RESEARCH CENTRE

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ACTIVITY REPORT

Project-Team

IDEFIX

Inversion of Differential Equations For Imaging and physiX

DOMAIN

Applied Mathematics, Computation and Simulation

THEME

Numerical schemes and simulations

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Project-Team IDEFIX

Creation of the Project-Team: 2021 August 01

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Computer sciences and digital sciences

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2 Overall objectives

Inverse problems are encountered in many real life applications and the ones we are interested in are those that can be formulated as parameter identifications in a PDE (system) modeling physical phenomena, primarily wave propagation and diffusion. As opposed to determining the solution of the forward model, identifying the parameters from measurements of this solution usually leads to an unstable and non linear problem that may be not uniquely solvable. A standard method to formulate this inverse problem is to consider it as a minimization of a cost functional that measures data fidelity. The solution to the latter is computationally much more costly than solving the PDE and may even not be realistic for number of applications that require real time answers or for very large scale problems. These considerations motivated the research guidelines items exposed above and that we shall develop further in the following.

At EDF, the need for algorithms to solve inverse problems is present in numerous applications (see Section 4 for instance). The team Signal, Image and Learning at EDF R&D, PRISME has developed solutions mainly based on signal processing methods that do not require fine modeling of the physical phenomena (describing the experiment). This enables fast simplified responses that can usually be satisfactory. The complexification of the measuring devices and environments appealed for more precise assessment of the experiments and therefore for more reliable/precise inversion methods. This was the motivation behind the intense collaborations between EDF R&D and the DEFI project team that lead to six co-supervised PhD thesis and one PostDoc on various themes (Eddy current imaging for pipes, data assimilation for primary cooling loops, sampling methods for concrete like materials, multi-element eddy current 3-D probes, qualitative inversion methods and spectral signatures for ultrasound applications). The joint team aims at pursuing this collaborative effort that has been beneficial to both partners, motivating at the same time fundamental research to establish solid theoretical foundations of promising inversion methods and (non trivial) adaptations of established methods to solve applications of interest for EDF.

3 Research program

Let us describe the outline of the main challenges that we would like to address for solutions to inverse problems, taking as a guideline the example of non destructive testing which is central for EDF applications. A typical experiment would be to probe some defects inside a given structure by sending waves that can propagate inside the domain of interest. The response of the media is recorded by some receivers and forms the data of the inverse problem. We can distinguish two types of inverse problems. In the first type, referred to by "imaging", one is interested by only the location and/or the shape of the defect/inclusion. In the second one, referred to by "identification", one is interested in getting information on the defect physical properties. Both problems (imaging and identification) are non linear and ill-posed (lack of stability with respect to measurements errors if some careful constrains are not added). Moreover, the unique determination of the geometry and/or the coefficients is not guaranteed in general if sufficient measurements are not available. As an example, in the case of anisotropic inclusions, one can show that an appropriate set of data uniquely determine the geometry but not the material properties. These theoretical considerations are usually difficult to address and are not only important in understanding the mathematical properties of the inverse problem, but also guide the choice of appropriate numerical strategies (which information can be stably reconstructed) and also the design of appropriate regularization techniques and improve the measurement techniques. Moreover, uniqueness proofs can be constructive proofs, i.e. they implicitly contain a numerical algorithm to solve the inverse problem, hence their importance for practical applications. The sampling methods introduced below are one example of such algorithms. As a complementary notion to identifiability is the notion of invisibility. The latter topic has attracted a large attention in the inverse problem community due in particular to the recent and rapid development of metamaterials that made plausible the design of cloaking devices based on transformation optics. However, these transformations require the use of non dissipative materials exhibiting singular physical coefficients taking infinite values, which is indeed not realistic. This motivated us to consider a weaker notion of invisibility where one would like to achieve invisibility for only a finite set of measurements and frequencies. This objective is less ambitious and consequently, it is more easily achievable. On the other hand, it is pertinent from a practical point of view because one always has a finite number of sensors and very often, one has only access to a small number of measurements. In addition to theoretically investigate this issue for some idealized models, we would like to fructify our findings for non destructive testings in waveguides.

An important part of our research activity is dedicated to numerical methods applied to the first type of inverse problems, where only the geometrical information is sought. In its general setting the inverse problem is very challenging and no method can provide a universal satisfactory solution to it (regarding the balance cost-precision-stability). This is why in the majority of the practically employed algorithms, some simplification of the underlying mathematical model is used, according to the specific configuration of the imaging experiment. The most popular ones are geometric optics (the Kirchhoff approximation) for high frequencies and weak scattering (the Born approximation) for small contrasts or small obstacles. They actually give full satisfaction for a wide range of applications as attested by the large success of existing imaging devices (radar, sonar, ultrasound, X-ray tomography, etc.), that rely on one of these approximations.

Generally speaking, the used simplifications result in a linearization of the inverse problem and therefore are usually valid only if the latter is weakly non-linear. The development of these simplified models and the improvement of their efficiency is still a very active research area. With that perspective we are particularly interested in deriving and studying higher order asymptotic models associated with small geometrical parameters such as small obstacles, thin coatings, periodic media, ... Higher order models usually introduce some non linearity in the inverse problem, but are in principle easier to handle from the numerical point of view than in the case of the exact model. Asymptotic analysis is also a corner stone in our methodology to prove invisibility for finite number of measurements.

A major research axis is dedicated to algorithms that avoid the use of such approximations and that are efficient where classical approaches may fail: i.e. roughly speaking when the non linearity of the inverse problem is sufficiently strong. This type of configuration is motivated by the applications mentioned below, and occurs as soon as the geometry of the unknown media generates non negligible multiple scattering effects (multiply-connected and closely spaces obstacles) or when the used frequency is in the so-called resonant region (wave-length comparable to the size of the sought medium). It is therefore much more difficult to deal with and requires different approaches such as sampling methods. The sampling methods are fast imaging solvers adapted to multi-static data (multiple receiver-transmitter pairs). Even if they do not use any linearization of the forward model, they rely on computing the solutions to a set of linear problems of small size, that can be performed in a completely parallel procedure. Our team is among the leading international groups in the developments of these techniques. We are one of the main contributors in recent advancements in this field and actively acting in its dissemination among the academic and industrial communities. We shall pursue our efforts in developing and promoting these techniques. A closely related subject is the study of so-called Transmission eigenvalues that naturally arise in the analysis of inverse medium problems and particularly in the theory behind sampling methods. These frequencies can be seen as the extension of the notion of resonant frequencies for impenetrable objects to the case of penetrable media. Our developments of sampling methods lead us to discover that transmission eigenvalues can be reconstructed from multi-frequency and multistatic measurements. The spectrum formed by these special frequencies can be related to the materiel properties of the medium and therefore can be used as a signature that characterizes some aspects of this medium (although a complete answer to this statement is far from being available). More specifically we promote the use of these quantities to obtain qualitative information on changes in the probed domain (as in non destructive testing). The study of transmission eigenvalues has become (as for sampling methods) a well identified branch in the inverse problem community that raises many challenges ranging from purely theoretical questions to numerical schemes and significance for applications.

