e.g., seismic waves from Earthquakes recorded by ground network). In the second stage, we rely on a reconstruction procedure which iteratively updates an initial model of physical parameters, so that numerical simulations approach the measurements. This procedure is employed, for instance, for seismic (reconstruction of subsurface layers) and medical (disease diagnostic) imaging.

Functional Description: The software solves time-harmonic forward and inverse wave problems for acoustic and elastic media using the Hybridizable Discontinuous Galerkin method for discretization. It combines MPI and OpenMP parallelism to solve large-scale applications such as Earth's imaging and helioseismology.

News of the Year: - Several choices of visco-acoustic and visco-elastic models have been added for the propagation, - New propagators dedicated to helioseismology have been implemented

URL: https://ffaucher.gitlab.io/hawen-website/

Publications: hal-03871831, hal-03877239, hal-03406861, hal-02982650, hal-03101659, hal-03101642, hal-02982619

Contact: Florian Faucher

Participant: Florian Faucher

7.1.4 MONTJOIE

Keywords: High order finite elements, Edge elements, Aeroacoustics, High order time schemes

Scientific Description: Montjoie is designed for the efficient solution of time-domain and time-harmonic linear partial differential equations using high-order finite element methods. This code is mainly written for quadrilateral/hexahedral finite elements, partial implementations of triangular/tetrahedral elements are provided. The equations solved by this code, come from the "wave propagation" problems, particularly acoustic, electromagnetic, aeroacoustic, elastodynamic problems.

Functional Description: Montjoie is a code that provides a C++ framework for solving partial differential equations on unstructured meshes with finite element-like methods (continuous finite element, discontinuous Galerkin formulation, edge elements and facet elements). The handling of mixed elements (tetrahedra, prisms, pyramids and hexahedra) has been implemented for these different types of finite elements methods. Several applications are currently available : wave equation, elastodynamics, aeroacoustics, Maxwell's equations.

URL: https://www.math.u-bordeaux.fr/~durufle/montjoie

Contact: Marc Durufle

Participants: Juliette Chabassier, Marc Durufle, Morgane Bergot

7.1.5 GEOSX

Keywords: Physical simulation, Multiphysics modelling

Functional Description: GEOSX is an open-source, multiphysics simulator developed cooperatively by Lawrence Livermore National Laboratory, Stanford University, and TotalEnergies. Its goal is to open up new horizons in modeling carbon storage and other subsurface energy systems. This includes: - taking advantage of the ongoing revolution in high-performance computing hardware, which is enabling orders-of-magnitude gains in performance, but also forcing a fundamental rethink of our software designs, - enriching the physics used in industrial simulations, allowing complex fluid flow, thermal, and geomechanical effects to be handled in a seamless manner, - developing highly-scalable algorithms for solving these coupled systems, - and improving workflows for modeling faults, fractures, and complex geologic formations. Inria contributes to the seismic wave propagators of GEOSX, and to its python interface. Inria also contributes advanced workflows for seismic inversion, and CO2 storage an monitoring.

News of the Year: Project-team Makutu has contributed to the integration of seismic propagators based on Q1 SEM (spectral element method), and to the development of the python interface (pyGEOSX), with the goal of later using it to integrate a complete seismic inversion workflow via full waveform inversion (FWI). These developments will carry on and expand in 2022.

URL: http://www.geosx.org/

Contact: Randolph Settgast

7.1.6 Gar6more2D

Keywords: Validation, Wave propagation

Functional Description: This code computes the analytical solution of problems of waves propagation in two layered 3D media such as- acoustic/acoustic- acoustic/elastodynamic- acoustic/porous-porous/porous,based on the Cagniard-de Hoop method.

News of the Year: In the framework of collaboration with Peter Moczo (Comenius University Bratislava and Slovak Academy of Sciences), David Gregor, Josef Kriztek, Miriam Kristekova (Comenius University Bratislava), Arnaud Mesgouez, Gaëlle Lefeuve-Mesgouez (Inrae, Avignon University) and Christina Morency (Laurence Livermore National Laboratory) and we have implemented the coupling between elastic and poroelastic media. The obtained results are presented in an article of Geophysical Journal Internation [15].

URL: `https://gitlab.inria.fr/jdiaz/gar6more2d`

Publications: inria-00274136, inria-00404224, inria-00305395, gregor:hal-03471065

Contact: Julien Diaz

Participants: Abdelaâziz Ezziani, Julien Diaz

Partner: Université de Pau et des Pays de l'Adour

7.1.7 GoTem3

Keywords: Trefftz, Electromagnetic waves, GMRES, Iterative method

Functional Description: GoTem3 is domain decomposition platform based on the ultra-weak formulation of Cessenat and Després for the solution of diffraction problems posed on regular grids. It uses matrix free strategies as well as local and global preconditioners to solve cases involving more than a billion degrees of freedom on a single computational core.

News of the Year: The Phd thesis of Margot Sirdey has been defended on December 22, 2022

Contact: Sebastien Tordeux

8 New results

8.1 Methodological contributions to the simulation of mechanical and electromagnetic waves in complex media

8.1.1 Linearly implicit energy-preserving time discretisation for non-linear wave equations

Participants: Juliette Chabassier, Guillaume Castera.

Non-linear phenomena can occur in vibrating structures, such as piano strings, due to large deformations or non-linear constitutive state laws. Integration of non-linear models in space and time can be achieved accurately in several ways, but preserving an energy identity at the discrete level is an effective way to address numerical stability when coupling with other systems (as in the case of the piano). Gradient-based integrators achieve this objective at the cost of solving a non-linear system at each time step. New formulations called Invariant Energy Quadratization (IEQ) and Scalar Auxiliary Variable (SAV) require only the inversion of a linear system while preserving a discrete energy identity. This work presents a convergence analysis of an interleaved time integrator based on IEQ and θ-scheme and numerical illustrations.

This work was presented at the international conference WAVES 2022: Guillaume Castera, Juliette Chabassier, Paul Fisette. Linearly implicit energy consistent time discretisation for nonlinear wave equations. WAVES 2022 - 15th International Conference on Mathematical and Numerical Aspects of Wave Propagation, Jul 2022, Palaiseau, France. ⟨hal-03757200⟩

This work has been done in collaboration with Paul Fisette, université catholique de Louvain, Belgium.

8.1.2 Trefftz-DG methods and Tent Pitcher algorithm for space-time integration of wave problems

Participants: Hélène Barucq, Henri Calandra, Julien Diaz, Vinduja Vasanthan.

We explored the optimization of Trefftz-Discontinuous Galerkin methods with the Tent-Pitcher algorithm and the elaboration of boundary conditions adapted to them. We consider these methods in the framework of the first-order acoustic wave equation in time-domain. The idea of Trefftz methods is to use local solutions of the considered Partial Differential Equations as basis functions. Such a formulation has the advantage of being posed on the skeleton of the mesh only and characteristics of the analytical solutions are injected into the discrete solution through the basis functions, which leads us to expect the obtained numerical solution to be more precise. However, the resulting scheme is implicit in time-domain, which leads to an increased computational cost. This is the reason why we investigated Tent-Pitcher algorithms. The Tent-Pitcher algorithm is a space-time meshing algorithm introduced for hyperbolic problems, that consists in constructing a causal mesh which allows to solve the problem element-by-element.

We have developed a Trefftz-DG framework for solving the acoustic wave equation using Tent-Pitching algorithms. In 2022, we have extended the existing code to unstructured meshes, which led to a modified Tent-Pitching algorithm and we have proposed a parallel version of our Trefftz-DG framework, which is carried out with the MPI library.

A second part of our work consisted in designing and implementing artificial boundary methods in order to consider simulations in very large domains. We derives a formulation for the Trefftz-Discontinuous Galerkin methods with Perfectly Matched Layers for the acoustic wave equation, which involves the computation of analytical solutions for this new system of equations because the principle of the Trefftz methods relies on the use of local solutions as basis functions. This is done by computing the Green's functions for the time-domain acoustic wave equation using the Cagniard-De Hoop method. Finally, we implement these boundary conditions into the Trefftz-Discontinuous Galerkin solver with Tent-Pitching on structured meshes and present the obtained results.

This work has been done in the framework of DIP and has been presented in several congresses, such as ECCOMAS [20] (jun. 2022) and Waves [19] (jul. 2022) and is the topic of the PhD. of Vinduja Vasanthan, defended on December, 8th [52].

8.1.3 Optimized Finite Differences methods and Machine Learning to reduce numerical dispersion for the wave equation

Participants: Hélène Barucq, Henri Calandra, Florian Faucher, Nicolas Victorion.

We consider the wave equation in acoustic media and evaluate the performance of Finite Difference (FD) schemes. The objective is to reduce the computational cost while maintaining the accuracy avoiding numerical dispersion. To do so, we study the size of stencils and optimized weight for the spatial derivative to obtain the best results in terms of computational cost. We review the optimized coefficients that have been introduced in the literature to minimize the numerical dispersion and we compare their performance on different test cases, with the perspective to reduce as much as possible the number of points per wavelength. To go further we propose a non conventional method, based on Machine Learning to remove numerical dispersion. Here, we simulate on a coarse grid and a small stencil. Hence the simulation is fast but numerical dispersion appears, which we correct with a Machine learning. This correction is applied during the simulation at selected time steps. Consequently, we reduce run time while avoiding the numerical dispersion.

This work has been presented at the Mathias conference [28]. It is a collaboration with Emmanuel Franck (Tonus, Inria, Nancy Grand Est).

8.1.4 Modal computation for open waveguides

Participants: Hélène Barucq, Marc Duruflé, Augustin Leclerc.

The study of electromagnetic (EM) wave propagation is essential for considering the impact of Human's technologies on the environment. For instance, the offshore wind energy is transported through twisted dynamic cables, which armours prevent a significant portion of the waves to irradiate outside the cable. Nevertheless, a remaining and possibly significant part might escape from the cable. Hence, our aim is to look at their scattering in the large stretch of sea water. To consider this problem, we propose to modelize the cable and the surrounding water by an open 3D waveguide, which is an invariant domain according to the cable direction and which is unbounded in the two other directions. We then take a modal approach for the resolution. Moreover, although Maxwell equations govern the propagation of EM waves, they are simplified to the Helmholtz equation, by considering Transverse Magnetic waves.Before studying the EM field far away from the cable, we focus on its behavior in its vicinity. We use absorbing boundary conditions around the cable. We have analyze their relevance, especially at low frequency. This work is part of a PhD program which started in October 2021. The topic has been proposed by the SME Kraken Subsea and is now the heart of a collaboration between this SME, Makutu and INSA Rouen with Christian Gout and Antoine Tonnoir. It has been presented at Waves Conference in July [22].

8.1.5 Polynomial-reproducing spline spaces from fine zonotopal tilings

Participants: Hélène Barucq, Henri Calandra, Julien Diaz, Stefano Frambati.

Given a point configuration A, we uncover a connection between polynomial-reproducing spline spaces over subsets of conv(A) and fine zonotopal tilings of the zonotope Z(V) associated to the corresponding vector configuration. This link directly generalizes a known result on Delaunay configurations and naturally encompasses, due to its combinatorial character, the case of repeated and affinely dependent points in A. We prove the existence of a general iterative construction process for such spaces. Finally, we turn our attention to regular fine zonotopal tilings, specializing our previous results and exploiting the dual graph of the tiling to propose a set of practical algorithms for the construction and evaluation of the associated spline functions. The construction of the spline spaces is presented in JCAM [11].

8.1.6 Practical unstructured splines: Algorithms, multi-patch spline spaces, and some applications to numerical analysis

Participants: Hélène Barucq, Henri Calandra, Julien Diaz, Stefano Frambati.

In this work, we build on our previous results on simplex spline spaces to construct a polynomial-reproducing space of unstructured splines on multi-patch domains of arbitrary shape and topology. The traces of these functions on the subdomain boundaries reproduce the usual traces of standard polynomial bases used in discontinuous Galerkin (DG) approximations, allowing to borrow many theoretical and practical tools from these methods. Concurrently, we recast some theoretical results on the construction and evaluation of spaces of simplex splines into an explicit, algorithmic form. Together, these efforts allow to formulate a practical, efficient and fully unstructured multi-patch discontinuous Galerkin-isogeometric analysis (DG-IGA) scheme that bridges the gap between some current multi-patch isogeometric analysis (IGA) approaches and the more traditional mesh-based interior penalty discontinuous Galerkin (IPDG) method. We briefly discuss the advantages of this unified framework for time-explicit hyperbolic problems, and we present some interesting numerical examples using the acoustic wave equation. This work has been published in JCP [14].

8.1.7 Frequency-domain acoustic wave modeling via unstructured isogeometric analysis: performance and pollution study

Participants: Hélène Barucq, Henri Calandra, Julien Diaz, Stefano Frambati.