For the identification problem, one would also like to have information on the physical properties of the targets. Of course optimization methods is a tool of choice for these problems. The application of non linear optimization methods for inverse problems has to be supplemented by regularization strategies. While convergence for Hilbertian regularization is well understood from the theoretical point of view, it is still far from being the case for non Hilbertian norms. For instance regularization strategies that promote sparsity belong to the latter class and is of great interest for inverse problems where the coefficients have singularities (point sources, crack like defects, piecewise constant material properties, etc...). Exploring theoretical and numerical issues raised by these regularization is of interest for applications. We plan to invest on these issues together with the use of non standard fidelity functional that may help reducing the number of local minima. Combining deterministic techniques with stochastic ones is also an interesting perspective that has not been sufficiently explored in the literature and that we aim at developing. This would allows us to also investigate feasibility of Bayesian inference for these non linear and computationally involving inverse problems. Exploiting neural networks in the design of solutions to inverse problems is major trend in the inverse problem community as in many other scientific area. Using these techniques to directly solve severe ill posed problems, as inverse scattering problems, does not seem a certifiable route. A more reasonable approach to benefit from the ability of these networks to encode high dimensional complex non linear functional would be to use them for automatically adjusting deterministic optimization parameters such as descent steps and/or regularization parameters (or priors). This also holds true for their use in the sampling methods invoked above and we shall start by exploring this combination first.

From the practical point of view, the major limitation of sampling methods would be the need of a large amount of data to achieve a reasonable accuracy. On the other hand, optimization methods do not suffer from this constrain but they require good initial guess to ensure convergence and reduce the number of iterations. Therefore it seems natural to try to combine the two class of methods in order to calibrate the balance between cost and precision.

Independently from the formulation of the optimization problem, the efficiency of inversion algorithm associated with this formulation greatly depends on the efficiency of the forward solver. Our team has already made significant contributions in acceleration techniques for solutions to the forward problem (waves and diffusion). We developed strong expertise in H-matrix compression and combination with other acceleration techniques such as FFT and fast multipole methods for wave problems. Fructifying this into the solution to large scale inverse problems in link with geophysical application or non destructive testing is promising for obtaining feasible inversion algorithm for the full non linear inverse problem. Domain decomposition technique is yet another expertise that we have developed and would like to explore for accelerating the solution of the forward and inverse problems. For the latter, methodologies where iterations on the inversion parameter and the forward and adjoint problems are combined merit investigations. Several approaches have been proposed in the literature, but the convergence of these schemes and their efficiency are not yet clear in the context of inverse ill-posed problems.

Although a major focus will be given to applications and methodologies that can be of interest for EDF, the contours of the IDEFIX research team include topics that may go beyond that perspective.

In particular we are also interested in applications involving the imaging of biological tissues with the technique of Diffusion Magnetic Resonance Imaging (DMRI). Roughly speaking, DMRI gives a measure of the average distance travelled by water molecules in the imaged medium and can give useful information on cellular structure and structural change when the medium is biological tissue. In particular, we would like to infer from DMRI measurements changes in tissue and cellular structure occurring under various physiological or pathological conditions, as well generally the cell morphology in the region of interest. The main challenges here are: 1) to model correctly the measured signals using diffusive-type evolution equations, 2) to handle numerically the geometical complexity of biological issue; 3) to use the first two to identify physically relevant parameters from the measurements. There are two main groups of approaches to the first two challenges. The first one relies on using random walkers to mimic the diffusion process in a given geometrical configuration. The second one exploits the model given by the Bloch-Torrey partial differential equation, which describes the evolution of the complex transverse water proton magnetization under the influence of diffusion-encoding magnetic field gradients pulses. We primarily work in the simulation and analysis of the Bloch-Torrey partial differential equation in complex geometries, in other words, we follow the second group of approaches. For the third challenge, we are particularly interested in constructing reduced models of the multiple-compartment Bloch-Torrey model using homogenization methods.

Our team will also develop computational tools specifically designed for acoustics. They are motivated by applications that need a high fidelity restitution of the sound distribution. This includes in particular fast simulation of head-related transfer function (HRTF) which is a response that characterizes how an ear receives a sound from a point in space. Obtaining the best way to define HRTF is still a matter of debate. To help addressing this issue we would like to study theoretically and numerically the injectivity of HRTF functionals and the pertinence of their simplifications. The main challenge for the numerical simulation of HRTF is the modeling of the ear tissue and its complex interaction with incoming sound. We also would like to develop quick algorithms for real time ambisonics (three dimensional sound captation/restitution). Fast and robust solutions to this inverse source problem would be of interest for solutions to immersive audio. We are also investing in the development of reduced models for the simulation of complex room acoustics and auralization.

4 Application domains

4.1 Eddy Current Imaging for steam generator and rotating machine

Eddy Current is an approximation of Maxwell system at low frequency. Probe that works in that quasi-stationary regime are commonly used in non destructive testing. We are interested in inverse problems for these type of measurement in steam generator and more recently for rotating machine.

Steam generators are critical components in nuclear power plants. For a sake of radioactive safety, the water flow (called the primary fluid) which ensures the cooling of the core reactor is separated from the water flow (called the secondary fluid) which is transformed in steam to generate electricity: the heat must be transferred via the steam generator. The primary fluid circulates in tubes with U-shape while the secondary fluid rises up in the steam generator along these tubes.

Without disassembling the steam generator, the lower part of the U-tubes is inaccessible for normal inspections. Therefore, a non-destructive examination procedure, called eddy current testing (ECT), is usually used to detect the presence of deposits. In an ECT, one introduces a probe consisting of coils of wire in the tube that deliver electromagnetic excitation at low frequencies (eddy current regime) and measure induced currents by the external media (ECT signals). The design of robust and reliable PDE based inversion methods to analyze ECT signals is a long term ongoing project with and within EDF R&D. We first developed and analyzed the simplified setting of axisymmetric geometries which allows to model the problem in 2D and to test various options for the direct and inverse algorithms and in particular an algorithm based on the Level Set method. We start extending this work to 3D inversions for various types of probes (with angular resolutions) and various types of defects. And will pursue this in the future in order to treat real data with multiple defects (i.e. cracks, deposit, thin deposit).