Many works have shown the usefulness of Isogeometric Analysis (IGA) [84] for the solution of the Helmholtz equation. In particular, the increased regularity of B-spline functions and their uniform shape often translate into a better precision per degree of freedom, a wider spectral convergence and a consequently reduced numerical pollution compared to standard finite element (FE) approaches (see, e.g., [75]). Recent advances in unstructured spline spaces [11] have allowed a new, fully unstructured IGA paradigm to emerge, with some intersting applications to explicit-time wave propa- gation. This scheme, based upon an unstructured point cloud, allows to produce IGA patches with full regularity and arbitrary domain topology. Moreover, these patches can be coupled via discontinuous Galerkin (DG) terms, yielding a fully unstructured multi- patch DG-IGA, or even the usual DG scheme as a limiting case. In this work, we explore the usefulness of this new paradigm for frequency-domain wave propagation. In particular, we study the convergence and spectral properties of this unstructured IGA multi-patch scheme on some selected models. We focus on its behavior with respect to the point cloud density and the number of degrees of freedom, and we analyze its computational performance, precision and numerical pollution. We also show how the generalized topology of domains allowed by this point-cloud formulation allows to go beyond the usual tensor-product IGA geometries. Finally, we give some perspective on how the meshfree character of this formulationcan be used to recover the location of sharp discontinuities starting from a smooth initial mode. This work has been presented at ECCOMAS conference (Oslo, June, [27])

8.1.8 Trefftz methods for Maxwell equations

Participants: Margot Sirdey, Sébastien Tordeux.

The simulation of time-harmonic electromagnetic waves requires a matrix inversion whose cost, especially in three-dimensional cases, increases quickly with the size of the computational domain. This is a tangible issue regarding the memory consumption. Trefftz methods consist in using a discontinuous Galerkin method whose basis functions are specific to the considered physical problem and thus reduce numerical dispersion phenomena. We propose an iterative Trefftz solver based on a domain decomposition method which will reduce considerably the memory consumption. However, iterative Trefftz methods based on a plane wave approximation are ill-conditioned. To overcome this problem, we propose improvements of the Cessenat and Després preconditioner and a basis reduction. A matrix-free strategy allows to avoid the assembly of the matrix associated to the linear system and GMRES solver does not require the computation of the inverse anymore. This is a joint work with Sébastien Pernet (ONERA). It has been presented in several congresses at ECCOMAS conference (Oslo) [43] Waves (Palaiseau) [42] and JCJC Sophia Antipolis [44] and a preprint has been written [55]. Margot Sirdey has defended her PhD thesis [51].

8.1.9 Mixed precision sparse direct solver applied to 3D wave propagation.

Participants: Florian Faucher.

Efficient numerical simulation of wave propagation phenomena is needed in several applications such as seismic imaging, non-destructive testing, or helioseismology. In this work, we consider time-harmonic waves and the hybridizable discontinuous Galerkin discretization method for which the efficiency of the wave propagator relies on the performance of finding the solution of systems of sparse linear equations. These systems have multiple sparse right-hand sides associated with several sources. This motivates the use of direct solvers which can efficiently reuse the LU factors to compute the solution of multiple right-hand sides at the cost however of a high memory footprint. Fortunately, matrices arising from the discretization of partial differential equations have been shown to have a low-rank property and the Block-Low Rank (BLR) format has been used to design fast direct solvers with reduced asymptotic complexity. Very recent work describes how the BLR LU factorization algorithm can benefit from mixed precision arithmetic. In the context of 3D frequency-domain wave equations, the BLR factorization in 32-bit single precision arithmetic has been shown to provide accurate enough solutions. In this talk, we will explain why and how we can exploit lower precision formats (such as 24 and 16 bit arithmetics) in the representation of BLR blocks, while preserving a satisfactory accuracy. This allows us to reduce the memory footprint of the solver by further compressing both the LU factor matrices and the working space without affecting the precision of the solution. The performance using recent features of the MUMPS sparse direct solver, including mixed precision, is analyzed with large-scale 3D acoustic and elastic experiments using hawen software, [77].

This is a joint work with the MUMPS group, in particular Patrick Amestoy (ENS Lyon), Jean-Yves L'Excellent (ENS Lyon), Théo Mary (Sorbonne University) and Chiara Puglisi. This work has been presented at ECCOMAS Conference, [24].

8.1.10 Iterative Trefftz methods for anisotropic acoustic problems equations

Participants: Hélène Barucq, Ibrahima Djiba, Sébastien Tordeux.

We are developing a numerical framework for the anisotropic wave equation thanks to a Trefftz method. We aim at solving a time harmonic problem without any matrix inversion. We resort to a Cessenat Després preconditioner and to a GMRES solver to accelerate the convergence of the algorithm wich allows to compute the solution of the considered problem with a low memory cost. A research report should be published in March 2023.

8.1.11 A HDG framework for convected Helmholtz equation.

Participants: Hélène Barucq, Nathan Rouxelin, Sébastien Tordeux.

In this work, we introduce three variants of the HDG method based on two weak formulations of the convected Helmholtz equation. Two of them are standard HDG methods with the same interpolation degree for all the unknowns and the last uses a higher interpolation degree for the volumetric scalar unknown. For those three numerical methods, a detailed analysis including local and global well-posedness, as well as convergence estimates is carried out. We then provide implementation details and numerical experiments to illustrate our theoretical results. A paper is currently under minor revisions.

8.2 Seismic imaging

8.2.1 Experimental characterization and modeling of electromagnetic waves generated by seismo-electric conversion at porous media interfaces

Participants: Hélène Barucq, Victor Martins Gomes.

Inside fluid-bearing porous media, mechanical disturbances created by traveling seismic waves entail the conversion of seismic into electromagnetic (EM) energy. Two forms of conversion, electro-kinetic in nature, have been continually investigated in the context of subsurface exploration: the first consists of a wave-field strictly bounded to the seismic wave, therefore referred as co-seismic fields, while the other only happens when the physical properties change, ergo at geological interfaces, and it radiates independently of the seismic waves, with EM-velocities (usually bigger than 10^6 m/s). Due to the sensitivity of the latter to lithology changes, in special variation in the pore-fluid, it is pertinent to near-surface investigation as a complement to seismic reflection, much like electromagnetic controlled-source. Because of that, there is a continuous effort to develop and promote the seismo-electric methods as an indirect geophysical procedure based on electro-kinetic conversions. However the large number of parameters involved, and the lack of comprehensive understanding of these phenomena delays a widespread use of seismolectrics: currently there are two main theoretical descriptions, but thus far, none validated in a proper quantitative manner. As a contribution to the existing knowledge about seismic-to-EM conversions, we propose an easily reproducible experimental setup, capable of measuring both conversions at the same time, with satisfactory signal-to-noise ratio. This setup allows the reproduction of diverse geological settings, including porous layers filled with different fluids, a peculiarity with respect to previous experiments designed to study the same subject. In parallel, an existing numerical code, built upon the most frequently used set of seismo-EM governing equations, was properly adapted to model the experiment, hence opening the path to comparisons between theory and laboratory measurements. As a consequence, a series of measurements in both homogeneous and layered media were conducted, as well as their corresponding numerical modeling. Simulations showed that even though amplitude disagreements exist, overall the theoretical predictions successfully agree with experimental data. Additionally, by studying, experimentally and numerically, the effects of layer thinning on the interface response, it was observed that a boosting of the measured signals happens when the layer has a thickness equal to half the P-wavelength in this layer (P, as usual, refers to compression waves). At last, the effect of fluid conductivity on interface-generated EM waves was investigated. It was noticed that, in the experiment realized, amplitudes decrease with increasing conductivity, whereas the ratio between interface response and co seismic amplitudes increase. Also, comparison with numerical simulations confirmed again that theory succeeds in providing a fair representation of experiments. This work has been done in collaboration with Daniel Brito (LFCR, CNRS, UPPA), Stéphane Garambois (Isterre, Grenoble) and Clarisse Bordes (LFCR, CNRS, UPPA). It was the subject of a Ph.D. thesis funded by E2S UPPA (CHICkPEA project) defended the 5th of December 2022 [50]. Some of the results have been presented at EGU in May (see [41]).

8.2.2 Pulsed-laser source characterization in laboratory seismic experiments

Participants: Julien Diaz, Chengyi Shen.

The present study aimed to characterize the properties of a laser-generated seismic source for laboratory-scale geophysical experiments. This consisted of generating seismic waves in aluminum blocks and a carbonate core via pulsed-laser impacts and measuring the wave-field displacement via laser vibrometry. The experimental data were quantitatively compared to both theoretical predictions and 2D/3D numerical simulations using a finite element method. Two well-known and distinct physical mechanisms of seismic wave generation via pulsed-laser were identified and characterized accordingly: a thermoelastic regime for which the incident laser power was relatively weak, and an ablation regime at higher incident powers. The radiation patterns of the pulsed-laser seismic source in both regimes were experimentally measured and compared with that of a typical ultrasonic transducer. This study showed that this point-like, contact-free, reproducible, simple-to-use laser-generated seismic source was an attractive alternative to piezoelectric sources for laboratory seismic experiments, especially those concerning small scale, sub-meter measurements.

This work was published in Geomechanics and Geophysics for Geo-Energy and Geo-Resources [16], in collaboration with Clarisse Bordes, Daniel Brito, Federico Sanjuan (LFCR, UPPA), and Stéphane Garambois (ISterre).

8.2.3 Analytical solutions for elasto/poroelastic coupling

Participant: Julien Diaz.

Our software Gar6more computes the analytical solution of waves propagation problems in 2D homogeneous or bilayered media, based on the Cagniard-de Hoop method. In the bilayered case, we had implemented the following coupling: acoustic/acoustic, acoustic/elastic, acoustic poroelastic, elastic/elastic, poroelastic/poroelastic. In the framework of collaboration with Peter Moczo (Comenius University Bratislava and Slovak Academy of Sciences), David Gregor, Josef Kriztek, Miriam Kristekova (Comenius University Bratislava), Arnaud Mesgouez, Gaëlle Lefeuve-Mesgouez (Inrae, Avignon University) and Christina Morency (Laurence Livermore National Laboratory) and we have implemented the coupling between elastic and poroelastic media. The obtained results are presented in an article of Geophysical Journal International [15].

8.2.4 Full Waveform Inversion on Seismic Data including Surface Waves.

Participants: Hélène Barucq, Julien Diaz, Florian Faucher, Chengyi Shen.

Makutu collaborated with RealTimeSeismic (RTS) SME as part of the FEDER-Poctefa PIXIL project (Pyrenees Imaging eXperience: an InternationaL network) on the topic of Full Waveform Inversion (FWI), with a particular focus on the surface waves. The PIXIL project focuses on geophysical method development for geothermal surveys, where surface waves carry essential information of near-surfaces especially for shallow geothermal explorations. A good image of the near-surface can further help improve deep imaging.

The collaboration RTS/Inria within the PIXIL project followed 3 main axes: data exchange/analyses, FWI strategy establishment and acquisition parameterization design. We aim at building a FWI tool suitable for surface waves and ultimately applying it onto real data acquired by RTS in a near-surface seismic exploration. The core of the numerical tool is a Fortran HPC code, named HAVEN [77] developed by Florian Faucher in time-harmonic domain featuring the Hybridizable Discontinuous Galerkin method. We conducted 2D synthetic case studies in order to establish Multi-level Strategies for FWI on seismic data including surface waves. A trade-off between robustness and high-resolution is achievable by elaborating suitable strategies such as combining seismic tomography and FWI featuring frequency groups, regularization and filtering. Meanwhile, Bash and Python programs are created to assist HAVEN for user-friendly concerns as well as data pre/post-processing, for instance, automatization of executions, data processing and visualization.

We constructed, tested and validated a new cost-function in the Frequency-Wavenumber (FK) domain following the suggestions of literatures tackling surface waves [95, 88]. The FWI results confirm the major advantage of such a cost-function: the "attraction basin" is larger and smoother than in the Frequency-Space (FX) domain, which is a favorable condition for the convergence of the FWI result towards the targeted model. We showed also that the strategy of multi-level inversion combining cycles of ascending and descending frequencies can help us escape local minima. A FWI featuring strong surface waves may work with both robustness and high-resolution in the FK domain.

8.2.5 Diffraction Tomography, Fourier Reconstruction, and Full Waveform Inversion.

Participant: Florian Faucher.

we study the mathematical imaging problem of diffraction tomography (DT), which is an inverse scattering technique used to find material properties of an object by illuminating it with probing waves and recording the scattered waves. Conventional DT relies on the Fourier diffraction theorem, which is applicable under the condition of weak scattering. However, if the object has high contrasts or is too large compared to the wavelength, it tends to produce multiple scattering, which complicates the reconstruction. We give a survey on diffraction tomography and compare the reconstruction of low and high contrast objects. We also implement and compare the reconstruction using the full waveform inversion method which, contrary to the Born and Rytov approximations, works with the total field and is more robust to multiple scattering.

This is a joint work with Clemens Kirisits (University of Vienna), Michael Quellmalz (TU Berlin), Otmar Scherzer (University of Vienna) and Eric Setterqvist (RICAM). A book chapter has been published as part of Handbook of Mathematical Models and Algorithms in Computer Vision and Imaging, Springer International Publishing, [49].

8.2.6 Quantitative inverse problem in visco-acoustic media under attenuation model uncertainty.

Participant: Florian Faucher.

We consider the inverse problem of quantitative reconstruction of properties (e.g., bulk modulus, density) of visco-acoustic materials based on measurements of responding waves after stimulation of the medium. Numerical reconstruction is performed by an iterative minimization algorithm. Firstly, we investigate the robustness of the algorithm with respect to attenuation model uncertainty, that is, when different attenuation models are used to simulate synthetic observation data and for the inversion, respectively. Secondly, to handle data-sets with multiple reflections generated by wall boundaries around the domain, we perform inversion using complex frequencies, and show that it offers a robust framework that alleviates the difficulties of multiple reflections. To illustrate the efficiency of the algorithm, we perform numerical simulations of ultrasound imaging experiments to reconstruct a synthetic breast sample that contains an inclusion of high-contrast properties. We perform experiments in two and three dimensions, where the latter also serves to demonstrate the numerical feasibility in a large-scale configuration.

This is a joint work with Otmar Scherzer (University of Vienna), a papar has been published in the Journal of Computational Physics, [13].

8.2.7 Quantitative Analysis of Seismic Waves with Computational and Laboratory-Scale Experiments.

Participants: Marine Deheuvels, Florian Faucher.

We recover physical properties of a material with a focus on the attenuation, using a laboratory-scale sample. We develop a method to accurately invert the attenuation models, and demonstrate its efficiency with 3D simulations in the frequency domain considering different rheological viscoelastic models. First, we consider a simplified numerical case where we avoid wave reflections from boundaries. Our analysis allows to characterize the wave behavior and the attenuation properties of the medium. Here, we use a complex wavenumber analysis, to recover a complex-valued mechanical modulus that accounts for the viscoelastic behavior. Secondly, we consider numerically an experimental configuration, with free-surface conditions on the sample boundaries, and measurements restricted to the faces of the sample. In this case, the free-surface boundaries lead to multiple reflections and wave conversions that must be taken into account to analyze both the body waves and surface waves displacements to recover the representative viscoelastic properties. Finally, we carry out laboratory-scale experiments on various rock samples designed to find out their attenuation properties. For this purpose, we run an experimental setup using piezoelectric transmitters acting as a seismic source, and a laser-doppler vibrometer for non-contact time-domain measurements. Then, we have to recover the appropriate attenuation laws and their corresponding parameters, depending on the nature of samples. This eventually serves to build initial models to perform iterative reconstruction with Full Waveform Inversion.

This is the subject of Marine Deheuvels Ph.D. at UPPA, she is supervised by Daniel Brito (UPPA) and Florian Faucher. This work has been presented at the conference EGU [35] and at the conference AGU [57].

8.2.8 High-resolution seismic tomography on a carbonate core.

Participants: Julien Diaz
, Chengyi Shen
.

We submitted an article to Geophysical Journal International to communicate our experimental and numerical work on high-resolution seismic tomography performed on a carbonate core at the laboratory-scale. The experimental part was done in the Laboratoire des Fluides Complexes et leurs Réservoirs (LFCR). The numerical simulation was performed by Hou10ni HPC code developed by our team. We developed an automate experimental prototype involving a point-like pulsed-laser (PL) or a piezoelectric transducer (PZT) as seismic sources and a single-point Laser Doppler Vibrometer (LDV) as a receiver. The PL-LDV setup is successfully applied to produce seismic propagation in the megahertz range and used to study the P-wave velocities inside the carbonate core through tomography. The seismic tomography obtained from both the PL-LDV and the PZT-LDV datasets are compared with an X-ray CT-scan image of the carbonate core. In parallel, numerical tests on synthetic data, simulated by Hou10ni, are run to study the hyperparameters and resolution of tomography, which helped us establish an optimal inversion strategy involving multi-grids. The tomography results are completed with a sensitivity analysis through spike tests. Therefore, we validated an experimental prototype featuring seismic sources of multi-physics origins for high-resolution measurements in laboratory as well as a tomography workflow: we propose an original and efficient geophysical core-probing configuration based on the PL-LDV set-up leading to a more accurate tomographic P-velocities reconstruction as compared to the PZT-LDV set-up. This work is in collaboration with Daniel Brito and Clarisse Bordes of LFCR, Jean Virieux and Stéphane Garambois of ISTerre, as well as the DMEX Center for X-ray Imaging.

8.2.9 Frequency analysis of the seismoelectric coupling operator

Participants: Hélène Barucq, Julien Diaz, Arjeta Heta.

Pride's equations [93] model seismoelectric effects resulting from the coupling between seismic and electromagnetic waves in porous media. They are thus equations of dynamic in porous media coupled with Maxwell's equations. The coupling is achieved in terms of a coefficient L which is defined in the time domain as a Fourier integral operator. The exact L is thus difficult to discretize and is approximate by a leading term L_0 independent of the frequency. When considering the time harmonic equations, the associated L is the inverse of a square root in the frequency. We address the idea of using approximate time-harmonic coupling terms defined as rational or polynomial functions of the frequency. By this way, it would be possible to switch from time-harmonic coupling terms to time-dependent ones. In practice, L is replaced in the time domain by a constant coefficient L_0 which should only reproduce the coupling accurately in the low frequency range. We have obtained approximate expressions of the coupling terms which can be derived in a frequency regime limited by the cut-off frequency. We use Padé approximants to approximate the square root by rational functions of frequency. Numerical experiments show that actually L_0 reproduces correctly the seismoelectric effect at low frequencies while higher-order rational approximations of L perform better at mid and high frequencies. This work is the topic of Arjeta Heta's Ph.D. thesis, it is a collaboration with Cristina Morency in the framework of the SEE4GEO project 10.1.2. It has been presented in a digital poster at the AGU conference in Chicago (Dec.2022)[58].

8.2.10 Elastic Full Waveform Inversion in the frequency domain with hybridizable discontinuous Galerkin method

Participants: Hélène Barucq, Florian Faucher, Ha Pham.

Seismic Full Waveform Inversion has clearly demonstrated its efficiency in providing accurate quantitative information of the subsurface. Its implementation strongly depends on the resolution of the forward problem which is performed repeatedly in an iterative inversion process. In this work, we perform seismic FWI when the forward problem is solved with a face-based discontinuous finite element method. Discontinuous finite elements are particularly efficient for solving wave equations in heterogeneous media since with hp-adaptivity feature, they not only can handle the topography of the propagation domain but also resist numerical pollution, which can be important in large-scale computations. Herein, we consider a Hybridizable Discontinuous Galerkin method based upon a mixed formulation of the problem coupled with static condensation. The computational burden mostly comes from the resolution of the global discrete problem whose size is proportional to only the degrees of freedom of the mesh skeleton. We work with the elastic wave equation in the frequency domain. We consider two different mixed formulations, the so-called strain-stress, and stress-strain formulations. This first one is widely used while the second one allows us to easily consider varying parameters inside the cells of the mesh. The HDG approximation of the elastic wave is the first step in the design of FWI process. The second and critical step consists in deriving the adjoint state in the same approximation framework. This turns out not to be an obvious task and thus deserves some attention. We illustrate the numerical performances of the HDG-based FWI with time-harmonic elastic wave equations on two and three dimensional test cases.

This work has been presented at the Mathias conference [31]. subsubsectionOptimized Full Waveform Inversion for seismic in GEOSX:

Participants: Hélène Barucq, Julien Besset, Henri Calandra, Stefano Frambati.

The reduction of energy carbon footprint justifies the recent major programs launched on CO2 storage in existing reservoirs known to geologists. Numerical simulation plays a key role in their implementation by providing a low-cost means of monitoring. This is a global concern that explains the use of open-source software platforms facilitating knowledge sharing and collaborations. Regarding monitoring aspects, Full Waveform Inversion (FWI) has demonstrated its ability in probing the subsurface accurately. FWI is an iterative process in which we need to solve forward problems in large-scale propagation domains whose discretization involves more than 108 cells each. Implementing an FWI algorithm needs thus an optimized architecture in terms of memory management and GPU-CPU computation. Among the existing open-source platforms, GEOSX targets such architecture. Moreover, GEOSX offers a multi-physics approach ready for reservoir simulation and offering the perspective of coupling with seismic.

During this year, we have developed a FWI workflow for GEOSX equipped with spectral elements for solving the forward problem. We have also investigated the opportunity of using Reduced Order Models (ROM) that are low-dimensional problems for fast simulations providing accurate solutions of the original problem. This approach has been widely used in computational fluid dynamics and seems to be gaining the interest of geophysicists as recent papers testify. However, the construction of ROM using for example Krylov subspace method or Propper Orthogonal Decomposition (POD) requires solving an eigenvalue problem, which tends to be computationally expensive. Hence, we are now considering the idea of introducing Physics-informed Machine Learning. This work has been presented at the conference Mathias Days in October 2022 (see [26]).

8.3 Helioseismology

8.3.1 Low-order Prandtl-Glauert-Lorentz based Absorbing Boundary Conditions for solving the convected Helmholtz equation with Discontinuous Galerkin methods

Participants: Hélène Barucq, Nathan Rouxelin, Sébastien Tordeux.

We construct Absorbing Boundary Conditions (ABCs) for the convected Helmholtz equation that are easy to implement in a Hybridizable Discontinuous Galerkin (HDG) formulation. The construction is based upon the Prandtl-Glauert-Lorentz map which transforms the convected Helmholtz equation into the regular Helmholtz equation. The new ABCs are thus issued from classical Bayliss-Gunztburger-Turkel ABCs and are valid for carrier flows that vary inside the computational domain but become uniform far away from the source. They lead to accurate numerical results for low and intermediate Mach numbers using a HDG formulation with the acoustic potential and the total flux as unknowns. This work has been published in the preprint [12]. It has been presented at CANUM 2022 in Evian [45], Waves 2022 [23] in Palaiseau and as an invited talk at CMAM - Computational Methods in Applied Mathematics- [46] in Vienna.

8.3.2 Outgoing modal solutions for Galbrun's equation in helioseismology.

Participants: Hélène Barucq, Florian Faucher, Ha Pham.

We construct modal outgoing Green's kernels for the simplified Galbrun's equation under spherical symmetry, in the context of helioseismology. The coefficients of the equation are C^2 functions representing the solar interior model S, complemented with an isothermal atmospheric model. We solve the equation in vectorial spherical harmonics basis to obtain modal equations for the different components of the unknown wave motions. These equations are then decoupled and written in Schrödinger form, whose coefficients are shown to be C^2 apart from at most two regular singular points, and to decay like a Coulomb potential at infinity. These properties allow us to construct an outgoing Green's kernel for each spherical mode. We also compute asymptotic expansions of coefficients up to order r^{-3} as r tends to infinity, and show numerically that their accuracy is improved by including the contribution from the gravity although this term is of order r^{-3}. In particular, these works allow us to (1) efficiently compute the solar power spectra for different configurations, and (2) evaluate the performance of radiation boundary conditions for applications to 3D.

This is a joint work with Laurent Gizon and Damien Fournier of the Max Plank Institute for Solar system research in Göttingen (MPS), supported by the INRIA associated team ANTS between Makutu and MPS. These results have been presented in conference ECCOMAS [30].

8.3.3 Efficient computation of modal Green's kernels for vectorial equations in helioseismology under spherical symmetry.

Participants: Hélène Barucq, Florian Faucher, Ha Pham.

We investigate the numerical computation of physical modal Green's kernels for the time-harmonic Galbrun's equation in helioseismology under spherical symmetry. These kernels are the coefficients of the 3D Green's kernels in the vector spherical harmonic expansion. In a previous work, we have characterized the physical kernels for the isothermal radial solar background model S-AtmoI and provide their well-posedness results. Here, we provide an algorithm to compute efficiently these kernels for all receiver and source positions in a region of interest and develop the technical ingredients for its implementation. The kernels are built from the solution of a scalar wave equation for the radial displacement. The solution and its derivative which are both necessary to assemble the Green's kernel are obtained by solving a first-order system using the HDG method. This approach extends previous works considering a scalar wave equation and allows to model not only the pressure modes but also the surface and internal gravity waves. While being physically more interesting, this problem raises additional numerical difficulties. In particular, the solution of the Schrödinger equation for the radial displacement is singular without attenuation and it is thus preferable to solve the original equation. Moreover, for low frequencies and high-modes, the potential switches sign in the atmosphere which requires the position of the artificial boundary to be further away from the solar surface in order to capture the correct physical solution.

This is a joint work with Laurent Gizon and Damien Fournier of the Max Plank Institute for Solar system research in Göttingen (MPS), supported by the INRIA associated team ANTS between Makutu and MPS. These results have been presented in conference ECCOMAS [30].

8.3.4 Imaging individual active regions on the Sun's far side with improved helioseismic holography

Participant: Hélène Barucq.