Finally related to Eddy Current modeling, we work on low frequency/quasi-stationary Maxwell system in alternators and engines. On those systems EDF is trying to assess from measurements the exact geometry and the physical properties which have potentially (parametric) non linear constitutive laws. A collaboration on this topic with the EDF team that contributes to code CARMEL. With the same team we are co-advising a PostDoc project, on the detection and extraction of information on transformer partial discharge measurement which is a non linear phenomenon where charge flow through an insulator in very short time.

4.2 Non destructive testing of concrete-like material

Concrete is a widely used material thanks to its appealing (when reinforced) properties and its manageable cost. However, it is a very complex material: highly heterogeneous, multiscale, evolving over time, etc. Yet, it has to be inspected to ensure that the structure is safe and especially when this structure is part of sensitive infrastructures such as power plants. Using mechanical waves to inspect concrete is widely used in practice but many aspects still constitute very challenging problems due to the complex properties of the material. Several defects are of interest and measurements might vary with respect to the target. Imaging are very difficult with conventional techniques due to potentially low contrast and complicated structure (i.e. reinforcing bar, metallic liners). Sampling methods are able to tackle this type of problem by integrating the information on the a priori structure of the geometry. Other methods such as homogenization could be a valuable approached for identifying this type of defects.

The region between air and the first reinforcement steel bar are of primary importance because it shields the steel from the exterior and therefore prevents corrosion. To inspect this area, engineers rely on surface wave techniques similar to Multi-channel Analysis of Surface Waves (MASW) in geophysics. However, concrete is not a layered material and therefore interpretation of this type of measurements is not easy. Basically this method constructs the dispersion curve of surface waves through data processing and then uses this information to invert a layered model for the material. This procedure shares similarities with spectral signature identification and it would be interesting to further clarify this link in order to obtain better interpretation (or reformulation) of MASW in this context.

Similarly to ultrasonic waves, electromagnetic waves are generally used to inspect concrete type materials, we will be involved in imaging complex structure with radar type measurements. A more challenging application is to determine the electromagnetic properties of the material and relate them to the hydration of the cement paste. MASW analysis of the measurements are also consider in this setting similarly to mechanical waves.

4.3 Subsurface imaging

Subsurface imaging up to one hundred meters is of primary importance for power plant safety assessment with respect to seismic activity. Issues range from testing the interface between the bedrock and the bottom of dam, to quantitative map and detection of fracture underneath nuclear power plant and imaging of the sea bed to evaluate the feasibility of construction of offshore wind turbine. Earth imaging is a well studies area but primarily at medium to long distance thanks to oil industry and seismology. However subsurface imaging is not very common and has its own difficulties due to the heterogeneous structure of the soil and the higher frequency of the wave needed to have a satisfactory resolution.

Dykes are structures that are difficult to inspect but are of primary importance for the safety of power plant and MASW is usually applied for that purpose. Using data processing techniques dispersion curves are extracted from recorded surface waves. Engineers then use semi-analytic model of dispersion curves for stratified media to obtain an subsurface image. Extending this type of methods to non-stratified media is challenging and it would be interesting to see how it compares with classical optimization based inversion methods.

As for concrete imaging mechanical, electromagnetic waves and conductivity are the various physics used to probe the medium. Both shared heterogeneous physical properties, embedded in potentially complex geometries and seek unknown of several types and are applications less investigated that medical, seismic or metallic imaging. As research on measurements techniques are carried by the same group in EDF R&D PRISME we will seek for synergy between this two fields.

4.4 Applications of concepts related to invisibility for finite set of measurements

As mentioned above, in the team we have developed different approaches to construct obstacles which are invisible for imaging techniques with a finite number of measurements. In what we did, obstacles are invisible at a fixed frequency. It would be important to study more the sensitivity of the invisibility results with respect to the frequency. In the construction algorithms, can we add constraints so that invisibility remains robust to the frequency? In our studies, we have mainly focused our attention on acoustics in waveguides. It would be interesting to investigate electromagnetic and elasticity problems. Moreover, it would be very instructive to investigate how the invisible objects we design theoretically and numerically behave in practice. To proceed, we contemplate to work with experimentalists at the Acoustic Department of the University of Le Mans with whom we are in contact.

Until now, we have only constructed obstacles which are invisible in time-harmonic regime. It would be interesting to study what can be done for time dependent problems. Maybe the first question is as follows: imagine that a time dependent source term is given (a pulse), how to design the geometry so that the signal passes through the structure as if they were no defect? For the applications, one can think to the optimal design of a stent to fix a damaged coronary artery. It is known that an inappropriate shape and material for the stent can produce scattered waves which are harmful for the cardiac muscle.

In the physical community, spectacular advances have recently been made in the development of a new field called “wave front shaping” . For a given unknown complex scatterer, the goal is to find the best entrance signal to obtain a given physical property (focalisation of the energy, good transmission, ...). We emphasize that in this context, optimization techniques cannot be used because the scatterer is complex and a priori unknown. This point of view is different from the one considered up to know in the team. Indeed, in our case, the entrance signal is given and we look for the scatterer to have invisibility. It would be interesting to study the connections existing between the two approaches.

Another area which would benefit from the expertise of the team is the design of barriers that would isolate critical buildings of nuclear power plant from seismic solicitation. This topic is directly related to the partial invisibility exposed above. Indeed, for this application, complete cloaking is not necessary as it is enough to transfer the seismic solicitation to other area in space and to reduce the maximal solicitation on specific modes of the structure (either by spreading the solicitation in time or by transferring the solicitation to a more robust mode of vibration). This boils down to design structures ensuring zero transmission of energy between different given modes, a question we also consider in our works dealing with waves propagation in waveguides. This problematic has not yet been planned by EDF in the short term perspectives but we believe it is worth exploring as there already exist realistic experiments of such cloaking constructions formed by stilts embedded in the soil.

4.5 Other potential applications of interest for EDF

One way to measure flow rate in stationary environment is to use ultrasound measurements. Ultrasound propagates faster in the direction of the flow and slower in the opposite direction. This principle has been used to measure flow rate in pipes with relatively clear water. It is also used for water carrying heterogeneities, like bubbles, sand, stone... but with an experimental approach, with few understanding of the limits of the method. Being able to model the propagation in such an heterogeneous medium and to adapt the analysis of the data would not only improve current measurement techniques but also give tools to know a priori the method limits. There are issue in hydraulic power plants to assess the presence of obstacles or objects in moving fluid using SONAR type measurements. Depending on the application it is not clear yet if the fluid motion could be neglect and it will be the purpose of further research. These applications would be a promising first step to open our expertise towards fluid related problems, which might have large perspectives in our collaboration with EDF. Similarly to non destructive testing of concrete, other approaches rely on electromagnetic or passive measurements (sources of sound locations) in order to assess the flow rate.

4.6 Sound modeling for realistic environments

To reproduce virtual environments as realistic as possible, it is essential to provide existing virtual/augmented reality devices with convincing audio solutions. Indeed, for the immersive experience to be complete, it is necessary to transpose a reality to the vision, but also to the other senses, without which undesirable effects are quickly felt (motion sickness). With this respect, hearing plays a major role as it not only complements the visual information, but also provides to the brain information that are not visible in the scene. The complete virtualization of a sound environment faces the following difficulties:

- Restore spatial dimension to sound effect (binaural, ambisonic (HOA), multi-channel, WFS, etc. techniques)
- Take into account information from the listener (position in space, listening direction, etc.)
- Recreate a credible acoustic environment (room acoustics, distance level, comb filtering, etc.)

4.7 Diffusion MRI for the classification of neuron populations

Sensing the microstructural characteristics of human brain tissue with clinical MRI scanners has been an area of heated debate in the diffusion MRI community. We have recently presented evidence that, if we focus on the cortex, specifically in the insula and anterior cingulate cortex (ACC), the unique characteristics of the cellular population in these gyri allow using clinical-grade scanners to sense the presence of Von Economo neurons (VENs). VENs, uniquely localized in the insula and ACC, are large neurons thought to play an important role in goal-directed behaviors and emotional regulation. However, there is a lack of tools enabling studies on VENs population characteristics and their link to brain function and behavior. We plan to attack a new frontier in diffusion MRI for microstructure quantification by focusing on specific areas in the cortex, rather than the heretofore much studied white matter areas. We will benefit from a collaboration with the Stanford Cognitive and Systems Neuroscience Laboratory lead by Dr. Vinod Menon and Dr. Wassermann of the Inria Parietal Team.

5 New software and platforms

5.1 New software

5.1.1 ECIP

Name: Eddy Current Imaging for Pipes

Keywords: Inverse problem, Partial differential equation, HPC, Domain decomposition

Functional Description: This software identifies deposit on pipes from measurements of eddy current probes. It is based on finite elements and domain decomposition through the softwares HPDDM, PETSc and FreeFEM, for the resolution of the PDE model of the eddy current measurements. It uses an iterative algorithm to identify the deposit properties.

Contact: Lorenzo Audibert

Partner: Edf

5.1.2 CASTOR

Keyword: C++

Functional Description: The objective of the castor library is to propose high-level semantics, inspired by the Matlab language, allowing fast software prototyping in a low-level compiled language. It is nothing more than a matrix management layer using the tools of the standard C++ library, in different storage formats (full, sparse and hierarchical). Indeed, the use of IDEs 1 such as Xcode, Visual studio, Eclipse, etc. allows today to execute compiled code (C, C++, fortran, etc.) with the same flexibility as interpreted languages (Matlab, Python, Julia, etc.).

A header-only template library for matrix management has been developed based on the standard C++ library, notably the std::vector class. Many tools and algorithms are provided to simplify the development of scientific computing programs. Particular attention has been paid to semantics, for a simplicity of use "à la matlab", but written in C++. This high-level semantic/low-level language coupling makes it possible to gain efficiency in the prototyping phase, while ensuring performance for applications. In addition, direct access to data allows users to optimize the most critical parts of their code in native C++. Finally, complete documentation is available, as well as continuous integration unit tests. All of this makes it possible to meet the needs of teaching, academic issues and industrial applications at the same time.

The castor library provides tools to :

create and manipulate dense, sparse and hierarchical matrices make linear algebra computations based on optimized BLAS library make graphical representations based on VTK library These tools are used by applicative projects :

finite and boundary element method using Galerkin approximation analytical solutions for scattering problems

URL: https://leprojetcastor.gitlab.labos.polytechnique.fr/castor/#

Contact: Matthieu Aussal

5.1.3 SpinDoctor

Name: SpinDoctor Diffusion MRI Simulation Toolbox

Keywords: MRI, Simulation, Finite element modelling

Functional Description: SpinDoctor can be used

1. to solve the Bloch-Torrey PDE to obtain the dMRI signal (the toolbox provides a way of robustly fitting the dMRI signal to obtain the fitted Apparent Diffusion Coefficient (ADC)), 2. to solve the diffusion equation of the H-ADC model to obtain the ADC, 3. a short-time approximation formula for the ADC is also included in the toolbox for comparison with the simulated ADC.

URL: https://github.com/jingrebeccali/SpinDoctor

Contact: Jing Rebecca Li

6 New results

6.1 Fast data driven imaging methods

Participants: Lorenzo Audibert, Houssem Haddar, Fabien Pourre, Jean-Marie Henault, Denis Vautrin.

6.1.1 Sampling method in linear elasticity for concrete : gravel honeycomb

L. Audibert, H. Haddar, JM Henault, F. Pourre
We consider the propagation of elastic waves at a given wavenumber in a penetrable medium. We gradually increase the complexity of the medium from an unbounded constant medium to a partially bounded medium with or without a microstructure mimicking aggregates in concrete. In those various configuration we study the LSM for various object from connected to a model gravel honeycomb defect. Numerically we simulate all those situation with FreeFEM together with PETSc to use parrallel computing.We also investigate plane wave, point sources and both pressure and shear waves.

6.1.2 Sampling method in linear elasticity applied to image the interface between dam and bedrock

L. Audibert, H. Haddar, D. Vautrin
We consider the issue of imaging the bottom of a dam. First we constructed a numerical model of elastic wave propagation at given wavenumber using parallel computing with FreeFEM and PETSc. We then used this numerical model to simulate an acquisition similar to the one that was carried at the Vassiviere dam based on the construction plan. We then performed the LSM inversion on those multifrequency data to assess the performance of the method. These first results were encouraging and we shall pursue our investigation on this subject.

6.2 Near-Field Linear Sampling Method for Axisymmetric Eddy Current Tomography

H. Haddar, K. Riahi
This work is concerned with Eddy-Current (EC) nondestructive testing of conductive materials and focuses, in particular, on extending the well-known Linear Sampling Method (LSM) to the case of EC equations. We first presented the theoretical foundation of the LSM in this context and in the case of point sources. We then explained how this method can be adapted to a realistic setting of EC probes. In the case of identifying the shape of external deposits from impedance measurements taken from inside of the tube (steam generator), we showed how the method can be applied to measurements obtained from a sweeping set of coils. Numerical experiments suggest that good results can be achieved using only a few coils and even in the limiting case of backscattering data.