Helioseismic holography is a useful method to detect active regions on the Sun's far side and improve space weather forecasts. We aim to improve helioseismic holography by using a clear formulation of the problem, an accurate forward solver in the frequency domain, and a better understanding of the noise properties. Building on the work of Lindsey et al., we define the forward- and backward-propagated wave fields (ingression and egression) in terms of a Green's function. This Green's function is computed using an accurate forward solver in the frequency domain. We analyse overlapping segments of 31 hr of SDO/HMI dopplergrams, with a cadence of 24 hr. Phase shifts between the ingression and the egression are measured and averaged to detect active regions on the far side. The phase maps are compared with direct EUV intensity maps from STEREO/EUVI. We confirm that medium-size active regions can be detected on the far side with high confidence. Their evolution (and possible emergence) can be monitored on a daily time scale. Seismic maps averaged over 3 days provide an active region detection rate as high as 75as low as 7attributed to the use of a complete Green's function (all skips) and to the use of all observations on the front side (full pupil). Improved helioseismic holography enables the study of the evolution of medium-size active regions on the Sun's far side.

This is a joint work with Laurent Gizon and Dan Yang of the Max Plank Institute for Solar system research in Göttingen (MPS), supported by the INRIA associated team ANTS between Makutu and MPS. This work is published in Astronomy & Astrophysics, [18].

8.4 Musical Acoustics

8.4.1 Comparative study of French and German bassoons

Participant: Augustin Ernoult.

The French "Basson" and the German "Fagott" are both descendants of the baroque bassoon. They have evolved differently by adding side holes, lengthening the main bore and changing the shape of the reed. These two cousins are played with different fingerings and have a slightly different sound colour: the French bassoon having the reputation of having a more nasal and less homogeneous timbre over the whole range. The aim of this work was to identify the sound differences between a Fagott and a Bassoon and to relate them to their geometry through acoustic considerations. The two instruments studied were played by a professional Fagott player, familiar with the French bassoon. Each bassoon is played with two reeds: its own reed and a single plastic reed, all fitted with a pressure sensor. The external sound and reed pressure are recorded for musical excerpts and a chromatic scale allowing, for each signal, the calculation of the average spectrum over a given range of notes (e.g. the first register). These recordings are complemented by a set of geometric measurements (main bore and holes) and impedance measurements for each fingering of the two instruments. Some notes are also played by an artificial mouth on both instruments with similar control parameters, avoiding the musician's "reflex" adaptation. This set of measurements makes it possible to quantify the difference between the two instruments in terms of acoustic properties and radiated spectrum. Furthermore, it gives the possibility to calculate the transfer function between the spectrum of the reed and the spectrum of the external sound. The evolution of this quantity along the frequency axis can be related to manufacturing elements such as the length of the hole chimney, the dimensions of the radiating apertures and the associated radiating impedance, the tone hole network, etc. This transfer function is also calculated for each instrument. This transfer function is also calculated from the geometry of the instrument using a simple wave propagation model.

This work was presented at the Vienna Talks 2020/22 held in Vienna (Austria) in September 2022. [39]

This comparison was complemented by the specific study of the effect of long stacks on the sound of these instruments. The bassoon has side holes a few tens of millimetres long, much longer than other wind instruments. When closed, the quarter-wave resonances of these "chimneys" create acoustic shorts in parallel with the bore. At these resonant frequencies, close to 2kHz, it is expected that the waves will not propagate beyond the so-called chimney, affecting both the input impedance and the radiated sound. Using parametric studies with varying stack lengths, these effects on impedance and radiated sound were measured for a French bassoon and a simplified conical 'model instrument'. The effects are clear on the model instrument, especially when several chimneys have the same length. For the bassoon, the passive filter effect remains, but its importance on the sound is faded due to changes in the oscillation regime and directivity, as confirmed by simulations. The effect is audible under laboratory conditions, but is of the same order of magnitude as the spatial level variations due to the directivity of the instrument. Therefore, it is unlikely that, under normal playing conditions, a chimney length increase of 5 mm, as observed between the German and French bassoon, would lead to a significant change in timbre.

This work is the subject of a presentation at the 2022 French Acoustical Congress [38] the German annual Conference on Acoustics [40] and an article under review in the Journal of the Acoustical Society of America [54].

8.4.2 Benchmark study on wind instrument models

Participants: Juliette Chabassier, Augustin Ernoult.

With the aim of updating the Pafi Instrumental Factoring Support Platform, we listed and compared existing tools for calculating the acoustic input impedance of wind instruments. A working group was set up, bringing together a dozen French research teams with expertise in modelling and resolution methods using transfer matrices, 1D finite elements, 3D finite elements, multimodal methods, waveguides, etc. This group defined a set of geometries for the calculation of impedance. This group has defined a set of standard resonator geometries involving different propagation conditions (cylinder, cone, elbow, side hole, etc.) or radiation (closed, with baffle, etc.). The input impedances of these tubes were calculated using the expertise of the working group members and then pooled on a collaborative platform. The resulting database can be used for comparative studies, model verification and comparison with an experimental database. Its analysis will make it possible to make an informed choice of methods and models to be implemented in an invoice support tool, taking into account their validity, versatility, complexity of implementation and the necessary computing resources. The analysis of a few cases has already brought to the fore consensus and cases for which further research is necessary.

In parallel to this benchmark on numerical models for their verification, an experimental campaign is underway to create an exhaustive reference database for model validation (the notions of verification and validation are based on ASME criteria), and the estimation of uncertainties associated with measurements. In particular, the random inter/intra measurement and inter/intra sample uncertainty is quantified. The experimental campaign is based on numerous batches of five specimens each. The experimental design allows for consolidated experimental results regarding taper, edge effects, boundary conditions and materials. The manufactured specimens have already been tested in two different laboratories with varying characterisation methods and should be extended to other institutions. The first results allow the establishment of a reproducible measurement protocol. This campaign gives first estimates of the variability of the measurements and allows to test different aspects of the experimental design.

This work was the subject of two presentations at the French Acoustics Congress in Marseille in April 2022. [37, 48]

8.4.3 Transmission line coefficients for viscothermal acoustics in conical tubes

Participants: Juliette Chabassier, Alexis Thibault.

Viscothermal acoustic propagation in gases contained in rigid straight or conical tubes is considered. Assuming that the wavelength is much larger than the boundary layer thickness and the tube radius, the pressure and flow rate are shown to be solutions of a pair of coupled 1D differential equations, formulated as transmission line equations involving complex loss coefficients. The derivation of these loss coefficients, which is usually performed in cylinders, is generalised here to conical geometries. In the well-known case of circular cylinders, the Zwikker–Kosten (ZK) theory is used. For circular cones, the expression for the loss coefficients is derived. It involves spherical harmonics of complex order, instead of Bessel functions for circular cylinders, and makes the hydraulic radius appear as a relevant natural geometrical parameter. We show that replacing the classical radius by the hydraulic radius in the ZK theory provides an affordable and accurate approximation to the derived analytical model for cones. The proposed formulae are used to calculate the input impedance of a cone, and compared to a 3D reference. In an ideal setting, the use of spherical harmonics or hydraulic radius in the 1D method accurately approximates the full 3D method, and increases the accuracy by about two orders of magnitude compared to the ZK theory.

This work has been published in a journal of acoustics: Alexis Thibault, Juliette Chabassier, Henri Boutin, Thomas Hélie. Transmission line coefficients for viscothermal acoustics in conical tubes. Journal of Sound and Vibration, Elsevier, 2022, 543, pp.117355. ⟨10.1016/j.jsv.2022.117355⟩. [17]

8.4.4 Modelling the influence of a porous wall on the acoustic propagation in a wind instrument

Participants: Juliette Chabassier, Alexis Thibault.

The inner wall of wind instruments can sometimes be porous or rough (wooden instruments, 3D prints); this condition modifies the acoustic properties of the instrument. We seek to model the coupling between an acoustic medium and a porous medium with a rigid skeleton, with the fluid satisfying the linearised Navier-Stokes equations in each domain. In the pores, or near the bore wall, air viscosity and thermal diffusion induce energy dissipation with a non-rational dependence on the complex frequency. A linear model of acoustic propagation in the porous medium is obtained from the theory of periodic homogenisation, which allows the formal separation of the microscopic and macroscopic scales. It is put in the form of It is put in the form of a Hamiltonian system with interaction ports, thus highlighting the structure of energy storage, exchange and dissipation within the model. A reduced model of the coupling between the porous wall and the 1D acoustic propagation in the bore of the instrument is proposed. A numerical scheme is established for the simulation in time of the 1D acoustic wave propagation taking into account the wall properties. This scheme verifies a discrete energy balance similar to that of the continuous model, and can be stably coupled to other subsystems (radiation, non-linear mouthpiece). Simulations of reed instruments with non-uniform porosity will be presented.

This work was presented at the CFA 2022 national conference: Alexis Thibault, Juliette Chabassier, Henri Boutin, Thomas Hélie. Modelling the influence of a porous wall on the acoustic propagation in a wind instrument. CFA 2022 - 16th French Congress of Acoustics, Apr 2022, Marseille, France. ⟨hal-03673860⟩

This work has been done in collaboration with Thomas Hélie and Henri Boutin (STMS, UMR9912, CNRS-SU-IRCAM).

8.4.5 Modelling the influence of a porous wall on the acoustic propagation in a wind instrument

Participants: Juliette Chabassier, Alexis Thibault.

Thermoviscous acoustic propagation in an isothermal corrugated rigid-walled tube is considered. At long wavelengths, it is equivalent to a 1D transmission line equation, in which the coefficients depend on the solution of a 2D scattering problem. It is shown that these coefficients exhibit predictable behaviour at low, high and intermediate frequencies. These results are demonstrated on a numerical example.

This work was presented at the international conference WAVES 2022: Henri Boutin, Juliette Chabassier, Thomas Hélie, Alexis Thibault. Thermoviscous acoustic propagation in thin rough tubes. WAVES 2022 - 15th International Conference on Mathematical and Numerical Aspects of Wave Propagation, Jul 2022, Palaiseau, France. ⟨hal-03780126⟩

This work has been done in collaboration with Thomas Hélie and Henri Boutin (STMS, UMR9912, CNRS-SU-IRCAM).

8.4.6 Influence of touch on the sound of the piano

Participants: Juliette Chabassier, Guillaume Castera.

What influence can the artist's touch have on the timbre of the piano? This question can be addressed through the modelling of piano sounds using the keystroke as the only input. In order to simulate sounds with the greatest precision from a real touch, physical models of each element of the instrument (hammer head and neck, string(s), soundboard, radiation in the air) have been developed and implemented in the Montjoie software of INRIA Bordeaux Sud Ouest. Limiting ourselves to modelling the vibro-acoustic part excludes the mechanics which allows the hammer to be set in motion by the artist pressing the key. It is therefore essential to provide the vibro-acoustic model with a fine representation of the forces exerted by the mechanics on the hammer as input data. In this case, our approach uses the force exerted by the escapement stick and by the repetition lever on the hammer handle, forces that are very complex to measure or estimate. A mechanics model implemented in the Robotran software at the Catholic University of Leuven in Belgium can calculate this force from any keystroke data. It is thus possible to analyse the repercussions of the subtleties brought in by the artist on the sound spectra, and to compare different simulations according to the type of touch used at the fingerboard, in particular the differences between legato and staccato or the dynamics between piano and forte.

This work was presented at the CFA 2022 national conference: Guillaume Castera, Timmerman Sébatien, Juliette Chabassier, Paul Fisette. Influence of touch on piano sound. French Congress of Acoustics, Apr 2022, Marseille, France. ⟨hal-03842214⟩

This work has been done in collaboration with Paul Fisette and Sébastien Timmermans, université catholique de Louvain, Belgium.

8.4.7 Control parameters for reed wind instruments or organ pipes including reed flow

Participant: Juliette Chabassier.

Sound synthesis of a pipe coupled to a reed requires fine tuning of the physical parameters of the underlying model. Although the geometry of the pipe is often well known, the parameters of the one-degree-of-freedom reed model are effective coefficients (mass, cross-section, etc.) and are difficult to evaluate. Studies of this coupled system have mainly focused on models without the reed-induced flow, and have presented two dimensionless parameters, which respectively describe the ratio between the supply pressure and the closing pressure of the reed, and a dimensionless opening of the reed at rest. The inclusion of the reed flow in the model and the subsequent scaling of the equations leads to a third dimensionless quantity, which we will call kappa. Varying the reed frequency with constant parameters over different pipe sizes shows some stability of the model when put into this form. Using a real-time sound synthesis tool, the parameter space is explored while the reed damping is also varied.

This work was presented at the international conference DAFx20in22: Chabassier, Juliette, and Auvray, Roman. Control parameters for reed wind instruments or organ pipes with reed induced flow. In DAFx 20in22 Sep 2022, Vienna, Austria

This work has been done in collaboration with Roman Auvray, Modartt, Toulouse, France.

8.4.8 Direct computation of modal parameters for wind instruments

Participant: Juliette Chabassier.

The parameters of the modal expressions for the input impedance of wind instruments can be calculated from the telegrapher's equations with radiating boundary conditions at the bell. One-dimensional finite elements are used for the spatial discretization. If the models can be put into a specified form, the modal parameters can be calculated directly by solving a generalized eigenvalue problem. Viscothermal effects can also be taken into account, as well as open or closed side holes. The modal deformations can be visualised along the instrument. The parameters of the modal expressions for the input admittance of flute-like instruments can also be calculated.