6.3 Differential imaging in periodic media

F. Cakoni, H. Haddar, T.P. Nguyen
We consider a problem of nondestructive testing of an infinite periodic penetrable layer using acoustic waves. This is an important problem with growing interest since periodic structures are part of many fascinating modern technological designs with applications in (bio)engineering and material sciences. In many sophisticated devises the periodic structure is complicated or difficult to model mathematically, hence evaluating its Green's function which is the fundamental tool of many imaging methods, is computationally expensive or even impossible. On the other hand, when looking for flows in such complex media, the option of reconstructing everything, i.e. both periodic structure and the defects, may

not be viable. We proposed in an earlier work an approach which provides a criteria to reconstruct the support of local anomalies without knowing explicitly or reconstructing the periodic healthy background. We extended the previous work by validating the methododlogy in 3D with bi-periodic layers. We also complemented the analysis of the method by treating the case where the defect is a missing component of the periodic media.

6.4 Invisibility

Participants: Lucas Chesnel, Houssem Haddar, Jérémy Heleine, Denis Vautrin.

6.4.1 A continuation method for building invisible obstacles in waveguides

A. Bera, A.-S. Bonnet-Ben Dhia, L. Chesnel
We consider the propagation of acoustic waves at a given wavenumber in a waveguide which is unbounded in one direction. We explain how to construct penetrable obstacles characterized by a physical coefficient ρ which are invisible in various ways. In particular, we focus our attention on invisibility in reflection (the reflection matrix is zero), invisibility in reflection and transmission (the scattering matrix is the same as if there were no obstacle) and relative invisibility (two different obstacles have the same scattering matrix). To study these problems, we use a continuation method which requires to compute the scattering matrix $\mathrm{S}(\rho)$ as well as its differential with respect to the material index $\mathrm{dS}(\rho)$. The justification of the method also needs for the proof of abstract results of ontoness of well-chosen functionals constructed from the terms of $\mathrm{dS}(\rho)$. We provide a complete proof of the results in monomode regime when the wavenumber is such that only one mode can propagate. And we give all the ingredients to implement the method in multimode regime. We also present numerical results to illustrate the analysis. [3]

6.4.2 Acoustic passive cloaking using thin outer resonators

L. Chesnel, J. Heleine, S.A. Nazarov
We consider the propagation of acoustic waves in a 2D waveguide unbounded in one direction and containing a compact obstacle. The wavenumber is fixed so that only one mode can propagate. The goal of this work is to propose a method to cloak the obstacle. More precisely, we add to the geometry thin outer resonators of width ε and we explain how to choose their positions as well as their lengths to get a transmission coefficient approximately equal to one as if there were no obstacle. In the process we also investigate several related problems. In particular, we explain how to get zero transmission and how to design phase shifters. The approach is based on asymptotic analysis in presence of thin resonators. An essential point is that we work around resonance lengths of the resonators. This allows us to obtain effects of order one with geometrical perturbations of width ε. Various numerical experiments illustrate the theory. [12]

6.4.3 Transmission Eigenvalues

F. Cakoni, D. Colton, H. Haddar
The study of eigenvalue problems for partial differential equations has a long history during which a variety of themes has emerged. Although historically such efforts have focused on eigenvalue problems defined on bounded domains, the importance of scattering theory in modern mathematical physics has led to an intensive study of eigenvalue problems in unbounded domains connected with the Schrödinger equation and the wave equation for propagation in an inhomogeneous medium. A particularly noteworthy development in this latter direction has been the theory of scattering resonances which now play a central role in mathematical scattering theory. More recently, a new eigenvalue problem in scattering theory has attracted increased attention both inside and outside the scattering community. This new problem is called the *transmission eigenvalue problem* and in a certain sense exhibits a duality relation to the theory of scattering resonances. We published in the AMS notices a short survey to introduce this

class of non-selfadjoint eigenvalue problems to the wider mathematical community that incorporated uptodate developments in the analysis of this problem.

6.5 Propagation of waves in waveguides

Participants: Lucas Chesnel.

6.5.1 Abnormal acoustic transmission in a waveguide with perforated screens

L. Chesnel, S.A. Nazarov
We consider the propagation of the piston mode in an acoustic waveguide obstructed by two screens with small holes. In general, due to the features of the geometry, almost no energy of the incident wave is transmitted through the structure. The goal of this article is to show that tuning carefully the distance between the two screens, which form a resonator, one can get almost complete transmission. We obtain an explicit criterion, not so obvious to intuit, for this phenomenon to happen. Numerical experiments illustrate the analysis. [7]

6.5.2 Design of an acoustic energy distributor using thin resonant slits

L. Chesnel, S.A. Nazarov
We consider the propagation of time harmonic acoustic waves in a device with three channels. The wave number is chosen such that only the piston mode can propagate. The main goal of this work is to present a geometry which can serve as an energy distributor. More precisely, the geometry is first designed so that for an incident wave coming from one channel, the energy is almost completely transmitted in the two other channels. Additionally, tuning a bit two geometrical parameters, we can control the ratio of energy transmitted in the two channels. The approach is based on asymptotic analysis for thin slits around resonance lengths. We also provide numerical results to illustrate the theory.[8]

6.5.3 Design of a mode converter using thin resonant slits

L. Chesnel, J. Heleine, S.A. Nazarov
The goal of this work is to design an acoustic mode converter. More precisely, the wave number is chosen so that two modes can propagate. We explain how to construct geometries such that the energy of the modes is completely transmitted and additionally the mode 1 is converted into the mode 2 and conversely. To proceed, we work in a symmetric waveguide made of two branches connected by two thin ligaments whose lengths and positions are carefully tuned. The approach is based on asymptotic analysis for thin ligaments around resonance lengths. We also provide numerical results to illustrate the theory. [6]

6.6 Analysis of negative metamaterials

Participants: Lucas Chesnel.

6.6.1 Maxwell's equations with hypersingularities at a conical plasmonic tip

A.-S. Bonnet-Ben Dhia, L. Chesnel, M. Rihani
In this work, we are interested in the analysis of time-harmonic Maxwell's equations in presence of a conical tip of a material with negative dielectric constants. When these constants belong to some critical range, the electromagnetic field exhibits strongly oscillating singularities at the tip which have infinite energy. Consequently Maxwell's equations are not well-posed in the classical L2 framework. The goal of the present work is to provide an appropriate functional setting for 3D Maxwell's equations when the dielectric permittivity (but not the magnetic permeability) takes critical values. Following what has

been done for the 2D scalar case, the idea is to work in weighted Sobolev spaces, adding to the space the so-called outgoing propagating singularities. The analysis requires new results of scalar and vector potential representations of singular fields. The outgoing behaviour is selected via the limiting absorption principle. [11]

6.7 Diffusion MRI

Participants: Jing Rebecca Li, S.D. Agdestein.

The complex transverse water proton magnetization subject to diffusion-encoding magnetic field gradient pulses in a heterogeneous medium such as brain tissue can be modeled by the Bloch-Torrey partial differential equation. The spatial integral of the solution of this equation in realistic geometry provides a gold-standard reference model for the diffusion MRI signal arising from different tissue microstructures of interest. A closed form representation of this reference diffusion MRI signal has been derived twenty years ago, called Matrix Formalism, that makes explicit the link between the Laplace eigenvalues and eigenfunctions of the tissue geometry and its diffusion MRI signal. In addition, once the Laplace eigendecomposition has been computed and saved, the diffusion MRI signal can be calculated for arbitrary diffusion-encoding sequences and b-values at negligible additional cost.

In a previous publication, we presented a simulation framework that we implemented inside the MATLAB-based diffusion MRI simulator SpinDoctor that efficiently computes the Matrix Formalism representation for biological cells subject to impermeable membrane boundary conditions. In this work, [1], we extend our simulation framework to include geometries that contain permeable cell membranes. We describe the new computational techniques that allowed this generalization and we analyse the effects of the magnitude of the permeability coefficient on the eigen-decomposition of the diffusion and Bloch-Torrey operators. This work is another step in bringing advanced mathematical tools and numerical method development to the simulation and modeling of diffusion MRI.

6.8 Modelling and HPC for wave propagation problems

Participants: Jing Rebecca Li, Marcella Bonazzoli, Matthieu Aussal, Houssem Haddar, Hadrien Montanelli.

6.8.1 Domain decomposition preconditioners for non-self-adjoint or indefinite problems

M. Bonazzoli, X. Claeys, F. Nataf, P.-H. Tournier

In this work we analyze the convergence of the one-level overlapping domain decomposition preconditioner SORAS (Symmetrized Optimized Restricted Additive Schwarz) applied to a generic linear system whose matrix is not necessarily symmetric/self-adjoint nor positive definite. By generalizing the theory for the Helmholtz equation developed in [I.G. Graham, E.A. Spence, and J. Zou, SIAM J.Numer.Anal., 2020], we identify a list of assumptions and estimates that are sufficient to obtain an upper bound on the norm of the preconditioned matrix, and a lower bound on the distance of its field of values from the origin. We stress that our theory is general in the sense that it is not specific to one particular boundary value problem. Moreover, it does not rely on a coarse mesh whose elements are sufficiently small. As an illustration of this framework, we prove new estimates for overlapping domain decomposition methods with Robin-type transmission conditions for the heterogeneous reaction-convection-diffusion equation. An article on this topic has been published [4].

6.8.2 Multi-Trace FEM-BEM formulation for acoustic scattering by composite objects

M. Bonazzoli, X. Claeys

This work is about the scattering of an acoustic wave by an object composed of piecewise homogenous parts and an arbitrarily heterogeneous part. We propose and analyze a formulation that couples, adopting a Costabel-type approach, boundary integral equations for the homogeneous subdomains with domain variational formulations for the heterogenous subdomain. This is an extension of Costabel FEM-BEM coupling to a multi-domain configuration, with junctions points allowed, i.e. points where three or more subdomains abut. Usually just the exterior unbounded subdomain is treated with the BEM; here we wish to exploit the BEM whenever it is applicable, that is for all the homogenous parts of the scattering object, since it yields a reduction in the number of unknowns compared to the FEM. Our formulation is based on the multi-trace formalism for acoustic scattering by piecewise homogeneous objects; here we allow the wavenumber to vary arbitrarily in a part of the domain. We prove that the bilinear form associated with the proposed formulation satisfies a Gårding coercivity inequality, which ensures stability of the variational problem if it is uniquely solvable. We identify conditions for injectivity and construct modified versions immune to spurious resonances. An article on this topic will be submitted soon.

6.8.3 Computing weakly singular and near-singular integrals in high-order boundary elements

M. Aussal, H. Haddar and H. Montanelli

We proposed algorithms for computing weakly singular and near-singular integrals arising when solving the 3D Helmholtz equation with high-order boundary elements. These are based on the computation of the preimage of the singularity on the reference element using Newton's method, singularity subtraction with high-order Taylor-like asymptotic expansions, the continuation approach, and transplanted Gauss quadrature. We demonstrated the accuracy of our method with several numerical experiments, including the scattering by two nearby half-spheres or conesphere geometries.

6.9 Optimization based inversion methods

Participants: Lorenzo Audibert, Marcella Bonazzoli, Houssem Haddar, Tuan Anh Vu, Xiaoli Liu.

6.9.1 Convergence analysis of multi-step one-shot methods for linear inverse problems

M. Bonazzoli, H. Haddar, T. A. Vu

To simulate large-scale inverse problems by gradient-based minimization algorithms, an option is to solve the corresponding direct and adjoint problems by iterative solvers, which are less memory-consuming than direct solvers. One-shot solvers, which iterate at the same time on the direct problem solution and on the inverse problem unknown, have been studied in the optimization literature, where strong convexity is usually assumed to ensure convergence. In the framework of inverse problems such assumptions are not verified and we would like to investigate strategies for which convergence can be established, and to study schemes where inner iterations are stopped before achieving convergence. We are currently finalizing a publication on the convergence of such schemes in the linear case.

6.9.2 Acceleration method for shape optimization in inverse scattering

L. Audibert, H. Haddar, X. Liu

To find the shape of an object from scattering data one could rely to optimisation based method and more precisely to gradient-based method. This could be applied to shape in order to retrieve an unknown geometry. an option is to use the adjoint method to compute the gradient efficiently. Yet it could be very costly if the minimization requires to many iteration. We investigate the extension of the famous Nesterov acceleration from convex analysis to shape optimization. First we show that the extension is natural for parametric model of shapes then we propose and motivate an extension to levelset parametrisation of shapes. This extension is not justified theoretically but we made an extensive numerical study that show as expected a reduction in iteration count and more surprisingly an increase in reconstruction quality. We will pursue this project by considering other imaging situation and by a theoretical analyses of our algorithm.