This work has been published in a journal of acoustics: Juliette Chabassier, Roman Auvray. Direct computation of modal parameters for musical wind instruments. Journal of Sound and Vibration, Elsevier, 2022, 528, pp.116775. ⟨10.1016/j.jsv.2022.116775⟩. ⟨hal-03613608⟩

This work has been done in collaboration with Roman Auvray, Modartt, Toulouse, France.

8.4.9 Understanding and predicting the acoustic properties of heritage instruments: the case of a Besson trumpet from the Musée de la Musique de Paris

Participants: Juliette Chabassier, Augustin Ernoult, Tobias van Baarsel.

Playing historical wind instruments is often in conflict with the conservation and protection of museum collections. Some of the musical and acoustic properties of these instruments are therefore unknown. Theoretical models can predict some of these properties from the knowledge of the geometry of the instruments alone. A collaboration between the Makutu Inria Bordeaux Sud Ouest team, the Musée de la Musique - Philharmonie de Paris, the Institut Technologique Européen des Métiers de la Musique (ITEMM) in Le Mans and the Centre de Recherche et de Restauration des Musées de France (C2RMF), led to a procedure applied to the collection of the Besson Museum, which was a large wind instrument factory, and more particularly to several natural trumpets dating from the beginning of the 20th century. The geometry of the instruments was measured non-invasively using X-ray tomography at the C2RMF. After extracting their bore (evolution of the inner diameter), their input impedance was calculated. For one specific trumpet (E.0925), the simulated data were compared with the measurements with excellent agreement. Despite many uncertainties about how these instruments were played, simulated sounds can be calculated. An 'acoustic facsimile' of E.0925 was made from the X-ray and impedance data and played by a professional natural trumpeter. This allows the simulated sounds to be compared with the sounds played by humans.

This work has been presented at several meetings and at the international conference Vienna Talk [25] and during the Congrès Français d'Acoustique 2022 [36].

This work has been done in collaboration with Clotilde Boust, Marguerite Jossic, Sebastian Kirsch, Elsa Lambert, Romain Viala.

9 Bilateral contracts and grants with industry

9.1 Bilateral contracts with industry

- Makutu research agreement.

  Period: January 2022 – December 2026; Amount: 350000 € per year.

- Tent Pitcher algorithm for space-time integration of wave problems

  Period: 2019 November - 2022 October, Management: INRIA Bordeaux Sud-Ouest, Amount: 165000 €.

- Numerical schemes assisted with Machine Learning for solving time-dependent seismic wave problems

  Period: 2021 November - 2024 October, Management: INRIA Bordeaux Sud-Ouest, Amount: 90000 euros.

- Petrophysics in pre-salt carbonate rocks

  Period: 2019 November - 2022 September, Management: INRIA Bordeaux Sud-Ouest, Amount: 110000 euros.

10 Partnerships and cooperations

10.1 International initiatives

10.1.1 Inria associate team not involved in an IIL or an international program

ANTS

Title: Advanced Numerical meThods for helioSeismology

Duration: 2019 -> 2022

Coordinators: Laurent Gizon (gizon@mps.mpg.de) and Ha Pham Howard Faucher (ha.howard@inria.fr)

Partners:

- Max Plank Institut at Göttingen (Allemagne)

Inria contact: Ha PhamHoward Faucher

Summary: Makutu has had an Associate Team project, Advanced Numerical meThods for helioSeismology (ANTS), with the Max Planck Institute for Solar System Research (MPS), led by Laurent Gizon, which ended by the end of 2022. The objective was to develop advanced software for accurate simulation of stellar oscillations and for the reconstruction of the Sun's interior. The novelty and challenge come from working with convected vector wave equations in the presence of complex flow and gravity, for a more accurate description of the physical phenomenon. The software hawen uses Hybridizable Discontinuous Galerkin (HDG) approximation. The scientific project benefited from the expertise of Makutu in seismic imaging, and the expert knowledge of the MPS group on Solar physics, in order to design accurate and efficient methodology. The project also helped strengthen the on-going collaboration between Makutu and MPS, that started five years ago. ANTS has been decisive to elevate the joint collaboration between Makutu and MPS. An ANR PRCI project is being submitted in 2023 to continue the collaboration. Two Ph.D. students from MPS will also visit Makutu in 2023 to improve their knowledge in applied mathematics.

10.1.2 Participation in other International Programs

SEE4GEO

Title: SeismoElectric Effects for GEOthermal resource assessment and monitoring

Duration: 2021 -> 2024

Coordinator: Christina Morency (morency1@llnl.gov) LLNL (Lawrence Livermore National Laboratory, US department of Energy)

Partners:

- University of Hawaii at Mänoa (USA);
- University of Pau and the Pays de l'Adour, UPPA (France);
- TLS Geothermics, TLS (France),
- NORCE (Norway)

Inria contact: Hélène Barucq

See also: SEE4GEO on Geothermica website.

Summary: Geothermal systems involve the injection of large amounts of fluid into the subsurface. Identifying fracture networks is of great importance to assess geothermal resources. Traditional seismic imaging techniques fail to resolve fluid-phase properties, while purely electromagnetic (EM) approaches provide limited, low-resolution constraints on the rock structure. Seismoelectric effects (SEE) arise from the seismic-to-electromagnetic conversion in naturally charged porous media with a certain degree of fluid saturation. With SEE, we leverage seismic and EM technique sensitivities. In this project, we offer an integrated SEE assessment for geothermal systems relying on numerical modelling, laboratory experiments and field surveys. Makutu is involved in the project as a joint team with UPPA (University of Pau and Pays de l'Adour).

10.2 International research visitors

10.2.1 Visits of international scientists

In the framework of the associate team ANTS, Makutu has welcomed a group of seven researchers from MPS from October 24 to October 28. They are listed in the section Team members, etc.

10.3 European initiatives

10.3.1 H2020 projects

MATHROCKS

Title: Multiscale Inversion of Porous Rock Physics using High-Performance Simulators: Bridging the Gap between Mathematics and Geophysics

Duration: April 2018 - March 2023

Coordinator: Universidad Del Pais Vasco (EHU UPV)

Partners:

- BARCELONA SUPERCOMPUTING CENTER - CENTRO NACIONAL DE SUPERCOMPUTACION (Spain)
- BCAM - BASQUE CENTER FOR APPLIED MATHEMATICS (Spain)
- CURTIN UNIVERSITY OF TECHNOLOGY (Australia)
- PONTIFICIA UNIVERSIDAD CATOLICA DE CHILE (Chile)
- REPSOL SA (Spain)
- UNIVERSIDAD CENTRAL DE VENEZUELA (Venezuela)
- UNIVERSIDAD DE BUENOS AIRES (Argentina)
- UNIVERSIDAD DEL PAIS VASCO/ EUSKAL HERRIKO UNIBERTSITATEA (Spain)
- UNIVERSIDAD NACIONAL DE COLOMBIA (Colombia)
- UNIVERSITAT POLITECNICA DE CATALUNYA (Spain)

Inria contact: Hélène BARUCQ

Summary: We will develop and exchange knowledge on applied mathematics, high-performance computing (HPC), and geophysics to better characterize the Earth´s subsurface. We aim to better understand porous rocks physics in the context of elasto-acoustic wave propagation phenomena. We will develop parallel high-continuity isogeometric analysis (IGA) simulators for geophysics. We will design and implement fast and robust parallel solvers for linear equations to model multi-physics electromagnetic and elasto-acoustic phenomena. We seek to develop a parallel joint inversion workflow for electromagnetic and seismic geophysical measurements. To verify and validate these tools and methods, we will apply the results to: characterise hydrocarbon reservoirs, determine optimal locations for geothermal energy production, analyze earthquake propagation, and jointly invert deep-azimuthal resistivity and elasto-acoustic borehole measurements. Our target computer architectures for the simulation and inversion software infrastructure consists of distributed-memory parallel machines that incorporate the latest Intel Xeon Phi processors. Thus, we will build a hybrid OpenMP and MPI software framework. We will widely disseminate our collaborative research results through publications, workshops, postgraduate courses to train new researchers, a dedicated webpage with regular updates, and visits to companies working in the area. Therefore, we will perform a significant role in technology transfer between the most advanced numerical methods and mathematics, the latest super-computer architectures, and the area of applied geophysics.

10.3.2 Other european programs/initiatives

PiXiL

Title: Multiscale Inversion of Porous Rock Physics using High-Performance Simulators: Bridging the Gap between Mathematics and Geophysics

Duration: September 2019 - April 2022

Coordinator: BARCELONA SUPERCOMPUTING CENTER - CENTRO NACIONAL DE SUPERCOMPUTACION (Spain)

Partners:

- BARCELONA SUPERCOMPUTING CENTER - CENTRO NACIONAL DE SUPERCOMPUTACION (Spain)
- BCAM - BASQUE CENTER FOR APPLIED MATHEMATICS (Spain)
- UNIVERSIDAD DEL PAIS VASCO/ EUSKAL HERRIKO UNIBERTSITATEA (Spain)
- UNIVERSITAT de BARCELONA (Spain)
- REALTIMESEISMIC (RTS)
- PÔLE AVENIA

Inria contact: Julien DIAZ

Summary: Part of the FEDER Poctefa Program the PIXIL project is a transnational and multidisciplinary scientific and technological cooperation. Its main goal is to develop the most advanced tools to analyze the Earth's subsurface, with a special focus on fostering the uptake of geothermal energy in the region. The project will contribute to making the trans-Pyrenean area a technology hub in subsoil characterization within two years. Its success is expected to boost the wealth and creation of jobs related to the generation and management of underground natural resources in the area.

See also: PiXiL website

10.4 National initiatives

10.4.1 Depth Imaging Partnership (DIP)

The research agreement DIP between TotalEnergies and Inria lasts since 2009. It focuses on the development of high-performance numerical methods for solving wave equations in complex media with the objective of characterizing geological reservoirs. It is fully funded by TotalEnergies. It came to its end in December with the Ph.D. defense of V. Vasanthan. This agreement has served as a guideline for 15 years of joint research with TotalEnergies. A dozen PhDs in applied mathematics have been trained, more than half of whom are now employed by TotalEnergies, the others holding jobs in public or private research.

10.5 Regional initiatives

10.5.1 Regional Council of Nouvelle Aquitaine Grants

Revival

Title: Revival

Duration: 2019-2024

Coordinator: Inria

Partners: University of Bordeaux, University of Montreal (Canada), Catholic University of Louvain (Belgium)

Inria contact: Juliette CHABASSIER

Summary: The objective is to develop numerical tools for the virtual restoration of heritage instruments.

Amount: 107 k€; half doctoral position of Guillaume Castera, half post-doctoral position (to be attributed)

10.5.2 Regional Council of Normandie Grants

Title: Modeling and numerical simulation of electromagnetic wave propagation in offshore conductor cables: applications to the environmental impact on the marine ecosystem.

Duration: 2021-2024

Coordinator: LMI Insa Rouen

Inria contact: Hélène Barucq

Summary: The objective is to develop a numerical library for simulating the radiation pattern of offshore conductor cables to assess their impact on the marine ecosystem.

Amount: 150 k€; doctoral position of Augustin Leclerc

11 Dissemination

11.1 Promoting scientific activities

11.1.1 Scientific events: organisation

- As part of the INRIA associate-team ANTS Makutu organized a one-week workshop on computational helioseismology at the University of Pau with the Max Planck institute for Solar System Research. It was held from October 24th to 28th.
- Hélène Barucq co-organized a mini-symposium (MS153) at ECCOMAS 2022 in OSLO, entitled Robust and Scalable Numerical Methods for Wave Propagation: Design, Analysis and Application, with Théophile Chaumont-Frelet (Atlantis, Inria), Rabia Djellouli (CSUN, USA) and Axel Modave (Poems, CNRS).

Reviewer

Augustin Ernoult has selected papers for a special session in musical acoustics during Congrès Français d'Acoustique 2022.

11.1.2 Journal

Member of the editorial boards

Hélène Barucq is member of the editorial board of Mathematics and Computers in Simulation (Imacs Journal MATCOM).

Reviewer - reviewing activities

Members of Makutu are regular reviewers for the following journals:

- Geophysical Journal International
- International Journal for Numerical Methods in Engineering
- Journal of Computational Physics
- Mathematics of Computation
- Journal of Acoustical Society of America
- Journal of Sound and Vibration
- Inverse problems
- Geophysics
- SIAM Journal of Scientific Computing
- Journal of Mathematical Imaging and Vision
- Numerical Functional Analysis and Optimization

11.1.3 Leadership within the scientific community

- Augustin Ernoult is elected member of the "Groupe spécialisé d'acoustique musicale" (Gsam) of the french acoustical society.
- Hélène Barucq has been in charge of a mission for the Hcéres (High Council for the evaluation of research and higher education) consisting to participate in the writing of the Synthèse Nationale des Mathématiques (SNM,) report which was presented in a press conference on 9/11/2022.
- Hélène Barucq co-leads the ExaMa project (Methods and Algorithms for Exascale) with Christophe Prud'homme (University of Strasbourg, UNISTRA) which is one of the five targeted projects of the PEPR (Priority Research Programs and Equipment) Numpex funded by the French National Research Agency (ANR).