6.9.3 Reconstruction of non linear constitutive law in magnetostatic

L. Audibert, H. Haddar, JP Ducreux, D. Zilberberg

We intitiated in 2021 with the internship of D. Zilberberg a long term collaboration with the EDF (center of Saclay) on the calibration of non linear models for electromagnetic waves inside a rotor at transient regimes. The first study was concerned with a quasi-static approximation and the use of Newton method with trust region regularisation. Using this type of method we successfully reconstruct the curve that represents the permeability as a function of the modulus of the magnetic field for various geometry from the academic case of torus to the case of an alternator with real data. This is the first step before addressing the more challenging fully transient regime that requires costly simulations of the non linear evolution equations and their adjoint linearized ones.

7 Bilateral contracts and grants with industry

7.1 Bilateral contracts with industry

Participants: Houssem Haddar, Lorenzo Audibert.

- Grant associated with two long internships with EDF R&D on imaging in concrete and reconstruction of non linear consitutive law parameters with eddy current measurements. The students are Fabien Pourre and Dana Zilberberg.

7.2 Bilateral Grants with Industry

- Grant from DGA on the development of numerical tools for simulating high frequency scattering problems. It partly served financing the Postdoc work of H. Montanelli (2021).
- Grant from DGA in the framework of the CIEDS, with the objective of extending sampling methods to passive imaging and imaging in a cluttered media (2021-2024).

8 Partnerships and cooperations

8.1 Regional initiatives

Participants: Lorenzo Audibert, Matthieu Aussal, Houssem Haddar.

- Funding from the chair “Energies Durables” created by Ecole polytechnique obtained in the framework of research studies supported by EDF. It served financing the PostDoc of X. Liu on Nesterov’s acceleration scheme for inverse shape problems (2020-2022).
- A PhD funding from DIM, a regional program promoting collaboration between academia and small industrial partners. It served financing the PhD of D. Lerévérand in collaboration with the association Le collectif with the goal of providing numerical solutions for realistic audio applicable to the project Le Cartable Connecté.

9 Dissemination

Participants: Jing Rebecca Li, Marcella Bonazzoli, Houssem Haddar, Lorenzo Audibert, Matthieu Aussal.

9.1 Promoting scientific activities

9.1.1 Scientific events: organisation

Member of the organizing committees

- L. Chesnel co-organized the Journée de rentrée of the CMAP.
- L. Chesnel co-organized the seminar of the CMAP.
- L. Chesnel co-organized the seminar of the Inria teams Defi-M3DISIM-Poems.
- L. Chesnel co-organized the matinée Développement durable of the CMAP.
- M. Bonazzoli and J. Heleine organized a francophone young researchers conference on software development for research at Inria Saclay (France) (JCJC Développement 2021)
- M. Bonazzoli organizes the group seminar of IDEFIX team.

9.1.2 Scientific events: selection

Member of the conference program committees

- L. Chesnel and H. Haddar are members of the scientific committee of the Waves conference.

9.1.3 Journal

Member of the editorial boards

- H. Haddar is
  - Member the editorial board of Inverse Problems, SIAM Journal on Scientific Computing and SIAM Journal of Mathematical Analysis.
  - Guest editor of a special issue on transmission eigenvalues in the journal Research in the Mathematical Sciences (to appear in 2022).

9.1.4 Invited talks

- L. Chesnel gave a course untitled "Small obstacle asymptotics" at the 11th Zurich Summer School 2021, August 2021.
- L. Chesnel: Acoustic passive cloaking using thin outer resonators, Days on Diffraction, Saint Petersburg, May 2021.
- M. Bonazzoli: Numerical Waves conference, Nice, Oct. 2021.
- H. Haddar gave a talk in the International Zoom Inverse Problems seminar, Feb 2021, on Duality between invisibility and resonance.
- H. Haddar gave a zoom talk at the seminar of the Math. Department University of Delaware, March 2021.
- H. Haddar gave a zoom talk at the seminar of the math department of Nancy University, June 2021.
- H. Haddar is invited speaker at the ICAAM conference, Sousse, Decempber 20-22, 2021.

9.1.5 Leadership within the scientific community

- J.-R. Li is a member of the SIAM Committee on Programs and Conferences

9.1.6 Research administration

- L. Audibert is a member of the scientific comitee of EDF-INRIA-CEA summer school (since 2020).
- L. Audibert was a member of the evaluating committe 46 of the ANR for the aapg 2021.
- M. Bonazzoli is the International partnerships Scientific Correspondent for Inria Saclay.
- M. Bonazzoli took part to the recruitment committee (jury d'admissibilité) for the 2021 Inria Saclay recruitment campaign of junior permanent researchers.
- M. Bonazzoli took part in Jul. 2021 to the prize committee for Prix Junior Maryam Mirzakhani awarded by Fondation Mathématique Jacques-Hadamard (FMJH) to two young female students for a mathematics project.
- M. Bonazzoli took part to the working group "Diffusion de l'information" (webpage, Intranet, welcome booklet) at CMAP (École Polytechnique).
- M. Bonazzoli is a volunteer member of Opération Postes (newsletter and website, which gathers detailed information about the French competitive selections for permanent positions in Mathematics and Informatics, supported by the French academic societies SMAI, SMF, SFdS, and SIF).

9.2 Teaching - Supervision - Juries

9.2.1 Teaching

- Doctorat: H. Haddar et L. Audibert, Inverse problems: Algorithms and Applications. Executive Education, Ecole Polytechnique.
- Licence: H. Haddar, Complex analysis and Elementary tools of analysis for partial differential equations, for students in the first year of Ensta ParisTech curriculum. 37 equivalent TD hours. 2021-present.
- Master: L. Chesnel, Elementary tools of analysis for partial differential equations, for students in the first year of Ensta ParisTech curriculum, 15 equivalent TD hours.
- Master: L. Chesnel, Analyse variationnelle des équations aux dérivées partielles, for students in the second year of Ecole Polytechnique, 2x5 TDs of 2h each.
- Master: L. Chesnel, Modal - Modélisation mathématique par la démarche expérimentale, for students in the second year of Ecole Polytechnique, creation and supervision of a project for two students.
- Master: L. Chesnel, cosupervision of a psc project of five students, for students in the second year of Ecole Polytechnique, 2h meetings every 2 weeks.
- Master: J.-R. Li, M2 internship supervision of Anh Tu Tran.
- Master: M. Bonazzoli, Mathematics for data science, 1st year of Informatics Master, Université Paris-Saclay, 21 hours (lessons and TD).
- Master: La méthode des éléments finis, 2nd year of Engineer School, ENSTA Paris, 12 TD hours.
- Bachelor: M. Bonazzoli, Fonctions de variable complexe, 1st year of Engineer School, ENSTA Paris, 12 TD hours;
- Bachelor: M. Bonazzoli, supervision of the 1st year Engineer school internship of S. El Mennaoui (ENSTA Paris).