11.1.4 Scientific expertise

- Hélène Barucq acts as a scientific expert for the FWO (Research Foundation - Flanders
- Hélène Barucq is member of the steering committee of CATIE
- Hélène Barucq has been awarded as an Expert for the European Science Foundation (ESF) for the period 2022-2024.
- Hélène Barucq is the Chair of the Thematic Committee CT6, "Computer Science, Algorithms and Mathematics" at GENCI.
- Hélène Barucq co-leads the ExaMA project (Methods and Algorithms for the Exascale) within the framework of the NumPEX PEPR, which will be launched in January 2023.

11.1.5 Research administration

- Augustin Ernoult is member of the Center Commitee of Inria Bordeaux Sud-Ouest.
- Hélène Barucq is appointed member of the scientific board of the LMA2S (Laboratory of Mathematics Applied to Aeronautics and Space) created to federate the activities in Applied Mathematics which are carried out in seven departments of the ONERA.
- Juliette Chabassier is member of the Research Position Commission of Inria Bordeaux Sud-Ouest.
- Julien Besset is elected member of Laboratory Commitee of LMAP.
- Julien Diaz is elected member of the Inria Technical Committee and of the Inria Administrative Board. He is appointed member of the Bureau du Comité des Projets (BCP) of Inria Bordeaux Sud-Ouest. Since 2018, he has been the head of the Mescal team of LMAP.

11.2 Teaching - Supervision - Juries

11.2.1 Teaching

- Master : Sébastien Tordeux, Outils Mathématiques pour la Mécanique, 49 eq. TD, Master1, UPPA, France
- Master : Margot Sirdey and Sébastien Tordeux, Introduction to wave phenomena, 48 eq. TD, Master, UPPA, France
- Licence : Sébastien Tordeux, Applied Mathematics, 63 eq. TD, L1, UPPA, France
- Licence : Ibrahima Djiba, Mathématiques appliquées pour les sciences économiques, 12h Eq. TD, L2, UPPA, France
- Licence : Julien Besset, Calcul numérique, 12h Eq. TD, L2, UPPA, France
- Licence : Arjeta Heta, Algèbre linéaire, 12h Eq. TD, L2, UPPA, France
- Licence : Arjeta Heta, Introduction aux probabilités, 20h Eq. TD, L2, UPPA, France
- Master : Marine Deheuvels, Signal Processing, UPPA, Pau, France, 18 eq. TD.
- Master : Florian Faucher, Inversion/Optimization, UPPA, Pau, France, 6 eq. TD.

11.2.2 Supervision

- PhD defended: Victor Martins Gomez, Experimental characterization and modeling of seismo-electromagnetic waves, Université de Pau et des Pays de l'Adour, December 5th, Hélène Barucq and Daniel Brito (LFCR).
- PhD defended: Vinduja Vasanthan, Trefftz-DG Methods and Tent-Pitcher Algorithm for Spacetime Integration of Wave Problems, December 8th, Hélène Barucq and Julien Diaz.
- PhD defended: Margot Sirdey, Méthode de Trefftz pour l'électromagnétisme, December 19th, Sébastien Tordeux and Sébastien Pernet (Onera).
- PhD in progress : Alexis Thibault, Modeling and simulation of wind musical instruments, October 2020, Juliette Chabassier and Thomas Hélie (IRCAM).
- PhD in progress : Guillaume Castera, Modeling and simulation of the piano touch, October 2020, Juliette Chabassier and Paul Fisette (Louvain Cath. Univ., Belgium)
- PhD in progress: Nicolas Victorion, Numerical schemes assisted with Machine Learning for solving time-dependent seismic wave problems, October 2021, Hélène Barucq, Florian Faucher and Emmanuel Franck (Inria Nancy Grand-Est, Tonus)

- PhD in progress: Arjeta Heta, Advanced numerical schemes to model seismoelectric effects and improve characterization of geological reservoirs, September 2021, Hélène Barucq and Julien Diaz.
- PhD in progress: Ibrahima Djiba, Trefftz domain decomposition method for wave propagation in geophysics, October 2021, Hélène Barucq et Sébastien Tordeux
- PhD in progress: Augustin Leclerc, Modeling and numerical simulation of electromagnetic wave propagation in offshore cables: applications to the environmental impact on the marine ecosystem, October 2021, Hélène Barucq, Christian Gout (LMI Insa de Rouen) and Antoine Tonnoir (LMI Insa de Rouen)
- PhD in progress: Marine Deheuvels, from quantitative analysis of wave amplitudes to full waveform inversion, October 2020, Daniel Brito (UPPA) et Florian Faucher
- PhD in progress : Julien Besset, Development of an optimized computing environment integrating seismic in CO2 storage and monitoring, January 2022, Hélène Barucq et Henri Calandra
- PhD in progress: Matthias Rivet, Optimization of numerical fluxes in Trefftz domain decomposition for electromagnetism: regular approach or artificial intelligence? October 2022, Sébastien Pernet (Onera) and Sébastien Tordeux
- PhD in progress: Lola Chabat, Large-scale spectral problems using hybridizable Galerkin discretization with application to helioseismology, October 2022, Ha Pham and Hélène Barucq

11.2.3 Juries

Hélène Barucq has been member of the HDR defense committee of:

- Paul Cupillard, Numerical simulation of the propagation of seismic waves in complex geological media, defended on March 22, University of Lorraine

Hélène Barucq has been referee for the Ph.D. dissertation of:

- David GASPERINI, entitled "A multi-harmonic finite element method for the micro-Doppler effect, with an application to automotive radar sensing" delivered by the Universities of Lorraine and Liège (Belgium), defended the 31st of March in Nancy;
- Maria EL GHAOUI, entitled "Méthodes de Trefftz avec reconstruction de la dérivée normale appliquée aux équations elliptiques", delivered by Paris-Sorbonne universités and Saint Joseph University, Lebanon, Beirut (USJ), defended the 16th of May.

Hélène Barucq has been member of the Ph.D. defense committee of

- Aimen Ben Hadj Hassine, dissertation entitled "Inversion of the reflection waveform with unidirectional propagation", delivered by the University of Pau and Pays de l'Adour, defended in December 8th in Pau;
- Margot Sirdey, dissertation entitled "Trefftz iterative method for the simulation of electromagnetic waves in dimension three", delivered by the University of Pau and Pays de l'Adour, defended in December 19th in Pau.
- Patryk DEC, dissertation entitled "Time domain simulations for railways problems with non-periodic geometry and properties", Université Aix-Marseille, defended the 4th of July

Juliette Chabassier has been member of the Ph.D. defence committee of:

- Akram BENI HAMAD, entitled "Modélisation et simulation numérique de la propagation d'ondes électromagnetiques dans les câbles coaxiaux." delivered by the Institut Polytechnique de Paris and by the University Of Sousse (Tunisia), defended the 30th of September in Paris;

Julien Diaz has been referee for the Ph.D. dissertation of:

- Akram BENI HAMAD, entitled "Modélisation et simulation numérique de la propagation d'ondes électromagnetiques dans les câbles coaxiaux." delivered by the Institut Polytechnique de Paris and by the University Of Sousse (Tunisia), defended the 30th of September in Paris;

Julien Diaz has been member of the Ph.D. defense committee of

- Javier ABREU-TORRES, dissertation entitled "Imagerie de milieux salifères aux échelles crustales et expérimentales par méthodes de migration sismique et méthode de l'adjoint: applications marines", delivered by the University of Toulouse, defended the 15th of June in Toulouse;
- Ilyes MOUFID, dissertation entitled "Étude théorique et modélisation numérique du comportement acoustique des milieux poreux rigides en régime temporel" delivered by the University of Toulouse, defended the 6th of December in Toulouse;

11.2.4 Academic recruitment committees

Hélène Barucq has been member of the recruitment committees in:

- Nice University, professor position
- Montpellier University, professor position
- Pau and Pays de l'Adour University, professor position
- INSA de Rouen, professor position
- Antilles University, assistant professor position

11.3 Popularization

11.3.1 Education

Hélène Barucq has been member of the discussion panel during the EYIC Career Forum at ECCOMAS 2022, 100 attendees, see here for more information.

11.3.2 Interventions

- Augustin Ernoult made a presentation for the "unithé ou café", an internal seminar at Inria for all the staff, 08/06/2022
- Augustin Ernoult made a large audience presentation together with a public rehearsal of the music ensemble Proxima Centauri, December 6th 2022 in Talence
- Hélène Barucq and Stefano Frambati have participated to the Roundtable "Energie : enjeux et défis futurs" at the Forum Emploi Maths 2022, presenting the role and importance of mathematics in the energy industry to math students.

12 Scientific production

12.1 Major publications

[1] H. Barucq, A. Bendali, J. Diaz and S. Tordeux. 'Local strategies for improving the conditioning of the plane-wave Ultra-Weak Variational Formulation'. In: *Journal of Computational Physics* 441 (15th Sept. 2021), p. 110449. DOI: 10.1016/j.jcp.2021.110449. URL: https://hal.inria.fr/hal-03235684.

[2] H. Barucq, H. Calandra, J. Diaz and S. Frambati. 'Polynomial-reproducing spline spaces from fine zonotopal tilings'. In: *Journal of Computational and Applied Mathematics* 402 (Mar. 2022), p. 113812. DOI: 10.1016/j.cam.2021.113812. URL: https://hal.archives-ouvertes.fr/hal-03505795.

[3] H. Barucq, J. Diaz, R.-C. Meyer and H. Pham. 'Implementation of Hybridizable Discontinuous Galerkin method for time-harmonic anisotropic poroelasticity in two dimensions.' In: *International Journal for Numerical Methods in Engineering* (2021). URL: https://hal.inria.fr/hal-03464413.

[4] H. Barucq, F. Faucher, D. Fournier, L. Gizon and H. Pham. 'Outgoing modal solutions for Galbrun's equation in helioseismology'. In: *Journal of Differential Equations* 286 (June 2021), pp. 494–530. DOI: 10.1016/j.jde.2021.03.031. URL: https://hal.archives-ouvertes.fr/hal-03406864.

[5] J. Chabassier and S. Imperiale. 'Construction and convergence analysis of conservative second order local time discretisation for linear wave equations'. In: *ESAIM: Mathematical Modelling and Numerical Analysis* 55.4 (July 2021), pp. 1507–1543. DOI: 10.1051/m2an/2021030. URL: https://hal.archives-ouvertes.fr/hal-03309010.

[6] A. Ernoult, J. Chabassier, S. Rodriguez and A. Humeau. 'Full waveform inversion for bore reconstruction of woodwind-like instruments'. In: *Acta Acustica* (Nov. 2021). DOI: 10.1051/aacus/2021038. URL: https://hal.inria.fr/hal-03231946.

[7] S. Frambati. 'Unstructured Isogeometric Analysis with Applications to Seismic Wave Propagation'. Université de Pau et des Pays de l'Adour, 13th Dec. 2021. URL: https://theses.hal.science/tel-03521487.

[8] S. Frambati, H. Barucq, H. Calandra and J. Diaz. 'Practical unstructured splines: Algorithms, multipatch spline spaces, and some applications to numerical analysis'. In: *Journal of Computational Physics* 471 (15th Dec. 2022), p. 111625. DOI: 10.1016/j.jcp.2022.111625. URL: https://hal.science/hal-03788980.

[9] P. Lalanne, T. Wu, D. Arrivault, M. Duruflé, A. Gras, F. Binkowski, S. Burger and W. Yan. 'Efficient hybrid method for the modal analysis of optical microcavities and nanoresonators'. In: *Journal of the Optical Society of America. A Optics, Image Science, and Vision* 38.8 (26th July 2021), p. 1224. DOI: 10.1364/JOSAA.428224. URL: https://hal.archives-ouvertes.fr/hal-03358012.

[10] A. Thibault and J. Chabassier. 'Dissipative time-domain one-dimensional model for viscothermal acoustic propagation in wind instruments.' In: *Journal of the Acoustical Society of America* 150.2 (Aug. 2021), pp. 1165–1175. DOI: 10.1121/10.0005537. URL: https://hal.archives-ouvertes.fr/hal-03328715.

12.2 Publications of the year

International journals

[11] H. Barucq, H. Calandra, J. Diaz and S. Frambati. 'Polynomial-reproducing spline spaces from fine zonotopal tilings'. In: *Journal of Computational and Applied Mathematics* 402 (Mar. 2022), p. 113812. DOI: 10.1016/j.cam.2021.113812. URL: https://hal.science/hal-03505795.

[12] H. Barucq, N. Rouxelin and S. Tordeux. 'Low-order Prandtl-Glauert-Lorentz based Absorbing Boundary Conditions for solving the convected Helmholtz equation with Discontinuous Galerkin methods'. In: *Journal of Computational Physics* 468 (1st Nov. 2022). DOI: 10.1016/j.jcp.2022.111450. URL: https://hal.inria.fr/hal-03288930.

[13] F. Faucher and O. Scherzer. 'Quantitative inverse problem in visco-acoustic media under attenuation model uncertainty'. In: *Journal of Computational Physics* 472 (Jan. 2023), p. 111685. DOI: 10.1016/j.jcp.2022.111685. URL: https://hal.archives-ouvertes.fr/hal-03871831.

[14] S. Frambati, H. Barucq, H. Calandra and J. Diaz. 'Practical unstructured splines: Algorithms, multipatch spline spaces, and some applications to numerical analysis'. In: *Journal of Computational Physics* 471 (15th Dec. 2022), p. 111625. DOI: 10.1016/j.jcp.2022.111625. URL: https://hal.science/hal-03788980.

[15] D. Gregor, P. Moczo, J. Kristek, A. Mesgouez, G. Lefeuve-Mesgouez, C. Morency, J. Diaz and M. Kristekova. 'Seismic waves in medium with poroelastic/elastic interfaces: a two-dimensional P-SV finite-difference modelling'. In: *Geophysical Journal International* 228.1 (24th Jan. 2022), pp. 551–588. DOI: 10.1093/gji/ggab357. URL: https://hal.inrae.fr/hal-03471065.

[16] C. D. Shen, D. Brito, J. Diaz, F. Sanjuan, C. Bordes and S. Garambois. 'Pulsed-laser source characterization in laboratory seismic experiments'. In: *Geomechanics and Geophysics for Geo-Energy and Geo-Resources* 8.1 (Feb. 2022). DOI: 10.1007/s40948-021-00315-9. URL: https://hal.science/hal-03494134.

[17] A. Thibault, J. Chabassier, H. Boutin and T. Hélie. 'Transmission line coefficients for viscothermal acoustics in conical tubes'. In: *Journal of Sound and Vibration* 543 (21st Oct. 2022), p. 117355. DOI: 10.1016/j.jsv.2022.117355. URL: https://hal.archives-ouvertes.fr/hal-03794474.

[18] D. Yang, L. Gizon and H. Barucq. 'Imaging individual active regions on the Sun's far side with improved helioseismic holography'. In: *Astronomy and Astrophysics - A&A* (2023). DOI: 10.1051/0004-6361/202244923. URL: https://hal.inria.fr/hal-03921130.

International peer-reviewed conferences

[19] H. Barucq, H. Calandra, J. Diaz and V. Vasanthan. 'On the construction of Shape Functions forSpacetime Trefftz-DG Formulations of Wave Problems with Perfectly Matched Layers'. In: Waves 2022 - 15th International Conference on Mathematical and Numerical Aspects of Wave Propagation. Palaiseau, France, 25th July 2022. URL: https://hal.inria.fr/hal-03883655.

[20] H. Barucq, H. Calandra, J. Diaz and V. Vasanthan. 'Spacetime Trefftz-DG Formulation for Modelling Wave Propagation in Unbounded Domains'. In: ECCOMAS - The 8th European Congress on Computational Methods in Applied Sciences and Engineering. Oslo, Norway, 5th June 2022. URL: https://hal.inria.fr/hal-03883662.

[21] H. Boutin, J. Chabassier, T. Hélie and A. Thibault. 'Thermoviscous acoustic propagation in thin rough tubes'. In: WAVES 2022 - 15th International Conference on Mathematical and Numerical Aspects of Wave Propagation. Palaiseau, France, 25th July 2022. URL: https://hal.archives-ouvertes.fr/hal-03780126.

[22] A. Leclerc, A. Tonnoir, H. Barucq, M. Durufle and C. Gout. 'Modal computation for openwaveguides'. In: WAVES 2022 - 15th International Conference on Mathematical and Numerical Aspects of Wave Propagation. Palaiseau, France, 25th July 2022. URL: https://hal.inria.fr/hal-03883658.

[23] N. Rouxelin, H. Barucq and S. Tordeux. 'Low-order Absorbing Boundary Conditions in HDGdiscretization of the convected Helmholtz equation'. In: Waves 2022 15th International Conference on Mathematical and Numerical Aspects of Wave Propagation, Jul 2022, Palaiseau, France. Palaiseau, France, 25th July 2022. URL: https://hal.inria.fr/hal-03883653.

Conferences without proceedings

[24] P. Amestoy, A. Buttari, F. Faucher, J.-Y. L'Excellent, M. Gerest and T. Mary. 'Mixed precision sparse direct solver applied to 3D wave propagation'. In: 8th European Congress on Computational Methods in Applied Sciences and Engineering (ECCOMAS 2022). Oslo, Norway, 5th June 2022. URL: https://hal.science/hal-03887660.

[25] T. van Baarsel, C. Boust, J. Chabassier, A. Ernoult, M. Jossic, S. Kirsch, E. Lambert and R. Viala. 'Understand and predict acoustic properties of heritage instruments: the case of a Besson trumpet of the Musée de la Musique of Paris'. In: VIENNATALK2020: FOURTH VIENNA TALK ON MUSIC ACOUSTICS. Vienna, Austria, 11th Sept. 2022. URL: https://hal.inria.fr/hal-03842072.

[26] H. Barucq, J. Besset, H. Calandra and S. Frambati. 'Design for optimized Full Waveform Inversion forseismic in GEOSX: challenges and current trends'. In: Mathias Days. Marne La Vallée, France, 3rd Oct. 2022. URL: https://hal.inria.fr/hal-03948011.

[27] H. Barucq, H. Calandra, J. Diaz and S. Frambati. 'Frequency-domain acoustic wave modeling via unstructured isogeometric analysis: performance and pollution study'. In: ECCOMAS Congress 2022. Oslo, Norway, 5th June 2022. URL: https://hal.archives-ouvertes.fr/hal-03788967.

[28] H. Barucq, H. Calandra, F. Faucher and N. Victorion. 'Optimized Finite Differences methods and Machine Learning to reduce numerical dispersion for the wave equation'. In: Mathias Days 2022. Marne-la -Vallée, France, 3rd Oct. 2022. URL: https://hal.inria.fr/hal-03947815.

[29] H. Barucq, F. Faucher, D. Fournier, L. Gizon and H. Pham. 'Atmospheric radiation boundary conditions for the wave equation in helioseismology'. In: The 8th European Congress on Computational Methods in Applied Sciences and Engineering ECCOMAS Congress 2022. Oslo, Norway, 5th June 2022. URL: https://hal.science/hal-03888472.

[30] H. Barucq, F. Faucher, D. Fournier, L. Gizon and H. Pham. 'Efficient computation of modal outgoing Green's kernels in helioseismology'. In: The 8th European Congress on Computational Methods in Applied Sciences and Engineering ECCOMAS Congress 2022. Oslo, Norway, 5th June 2022. URL: https://hal.archives-ouvertes.fr/hal-03888476.

[31] H. Barucq, F. Faucher and H. Pham. 'Elastic Full Waveform Inversion in the frequency domain with a face-based finiteelement method'. In: Mathias Days 2022. Marne-la -Vallée, France, 3rd Oct. 2022. URL: https://hal.inria.fr/hal-03944440.

[32] G. Castera and J. Chabassier. 'Linearly implicit energy consistent time discretisation for nonlinear wave equations'. In: WAVES 2022 - 15th International Conference on Mathematical and Numerical Aspects of Wave Propagation. Palaiseau, France, 25th July 2022. URL: https://hal.archives-ouvertes.fr/hal-03757200.

[33] G. Castera, T. Sébatien, J. Chabassier and P. Fisette. 'Influence du toucher sur le son du piano'. In: Congrès français d'acoustique. Marseille, France, Apr. 2022. URL: https://hal.inria.fr/hal-03842214.

[34] J. Chabassier, A. Ernoult, O. Geber, A. Thibault and T. van Baarsel. 'OpenWind : une toolbox python au service de la recherche en acoustique musicale'. In: 16ème Congrès Français d'Acoustique, CFA2022. Marseille, France, 11th Apr. 2022. URL: https://hal.science/hal-03848533.

[35] M. Deheuvels, F. Faucher and D. Brito. 'Quantitative Analysis of Seismic Waves Attenuation: Numerical Analysis and Laboratory-Scale Experiments'. In: EGU22. Vienna, Austria, 23rd May 2022. URL: https://hal.archives-ouvertes.fr/hal-03881286.

[36] A. Ernoult, T. van Baarsel, C. Boust, J. Chabassier, M. Jossic, S. Kirsch, E. Lambert and R. Viala. 'Prédire les propriétés acoustiques des instruments du patrimoines: le cas d'une trompette Besson du Musée de la musique: [Prix Yves Rocard 2019]'. In: 16ème Congrès Français d'Acoustique, CFA2022. Marseille, France, 11th Apr. 2022. URL: https://hal.archives-ouvertes.fr/hal-03848341.

[37] A. Ernoult, H. Boutin, J. Cabaret, J. Chabassier, T. Colinot, J.-P. Dalmont, J.-B. Doc, B. Fabre, S. Félix, V. Fréour, M. Pachebat, F. Silva and R. Viala. 'Étude comparative collaborative des modèles pour le calcul d'impédance d'instruments à vent'. In: 16ème Congrès Français d'Acoustique, CFA2022. Marseille, France, 11th Apr. 2022. URL: https://hal.archives-ouvertes.fr/hal-03848338.

[38] A. Ernoult and T. Grothe. 'Étude expérimentale de l'effet des longues cheminées sur le son des instruments à vent: [Prix Yves Rocard 2019]'. In: 16ème Congrès Français d'Acoustique, CFA2022. Marseille, France, 11th Apr. 2022. URL: https://hal.archives-ouvertes.fr/hal-03847818.

[39] A. Ernoult and T. Grothe. 'Spectrum difference between the German Fagott and the French Basson'. In: Vienna Talk 2020/22. Vienne, Austria, 11th Sept. 2022. URL: https://hal.inria.fr/hal-03807886.

[40] T. Grothe and A. Ernoult. 'How does a closed long chimney affect the sound of conical reed wind instruments?' In: *48th Annual Conference on Acoustics (DAGA)*, DAGA 2022 - 48th German Annual Conference on Acoustics. Stuttgart / Online, Germany, 21st Mar. 2022. URL: https://hal.archives-ouvertes.fr/hal-03789400.

[41] V. Martins Gomes, D. Brito, S. Garambois, C. Bordes and H. Barucq. 'Quantitative comparison of seismoelectric laboratory data with numerical modelling based on electrokinetic theory'. In: EGU General Assembly 2022. Vienna, Austria, 23rd May 2022. URL: https://hal.inria.fr/hal-03927324.

[42] S. Pernet, M. Sirdey and S. Tordeux. 'Iterative Trefftz method for three-dimensional electromagnetic waves propagation'. In: WAVES. Palaiseau (FR), France, 25th July 2022. URL: https://hal.science/hal-03945383.

[43] S. Pernet, M. Sirdey and S. Tordeux. 'Trefftz iterative method for three-dimensional electromagnetic waves propagation'. In: ECCOMAS. Oslo (Norway), France, 5th June 2022. URL: https://hal.science/hal-03945416.

[44] S. Pernet, M. Sirdey and S. Tordeux. 'Trefftz iterative method for three-dimensional electromagnetic waves propagation'. In: JCJC. Sophia Antipolis, France, 2022. URL: https://hal.science/hal-03945447.

[45] N. Rouxelin, H. Barucq and S. Tordeux. 'A HDG Framework For Convected Wave Equations. Applications In Heliosesimology.' In: Computational Methods in Applied Mathematics. Vienna, Austria, 29th Aug. 2022. URL: https://hal.inria.fr/hal-03927545.

[46] N. Rouxelin, H. Barucq and S. Tordeux. 'Conditions aux Limites Absorbantes d'ordre faible pour l'équation de Helmholtz convectée'. In: 45ème Congrès d'Analyse Numérique. Évian-les-bains, France, 13th June 2022. URL: https://hal.inria.fr/hal-03927568.

[47] A. Thibault, J. Chabassier, H. Boutin and T. Hélie. 'Modélisation de l'influence d'une paroi poreuse sur la propagation acoustique dans un instrument à vent'. In: CFA 2022 - 16ème Congrès Français d'Acoustique. Marseille, France, 11th Apr. 2022. URL: https://hal.archives-ouvertes.fr/hal-03673860.

[48] R. Viala, H. Boutin, J. Cabaret, T. Colinot, J.-P. Dalmont, J.-B. Doc, A. Ernoult, B. Fabre, V. Fréour, M. Pachebat and F. Silva. 'Mise en place d'une base de données expérimentales, pour la validation de modèles de résonateurs et la comparaison de géométries et matériaux'. In: 16ème Congrès Français d'Acoustique, CFA2022. Marseille, France, 11th Apr. 2022. URL: https://hal.archives-ouvertes.fr/hal-03848339.

Scientific book chapters

[49] F. Faucher, C. Kirisits, M. Quellmalz, O. Scherzer and E. Setterqvist. 'Diffraction Tomography, Fourier Reconstruction, and Full Waveform Inversion'. In: *Handbook of Mathematical Models and Algorithms in Computer Vision and Imaging*. Springer International Publishing, 5th Apr. 2022, pp. 1–40. DOI: 10.1007/978-3-030-03009-4_115-1. URL: https://hal.archives-ouvertes.fr/hal-03877239.

Doctoral dissertations and habilitation theses

[50] V. Gomes-Martins. 'Caractérisation Expérimentale et modélisation numérique des ondes électromagnétiques générées par conversion sismo-électrique aux interfaces dans les milieux poreux.' Université de Pau et des Pays l'Adour, Dec. 2022.