9.2.2 Supervision

- PhD in progress: M. Rihani, Maxwell's equations in presence of metamaterials (to be defended in February 2022), A.-S. Bonnet-BenDhia and L. Chesnel.
- PhD in progress: C. Fang, Enabling cortical cell-specific sensitivity on clinical multi-shell diffusion MRI microstructure measurements (2019-), J.-R. Li and D. Wassermann.
- PhD in progress: Z. Yang, Reduced model of diffusion MRI in the brain white matter (2020-), J.-R. Li.
- PhD in progress: T.A. Vu, One-shot inversion methods and domain decomposition (2020-), M. Bonazzoli and H. Haddar.
- PhD in progress: F. Pourre, Construction and analysis of spectral signatures for defects in complex media(2021-), L. Audibert and H. Haddar.
- PhD in progress: Dorian Lerévérend, 3D audio for connecting children with classrooms, (to be defended in 2023), M. Aussal and H. Haddar.
- PhD in progress: Nouha Jenhani, Imaging of local defects in periodic layers, (to be defended in 2023), Y. Boukari and H. Haddar
- PhD in progress: Amal Labidi, Stability analysis of inverse problems for the magnetic Schrödinger equation (to be defended in 2023), M. bellasoued and H. Haddar
- PhD in progress: Rahma Jribi, Imaging of discontinuous parameters using Khon-Vogelius functional and one shot approach, (to be defended in 2023), S. Chaabane and H. Haddar

9.2.3 Juries

- H. Haddar president of the PhD jury of Damien CHICAUD, December 2021.

9.3 Popularization

9.3.1 Internal or external Inria responsibilities

- L. Chesnel was a coordinator of the Sustainable development commission of CMAP.
- J.-R. Li is a member of the INRIA Commission d'Evaluation.
- M. Bonazzoli supervised the "science popularization doctoral mission" of A. J. Kouam Djuigne (Inria Saclay research center offers to PhD students complementary funding for science popularization missions).

9.3.2 Education

- L. Chesnel made a presentation in the context of the Fête de la science 2021 to several groups of young students (from 10 to 17 years old).

9.3.3 Interventions

- L. Audibert gave a talk at Journée Scientifique Inria (JSI) on the IDEFIX joint team with EDF R&D (2021).
- M. Bonazzoli participated to several speed-meetings with female high school students (Rendez-vous des Jeunes Mathématiciennes et Informaticiennes, Inria Saclay, Feb. 2021; Journée Filles, Maths et Informatique : une équation lumineuse, École Polytechnique, Apr. 2021; JFMI, Animath and Femmes&Mathématiques, Nov. 2021) to answer their questions about the studies and career as a mathematician.

- M. Bonazzoli gave a science popularization talk on the International Day of Women and Girls in Science (École Polytechnique, Feb. 2021) for high school and middle school students, and another one at a lecture series organized by Pôle Diversité et Réussite de l'École Polytechnique (Jan. 2021) for high school students.

10 Scientific production

10.1 Publications of the year

International journals

[1] S. D. Agdestein, T. N. Tran and J.-R. Li. 'Practical computation of the diffusion MRI signal based on Laplace eigenfunctions: permeable interfaces'. In: *NMR in Biomedicine* (2021). DOI: 10.1002/nbm.4646. URL: https://hal.archives-ouvertes.fr/hal-03477416.

[2] L. Audibert, L. Chesnel, H. Haddar and K. Napal. 'Qualitative indicator functions for imaging crack networks using acoustic waves'. In: *SIAM Journal on Scientific Computing* (2021). URL: https://hal.archives-ouvertes.fr/hal-02873118.

[3] A. Bera, A.-S. Bonnet-Ben Dhia and L. Chesnel. 'A continuation method for building invisible obstacles in waveguides'. In: *Quarterly Journal of Mechanics and Applied Mathematics* (26th Feb. 2021). URL: https://hal.archives-ouvertes.fr/hal-02573706.

[4] M. Bonazzoli, X. Claeys, F. Nataf and P.-H. Tournier. 'Analysis of the SORAS domain decomposition preconditioner for non-self-adjoint or indefinite problems'. In: *Journal of Scientific Computing* 89 (2021). DOI: 10.1007/s10915-021-01631-8. URL: https://hal.archives-ouvertes.fr/hal-02513123.

[5] F. Cakoni, D. Colton and H. Haddar. 'Transmission Eigenvalues'. In: *Notices of the American Mathematical Society* 68.09 (1st Oct. 2021), pp. 1499–1510. DOI: 10.1090/noti2350. URL: https://hal.archives-ouvertes.fr/hal-03503132.

[6] L. Chesnel, J. Heleine and S. A. Nazarov. 'Design of a mode converter using thin resonant ligaments'. In: *Communications in Mathematical Sciences* (2021). URL: https://hal.archives-ouvertes.fr/hal-03141128.

[7] L. Chesnel and S. Nazarov. 'Abnormal acoustic transmission in a waveguide with perforated screens'. In: *Comptes Rendus. Mécanique* (2021). URL: https://hal.archives-ouvertes.fr/hal-02907039.

[8] L. Chesnel and S. A. Nazarov. 'Design of an acoustic energy distributor using thin resonant slits'. In: *Proceedings of the Royal Society of London. Series A, Mathematical and physical sciences* (2021). URL: https://hal.archives-ouvertes.fr/hal-03003171.

[9] H. Haddar and M. K. Riahi. 'Near-field linear sampling method for axisymmetric eddy current tomography'. In: *Inverse Problems* 37.10 (27th Aug. 2021), p. 105002. DOI: 10.1088/1361-6420/ac1c50. URL: https://hal.inria.fr/hal-03517989.

Reports & preprints

[10] L. Audibert, H. Haddar and X. Liu. *An accelerated level-set method for inverse scattering problems.* 3rd Dec. 2021. URL: https://hal.archives-ouvertes.fr/hal-03465136.

[11] A.-S. Bonnet-Ben Dhia, L. Chesnel and M. Rihani. *Maxwell's equations with hypersingularities at a conical plasmonic tip.* 22nd Dec. 2021. URL: https://hal.archives-ouvertes.fr/hal-02969739.

[12] L. Chesnel, J. Heleine and S. A. Nazarov. *Acoustic passive cloaking using thin outer resonators.* 3rd May 2021. URL: https://hal.archives-ouvertes.fr/hal-03216053.

[13] H. Montanelli, M. Aussal and H. Haddar. *COMPUTING WEAKLY SINGULAR AND NEAR-SINGULAR INTEGRALS IN HIGH-ORDER BOUNDARY ELEMENTS.* 25th Nov. 2021. URL: https://hal.archives-ouvertes.fr/hal-03518653.