[51] M. Sirdey. 'Méthode de type Trefftz pour la simulation d'ondes électromagnétiques à haute fréquence.' Université de Pau et des Pays l'Adour, Dec. 2022.

[52] V. Vasanthan. 'Trefftz-DG Methods and Tent-Pitcher Algorithm for Spacetime Integration of Wave Problems'. Université de Pau et des Pays l'Adour, Dec. 2022.

Reports & preprints

[53] J. A. L. Benitez, T. Furuya, F. Faucher, X. Tricoche and M. V. de Hoop. *Fine-tuning Neural-Operator architectures for training and generalization.* 26th Jan. 2023. URL: https://hal.science/hal-03963324.

[54] A. Ernoult and T. Grothe. *Experimental study of the effect of the long chimney of a closed tonehole on the sound of a bassoon.* 12th Dec. 2022. URL: https://hal.archives-ouvertes.fr/hal-03789436.

[55] S. Pernet, M. Sirdey and S. Tordeux. *Ultra-weak variational formulation for heterogeneous maxwell problem in the context of high performance computing*. 14th Apr. 2022. URL: https://hal.science/hal-03642116.

[56] D. Yang, L. Gizon and H. Barucq. *Imaging individual active regions on the Sun's far side with improved helioseismic holography*. 6th Dec. 2022. URL: https://hal.archives-ouvertes.fr/hal-03886961.

Other scientific publications

[57] M. Deheuvels, F. Faucher and D. Brito. 'Attenuation Measurements using Ultrasonic Seismic Waves Propagation: Numerical and Laboratory-Scale Experiments'. In: AGU22. Chicago, United States, 12th Dec. 2022. URL: https://hal.science/hal-03935780.

[58] A. Heta, H. Barucq, J. Diaz and C. Morency. 'Approximate Coupling Terms In Seismoelectric Theory: From Frequency Domain To Time Domain'. In: AGU22 - AGU Fall Meeting 2022. Chicago (Illinois), US, United States, 12th Dec. 2022. URL: https://hal.inria.fr/hal-03948879.

[59] M. Regaieg, C. Varloteaux, T. Farhana Faisal and Z. Elabid. *Towards large scale DRP simulations: generation oflarge super-resolution images and extraction oflarge pore network models*. 29th Sept. 2022. URL: https://hal.inria.fr/hal-03891895.

12.3 Other

Scientific popularization

[60] J. Chabassier. *Modélisation et simulation numérique d'instruments de musique*. 22nd Sept. 2022. URL: https://hal.inria.fr/hal-03841948.

[61] A. Ernoult and J. Chabassier. 'Replicate the sound characteristics of a historical trumpet.' In: Festival des 20 ans du SCRIME. Talence, France, 24th June 2022. URL: https://hal.inria.fr/hal-03875692.

12.4 Cited publications

[62] A. Ernoult and J. Kergomard. 'Transfer matrix of a truncated cone with viscothermal losses: application of the WKB method'. In: *Acta Acustica* 4.2 (12th May 2020). DOI: 10.1051/aacus/2020005. URL: https://hal.archives-ouvertes.fr/hal-02428009.

[63] A. Ernoult, C. Vergez, S. Missoum, P. Guillemain and M. Jousserand. 'Woodwind instrument design optimization based on impedance characteristics with geometric constraints'. In: *Journal of the Acoustical Society of America* 148.5 (Nov. 2020), pp. 2864–2877. DOI: 10.1121/10.0002449. URL: https://hal.archives-ouvertes.fr/hal-02479433.

[64] G. Alessandrini, M. V. de Hoop, F. Faucher, R. Gaburro and E. Sincich. 'Inverse problem for the Helmholtz equation with Cauchy data: reconstruction with conditional well-posedness driven iterative regularization'. In: *ESAIM: Mathematical Modelling and Numerical Analysis* 53.3 (May 2019), pp. 1005–1030. DOI: 10.1051/m2an/2019009. URL: https://hal.archives-ouvertes.fr/hal-02168474.

[65] A. Almeida, W. Li, J. R. Smith and J. Wolfe. 'The mechanism producing initial transients on the clarinet'. In: *The Journal of the Acoustical Society of America* 142.6 (2017), pp. 3376–3386.

[66] A. Almeida, C. Vergez and R. Caussé. 'Quasistatic nonlinear characteristics of double-reed instruments'. In: *The Journal of the Acoustical Society of America* 121.1 (2007), pp. 536–546.

[67] A. Bamberger, G. Chavent and P. Lailly. 'About the stability of the inverse problem in 1-D wave equations—Application to the interpretation of seismic profiles'. In: *Applied Mathematics and Optimization* 5.1 (1979), pp. 1–47.

[68] H. Barucq, H. Calandra, J. Diaz and E. Shishenina. 'Space-time Trefftz-DG approximation for elasto-acoustics'. In: *Applicable Analysis* 00 (Aug. 2018), pp. 1–16. URL: https://hal.inria.fr/hal-01940623.

[69] H. Barucq, T. Chaumont-Frelet and C. Gout. 'Stability analysis of heterogeneous Helmholtz problems and finite element solution based on propagation media approximation'. In: *Mathematics of Computation* 86.307 (2017), pp. 2129–2157. DOI: 10.1090/mcom/3165. URL: https://hal.inria.fr/hal-01408934.

[70] S. Bilbao. 'Direct Simulation of Reed Wind Instruments'. In: *Computer Music Journal* 33.4 (2009), pp. 43–55.

[71] M. Bonnasse-Gahot, H. Calandra, J. Diaz and S. Lanteri. 'Hybridizable discontinuous Galerkin method for the two-dimensional frequency-domain elastic wave equations'. In: *Geophysical Journal International* 213.1 (Apr. 2018), pp. 637–659. DOI: 10.1093/gji/ggx533. URL: https://hal.inria.fr/hal-01656440.

[72] G. Chavent. 'Identification of functional parameters in partial differential equations'. In: *Joint Automatic Control Conference*. 12. 1974, pp. 155–156.

[73] J. Christensen-Dalsgaard. 'Helioseismology'. In: *Reviews of Modern Physics* 74.4 (2002), p. 1073.

[74] P. Dickens, J. Smith and J. Wolfe. 'Improved precision in measurements of acoustic impedance spectra using resonance-free calibration loads and controlled error distribution'. In: *The Journal of the Acoustical Society of America* 121.3 (2007), pp. 1471–1481.

[75] G. C. Diwan and M. S. Mohamed. 'Pollution studies for high order isogeometric analysis and finite element for acoustic problems'. In: *Computer Methods in Applied Mechanics and Engineering* 350 (2019), pp. 701–718.

[76] F. Faucher. 'Contributions to Seismic Full Waveform Inversion for Time Harmonic Wave Equations: Stability Estimates, Convergence Analysis, Numerical Experiments involving Large Scale Optimization Algorithms'. Theses. Université de Pau et des Pays de l'Adour, Nov. 2017. URL: https://hal.archives-ouvertes.fr/tel-01807861.

[77] F. Faucher. 'hawen: time-harmonic wave modeling and inversion using hybridizable discontinuous Galerkin discretization'. In: *Journal of Open Source Software* 6.57 (Jan. 2021), p. 2699. DOI: 10.21105/joss.02699. URL: https://hal.archives-ouvertes.fr/hal-03406861.

[78] D. Fournier, C. S. Hanson, L. Gizon and H. Barucq. 'Sensitivity kernels for time-distance helioseismology-Efficient computation for spherically symmetric solar models'. In: *Astronomy & Astrophysics* 616 (2018), A156.

[79] V. Gibiat and F. Laloë. 'Acoustical impedance measurements by the two-microphone-three-calibration (TMTC) method'. In: *The Journal of the Acoustical Society of America* 88.6 (1990), pp. 2533–2545.

[80] L. Gizon, H. Barucq, M. Duruflé, C. Hanson, M. Leguèbe, A. Birch, J. Chabassier, D. Fournier, T. Hohage and E. Papini. 'Computational helioseismology in the frequency domain: acoustic waves in axisymmetric solar models with flows'. In: *Astronomy and Astrophysics - A&A* 600 (Apr. 2017), A35. DOI: 10.1051/0004-6361/201629470. URL: https://hal.archives-ouvertes.fr/hal-01403332.

[81] L. Gizon and A. C. Birch. 'Local helioseismology'. In: *Living Reviews in Solar Physics* 2.1 (2005), p. 6.

[82] L. Gizon, A. C. Birch and H. C. Spruit. 'Local helioseismology: three-dimensional imaging of the solar interior'. In: *Annual Review of Astronomy and Astrophysics* 48 (2010), pp. 289–338.

[83] P. Guillemain, J. Kergomard and T. Voinier. 'Real-time synthesis of clarinet-like instruments using digital impedance models'. In: *The Journal of the Acoustical Society of America* 118.1 (2005), pp. 483–494.

[84] T. J. Hughes, J. A. Cottrell and Y. Bazilevs. 'Isogeometric analysis: CAD, finite elements, NURBS, exact geometry and mesh refinement'. In: *Computer methods in applied mechanics and engineering* 194.39-41 (2005), pp. 4135–4195.

[85] J. Kasahara, Y. Hasada and T. Yamaguchi. 'Seismic imaging of supercritical geothermal reservoir using full-waveform inversion method'. In: *Proceedings*. 2019.

[86] C. M. Krawczyk, M. Stiller, K. Bauer, B. Norden, J. Henninges, A. Ivanova and E. Huenges. '3-D seismic exploration across the deep geothermal research platform GroßSchönebeck north of Berlin/Germany'. In: *Geothermal Energy* 7.1 (2019), pp. 1–18.

[87] P. Lailly and J. Bednar. 'The seismic inverse problem as a sequence of before stack migrations'. In: *Conference on inverse scattering: theory and application*. Siam Philadelphia, PA. 1983, pp. 206–220.

[88] I. Masoni. 'Inversion of surface waves in an oil and gas exploration context'. PhD thesis. Université Grenoble Alpes (ComUE), 2016.

[89] R.-E. Plessix. 'A review of the adjoint-state method for computing the gradient of a functional with geophysical applications'. In: *Geophysical Journal International* 167.2 (2006), pp. 495–503.

[90] R. G. Pratt, C. Shin and G. Hick. 'Gauss–Newton and full Newton methods in frequency–space seismic waveform inversion'. In: *Geophysical Journal International* 133.2 (1998), pp. 341–362.

[91] R. G. Pratt and M. H. Worthington. 'INVERSE THEORY APPLIED TO MULTI-SOURCE CROSS-HOLE TOMOGRAPHY. PART 1: ACOUSTIC WAVE-EQUATION METHOD 1'. In: *Geophysical prospecting* 38.3 (1990), pp. 287–310.

[92] R. Pratt, Z.-M. Song, P. Williamson and M. Warner. 'Two-dimensional velocity models from wide-angle seismic data by wavefield inversion'. In: *Geophysical Journal International* 124.2 (1996), pp. 323–340.

[93] S. Pride. 'Governing equations for the coupled electromagnetics and acoustics of porous media'. In: *Physical Review B* 50.21 (1994), p. 15678.

[94] S. Rienstra. 'Webster's Horn Equation Revisited'. In: *SIAM Journal on Applied Mathematics* 65.6 (2005), pp. 1981–2004.

[95] C. A. P. Solano. 'Two-dimensional near-surface seismic imaging with surface waves: alternative methodology for waveform inversion'. PhD thesis. Ecole Nationale Supérieure des Mines de Paris, 2013.

[96] G. Sosio, A. Gendrin, U. Miersemann, L. Pekot, R. Andrés, P. González, A. Giménez and J. C. Ballesteros. 'Property modelling of a potential CO2 storage site using seismic inversion'. In: *EGUGA* (2013), EGU2013–10470.

[97] A. Tarantola. *Inverse problem theory: methods for data fitting and model parameter estimation*. Amsterdam, Netherlands: Elsevier Science Publishers, 1987.

[98] A. Tarantola. *Inverse problem theory and methods for model parameter estimation*. Vol. 89. siam, 2005.

[99] T. A. Torp and J. Gale. 'Demonstrating storage of CO2 in geological reservoirs: The Sleipner and SACS projects'. In: *Energy* 29.9-10 (2004), pp. 1361–1369.

[100] R. Tournemenne and J. Chabassier. 'A comparison of a one-dimensional finite element method and the transfer matrix method for the computation of wind music instrument impedance'. In: *Acta Acustica united with Acustica* 5 (2019), p. 838. URL: https://hal.inria.fr/hal-01963674.

[101] M. P. Verge, A. Hirschberg and R. Caussé. 'Sound production in recorderlike instruments. II. A simulation model'. In: *The Journal of the Acoustical Society of America* 101.5 (1997), pp. 2925–2939.

[102] H. Yamabe, T. Tsuji, Y. Liang and T. Matsuoka. 'Influence of fluid displacement patterns on seismic velocity during supercritical CO2 injection: Simulation study for evaluation of the relationship between seismic velocity and CO2 saturation'. In: *International Journal of Greenhouse Gas Control* 46 (2016), pp. 197–204.